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Heinrich events triggered by ocean forcing and modulated by isostatic adjustment

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During the last glacial period, the Laurentide Ice Sheet sporadically discharged huge numbers of icebergs through the Hudson Strait into the North Atlantic Ocean, leaving behind distinct layers of ice-rafted debris in the ocean sediments[1–3]. Perplexingly, these massive discharge events—Heinrich events—occurred during the cold portion of millennial-scale climate oscillations called Dansgaard–Oeschger cycles[2,4]. This is in contrast to the expectation that ice sheets expand in colder climates and shrink in warmer climates. Here we use an ice sheet model to show that the magnitude and timing of Heinrich events can be explained by the same processes that drive the retreat of modern marine-terminating glaciers. In our model, subsurface ocean warming associated with variations in the overturning circulation increases underwater melt along the calving face, triggering rapid margin retreat and increased iceberg discharge. On millennial timescales, isostatic adjustment causes the bed to uplift, isolating the terminus from subsurface warming and allowing the ice sheet to advance again until, at its most advanced position, it is poised for another Heinrich event. This mechanism not only explains the timing and magnitude of observed Heinrich events, but also suggests that ice sheets in contact with warming oceans may be vulnerable to catastrophic collapse even with little atmospheric warming.

Despite decades of study, Heinrich events remain an enigma. Any proposed mechanism for Heinrich events must explain all the observed characteristics, including the rapid onset indicated by the sharp base of ice-rafted debris (IRD) layers[2], the sporadic timing between events[2–4], and the consistent alignment of Heinrich events within the cold phases of Dansgaard–Oeschger cycles when atmospheric temperatures were coldest[4]. Early theories suggested that Heinrich events were driven by internal instabilities associated with ice sheet flow[5,6] (the "binge-purge" mechanism). However, explanations based purely on ice dynamics cannot explain the synchronization of Heinrich events within Dansgaard–Oeschger cycles. More recent hypotheses have invoked the disintegration of an ice shelf that buttressed the Hudson Strait Ice Stream[7–9]. Proxy data showing subsurface ocean warming preceding Heinrich events[8] has fuelled speculation that subsurface ocean warming associated with weakening of the Atlantic Meridional Overturning Circulation eroded a Labrador Sea ice shelf, triggering ice stream acceleration and increased ice discharge once the buttressing force of the ice shelf was removed[8,10,11]. This mechanism explains how an ice sheet could collapse while air temperatures remained cold, but a large ice shelf covering the Labrador Sea is incompatible with evidence of warm surface waters and an open ocean during many parts of the glacial interval, including immediately before some Heinrich events[12,13].

Given the lack of evidence for an ice shelf, a more relevant modern analogy comes from observations of widespread retreat of glaciers surrounding Greenland driven by the intrusion of warm subsurface ocean waters into fjords[14–18]. We use both a width-averaged flowline and a regional ice sheet model of the Laurentide Ice Sheet and Hudson Strait Ice Stream to show that small increases in submarine melt at the calving front caused by subsurface ocean warming can trigger Heinrich events. The ice dynamics models we use calculate the depth-integrated flow of a rapidly sliding ice stream confined to a channel (Supplementary Information, section 3.2). We compute terminus advance and retreat based on the hypothesis that the height of the calving cliff at the

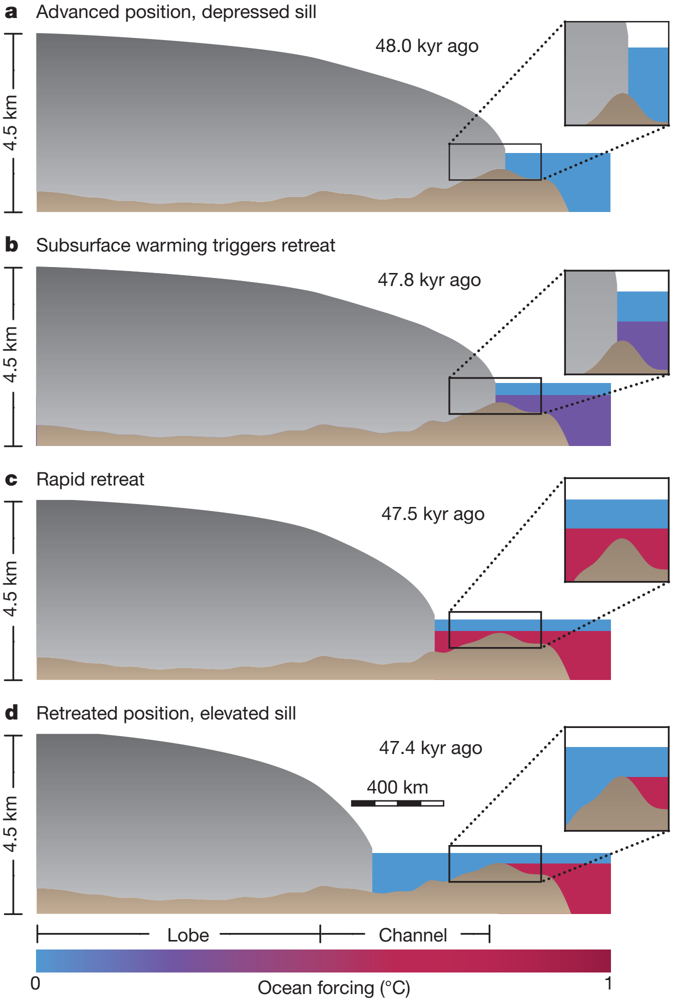

Figure 1 | Stages of the proposed Heinrich event mechanism. With the ice sheet in its most advanced state, the terminus is grounded 300 m beneath sea level (**a**). An ocean-warming event triggers retreat (**b**), which is further amplified by enhanced calving as the ice sheet retreats into deeper water (**c**). After the collapse, the ice sheet is in its most retreated position (**d**), with the elevated sill cutting off contact with the warm subsurface waters. Isostatic adjustment uplifts the bed allowing the ice sheet to advance again. Insets show a close-up around the sill.

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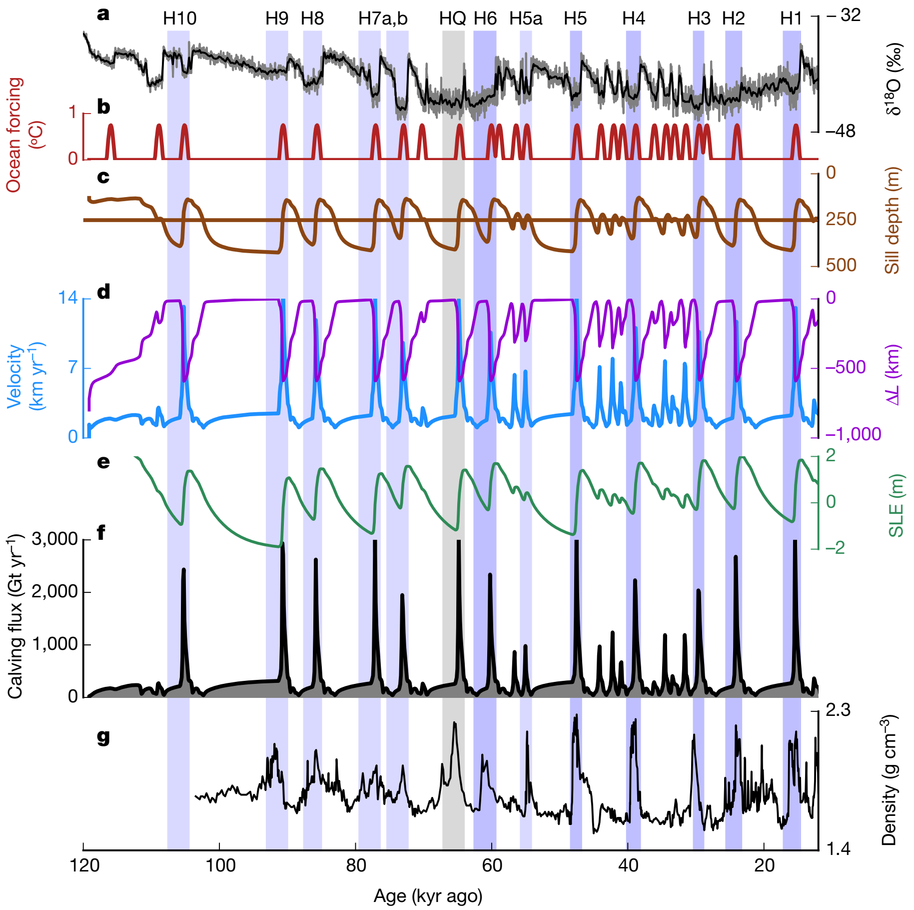

Figure 2 | Time series of simulated Hudson Strait Ice Stream activity. a, Time series of raw (grey) and smoothed (black) $\delta^{18}O_{ice}$ from the NGRIP ice core[29]. **b**, Synthetic ocean forcing, created from Dansgaard–Oeschger cycles. **c**, Depth of the sill below sea surface. **d**, Terminus velocity and the change in terminus position relative to channel mouth (ΔL). **e**, Change in eustatic sea level (SLE) caused by ice discharge. **f**, The flux of ice discharged into the ocean. **g**, Sediment density from sediment core MD95-2025[28]. Approximate timing and duration of observed Heinrich events[30] are denoted with blue-shaded rectangles. The grey-shaded rectangle at about 65 kyr ago denotes the newly named IRD event predicted by our model (HQ).

terminus is limited by the strength of glacier ice, a theory proposed in refs 19 and 20 and called the "marine ice cliff instability"[21]. This parameterization is calibrated to a wide variety of Greenland, Svalbard and Alaskan marine-terminating-glaciers (Supplementary Information, section 3.3). Isostatic adjustment of the bed, which is important on millennial timescales[22,23], is modelled as an elastic lithosphere overlying a viscous mantle[24] with upper-mantle viscosity consistent with inferences based on Hudson Bay uplift data[25] (Supplementary Information, section 3.6).

Atmospheric forcing was held constant to simulate the onset of Heinrich events when atmospheric temperatures were cold. We drove the model with a prescribed ocean thermal forcing at the calving front to simulate subsurface warming linked to reductions in the Atlantic Meridional Overturning Circulation. We increased subsurface water temperatures in pulses timed with the cold phase of each Dansgaard–Oeschger cycle with warm water penetrating up to approximately 250 m below the surface. The pulse magnitude and depth was constrained by proxy observations of ocean temperature recorded near the mouth of the Labrador Sea showing 1–3 °C warming at intermediate depths preceding Heinrich events[8] (Supplementary Information, section 3.7). This record is selected for its proximity to the Hudson Strait, but the presence of subsurface warming during cold phases of Dansgaard–Oeschger cycles is widely supported by multiple proxy and modelling studies.

Our simulated Heinrich events show a pattern of rapid retreat followed by slow advance (Figs 1 and 2, Supplementary Videos 1–3). When the ice is at its full extent (Fig. 1a), the deepest portion of the bed is depressed more than 1 km beneath sea level, comparable to modern marine-based ice sheets. Near the mouth of the channel, the terminus remains grounded on bed topography depressed about 300 m beneath sea level, leaving it vulnerable to subsurface ocean warming. A small warming in the subsurface ocean triggers rapid retreat of the ice sheet into the over-deepening bed (Fig. 1b, c). Retreat continues until isostatic adjustment allows the bed (and sill) to rise, isolating the terminus from ocean forcing. At this point, retreat ceases and, with the ice sheet at its minimum extent, bed uplift facilitates regrowth on a slower timescale than collapse (Fig. 1d). When the ice sheet is of small or intermediate size, the elevated sill near the terminus protects the interior basin from attack by the subsurface ocean warming pulse during the next Dansgaard–Oeschger cycle.

During the retreat phase, our modelled Hudson Strait Ice Stream retreats at a peak rate of 1–2 km yr^{-1} and flow speeds increase to over 12 km yr^{-1} (Fig. 2d), comparable to rates observed during retreat of modern marine-terminating glaciers in Greenland[18]. However, because the Hudson Strait Ice Stream was more than an order of magnitude larger than the largest marine-terminating glaciers in existence today, an average modelled Heinrich event results in about 2 m of eustatic sea level rise (Fig. 2e), similar to the magnitude of sea level rise estimated for Heinrich events[3,26]. In some cases, a small pulse of calving occurs between full Heinrich events (Fig. 2), a pattern also seen in sedimentological changes offshore of the Hudson Strait during Dansgaard–Oeschger cycles that do not contain Heinrich events[27]. Full ice sheet collapse is triggered in our model only when the ice sheet is near its maximum extent with a bed grounded deep beneath sea level.

Despite the idealized nature of our forcing, the simple feedback cycle between ocean forcing and isostatic adjustment predicts the observed timing of Heinrich events (Fig. 2), with the exception of Heinrich event 5a (H5a), one of the smaller, non-canonical Heinrich events, where we predict a smaller event. Moreover, because isostatic adjustment modulates the sensitivity of the ice sheet to ocean forcing, Heinrich events in our model are only associated with ocean warming events that occur when the ice sheet is near its maximum extent. Our model further predicts an extra, previously unidentified ice-rafting event between H7b and H6, which we label HQ (grey bar in Fig. 2). This event is a robust feature in our model and is caused by the long, cold phase preceding the Dansgaard–Oeschger event that occurred about 65,000 years ago. This long delay allows the ice sheet to re-advance and depress the bed near the terminus. Intriguingly, examining a long sediment core from the mouth of the Labrador Sea[28] suggests that an ice-rafting event occurred during this cold phase (Fig. 2g). So far, this event has not been identified in the central North Atlantic IRD belt, where the original six Heinrich events were discovered[1,2], but most sediment cores from the IRD belt either do not extend past H6 to the relevant time interval[2,4] or show a much weaker signature for events older than H6[1]. The independent prediction of an additional ice-rafting event captured in the geological record strongly supports our proposed mechanism. Furthermore, our proposed mechanism is robust, with submarine melt triggering Heinrich events in both the flowline and regional model at the appropriate intervals over a wide range of model parameters (Supplementary Discussion and Supplementary Figs 6–13).

Researchers have struggled for decades to understand why the Laurentide Ice Sheet collapsed repeatedly during the cold intervals of the last glacial cycle. Our model solves this problem and shows that Heinrich events can be triggered by relatively small millennial-scale fluctuations in subsurface ocean temperature. This mechanism explains the observed abrupt collapse, long recovery and recurrence interval of Heinrich events, as well as the alignment between Heinrich events within the cold phases of Dansgaard–Oeschger events when atmospheric temperatures are coldest, without requiring an ice shelf. The presence of IRD from other ice sheets within Heinrich layers dominated by Hudson-Strait-derived IRD[2,3] further strengthens our hypothesis, as it is likely that the basin-wide subsurface warming that triggers Heinrich events would also trigger other ice masses to release smaller amounts of IRD. The much smaller size of these other ice masses allows a more rapid recovery, making them more susceptible to ocean warming during non-Heinrich-event stadials, analogous to the increased calving flux associated with ocean-driven retreat of Greenland's modern tidewater glaciers and as observed in the sediment record. Finally, observations from Greenland's largest glaciers show that sediment-rich icebergs frequently capsize after detaching, providing a mechanism that allows icebergs to travel great distances before depositing their sediment load to form the Heinrich layers.

The mechanism we propose implies that Heinrich events are controlled by the same processes that drive retreat of modern marine-terminating glaciers[14–18], albeit on a much grander scale than is possible in the confines of Greenland's smaller outlet glaciers. This suggests that portions of West Antarctica already at risk of collapse[21], like the Amundsen Sea Embayment, where wide ice streams are grounded deep beneath sea level, could be vulnerable to an ocean-triggered Heinrich-event-style demise, even in the absence of atmospheric warming.

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1. Heinrich, H. Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years. *Quat. Res.* **29,** 142–152 (1988).
2. Bond, G. C. & Lotti, R. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science* **267,** 1005–1010 (1995).
3. Hemming, S. R. Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys*. **42,** RG1005 (2004).
4. Bond, G. *et al.* Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* **365,** 143–147 (1993).
5. MacAyeal, D. R. Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich events. *Paleoceanography* **8,** 775–784 (1993).
6. Clarke, G., Marshall, S. J., Hillaire-Marcel, C., Bilodeau, G. & Veiga-Pires, C. in *Mechanisms of Global Climate Change at Millennial Time Scales* (eds Clark, P. U., Webb, R. S. & Keigwin, L. D.) 394 (1999).
7. Hulbe, C. L., MacAyeal, D. R., Denton, G. H., Kleman, J. & Lowell, T. V. Catastrophic ice shelf breakup as the source of Heinrich event icebergs. *Paleoceanography* **19,** PA1004 (2004).
8. Marcott, S. A. *et al.* Ice-shelf collapse from subsurface warming as a trigger for Heinrich events. *Proc. Natl Acad. Sci. USA* **108,** 13415–13419 (2011).
9. Alvarez-Solas, J., Robinson, A., Montoya, M. & Ritz, C. Iceberg discharges of the last glacial period driven by oceanic circulation changes. *Proc. Natl Acad. Sci. USA* **110,** 16350–16354 (2013).
10. Shaffer, G., Olsen, S. M. & Bjerrum, C. J. Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events. *Geophys. Res. Lett.* **31,** L24202 (2004).
11. Alvarez-Solas, J. & Ramstein, G. On the triggering mechanism of Heinrich events. *Proc. Natl Acad. Sci. USA* **108,** E1359–E1360 (2011).
12. Hesse, R., Klauck, I., Khodabakhsh, S. & Piper, D. Continental slope sedimentation adjacent to an ice margin. III. The upper Labrador slope. *Mar. Geol*. **155,** 249–276 (1999).
13. de Vernal, A., Hillaire-Marcel, C., Turon, J. L. & Matthiessen, J. Reconstruction of sea-surface temperature, salinity, and sea-ice cover in the northern North Atlantic during the Last Glacial Maximum based on dinocyst assemblages. *Can. J. Earth Sci*. **37,** 725–750 (2000).
14. Holland, D. M., Thomas, R. H., de Young, B., Ribergaard, M. H. & Lyberth, B. Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nat. Geosci*. **1,** 659–664 (2008).
15. Nick, F. M., Vieli, A., Howat, I. M. & Joughin, I. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nat. Geosci*. **2,** 110–114 (2009).
16. Rignot, E., Koppes, M. & Velicogna, I. Rapid submarine melting of the calving faces of West Greenland glaciers. *Nat. Geosci*. **3,** 187–191 (2010).
17. Straneo, F. & Heimbach, P. North Atlantic warming and the retreat of Greenland's outlet glaciers. *Nature* **504,** 36–43 (2013).
18. Murray, T. *et al.* Extensive retreat of Greenland tidewater glaciers, 2000–2010. *Arct. Antarct. Alp. Res.* **47,** 427–447 (2015).
19. Bassis, J. N. & Walker, C. C. Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. *Proc. R. Soc. A* **468,** 913–931 (2012).
20. Bassis, J. N. & Jacobs, S. Diverse calving patterns linked to glacier geometry. *Nat. Geosci*. **6,** 833–836 (2013).
21. DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531,** 591–597 (2016).
22. Gomez, N., Mitrovica, J. X., Huybers, P. & Clark, P. U. Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nat. Geosci*. **3,** 850–853 (2010).
23. Konrad, H., Sasgen, I., Pollard, D. & Klemann, V. Potential of the solid-earth response for limiting long-term West Antarctic Ice Sheet retreat in a warming climate. *Earth Planet. Sci. Lett.* **432,** 254–264 (2015).
24. Bueler, E., Lingle, C. S. & Brown, J. Fast computation of a viscoelastic deformable Earth model for ice-sheet simulations. *Ann. Glaciol*. **46,** 97–105 (2007).
25. Mitrovica, J. & Forte, A. A new inference of mantle viscosity based upon joint inversion of convection and glacial isostatic adjustment data. *Earth Planet. Sci. Lett.* **225,** 177–189 (2004).
26. Roberts, W. H. G., Valdes, P. J. & Payne, A. J. A new constraint on the size of Heinrich events from an iceberg/sediment model. *Earth Planet. Sci. Lett.* **386,** 1–9 (2014).
27. Andrews, J. T. & Barber, D. C. Dansgaard-Oeschger events: is there a signal off the Hudson Strait Ice Stream? *Quat. Sci. Rev.* **21,** 443–454 (2002).
28. Stoner, J., Channell, J., Hillaire-Marcel, C. & Kissel, C. Geomagnetic paleointensity and environmental record from Labrador Sea core MD95–2024: global marine sediment and ice core chronostratigraphy for the last 110 kyr. *Earth Planet. Sci. Lett.* **183,** 161–177 (2000).
29. Rasmussen, S. O. *et al.* A stratigraphic framework for abrupt climatic change during the last glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* **106,** 14–28 (2014).
30. Seierstad, I. K. *et al.* Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale δ^{18}O gradients with possible Heinrich event imprint. *Quat. Sci. Rev.* **106,** 29–46 (2014).

Supplementary Information is available in the online version of the paper.

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