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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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1. Response to 'magnitude and pacing of oxygen-isotope shift' and 'background Middle Miocene':

   In the *Introduction* of the manuscript the background information concerning Antarctica in the Middle Miocene is extended. The rapid increase in oxygen isotopes can be seen in the three high-resolution benthic oxygen-isotope records (Shevenell et al., 2004; Holbourn et al., 2005) now shown in Figure 1. This could be the last step in an orbitally paced series of Antarctic glaciations as proposed by Shevenell et al. (2008). Our model simulations started at 14.1 or 14.2 Ma and therefore can not give any conclusive remarks about the period before. However, variations in the modeled ice volume are orbitally related. Also the timing of the

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major ice-sheet expansion between 13.8 and 13.9 Ma is triggered by a minimum in summer insolation.

In both, the high-resolution oxygen-isotope records and the modeled ice-volume records, we defined the increase over the transition as the difference between the mean value of the period after (14.5–13.9 Ma) and the period before the transition (13.8–13.2 Ma). The mean increase in oxygen-isotope values is approximately 0.5 ‰. The mean ice volumes for the periods are 6.5 and 23.7×10^{15} m^3, respectively. This would account for a sea-level lowering of about 43.3 m. The related increase in the oxygen-isotopic composition of the ocean of $\sim$0.43 ‰ can explain a significant part of the proxy records. In a companion manuscript, submitted elsewhere, oxygen isotopes are included in the ice sheet-climate model in order to better compare the Middle Miocene transition.

2. Response to 'high climate sensitivity and polar amplification' as discussed before with Anonymous Referee 2:

The relatively low threshold values and the large polar amplifications in the previously submitted version of this manuscript 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 read:

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

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

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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 $\mathrm{CO_2}$ proxy data and the previously modeled values. All simulations (hysteresis, constant $p\mathrm{CO_2}$, sensitivity experiments, etc.) were repeated

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using the new model version. The fact that they show the same quantitative response to changes in pCO_2 and insolation as in the previous model version, only for the higher absolute pCO_2 values, is an extra indication that the conclusions based on these results are robust.

3. Response to 'CO$_2$ hysteresis':

   The glaciation threshold for the new model version is approximately 615 ppm. Deglaciation occurs when pCO_2-levels reach $\sim$725 ppm. The resulting hysteresis window of approximately 110 ppm is just slightly smaller than Pollard and DeConto (2005) ($\sim$120 ppm). Huybrechts (1993) performed hysteresis experiments under different bedrock conditions. Depending on the initial bedrock topography he found a hysteresis window varying between $\sim$1 and 5° C. The Antarctic temperatures in our ice sheet-climate model show a difference of approximately 2.5° C between the glaciation and deglaciation threshold, falling well into the range proposed by Huybrechts (1993).

4. Response to 'results weakly influenced by orbital forcing':

   The reduced model sensitivity to changes in pCO_2 causes the orbital forcing to have a relatively stronger influence. Still the constant and step-wise decreasing pCO_2 experiments show that a pCO_2-threshold needs to be crossed in order to glaciate the Antarctic continent. The exact timing of the ice-volume expansion hereafter depends on the orbital forcing. The second set of sensitivity experiments dealing with the timing of the pCO_2-drop are now also compared to annual and summer mean insolation (Figure 8 in manuscript). All experiments under constant pCO_2 conditions show a large connection to orbital forcing (see the comparison to insolation).

5. Response to 'late glaciation when pCO_2 is close to threshold value':

   Based on a number of sensitivity experiments it appears that the previous ice history and the orbital forcing conspire to produce the transition at this particular moment in time, approximately 450 ka later than derived from oxygen-isotope records.

6. Response to 'background/previous work needs to be better discussed':

   The revised manuscript discusses the Middle Miocene background as well as previous work covering that period in more detail. This extra discussion can be found in the second and third paragraph in Introduction, the discussion of hysteresis experiments and the first paragraph of *Discussion - Constant* pCO_2 *experiments*. Unfortunately the Middle Miocene results of the ANDRILL project are not yet available.

7. Response to 'implication title':

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

8. Response to 'deglaciation Antarctica':

   In the new model results the deglaciation threshold is found at around 725 ppm. Using a present-day atmospheric CO_2 level of 385 and a moderate pCO_2 increase of 1 ppm/yr (Randall et al., 2007), this threshold might be reached in about 340 yr. Mean hemispheric temperature is than almost 4° C higher than the present-day mean. Compared to previous model studies (e.g. Huybrechts, 1993; DeConto and Pollard, 2003, (15–20° C and $\sim$900 ppm, respectively)) this value is small, but it is possible that ice-sheets are more sensitive to climate changes than previously thought. A new section is included in the manuscript (*Discussion - Hysteresis experiments*) comparing the results of our modeled hysteresis experiments with previous work.

9. Response to 'summer intensity versus duration':

   Both, the large and the small ice sheet, responded to precession and obliquity forcing. However, the ice volume of the large ice sheet is comparatively more dominated by precession. Therefore, it has a stronger correlation to summer insolation and a weaker correlation to annual mean insolation, compared to the small ice sheet. The rapid ice-sheet expansion is paced by a strong minimum in summer insolation, which would indicate a greater importance of precession forcing and summer intensity. In the manuscript this is discussed in the first paragraph of *Constant* p*CO*$_2$ *experiments* and in the last paragraph of the *Sensitivity experiments* in the *Discussion*.

10. Response to 'small ice volume in calibration between sea level and ice volume':

    In this calibration the standard deviations of the model experiments are computed and compared to the standard deviations found in the oxygen-isotope records of Holbourn et al. (2005). We use the relation between apparent sea level and seawater oxygen-isotopes (100 m = 1 ‰) to compare the standard deviations of the ice modeled ice volumes to the standard deviations of the oxygen-isotope records and to estimate the increase in oxygen isotopes due to the modeled ice-sheet expansion. A pCO$_2$ decrease from 640 to 590 ppm, would result in an oxygen-isotope increase of approximately 0.43 ‰, accounting for a large part of the measured 0.5 ‰.

11. Response to 'surprisingly limited East Antarctic ice sheet hysteresis':

    In the new simulation the range in pCO$_2$ forcing glacial-interglacial ice-volume variability needs to be much larger, indicating the relatively much stronger effect of the orbital parameters. The hysteresis resulting from our ice sheet-climate model is discussed and compared to previous work in *Discussion - Hysteresis experiments*.

12. The editorial recommendations have all been done.

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