Ocean circulation - Does large-scale ocean overturning circulation vary with climate change?

PRESENT PAST

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Earth's oceans undergo a relentless churning as water responds to the interplay of temperature, salinity and prevalent winds. In the Atlantic Ocean, roughly 18 Sv[1] of warm, saline near-surface water is carried northward by the Gulf Stream/ North Atlantic Current system (Cunningham et al. 2007). An equivalent amount of cold, deep water from the Nordic and Labrador Seas is guided by topography to the Southern Ocean. Here, it returns to the upper ocean more slowly via the mixing of deeper and shallower waters and/or the upwelling of deeper water in response to the strong westerly winds. This global-scale Meridional Overturning Circulation (MOC) is responsible for the observed temperature contrast of 15°C at low-latitudes in the Atlantic between the upper ocean and the deep ocean. In contrast, the absence of deep water formation in the Northern Pacific and Indian Oceans means that oceanic northward heat transport is significantly less than in the North Atlantic (Lumpkin and Speer 2007).

In its fourth assessment report the Intergovernmental Panel of Climate Change considers it "very likely" that the MOC will have gradually slowed by the end of the 21st century as a consequence of global warming. Climate model projections predict a slowdown between 0 and 50% by the year 2100, although complete shutdown is considered "unlikely" for this time horizon. The reasons for the slowdown include factors that impede deep-water formation – warming of surface waters and salinity reduction at high latitudes due to the melting of continental ice sheets and the intensification of the hydrological cycle. Uncertainties regarding the freshwater fluxes and the locations of deep-water formation at high latitudes are the primary causes of the large uncertainties in the model projections.

Future changes to the MOC will also be determined by changes in the mechanisms leading to the upwelling of warmer waters. Winds have intensified by 30% over the Southern Ocean during the second half of the last century (Huang et al. 2006), possibly due to decreasing stratospheric ozone concentrations. This trend is expected to prevail until 2100 (Shindell and Schmidt 2004). Beyond the end of this century, in what will be a different climate, upwelling in the Southern Ocean might gain in importance relative to sinking in the North Atlantic. Other long-term influences on the overturning in the North Atlantic Ocean are related to increased surface saltwater exchanges between the Indian and South Atlantic Oceans in the Agulhas Current System.

At present, there is no convincing observational evidence for a long-term weakening of the Atlantic MOC. This absence of evidence should not be mistaken as evidence of absence of a slowdown, especially when there is a lack of adequate long-term and sustained monitoring. Discontinuous historic observations do not capture the large intraseasonal-to-interannual variations, thereby reducing the reliability of the projections of the long-term changes in the MOC. Continuous measurements spanning the past decade or so are not indicative of a "strong" MOC decline. But on decadal time scales, natural variations have considerably larger amplitudes than the anthropogenic signature (on the order of 0.5 Sv per decade). Thus, observations sustained over several decades are required to distinguish between natural and anthropogenic changes.

Monitoring of the MOC has improved since the beginning of this century (Kanzow et al. 2010; Send et al., in press). Methods include those based on ocean state estimates and those using numerical models to identify observable variables (indices) that correlate well with the MOC strength in the models. Careful validation against the existing direct observations is now required to establish the robustness of state-estimate-based and index-based changes to the MOC. In principle these methods could also be applied to paleoceanographic proxies, to open a window to ocean-induced changes in past climate.

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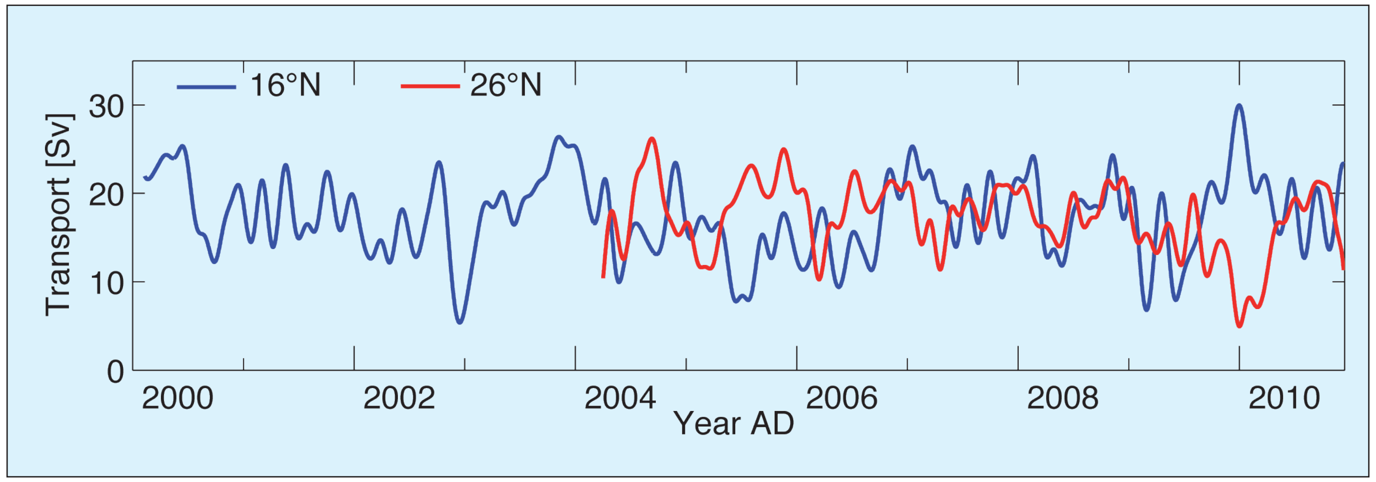

*Figure 1: Southward Deepwater Transport at 16°N (**blue** line) and Strength of Meridional Overturning at 26°N (**red** line) for the period 2000-2010 AD.*

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[1] 1 Sv= 10^6 m^3s^{-1}, unit for volumetric transport. For comparison, the Amazon River discharge in the Atlantic is about 0.2 Sv

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A foundational geological concept that is attributed to James Hutton, the principle of "uniformitarianism", holds that *the present is the key to the past*. However, the observable present cannot capture the full dynamic range of the climate system, and it is therefore to the past that we must turn for a broader perspective on climate change. What is clear from the geological record is that the large-scale ocean circulation is not immutable; it has changed repeatedly in the past and in intimate connection with global and regional climate shifts. What is generally less clear, is exactly what aspect of the ocean circulation has changed in each instance (mass transport, interior mixing rates, transport pathways?), to what degree, and why. These ambiguities arise from two principle challenges in paleoceanography: first, the challenge of inferring hydrographic observations from "proxies"; and second, the challenge of inferring the ocean's large-scale circulation from sparse hydrographic observations, often with highly uncertain age-control. These difficulties become exacerbated when attempting to reconstruct analogues of the relatively subtle, high frequency or seasonally expressed changes in the ocean circulation that are likely to be most relevant to climate change in the decades to come.

Perhaps the most robust case study in past ocean-climate linkages comes from the last 60 ka. This time period has witnessed a succession of regional climate changes, with Greenland and the North Atlantic region exhibiting rapid warm/cold alternations in association with coupled but asynchronous changes in Antarctic temperature. The largest of these climatic perturbations also coincide with changes in the chemistry of waters filling the deep Atlantic (Fig. 1B). The latter are most easily attributed to shifts in the distribution of different water-masses, and therefore to changes in the ocean circulation; a view that is broadly consistent with some numerical model simulations (Ganopolski and Rahmstorf 2001; Liu et al. 2009).

The prevailing interpretation of the records shown in Figure 1 is that they represent the operation of a "thermal bipolar seesaw", resulting from changes in the "effectiveness" of the Atlantic overturning circulation as a heat pump from southern to northern latitudes (Schmittner et al. 2003).

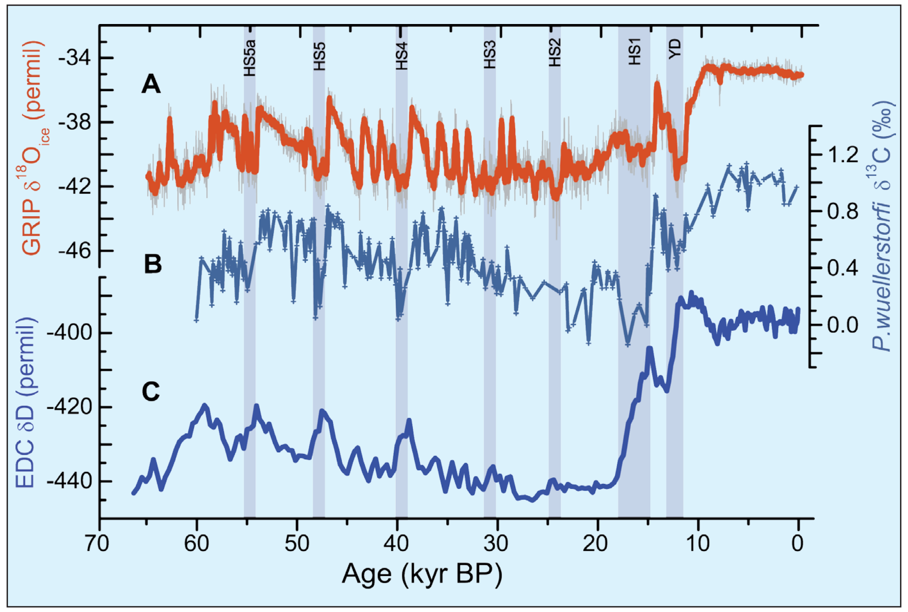

*Figure 1: Changes in the ocean-climate system over the past 60 ka, showing climate anomalies over Greenland (**A**) and Antarctica (**C**) (Lemieux-Dudon et al., 2010) compared with evidence for ocean circulation changes from the deep Northeast Atlantic (**B**) (Skinner et al. 2007). The evidence for circulation changes is derived from benthic foraminiferal stable carbon isotopes, which are interpreted here to represent primarily the preformed macro-nutrient content of deep waters, and therefore the relative dominance of northern- versus southern deep-waters in the deep North Atlantic. HS: Heinrich Stadial, YD: Younger Dryas.*

The hypothesized trigger for these overturning perturbations is anomalous meltwater supply to the North Atlantic: i.e. ice-sheet or ice-shelf surges that may well have been climatically driven (Alvarez-Solas et al. 2010; Flückiger et al. 2006). Interestingly, the patterns and associations of these rapid ocean-climate changes appear to be consistent with an overturning circulation that is conditionally stable, and that may respond non-linearly to relatively subtle perturbations, depending on the prevailing climate/forcing conditions (Margari et al. 2009; Rahmstorf et al. 2005). Indeed, through their inter-hemispheric teleconnections and their inferred impact on the carbon cycle (Anderson et al. 2009), such non-linear shifts in the ocean circulation are thought to have played a key role in tipping global climate out of its glacial state ca. 15-20 ka ago (Barker et al. 2011). Once this happened, ocean-climate variability appears to have become more subdued. Although this suggests a relative stabilization of the ocean circulation under interglacial conditions, it does not imply the complete elimination of ocean-climate variability during the Holocene. Indeed, evidence exists for centennial to millennial perturbations during the Holocene that are likely to have dwarfed those recorded in the instrumental record.

What can these impressive, if incompletely understood, changes in the past ocean-climate system teach us? In general, they question the paradigm of the ocean circulation as a millennially sluggish flywheel in the climate system. They suggest a capacity to respond sensitively to, and in turn impact significantly on regional and global climate, possibly in a non-linear fashion and with important ramifications for the carbon cycle and the global energy budget. However, the past does not provide an easy template for the future. If the geological record is to inform more directly on the stability properties of our modern circulation and its immediate future, paleoceanographers will need to focus on past ocean-climate variability in increasingly fine detail, and with a particular emphasis on relatively warm climate conditions.

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