ABSTRACT
Climate sensitivity is investigated for 10 models that are participating in the IPCC Fourth Assessment Report. We consider the temporal evolution of climate sensitivity and we analyze the transient climate sensitivity from fully coupled simulations with a 1% per year increase in CO$_2$ in terms of the all sky, clear sky and cloudy sky components. We find the following results: 1) there is nearly a factor of two spread in the transient climate response (1.39 to 2.66 °C) among the 10 models, 2) there is little over a factor of two spread in climate sensitivity, 3) there is nearly a factor of two spread in the ocean heat uptake efficiency among the models.

In the past, much of the difference in climate sensitivity has been ascribed to clouds. However, we find that there is also a significant range of uncertainty in the clear sky sensitivity, where the longwave clearsky sensitivity varies by a factor of ~60% and the shortwave clearsky sensitivity varies by a factor of ~4. We also find poor correlation between the transient climate response and the equilibrium climate sensitivity, which calls into question the relevance of equilibrium sensitivity in defining probability density functions for climate change research.

Model Simulation
We use results from the PCMDI archive for the IPCC AR4. At present we have analyzed ten models, listed in the table below.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Institution / Country</th>
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</thead>
<tbody>
<tr>
<td>MIROC3.2 Hires</td>
<td>CCSR / Japan</td>
</tr>
<tr>
<td>CM4</td>
<td>IPSL / France</td>
</tr>
<tr>
<td>ECHAM5-MPIOM</td>
<td>MPI / Germany</td>
</tr>
<tr>
<td>CGCM3.1</td>
<td>CCCMA / Canada</td>
</tr>
<tr>
<td>HadGEM1</td>
<td>UKMO / UK</td>
</tr>
<tr>
<td>GISS-ER</td>
<td>GISS / USA</td>
</tr>
<tr>
<td>GISS-EH</td>
<td>GISS / USA</td>
</tr>
<tr>
<td>CM2.1</td>
<td>GFDL / USA</td>
</tr>
<tr>
<td>MK.3</td>
<td>CSIRO / Australia</td>
</tr>
<tr>
<td>CCSM3</td>
<td>NCAR / USA</td>
</tr>
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</table>

The simulations are from fully coupled models where CO$_2$ has been increased by 1% per year past the point of doubling (~year 70). We have focused on an analysis of climate response centered at the point of doubling. Results at the point of doubling are based on a 20 year centered average from the 1% simulations and a 100 year average of the model control simulations.

Methodology
We employ the methodology developed by Gregory and Mitchell (1997) and Raper et al. (2002) to analyze the model sensitivities. This method is based on the following formulation. In the global mean the energy budget of the climate system is:

\[ \Delta Q = \Delta \lambda T + \Delta T \]

where the left hand side is the heat storage of the system, \( \Delta Q \) is the amount of energy applied to the system (i.e. the climate forcing), \( \lambda \) is the climate sensitivity and \( \Delta T \) is the climate response, as given by the change in global mean surface air temperature. For annual means or longer, the heat storage is dominated by the amount of energy, \( \Delta Q \). It is assumed that the climate sensitivity is constant as the climate changes.

If we define the ocean heat uptake efficiency as:

\[ \eta = \frac{\Delta Q}{\Delta T} \]

then, \( \Delta Q = \eta \Delta T \).

The climate sensitivity factor is given by:

\[ \lambda = \frac{\Delta \lambda}{\Delta T} \]

where \( \Delta \lambda \) is the change in longwave sensitivity, \( \Delta \lambda \) is the change in shortwave sensitivity.

At the doubling point of CO$_2$, we use a \( \Delta Q \) value of 3.6 Wm$^{-2}$ (Kiehl et al. 2006). These relations imply that:

\[ \lambda_c = \frac{\Delta \lambda_c}{\Delta T} \]

where \( \lambda_c \) denotes top of atmosphere longwave and shortwave fluxes. Ideally these should be top of model fluxes, but we have shown for the CCSM3 that the change in this flux is very similar to the change in top of atmosphere flux, at least out to a doubling of CO$_2$. Note that a positive cloud sensitivity (\( \lambda_{cloud} > 0 \)) implies a larger \( \lambda \), and hence a larger climate response for a given forcing.

Inter-Model Comparison
There are significant differences in both longwave and shortwave clear sky sensitivities. A dominant factor is changes in upper tropospheric water vapor, and we are currently examining this. Changes in snow cover and sea-ice are also important factors. The net clear sky sensitivity is the difference between the longwave and shortwave sensitivities. As expected, there are large differences in the cloud sensitivities. Three models (MIROC, IPSL and CCMA) have positive net cloud sensitivity, where the dominant term is the positive shortwave cloud forcing. This is most likely due to a decrease in low cloud amount for a warmer climate. The other 7 models have net negative cloud sensitivity and therefore suppress warming due to increased CO$_2$. The agreement in sign is due to different reasons. The CCSM3 has both negative longwave and shortwave cloud sensitivity, while the GISS models have positive shortwave cloud sensitivity, but a large negative longwave sensitivity as do all other models.

An interesting relation exists between the climate sensitivity and the transient climate response, as in the figure on the left. There is a near linear relationship between \( \lambda \) and the TCR, while the ocean heat uptake efficiency is nearly invariant with the TCR. Finally, it is of interest to ask to what extent the TCR is correlated to the equilibrium climate sensitivity, i.e. the change in global mean surface temperature due to a doubling of CO$_2$ obtained from atmospheric models coupled to slab ocean models. The figure on the right shows that there is little correlation. Note there are three models whose equilibrium response is nearly identical at two points (i.e. near 3.4 °C and 4.4 °C) and that the TCR varies by ~50%. This is very relevant for techniques that employ the equilibrium sensitivity to determine a PDF for climate change research. This figure also indicates that the PDF of the TCR would be different from that of the equilibrium response at doubling.

Climate Sensitivity Factor Timeseries
It is of interest to consider the time dependence of the climate sensitivity. Low order models assume that the climate sensitivity is constant as the climate changes. Although there is some variation in time, to first order the climate sensitivity of the models appears to be relatively constant as the climate warms.

Summary
We have carried out a sensitivity analysis of 10 models participating in the IPCC AR4. We find significant variation in not only cloud sensitivity, but also the longwave and shortwave clear sky sensitivity. We also find an indication that the TCR is poorly correlated with the equilibrium response, indicating that this could affect a PDF approach to looking at climate sensitivity.

References:
