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Mending Milankovitch theory: obliquity amplification by surface feedbacks

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Abstract

Milankovitch theory states that orbitally induced changes in high-latitude summer insolation dictate the waxing and waning of ice-sheets. Accordingly, precession should dominate the ice-volume response because it most strongly modulates summer insolation intensity. However, Early Pleistocene (2.6–0.8 Ma) ice-volume proxy records vary almost exclusively at the frequency of the obliquity cycle. To explore this paradox, we use an Earth system model coupled with a dynamic ice-sheet to separate the climate responses to idealized transient orbits of obliquity and precession that maximize insolation changes. Our results show that positive surface albedo feedbacks between high-latitude annual-mean insolation, ocean heat flux and sea-ice coverage, and boreal forest/tundra exchange enhance the ice-volume response to obliquity forcing relative to precession forcing. These surface feedbacks, in combination with modulation of the precession cycle power by eccentricity, may explain the dominantly 41 kyr cycles in global ice volume of the Early Pleistocene.

1 Introduction

Paleoclimate proxy records often display variations on timescales of 10^4 to 10^6 yr. These quasi-cyclic variations in climate, called Milankovitch cycles, are attributed to the combined effects of changes in Earth's degree of axial tilt (obliquity), direction of axial tilt (precession), and circularity of orbit (eccentricity). Milankovitch cycles are thought to be responsible for the growth and retreat of the large Northern Hemisphere (NH) ice sheets that characterize the Pleistocene through the influence of Earth's orbit on high-latitude summer insolation. According to Milankovitch theory, times of high (low) summer insolation produce high (low) rates of summer melting, leading to NH ice-sheet retreat (growth). This theory is the most widely accepted explanation for the strong correlation between ice-volume proxy records and orbital variations (Hays et al., 1976).

One of the most intriguing inconsistencies between Milankovitch theory and proxy records is the lack of a strong precession signal in Early Pleistocene (2.6–0.8 Ma) ice-volume proxies (i.e. benthic δ^{18}O from sediment cores), despite the fact that precession accounts for most of the variability in high-latitude summer insolation intensity (Raymo and Nisancioglu, 2003). While the orbital influences of precession/eccentricity can produce a high-latitude (60–75° N) May, June, July (MJJ) insolation amplitude that is more than 2.5 times that of obliquity for the cycle extremes of the Pleistocene, the power spectra of the Early Pleistocene δ^{18}O sediment records show almost no variability at the precession cycle frequency (∼ 21 kyr). Instead, the bulk of the signal strength appears at the obliquity cycle frequency (∼ 41 kyr).

This apparent failure of Milankovitch theory has led to new hypotheses for how orbital cycles influence ice-volume. In contrast to summer insolation intensity, obliquity has the largest influence on summer half-year equator-to-pole insolation gradient, leading to the suggestion that variations in gradient-driven northward moisture fluxes enhance ice-sheet sensitivity (Raymo and Nisancioglu, 2003). Obliquity also has a dominant effect on annual-mean insolation. Additionally, even though precession has the stronger effect on summer insolation, the peak insolation intensity occurs when summer duration is the shortest. Taken together, these differences cause obliquity to have a greater effect than precession on integrated summer energy amplitude above an ice-melt threshold. If the ice-melt insolation threshold is low enough, then periods of high obliquity will produce more summer melt and therefore, a larger ice volume response (Huybers, 2006). Finally, it has been suggested that precessional variation in marine δ^{18}O records are damped because precession insolation forcing is out-of-phase between hemispheres, potentially causing simultaneous (and partially offsetting) ice-sheet growth and retreat (Raymo et al., 2006; Lee and Poulsen, 2009). Despite many theories, there is no strong consensus as to the cause of the Early Pleistocene δ^{18}O signal.

Here we employ an Earth system model asynchronously coupled with a thermo-mechanical ice-sheet to better understand the differences in climate response to changes in precession and obliquity. Using idealized orbits, we demonstrate that internal climate feedbacks not considered in Milankovitch theory help explain the relatively strong obliquity signal observed in the Early Pleistocene δ^{18}O sediment records.

2 Methods

In this study, we use an Earth system model consisting of the GENESIS 3.0 atmospheric global climate model (AGCM) and land-surface model with a slab ocean coupled to a thermo-mechanical sea-ice model (Pollard and Thompson, 1997), the Pennsylvania State University ice-sheet model (Pollard and DeConto, 2012), and the BIOME4 vegetation model (Kaplan et al., 2003). To gain a better understanding of the climate feedbacks and ice dynamics associated with changes in orbital configuration, we design two sets of transient orbit experiments, one without an ice-sheet model (climate-only) and one with an ice-sheet model (climate-ice sheet). For each set of experiments, we run two transient orbital configurations in which either precession or obliquity systematically varies through a full orbital cycle (Table 1) with ranges representing extremes of the Pleistocene (Berger and Loutre, 1991). In our experiments, obliquity and precession cycles are 40 and 20 kyr respectfully, slightly less than the known durations of 41 and 21 kyr, for computational efficiency and ease of comparison (DeConto and Pollard 2003; Horton and Poulsen, 2009). The ice-sheet model is run over a domain consisting of Greenland and North America at latitudes greater than 40° N. Since our focus is the role of orbital configuration, greenhouse gas concentrations (GHG) are fixed with values representing averages of the last 400 kyr (Petit et al., 1999; Bender, 2002) (CO_2 = 230 ppmv, CH_4 = 520 ppbv, N_2O= 250 ppbv). All simulations use modern continental arrangement and start with modern ice-sheet extents. Resolutions for the AGCM, land surface, and ice-sheet models are T31 ($\sim 3.75^\circ \times 3.75^\circ$), $2^\circ \times 2^\circ$, and $0.5^\circ \times 0.25^\circ$, respectively. We decrease high Alaskan elevations in our simulations to prevent excessive ice build-up caused by the inability of the AGCM to capture valley ablation in Alaska (Marshall and Clarke, 1999). For these experiments, no floating ice or grounding-line advance into water is allowed in the ice-sheet model. Sea level is lowered by 275 m relative to modern to allow ice-sheet growth over the Hudson Bay and continental shelf.

Because response times of the atmosphere and ice sheets differ by several orders of magnitude, we apply an asynchronous technique to couple the AGCM and the ice-sheet model. This process involves running the AGCM for short durations of 20 yr, passing AGCM outputs to the ice-sheet model, running the ice-sheet model for longer durations of 2.5 kyr, and updating the AGCM with new topography and land-surface type. We use an average of the final 10 yr of AGCM outputs to force the ice-sheet model. Due to the continuous nature of the orbital changes and the rapid response time of the slab ocean, 10 yr of spin-up prior to the averaging period is sufficient to produce near equilibrium climate states. Herrington and Poulsen (2011) show that ice-sheet volume is sensitive to the asynchronous coupling period due to ice albedo and atmospheric circulation feedbacks. Here the model produces fairly continuous ice-volume and area responses to the transient orbital forcings, which suggests our coupling time is sufficiently small to capture the majority of the transient climate signal. In the ice-sheet model, we implement an insolation/temperature melt (ITM) scheme (van den Berg, 2008) calculated using AGCM outputs instead of the default positive degree-day melt (PDD) scheme (Pollard and DeConto, 2012). Robinson et al. (2010) find that the ITM approach produces greater and more realistic ice-sheet sensitivity in transient climate experiments than the PDD approach, making the ITM scheme preferable for paleoclimate simulations.

We run all ice-sheet experiments for 160 kyr model years, representing 4 cycles of obliquity and 8 cycles of precession. The first 40 kyr model years are not considered in our analysis since the ice sheets are still equilibrating during that time. Subsequent cycles are averaged to simplify the results. Because orbits with high eccentricity and transient precession cause significant changes in seasonal duration, we convert monthly AGCM outputs from a Gregorian calendar to an angular calendar using the methods detailed in Pollard and Reusch (2003). All monthly and seasonal analyses use the converted angular calendar outputs.

3 Results

3.1 Climate-only experiments

Our initial analysis examines the climate response to transient cycles of obliquity and precession in absence of dynamic ice sheets. Model results show that differences in the ocean and vegetation feedbacks to the cycles of obliquity and precession produce greater climate sensitivity to insolation forcing from obliquity (described below). This climate sensitivity difference is due in part to the influence of obliquity-controlled variations in annual-mean insolation on the high-latitude ocean. The amount of absorbed insolation by the high-latitude ocean is mainly controlled by the amount of incident insolation and sea-ice cover. Because the obliquity cycle generates variations in annual-mean insolation, the high-latitude oceans absorb a greater range of insolation annually from obliquity than precession (Fig. 1a).

Changes in the amount of ocean-absorbed insolation modify the timing of sea-ice growth and retreat (Fig. 1a). Sea-ice coverage produces a positive feedback with ocean-absorbed insolation because of the albedo difference between ocean and ice. The annual-mean insolation signal of obliquity causes the change in ocean-absorbed insolation due to obliquity to be greater than those due to precession, resulting in a larger sea-ice feedback (Fig. 1a). The contrast in sea-ice coverage is particularly apparent during spring and fall (not shown). For example, total April sea-ice area varies by $\sim 2\,065\,900\,\mathrm{km}^2$ through an obliquity cycle but only $\sim 1\,340\,300\,\mathrm{km}^2$ through a precession cycle, a difference of $\sim 43\,\%$.

Although smaller than obliquity, precession does have an effect on annual-mean high-latitude ocean-absorbed insolation and sea-ice coverage, despite no annual-mean insolation forcing, due to changes in the timing of seasonal insolation and interactions with sea-ice coverage. The summer insolation amplitude of obliquity also has some effect on the amount of ocean-absorbed insolation, but it is smaller than precession, and smaller still than the annual-mean effect of obliquity, so is of secondary importance in the transient obliquity experiments.

In combination, the effects of incident insolation and sea-ice feedbacks produce an annual-mean high-latitude ocean absorbed insolation amplitude of $\sim 12\,\mathrm{W\,m^{-2}}$ from obliquity forcing but only $\sim 6\,\mathrm{W\,m^{-2}}$ from precession forcing (Fig. 1a). The ocean acts as a seasonal energy integrator, which allows it to store and reemit the absorbed insolation as heat throughout the year. During times of maximum (minimum) high-latitude summer insolation, the high-latitude ocean absorbs and releases to the atmosphere a larger (smaller) amount of heat for obliquity than precession (Fig. 1b). The greater heat flux response to obliquity relative to precession adds to the direct insolation heating, increasing the seasonal climate sensitivity to the insolation forcing.

The larger influences of obliquity compared to precession on ocean heat flux and sea-ice have been found in other modeling studies (e.g. Gallimore and Kutzbach, 1995). Additionally, Eemian sea surface temperature estimates from planktonic foraminifera along a North Atlantic meridional transect correlate well with local changes in mean annual insolation (Cortijo et al., 1999). However, transient orbital studies using a dynamic ocean model are needed to assessment the robustness of our result.

Changes in obliquity also produce greater North American high-latitude vegetation responses, mainly between tundra and boreal forest, than precession (Fig. 1b). In BIOME4, net primary productivity and number of growing degree-days above 0 °C determine the threshold between tundra and boreal forest (Kaplan et al., 2003). Due to annual-mean insolation changes, obliquity produces a larger range of annual temperature and sunlight reaching the surface and accordingly, a larger amount of tundra/boreal forest exchange. As a result, 22.7 % more land area transitions from tundra to boreal forest in the high-latitudes of North America during periods of peak summer insolation from obliquity forcing than precession forcing. The greater boreal forest coverage decreases annual-mean high-latitude North American surface albedo by an additional 0.040 (27.6 %) for obliquity compared to precession; the differences are especially large in the winter and spring months (over 0.077 in March) when the tree canopy masks the snow cover.

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The lower albedo and greater moisture content of boreal forest compared to tundra causes more near-surface warming year-round. Additionally, like sea-ice changes, the boreal forest/tundra exchange influences the timing of spring warming and fall cooling and amplifies seasonal temperature differences of orbital extremes. In turn, the timing of snowmelt varies, further modifying surface albedo and temperature responses.

While proxy studies show a correlation between vegetation and orbit (e.g. Gonzalez-Samperiz et al., 2010), we are not aware of any records directly documenting an orbitally-driven Arctic taiga-tundra feedback. This feedback has, however, been recognized in modeling studies that looked at snapshots outputs from several orbital configurations (Gallimore and Kutzbach, 1996; Koenig et al., 2011) as well as transient experiments with a model of intermediate complexity (Claussen et al., 2006). Moreover, Horton et al. (2010) found the taiga-tundra feedback was essential for producing orbitally-driven ice-sheet retreat in simulations of Late Paleozoic glacial cycles.

The cycles of obliquity and precession both affect seasonal temperatures. However, annual-insolation-enhanced positive feedbacks of ocean heat flux, sea-ice coverage, and vegetation type work synergistically to amplify the temperature sensitivity to changes in the obliquity compared to precession. For all months, obliquity-forced changes in high-latitude insolation produce a larger temperature response than precession (see Supplement). Arguably the most important temperature sensitivity to insolation forcing for ice-sheet response is during the summer months. The regression in mean high-latitude North American June, July, August (JJA) surface temperature with MJJ insolation is 1.73 times steeper for obliquity than precession (Fig. 2a, b), resulting in a similar range of summer temperatures despite a large difference in summer insolation amplitude. Even though summer insolation is the dominant factor for determining perennial snow cover through seasonal melting in the high-latitudes of North America, annual-mean insolation intensifies the climate response to changes in obliquity.

Studies have proposed that the greater latitudinal summer insolation gradient caused by the obliquity cycle enhances eddy fluxes, which leads to greater Arctic snowfall variability (e.g. Jackson and Broccoli, 2003; Lee and Poulsen, 2008). While the midlatitudes eddy fluxes vary as a result of changes in insolation gradient, we find little difference in the NH high-latitude eddy kinetic, heat, or moisture flux between orbits. Instead, local changes direct most moisture and heat transport.

3.2 Climate-ice sheet experiments

We ran the same transient orbital configurations of obliquity and precession with the inclusion of an asynchronously coupled thermo-mechanical ice-sheet model. Results show that while summer insolation intensity is the main mechanism controlling ice-sheet volume, the ice-sheet rate of change to variations in obliquity and precession are similar, despite summer insolation changes due to precession being much larger (Fig. 3b). This is due to ocean heat flux, sea-ice, and vegetation feedbacks, which are greater for obliquity (Fig. 2c, d). The similar growth and decay rate, combined with the longer cycle duration for obliquity (40 versus 20 kyr), results in a total ice-volume amplitude that is 42 % larger for obliquity than precession (Fig. 3c).

To evaluate the influence of the different durations of obliquity and precession cycles on ice volume, we ran an additional experiment with a transient obliquity cycle scaled to 20 kyr. The percent difference in ice-volume range through a precession cycle is larger by only 22.5 % (Fig. 4b) even though mean MJJ high-latitude insolation range is larger for precession by 87 %. The similar ice volume ranges in Fig. 4b demonstrate that the annual-mean insolation forcing of obliquity and resulting surface feedbacks are strong enough to cancel the nearly 2 times greater MJJ summer insolation forcing of precession. The standardized duration experiment shows that the potential lesser damping of the 40 kyr obliquity forcing due to ice-sheet mass inertia (vs. 20 kyr for precession) would be insufficient on its own to yield the greater obliquity response in Fig. 3c. Without considering the surface feedbacks to the annual-mean insolation forcing from obliquity, traditional Milankovitch theory is unable to explain the relative amplitudes of ice sheet response in our model results.

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4 Discussion and conclusion

The results of this study show that positive surface feedbacks enhance the ice-volume response to the cycles of obliquity relative to precession. Our choice of orbital configurations further highlights the influence of obliquity on the climate system. Insolation forcing from precession changes significantly between cycles due to power modulation by eccentricity. Here we use the largest eccentricity value of the Pleistocene, producing the maximum precession summer insolation amplitude. A precession cycle with similar summer insolation amplitude to these experiments occurs at most once every 100 kyr. Like the precession cycle, the obliquity cycle in these experiments represents the maximum range of the Pleistocene; however, the extreme orbital amplitude of obliquity is a smaller deviation from the average (47 % difference) than the extreme orbital amplitude of eccentricity/precession (66 % difference).

In this study, we do not examine the ice-volume response to combined changes in precession, obliquity, and eccentricity. Nevertheless, assuming similar climate feedbacks to our current results, we would expect to find a strong obliquity signal. The obliquity signal should appear continuously while the precession cycle will only have a significant influence on ice-volume when eccentricity is large (every ∼ 100 kyr), reducing the signal frequency. Combined with the potential for melting offset by Antarctica from precession forcing (Raymo, 2006; Lee and Poulsen, 2009), the obliquity dominated δ^{18}O record of the Early Pleistocene might not be difficult to replicate.

The goal of this study was to investigate climate sensitivity to orbital configuration rather than simulate specific intervals of ice-volume change. However, it is worth noting that the ice sheets in our experiments are fairly small; over obliquity and precession cycles, the mean sea-level equivalent change is 13.5 and 9.5 m (Fig. 3c), significantly less than Early Pleistocene global sea-level change estimates of 60–80 m (Sosdian and Rosenthal, 2009). Much of this volume change is due to variations in the North American ice sheets, and our simulated ice sheets are much smaller than those at glacial maxima, even for the Early Pleistocene (Clark and Pollard, 1998). This discrepancy is likely a combination of factors. First, there is a known warm bias in modern-day GENESIS AGCM climate simulations over Northern Canada (Herrington and Poulsen, 2011). Second, our idealized orbits do not capture the strongly reduced NH summer insolation produced by combinations of obliquity, precession, and eccentricity that lead to past glacial maxima. Thirdly, a lack of GHG fluctuations might contribute to the small ice-volume changes in our model (Abe-Ouchi et al., 2007). We plan to address the significance of more realistic climate variability in a future study. Regardless, we believe our results are robust even if the model under predicts the scales of the changes in ice-volume.

Our findings support Milankovitch theory; high-latitude summer insolation forcing remains the largest single factor for determining ice-sheet volume response. Yet Milankovitch theory alone cannot explain the Early Pleistocene δ^{18}O records or our model results. Surface feedbacks remedy these incongruities. The changes in high-latitude annual-mean insolation resulting from a transient obliquity orbit leads to significant modification in high-latitude ocean heat flux, sea-ice cover, and vegetation type, which work in concert to amplify the annual and seasonal climate sensitivity to changes in insolation. This causes the summer climate sensitivity to changes in insolation from obliquity to become magnified, producing a larger ice-sheet response than expected given the much small summer insolation amplitude than precession. These results highlight the significance of annual-mean insolation on the climate and help explain the strength of the obliquity signal found in δ^{18}O proxies, particularly before the mid-Pleistocene transition. We demonstrate the amplification of surface feedbacks by obliquity with and without dynamic ice sheets and in a duration-standardized experiment. Our results offer a new solution to the Early Pleistocene Milankovitch theory paradox and emphasize the importance of using complex models when investigating long-term changes in climate. Future work will examine the combined interactions between obliquity and precession.

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Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/9/3769/2013/cpd-9-3769-2013-supplement.pdf.

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Table 1. Orbital configurations.

Experiment	Obliquity	Precession	Eccentricity
OBL	22.079°–24.538°	NA	0
PRE	23.3085°	0°–360°	0.056596

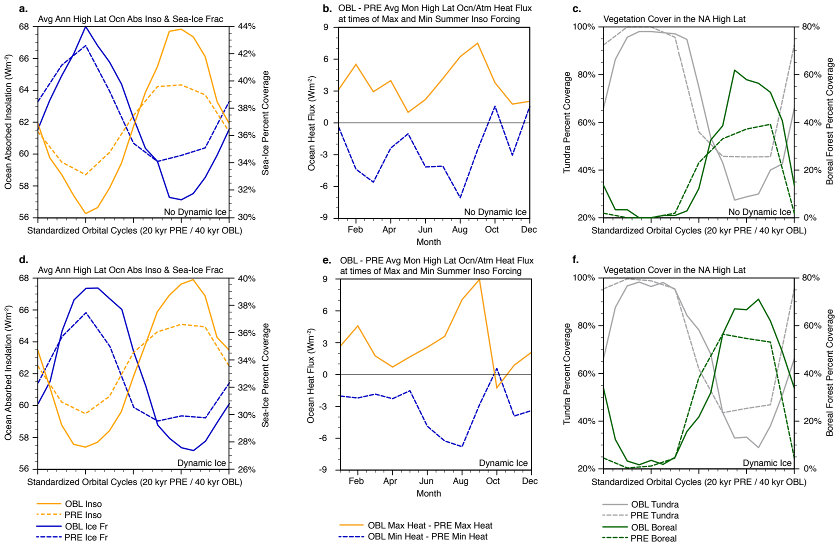

Fig. 1. (a) Annual-mean ocean-absorbed insolation ($\mathrm{W\,m^{-2}}$) and sea-ice coverage (%) between 60–75° N through time for the climate-only experiments. **(b)** Differences in monthly average sensible + latent heat flux ($\mathrm{W\,m^{-2}}$) over the ocean between 60–75° N during the maximum and minimum high-latitude summer insolation forcing from obliquity and precession for the climate-only experiments. **(c)** Annual-mean coverage (%) of tundra and boreal forest over North America between 60–75° N through time for the climate-only experiments. **(d)** Annual-mean ocean-absorbed insolation ($\mathrm{W\,m^{-2}}$) and sea-ice coverage (%) between 60–75° N through time for climate-ice sheet experiments. **(e)** Differences in monthly average sensible + latent heat flux ($\mathrm{W\,m^{-2}}$) over the ocean between 60–75° N during the maximum and minimum high-latitude summer insolation forcing from obliquity and precession for climate-ice sheet experiments. **(f)** Annual-mean coverage (%) of tundra and boreal forest over North America between 60–75° N through time for climate-ice sheet experiments. Cycle lengths were standardized and aligned by peak summer insolation to more easily compare the 40 kyr obliquity cycle with the 20 kyr precession cycle.

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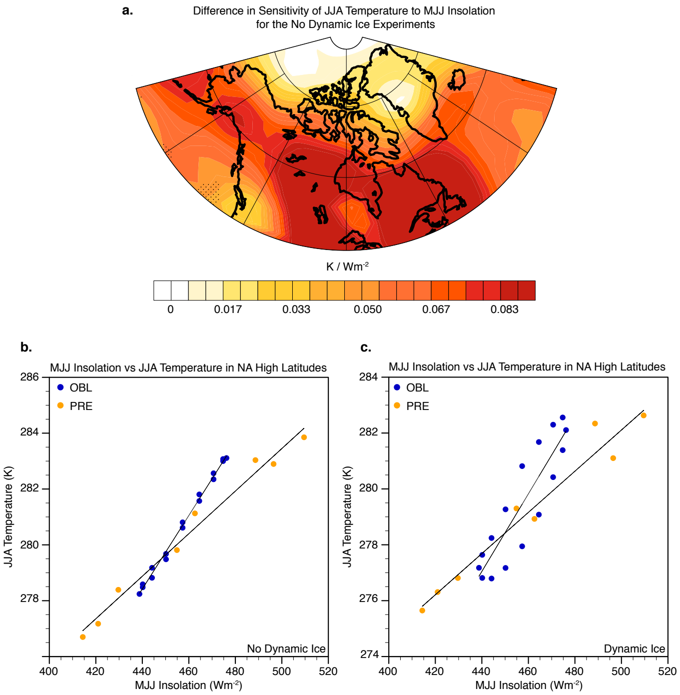

Fig. 2. **(a)** The regression slope of MJJ insolation against JJA temperature (°C $(\mathrm{W\,m^{-2}})^{-1}$) for obliquity minus precession over northern North America for the climate-only experiments. Stippling represents areas where linear regressions are not significant at the 95 % confidence level. **(b)** JJA temperature response to MJJ insolation forcing from obliquity and precession averaged over North America between 60–75° N for climate-only experiments. **(c)** JJA temperature response to MJJ insolation forcing from obliquity and precession averaged over North America between 60–75° N for climate-ice sheet experiments. For **(b)** and **(c)**, each dot represents the AGCM averaged equilibrium output for a given orbital configuration.

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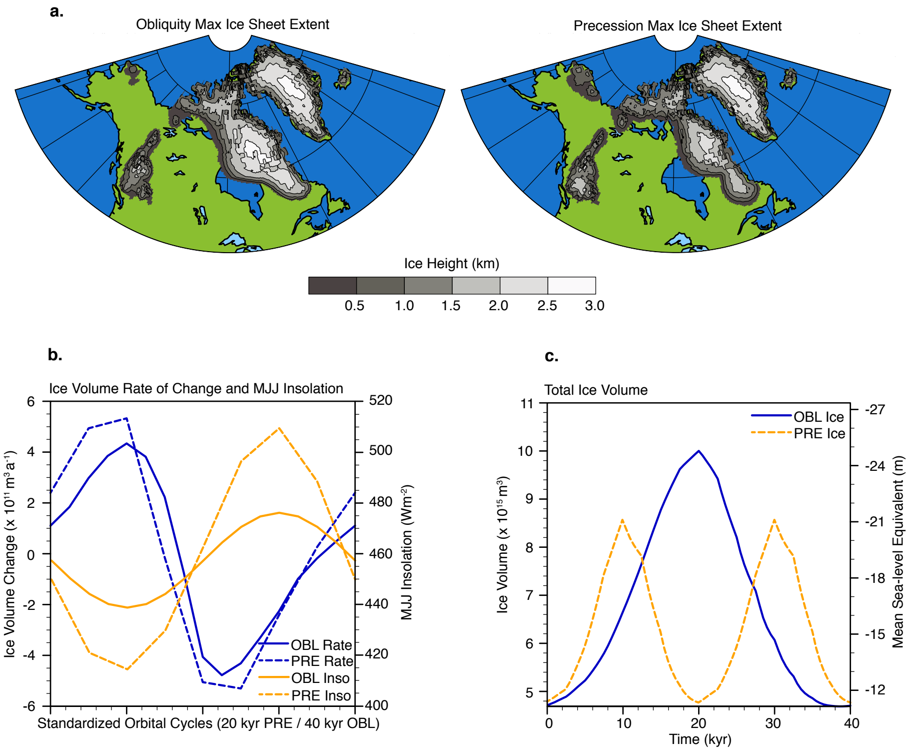

Fig. 3. **(a)** Maximum ice-sheet extents simulated over the 40 kyr obliquity and 20 kyr precession cycles. **(b)** Ice-volume rate of change (ma^{-1}) and MJJ insolation forcing between 60–75° N (W m^{-2}) through a 40 kyr cycle of obliquity and a 20 kyr cycle of precession. Cycle lengths were standardized and aligned by peak summer insolation for comparison. **(c)** Total North American ice-volume (m^3) from obliquity and precession orbital forcing over a 40 kyr period. Mean sea-level equivalent values (m^2) relative to modern-day are also provided.

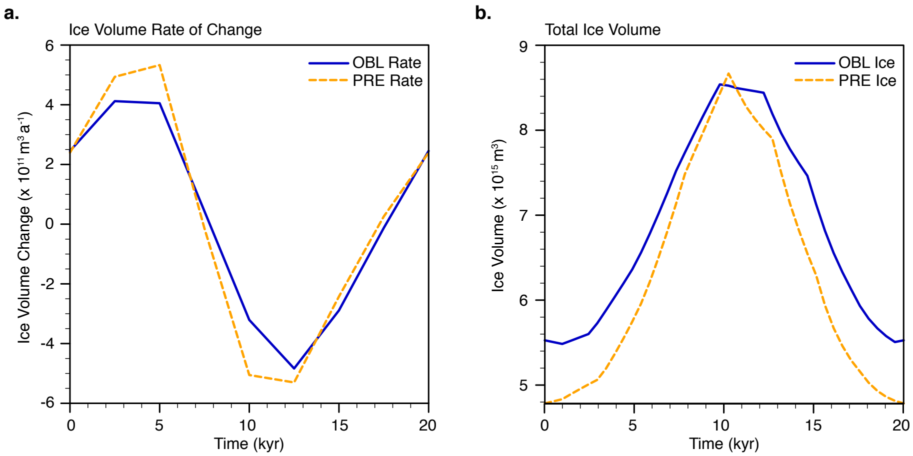

Fig. 4. **(a)** The ice-volume rate of change (ma^{-1}) and **(b)** total North American ice volume (m^3) for a 20 kyr cycle of obliquity and a 20 kyr cycle of precession.