Pliocene sea level revisited: Is there more than meets the eye?

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We reassess available studies of mid-Pliocene sea level and provide new estimates. The relative amplitude of glacial-interglacial sea-level variability was likely between 6.2 m (16th percentile) and 16.7 m (84th percentile), leading to an average ice-volume sensitivity of 4 m/°C sea-level equivalent.

The mid-Pliocene warm period (MPWP), 3.3–3 million years ago, is the most recent time when Earth’s climate reached equilibrium under atmospheric CO₂ concentration of ~400 ppm, with global temperatures 2–3°C higher than during the pre-industrial era (1750 CE; Masson-Delmotte et al. 2013). Sea-level reconstructions for this period suggest peak interglacial sea levels were up to 40 m above present (e.g. Dutton et al. 2015), implying loss of the Greenland, West Antarctic, and marine sectors of the East Antarctic ice sheets, as well as partial loss of the terrestrial East Antarctic Ice Sheet.

Peak magnitude vs relative amplitude
Reconstructions of peak MPWP interglacial sea level are usually reported as global mean sea level (GMSL) with reference to the Holocene. While peak GMSL provides insight into the full magnitude of polar ice-sheet loss and the magnitude of sea-level rise that might be expected because of near-future climate change, it does not capture the full amplitude of glacial-interglacial ice-volume change (Fig. 1), or the full amplitude of sea-level change in response to climate forcing, which may lead to an underestimation of ice volume sensitivity (defined here as the change in sea level equivalent (SLE) of ice volume (m) per 1°C of temperature change).

For example, calibrations of the benthic δ¹⁸O proxy of global ice volume and sea level (e.g. Lisiecki and Raymo 2005) place the sea level during many Pliocene glacials below that of present-day, implying larger-than-present ice-sheet configurations at the beginning of deglaciations. This has significant implications for estimating both the amplitude and rate of sea-level rise in response to relatively small amounts of global warming.

We have categorized “continuous” sedimentary sequences used in reconstructing the amplitude of MPWP GMSL into “direct” (e.g. geologic) and “indirect” (e.g. calibrations of foraminifera δ¹⁸O curves; Fig. 1; Fig. 2a). We compare these glacial-interglacial amplitudes with estimates of the peak MPWP GMSL derived from “direct” but “discontinuous” geological remnants preserved in the far field (e.g. paleo shorelines). In addition, we use ice-volume constraints provided by polar continental margin drill cores (Fig. 1; Fig. 2b). Finally, we provide a quantitative reassessment of peak GMSL and the amplitude of glacial-interglacial global sea-level change during MPWP.

Where the uncertainty lies
Many of these peak GMSL estimates have not been corrected for regional deviations due to tectonics, glacio-isostatic adjustment (GIA), or dynamic topography. Deformation of the Earth may cause local sea-level changes large enough to either cancel out or double the amplitude of the ice-volume contribution (Raymo et al. 2011). Although some recent studies have attempted to correct for these regional effects, significant uncertainty remains concerning the role of dynamic topography (Rovere et al. 2015; Dumitru et al. 2019).

Deep-ocean foraminiferal δ¹⁸O records provide one of the most detailed proxies for glacial-interglacial climate variability during the Pliocene; however, the signal is affected by ocean temperature, ice-sheet δ¹⁸O composition and ice volume (Lisiecki and Raymo 2005). Several studies have used Mg/Ca paleothermometry to calibrate benthic δ¹⁸O records (Dwyer and Chandler 2009; Sosdian and Rosenthal 2009; Miller et al. 2012; Miller et al. 2020). Another approach incorporates sill-depth and salinity changes from the Mediterranean to calibrate sea level in a planktic δ¹⁸O record (Rohling et al. 2014), but large uncertainties (>±10 m) remain.

On the other hand, sea-level calibrations of the benthic δ¹⁸O record, constrained by backstripped continental margins (sedimentary sequences used in reconstructing the terrestrial East Antarctic Ice Sheet), incorporate sill-depth and salinity changes due to tectonics, glacio-isostatic adjustment (GIA), or dynamic topography. Deformation of the Earth may cause local sea-level changes large enough to either cancel out or double the amplitude of the ice-volume contribution (Raymo et al. 2011). Although some recent studies have attempted to correct for these regional effects, significant uncertainty remains concerning the role of dynamic topography (Rovere et al. 2015; Dumitru et al. 2019).

In contrast, Grant et al. (2019) derived a continuous but floating sea-level record that was not corrected for regional deviations due to tectonics, glacio-isostatic adjustment (GIA), or dynamic topography. Deformation of the Earth may cause local sea-level changes large enough to either cancel out or double the amplitude of the ice-volume contribution (Raymo et al. 2011). Although some recent studies have attempted to correct for these regional effects, significant uncertainty remains concerning the role of dynamic topography (Rovere et al. 2015; Dumitru et al. 2019).

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Figure 1: Studies of MPWP sea-level estimates (shown in Fig. 2) are placed into four categories. The schematic sea-level curve illustrates the difference between peak GMSL as a single point referenced to a datum, and relative amplitude of sea-level change over the glacial-interglacial range.
for the MPWP termed PlioSeaNZ from Whanganui, New Zealand, that is completely independent of the global benthic δ¹⁸O record. It calculates a theoretical relationship between sediment transport by waves and water depth, and applies the technique to grain size in a well-dated, continuous, shallow marine sequence. Water-depth variations obtained in this way, after corrections for compaction, tectonic subsidence, and glacial isostatic adjustment (GIA), yield the full amplitude of glacial-interglacial sea-level variability with precision of ±5 m and are relatively unaffected by dynamic topography.

Revisited estimates

The amplitude of glacial-to-interglacial sea-level change in continuous sedimentary records spanning MPWP (Fig. 1 and references therein) are compared in Figure 2a. The relative amplitude (maximum range) is calculated for a moving 20,000-year window at variable time steps for each record determined by sample spacing in the individual records. The 20,000-year window is chosen to capture the minimum orbital frequency changes therein) are compared in Figure 2a.

If all the variability in the PlioSeaNZ record was above present-day sea level, then GMSL during the warmest mid-Pliocene interglacial was at least +4.1 m and no more than +20.7 m, with a median of +10.7 m and likely (66%) range between 6.2 m (16th percentile) and 16.7 m (84th percentile; Fig. 2b). This maximum range is consistent with sediment composition from polar continental sediment cores, far-field sea-level reconstructions (Fig. 2b and refs. therein), and ice-sheet model constraints (e.g. DeConto and Pollard 2016). On this basis, we suggest that estimates using a calibration of the deep-sea δ¹⁸O record by Mg/Ca paleothermometry and a sill depth-salinity relationship tend to overestimate the amplitude of global sea-level change during the MPWP.

This range also implies an equilibrium polar ice-sheet sensitivity of 2–8 m of sea-level change for every degree of temperature change, with a mean value of 4 m/°C. This empirical estimate does not consider ice-sheet dynamics, such as a potential stability threshold in the Antarctic Ice Sheet, caused by the loss of ice shelves, which may be crossed at 1.5–2°C of global warming, after which ongoing mass loss may be rapid and non-linear (Golledge et al. 2015).

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