From the warm Pliocene to the cold Pleistocene: A tale of two oceans

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What drove the transition from a warm Pliocene to a cold Pleistocene, dominated by widespread Northern Hemisphere glaciation? This has become one of the most intriguing questions in the earth sciences. Although we can constrain each of these individual global climate states via continental and oceanic records, we have little consensus on why the transition occurred and what this might mean for climate plateaus, and by extension, for tipping points in our current climate system (Hansen et al., 2008). Transitions between one climate state and another are particularly intriguing, in that these are intervals where a number of proxies tend to be driven to agreement. For example, although productivity, nutrient, and circulation proxies sometimes diverge from each other during either glacial or interglacial states of the Pleistocene ocean, they typically agree strongly during Termination events between these climatic states (Filippelli et al., 2007; Flores et al., 2003). This reveals as much about the nature of strong connections between circulation, upwelling, and productivity in the ocean in times of turmoil as it does about the tendency of other factors that allow some secular drift during times of "stability."

The Pliocene and the Pleistocene oceans are completely different in terms of circulation, biological productivity, and upwelling states. The Pliocene ocean, from low to high latitudes, was characterized by temperatures ~3 °C higher than today's ocean temperatures (Haywood et al., 2000, 2009; Dowsett et al., 2009; Dowsett and Robinson, 2009; Naish et al., 2009). Based on continental and oceanic studies, the atmosphere had ~30% higher CO_2 concentrations than pre-Industrial Holocene levels (Kürschner et al., 1996; Raymo et al., 1996). In the Pacific Ocean, it appears that a "permanent" El Niño state prevailed (Ravelo et al., 2004; Wara et al., 2005; Dowsett et al., 2009), with a reduction in the east-west pressure gradient affecting wind regimes and heat distribution. This atmospheric state resulted in a deepening of the thermocline and reduction of upwelling intensities in the Pacific Ocean. In the North Atlantic Ocean, several authors (Raymo et al., 1996; Haywood et al., 2009; Dowsett et al., 2009) suggested intensification of the thermohaline circulation, and consequently the Gulf Stream and North Atlantic Current, enhancing heat transport from the tropics and increasing North Atlantic temperatures. This combination of higher CO_2 levels and the positive feedback caused by the meridional heat transport with a more stratified ocean is the most convincing evidence to explain the warmer Pliocene ocean.

After 3 Ma, the global scenario changed progressively. At this time, the closure of the Panama and Indonesia corridors in the tropics (Mikolajewicz and Crowley, 1997; Haug and Tiedemann, 1998; Haug et al., 2001; Cane and Molnar, 2001) was complete, especially affecting deep thermohaline circulation, thus contributing to a substantial reorganization of the oceanic and atmospheric system (Philander and Fedorov, 2003). A progressive reduction in sea-surface temperature occurred at the same time that upwelling of the equatorial Pacific and the eastern ocean basin coastal regions intensified (Ravelo et al., 2004; Marlow et al., 2000). The enhanced coastal upwelling caused a general aridification of proximal landmasses to the east due to lowered water vapor content above cold upwelling zones. Waddell et al. (2009) suggested that respiration-derived CO_2 might have been stored in the deep Southern Ocean during this interval as well. Glacial-interglacial cyclicity linked to the buildup and retreat of the Northern Hemisphere ice sheet, as well a strong variability in atmospheric CO_2, became characteristic features of the Earth's climate system at this time (Tiedemann et al., 1994). In general terms, the Pleistocene ocean was characterized by the shoaling of the thermocline and the development of active upwelling cells (linked to wind-cell intensification) in the equatorial Pacific Ocean and in the eastern side of ocean basins, provoking a net increase of primary productivity in these regions (Marlow et al., 2000) and thus likely an enhanced drawdown of atmospheric CO_2.

In an exciting new analysis using ocean sediment core records from the Ocean Drilling Program, Etourneau et al. (2009, p. 871 in this issue of *Geology*) peer into the Pliocene-Pleistocene transition in the southeastern Atlantic Ocean, revealing the impacts that the reorganization of ocean circulation in the Atlantic and Southern oceans had in transforming upwelling, biological productivity, and even continental climate during this interval. Their work effectively utilizes a multi-proxy and multi-site approach, finding that Benguela Current upwelling and resultant nitrate utilization by organisms intensified at the end of the Pliocene due to the strengthening of zonal wind systems. This coincides with a general tightening of wind-driven upwelling patterns in equatorial systems and an increase in subsurface nutrient export toward surface waters in lower latitudes (Philander and Fedorov, 2003). In this way, the warm, relatively well-ventilated and potentially more sluggish Pliocene ocean gave way to the colder, more stratified (but with more vigorous coastal upwelling) Pleistocene ocean; each of these oceanic states reveal clear differences not just in circulation but also in nutrient distribution and ecosystem structure. This Pliocene-Pleistocene transition is a state change of atmospheric and oceanographic conditions, where the magnitude and rate of change are great enough to force proxies to tell a straightforward story.

Much of the interpretation of water mass nutrient and productivity changes comes from the nitrogen isotopic composition of bulk sediment. A number of studies (Altabet and Francois, 1994; Brandes and Devol, 1997; Sigman et al., 1999; Ganeshram et al., 2000; Robinson et al., 2007; Liu et al., 2008) have utilized this proxy to interpret nitrate utilization related to productivity (which lowers the ratio), denitrification related to the consumption of nitrate as an alternative electron acceptor in suboxic waters (which increases the ratio), and the nature of preformed nutrient sources, which basically sets the baseline nitrogen isotopic composition. It can be difficult to separate these various drivers of the nitrogen isotopic composition, and thus this proxy is best used along with other proxies of water mass sources and biological productivity, as well as some reference sites for the potential baseline nitrogen isotopic composition of source water.

Etourneau et al. (2009) conclude by suggesting that Southern Ocean circulation patterns may have impacted the global ocean nitrogen cycle, and hence the nitrogen isotopic composition of nitrate in the ocean. This is supported by the observed shift in nitrogen isotopic composition that occurs between Antarctic (Sigman et al., 2004), sub-Antarctic, and Benguela upwelling sites presented by Etourneau et al., as well as by Liu et al. (2008), on the California Margin. This global shift in oceanic nitrogen cycling is also supported by a new record from the northern portion of the equatorial Pacific Ocean (Rowan et al., 2008), and together these individual records (Fig. 1) make a compelling case for a widespread increase in the denitrification:nitrate

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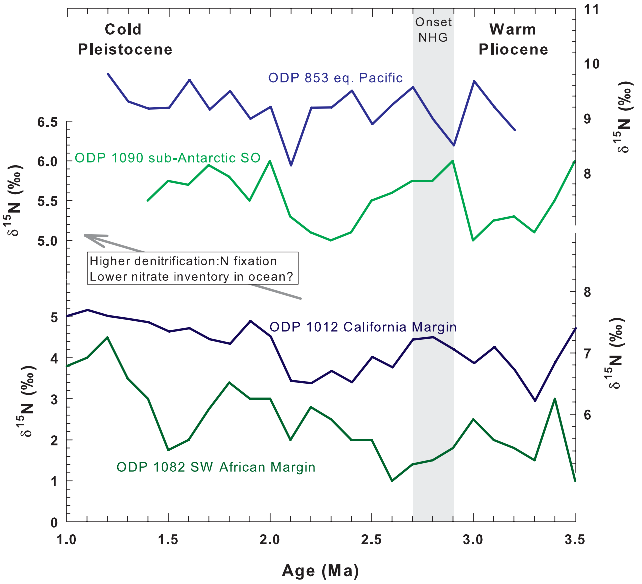

Figure 1. Nitrogen isotopic records from Ocean Drilling Program (ODP) Sites 1082 and 1090 in the southeastern Atlantic Ocean (Etourneau et al., 2009) and from ODP Site 853 (Rowan et al., 2008) and Integrated Ocean Drilling Program (IODP) Site 1012 (Liu et al., 2008) in the Pacific Ocean. All values binned into 100 k.y. averages to facilitate varying resolutions and to examine longer-term trends in nitrogen isotopic evolution. The 2‰ offset in the southeastern Atlantic records is similar to that from the Pacific records, reflecting consistent gradients in preformed nitrate isotopic composition. Note similar longer-term trends toward more enriched values after the Pliocene, supporting the interpretation of significant changes in the nitrogen cycle since the Pliocene.

utilization ratio after the end of the Pliocene. One implication of this is that with enhanced dentrification, there is a consumption of bioavailable nitrate, and thus a potential decrease in oceanic biological productivity as driven by nitrate at least. Whether this decrease in the marine nitrate inventory significantly impacted net organic carbon burial is debatable, given the central role that the other key nutrient, phosphorus, plays in marine productivity on geologic time scales. Future work certainly needs to address oceanic nutrient cycle changes through time, as these are central to any examination of longer-term carbon cycle dynamics (Berner, 2004).

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