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Climate model sensitivity to atmospheric CO_2 concentrations for the middle Miocene

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ABSTRACT

We present results of the first middle Miocene climate modelling study using the latest NCAR Community Atmosphere Model (CAM v.3.1) and Community Land Model (CLM v.3.0) coupled to a slab ocean. We examine the sensitivity of the middle Miocene climate to varying concentrations of atmospheric carbon dioxide (180, 355 and 700 ppm). Model simulations are forced with realistic Miocene boundary conditions for continental geometry, topography and vegetation. Global annual mean surface temperature increases by 2.2 °C with each successive doubling of CO_2 which is consistent with climate sensitivity of previous paleoclimate studies and estimates for future climate. In addition to growing evidence that tropical sea surface temperatures were higher than suggested by proxy-data, our understanding of middle to high latitude warming mechanisms is still incomplete. We compare our results to the late Miocene study of Steppuhn et al. [Steppuhn, A., Micheels, A., Bruch, A., Uhl, D., Utescher, T., Mosbrugger, V., 2007. The sensitivity of ECHAM4/ML to a double CO_2 scenario for the Late Miocene and the comparison to terrestrial proxy data. Global and Planetary Change, 57, 189–212] to explore the dependence of paleoclimate model sensitivities on different software systems and boundary conditions. Our comparison shows climate sensitivity to be overall quite robust — this is as significant, as it is often unclear to what extent simulation behaviour and outputs are dependent on a particular model implementation and initial/boundary conditions. Some distinct differences in model outputs, such as our reduced latitudinal surface temperature gradient and stronger Asian monsoon system, compared to the late Miocene study of Steppuhn et al. [Steppuhn, A., Micheels, A., Bruch, A., Uhl, D., Utescher, T., Mosbrugger, V., 2007. The sensitivity of ECHAM4/ML to a double CO_2 scenario for the Late Miocene and the comparison to terrestrial proxy data. Global and Planetary Change, 57, 189–212] are shown to be closely linked to the choice of topography, vegetation and ocean heat flux.

1. Introduction

The middle Miocene Climatic Optimum, ~17 to 15 Ma, represents the last long-lived warming event of the Cenozoic Era with the possibility of middle latitudes about 6 °C warmer compared to present day (Flower and Kennett, 1994). Recent research efforts have focused on understanding the driving mechanisms for warm climate events in the geological past (Huber and Sloan, 2001; Shellito et al., 2003), seeking to unravel analogies with potential future warming. In the past, the most frequent explanations for warm paleo "greenhouse" climates have been elevated concentrations of greenhouse gases and increases in ocean heat transport.

A wide range of atmospheric carbon dioxide (CO_2) concentration estimates have been made for the middle Miocene (Table 1), adding to the challenge of specifying the climate driving mechanisms from a myriad of boundary conditions. Estimations span concentrations at or below preindustrial levels to almost double present day levels. Due to marine isotopic reconstruction of relatively low and constant CO_2 levels throughout the Miocene, there is currently a strong controversy over the role of atmospheric CO_2 on influencing climate and the inference of a CO_2-temperature decoupling (Pagani et al., 1999; Mosbrugger et al., 2005). Tectonic and oceanographic processes have been argued as the primary driver of Miocene climate with CO_2 playing a secondary role. Furthermore, studies have supported elevated CO_2 throughout the Miocene (Cowling, 1999; Sheldon, 2006), in light of global vegetation patterns and reproduction of observed mineral assemblage of paleosols. A recent study by Kürschner et al. (2008) presents Miocene CO_2 reconstructions from stomatal frequency data showing strong fluctuations between ~300 and 600 ppm. The fluctuations are shown to be coupled to climate events, hence providing evidence that CO_2 did play a major role in influencing the long-term climate evolution of the Miocene as recorded from marine oxygen isotope records (Zachos et al., 2001).

Numerous paleoclimate studies have checked climate sensitivity to increases in atmospheric CO_2 such as Steppuhn et al. (2007) for the late Miocene and Shellito et al. (2003) for the early to middle Paleogene. Alternatively, the reconfiguration of oceanic gateways may have altered oceanic circulation enhancing poleward heat transport,

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Table 1
Middle Miocene atmospheric CO_2 estimations (ppm) by different authors.

Reference	CO_2 (ppm)	Estimation method
Pearson and Palmer (2000)	140 to 300	Marine $\delta^{11}B$
Pagani et al. (1999)	180 to 290	Marine $\delta^{13}C$ and $\delta^{18}O$
Royer et al. (2001)	300 to 450	Leaf stomatal indices/partial pressure of CO_2
Kürschner et al. (2008)	300 to 600	Stomatal frequency data from tree species
Cerling (1991)	<700	Paleosol carbonate $\delta^{13}C$

however mechanisms driving this process have yet to be identified. Huber and Sloan (2001) used a fully dynamical model to simulate Eocene climate, and rejected the hypothesis of increased ocean heat transport sustaining high latitude warming. The consistent problem in paleoclimate modelling of the inability to reproduce the shallower latitudinal sea surface temperature (SST) gradient characteristic of past "greenhouse" climates (Sloan and Rea, 1995; Shellito et al., 2003) is yet to be resolved. There is growing evidence of a poor representation of paleo-water temperatures in proxy data. In the event of recrystallization of planktonic foraminifer shells during burial on the sea floor, oxygen isotope paleo SST estimates will have a bias towards colder temperatures, especially at low latitudes where there is a strong temperature gradient through the water column (Wilson et al., 2002; Pearson et al., 2007). Limitations in interpretation methods also add uncertainty. It can be difficult to constrain seawater oxygen isotope and Mg/Ca ratios due to temporal and spatial variations of oxygen isotopes and carbonate ion concentrations (Shevenell et al., 2004; Pearson et al., 2007). Furthermore, measurements are not always within the range of calibration, consequently requiring extrapolation of the calibration. This was necessary in the work of Pearson et al. (2007) in which the TEX_{86} (tetraether index of 86 carbon atoms) method was used for analysis of membrane lipids.

Model comparison studies are important in the field of climate modelling. Due to the complex physics integrated in general circulation models and the various methods of numerical computation, it is ideal that climate experiments be conducted with various models in order to test the deviation of results. In addition, such studies allow examination of the role different forcing boundary conditions play in influencing climate mechanisms. Result similarities may reflect overall robustness of the models despite their complexity which can be quite reassuring, while differences can usually be associated with boundary conditions and model biases. Model–model comparison studies are a key objective of the Paleoclimate Modelling Intercomparison Project (PMIP).

There are two main objectives of the present study. First, to examine climate sensitivity of our "best guess" middle Miocene climate model to increasing CO_2 concentrations. The middle Miocene is a period for which

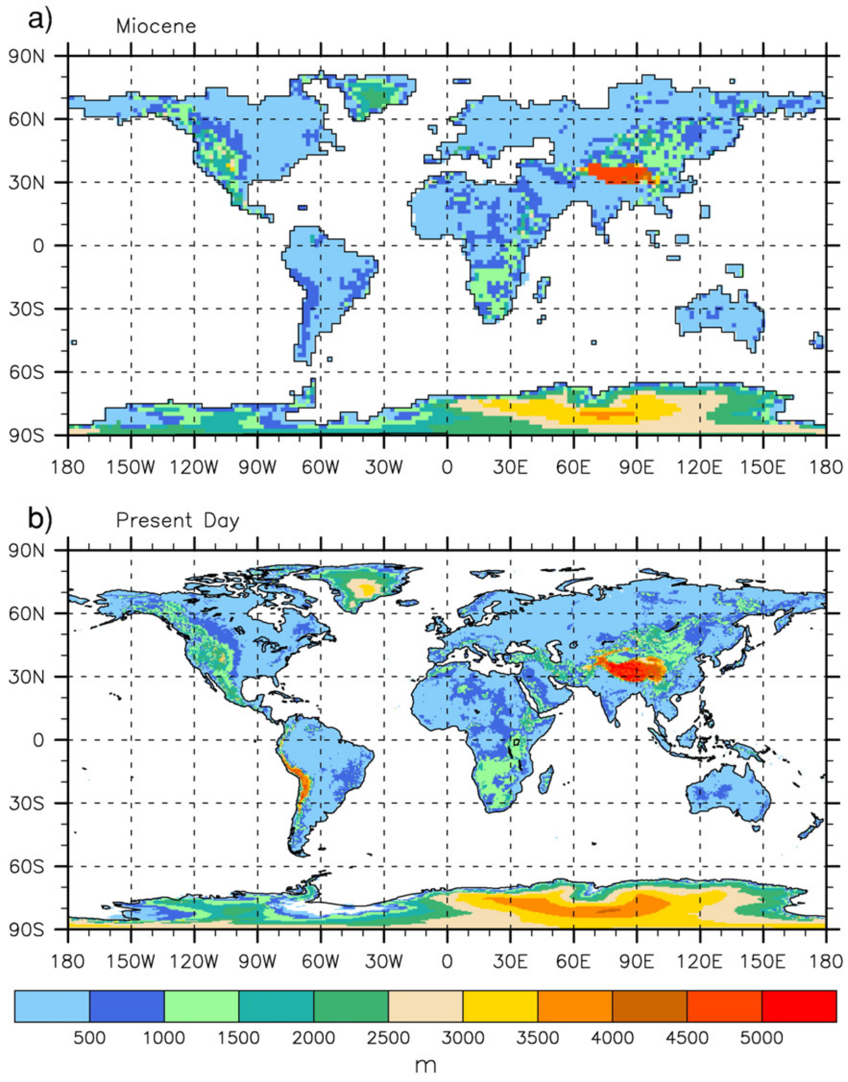

Fig. 1. (a) The topography boundary condition for the middle Miocene simulations and (b) the present day topography profile based on the U.S. Geological Survey GTOPO30 digital elevation model.