Ice-shelf collapse from subsurface warming as a trigger for Heinrich events

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Episodic iceberg-discharge events from the Hudson Strait Ice Stream (HSIS) of the Laurentide Ice Sheet, referred to as Heinrich events, are commonly attributed to internal ice-sheet instabilities, but their systematic occurrence at the culmination of a large reduction in the Atlantic meridional overturning circulation (AMOC) indicates a climate control. We report Mg/Ca data on benthic foraminifera from an intermediate-depth site in the northwest Atlantic and results from a climate-model simulation that reveal basin-wide subsurface warming at the same time as large reductions in the AMOC, with temperature increasing by approximately 2 °C over a 1–2 kyr interval prior to a Heinrich event. In simulations with an ocean model coupled to a thermodynamically active ice shelf, the increase in subsurface temperature increases basal melt rate under an ice shelf fronting the HSIS by a factor of approximately 6. By analogy with recent observations in Antarctica, the resulting ice-shelf loss and attendant HSIS acceleration would produce a Heinrich event.

Results

Two independent temperature proxies support our Mg/Ca-derived BWTs. First, our reconstructed BWT at approximately 19 ka of 0 ± 1.3 °C agrees at 1σ with a Last Glacial Maximum temperature of −1.2 ± 0.2 °C reconstructed from pore fluids at site 981 on the Fenı Drıt (2,184 m; 55°29′N, 14°39′W) (17). Second, the amplitude and structure of the BWT change during the last deglaciation is in excellent agreement with the temperature change derived from the ice-volume corrected δ18O (δ18OIVC) measured on benthic fauna from this core assuming a temperature-dependent fractionation of 0.25‰ °C−1 for calcite (18) (SI Text) (Fig. 2B). The Mg/Ca data from EW9302-2JPC identify several systematic BWT changes that occurred in association with each of the four Heinrich ice rafted debris layers for which we have sufficient data (Fig. 2B) (1). Temperatures gradually increased prior to the start of each Heinrich layer, with the start of the warming beginning

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Heinrich layer. Approximately 3.4 °C and reaches a maximum BWT of 5 °C around a mean value that is close to the present BWT of approximately 1 °C, following each Heinrich event. This early warming is replicated by the reconstructed marine records for core EW9302-2JPC. Location of core sites also shown: site a is core M35003-4, site b is core OCE326-GGC5, site c is core EW9302-2JPC, site d is core ENAM93-21, and site e is core MD95-2010.

A number of proxy records show that the AMOC began to decrease 1–2 kyr prior to Heinrich events (3, 19–22); this decline has been attributed to a climatically induced increase in freshwater fluxes from Northern Hemisphere ice sheets (4, 23). Model simulations indicate that, without an active AMOC and associated cooling of the ocean interior by convection, continued downward mixing of heat at low latitudes warms subsurface waters to a depth of approximately 2,500 m. Some of the heat accumulated in the subsurface is transported poleward, causing a temperature inversion in the northern North Atlantic (Fig. 1B) (4, 5, 12). We use results from a simulation with the National Center for Atmospheric Research Community Climate System Model version 3 (NCAR CCSM3) (12) to evaluate the transient response of the BWT at our core site to a reduction in the AMOC during the last deglaciation. Initial reduction in the AMOC occurs in response to increased freshwater fluxes to the North Atlantic associated with onset of deglaciation from the last glacial maximum at approximately 19 ka (Fig. 3A) (12, 23). Here we find that the simulated BWT anomaly at our core site caused by the change in the AMOC is in good agreement with our Mg/Ca-derived record, with temperature increasing by approximately 2 °C prior to H1, followed by cooling induced by the resumption of the AMOC at the start of the Bolling interstadial approximately 14.6 ka (Fig. 3C).

Although similar subsurface warming preceding H1 has been inferred in the subtropical (24) and high-latitude (25, 26) North Atlantic from changes in benthic foraminifera δ18O, the δ18O changes in the Nordic Seas have alternatively been interpreted as recording increased brine formation beneath expanded sea ice (9, 10) and thus are largely independent of temperature. Our previously undescribed Mg/Ca measurements on Cibicidoides spp. (N = 1), Cibicidoides lobulatus (N = 3), and Melonis barkeeanum (N = 16) for a core from the Nordic Seas (MD95-2010, 1,226-m depth) (Fig. 1B) demonstrate that the 1.5 per mil δ18Oivc signal at this site can be explained by approximately 6 °C of warming (Fig. 4A), thus supporting subsurface warming rather than brine formation as the cause of the large δ18Oivc signal. Changes in temperature simulated by the CCSM3 model further suggest that the δ18Oivc signal at this and other North Atlantic sites represents a dominant temperature control reflecting basin-wide subsurface warming (Fig. 4). The model also simulated small changes in salinity at intermediate depths as freshwater added to the surface was convected downward through the Labrador Sea in the subpolar gyre, suggesting that the associated advection of light δ18O water may account for some small fraction of the δ18Oivc signal (Fig. 4).

Our Mg/Ca data also suggest a similar phasing between earlier changes in the AMOC, subsurface temperatures, and Heinrich events during marine isotope stage 3 (60–26 ka). In particular, correlation of marine records with synchronized Greenland
and Antarctica ice-core temperature records shows that Heinrich events during this interval occurred only when Greenland was at its coldest and Antarctica was at its warmest (Fig. 2 C and D) (27, 28), which is the maximum expression of a strong reduction in the AMOC and its attendant meridional ocean heat transport (29). These changes in the AMOC are documented by a variety of proxy records that show a gradual AMOC reduction prior to and during the near-complete replacement of North Atlantic Intermediate Water with Antarctic Bottom Water in the North Atlantic basin at the times of Heinrich events (3, 22, 30). The 1- to 2-kyr interval of gradual subsurface warming suggested by our Mg/Ca data that peak at the same time as H3, H5a, and H6 (Fig. 2A) is thus consistent with a response to a maximum reduction in the AMOC at these times as well.

Because of the complex ocean-ice processes that exist beneath the ice shelves (11), the effect of the open-ocean subsurface warming documented here on the stability of an ice shelf fronting the HSIS is unclear. We apply a high-resolution ocean model coupled to a nonevolving but thermodynamically active ice shelf (SI Text) to explore the sensitivity of basal melt rate to subsurface warming for a specified ice shelf filling Baffin Bay and the Labrador Sea (31). Initial model hydrography is derived from the CCSM3 simulation of the last deglaciation (SI Text) (12). We refer to an active AMOC, with cold subsurface temperatures, as the “cold state,” corresponding to model years 19.5–19.0 ka, and an inactive AMOC, with warm subsurface temperatures, as the “warm state,” corresponding to model years 17.0–16.5 ka.

For the cold state, we find that the shelf-averaged basal melt rate is 0.17 m a⁻¹, with the integrated volume loss from the ice shelf by basal melt being approximately 10% of the estimated flux of approximately 660 km² a⁻¹ across the HSIS grounding line (31). For the warm state, the averaged basal melt rate is 1.03 m a⁻¹. We also performed three additional intervening simulations with our regional model, for a total of five spanning the interval from 19.5 to 16.5 ka, which allows us to derive the rela-
tion between ocean temperature $T_o$ at the typical depth of the ice-shelf base (400–800 m), and shelf-averaged melt rate $M_{av} = 0.54 + 0.34 T_o$ (m a$^{-1}$). Based on the simulated temperature evolution for water depths of 400–800 m, our computed time history of ice-shelf thinning in response to the warming of intermediate-depth waters indicates an approximate 1,000-year time scale for collapse of the ice shelf (red curve in Fig. 3B), although based on modern analogs, it is likely that the ice shelf would collapse before it thinned to zero; we thus expect that our estimate of this time scale is a maximum. Additional factors (rate of grounding line migration and calving rate) may modulate this response, but are unlikely to significantly change the time scale (SI Text). The model also indicates that maximum melt rates along the deep grounding line of the H1S increased sixfold, from approximately 6 m a$^{-1}$ to 35–40 m a$^{-1}$, comparable to estimates from empirical models based on modern observations of grounding line melt rates (32). By analogy with recent studies of Antarctic ice shelves and buttressed ice streams (33), more rapid grounding line thinning would accelerate the HS1 outflow prior to ice-shelf collapse.

Conclusions

Our data and model results indicate that basin-wide subsurface warming occurred in the North Atlantic in response to a reduction in the AMOC prior to Heinrich events and that Heinrich events did not occur until the AMOC was at its weakest and subsurface temperatures were near their maximum values. We also find that the open-ocean subsurface warming significantly increases the rate of mass loss from the ice shelf fronting the HS1. Our results thus support simplified climate modeling results, suggesting that a weakened or collapsed ice shelf would trigger an ice-stream surge, producing a Heinrich event (5, 6), analogous to the recent response of Antarctic glaciers to the loss of buttressing ice shelves (34). By confirming the significance that subsurface warming played in triggering past ice-sheet instabilities, our results provide important insights into possible future behavior of similarly configured Antarctic ice-sheet sectors, should warmer waters penetrate beneath their large, buttressing ice shelves.

Methods

We used an automated flow-through system (35) that cleans and dissolves the carbonate shells and thus minimizes the effects of secondary calcite and clay contamination (SI Text). We analyzed the benthic species C. lobula-tus (N = 46), C. spp. (N = 23), and M. barleeanum (N = 44), including 15 replicate analyses, and converted Mg/Ca ratios to BVTs following published calibration curves (SI Text). The age model for EW9302-2JPC is based on six previously published $^{14}$C dates, (8), well-dated tephra layers at 16–(Vedde Ash) and 408-cm depth (ASH II), an age-to-depth tie point at the midpoint of $H$ (36) corresponding to the peak in ice-raftered detrital carbonate at 496-cm depth in EW9302-2JPC, and the marine isotope stage 5/4 boundary (544 cm) based on the $^{13}$O planktonic foraminifera data from the core (8) (SI Text). We emphasize, however, that the relative timing of changes of any given proxy within the core relative to those of another proxy is established directly from the stratigraphic position of each sample within the core and is thus insensitive to any uncertainties in numerical chronology.

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