



Obliquity-driven expansion of North Atlantic sea ice controls structure of the last glacial

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North Atlantic late-Pleistocene climate was characterised by a series of abrupt climate changes, the most extreme of which were the Dansgaard-Oeschger (D-O) events; millennial-scale oscillations that switched rapidly between cold and warm atmospheric conditions of up to $\Delta 16^{\circ}\text{C}$, most strongly expressed during the period 60-30 ka. Time series analysis of palaeoclimate ice core records is one of the best ways to detect threshold behaviour in the climate system; however, some of these techniques can be age model dependent. Spectral analysis of a new Greenland-Cariaco GICC05 age model (GICC05-CB), generated by combining the GICC05 and Cariaco $\delta^{18}\text{O}$ chronologies, reveals a change in the dominant periodicities at ~ 31 ka, consistent with the cessation of the D-O events. While the GICC05-CB has the same $\delta^{18}\text{O}$ structure as GICC05, the different periodicity profile reveals a change in the climate system at 31 ka. Stability analysis of the $\delta^{18}\text{O}$ time series over the last 60 ka determines the number of states the climate experienced over time, and reveals a bifurcation in the climate system at 31 ka, switching from a bistable to a monostable state. Early warning signals of this bifurcation are also detected starting 10,000 years before the shift in the form of increasing autocorrelation and variance. This is consistent with the climate system experiencing a slow forcing towards a critical threshold. These signals are found in both the GICC05-CB and GICC05 chronologies, though the timing of the bifurcation point varies slightly. We suggest that this bifurcation is linked to a minima in obliquity, causing greatly expanded sea ice in the Labrador sea. Modelling runs from the CSIRO Mk3L Earth-system model indicates that extensive sea ice cover is established in the Labrador Sea and North Pacific at the obliquity minima centred on 28.5 ka. This expanded sea ice is thus responsible for shifting the Northern Hemisphere westerlies southwards and reducing the strength of the AMOC, preventing the establishment of the cold state from 31 ka.