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Subtropical iceberg scours and meltwater routing in the deglacial western North Atlantic

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Abrupt centennial-to-millennial shifts in Northern Hemisphere climate during the last deglaciation are thought to have been triggered by the discharge of large volumes of meltwater and icebergs to the subpolar North Atlantic[1]. Here we show that meltwater and icebergs were also transported directly from the Laurentide ice margin to the subtropical North Atlantic in a narrow coastal current. We present high-resolution bathymetric data from south of Cape Hatteras showing numerous scours that we interpret as relict iceberg keel marks. This indicates that icebergs up to 300 m thick drifted to southern Florida (24.5° N). In simulations with an ocean circulation model, during deglaciation, fresh water and icebergs routinely reached as far south as 32.5° N, in a period of less than four months. The southernmost scours formed only during periods of high meltwater discharge from the Northern Hemisphere ice sheets. In the simulations, such extreme periods of meltwater release led to a reversal of the typically northward surface flow in the nearshore subtropical western North Atlantic. We therefore suggest that significant volumes of iceberg-laden meltwater routinely bypassed subpolar regions and spread across the subtropical North Atlantic.

The retreat of the Northern Hemisphere ice sheets during the last deglaciation (20–6 kyr ago) was accompanied by the discharge of meltwater and icebergs to the North Atlantic[1]. During this period, the onset of several prominent cold episodes coincided with times of particularly high freshwater release to the North Atlantic, suggesting that a freshening of the ocean weakened the strength of the Atlantic meridional overturning circulation[1,2] and reduced the transport of heat to Europe and North America. It is typically believed that freshwater runoff was routed to the subpolar North Atlantic, with little penetration south of ∼40° N (ref. 1). More recently, iceberg scours have been identified outside this region, on the Scotian shelf and Bay of Fundy[3–5], Massachusetts and New Jersey margins[6–8], as well as offshore of South Carolina (∼32.5° N; ref. 9). In addition, ice-rafted debris (IRD) in marine sediment records from Blake Plateau (∼31° N, 79° W) and Bermuda Rise (32° N, 65° W) show that icebergs drifted to the subtropics during Heinrich events[10,11]. Determining how far south of the subpolar gyre icebergs and meltwater penetrated is vital for understanding the sensitivity of North Atlantic Deep Water formation and climate to past changes in high-latitude freshwater runoff. Here we use a combination of high-resolution multibeam bathymetry data and high-resolution numerical ocean circulation modelling to highlight a new ocean circulation pathway capable of rapidly transporting icebergs and meltwater along the east coast of North America to the subtropical North Atlantic.

Analysis of high-resolution, multibeam bathymetry data reveals numerous iceberg scours along the continental slope from Cape Hatteras (∼35° N) to the Florida Keys (∼24.5° N; see Methods, Figs 1 and 2 and Supplementary Fig. 1). The identified iceberg keel marks are found in water 170–380 m deep, and are traceable for >30 km. The scour marks, oriented south-southwest along regional bathymetric contours, exhibit lateral berms that record the ploughing of iceberg keels along the sea floor and semi-circular terminal grounding pits where icebergs came to rest (Fig. 2). The scours observed offshore of South Carolina are found in water 170–380 m deep; farther south the scours are found in shallower water ∼215–280 m deep (Supplementary Fig. 1). The keel marks decrease in size and abundance moving south along the margin, concordant with increased iceberg melt farther from the ice calving margin. The scour depressions offshore of South Carolina (∼32.5° N) are ∼10–100 m wide and 10–20 m deep[9], whereas the Florida margin scours (31° N–24.5° N) are narrower (10–50 m wide) and 2–5 m deep. The scour features are best preserved where shoaling platforms came into contact with the icebergs. Elsewhere, oversteepened slopes along large stretches of the margin limited seafloor–iceberg interaction and allowed unhindered iceberg transport over long distances.

Both the scour morphology and correlation with stratigraphic controls on the New Jersey margin indicate that the South Carolina and Florida scours were probably formed by icebergs calving from the Laurentide Ice Sheet (LIS) following the Last Glacial Maximum[8] (LGM). Relative sea level constraints at this time (70–120 m lower than modern[12]) imply that iceberg keel depths ranged from 50–310 m to generate the observed scour distribution. Icebergs at this subtropical latitude would therefore have been comparable in size to those calving from the modern-day Greenland Ice Sheet margin. As iceberg melt rate is inversely related to size[13], icebergs from the LIS must have been considerably larger to reach this far south without completely melting. Indeed, seafloor scours in Hudson Bay show that extremely large, tabular 'megabergs' (keel drafts >650 m) were sourced from the Canadian margin following the LGM (ref. 14).

The south-southwest orientation of the iceberg scours, reduction in incision depth, and decrease in scour frequency with increasing distance from the former LIS (Fig. 2 and Supplementary Fig. 1) imply that icebergs drifted south along the continental margin in regions where the modern Gulf Stream consistently flows northward at $>1\ \mathrm{m\ s^{-1}}$. Here we use a high-resolution (1/6°, ∼18 km), coupled global ocean/sea-ice model configured for the LGM (Methods and Supplementary Fig. 2) to investigate the ocean circulation dynamics necessary to transport icebergs from the LIS to subtropical latitudes. The model is able to resolve both narrow coastal boundary currents and nearshore shelf and slope circulation patterns that are important for realistically simulating freshwater transport in the ocean[15,16] (Supplementary Fig. 3).

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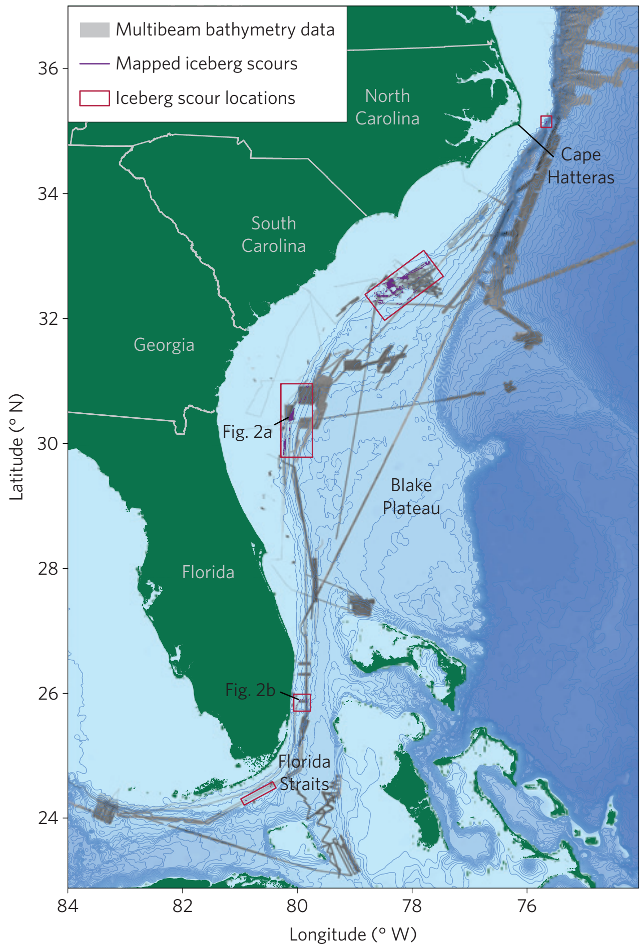

Figure 1 | Southern US Atlantic margin iceberg scour locations. Multibeam bathymetry data are shown in grey; the iceberg scour tracks are digitized in purple; and the general iceberg scour locations are outlined in red.

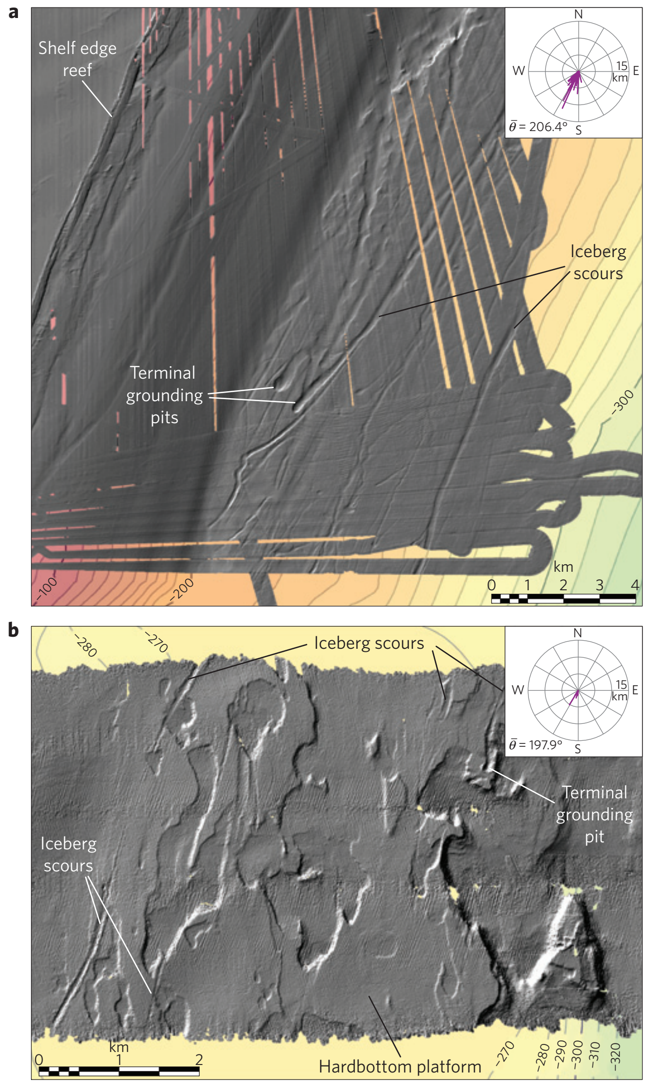

Figure 2 | Iceberg scours along the Florida margin. a,**b**, High-resolution shaded relief multibeam bathymetry from northern Florida (~30° N; **a**) and southern Florida (~25° N; **b**) overlain on regional bathymetric contours derived from the NOAA NGDC coastal relief model. The iceberg scours are characterized by relatively linear seafloor depressions with lateral berms and terminal grounding pits. Insets: rose diagrams showing the measured azimuths and lengths of the iceberg scours in each region.

In our Control model simulation, southward-flowing Labrador slope water dominates the continental shelf from the Grand Banks of Newfoundland to Cape Hatteras, although during winter the slope waters penetrate to South Carolina (Supplementary Fig. 3). A calculation of the ocean drag forces exerted on icebergs in the nearshore region (Supplementary Section) indicates that icebergs with keel depths ≤90 m could seasonally drift to South Carolina, creating scours on the sea floor in modern water depths of ~160–210 m. These depths are consistent with most scours in this region (170–220 m), although icebergs of this size are not large enough to create the scours observed in deeper water, indicating that larger icebergs drifted to this region. South of here, the nearshore circulation is northward flowing, which prevents icebergs of any size reaching the scour sites observed off the coast of Florida.

To investigate how icebergs might have drifted to southern Florida, we simulated the release of a series of glacial meltwater floods in our high-resolution ocean circulation model at the former LIS iceberg calving margins of Hudson Bay and the Gulf of St. Lawrence with a range of magnitudes (0.5, 1.0, 2.5 and 5.0 Sv ($\mathrm{Sv} = 1 \times 10^6\,\mathrm{m^3 s^{-1}}$); Methods). In all cases, meltwater from Hudson Bay propagates along the Labrador coast as a narrow coastal boundary current, with little penetration into the central Labrador Sea (Fig. 3). At the Grand Banks of Newfoundland, part of the meltwater turns to the right and flows south-southwest along the continental margin towards Cape Hatteras; here a 5 Sv meltwater flood will cause the upper ~150–160 m of the water column to become extremely fresh (4.5 psu) and cold (−1 to −1.5 °C), whereas smaller discharge events have less impact in this region (Supplementary Table 1).

In our model, the meltwater flux must be ≥2.5 Sv to reach the southern scour sites along the Florida coast (Supplementary Fig. 4) as smaller magnitude floods are unable to overcome the northward flow of the Gulf Stream south of South Carolina. A 5 Sv meltwater flood reaches Florida Strait in ~4 months (Fig. 3) with little change in physical properties from the time of its release >5,000 km to the north. Remarkably, the meltwater current at this latitude is still ~100–110 km wide, 70 m deep, and flowing south at ~1 $\mathrm{m s^{-1}}$ with a temperature and salinity of ~2.6 °C and 6.6 psu, respectively (Supplementary Table 1 and Supplementary Fig. 5). For comparison, ocean waters in this region in the Control simulation are ~20–25 °C and flowing northward at ~1 $\mathrm{m s^{-1}}$. The arrival of meltwater would have been marked by a 180° reversal (from north to south) in the nearshore surface circulation of the subtropical western North Atlantic (Supplementary Fig. 4) and the sudden appearance of massive icebergs along the coast, from South Carolina

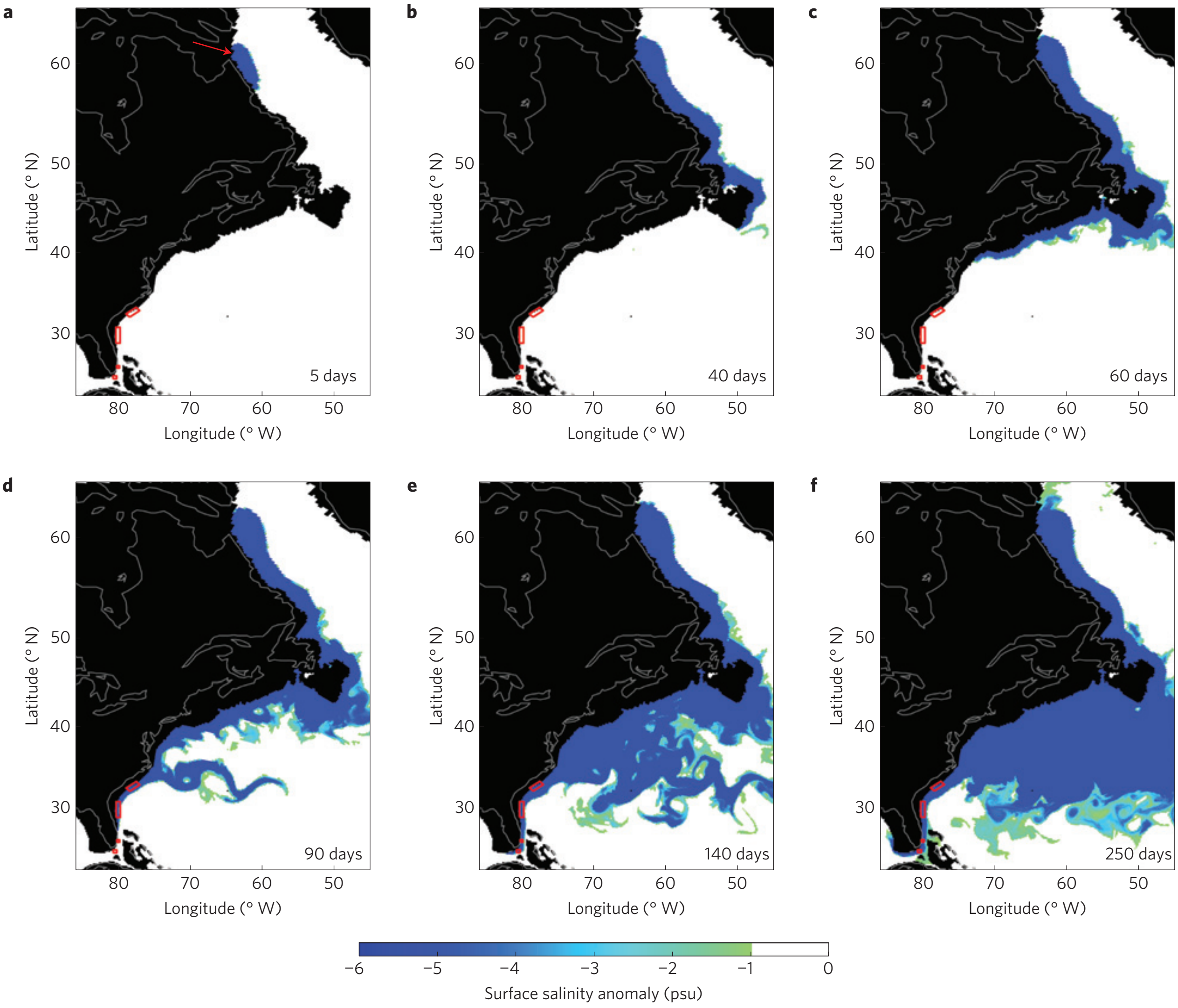

Figure 3 | Advection pathway of meltwater released from Hudson Bay. The colours (green–blue) show the difference in surface salinity (perturbation minus control) in response to releasing 5 Sv of meltwater from Hudson Bay. **a**–**c**, Meltwater is confined to the Labrador coast as a narrow buoyant coastal current (**a**) and rapidly propagates southwards towards Cape Hatteras (**b**,**c**). **d**–**f**, After 90 days meltwater reaches northern Florida (**d**) and penetrates through the Florida Strait (**e**) and into the Gulf of Mexico (**f**). Red outlines highlight the locations of the subtropical iceberg scours; LGM landmasses are shown in black and the modern coastline by the grey line.

to Florida Keys. The transport of iceberg-laden meltwater along the coast would also have been very abrupt and short-lived, lasting <1 year for the events we have simulated (Supplementary Fig. 4f–h). Model experiments conducted with meltwater floods released from the Gulf of St. Lawrence showed similar results (Supplementary Fig. 6), which suggests that the icebergs could have been sourced from either calving location.

Our numerical model results suggest that icebergs could have routinely drifted to South Carolina, whereas the scours farther south were formed during periods of enormous meltwater discharge from the LIS (Supplementary Table 2). In our model, only a 5 Sv meltwater flood can generate drag forces sufficiently large to transport icebergs with keels thick enough to create both the deeper water scours off the coast of South Carolina and those at the southern tip of Florida (modern water depths of ∼200 m). Although a 2.5 Sv flood can transport icebergs with ∼80 m keels to northern Florida, producing scours in modern-day water depths of 150–200 m, a flood of this magnitude will transport only ∼10-m-thick icebergs through Florida Strait; larger iceberg keels would extend deeper than the relatively shallow meltwater into the northward flowing Gulf Stream, impeding their progress. This finding is consistent with the more numerous scours identified offshore of South Carolina, compared with farther south.

Along the continental slope, meltwater is transported away from the nearshore environment in narrow filaments caused by interaction between the cold fresh meltwater current and the saltier open ocean (Fig. 3) and leads to a significant freshening of the subtropical North Atlantic (20° N–40° N) after 1 year (Supplementary Fig. 7). This mechanism is an important contributor of cold, potentially iceberg-laden meltwater to the subtropical gyre, including the Blake Plateau and Bermuda Rise regions that lie offshore of the Carolinas (31° N–35° N). Previous work has attributed abrupt decreases in sea surface temperature, lower salinity, and IRD at these locations to iceberg entrainment in cold-core rings transported across the Gulf Stream[10,11]. Our results suggest an additional mechanism for transporting fresh water and icebergs to these regions. The offshore advection of cold water into the subtropical gyre also offers an explanation for the cooling observed in the eastern subtropical Atlantic around the Iberian margin at this time[17,18].

Freshwater initially transported to the subtropical gyre by the narrow coastal current undergoes significant mixing with the Gulf Stream and is gradually advected northwards towards the subpolar gyre (Supplementary Fig. 8). By the time freshwater reaches regions where deep-water mass formations occur it is much saltier than if it had been directly transported from Hudson Bay to these subpolar locations. This indicates that the high-latitude freshwater forcing of climate is far more complicated than meltwater instantly freshening the entire subpolar gyre, as nearshore flows and mesoscale ocean eddies play a significant role in ocean freshwater transport. Advection pathways similar to those described here also were observed using modern-day simulations of meltwater floods from Hudson Bay[16], Gulf of St. Lawrence and the Arctic Ocean[19]. This suggests that future ice sheet melt from Greenland will be distributed in narrow coastal boundary currents and undergo intense mixing with the Gulf Stream before freshening the subpolar gyre.

Our results highlight an ocean circulation pathway capable of rapidly transporting massive icebergs and significant volumes of cold, fresh meltwater from the Northern Hemisphere ice sheets to the subtropical North Atlantic. Iceberg-laden meltwater would have rapidly travelled south along the North American continental margin and reached the location of the iceberg scours identified south of Cape Hatteras in <1 year. Although the abundance of IRD in the northern Atlantic has previously been taken to mean that icebergs and meltwater from the LIS remained in the cyclonic subpolar gyre, both the iceberg scours we identify along the southern US Atlantic margin and our simulated meltwater pathways suggest that icebergs and meltwater also significantly freshened the subtropical North Atlantic. These results are consistent with other studies showing a subtropical component to LIS meltwater, before advection into the subpolar gyre[20]. The coastal meltwater pathway we identify highlights a need to account for coastal boundary currents in redistributing ice sheet runoff and subpolar freshwater when examining the driving mechanisms of abrupt climate change.

Methods

The Massachusetts Institute of Technology General Circulation Model[21] (MITgcm) is a coupled ocean/sea-ice free-surface, three-dimensional, primitive equation model that uses both the Boussinesq and the hydrostatic approximations. The model is configured to simulate ocean circulation and sea ice during the LGM. Sea level is 120 m lower than modern[12] and Northern Hemisphere ice sheets are at their full glacial extent, based on LGM reconstructions[22,23] (Supplementary Section). The model has a global horizontal resolution of 1/6° (~18 km) that is eddy permitting and resolves ocean bathymetry, narrow coastal boundary currents, nearshore shelf and slope circulation patterns, and the separation of the Gulf Stream at Cape Hatteras more accurately than coarser resolution palaeoclimate models (Supplementary Fig. 3). This is extremely important for realistically simulating freshwater transport in the ocean as shelf and slope waters comprise of narrow, fast-flowing boundary currents that remain trapped along the coast and spread offshore only in areas of high turbulent mixing induced by bathymetric roughness[15,16]. The spatial resolution of our ocean model is ~5–10 times higher than all existing palaeoclimate simulations, including all of the major models taking part in the latest LGM Paleoclimate Modelling Intercomparison Project Phase III, as these have a spatial resolution of ~1°–2° (ref. 24). The current PMIP3 models are therefore not capable of resolving the narrow coastal freshwater pathway from the Northern Hemisphere ice sheets directly to the subtropical North Atlantic that we simulate and investigate in this study.

The numerical simulations are designed to study the ocean advection pathways of meltwater from the LIS. Meltwater events are assumed to be caused by the opening of a new drainage route to the ocean allowing a proglacial lake to drain to a new level[25]. Reconstructions of the volumes of freshwater released to the ocean during these events throughout the last deglaciation are poorly known, but they are estimated to have peaked at ~5 Sv during the 8.2 kyr event[26]. The time taken for a lake to lower to its new outlet is also uncertain, although hydrologic modelling estimates suggest that these events may have lasted only for up to 1 year[27].

To understand how iceberg-laden meltwater advected along the US continental margin and created iceberg scours traceable to southern Florida, freshwater fluxes of 1 Sv, 2.5 Sv and 5 Sv were released for 1 year at the mouth of Hudson Bay (~60.8° N, 64° W) in separate experiments to simulate the rapid drainage of a proglacial lake[27]. Meltwater was released over an area of ~130 km^2 at the surface of the ocean model into the four model grid points closest to the drainage outlet. Before any mixing the meltwater is entirely fresh (0 psu) and has the same temperature as the surface waters into which it drains. The meltwater forcing was turned off after 1 year and the model integrated forward for 6 more years. An additional experiment was run to simulate the impact of a prolonged routing event[28] on freshwater transport to Florida in which meltwater was continuously discharged to the ocean from Hudson Bay, but at a lesser rate of 0.5 Sv for the entire model integration.

Consistent with theoretical and laboratory studies of buoyant gravity currents along a sloping bottom in a rotating fluid[29], meltwater advecting along the continental shelf is thickest closest to the coast and gradually thins offshore. The offshore extent and vertical thickness of the meltwater are influenced by the original magnitude of the meltwater flood, with larger discharge events producing buoyant gravity currents that are thicker and extend farther offshore (Supplementary Fig. 5).

An accompanying set of experiments were also run by repeating the above procedure with meltwater released at the mouth of the Gulf of St. Lawrence (~44.7° N, 56.8° W). The results from these experiments are very similar to those for Hudson Bay, although we find that only a 5 Sv discharge can reach the southern tip of Florida, compared with the 2.5 Sv flood from Hudson Bay that is able to reach this latitude (Supplementary Figs 4 and 6). The reduced southward penetration of meltwater results from a reduction in the entrainment of Labrador shelf and slope waters into the meltwater flood en route to the subtropics, compared with when meltwater is released from Hudson Bay.

All of the numerical model data discussed and presented in this manuscript are publicly available for download from www.geo.umass.edu/faculty/condron/icebergs/subtropical_data.htm. The multibeam bathymetry data were compiled from ~30 surveys and gridded at 3–10 m resolution, depending on water depth. The scour features were identified and digitized to measure parameters such as depth, length, width and direction using Geographic Information Systems (GIS) software. The multibeam bathymetry data are available for download from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC) archive, online at www.ngdc.noaa.gov.

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Author contributions

J.C.H. was responsible for the seafloor data interpretation; A.C. performed the modelling studies. Both authors contributed to the discussion of results and preparation of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.C.H.

Competing financial interests

The authors declare no competing financial interests.