Clim. Past Discuss., 4, S776–S782, 2009
www.clim-past-discuss.net/4/S776/2009/

Climate
of the Past
Discussions

Interactive comment on “Constraining atmospheric CO_2 content during the Middle Miocene Antarctic glaciation using an ice sheet-climate model” *by* P. M. Langebroek et al.

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Received and published: 13 July 2009

1. The main goal of the manuscript is to compare the effects of atmospheric CO_2 content (pCO$_2$) and insolation on the expansion of the Antarctic ice sheet. We chose to apply our pCO$_2$ and insolation sensitivity experiments to the Middle Miocene, because for that time period it has been proposed that a special configuration in orbital parameters could have had an impact on the waxing of the Antarctic ice sheet. Instead of perfectly constraining the pCO$_2$ in the Middle Miocene, we rather explore its potential influence on the ice-sheet expansion.

   The title is changed accordingly to: ’Antarctic-ice sheet response to atmospheric CO_2 and insolation in the Middle Miocene’.

2. Response to 'The results from such a study are likely to be highly model dependent':

   The absolute modeled values of $p\mathrm{CO}_2$ are indeed depending on the model parameters. However the results appear rather robust based on extensive sensitivity experiments. The main purpose of the manuscript is to show that the $p\mathrm{CO}_2$-level must have declined just before (or during) the period of oxygen-isotope increase, crossing a $p\mathrm{CO}_2$ glaciation threshold. Hereafter, the exact timing of the Antarctic ice-sheet expansion depends also on the timing of the orbital parameters and the relative minimum in summer insolation at approximately 13.89 Ma. During the revision, the ice sheet-climate model was once more very thoroughly tested. As a result the parameterization of the greenhouse effect was made more realistic, leading to a less extreme polar amplification of the temperature response to an increase in atmospheric $p\mathrm{CO}_2$ concentration.

3. Response to 'lack of Miocene boundary conditions' and 'paleo-boundary conditions':

   The model set-up enables the possibility of performing many sensitivity and hysteresis simulations. The two forcings investigated are $p\mathrm{CO}_2$ and insolation. The latter is derived from orbital parameters (well-defined by Laskar et al., 2004) and is therefore specifically related to the Middle Miocene. The level of atmospheric CO_2 in the Middle Miocene is not defined well enough to directly use as model forcing. This lack of appropriate boundary conditions motivated us to asses the potential range of $p\mathrm{CO}_2$ change. A more detailed discussion comparing our $p\mathrm{CO}_2$ levels with data and other modeling studies is included in the manuscript and briefly discussed below.

   The model does not include an explicit ocean component. Near-surface atmospheric temperatures and albedos, however, are computed in the entire Southern Hemisphere. The extent of sea-ice depends on these atmospheric temperatures and in turn has an effect on the surface albedos.

Initial bedrock topography is likely to have a strong effect on the modeled results. Most three dimensional ice-sheet models (such as DeConto and Pollard, 2003; Pollard and DeConto, 2005) obtain an ice-free bedrock topography from present-day elevations, which is then isostatically adjusted for the removed ice. In this axially symmetric model, we captured the main characteristics of the three-dimensional initial bedrock topography (bulge near the coast and a flatter hinterland) to reconstruct our initial bedrock profile. However, we note that the ice-free topography of Antarctica in the Middle Miocene is poorly constrained and probably differs from the present-day isostatically adjusted bedrock topography. Therefore, other studies use an even more idealized bedrock topography not directly derived from present-day elevations (e.g. Pollard 1983; Oerlemans 2004; Van Tuyll et al., 2007).

4. Response to '(climate) sensitivity of model to $p\text{CO}_2$ change' and '$p\text{CO}_2$ glaciation threshold':

   In the studies of DeConto and Pollard a glaciation threshold of approximately 780 ppm was found. Their study was applied to the Eocene-Oligocene transition, where a strong decrease in $p\text{CO}_2$, crossing the Antarctic glaciation threshold, could have occurred (e.g. DeConto et al., 2008; Zachos et al., 2008). From the Miocene onward the $p\text{CO}_2$ level stayed fairly constant. However, the available published data (e.g. Pearson and Palmer, 2000; Demicco et al., 2003; Pagani et al., 2005; Kürschner et al., 2008) contains large uncertainties. The different methods also result in values that differ by 100-200 ppm between each others indicating an even larger uncertainty with regard to $p\text{CO}_2$.

   In the previously submitted version of this manuscript, an Antarctic glaciation threshold of approximately 400 ppm was suggested. This relatively low threshold was the result of a relatively high sensitivity of the model parameterization of the greenhouse effect. In this regard the equation following Equation (2) of the Appendix in the original manuscript was unfortunately wrong. It should have red:

$$\varepsilon_{10} = \varepsilon_{10}^{\mathrm{CO_2}} + \varepsilon_{10}^{\mathrm{H_2O}} = -0.3 + 0.15 \ln(\mathrm{CO_2}).$$

The resulting Southern Hemisphere climate sensitivity of the original model was 2.8° C for a doubling of $p\mathrm{CO_2}$, which was in the range of values stated in the IPCC report (Randall et al., 2007. However, in Antarctica the temperature increase reached values of 11.6° C. This temperature increase was indeed much larger than the range of global climate models (GCMs) analyzed by Masson-Delmotte et al. (2006a,b). Hence the experiments in the current manuscript are based on a less strong sensitivity of the greenhouse parameterization:

$$\varepsilon_{10} = \varepsilon_{10}^{\mathrm{CO_2}} + \varepsilon_{10}^{\mathrm{H_2O}} = 0.27 + 0.05 \ln(\mathrm{CO_2}).$$

This parameterization is more equivalent to the original equations of Staley and Jurica (1970) and Jentsch (1991), except that the sensitivity to changes in$p\mathrm{CO_2}$ is doubled to account for other greenhouse gasses than $\mathrm{CO_2}$ (for example water vapor).

In a similar way, the $\mathrm{CO_2}$ factor in the lower latitude boxes is doubled from 4 to 8 W/m^2:

$$f_{\mathrm{CO_2}} = -8 \frac{\ln(\frac{\mathrm{CO_2}}{280})}{\ln(2)}.$$

The Southern Hemispheric climate sensitivity in the new model version is 2.5° C. Again the largest increase is found in the surface and atmospheric temperatures on Antarctica, but now with maxima of 4.4 and 3.9° C, respectively. This polar amplification is in the range of GCMs (e.g. Masson-Delmotte et al., 2006a,b). In order to further investigate the sensitivity of the model, we computed the radiative forcing at the top of the atmosphere before and after the doubling of $p\mathrm{CO}_2$. The difference in radiative forcing is around 8 W/m^2. This supposedly includes the feedbacks of $p\mathrm{CO}_2$, water vapor and other greenhouse gasses. The water vapor feedback by itself nearly doubles the climate sensitivity (e.g. Hartmann1994).

Due to the weaker climate sensitivity, the glaciation threshold for the new model version is higher than before and has a value of approximately 615 ppm. This level is between the CO_2 proxy data and the previously modeled values. All simulations (hysteresis, constant $p\mathrm{CO}_2$, sensitivity experiments, etc.) were repeated using the new model version. The fact that they show the same quantitative response to changes in $p\mathrm{CO}_2$ and insolation as in the previous model version, only for the higher absolute $p\mathrm{CO}_2$ values, is an extra indication that the conclusions based on these results are robust.

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