Roles of astronomical forcings and atmospheric pCO_2 in establishing the periodicity and amplitude of the glacial cycles during the early Pleistocene

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Climate change during the Pleistocene is characterized by the glacial-interglacial cycles caused by the astronomically-driven growth and reductions of the northern hemisphere (NH) ice sheets. The main periodicity of the glacial cycles shifted from 41 kyr in the early Pleistocene to 100 kyr in the late Pleistocene (e.g. Clark et al., 2006). During the late Pleistocene, the variation in climatic precession played a key role in driving the deglaciations (e.g., Raymo, 1997; Abe-Ouchi et al., 2013). It has been recently shown that deglaciations occur at minima in the climatic precession even during the early Pleistocene (Barker et al., 2022). However, the relative contributions of obliquity and precession in determining the timings of the terminations of the glacial cycles and the duration of interglacials during the early Pleistocene have not been quantitatively elucidated. For this reason, the reason that led to the short periodicity of glacial cycles during the early Pleistocene was unclear. Here we employ the IcIES-MIROC model, a dynamic three-dimensional NH ice-sheet model (IcIES) coupled with a climate parameterization based on MIROC GCM experiments (Abe-Ouchi et al., 2013). We simulate the glacial cycles at ~1.6–1.2 Ma when the 41-kyr glacial cycles are clearly observed in the $\delta^{18}O$ signatures (e.g. Hodell and Channell, 2016). We further conducted sensitivity tests using a set of artificially modified astronomical forcings and a set of constant atmospheric pCO_2 forcings to clarify the relative importance of the astronomical and CO_2 forcings during ~1.6–1.2 Ma. Based on these results, we discuss the reason behind the dominance of the 41-kyr periodicity during ~1.6–1.2 Ma.

We show that the shapes of glacial cycles, lengths of interglacials, the timing of deglaciations, and the glacial ice geometry during ~1.6–1.2 Ma are controlled by the lead-lag relationship between precession and obliquity forcings. We also show that the 100-kyr periodicity of the ice volume intensifies during ~1.6–1.2 Ma when the amplitude of eccentricity is reduced. With a decreased obliquity amplitude (e.g., 60%), the glacial cycles also exhibit an enhanced 100-kyr periodicity. During ~1.6–1.2 Ma, the amplitude in eccentricity variations is largest in the Quaternary, which is associated with the amplitude modulation at a periodicity of ~2.4 Myr (e.g. Laskar et al. 2004). In addition, this period also corresponds to a large amplitude in obliquity owing to the amplitude modulation at a periodicity of ~1.2 Myr. The large amplitudes of the variations of astronomical forcings would have helped to sustain the clear 41-kyr glacial cycles during ~1.6–1.2 Ma. On the other hand, when a constant value of atmospheric pCO_2 is reduced, the 41-kyr periodicity dominates the glacial cycles and the 100-kyr signal is not enhanced even under a low constant atmospheric pCO_2 (190 ppm). In contrast, for the calculation of the last 0.4 Myr, this low constant pCO_2 enhances the 100-kyr variability. This means that the impact of lowering the constant atmospheric pCO_2 on the periodicity of the glacial cycle is likely to be different between the period of ~1.6–1.2 Ma and the last 0.4 Myr, depending on the configurations of astronomical forcings. These results indicate the importance of the interaction between the ice sheets, climate, and atmospheric $pCO_{2,}$ especially during the late Pleistocene.

Keywords: Glacial-interglacial cycles, Ice-sheet model, Quaternary

