COMMENTARY

Tantalizing evidence for the glacial North Atlantic bottom water

Katsumi Matsumoto[a,1]

The global Meridional Overturning Circulation (MOC) is one of the key components of the global climate system. Over timescales of 10^2 to 10^3 y, MOC connects the cold, carbon-rich waters in the deep ocean with warmer, carbon-poorer surface waters through localized deep water formation and more widespread upwelling of deep water. By redistributing heat near the surface and affecting carbon storage at depth and therefore atmospheric pCO_2, MOC exerts a strong control on the global climate. A long-standing puzzle in paleoclimatology is the configuration of MOC in the Atlantic basin during the cold climate conditions of the last glacial period. The Atlantic is of special interest, because the North Atlantic Deep Water (NADW), a key driver of the global MOC, forms there today. In PNAS, Keigwin and Swift (1) present intriguing new carbon isotope data from a very deep site in the western North Atlantic that indicate the presence of hitherto unidentified bottom water sourced in the glacial North Atlantic.

In the modern ocean, two water masses dominate the deep Atlantic Ocean: NADW and the Antarctic Bottom Water (AABW) (Fig. 1*A*). NADW is composed of two varieties. The upper NADW is formed in the Labrador Sea by wintertime open ocean convection that may reach as deep as 2,000 m. The denser, lower NADW originates in the Nordic Seas through open ocean convection and mixing with Arctic Ocean water. It overflows southward over the Greenland–Iceland–Scotland Ridge. Both varieties flow southward as the deep western boundary current of the Atlantic basin in the depth range of 1,500 m to 4,000 m. In contrast, AABW originates on the continental shelves of Antarctica, where brine rejection during sea ice formation in coastal polynyas increases the seawater density. AABW flows northward in the Atlantic basin beneath NADW.

Nutrient content, a property of seawater, distinguishes NADW and AABW and thus is exploited by paleoceanographers in reconstructing past deep water masses. NADW is depleted in nutrients (e.g., phosphorus), because it is formed from waters that have been at the surface for a long time, from which marine phytoplankton have stripped most of the nutrients. In contrast, AABW has abundant nutrients, because it is formed from surface waters whose surface residence time is much shorter. A widely used nutrient proxy in paleoceanography is the stable carbon isotope composition (i.e., $\delta^{13}C$) of fossil foraminiferal shells obtained from deep sea sediments. The $CaCO_3$ shells of bottom-dwelling benthic foraminifera largely reflect the ambient seawater chemistry at the time of the foraminifera's growth. At the surface, phytoplankton preferentially uptake the lighter isotope ^{12}C over ^{13}C during photosynthesis, imparting high $\delta^{13}C$ and low nutrient signal in the ambient water; in the ocean interior, the remineralization of sinking organic matter imparts low $\delta^{13}C$ and high nutrient signal. Thus, $\delta^{13}C$ of modern seawater is largely inversely related to nutrient content. So, high benthic foraminiferal $\delta^{13}C$ in the glacial Atlantic is typically interpreted to indicate a northern source water (NSW) like today's NADW and low benthic $\delta^{13}C$ a southern source water (SSW) like the modern AABW. However, benthic foraminiferal $\delta^{13}C$ is an imperfect water mass tracer, because the nutrient content of deep waters can change without their dynamics changing.

Over the past few decades, paleoceanographers have produced many measurements of benthic foraminiferal $\delta^{13}C$ for the Last Glacial Maximum (LGM), a period of extreme cold ∼18,000–21,000 y ago, when continental ice covered much of Canada and northern Europe, and global sea level was lower by ∼120 m (2). An early compilation of benthic $\delta^{13}C$ data from the Atlantic Ocean (3) indicated the presence of NSW with high $\delta^{13}C$ overlying SSW with much lower $\delta^{13}C$. This is not unlike the modern situation, except that the boundary between the two glacial water masses occurred much shallower in the water column at ∼2.5 km water depth compared with ∼4 km today (Fig. 1*B*). This high $\delta^{13}C$ water mass above ∼2.5 km is often referred to as the glacial North Atlantic intermediate water (GNAIW), even though it is found much deeper than the modern intermediate waters.

A more recent compilation of glacial $\delta^{13}C$ data (4) confirmed that SSW occupied a larger volume of the

[a]Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55455
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[1]Email: katsumi@umn.edu.

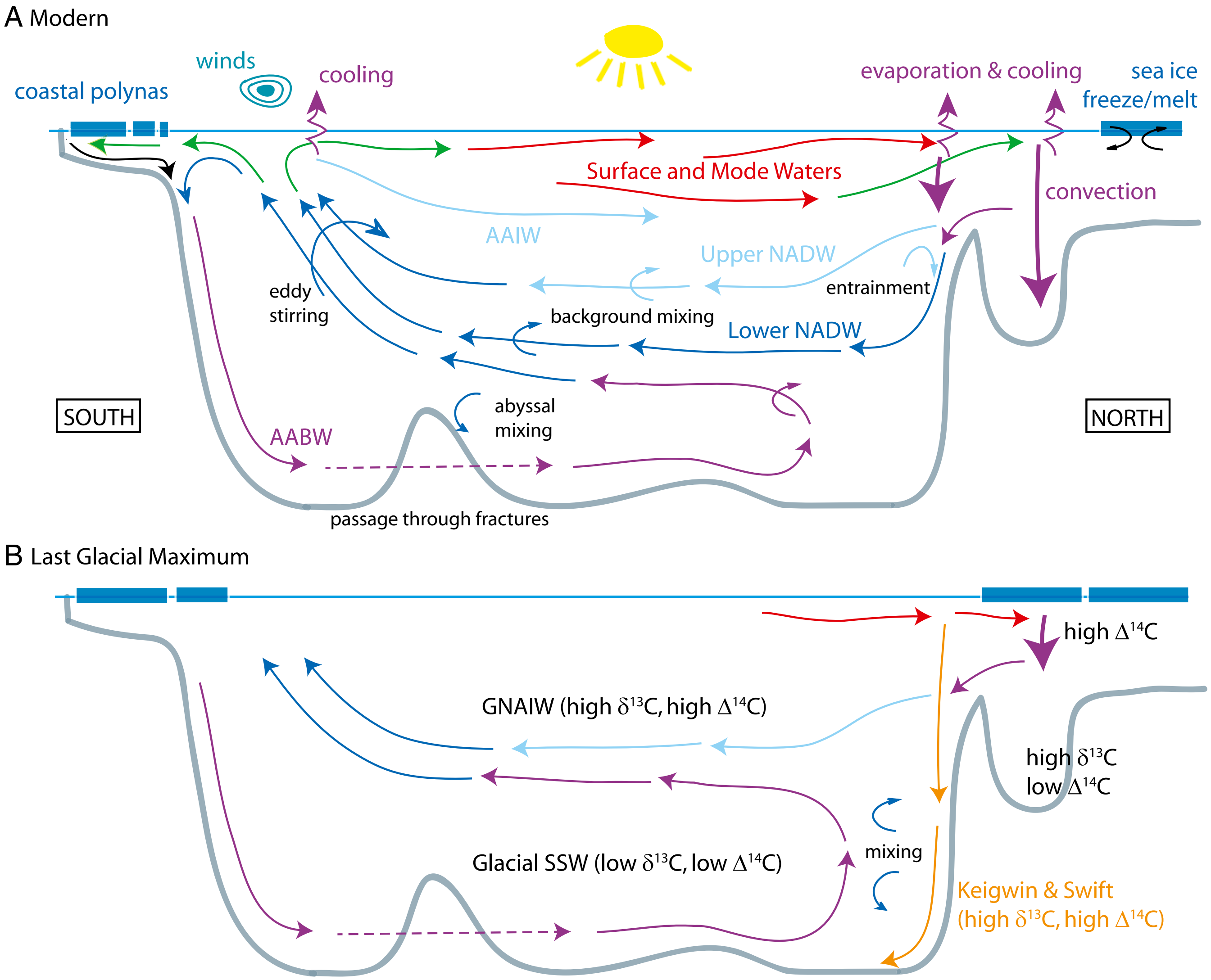

Fig. 1. Schematic diagram of AMOC. (*A*) Modern AMOC is dominated by AABW and NADW. Open ocean convection in the Labrador and Nordic Seas is key to forming NADW. Modified with permission from Robert Marsh. (*B*) Glacial AMOC is characterized by a larger presence of SSW and a shoaled NSW in GNAIW. Keigwin and Swift (1) proposed a new glacial bottom water formed in the Labrador Sea. Here GNAIW is drawn to originate from the upper water column of the Nordic Seas (8).

deep Atlantic than today's AABW, at the expense of nutrient and carbon-poor GNAIW (Fig. 1*B*). This view is generally supported by other geochemical measurements on foraminifera, including another nutrient proxy, Cd/Ca (5), a proxy of carbonate ion, B/Ca (6), and an indicator of deep ocean ventilation, $\Delta^{14}C$ (7). The change in the volumes of the carbon-rich and carbon-poor deep waters is a critical piece of knowledge for explaining the low levels of atmospheric pCO_2 during LGM.

Keigwin and Swift (1) present intriguing new benthic foraminiferal $\delta^{13}C$ and $\Delta^{14}C$ data, which do not conform to the traditional view. At 5,010 m, theirs is the deepest western North Atlantic core from which benthic foraminiferal data have been obtained. The traditional view would have this core site, located well below GNAIW, be bathed by the nutrient-rich SSW during LGM. Unexpectedly, their new glacial $\delta^{13}C$ is higher than previous $\delta^{13}C$ data from the western North Atlantic taken to indicate glacial SSW by 0.2 to 0.5‰. Taken at face value, the new data indicate the presence of distinctly nutrient-poor water near the bottom of the western North Atlantic below SSW (Fig. 1*B*). This finding is further supported by new $\Delta^{14}C$ measurements from the same core. These data indicate that the core site was well ventilated, which is inconsistent with glacial SSW, whose high nutrient content indicates poor ventilation. Indeed, $\Delta^{14}C$ data from the glacial SSW elsewhere indicate poor ventilation (7). If real, the new water mass at 5,010 m would have to be called bottom water.

There have been many paleoceanographic investigations based on sediment cores from the North Atlantic over the past few decades, but the presence of a distinctly young water mass below glacial SSW has not been proposed until now. One of the reasons is likely that paleoceanographers have tended to avoid very deep cores, because the preservation of foraminiferal shells deteriorates with increasing depth (i.e., pressure effect on the solubility of $CaCO_3$). Perhaps another reason is that, today, we find AABW at the bottom of the major ocean basins, and so there may be little expectation of finding a denser water mass below glacial AABW.

Here too, Keigwin and Swift (1) point to a surprising data set. They dug up decades-old water column data from the 1972

Atlantic Geochemical Ocean Sections Study (GEOSECS) that show a clear sign of NSW near the bottom. At GEOSECS station 27 in the Newfoundland Basin at 4.5 km to 5 km, silicic acid concentration suddenly becomes much lower than in the overlying water. At the same time, elevated values of both $\Delta^{14}C$ and tritium indicate a recent penetration of thermonuclear bomb signal to those depths. The low silicic acid water undercutting more-silicic acid-rich water, which presumably had an AABW contribution, is also seen in the adjacent GEOSECS station 28, but not in other stations. Interestingly, this low silicic acid phenomenon is repeatedly seen in later surveys Transient Tracers in the Ocean (1990) and Climate Variability and Predictability (2004) but not in World Ocean Circulation Experiment (1997). Clearly, the presence of this well-ventilated NSW below AABW is very limited in space and time and not comparable to the ubiquitous NADW or AABW. It nevertheless serves as an interesting if imperfect modern analog for Keigwin and Swift to propose that the glacial bottom water they find was formed in the North Atlantic.

The Nordic Seas would appear to be out of contention as the formation site of this well-ventilated glacial bottom water, if the deep Nordic Seas were indeed very poorly ventilated during the last glacial period as indicated by recent $\Delta^{14}C$ data (8). By process of elimination, Keigwin and Swift (1) suggested the Labrador Sea as the site of the new bottom water, but there is currently no evidence for this. This suggestion could be a target of investigation in the future, if the newly proposed water mass is confirmed by others.

Perhaps a more pressing topic of investigation is the nature of SSW, over which the new study appears to be at odds with a recent study on AMOC based on neodymium (Nd) isotope composition (9). The new study concludes that "water of southern source was sandwiched between glacial North Atlantic intermediate water and the new dense bottom water" (1). Keigwin and Swift thus embraced the traditional view of AMOC, noting that organic matter respiration makes little contribution to seawater $\delta^{13}C$ below 1 km, and interpreting benthic foraminiferal $\delta^{13}C$ as mostly a tracer of paleocirculation. In contrast, Howe et al. (9) conclude, in their Nd study, that the low $\delta^{13}C$ in the glacial Atlantic below ~2.5 km does not necessarily imply that NADW was unimportant but that it continued to exist with a more negative $\delta^{13}C$ imprint of respired CO_2. Their Nd isotope data indicate a sizable production of NADW during LGM (e.g., their estimated fractional contribution of NADW at the deep Bermuda Rise is at least 44% but more like 72%). They thus do not accept benthic foraminiferal $\delta^{13}C$ as a faithful tracer of paleocirculation.

It is worth pointing out that the NSW envisioned by Howe et al. (9) is likely not the same as the NSW envisioned by Keigwin and Swift (1). Whereas the former NSW would presumably have a density similar to the glacial SSW in order to mix laterally, the latter NSW would have to be much denser to sit below the glacial SSW. If they are both real, and there is already a well-established GNAIW, there would be three different glacial NSWs, which would seem quite a lot.

An obvious, and the most immediate, task following the work of Keigwin and Swift (1) is to confirm the presence of the glacial North Atlantic bottom water with measurements from other deep cores from the North Atlantic. The spatial extent of the new water mass in the Atlantic basin is also of great interest. In either case, paleoceanographers will have to look harder to find suitable cores, because the deep ocean carbonate ion concentration and hence $CaCO_3$ preservation declines not just with increasing depth but also farther away from the North Atlantic.

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