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Inferring spatiotemporal patterns of insolation forcing of ice volume over the late Pleistocene

Kristian Agasøster Haaga (1), Jo Brendryen (1), David Diego (1), and Bjarte Hannisdal (1)

(1) Department of Earth Science, University of Bergen, Bergen, Norway (kristian.haaga@uib.no), (2) K.G. Jebsen Centre for Deep Sea Research, University of Bergen, Bergen, Norway, (3) Bjerknes Centre for Climate Research, Bergen, Norway

A fundamental assumption underpinning paleoclimate science is the notion that insolation has paced glacial-interglacial climate variability. However, the spatial structure of insolation forcing has not been directly quantified. Here, we use methods from dynamical systems theory, empirical dynamical modelling, to infer at which latitudes and for what times of the year insolation acted as a driver of global ice volume during the past 800 kyr. To quantify the insolation forcing, we use a global ice volume record on an orbitally independent age model and summer energy time series for all latitudes over a range of thresholds. This data-driven approach, which assumes no *a priori* connection between insolation and ice volume, neither in the form of age model assumptions nor explicit models or equations, provides statistical evidence that local insolation in several latitudinal bands acted as a causal dynamical forcing of global ice volume.

Our results are consistent with direct summer energy forcing of ice sheets through summer melting at northern latitudes, and the dominant forcing mode at the northernmost latitudes is well-represented by the canonical Milankovitch forcing, for example by summer half-year insolation at 65°N. Moreover, we find that insolation at northern equatorial-to-mid latitudes, from annual to peak summer energy, also significantly influenced ice volume. However, the dominant forcing mode at Northern Hemisphere low-latitudes is generally opposite in phase with that of latitudes where the major paleo ice sheets existed and may suggest that insolation gradients in the Northern Hemisphere affected ice volume. Our results also suggest that insolation at southern mid-latitudes, a region coinciding with the Patagonian ice sheet and the position of the subtropical front and mid-latitude westerlies, also significantly forced ice volume with a dominant forcing mode very similar to that of the northernmost latitudes in the Northern Hemisphere. This may suggest that insolation forcing in the Southern and Northern Hemispheres acted in tandem to modulate the global ice volume signal.

Our results suggest significant forcing for a range of summer energy time series over the entire spectrum of obliquity/precession ratios. Hence, there is no clear answer to the question of which orbital parameter is most important for ice volume. This result arises naturally as a consequence of the spatiotemporally variable insolation forcing. The total contribution of insolation forcing to the global ice volume budget involves both direct Milankovitch type forcing of ice sheets and nonlinear climatic feedbacks that are not resolvable using global data sets.