12. O. Gudmundsson, M. Sambridge, *J. Geophys. Res.* **103**, 7121 (1998).
13. A statistical F-test shows that the improvement in data fit with respect to Model M2 by including the additional two parameters of the Andaman segment is significant at 99.93% confidence (Model M1) or 99.76% confidence (Model M3).
14. R. G. Bilham, E. R. Engdahl, N. Feldl, S. P. Satyabala, *Seismol. Res. Lett.*, in press.
15. F. Gilbert, A. M. Dziewonski, *Philos. Trans. R. Soc. London Ser. A* **278**, 187 (1975).
16. We thank C. P. Rajendran and R. Bilham for providing results before publication. GPS data processing was carried out under a Department of Science and Technology, Government of India–sponsored project (to P.B.).

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Dilution of the Northern North Atlantic Ocean in Recent Decades

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Declining salinities signify that large amounts of fresh water have been added to the northern North Atlantic Ocean since the mid-1960s. We estimate that the Nordic Seas and Subpolar Basins were diluted by an extra 19,000 ± 5000 cubic kilometers of freshwater input between 1965 and 1995. Fully half of that additional fresh water—about 10,000 cubic kilometers—infiltrated the system in the late 1960s at an approximate rate of 2000 cubic kilometers per year. Patterns of freshwater accumulation observed in the Nordic Seas suggest a century time scale to reach freshening thresholds critical to that portion of the Atlantic meridional overturning circulation.

The salinities of water masses originating in the high-latitude North Atlantic Ocean have been cascading downward since the early 1970s (*1–4*). This region has climatic importance because the Nordic Seas and the Labrador and Irminger basins are sites where cold, dense waters are formed—an integral component of what is often termed the meridional overturning circulation (MOC). The Atlantic MOC involves a northward flow of warm surface waters in exchange for a southward flow of cold, dense waters in the deep ocean along the pathways shown in Fig. 1. This component of circulation transports heat northward and thus contributes to moderating the cold-season climate at high northern latitudes. Excessive amounts of fresh water could alter the ocean density contrasts that drive the northernmost extension of the Atlantic MOC, diminish its northward heat transport, and substantially cool some regions of the North Atlantic (*5–10*). The MOC's sensitivity to greenhouse warming remains a subject of much scientific debate (*10*). The observed freshening does not yet appear to have substantially altered the MOC and its northward heat transport (*11*, *12*). But uncertainties regarding the rates of future greenhouse warming and glacial melting limit the predictability of their impact on ocean circulation (*8*, *10*).

What has been missing from the evolving picture thus far is an explicit quantification of how much additional fresh water it took to cause the observed salinity changes, how fast it entered the sub-Arctic ocean circulation, and where that fresh water had been stored. All three factors are important for assessing the present and future impacts of freshening on the Atlantic MOC, and provide the types of information that facilitate climate model validation studies. To address these issues, we reconstructed the history of volumetric changes in ocean temperature, salinity, and density in the Nordic Seas and Subpolar Basins and estimated the magnitude of freshwater storage and net volume flux anomalies required to account for the observed dilution over the past 50 years. We then examined the degree to which density has responded to this freshening, as a means of gaining perspective on its seemingly negligible MOC impact. Finally, we used this perspective to estimate how much additional fresh water might be required to equalize the density contrast that contributes to the exchange of mass and heat between the Nordic Seas and the subpolar North Atlantic.

Extensive amounts of hydrographic data have been collected in the seas between Labrador and northern Europe in the past 50 years. We used these data to construct well-constrained, three-dimensional representations of ocean properties for successive 5-year time frames spanning the years 1953 to 2002 (*13*). Because salinity is approximately conserved in the ocean, salinity anomaly fields can be used to quantify the volume of additional fresh water that had to be added or removed to account for salinity changes accumulated through the entire water column (*13*). Mapping this quantity, layer by layer, time frame by time frame, throughout the domain describes the evolution of freshwater storage in space and time. Integrating it over a geographic area provides a history of the volumetric freshwater storage anomaly in cubic kilometers, and differencing this storage anomaly in consecutive time frames implies a rate of change—the net freshwater flux anomaly—in sverdrups (1 Sv = 10^6 m^3 s^{-1}).

Time series of freshwater storage anomaly and net flux anomaly for the Nordic Seas and Subpolar Basins were considered separately and as a whole (Fig. 2) (table S1). From the earliest part of the record through the mid-1960s, salinities increased in the upper 2000 m of all the Subpolar Basins. Its volumetric expression was a net loss in subpolar freshwater storage of ~5000 km^3 between 1955 and 1965. By contrast, the net change in the Nordic Seas was comparatively small at that time. Between 1965 and 1990, however, both the Nordic Seas and Subpolar Basins became increasingly freshened. Net freshwater storage increased by ~19,000 km^3, of which ~4000 km^3 spread into the Nordic Seas and ~15,000 km^3 accumulated in the Subpolar Basins. A recovery from the early 1990s peak of freshwater storage in the Subpolar Basins occurred in the mid-1990s, but our volumetric analysis falters for the last time frame (1998 to 2002) because of inadequate data coverage (*14*). For the Nordic Seas, an approximate balance between import and export of fresh and saline waters resulted in little net volumetric change in the late 1990s.

The most striking event of the time series occurred in the early 1970s. During the late 1960s, a large pulse of fresh water entered the Nordic Seas through Fram Strait and rapidly moved southward along the western boundary in the East Greenland Current. This event has been labeled the Great Salinity Anomaly (GSA) (*15*), and we can here confirm that the name is appropriate, for it contributed an extra ~10,000 km^3 of fresh water to the sub-Arctic seas in the late 1960s and early 1970s, implying a net flux anomaly of ~0.07 Sv during a 5-year period. The GSA was previously thought to be equivalent to ~2000 km^3 of excess fresh water (*15*) and has been attributed to several years of anomalously large sea ice export from the Arctic (*16*, *17*). The Arctic freshwater budget includes inflows from the Pacific (~1600 km^3 $year^{-1}$) and rivers (~3500 km^3 $year^{-1}$) that are mainly balanced by annual exports of fresh water and sea ice through Fram Strait and the Canadian

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Archipelago of ~5000 km³ year⁻¹ (*16*). Thus, volumetric changes in freshwater storage suggest that exports associated with the GSA ran ~40% above normal on average during that 5-year time frame.

Only a fraction of the GSA's fresh water remained in the Nordic Seas. The East Greenland Current provides a direct transport route from the Arctic to the Subpolar Basins, and the ocean circulation at that time sent the majority south of Denmark Strait. A small portion of fresh water did quickly spread across the surface of the western Nordic Seas in the early 1960s (fig. S3), but only subsequently was additional fresh water mixed into the subsurface layers. Salinities in the dense overflow waters from the Nordic Seas to the North Atlantic began to decline only in the early 1970s (*4*). Similarly, freshening in the Subpolar Basins first spread across the surface layer in the late 1960s. During the 1970s, the bulk of the GSA's fresh water was vertically mixed downward in the Labrador and Irminger basins and then horizontally circulated at mid-depths around the Subpolar Basins.

Pulses of excess fresh water and ice also appear to have been emitted from the Arctic in the 1980s and 1990s (*18*), and freshening of the Subpolar Basins and Nordic Seas continued from the GSA period into the early 1990s. Of the estimated 19,000 km³ of anomalous freshwater influx between 1965 and 1995, nearly 80% ended up in the Subpolar Basins, whose geographic area is slightly more than twice that of the Nordic Seas. Normalized for this difference, the subpolar storage anomaly amounted to an equivalent freshwater layer ~3.0 m thick spread evenly over its total area, compared to ~1.8 m for the Nordic Seas.

Although not statistically well quantified in our volumetric analysis (and thus not plotted in Fig. 2), warm, saline influences were clearly building in the eastern Subpolar Basins in our last time frame (1998 to 2002; fig. S3). There were also indications of higher salinities in the Atlantic inflow to the eastern Nordic Seas, but the most striking feature there is the accumulation of fresh water, since the 1980s, in the upper 1000 m (fig. S3, left and middle columns). In the 1990s, freshening spread ubiquitously in this layer across the Nordic Seas. By contrast, fresh water accumulated in the entire water column of the Subpolar Basins (fig. S3, right column), but most conspicuously in the intermediate layers—the depths reached by vertical wintertime mixing in the Labrador Basin.

About 6 Sv—or one-third of the Atlantic MOC—crosses the Greenland-Scotland Ridge, which separates the Nordic Seas from the North Atlantic (*19*). A pressure gradient between the waters north and south of the ridge causes dense waters from the Nordic Seas to flow southward across the ridge and spill downward into the depths of the Subpolar Basins. These southward-exiting waters, collectively called Nordic Seas Overflow Waters (NSOW), are replaced by warm, salty surface waters flowing northward via the Norwegian Atlantic Current. The rate of dense water export across the Greenland-Scotland Ridge is roughly proportional to the density contrast in the layers (200 to 900 m) that feed the overflows (*20*). This exchange has been monitored directly for more than a decade: Arrays of instruments have been maintained in key locations south of Denmark Strait (DS) since about 1986 and in the Faroe Bank Channel (FBC) since 1995. During this time, the flow has been measured to be ~3 Sv at each location, with little indication of sustained changes despite steadily declining salinities in the NSOW (*11*, *21*). This reflects the fact that the amount of fresh water thus far accumulated has not had a substantial impact on the density contrast that drives the overflows.

Although immediately adjacent to one another, the Nordic Seas and Subpolar Basins exhibit distinctly independent salinity, temperature, and density trends. Salinity and density evolution are described by a time series of 5-year-average salinity and density values at DS sill depth (~550 m) both upstream and downstream (Fig. 3); a more complete view is obtained from vertical property sections running perpendicular to the sill (fig. S4). Downstream in the Irminger Basin, the upper waters are less dense and are alternately influenced by subtropical warm and saline waters (e.g.,

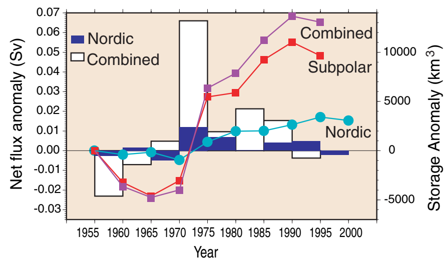

Fig. 2. Time series of freshwater storage anomaly (symbols, scale on right axis) for Nordic Seas (cyan circles), Subpolar Basins down to 50°N (red squares), and both regions combined (purple squares). The net freshwater flux anomaly (difference in storage anomaly between successive 5-year time frames) is shown as bars with scale on left axis (blue, Nordic Seas component; white, total freshwater flux anomaly including Subpolar Basins component).

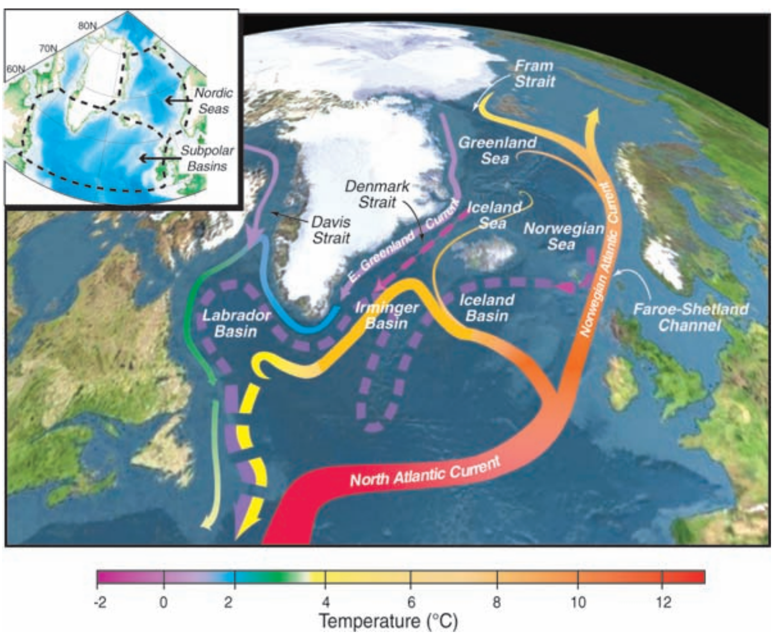

Fig. 1. Topographic map of Nordic Seas and Subpolar Basins with schematic circulation of surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic MOC. Colors of curves indicate approximate temperatures. Map inset delineates the boundaries of the Nordic Seas and Subpolar Basins used in the volumetric analysis (dashed black lines).

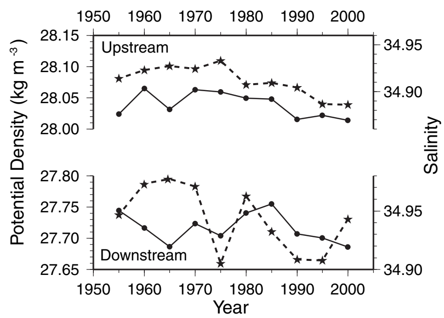

Fig. 3. Time series of 5-year-average density (solid lines, circles) and salinity (dashed lines, stars) at the sill depth of Denmark Strait (550 m). The upstream profiles are taken from the Iceland Sea at 68.5°N, 23.5°W; the downstream profiles are in the Irminger Basin at 64.5°N, 31.5°W.

1960s) and by colder, fresher subpolar waters (e.g., 1985 to 1995) (*22*). At sill depth, the downstream salinity jumped ±0.05 at several points in the time series, whereas density variations, moderated by temperature, ranged between 27.68 and 27.75 kg m^{-3}, although not monotonically through time. Upstream in the western Iceland Sea, by contrast, salinity at sill depth began a persistent decline of –0.05 in the mid-1970s, which contributed to the decline in density from a high of ~28.06 kg m^{-3} around 1970 to ~28.01 kg m^{-3} in the 1990s.

Vertical profiles of density contrast and hydraulic theory provide a basis for calculating the volume transport over the sill (*13*). Using this method, we find that the overflow rates in each time frame varied only slightly (3.0 ± 0.2 Sv at DS, 3.5 ± 0.1 Sv for FBC) and did not vary in any persistent manner during the past 50 years (figs. S5 and S6). Thus, the observed freshening did not sufficiently lower the Nordic Seas density—and hence the density contrast across the ridge—to have an enduring impact on the intensity of the overflows.

Because the overflow rates depend on this north-south density contrast, we address the question of how much additional fresh water would be required to reduce the present upstream density (~28.00 kg m^{-3}) to values found downstream in the Subpolar Basins (~27.70 kg m^{-3}). The observational record indicates that fresh water has been accumulating in the upper 1000 m everywhere across the Nordic Seas for the past 30 years (fig. S3), and we have extrapolated this pattern of dilution forward to gain perspective on our question (*13*). We find that a volume of ~9000 km^3—roughly equivalent to one GSA—mixed into the upper 1000 m of the Nordic Seas would be required to substantially reduce the overflows; two GSAs (~18,000 km^3) could essentially shut them down. We emphasize that these are not predictions, but merely a process to better understand what magnitude of changes would be involved.

Of the total 19,000 km^3 of additional fresh water that diluted the northern Atlantic since the 1960s, only 4000 km^3 remained in the Nordic Seas. Of this latter volume, our analysis indicates that ~2500 km^3 accumulated in the layer 200 to 1000 m between 1970 and 1995. This observed rate of net accumulation (~100 km^3 $year^{-1}$) integrates various dynamical processes controlling the mixing of fresh water into this layer and provides a basis for estimating future dilution. At the observed rate, it would take about a century to accumulate enough fresh water (e.g., 9000 km^3) to substantially affect the ocean exchanges across the Greenland-Scotland Ridge, and nearly two centuries of continuous dilution to stop them. In this context, abrupt changes in ocean circulation do not appear imminent.

Uncertainties remain in assessing the possibility of such disruptions. A weakened Atlantic MOC in the 21st century is a feature of numerous climate simulations of greenhouse warming (*5–9*, *23–27*). The cause is similar in all the models: glacial melting, enhanced precipitation, and continental runoff, which are projected to increase freshwater input to the Arctic and sub-Arctic seas (*26*, *27*). Pooling and sudden release of glacial meltwater, disintegration of shelf ice followed by a surge in glacier movement, and lubrication of the glacier base by increased melting are all possible mechanisms that could inject large amounts of fresh water from Greenland's ice sheet into the upper layers of the Nordic Seas (*28*). The possibility of such events precludes ruling out a substantial slowing or shutdown of the overflows as a result of greenhouse warming.

References and Notes

1. J. R. N. Lazier, in *Natural Climate Variability on Decade-to-Century Time Scales*, D. G. Martinson *et al.*, Eds. (National Academy Press, Washington, DC, 1995), pp. 295–302.
2. W. R. Turrell, G. Slesser, R. D. Adams, R. Payne, P. A. Gillibrand, *Deep Sea Res. I* **46**, 1 (1999).
3. J. Blindheim *et al.*, *Deep Sea Res. I* **47**, 655 (2000).
4. R. R. Dickson *et al.*, *Nature* **416**, 832 (2002).
5. S. Manabe, R. J. Stouffer, *J. Clim.* **7**, 5 (1994).
6. S. Manabe, R. J. Stouffer, *Nature* **378**, 165 (1995).
7. M. Vellinga, R. Wood, *Clim. Change* **54**, 251 (2002).
8. M. Schaeffer, F. M. Selten, J. D. Opsteegh, H. Goosse, *Geophys. Res. Lett.* **29**, 10.1029/2002GL015254 (2002).
9. G. L. Russell, D. Rind, *J. Clim.* **12**, 531 (1999).
10. Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001).
11. A 20% reduction in overflow strength reported in (*29*) was not persistent. Continuing measurements show that the trend has stopped and perhaps changed sign in the past 2 or 3 years (B. Hansen, personal communication).
12. P. Wu, R. Wood, P. Stott, *Geophys. Res. Lett.* **31**, L02301 (2004).
13. See supporting data on *Science* Online.
14. In the last time frame, 1998 to 2002, only 62% of the Subpolar Basins' total volume can be estimated from measurements, versus 90% or better for all other time frames (*13*).
15. R. R. Dickson, J. Meincke, S.-A. Malmberg, A. J. Lee, *Prog. Oceanogr.* **20**, 103 (1988).
16. K. Aagaard, E. C. Carmack, *J. Geophys. Res.* **94**, 14485 (1989).
17. S. Häkkinen, *J. Geophys. Res.* **98**, 16397 (1993).
18. I. Belkin, *Geophys. Res. Lett.* **31**, L08306 (2004).
19. W. Schmitz, *Rev. Geophys.* **33**, 151 (1995).
20. J. Whitehead, *Rev. Geophys.* **36**, 423 (1998).
21. The time series of current meter measurements maintained since 1986 near Angmassalik, Greenland, has shown remarkably steady volume fluxes in the NSOW, although the properties (temperature, salinity) have fluctuated (R. R. Dickson, personal communication).
22. M. Bersch, *J. Geophys. Res.* **107**, 10.1029/2001JC000901 (2002).
23. T. Stocker, A. Schmittner, *Nature* **388**, 862 (1997).
24. R. Wood, A. Keen, J. Mitchell, J. Gregory, *Nature* **399**, 572 (1999).
25. S. Rahmstorf, A. Ganopolski, *Clim. Change* **43**, 353 (1999).
26. T. Fichefet *et al.*, *Geophys. Res. Lett.* **30**, 10.1029/2003GL017826 (2003).
27. P. Wu, R. Wood, P. Stott, *Geophys. Res. Lett.* **32**, L02703 (2005).
28. Q. Schiermeier, *Nature* **428**, 114 (2004).
29. B. Hansen, W. R. Turrell, S. Østerhus, *Nature* **411**, 927 (2001).
30. Supported by NSF grant OCE-0326778 (R.C.), a WHOI Independent Study Award (R.C., C.M.), and Norwegian Research Council grant 139 815/720 (NoClimII) (C.M.).

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Secondary Evolutionary Escalation Between Brachiopods and Enemies of Other Prey

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The fossil record of predation indicates that attacks on Paleozoic brachiopods were very rare, especially compared to those on post-Paleozoic mollusks, yet stratigraphically and geographically widespread. Drilling frequencies were very low in the early Paleozoic (≪1%) and went up slightly in the mid-to-late Paleozoic. Present-day brachiopods revealed frequencies only slightly higher. The persistent rarity of drilling suggests that brachiopods were the secondary casualties of mistaken or opportunistic attacks by the enemies of other taxa. Such sporadic attacks became slightly more frequent as trophic systems escalated and predators diversified. Some evolutionarily persistent biotic interactions may be incidental rather than coevolutionary or escalatory in nature.

Our understanding of the long-term evolutionary dynamics of predator-prey interactions has advanced recently, primarily due to multiple synoptic studies of the post-Paleozoic marine mollusks (*1–5*). There is growing evidence that predatory (or parasitic) activities [in particular, those recorded by drill holes (*6*)] were widespread in the Paleozoic as well (*7–17*),