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Palaeoclimate

Ocean tides and Heinrich events

Climate varied enormously over the most recent ice age[1] — for example, large pulses of ice-rafted debris[2], originating mainly from the Labrador Sea[3], were deposited into the North Atlantic at roughly 7,000-year intervals, with global climatic implications[3]. Here we show that ocean tides within the Labrador Sea were exceptionally large over the period spanning these huge, abrupt ice movements, which are known as Heinrich events. We propose that tides played a catalytic role in liberating iceberg armadas during that time.

We investigated whether tides could have been linked to Heinrich events for two reasons. First, tidal controls on continental ice streams and floating ice shelves, both proposed[4,5] as sources of Heinrich icebergs, are well documented[6,7] in present-day Antarctica. Second, ice-age tides should differ from those of today. The growth of continental ice sheets was accompanied by lower globally averaged sea levels (up to 130 m)[8], with an implied decrease in tidal phase speeds and in ocean-basin size, both of which affect the strong resonance[9] of North Atlantic semidiurnal tides. Lower sea levels also affected tides by reducing the area of shallow-water regions, where much of the dissipation of present-day tides takes place.

We predicted ice-age tides in a global numerical model[10] that captures 92% of the present-day open-ocean tidal-height variance. The ice-age simulations required, as input, the space–time history of the ice-sheet distribution and of the complex global geometry of sea-level variations. The latter fields were generated using a formulation[11] for predicting gravitationally self-consistent sea-level changes on viscoelastic Earth models. (For details of tide and sea-level models, see supplementary information.)

Figure 1a shows the modelled amplitudes of M_2, the largest tidal constituent, 45,000 years ago (45 kyr). The Labrador Sea amplitude (about 3.2 m) is much larger than in other deep areas of either the 45-kyr or present-day ocean. The black line in Fig. 1b shows the predicted M_2 amplitude at 61.5° N, 64° W, the approximate discharge point of the Hudson Strait ice stream[5], over the past 65 kyr. All simulations spanning the Heinrich events (H1–H6), and extending to about 7 kyr, predict amplitudes of 2.7–3.9 m; such amplitudes are roughly twice the present-day value (about 1.5 m; ref. 12). Experiments with many

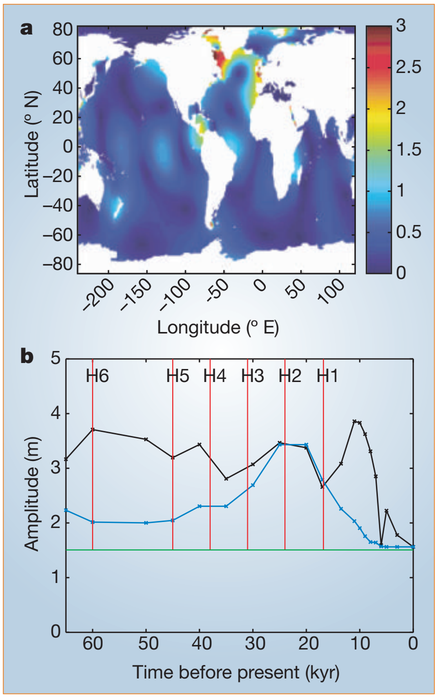

Figure 1 Ice-age tidal amplitudes. **a,** Amplitude (m) of the principal lunar semidiurnal tide M_2 at 45,000 years ago (45 kyr) in a hydrodynamical model[10] coupled to a gravitationally self-consistent (hence geographically variable) prediction[11] of sea-level change. **b,** Black line: M_2 amplitude (m) from the same models, at the estimated discharge point of the Hudson Strait ice stream, over the past 65 kyr. (See supplementary information for discussion of uncertainties.) Blue line: M_2 amplitudes at the same Labrador Sea location in simulations using globally averaged sea-level change applied in a spatially uniform manner. In this calculation, ocean-basin geometry is altered by the uniform sea-level change, but not by any growth or collapse of marine-based ice. Green line: present-day M_2 amplitude at the same location in a very accurate satellite-constrained tide model[12]. Timings of Heinrich events H1–H6 are from ref. 3.

tidal frequencies yield maximum peak-to-peak ranges over the spring–neap cycle that are 3.6 times larger than the M_2 amplitudes, or 10–14 m. This greatly exceeds the maximum ranges in present-day Antarctica, where tides are thought to weaken floating ice shelves by forming crevasses at their hinge lines.

What feature of the ice-age ocean amplifies Labrador Sea tides? The blue line in Fig. 1b shows Labrador Sea M_2 amplitudes in simulations for which the globally averaged sea-level change is applied in a spatially uniform manner. Furthermore, the ocean-basin geometry is assumed to be influenced by the sea-level changes but not by changes in the ice geometry. In this case, large Labrador Sea tides are predicted over a limited time across the H2 event alone, when sea level was near its minimum. We performed an experiment in which the 25-kyr land-plus-ice geometry defined the perimeter of the ocean and present-day values of water-column thickness were used. The Labrador Sea amplitudes were similar to those shown in Fig. 1a, and we conclude that basin geometry, for instance, the existence or absence of ice cover over Hudson Bay, exerts primary control on Labrador Sea tides.

A numerical study[13] of tidal dissipation over the past 20 kyr also recorded large North Atlantic palaeotides. We have focused on Labrador Sea tides in particular and have shown that they were large over the period between 65 kyr ago and 7 kyr ago. We suggest that these tides preconditioned ice streams and shelves for other forcings, such as climate warming, sea-level rise or ice-stream instabilities[4], to trigger discrete Heinrich events. Ice-age tides in Europe were comparable to Labrador Sea tides only near the British Isles (Fig. 1a), which may in part explain the greater amount of Canadian material in the ice-rafted debris[3]. The large Labrador Sea palaeotides represent a hitherto unrecognized negative feedback on North American ice-sheet stability, and a potentially important link in our understanding of millennial-scale ice-age climate change.

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