SUPPLEMENTARY INFORMATION

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

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Please contact Dr. Jenna Hill (jchill@coastal.edu) about the iceberg scours and Dr. Alan Condron (acondron@geo.umass.edu) with questions about the high resolution numerical model configuration and simulations.

1. **Numerical Model Configuration**

All our numerical were performed by integrating the Massachusetts Institute of Technology General Circulation Model (MITgcm)[1] on a global 'cube-sphere' grid[2,3] to permit relatively even grid spacing throughout the domain and avoid polar singularities (Fig.S2). The model grid has a horizontal resolution of 1/6° (~18km) and 50-levels in the vertical with spacing set from ~10m in the near surface to ~450m at a depth of ~6000m. Ocean tracer transport equations are solved using a seventh-order monotonicity preserving advection scheme. There is no explicit horizontal diffusion and vertical mixing follows the K-Profile Parameterization. The ocean model is coupled to a dynamic-thermodynamic sea ice model that computes ice thickness, ice concentration, and snow cover, as per Losch et al.[4], and simulates a viscous-plastic rheology using an efficient parallel implementation of the Zhang and Hibler[5] algorithm. In all of our simulations there is no restoring of temperature or salinity to climatological fields.

Global, monthly climatological, Last Glacial Maximum (LGM) atmospheric boundary conditions (10-m wind, 2-m air temperature, surface humidity, downward longwave and shortwave radiation, precipitation, and runoff) were used to force the ocean and sea ice model. The fields were derived from averaging monthly output from the last decade of the fully coupled Community Climate System Model version 3 (CCSM3) LGM integration[6], and have a spatial resolution of ~2.8°. Our initial global, three-dimensional, LGM ocean temperature and salinity fields were created by averaging monthly output for January from the last 10-years of the ocean model component of the CCSM3 integration. The fields were then interpolated from ~1° spatial resolution and 40 vertical levels to our 1/6° grid with 50 vertical levels. The model was spun-up for 50 years and run forward for an additional 10 years to create a Control integration. The physical properties for each model simulation are summarized in Table S1.

Our Control integration shows that the Gulf Stream is more zonal during the LGM due to an equatorward shift in the North Atlantic subtropical gyre and expansion of the subpolar gyre (Fig.S3). The model has a mean Atlantic meridional overturning strength at 26°N of 18.1±5.9 Sv and mean transport at Florida Strait of 29.6±1.57 Sv, consistent with transports observed in these regions in the CCSM3 LGM integration used to force the model[6]. Horizontal flows in the Control integration at Florida Strait are northward at all levels, thus preventing icebergs from freely drifting south of South Carolina.

2. Iceberg drag calculations

The water drag force (F_w) exerted on an iceberg is calculated using the general relationship given by Smith[7]:

$$F_w = \frac{1}{2}\rho_w C_w L T_k |v_w| v_w \qquad (1)$$

where p_w is the density of water, C_w is the form drag coefficient, L is the iceberg length, T_k is iceberg keel thickness, and V_w is the horizontal ocean velocity. In all of our calculations, icebergs are assumed to be tabular in shape and initially at rest. For simplicity the wind drag force is neglected as this is negligible compared to the drag from either the southward flowing meltwater or the northward flowing Gulf Stream. The total drag exerted on an iceberg by the ocean is calculated by taking into consideration the horizontal velocity at each vertical level in the model that an iceberg of thickness T_k will penetrate. The high vertical resolution of our ocean model allows us to very accurately calculate drag as the upper 10 levels of the model each have a vertical thickness of ~10m. Therefore the drag force exerted on an iceberg with a keel 50m thick will take into account horizontal ocean velocity in the upper 5 model levels. It is essential to accurately account for changes in horizontal velocity with depth because the Gulf Stream continues to flow northwards along the continental slope below the southward flowing meltwater south of Cape Hatteras. The iceberg drag calculations discussed in the main text are summarized in Table S2.

Supplementary References

1. Marshall, J., Adcroft, A., Hill, C., Perelman, L. & Heisey, C. A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. *J. Geophys. Res.* **102,** 5753 (1997).

2. Adcroft, A., Campin, J.-M., Hill, C. & Marshall, J. Implementation of an Atmosphere–Ocean General Circulation Model on the Expanded Spherical Cube. *Month. Weath. Rev.* **132,** 2845–2863 (2004).

3. Menemenlis, D. *et al.* ECCO2: High Resolution Global Ocean and Sea Ice Data Synthesis. *Mercator Ocean Quart. News.* **31,** 13–21.

4. Losch, M., Menemenlis, D., Campin, J.-M., Heimbach, P. & Hill, C. On the formulation of sea-ice models. Part 1: Effects of different solver implementations and parameterizations. *Ocean Modelling* **33,** 129–144 (2010).

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6. Otto-Bliesner, B. L. *et al.* Last Glacial Maximum and Holocene Climate in CCSM3. *J. Clim.* **19,** 2526–2544 (2006).

7. Smith, S. D. Hindcasting iceberg drift using current profiles and winds. *Cold Reg. Sci. and Tech.* **22,** 33–45 (1993).

Supplementary Figures

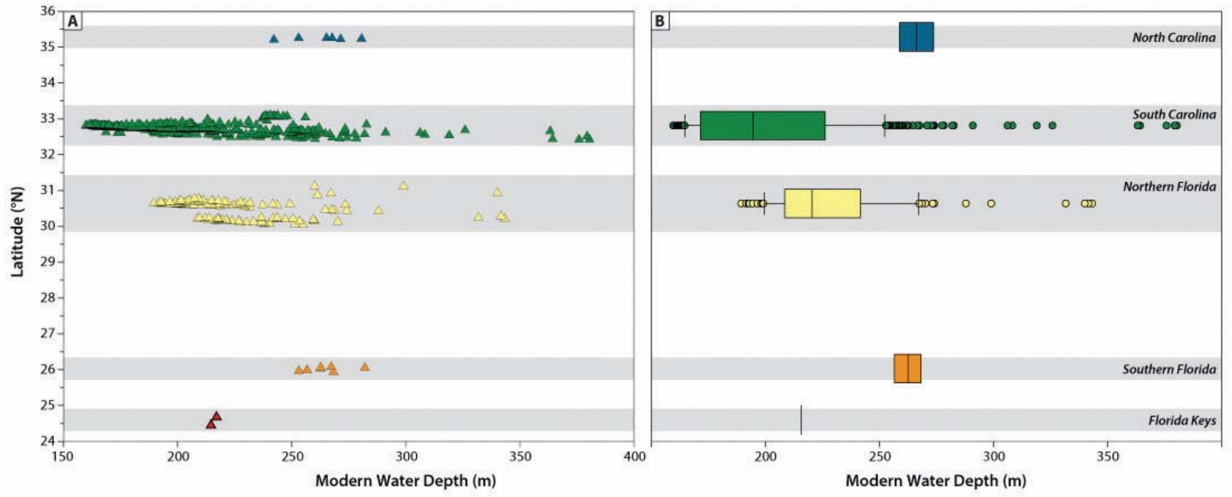

Fig. S1: Distribution of iceberg scour depths with latitude. (a) Full distribution of average observed iceberg scour depths plotted versus latitude. (b) Box plots showing the relative distribution of scour depths for each geographic area. The error bars show the 10th and 90th percentiles. The higher number of scour observations in the South Carolina and northern Florida regions in part reflects the greater availability of high-resolution multibeam bathymetry data in these regions. Outside of the geographic areas identified, scour observations are absent due to insufficient seafloor bathymetry data.

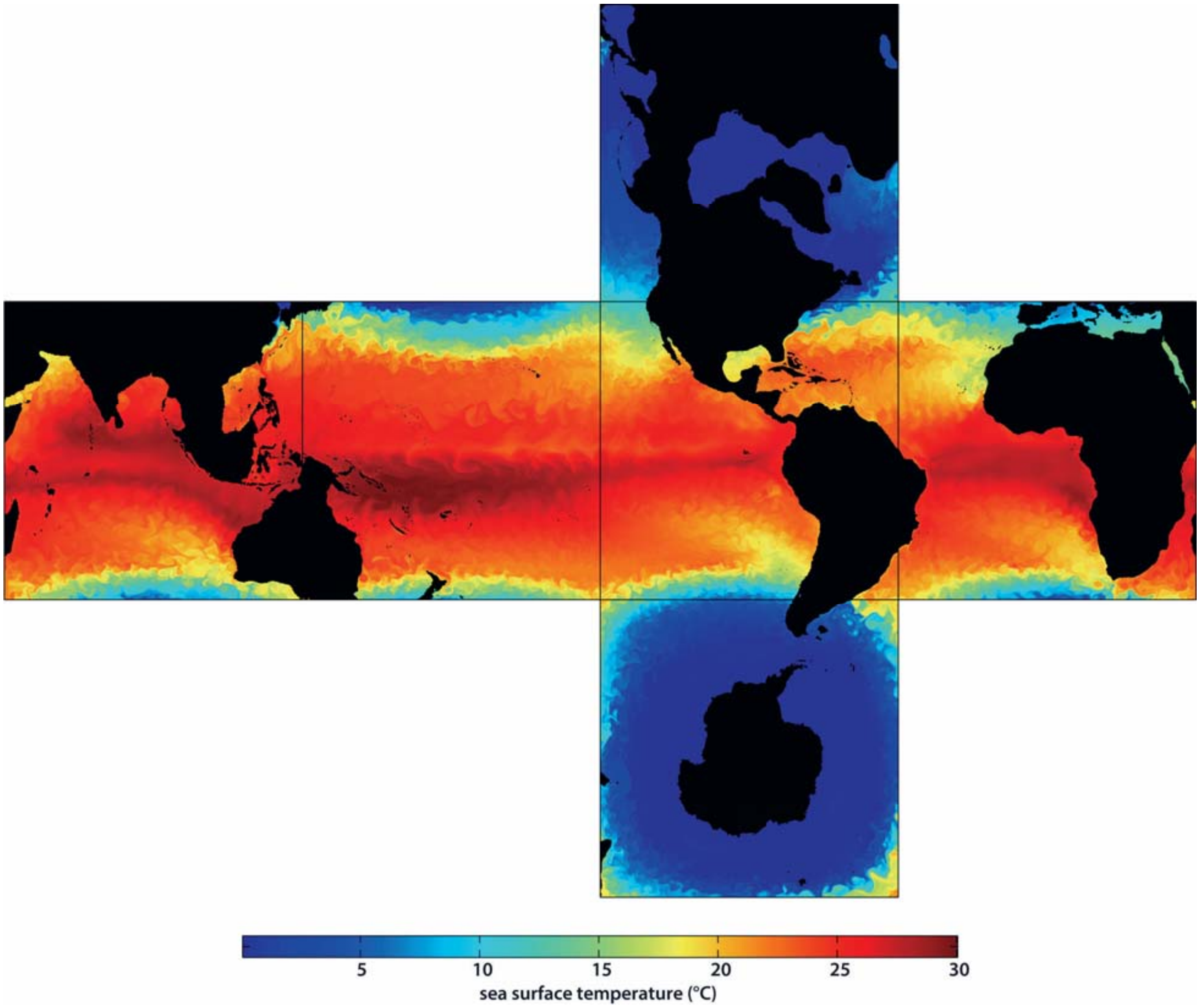

Fig. S2: MITgcm cube-sphere global ocean model configuration for the Last Glacial Maximum. The figure shows a snapshot of simulated January (winter) sea surface temperatures in the Control integration. Sea level is 120m lower than modern day and large ice sheets over Europe and North America restrict flow into the Arctic through Barents Sea and the Canadian Archipelago. Each face of the cube comprises 510 by 510 grid cells with a mean horizontal resolution of 1/6° (18 km). Note that sea ice is not shown in this snapshot.

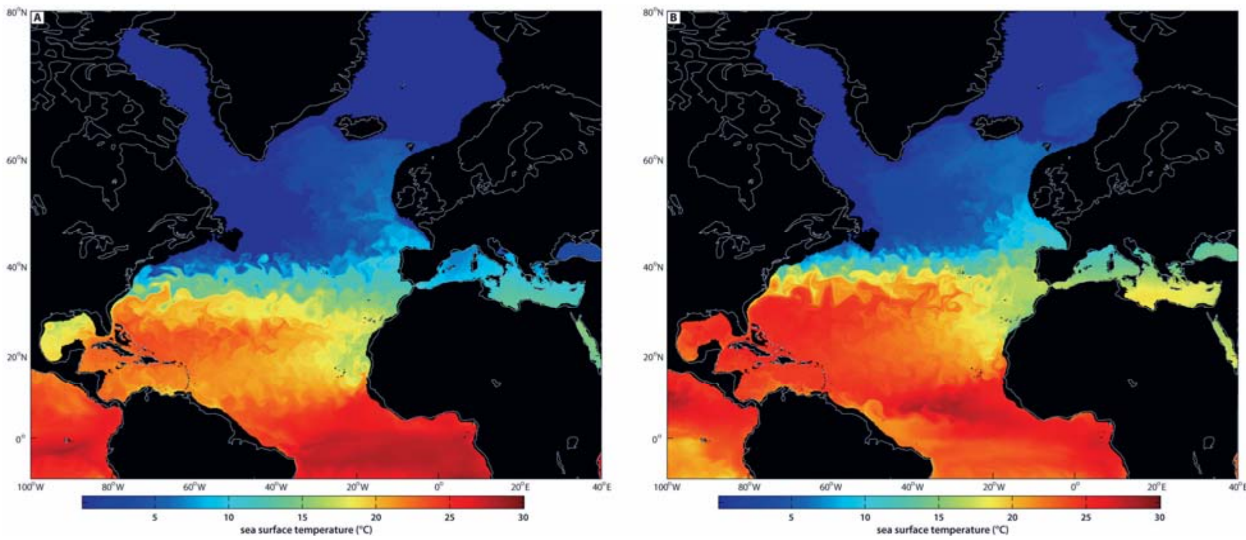

Fig. S3: Snapshots of sea surface temperatures. (a) January and (b) August from the high-resolution (1/6°) MITgcm cube-sphere Control simulation for the Last Glacial Maximum, shown here on a Miller projection. The LGM landmasses are shown in black and the modern-day coastline by the gray line. Sea-ice is not shown in this snapshot.

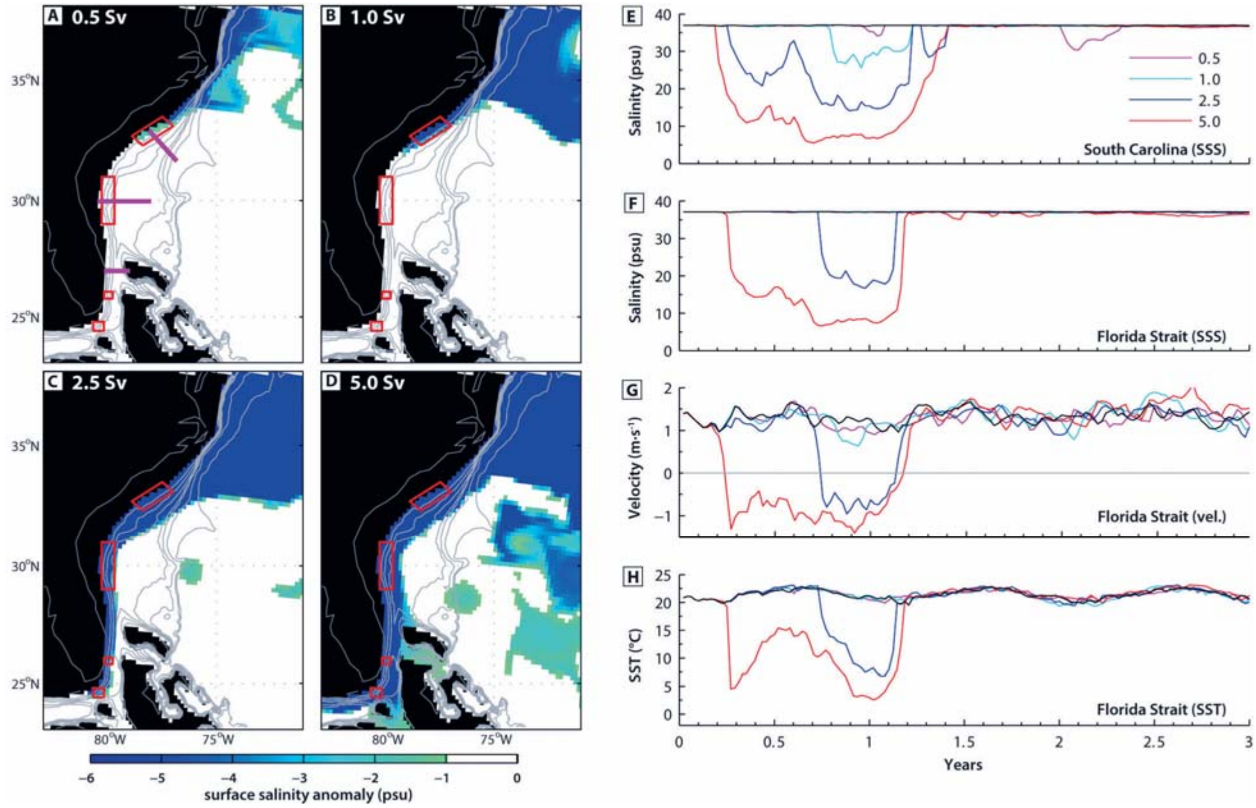

Fig. S4: The southward penetration of meltwater released from Hudson Bay. Meltwater was discharged at rates of a) 0.5 Sv, b) 1 Sv, c) 2.5 Sv and d) 5 Sv. The shading (green-blue) in panels a – d show the difference in surface salinity (perturbation minus control) ~9 months after the initial release of meltwater to the ocean. The red boxes show the approximate location of the iceberg scours discussed in the main manuscript, while the scour location off South Carolina (most northern red box, ~33°N) was used to compile the time series of SSS in panel e. The magenta line at Florida Strait (in panel a) highlights the cross section used to compile the time series shown in panels f – h. The time series show bi-monthly (e) sea surface salinity (SSS) at South Carolina, (f) SSS (g) meridional (north –south) surface velocity and (h) sea surface temperature (SST) at Florida Strait for each meltwater experiment. Periods when meltwater flows south (i.e. opposite to the Gulf Stream) appear in panel g as negative values.

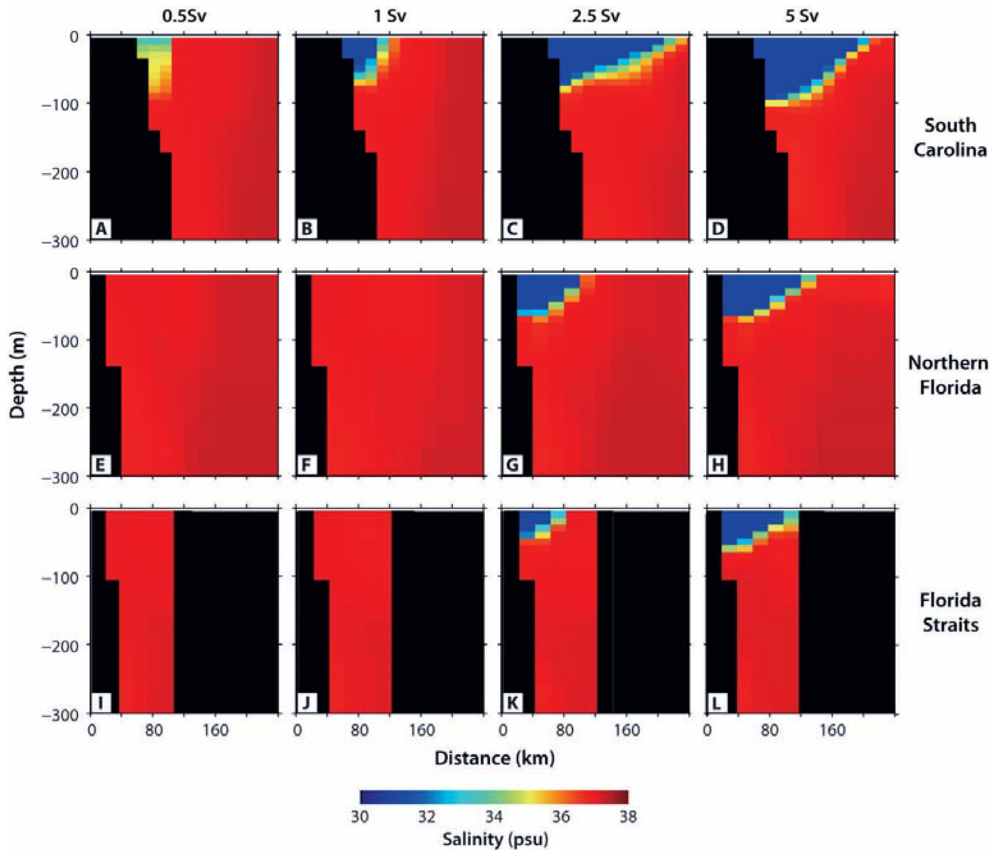

Fig. S5: Cross sections of ocean salinity showing the vertical properties of meltwater in the western subtropical North Atlantic. The colors (blue – red) show ocean salinity at (from top to bottom) South Carolina, northern Florida, and the Florida Straits ~9 months after meltwater is released from Hudson Bay at rates of (from left to right) 0.5 Sv, 1 Sv, 2.5 Sv and 5 Sv. Southward flowing meltwater is identifiable by low salinity (blue-green color) waters in the upper ~100m of the water column. The cross sections are drawn from west to east looking northward through the section. The locations used to construct each section are shown by the magenta lines in Fig.S4a.

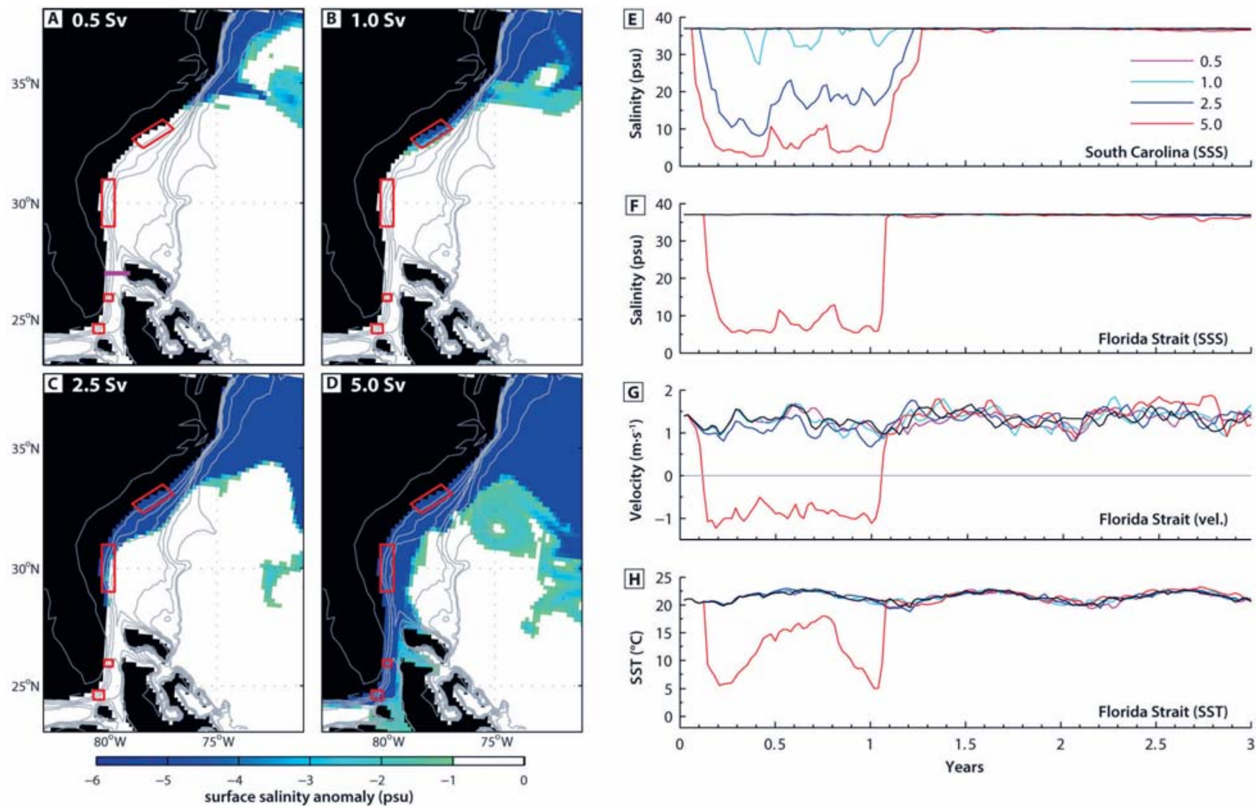

Fig. S6: The southward penetration of meltwater released from the Gulf of St. Lawrence. *See fig. S4 for full description of panels a-h.* The results are similar to Hudson Bay in that meltwater remains trapped to the near-shore western subtropical North Atlantic and propagates south towards Cape Hatteras, although only a 5Sv flood reaches the southern tip of Florida.

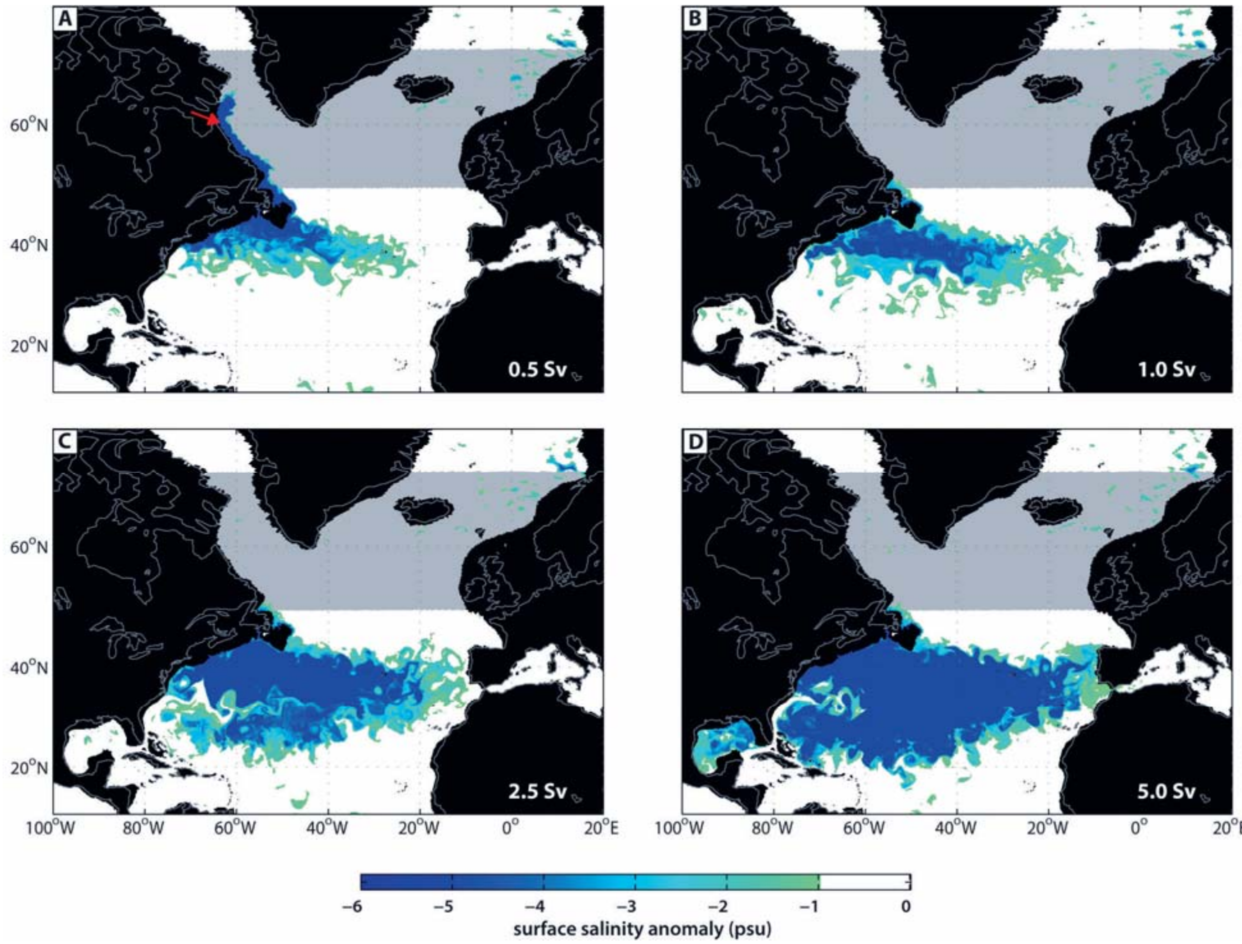

Fig. S7. The dispersal of meltwater from Hudson Bay. The colors (green-blue) show the difference in surface salinity (perturbation minus control) 1 year after the initial meltwater release from Hudson Bay (red arrow) and coincide with the time of maximum surface freshening. In all discharge experiments we find an initial freshening of the subtropical gyre (20°N – 40°N). Note that meltwater is not present along the coast of Florida in panels c and d because this snapshot is taken after the meltwater flood has diminished. The grey shading to the north of the meltwater (50°N to 70°N) denotes the region typically freshened in climate models to simulate the impact of freshwater forcing on climate.

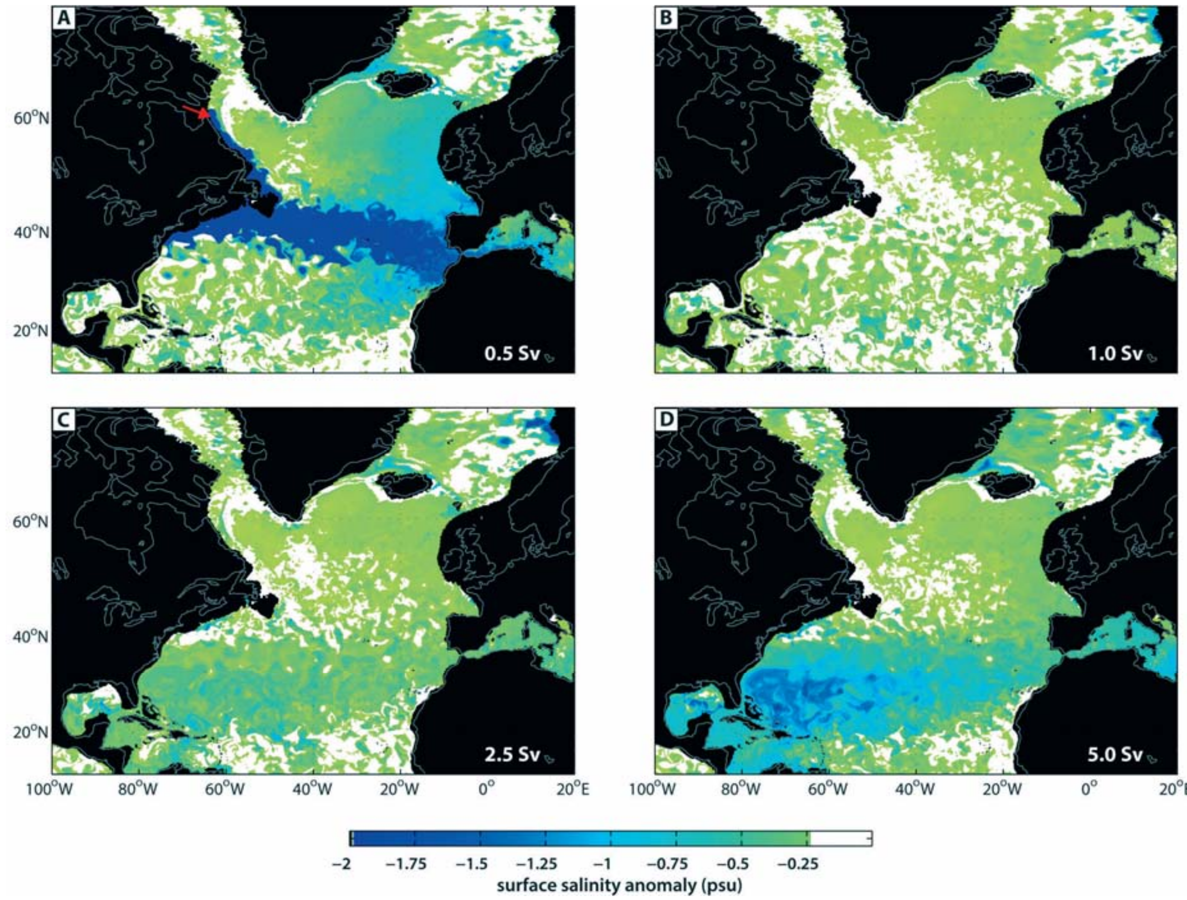

Fig. S8. The dispersal of meltwater from Hudson Bay after 6 years for the different freshwater forcing experiments. The colors (green-blue) show the difference in surface salinity (perturbation minus control) drawn 6-years after the initial meltwater release from Hudson Bay (red arrow). The freshening of the subpolar gyre results from cross-gyre exchange whereby freshwater initially injected into the subtropical gyre is advected northwards by the Gulf Stream. The large freshening across the entire North Atlantic (at ~40°N) in panel A is due to the constant release of freshwater from Hudson Bay in this simulation, whereas freshwater in the other experiments (b-d) was only released for the first year of the integrations.

Table S1. A summary of the physical properties (minimum sea surface temperature (SST), minimum sea surface salinity (SSS), maximum southward velocity and maximum vertical meltwater thickness) of meltwater discharged from Hudson Bay (at 0.5 Sv, 1 Sv, 2.5 Sv and 5 Sv) recorded at Cape Hatteras, northern Florida, Florida Strait, and Florida Keys.

	SST min (°C)	**SSS min (PSU)**	**Max. south velocity (m/s)**	**Meltwater thickness (m)**
	Cape Hatteras			
control	5.6	36.4	-0.29	--
0.5 Sv	-1.4	28.3	-0.99	50
1.0 Sv	-1.3	22.6	-1.76	60
2.5 Sv	-1.0	11.6	-2.45	80
5.0 Sv	-1.3	4.5	-2.82	100
	Northern Florida			
control	16.4	37.0	--	--
0.5 Sv	16.6	37.0	--	--
1.0 Sv	14.1	31.8	-0.31	10
2.5 Sv	2.9	14.6	-0.43	50
5.0 Sv	1.4	6.0	-1.02	70
	Florida Strait			
control	19.5	36.9	--	--
0.5 Sv	19.8	36.9	--	--
1.0 Sv	19.3	36.8	--	--
2.5 Sv	6.8	16.7	-0.95	30
5.0 Sv	2.6	6.6	-1.40	70
	Florida Keys			
control	19.3	36.8	--	--
0.5 Sv	19.7	36.8	--	--
1.0 Sv	19.3	36.7	--	--
2.5 Sv	11.2	19.8	-0.50	20
5.0 Sv	3.3	7.0	-1.29	60

Table S2. The maximum keel depth of icebergs (in meters) at South Carolina, northern Florida, Florida Strait, and Florida Keys for the Control integration and for each meltwater outburst simulation (0.5 Sv, 1Sv, 2.5 Sv, and 5 Sv). Values in parentheses indicate the modern-day water depth (in meters) that scours produced by these icebergs would be found in, assuming sea-level was 70 – 120m lower than modern-day.

	Control	**0.5 Sv**	**1.0 Sv**	**2.5 Sv**	**5.0 Sv**
South Carolina	90 (160-210)	160 (230-280)	180 (250-300)	210 (280-330)	240 (310-360)
Northern Florida	--	--	--	80 (150-200)	150 (220-270)
Florida Strait	--	--	--	10 (80-130)	70 (140-190)
Florida Keys	---	--	--	10 (80-130)	70 (80-190)