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Modeling the oxygen isotope composition of the Antarctic ice sheet and its significance to Pliocene sea level

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SUPPLEMENTARY INFORMATION

Isotope budget calculations:

Calculations shown in Table 1 follow the mass-balance approach used by Winnick and Caves (2015):

$$M_{\mathrm{O}} + M_{\mathrm{GIS}} + M_{\mathrm{WAIS}} + M_{\mathrm{EAIS}} = M_{\mathrm{pO}} + M_{\mathrm{pGIS}} + M_{\mathrm{pWAIS}} + M_{\mathrm{pEAIS}} \quad (1)$$

$$M_{\mathrm{O}}\delta^{18}\mathrm{O}_{\mathrm{SW}} + M_{\mathrm{GIS}}\delta^{18}\mathrm{O}_{\mathrm{GIS}} + M_{\mathrm{WAIS}}\delta^{18}\mathrm{O}_{\mathrm{WAIS}} + M_{\mathrm{EAIS}}\delta^{18}\mathrm{O}_{\mathrm{EAIS}} = M_{\mathrm{pO}}\delta^{18}\mathrm{O}_{\mathrm{pSW}} + M_{\mathrm{pGIS}}\delta^{18}\mathrm{O}_{\mathrm{pGIS}} + M_{\mathrm{pWAIS}}\delta^{18}\mathrm{O}_{\mathrm{pWAIS}} + M_{\mathrm{pEAIS}}\delta^{18}\mathrm{O}_{\mathrm{pEAIS}}$$

(2)

Where M_x is the total mass of the modern (M_{O}) and Pliocene (M_{pO}) oceans and Greenland (GIS), West Antarctic (WAIS) and East Antarctic (EAIS) ice sheets. Winnick and Caves (2015) solved these equations for M_{pO} and M_{pEAIS}. In this study we are interested in the Antarctic contribution to $\Delta\delta^{18}\mathrm{O}_{\mathrm{seawater}}$ and are using Pliocene Antarctic ice sheet model simulations for M_{pEAIS}. We therefore ignore changes in the Greenland ice sheet and treat the West and East Antarctic ice sheets together:

$$M_{\mathrm{O}} + M_{\mathrm{AIS}} = M_{\mathrm{pO}} + M_{\mathrm{pAIS}} \quad (3)$$

$$M_{\mathrm{O}}\delta^{18}\mathrm{O}_{\mathrm{SW}} + M_{\mathrm{AIS}}\delta^{18}\mathrm{O}_{\mathrm{AIS}} = M_{\mathrm{pO}}\delta^{18}\mathrm{O}_{\mathrm{pSW}} + M_{\mathrm{pAIS}}\delta^{18}\mathrm{O}_{\mathrm{pAIS}} \quad (4)$$

We take M_{pAIS} and $\delta^{18}O_{pAIS}$ from our simulations and then calculate $\delta^{18}O_{pSW}$ (the Antarctic contribution to $\Delta\delta^{18}O_{benthic}$):

$$\delta^{18}\mathrm{O}_{\mathrm{pSW}} = \frac{M_{\mathrm{O}}\delta^{18}\mathrm{O}_{\mathrm{SW}} + M_{\mathrm{AIS}}\delta^{18}\mathrm{O}_{\mathrm{AIS}} - M_{\mathrm{pAIS}}\delta^{18}\mathrm{O}_{\mathrm{pAIS}}}{M_{\mathrm{O}} + M_{\mathrm{AIS}} - M_{\mathrm{pAIS}}} \quad (5)$$

Our simulated value for the modern mean oxygen isotopic composition of the Antarctic ice sheet is –33.8‰. This is considerably higher than the calculated whole Antarctic value of –54.7‰ of Lhomme et al. (2005). The reason for this discrepancy is due in part to a GCM bias of ~10‰ in modern values for $\delta^{18}O_{precip.}$ when compared with observations over the Antarctic interior, caused by modeled surface temperatures that are too warm (Mathieu et al., 2002). Additionally, our values are in equilibrium with the modern surface climate, in contrast to the values from Lhomme et al. (2005) which account for change in $\delta^{18}O_{ice}$ through successive glacial periods with predominantly lower $\delta^{18}O_{precip}$. We therefore use the Lhomme et al. (2005) values (–54.7‰) throughout for modern $\delta^{18}O_{AIS.}$ For Pliocene values of $\delta^{18}O_{pAIS}$ we use the anomaly between our Pliocene ($\delta^{18}O_{PLIOCENE}$) and pre-industrial control ($\delta^{18}O_{CONTROL}$) simulations:

$$\delta^{18}\mathrm{O}_{\mathrm{pAIS}} = -54.7 + \left(\delta^{18}\mathrm{O}_{\mathrm{PLIOCENE}} - \delta^{18}\mathrm{O}_{\mathrm{CONTROL}}\right) \quad (6)$$

Note that we do not change mean ocean $\delta^{18}O$ in our GCM simulations. The GCM used is an isotope-enabled version of the GENESIS GCM.

<u>Calculation of $\Delta\delta^{18}O_{benthic}$:</u>

In the main paper we highlight two different values for $\Delta\delta^{18}O_{benthic}$ in the literature, 0.31‰ for Modern:G17 and 0.40‰ for Holocene:G17. Although we do not suggest a preference for either value, here we discuss reasons for these differences. The modern value for $\delta^{18}O_{benthic}$ in the LR04 stack (Lisiecki and Raymo, 2005) is 3.23‰, compared with 3.32‰ when averaged over the last 10 kyr and 2.92‰ during MIS G17 (2.95 Ma). The higher value for Holocene $\delta^{18}O_{benthic}$ may be a result of the ice sheets having lower mean $\delta^{18}O_{ice}$ as they would be less equilibrated to modern $\delta^{18}O_{precip}$. Additionally, remnant glacial ice in the early Holocene would also lead to higher values for $\delta^{18}O_{benthic}$ when averaged over the last 10 kyr. Both of these arguments would suggest that Modern:MPWP should be used for $\Delta\delta^{18}O_{benthic}$ over Holocene:MPWP. However, these effects could also lead to higher $\delta^{18}O_{benthic}$ during MPWP interglacials, which are time-averaged due to poor temporal resolution (2.5–5 kyr). A potential solution would be to use a high-resolution $\delta^{18}O_{benthic}$ record. The recently published deep-Pacific ODP Site 1208 shows a Modern:MPWP $\Delta\delta^{18}O_{benthic}$ of 0.49‰ (Woodard et al., 2015). However individual sites may also be affected by ocean circulation changes (this could equally affect the LR04 stack which is weighted towards the Atlantic). Indeed other high-resolution sites show a Modern:MPWP $\Delta\delta^{18}O_{benthic}$ <0.3‰ (M. Patterson, personal communication). A more detailed statistical analysis of $\Delta\delta^{18}O_{benthic}$ is required for individual sites (e.g. Mudelsee et al., 2014), which is beyond the scope of this paper. Here we use the range of 0.3–0.4‰ for $\Delta\delta^{18}O_{benthic}$ and add a ±0.1‰ uncertainty for analytical error, giving a total range of 0.2–0.5‰.

Calculation of Antarctic contribution to MPWP sea level:

We calculate maximum and minimum contributions from the Antarctic ice sheets to MPWP sea level. From $\Delta\delta^{18}O_{benthic}$ we calculate an Antarctic ice sheet component of 0.18 ±0.13 ‰ using Monte-Carlo error propagation to account for uncertainty in the

$\Delta\delta^{18}O_{seawater}$:$\Delta\delta^{18}O_{temperature}$ ratio, retreat of the Greenland ice sheet and analytical error in $\delta^{18}O_{benthic}$. Rearranging equation (5) we determine the Antarctic ice sheet mass change required for $\Delta\delta^{18}O_{seawater}$ at the upper (0.31‰) and lower ends (0.05‰) of our error estimate. For $\Delta\delta^{18}O_{ice}$ we use the upper and lower estimates from our simulations (+2.7 to +3.9‰). This results in an Antarctic mass change of +0.53 to -6.61 $\times 10^{18}$kg. To account for the nonlinear relationship between ice sheet mass change and sea level due to the effect of marine-subglacial basins we use the calibration generated from an Antarctic ice sheet deglaciation simulation (Figure DR2) to convert from mass change to sea level change. This leads to a lower estimate for the Antarctic contribution to MPWP sea level of -1.4 m (a sea level fall) and an upper estimate of +13.1 m.

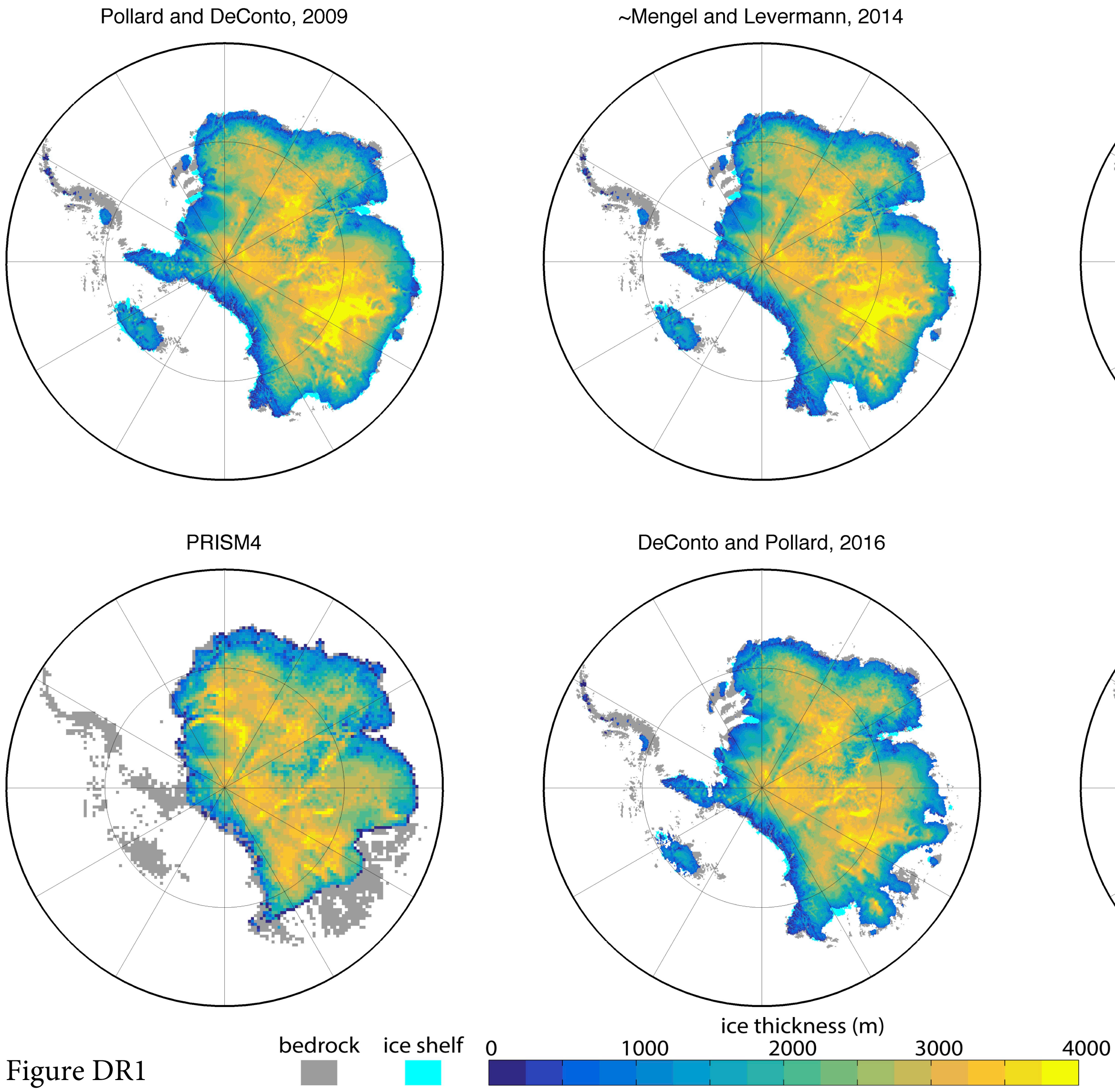
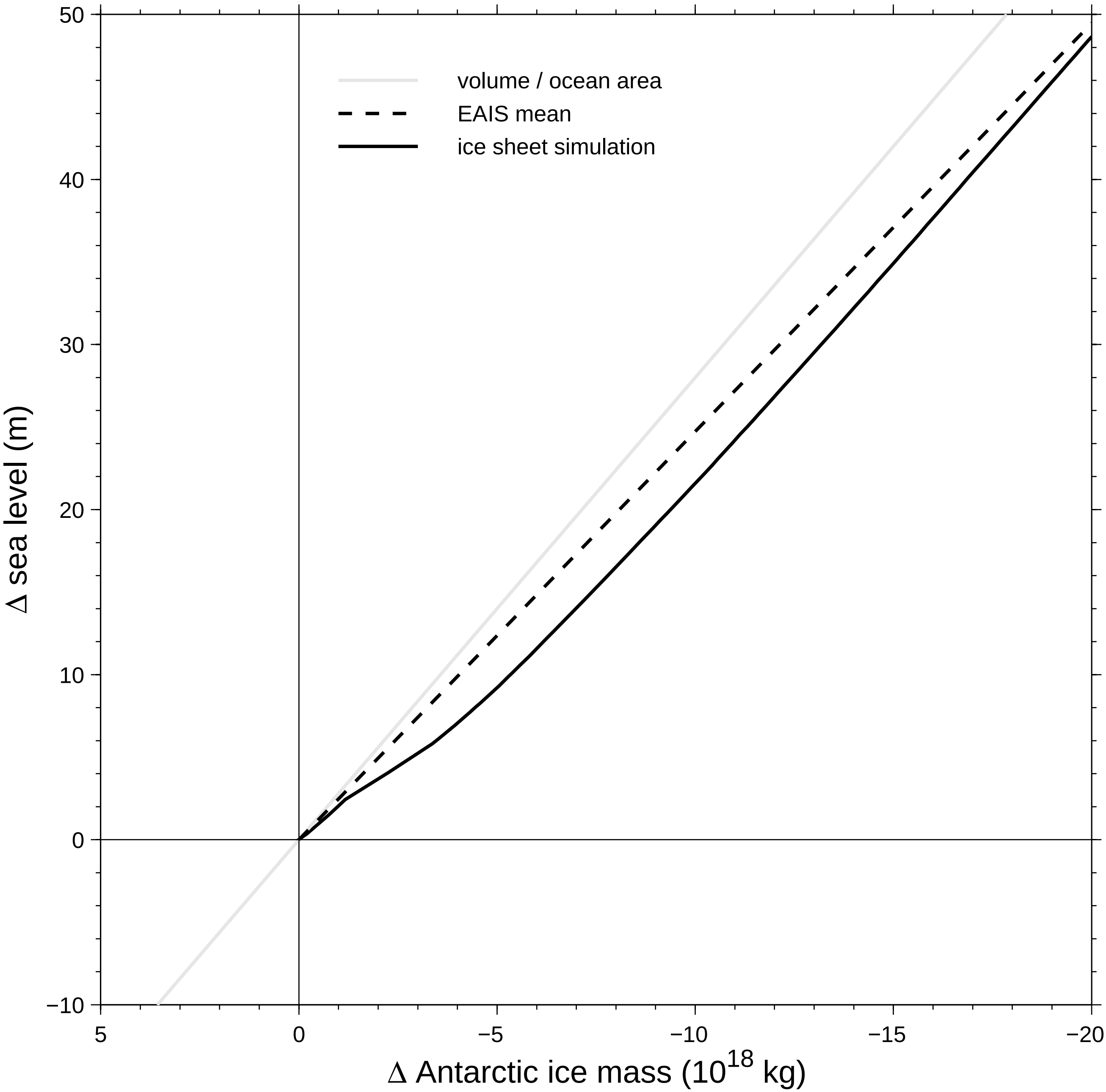

Pollard and DeConto, 2009
~Mengel and Levermann, 2014
Austermann et al., 2015
PRISM4
DeConto and Pollard, 2016
Pollard et al., 2015
bedrock
ice shelf
ice thickness (m)
0
1000
2000
3000
4000

Figure DR1



volume / ocean area
EAIS mean
ice sheet simulation
50
40
30
20
10
0
−10
Δ sea level (m)
5
0
−5
−10
−15
−20
Δ Antarctic ice mass (10^18 kg)

Figure DR2

Figure DR1. Previously published Antarctic ice sheet simulations for the mid-Pliocene warm period, repeated or approximated here using isotope enabled climate and ice sheet models.

Figure DR2. Relationship between Antarctic ice sheet mass change and sea level change. Gray line shows ice volume divided by ocean area after accounting for the change in state from ice to seawater. Dashed black line is the mean relationship for the East Antarctic ice sheet for a total ice mass of 21.55×10^{18}kg and sea level rise of 53.3 m (Fretwell et al., 2013; Winnick and Caves, 2015). Black line is from an Antarctic ice sheet deglacial simulation with initial loss of ice predominantly from marine subglacial basins.