On the linearity of Climate Sensitivity:

A case study for the future and the PETM.

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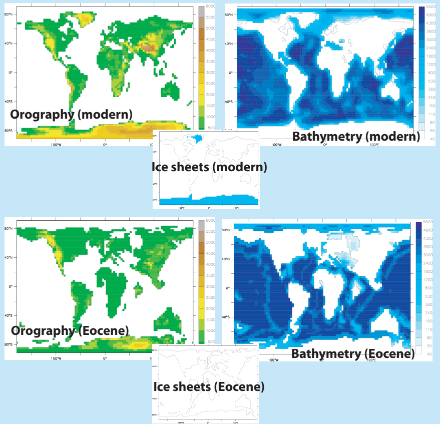
(1) INTRODUCTION

Climate Sensitivity is a key parameter for quantifying the response of the entire Earth System to a perturbation in radiative forcing, via a doubling of atmospheric CO_2 concentration. However, Climate Sensitivity is expected to be non-linear, due to the non-linear nature of climatic feedbacks. It is expected to have a different value if doubling CO_2 from a preindustrial level (x1 to x2), to doubling CO_2 from an already elevated level (e.g. x2 to x4). Climate Sensitivity is also expected to have varied in Earth's history, where potential feedback mechanisms, in particular ice-albedo, may have been considerably different to modern (e.g. at the Last Glacial Maximum, or in the icesheet-free world of the Eocene, 50 million years ago). Here, we investigate Climate Sensitivity on geological timescales. In particular, we investigate the non-linearity of Climate Sensitivity under modern-day and Eocene boundary conditions. We carry out simulations at x1, x2, x4, x8, and x16 CO_2 concentrations, relative to pre-industrial. We then carry out an similar suite of CO_2 simulations but under Eocene boundary conditions (i.e. solar constant, paleotopography and paleobathymetry appropriate for 50 million years ago).
The modern simulations are a proxy for future climate change, and the Eocene simulations for the climate of the PETM (Paleocene-Eocene Thermal Maximum, 55.5 Ma).

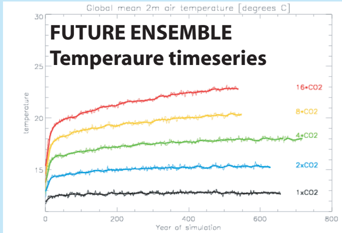
(2) EXPERIMENTAL DESIGN

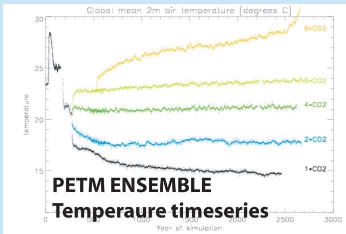
We carry out a suite of fully-coupled atmosphere-ocean simulations, using the UK Met Office model, HadCM3L. We run for two time periods (modern and Eocene), and with a variety of CO_2 concentrations
The boundary conditions for the two time periods considered are shown below:



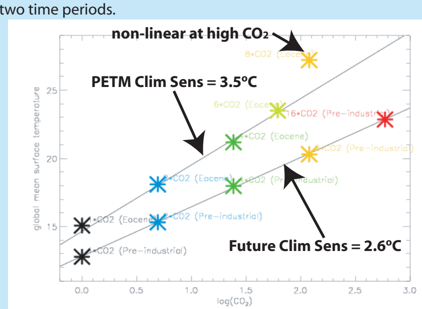
(3) GCM RESULTS

Below are timeseries of global annual mean surface temperature, for our future and PETM ensembles of simulations. Note that the PETM simulations are of the order 2500 years long, whereas the future simulations are around 600 years long.





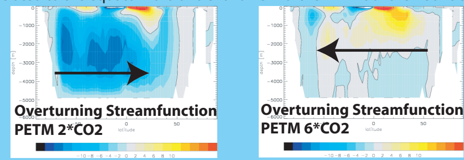
Below is a plot illustrating the resulting climate sensitivity for the two time periods.

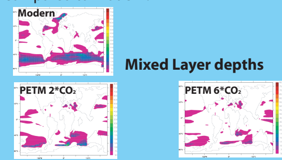


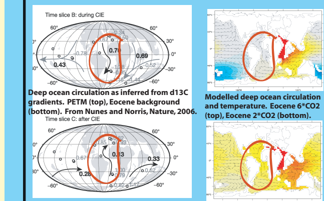
The offset in surface temperature between the future and the PETM is due to the fact that there are no ice sheets in our PETM simulations The greater gradient at the PETM is also due to the lack of permanent ice sheets - a given change in forcing leads to a greater albedo change at the PETM as snow can be melted, whereas in the model ice sheets are fixed. The non-linearity at high CO_2 at the PETM is due to a runaway greenhouse effect. If the model is correct, this puts some sort of limit on the maximum CO_2 concentration likely at the PETM.

(5) OCEAN CIRCULATION CHANGES AT THE PETM

There are some fascinating ocean circulation changes which occur in our PETM simulations, which have some support from proxy data. Below (left) is the global ocean meridional streamfunction for the 2*CO_2 and 6*CO_2 cases. The low CO_2 regime is characterised by sinking in the Southern Ocean, whereas at high CO_2 the ocean becomes more diffusive, with little sinking except in the Indian Ocean (see also mixed layer depths, below right). The cause of these ocean circulation changes appears to be related closely to the Antarctic climate. At low CO_2, there is significant snow cover over Antarctica, which acts to maintain cold temperaures, and results in dense surface waters off Antarctica, which are able to sink. At high CO_2, a threshold is reached where the snow mostly dissappears, and the surface Southern Ocean waters are less dense, resulting in stratification. The lack of Northern Hemisphere sinking in any PETM simulations appears to be related to the equatorward and shallower northern limit of the Atlantic basin compared to modern.







The plots on the far left show possible changes in circulation at the PETM, inferred from changes in gradients of d^{13}C (Nunes and Norris, Nature, 2006). The model results (right) appear to support this interpretation, indicating a reversal in the direction of Atlantic deep water in a high CO_2 climate during the Eocene. The model results suggest that the changes in circulation are a possible consequence of elevated greenhouse gas concentrations, rather than a driver of elevated PETM temperatures.

(6) CONCLUSIONS

We have carried out 2 suites of CO_2 sensitivity studies, under modern and Eocene boundary conditions. The modern suite is an analogue for future climate change; the Eocene suite is an analogue for the PETM. The modern is extremely linear, with a climate sensitivity to doubling CO_2 of 2.6°C. The Eocene is mostly linear (3.5°C), but dispays a strong water-vapour runaway feedback at high CO_2. The higher Eocene Climate Sensitivity is due to the lack of an Antarctic ice sheet; the fixed ice sheet suppresses albedo feedback in the modern.
The ocean circulation in the Eocene simulations is diagnosed. In particular, there is a reversal in the direction of the deep Atlantic water transport, going from northward in the 2*CO_2 simulation to southward in the 6* CO_2 simulation, in agreement with recent data (Nunes and Norris, 2006). The switch is associated with the formation of Antarctic Deep Water, and is driven by increasing atmospheric air temperatures over Antarctica, enhanced by snow melt. The model results suggest that the changes in circulation are a possible consequence of elevated greenhouse gas concentrations, rather than a driver of elevated PETM temperatures.