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Atlantic Meridional Overturning Circulation During the Last Glacial Maximum

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The circulation of the deep Atlantic Ocean during the height of the last ice age appears to have been quite different from today. We review observations implying that Atlantic meridional overturning circulation during the Last Glacial Maximum was neither extremely sluggish nor an enhanced version of present-day circulation. The distribution of the decay products of uranium in sediments is consistent with a residence time for deep waters in the Atlantic only slightly greater than today. However, evidence from multiple water-mass tracers supports a different distribution of deep-water properties, including density, which is dynamically linked to circulation.

In today's Atlantic Ocean, water more shallow than about 1 km flows northward while deeper water flows south, forming what is called a meridional overturning circulation (MOC) (Fig. 1A). The northward-flowing surface and intermediate waters lose buoyancy in the North Atlantic, where they are transformed into the southward-flowing North Atlantic Deep Water (NADW). This meridional circulation is considered an important element of the climate because of its attendant meridional heat flux; the northward-flowing surface waters are warm, whereas the southward-flowing deep waters are cold, so the MOC is accompanied by a net northward transport of heat in the Atlantic. The possibility that this overturning circulation could change in the future motivates us to understand how it may have differed in the past. The Last Glacial Maximum (LGM), a time interval centered at about 21,000 years ago and with a duration of a few millennia [e.g., (*1*)], was a period during which the factors controlling the structure of the Atlantic MOC (e.g., freshwater budgets and atmospheric circulation in the northern and southern high latitudes) appear to have differed from today.

In the 1980s, a prominent community effort in the emerging field of paleoceanography provided evidence suggesting that this Atlantic overturning circulation may not have existed in its current form during the LGM. The nutrient-poor NADW seemed to have been replaced by higher-nutrient waters like those formed in the Southern Ocean today (*2*–*5*). Both theoretical studies (*6*) and ocean general circulation model experiments (*7*) suggested that the MOC may have multiple equilibria and that transitions between the equilibria may be triggered by anomalies in the freshwater fluxes at the sea surface.

A new generation of coupled ocean-atmosphere general circulation models has since been developed. When forced with estimated LGM atmospheric CO_2 concentration and continental ice sheets, these models produce widely different Atlantic circulation scenarios. Some show a stronger overturning cell associated with NADW formation either extending slightly deeper (*8*) or unchanged in vertical extent (*9*); others show a weaker and shallower overturning cell associated with NADW production (*10*, *11*). Only when perturbed with enhanced freshwater fluxes to the North Atlantic, as presumably occurred in the past during brief periods of accelerated decay of the continental ice sheets, do the coupled models produce a shutdown of NADW (*12*, *13*). The large freshwater fluxes capable of shutting down the Atlantic MOC in these models would not have been sustainable for the entire LGM. It is of more than academic interest to determine which models (if any) show the correct response to ice age conditions, as these are the same models that are used to predict future changes in the Atlantic MOC resulting from increasing levels of carbon dioxide in the atmosphere. Here we review the currently available paleoceanographic data for the LGM and find support for an active circulation in the deep Atlantic, but not for the strong, deep MOC involving enhanced production of NADW in the northern North Atlantic.

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Density Gradients in the Main Thermocline and Below

The tilt of the surfaces of equal seawater density between the western and eastern sides of the basin provides tangible evidence for a meridional overturning in the Atlantic Ocean today [e.g., (*14*)] (Fig. 2A). The very fact that these surfaces are not strictly horizontal suggests the existence of a vertical shear in the average meridional flow in the basin: For a fluid on a rotating planet, a zonal density contrast must be balanced by a vertical shear in the meridional motion to lowest order (the "thermal wind relationship"). The shear reflects a northward flow near the surface and southward flow below (i.e., a MOC) (*15*).

Seawater density depends on temperature, salinity, and pressure. Density at a given depth on either side of the Atlantic Basin in the past can be estimated from the ratio of oxygen isotopes, $^{18}O/^{16}O$, in the fossil carbonate tests of benthic foraminifera, bottom-dwelling protists (*16*). This ratio reflects both the temperature and the $^{18}O/^{16}O$ ratio (which generally covaries with salinity in the upper ocean) of the seawater in which the foraminifera calcify (*16*, *17*).

The density contrast across the width of the entire ocean basin reflects the vertical shear in the integrated meridional flow across the basin (*18*–*20*). In the South Atlantic at 30°S, density is higher along the eastern margin in the upper 2 km, reflecting the vertical shear in mass transport associated with the MOC (Fig. 2A). The benthic foraminifera from surface sediments reflect this contrast, with higher $^{18}O/^{16}O$ on the higher-density eastern margin (Fig. 2B). During the LGM, however, the cross-basin gradient in the oxygen isotopes of the foraminifera was reduced and perhaps even reversed (*21*) (Fig. 2C). The circulation that we see today (flow to the north above 1 km and to the south below this depth), or a similar overturning circulation with a shallower southward flow of NADW as in some of the model simulations for the LGM (*10*, *11*), would require higher densities along the eastern margin than along the western margin in the upper 2 km of the South Atlantic. If the LGM relationship between the oxygen isotope ratio in the foraminifera and density was similar on both sides of the South Atlantic Basin (as it is today), these scenarios would be incompatible with the oxygen isotope data. Water masses with very different temperatures, salinities, and oxygen isotope ratios occupying the same density horizon on either side of the ocean basin could potentially cause a change in the oxygen isotope ratios

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across the South Atlantic without a change in density contrast. These properties need to be better constrained before any circulation scenarios can be ruled out on the basis of the oxygen isotope data alone (*21*, *22*).

Deep-Water Nutrient Properties

Surface waters sinking in the Greenland, Iceland, Norwegian, and Labrador seas collectively form the NADW, which is readily identifiable as a tongue of nutrient-poor water extending to great depths in the Atlantic and eventually reaching the Southern Ocean (Fig. 1A). Some high-nutrient water from the Southern Ocean (Antarctic Bottom Water, AABW) can be seen penetrating northward beneath the NADW. The nutrient distributions for times in the past are reconstructed by measuring the carbon isotopic composition ($^{13}C/^{12}C$) of fossil shells of benthic foraminifera buried in the sediments. Primary producers in the surface ocean take up both nutrients and carbon, discriminating against the heavy isotope of carbon as they do so, leading to high $^{13}C/^{12}C$ ratios in surface waters and low-nutrient water masses (e.g., NADW). Higher nutrient concentrations and lower $^{13}C/^{12}C$ in AABW reflect the longer time these waters have spent away from the surface, collecting nutrients and ^{13}C-poor carbon from the decay of organic matter transported to depth in particulate and dissolved forms. Past nutrient distributions have also been reconstructed from the ratio of cadmium to calcium in tests of benthic foraminifera. Like the major nutrients, Cd is taken up by organisms at the sea surface and released at depth as the organic material is decomposed. Both of these nutrient proxies ($^{13}C/^{12}C$ and Cd/Ca) show that during the LGM there was a low-nutrient water mass above a depth of about 2 km (often referred to as Glacial North Atlantic Intermediate Water, GNAIW) and high-nutrient waters below 2 km (*23*–*27*) (Fig. 1, B and C). There are multiple factors (air-sea exchange of carbon, carbonate saturation state, oxidation of organic matter in sediments) controlling the isotopic and chemical compositions of the foraminifera tests that can potentially decouple the nutrient proxies from nutrient distributions in the open ocean (*28*). Nonetheless, the agreement between the reconstructions based on these two water-mass tracers provides increased confidence in the overall picture.

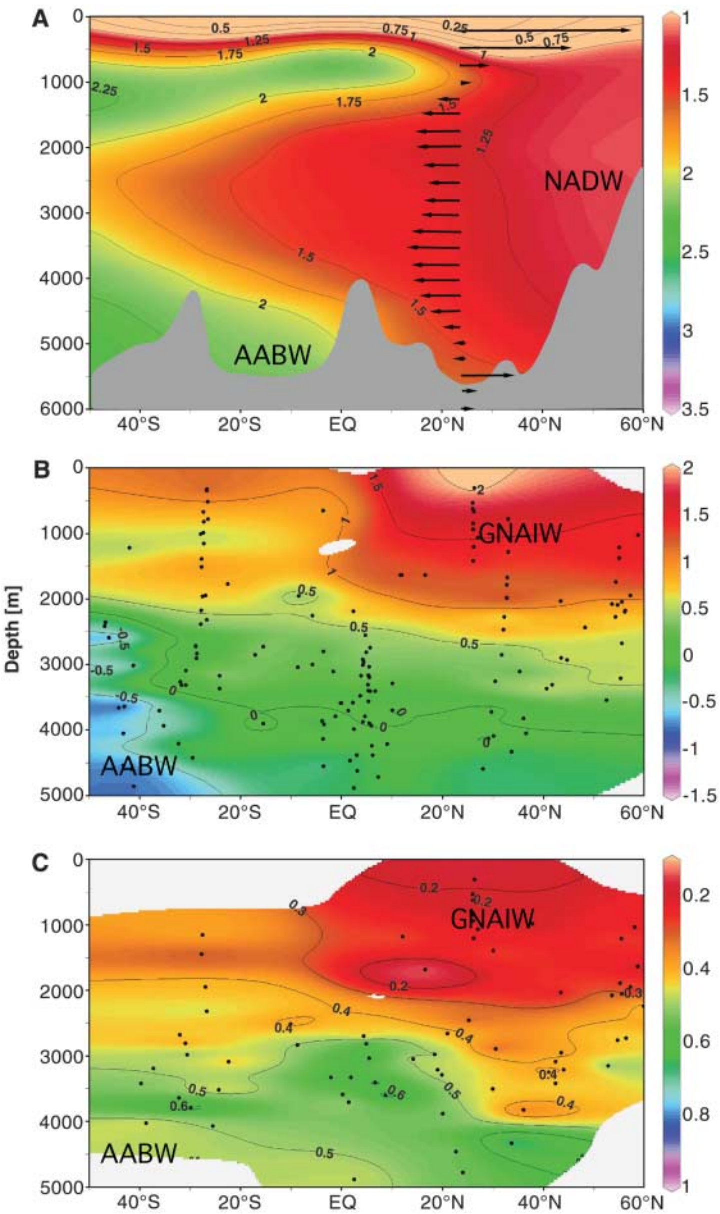

Fig. 1. (**A**) The modern distribution of dissolved phosphate (µmol liter^{-1})—a biological nutrient—in the western Atlantic (*61*). Also indicated is the southward flow of North Atlantic Deep Water (NADW), which is compensated by the northward flow of warmer waters above 1 km, and the Antarctic Bottom Water (AABW) below. (**B**) The distribution of the carbon isotopic composition ($^{13}C/^{12}C$, expressed as $\delta^{13}C$, Vienna Pee Dee belemnite standard) of the shells of benthic foraminifera in the western and central Atlantic during the LGM (*23*, *24*). Data from different longitudes are collapsed in the same meridional plane. (**C**) Estimates of the Cd (nmol kg^{-1}) concentration for LGM from the ratio of Cd/Ca in the shells of benthic foraminifera from (*25*). Today, the isotopic composition of dissolved inorganic carbon and the concentration of dissolved Cd in seawater both show "nutrient"-type distributions similar to that of PO_4.

The LGM configuration is often interpreted as a shoaling of NADW and a northward extension of AABW in the Atlantic Ocean. The high-nutrient water below 2 km also appeared to be rich in zinc, which supports the idea that some of this water mass comes from the Southern Ocean (*29*). However, the deep (>2 km) water mass does show higher $^{13}C/^{12}C$ and lower Cd in the deep North Atlantic than in the deep South Atlantic; this finding suggests that waters originating in the North Atlantic also contributed to the deep (>2 km) water mass in the LGM Atlantic. This contribution may be simply the result of mixing between GNAIW—which may form as far south as the Labrador Sea or the subpolar open North Atlantic—and the deeper water mass originating in the south, or it may consist of the addition of small amounts of a distinct, denser water mass forming in the far North Atlantic (*30*).

Although the nutrient tracers provide a coherent picture of the distribution of water masses, they provide little information about the absolute rates of flow in the deep ocean. A fundamental reason is that the remineralization of organic matter has a relatively small effect on the nutrient concentration of deep waters in the Atlantic (at least today) and is relatively poorly understood.

Deep-Water Radiocarbon Activities

The rate of radioactive decay of ^{14}C is well understood and, in principle, could provide a measure of the rate of deep-water renewal or ventilation. Two approaches have been developed to correct past ^{14}C ages from carbonate that grew in the deep ocean for the time since their deposition. Radiocarbon measurements on benthic foraminifera can be corrected using ages of contemporaneous planktonic (surface-dwelling) foraminifera (*31*–*33*), and radiocarbon measurements on deep-sea corals can be adjusted using independent ages derived from uranium and thorium isotopes (*34*–*36*). Today, the radiocarbon distribution in the deep Atlantic mostly reflects the relative contributions of water from the north with high ^{14}C activity and water from the south with low ^{14}C activity, with only a small decrease in ^{14}C activity due to in situ decay within the deep North Atlantic. Similar to its use in the modern ocean, past ^{14}C could be combined with other water-mass tracers to account for this overprint of water-mass

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mixing and thereby estimate the contribution due to radiocarbon decay within the Atlantic (*37*). To use radiocarbon to directly constrain the LGM circulation in the Atlantic would require a large number of precise measurements (*38*, *39*).

However, the existing measurements of ^{14}C activity in benthic foraminifera suggest a water-mass structure in the LGM Atlantic that is consistent with the nutrient proxies, with ^{14}C-rich waters indicating recent exchange with the atmosphere above 2 km depth and ^{14}C-poor waters below this depth (*40*). The interpretation of the ^{14}C is complicated by assumptions about the surface-ocean radiocarbon activity and the mixing of shells of different ages by organisms living within the sediments, so the agreement between the reconstructions based on ^{14}C and the nutrient tracers gives us further confidence in the overall picture of the deep-water masses in the LGM Atlantic.

Radioisotopes of Protactinium and Thorium

The contrasting chemical behavior of uranium decay-series nuclides provides a means for assessing the rate of deep circulation. Uranium is highly soluble in seawater and thus has a residence time of several hundred thousand years in the ocean. Because this is far longer than the overall oceanic mixing time (a millennium or two), uranium is approximately evenly distributed throughout the ocean. This means that the radioactive decay of U isotopes, and hence the production of its daughter isotopes, is spatially uniform to a good approximation. By contrast, these radioactive-decay products, thorium and protactinium, are extremely particle-reactive (*41*) and are rapidly removed from seawater by settling particles and subsequently buried on the sea floor. The resulting oceanic residence times are on the order of decades for ^{230}Th and centuries for ^{231}Pa. Because the residence time of deep waters in the Atlantic is also on the order of centuries, most of the ^{230}Th produced in the Atlantic is buried in Atlantic Ocean sediments, whereas some of the ^{231}Pa is exported to the Southern Ocean. This leaves the modern ^{231}Pa/^{230}Th ratio in Atlantic sediments below the ratio at which these isotopes are produced by the decay of U (*42*). A longer residence time of water in the Atlantic should cause the ^{231}Pa/^{230}Th ratio in the underlying sediments to increase, but there was no significant difference in the mean ^{231}Pa/^{230}Th of Atlantic sediments deposited during the LGM relative to those laid down more recently (*42*). These data could be consistent with a range of past circulation states, from a slight increase in the MOC to a decrease of up to 30% (*43*). More recently, with detailed downcore records, slightly higher ratios were found for the LGM sediments relative to the Holocene at a water depth of 4.5 km near Bermuda (*44*), consistent with an overall small increase in the residence time of overlying deep waters (GNAIW and AABW). Lower ratios were found at 1.7 km depth in the northern North Atlantic (*45*) and 3.4 km depth on the Iberian margin (*46*), allowing for the possibility of vigorous renewal of GNAIW. Because variations in particle flux (*47*) and composition (*48*) can also influence sedimentary ^{231}Pa/^{230}Th, a better understanding of these factors will strengthen our ability to quantify past ocean circulation with the use of these nuclides.

Glacial Circulation of the Atlantic

At this point, the most robust observations that can help to constrain scenarios of past variability in the Atlantic MOC are as follows: (i) There was a water-mass divide in the LGM Atlantic, with a nutrient-poor, radiocarbon-rich water mass (GNAIW) dominant above 2 km and more nutrient-rich, radiocarbon-poor water below 2 km (perhaps a glacial analog of AABW). The maintenance of these two distinct water masses in the face of mixing processes similar to those in the modern ocean that would tend to erase these boundaries requires one or both water masses to be renewed fairly rapidly (*24*). (ii) ^{231}Pa/^{230}Th ratios in deep-ocean sediments deposited during the LGM are comparable to those deposited under modern conditions. This also argues against a much slower circulation for both deep-water masses in the Atlantic. (iii) The cross-basin contrast in oxygen isotopes in benthic foraminifera in the South Atlantic collapsed during the LGM. This would argue against a strong MOC that imports surface and intermediate waters to the Atlantic compensated by the export of deeper waters. Hence, we have good evidence for a circulation of deep waters in the LGM Atlantic that was not completely sluggish. The data also do not support a MOC with the same extent and structure as today. Sea surface temperature reconstructions in the North Atlantic (*49*, *50*) also appear inconsistent with a stronger version of today's overturning cell characterized by surface water inflow compensating deep-water export from the polar seas of the North Atlantic. These observations seem to rule out at least some of the more extreme circulation states produced by climate models for the LGM.

Outlook

What would be required to provide a reliable observational estimate of the Atlantic MOC during the LGM? Paleoceanographic methods inherently are associated with larger errors and have a sparser geographic coverage than modern oceanographic measurements, and using this type of data to produce a conclusive quantitative reconstruction of past ocean circulation is a challenge. It will almost certainly require a combination of different paleoceanographic proxies such as those discussed here (*38*, *51*). Ocean margin density reconstructions and ^{231}Pa/^{230}Th measurements may be particularly useful, as they may integrate the effects of circulation in the ocean interior where paleoceanographic measurements are not possible; measurements of ^{14}C may also be useful as a direct measure of elapsed time. But work remains to be done in order to (i) better understand the processes by which Pa and Th are removed from the water column; (ii) better assess past ocean temperatures and salinities for paleodensity reconstructions, possibly by using the elemental chemistry of

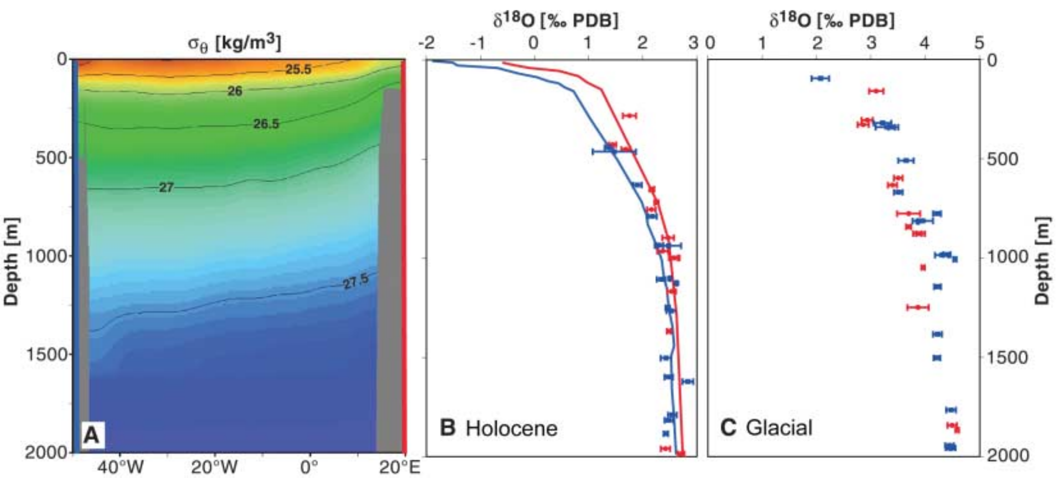

Fig. 2. (**A**) Density (σ_θ) of seawater across the South Atlantic at 30°S (*61*). The waters are denser on the eastern side of the basin, reflecting the presence of the meridional overturning circulation. (**B**) Oxygen isotopic composition of the shells of benthic foraminifera (δ^{18}O) in recent sediments on the eastern (red symbols) and western (blue symbols) side of the basin, reflecting the density contrast across the basin today, with higher δ^{18}O for the higher-density waters on the eastern side. The solid lines are the predicted δ^{18}O values based on modern hydrographic data (*21*). (**C**) Oxygen isotopic composition of the shells of benthic foraminifera for the LGM suggest that the modern density contrast in the upper 2 km was absent or reversed (*21*).

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the shells (*52*) and paleosalinity estimates from measurements of chloride in pore waters (*53*); and (iii) better constrain water-mass properties for accurate use of the ^{14}C clock. Other approaches that show promise are the quantitative analysis of the grain size population in the terrigenous sediment fine fraction that provides a proxy for near-bottom flow speed, which has the advantage of having a direct physical connection to flow and an immediate response to any changes in flow speed (*54*). New water-mass tracers that are independent of nutrient cycling, such as the Nd isotopic composition of metallic precipitates in deep-sea sediments, are also being developed and successfully applied on a number of time scales [e.g., (*55*)], and magnetic properties have been used to reconstruct the flow path of bottom waters (*56*). Although challenges remain before we arrive at a well-constrained quantitative estimate of the glacial circulation, much will be gained in the coming years by the combined use of the tools currently at our disposal. It is worth recalling that the basic structure of the modern Atlantic MOC was largely described by the 1950s on the basis of a few measurements of water-mass properties and the thermal wind relationship, whereas quantitative estimates of the modern MOC based on inverse methods have only been possible in the past two decades or so (*57*).

Different circulation scenarios are consistent with the currently available data for the LGM, but certain hypotheses regarding the glacial circulation in the Atlantic already are testable. In particular, general circulation models provide a set of circulation hypotheses that are physically consistent (given the assumptions used in constructing the models) with the ice sheets and CO_2 concentration of the last ice age. We can already say with some confidence that the data can rule out some of the more extreme scenarios produced by the models. To compare the less extreme model scenarios directly with the data, we need to account for the multiple physical, chemical, and biological controls on the paleoceanographic observations. A better representation in the models of the full complexity of these processes that lead to the record left behind in the sediments and the explicit prediction of the values of the paleoceanographic proxies will allow for a more direct comparison between model output and data [e.g., (*58*, *59*)].

Reconstructing ocean circulation during the LGM is a critical first step, but there is already a strong community focus on generating the time-series data that will allow for the reconstruction of a detailed history of ocean circulation over the abrupt climate changes that punctuated the cooler climates of the past. Changes in the Atlantic MOC play a critical role in many of the hypotheses put forth to explain these abrupt climate transitions, and there is already compelling evidence to support this link, at least for the most recent of these abrupt climate change events (*44*, *60*). The quantitative reconstruction of these circulation changes remains a challenge that, if tackled successfully, will further our understanding of the relationship between ocean circulation and climate, enabling us to better constrain the scenarios for the future.

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