

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 $p\text{CO}_2$, 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. 1A). 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., $\delta^{13}\text{C}$) 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 $\delta^{13}\text{C}$ and low nutrient signal in the ambient water; in the ocean interior, the remineralization of sinking organic matter imparts low $\delta^{13}\text{C}$ and high nutrient signal. Thus, $\delta^{13}\text{C}$ of modern seawater is largely inversely related to nutrient content. So, high benthic foraminiferal $\delta^{13}\text{C}$ in the glacial Atlantic is typically interpreted to indicate a northern source water (NSW) like today's NADW and low benthic $\delta^{13}\text{C}$ a southern source water (SSW) like the modern AABW. However, benthic foraminiferal $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ for the Last Glacial Maximum (LGM), a period of extreme cold $\sim 18,000$ – $21,000$ 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 $\delta^{13}\text{C}$ data from the Atlantic Ocean (3) indicated the presence of NSW with high $\delta^{13}\text{C}$ overlying SSW with much lower $\delta^{13}\text{C}$. 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. 1B). This high $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$ data (4) confirmed that SSW occupied a larger volume of the

^aDepartment of Earth Sciences, University of Minnesota, Minneapolis, MN 55455

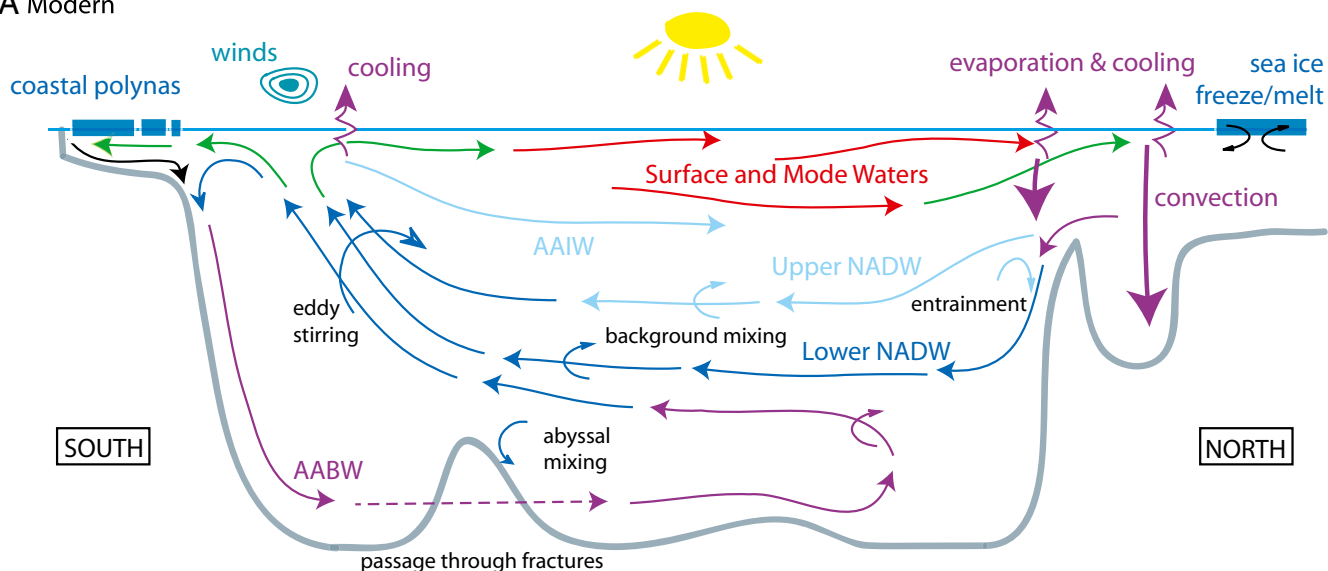
Author contributions: K.M. wrote the paper.

The author declares no conflict of interest.

See companion article on page 2831.

¹Email: katsumi@umn.edu.

A Modern



B Last Glacial Maximum

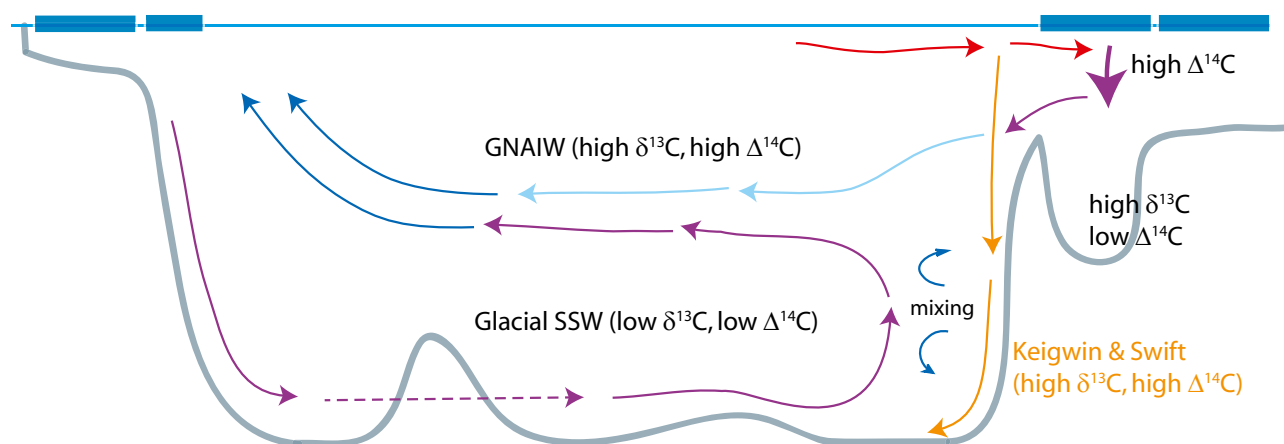


Fig. 1. Schematic diagram of AMOC. (A) Modern AMOC is dominated by AABW and NADW. Open ocean convection in the Labrador and Nordic Seas is key to forming NADW. Modified with permission from Robert Marsh. (B) Glacial AMOC is characterized by a larger presence of SSW and a shoaled NSW in GNAIW. Keigwin 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. 1B). 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, $\Delta^{14}\text{C}$ (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 $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ data, which do not conform to the traditional view. At 5,010 m, there 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 $\delta^{13}\text{C}$ is higher than previous $\delta^{13}\text{C}$ 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. 1B). This finding is further

supported by new $\Delta^{14}\text{C}$ 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, $\Delta^{14}\text{C}$ 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

