Quantifying changes in the global thermohaline circulation: A circum-Antarctic perspective

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Summary The Circum-Antarctic Ocean plays a particularly important role in the present-day global ocean circulation system, connecting the three major ocean basins, and acting as the intermediary of global water-mass exchange. As the global "blender" of water masses, changes in its tracer inventory through time reflect the vigor of the global thermohaline circulation (THC) system. Nd isotopes provide a unique potential to quantify present and past ocean circulation changes, as the only quasi-conservative paleocirculation tracer. We present the first Nd isotope record representing the Circum-Antarctic over the last 28 kyr. First order implications include shutdown of the THC during Heinrich Event 1 and during the early part of MIS 2, and a distinct but less intense weakening during the Younger Dryas, but increased THC vigor during the Last Glacial Maximum. Ongoing work with greater temporal resolution and on complementary records will allow quantification of THC intensity through time.

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Introduction

Rapid changes in ocean circulation of surface, intermediate and deep-water masses are well documented in paleoceanographic archives and have a close connection with abrupt changes in the global climate system. The Circum-Antarctic Ocean plays a particularly important role in the present-day global ocean circulation system, connecting the three major ocean basins, and acting as the intermediary of global water-mass exchange. As the global "blender" of water masses, changes in its tracer inventory through time have direct bearing on our ability to constrain the vigor of the global thermohaline circulation (THC) system. For example, a weakening of the export of North Atlantic Deep Water (NADW) during colder climate would be reflected by a reduction in North Atlantic chemical signatures in the Southern Ocean. Hence, constraints on the inventory of appropriate chemical tracers in the Circum-Antarctic over time are key for a better understanding of ocean circulation changes and their relation to global climate variations.

Despite abundant evidence that changes in THC accompanied major climate changes, the magnitudes of the changes have been difficult to constrain, due to the fact that the most widely used paleo-circulation tracers (e.g. benthic $\delta^{13}C$, Cd/Ca) are nutrient proxies that are affected by processes other than ocean circulation, such as biological productivity, air-sea gas exchange, and changes in carbonate ion concentration of seawater. They are thus non-conservative and cannot be used to quantify ocean circulation changes. In contrast to these conventional tracers, the quasi-conservative behavior of Nd isotopes in the oceans provides a unique means to trace water-masses with the potential to quantify present and past changes in THC vigor. Recent Nd isotope studies from the deep Cape Basin in the South Atlantic (Piotrowski et al., 2004, 2005) indicate a stronger THC when Greenland was warmer, and a weaker THC when Greenland was colder, on orbital to sub-millennial time scales over the past ~100 kyr (Figure 1).

Here we present the first Nd isotope record representing the composition of the Circum-Antarctic ocean over the last 28 kyr. While the previously generated South Atlantic record (Figure 1) represents intermediate mixtures of components from high latitudes to the north and south, we interpret the new record to represent the global "blend" of components in the Circum-Antarctic, allowing a first order quantification of THC strength. The data imply significant North Atlantic-derived contributions to the Circum-Antarctic during the Last Glacial Maximum (LGM), shutdown of North Atlantic-derived contributions during Heinrich Event 1, as well as during the early part (>23 kyr) of Marine Isotope Stage (MIS) 2, and distinct but less intense weakening of the THC during the Younger Dryas.

Nd isotopes as a tracer of ocean circulation

^{143}Nd is produced by radioactive decay of ^{147}Sm ($t_{1/2}$ = 106 Ga) and the Nd isotope ratio is expressed here as ε_{Nd}, the deviation of the $^{143}Nd/^{144}Nd$ ratio in parts per 10^4 from the "bulk Earth" value (defined as ε_{Nd} =0). Nd is enriched relative to Sm in the continents compared to the average Earth. As a result, continental crust has lower ε_{Nd} than the bulk Earth and the mantle. Moreover, the values vary directly with crustal age such that older continents have lower ε_{Nd}. The use of Nd isotopes as water mass tracers is based on distinct ε_{Nd} of different water masses, reflecting the short residence time of Nd in seawater compared with the mixing time of the oceans, and is reviewed in Goldstein and Hemming (2003). The Nd isotopic signature of ocean water is ultimately derived from the continents through weathering. Low ε_{Nd} values that characterize NADW (about -13.5) reflect derivation of dissolved Nd from the old continental terrains surrounding the North Atlantic. Deep water in the North Pacific has high ε_{Nd} values (-2 to -4), reflecting contributions of Nd from Circum-Pacific volcanism. Intermediate ε_{Nd} values (ε_{Nd}= -7 to -9) are found in the Circum-Antarctic and Indian Oceans, as well as in intermediate and bottom Atlantic and Pacific waters formed in the Circum-Antarctic Ocean (e.g. AAIW, AABW). Data on Drake Passage seawater indicate uniform values with depth of ε_{Nd}= -8 to -9, which tags the Circum-Antarctic-derived water masses entering the Atlantic. The contrast between North Atlantic and Circum-Antarctic Ocean water-mass ε_{Nd} signatures allows clear detection and mapping of the different water masses in the Atlantic basin. In the Atlantic, the variability of ε_{Nd} in deep seawater is consistent with mixing of North Atlantic and Circum-Antarctic-derived end-members.

Water-mass compositions of the past can be mapped using Nd isotopes because authigenic Fe-Mn oxide precipitates dispersed in marine sediments record the ε_{Nd} signature of the overlying water-mass from which they precipitated and hence constitute a potent archive of past seawater Nd isotopic compositions. Recent studies of the ε_{Nd} of the North Atlantic and North Pacific global end-members show that they have been relatively constant on glacial-interglacial to millennial time scales through the Pleistocene (Abouchami et al., 1997, Marchitto et al., 2005, van de Flierdt et al., 2006, Foster et al., 2007). Therefore, to a first order the temporal variability of Circum-Antarctic ε_{Nd} should reflect changes in the balance of inputs from the North Atlantic and North Pacific.

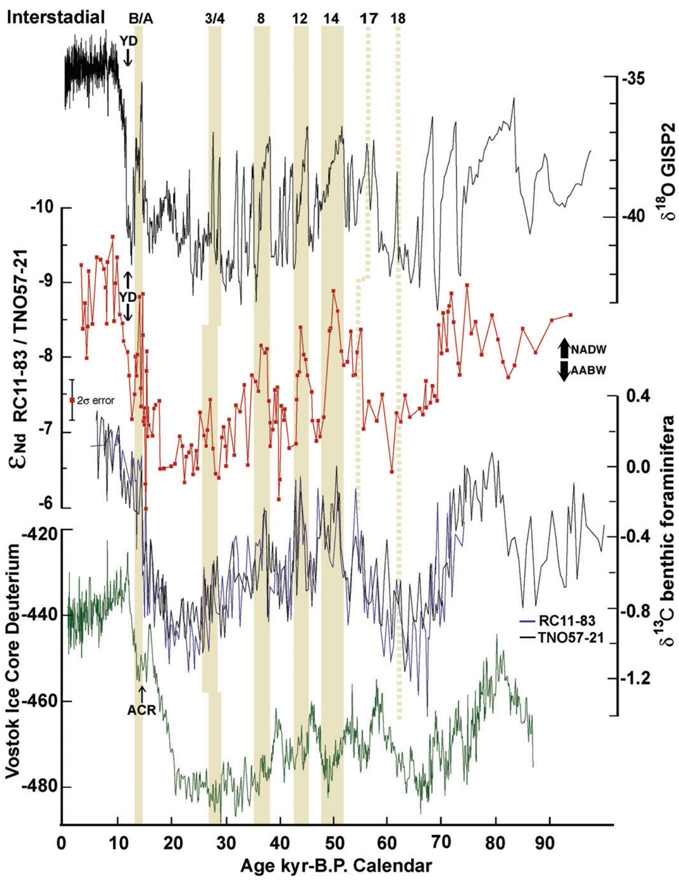

Figure 1. Authigenic ε_{Nd} and benthic foraminiferal $\delta^{13}C$ of RC11-83-TNO57-21, SE Atlantic, $\delta^{18}O$ and δD records from Greenland (GISP2) and Antarctica (Vostok). The ε_{Nd} variations indicate greater export of North Atlantic-derived water to the South Atlantic during warm periods in Greenland on millennial and longer time scales, thus demonstrating the utility of ε_{Nd} as a monitor of the vigor of the global thermohaline circulation. Figure is modified from Piotrowski et al. (2005).

Samples and results

The new Nd isotope record is on core V19-188 from the Indian Ocean (6.87°S, 60.67°W, 3356 mbsl) on the southeast flank of the Carlsberg Ridge in the Somali Basin. The core shows an average sedimentation rate of ~3 cm/kyr. It is bathed by North Indian Ocean Deep Water (NIDW), which is derived from Circumpolar Deep Water (CDW) that has acquired higher salinity and some nutrient enrichment in the northern Indian Ocean, through modification by sediment-water interaction and saline overflows from the marginal seas (Mantyla and Reid 1995). Sr isotope ratios of Fe-Mn oxide leachates show Quaternary seawater values close to 0.7092, strongly indicating that the integrity of the marine signal is uncompromised. The ε_{Nd} values near -8 of the late Holocene samples (Figure 2) agree with direct seawater measurements of ε_{Nd} = -8±1 in the deep Somali Basin. They are consistent with a Circum-Antarctic seawater provenance, and indicate that the transformation of CDW into NIDW does not modify its Nd isotopes, and therefore that NIDW can be used to monitor changes in ε_{Nd} of CDW. The age model for the core is based on 13 ^{14}C AMS dates (0-26 kyr) from the CLIMAP program, and is corrected to calendar years.

The V19-188 results (Figure 2) show clear glacial-to-interglacial variations, with more NADW-like ε_{Nd} values in the late Holocene compared to more Pacific-like ε_{Nd} values earlier. During the oldest portion of the record (>23 kyr) in the early part of full glacial MIS 2, the ε_{Nd} shows high values of -4, indistinguishable from central Pacific seawater. ε_{Nd} values decrease toward more North Atlantic-like values at ~22 kyr (from -4 to -6) while the planktonic $\delta^{18}O$ remains at full glacial values. A marked ε_{Nd} increase to about -4, again similar to Pacific seawater, occurs at 17-14 kyr at about the time of Heinrich Event 1. A smaller ε_{Nd} increase at ~12 kyr corresponds to Younger Dryas time. The ε_{Nd} reaches full Holocene values somewhere between the samples from 6 and 8.5 kyr.

Discussion

The V19-188 record (Figure 2) indicates large variations in the ε_{Nd} of the Circum-Antarctic "blend" over the past 28 kyr, broadly consistent with strong THC during the Holocene and weaker THC during the last glacial period. The marked ε_{Nd} increase centered at ~15 kyr coincides with the time of Heinrich Event 1 in the North Atlantic and indicates a decrease in North Atlantic water-mass export to the Circum-Antarctic, consistent with other records indicating reduced NADW and Glacial North Atlantic Intermediate Water (GNAIW) formation at this time. A conspicuous feature of the V19-188 record is Pacific-like ε_{Nd} values during this time period, and during the early part of MIS 2 at >23 kyr, indicating absence of any North Atlantic-derived component and thus implying shut-down of the global THC, both in association with Heinrich Event 1 and during the early portion of the last full glacial period. The Younger Dryas also imparts a significant, though smaller magnitude weakening of the THC. The record shows an increase in the supply of low (more North Atlantic-like) ε_{Nd} during the later portion of MIS 2 (<23 kyr), corresponding to the LGM. Possible causes include an increase in THC vigor with greater North Atlantic water export to the Circum-Antarctic, or a stronger contribution of Nd from Antarctica concurrent with maximum glaciation. We favor stronger THC based on comparison with the $^{231}Pa/^{230}Th$ record from the Bermuda Rise in the North Atlantic (McManus et al., 2003), which also suggests relatively strong water-mass export from the North Atlantic during the LGM as GNAIW. Indeed, the Southern Ocean ε_{Nd} and North Atlantic $^{231}Pa/^{230}Th$ records are remarkably coincident (Figure 2, middle plot), both indicating a THC shutdown in the around Heinrich Event 1 time, and a smaller magnitude THC weakening effect during the Younger Dryas, as well as a strong THC at ~20 kyr.

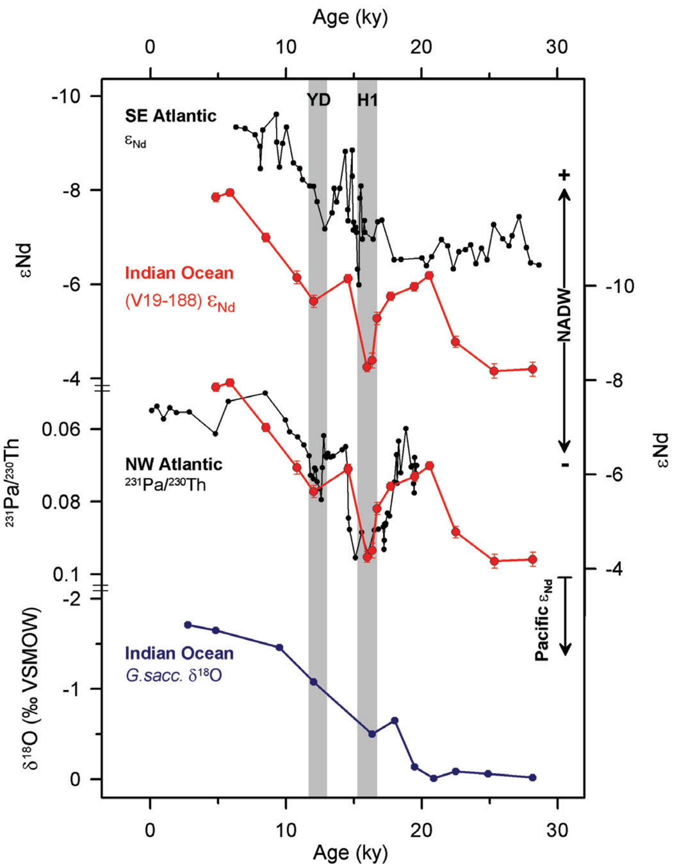

Figure 2: Authigenic ε_{Nd} (red) and planktonic foraminiferal $\delta^{18}O$ (blue) of core V19-188 from the Somali Basin as a proxy for Circum-Antarctic Nd. Top: Comparison with the ε_{Nd} record from SE Atlantic cores RC11-83-TNO57-21 (Piotrowski et al., 2004, 2005). Center: Comparison with the $^{231}Pa/^{230}Th$ record, which is another THC proxy, from the Bermuda Rise in the NW Atlantic (McManus et al., 2004).

Comparison with the RC11-83 ε_{Nd} record (Figure 2, top plot), from the deep Cape Basin in the South Atlantic shows many similarities, including weak THC during early MIS 2, a THC minimum at ~15 kyr, and a decrease in THC vigor during the Younger Dryas. There are also a number of differences, for example, RC11-83 reaches its Holocene THC maximum earlier and does not show indications of stronger THC at ~20 kyr. Importantly, V19-188 remained more Pacific-like throughout the entire time interval, which we interpret to be a purer representation of the characteristics of the Circum-Antarctic. The Cape Basin record thus might be interpreted as mixing of Circum-Antarctic (as represented by V19-188) and Northern Hemisphere-derived components throughout (interestingly, RC11-83 appears to be most like the "pure" Circum-Antarctic at ~20 kyr, when the patterns of variability diverge). The offset between the records may reflect continuous influence in the Cape Basin from flow of GNAIW to the South Atlantic even when GNAIW was not significantly exported to the Circum-Antarctic.

Summary

As the global "blender" of water masses, changes in the tracer inventory of the Circum-Antarctic Ocean have direct bearing on our ability to constrain the volume transport of the global thermohaline circulation, and hence on the northward flow of upper-ocean waters that deliver heat and moisture from the tropics to the high latitude North Atlantic. The quasi-conservative behavior of Nd isotopes in the oceans provides a unique means to trace water-masses with the potential to quantify present and past ocean circulation changes. We present the first Nd isotope record representing the Circum-Antarctic over the last 28 kyr, which we interpret to represent the global "blend" of components input from the other oceans. The data document a weaker overall THC during the last ice age, including a shutdown during the early part (>23 kyr) of Marine Isotope Stage 2, an increase in vigor during the Last Glacial Maximum, another shutdown during Heinrich Event 1, an increase during the Bølling warming, and a weakening during the Younger Dryas that did not approach a full shutdown. The temporal pattern of variability shows a remarkable similarity to the ^{231}Pa/^{230}Th record from the North Atlantic of McManus et al. (2004). Ongoing work with greater temporal resolution and on complementary records will allow quantification of the thermohaline circulation intensity through time.

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