doi.org/10.22498/pages.31.2.58

On the role of precession in Quaternary glacial cycles

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An outstanding question of the Quaternary glacial cycles is the gradual emergence of a precession signal. Its absence in the Early Pleistocene may be explained by Northern Hemisphere ice sheets varying out-of-phase with a dynamic Antarctic ice sheet.

The Quaternary glacial cycles and Milankovitch's theory

The Quaternary period (from ~2.6 Ma to present) is renowned for the cyclical growth and decay of large ice sheets in the Northern Hemisphere (NH). An important archive of this climate variability is the oxygen isotope ratio of benthic foraminifera (hereafter benthic $\delta^{18}O$) recovered from deep-sea sediment cores. Temporal variability in benthic $\delta^{18}O$ serves as a proxy for changes in global ice-volume and deep-ocean temperatures. Lisiecki and Raymo (2005) compiled numerous records to produce a globally averaged "stack" of benthic $\delta^{18}O$ for the last 5 Myr BP (LR04) with more positive values indicative of glacial conditions (Fig. 1a). Spectral analysis of this stack demonstrates that glacial cycles have a quasi-regular 100-kyr periodicity for the last ~0.8 Myr BP, together with smaller 23-kyr and 41-kyr cycles (Fig. 1b). Thereafter, shorter cycles begin to emerge with a regular 41-kyr period (Figs. 1c–d). The transition from the "41-kyr world" of the Early Pleistocene (from ~2.6 Ma to ~1.2 Ma) to the "100-kyr world" of the Late Pleistocene (from ~0.8 Ma to present-day) is referred to as the Mid-Pleistocene Transition (MPT).

Since the first $\delta^{18}O$ measurements of marine sediment cores, the importance of changes in the Earth's orbit around the Sun for pacing glacial cycles has been widely acknowledged. In particular, there are oscillations in the eccentricity of the Earth's orbit with periods of 100-kyr and 400-kyr, the obliquity (tilt) of the Earth's rotational axis with periods of 41-kyr, and the precession of the Earth's rotational axis and orbital path with periods of 19- and 23-kyr. Variations in these three orbital parameters led to a redistribution of solar radiation received at the top of the atmosphere in space and time. Milankovitch (1941) hypothesized that summer insolation at the high northern latitudes was critical for the stability of ice sheets by controlling summer melting. Indeed, spectral analysis of deep-sea sediment and ice-core records support the importance of orbital cycles for Quaternary climate variability (Figs. 1b–d).

The Mid-Pleistocene Transition and precession cycles

On the other hand, Milankovitch's theory cannot explain the MPT based on radiation changes alone, nor the ~100-kyr cycles of the Late Pleistocene. The MPT occurred with no major changes in the variations of Earth's orbital parameters. The ~100-kyr cycles which followed the MPT coincide with variations in the Earth's eccentricity, despite this orbital parameter having a negligible influence on summer-insolation intensity. Theories for the MPT are abundant. They include changes in the dynamics of NH ice sheets (Bintanja and van de Wal 2008) and changes in atmospheric CO_2 concentrations (Raymo et al. 1988). For the 100-kyr glacial cycles of the Late Pleistocene, glacial terminations cluster into intervals of 80- and 120-kyr, and have been explained as a combination of two to three obliquity cycles (Huybers 2007).

Another ongoing question of the Quaternary is the absence of strong precession cycles in the Early Pleistocene. Climatic precession modulates the distance of the Earth relative to the Sun at the solstices and equinoxes, which leads to significant variations in summer-insolation intensity, as exemplified by insolation changes at 65°N during the summer solstice (Figs. 2a–b). Indeed, the conspicuous absence of this precession signal (Fig. 1d) has been referred to as Milankovitch's other unsolved mystery (Raymo and Nisancioglu 2003). Other studies reveal more significant precession variability in the Early Pleistocene (Liautaud et al. 2020), but also demonstrate a strengthening of precession across the Quaternary, as shown in Figures 1b–d. So, what causes the strengthening of these precession cycles?

Precession counterbalancing and integrated summer insolation

One process that diminishes the precession forcing is a counterbalancing that exists between summer-insolation intensity and the duration of the summer. When the Earth is closest to the Sun during the summer of either hemisphere, there is a prominent increase in insolation intensity. However, due to Kepler's second law, the Earth has a higher orbital velocity when closer to the Sun, and subsequently the length of the summer season becomes shorter. Huybers (2006) demonstrates that the time-integral of the summer-insolation forcing above a critical threshold causes these two effects to largely cancel each other out, which can

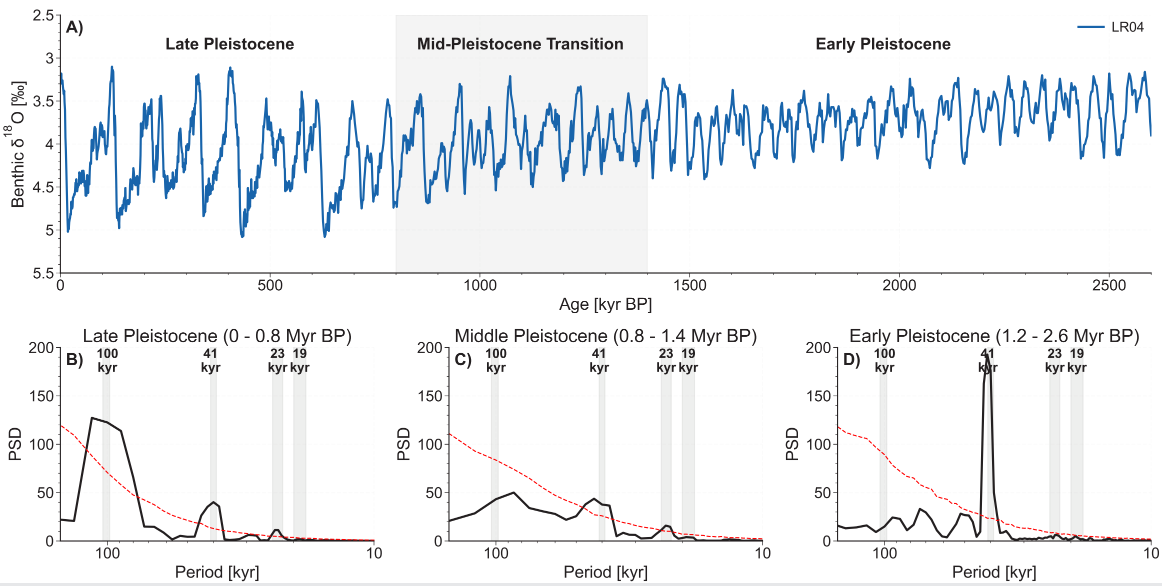

Figure 1: (A) The LR04 benthic $\delta^{18}O$ stack from Lisiecki and Raymo (2005) and the power spectral density (PSD) of the **(B)** Late, **(C)** Middle and **(D)** Early Pleistocene using the multi-taper method from the Pyleoclim python package (Khider et al. 2022). Red lines denote 99% significance level.

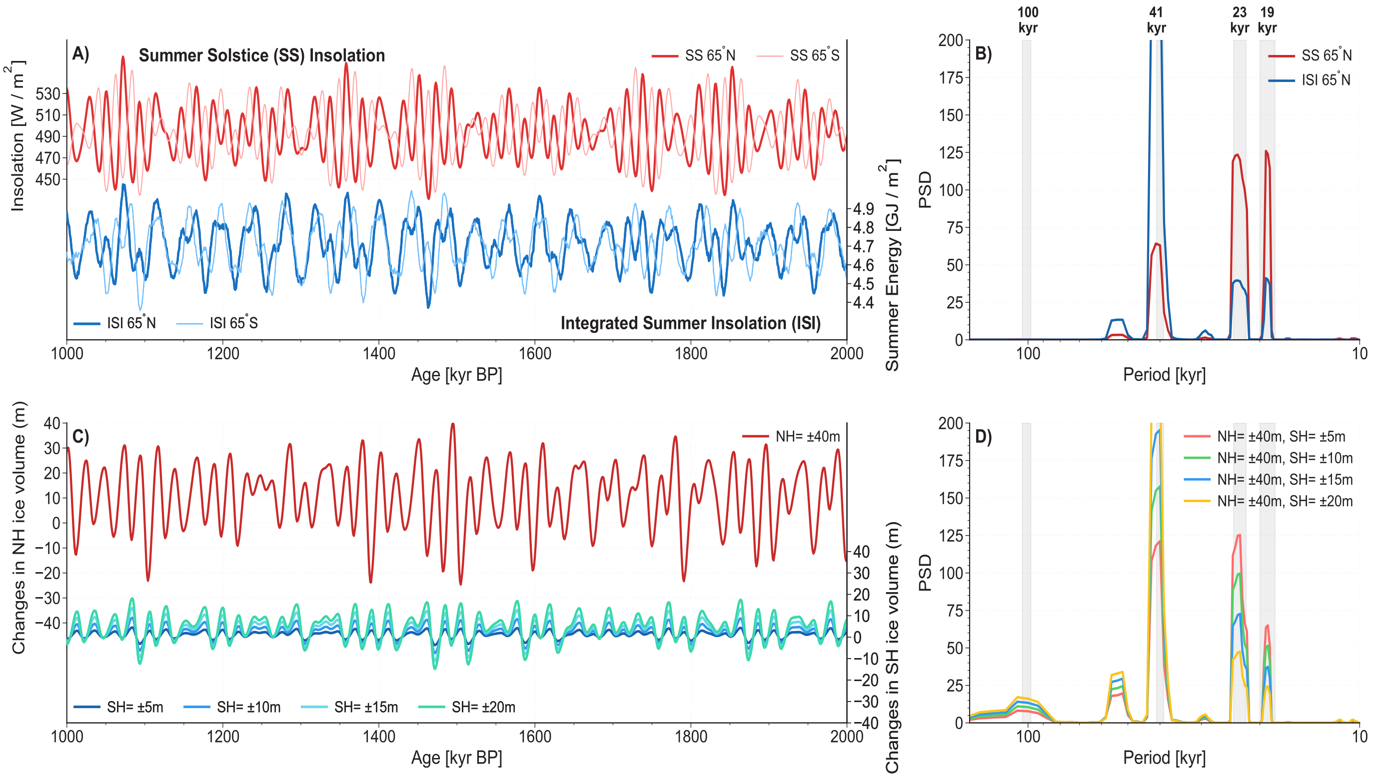

Figure 2: (A) Changes in summer solstice and integrated summer insolation for 65°S and 65°N and **(B)** their respective PSD. **(C)** Modeled variations of a SH and NH ice sheet using a nondimensional ice-volume model (Imbrie and Imbrie 1980) which simulates their lagged response to summer solstice insolation at 65°S and 65°N. **(D)** The model output is scaled for ice-volume variations of up to ±20 m for the SH ice sheet and ±40 m for the NH ice sheet, to illustrate how precession-driven variations of the SH and NH ice sheet can cancel each other in the global record. Panels (C) and (D) replicate plots from Raymo et al. (2006).

significantly reduce the precession variability (as shown in Figs. 2a–b). What then caused the precession signal to become stronger in the Late Pleistocene? Huybers and Tziperman (2008) suggest that a gradual cooling across the Quaternary would shorten the summer melt season and lessen this counterbalancing effect, together with a southward extension of the NH ice sheets into latitudes more sensitive to precession. However, there is the possibility of another contributing factor to the strengthening of precession cycles which lies in Antarctica.

Antarctica and the anti-phased hypothesis

Precession-driven changes in summer insolation are out-of-phase between the hemispheres. With this in mind, Raymo et al. (2006) propose that precession-driven variations of Antarctica and the NH ice sheets may have cancelled each other out in globally averaged proxies of ice volume. This concept can be illustrated by using a simple model of ice-volume change (Imbrie and Imbrie 1980) to simulate variations of both a Southern Hemisphere (SH) and NH ice sheet (Fig. 2c). The nondimensional model simulates the lagged response of each ice sheet to changes in local summer insolation and the output has been scaled to ±40 m of ice volume in the NH and up to ±20 m in the SH. We can see by progressively increasing the variability of the SH ice sheet that these hemispherically out-of-phase precession cycles increasingly interfere with each other, leaving behind a stronger 41-kyr obliquity signal in global ice volume (Fig. 2d). In this way, the notable absence of a precession signal in the Early Pleistocene could be explained by the cancellation of out-of-phase precession cycles between the SH ice sheet (i.e. Antarctica) and the NH ice sheets. Intrinsic to this hypothesis is the notion that the mass balance of Antarctica is driven by changes in local summer insolation, as proposed by Raymo et al. (2006) for the Early Pleistocene. What then caused the increase in precession variability recorded across the Pleistocene? A gradual cooling across the Quaternary would lead to the development of a marine-based Antarctica with virtually no surface melting, as observed today. Together with the gradual expansion of the NH ice sheets, this stabilisation of Antarctica would decrease the ratio between SH and NH ice-volume variations, enhancing the precession signal observed in global ice volume (as shown in Fig. 2d).

Outlook

Interestingly, a strengthening of precession cycles across the Quaternary, driven either by a reduction in the counterbalancing effect between summer-insolation intensity and duration and/or an increasing imbalance between NH and SH precession cycles, requires a cooling across the Quaternary. However, reconstructions of CO_2 across the MPT have produced conflicting results (Hönisch et al. 2009; Yamamoto et al. 2022). On the other hand, the anti-phased hypothesis predicts that Antarctic temperatures should vary in-phase with local summer insolation in the Early Pleistocene, as has been suggested by ice cores recovered from the Allan Hills Blue Ice Area (Yan et al. 2022). Ultimately, the arrival of the Beyond EPICA Ice Core will prove important to test the anti-phased hypothesis by providing a high-resolution record of changes in CO_2 and local Antarctic temperatures across the MPT.

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