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# Ice sheet mass balance and the timing of 100,000-year glacial cycles

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The waxing and waning of Northern Hemisphere ice sheets over the past one million years is characterised by an approximately 100,000-year (100-kyr) periodicity and a sawtooth pattern (gradual growth and fast termination){Clark, 2009}{Hays, 1976}. The Milankovitch theory proposes that summer insolation at high northern latitudes drive the glacial cycles{Milankovitch, 1941}, but no significant 100-kyr periodicity exists in insolation intensity{Hays, 1976}. Statistical tests have demonstrated that the glacial cycles are linked to orbital eccentricity, obliquity and precession cycles, presumably through internal feedbacks{Saltzman, 1984}{Tziperman, 2006}{Lisiecki, 2010}{Huybers, 2011}. Furthermore, conceptual models have reproduced the glacial cycles by imposing a threshold of ice volume,˜ excess 100-kyr ice˜, for glacial terminations{Raymo, 1997}{Paillard, 1998}{Parrenin, 2003}{Imbrie, 2011}{Huybers, 2011}; however, physical mechanisms have not been identified. Here, using comprehensive climate and ice sheet models, we show that the ˜100-kyr periodicity is explained by orbital forcing and internal feedback amongst climate, ice sheet and lithosphere/asthenosphere system. We found that ice sheets exhibit hysteresis responses to summer insolation{Abe-Ouchi, 1993}{Calov, 2005}{Pollard, 2005}, and that the shape and position of the hysteresis loop play a key role to determine the periodicities of glacial cycles. The hysteresis loop of the North American ice sheet is such that, after its inception, the ice sheet mass balance remains mostly positive or neutral through several climatic precession cycles whose amplitude decreases towards eccentricity minimum. The larger it grows and extends towards lower latitudes, the smaller is the required insolation to turn the mass balance to negative. Once the large ice sheet is established, therefore, significantly negative mass balance continues for several thousand years even with a moderate increase in insolation amplitude, allowing time for disintegration. The fast retreat is governed mainly by rapid ablation due to the lowered surface elevation resulting from delayed isostatic rebound. CO2 plays a supporting, but not controlling, role in the evolution of the ˜100-kyr cycle of ice sheet volume and global climate change.

Keywords: climate, climate model, paleoclimate