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Increased Pliocene North Atlantic Deep Water: Cause or consequence of Pliocene warming?

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Abstract. *Raymo et al.* [1996] suggested that the mid-Pliocene (~3 Ma) warm period was associated with increased North Atlantic Deep Water (NADW) production. Is this circulation change a cause or consequence of Pliocene warming? We test the hypothesis that increased strength of NADW was a consequence of the warming around Antarctica affecting deep Antarctic outflow. A sensitivity experiment with an ocean general circulation model with Pliocene surface conditions changed only over the Southern Ocean (SO) indicates that warmer temperatures around Antarctica result in lower rates of sea ice formation and SO deep water outflow. The decreased abyssal density gradient in the SO directly leads to about a 20% increase in NADW outflow at 30°S, a 10% increase in NADW overturning in the subpolar North Atlantic, and a 20% increase in poleward heat transport in the North Atlantic. We postulate that the largest initial Pliocene climate change was in the SO because the greater sea ice area in this region is more sensitive to inferred slightly higher CO_2 levels in the mid-Pliocene.

1. Introduction

The thermohaline circulation plays a significant role in regulating global climate by redistributing heat and influencing the rate of CO_2 exchange between the ocean surface and the deep ocean [*Broecker*, 1997]. At present, the thermohaline circulation is composed of two main water masses: North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). Produced in the northern North Atlantic, NADW propagates toward the south and influences other ocean basins, while AABW, produced mainly in the Weddell Sea and the Ross Sea, propagates toward the low latitudes in all ocean basins. Because the NADW and AABW overturning cells are interrelated, the relative abundance of these water masses in ocean basins can be modified by a change in production rate of only one of them.

Most large-scale paleoclimate studies have focused on the latest Pleistocene and Holocene, partially due to the limitation of data. However, to predict future climate change, observation and modeling studies should also focus on periods significantly warmer than the Holocene. One of the last times when climate was significantly warmer than present was the early Pliocene (3-5 Ma). This time interval has been the subject of an investigation aimed at developing a more comprehensive picture of the climate of a warm interval [*Poore and Sloan*, 1996]. For example, *Dowsett et al.* [1996] utilized biotic transfer functions to estimate that Pliocene sea surface temperatures (SSTs) were significantly warmer than present in the middle and high latitudes and that there was little change in low latitudes. Pliocene warmth is also recorded in $\delta^{18}O$ isotopic records [e.g., *Hodell and Venz*, 1992] (Figure 1). The reasons for mid-Pliocene warmth are not yet clear. In a review paper, *Crowley* [1996] summarized several possible reasons: changing CO_2 levels, orographic effects related to late Cenozöic uplift, and/or changes in meridional heat transport [*Rind and Chandler*, 1991] due to, for example, closure of the Central American isthmus [*Maier-Reimer et al.*, 1990].

In an attempt to assess the relative importance of different mechanisms, $\delta^{13}C$ studies by *Raymo et al.* [1996] suggested that average CO_2 level during Pliocene was between ~350 and 400 ppm. A similar conclusion was derived from stomatal counts of Pliocene leafs [*van der Burgh et al.*, 1993]. This is about a 10% increase from the present level (~360 ppm) and about 100 ppm higher than the preanthropogenic level. Although CO_2 content may have increased slightly during the Pliocene, the relative abundance of NADW in ocean basins is also observed to increase [*Raymo et al.*, 1992, 1996; *Ravelo and Andreasen*, 2000]. Increased NADW outflow between 2.7 and 3.4 Ma is also indicated in Figure 1 by $\delta^{13}C$ values, which are more positive than present [*Hodell and Venz*, 1992]. *Raymo et al.* [1992, 1996] attributed the Pliocene warmth to the increased CO_2 and NADW, but they did not stipulate why NADW increased in the Pliocene. Ocean general circulation model (OGCM) experiments have shown that NADW production might decrease with increased CO_2 [*Mikolajewicz et al.*, 1990; *Manabe et al.*, 1991]. A partially open Central American isthmus should also have lowered salinity in the central North Atlantic [*Maier-Reimer et al.*, 1990; *Mikolajewicz and Crowley*, 1997].

This study attempts to find a possible explanation for the observed increased NADW outflow in the mid-Pliocene. On the basis of previous theoretical studies by *Stommel* [1961] and *Rooth* [1982] we hypothesize that changes in water mass density associated with deep water production in one hemisphere can affect the overturning in the other hemisphere. What is different in our approach from the earlier

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more theoretical studies is that we apply the concept to a specific time interval, using a more realistic estimate of the atmospheric forcing changes and a fully three-dimensional OGCM to test the response.

2. Model and Experiment

This study employs the Hamburg Ocean Primitive Equation (HOPE) model, which is based on the primitive equations with a prognostic free surface and conservation equations for tracers. The equations are discretized on an Arakawa E grid [*Arakawa and Lamb*, 1977] where the model grid consists of two C grids staggered to one another. The model version used in this study is global with an effective horizontal resolution of 3.5° in latitude and longitude, 11 vertical layers, and a time step of 20 hours with real bottom topography. Detail features of the ocean model are given by *Wolff et al.* [1997].

The model includes a comprehensive dynamic-thermodynamic sea ice model. The sea ice dynamics employs the viscous-plastic constitutive law of *Hibler* [1979] to describe the internal ice stress, while the sea ice thermodynamics are adopted from *Owens and Lemke* [1990]. Because the presence of sea ice influences the air-ice-sea interaction by modifying the albedo, the heat exchange (insulation), and the momentum transfer, the surface heat and salinity budgets are calculated separately over the ice-free and ice-covered part of a model grid cell. In ice free grid cells, surface temperature and salinity are "relaxed" to prescribed surface air temperature (SAT) from Comprehensive Ocean – Atmosphere Data Set (COADS) [*Woodruff et al.* 1987] and surface salinity from *Levitus* [1982] with timescales of 80 and 40 days, respectively. As long as grid cells contain sea ice, the surface temperature is assumed to be at the freezing point, while the surface salinity is modified by the rate of change of ice thickness. The ocean is forced by climatological monthly mean winds from *Hellerman and Rosenstein* [1983], except over the Southern Ocean (SO) where daily European Centre for Medium-Range Weather Forecast (ECMWF) winds have been used to provide a better climatology and synoptic-scale variability [*Stössel et al.*, 1998; *Kim and Stössel*, 1998].

Two experiments are included in this study. While in the reference experiment, called REF, SST is relaxed to the present atmospheric temperature, in the sensitivity experiment we increased the SAT only in the SO south of 40°S gradually up to 6°C at the southern most grid row for the whole year. *Dowsett et al.* [1996] estimated that during the mid-Pliocene, SSTs were overall higher than present in high latitudes, particularly ~3°C in the SO. Because the Pliocene SAT is not available and SAT is much lower than SST in high latitudes, to reproduce quasi-Pliocene SST, higher SATs than Pliocene SST were applied over the SO. This sensitivity experiment is referred to as TEMP.

The boundary conditions applied in this study are monthly for all experiments. The model was run for 600 years for the control and 1200 years for the perturbation run. Results are annual means averaged over the last 10 model years of the model run.

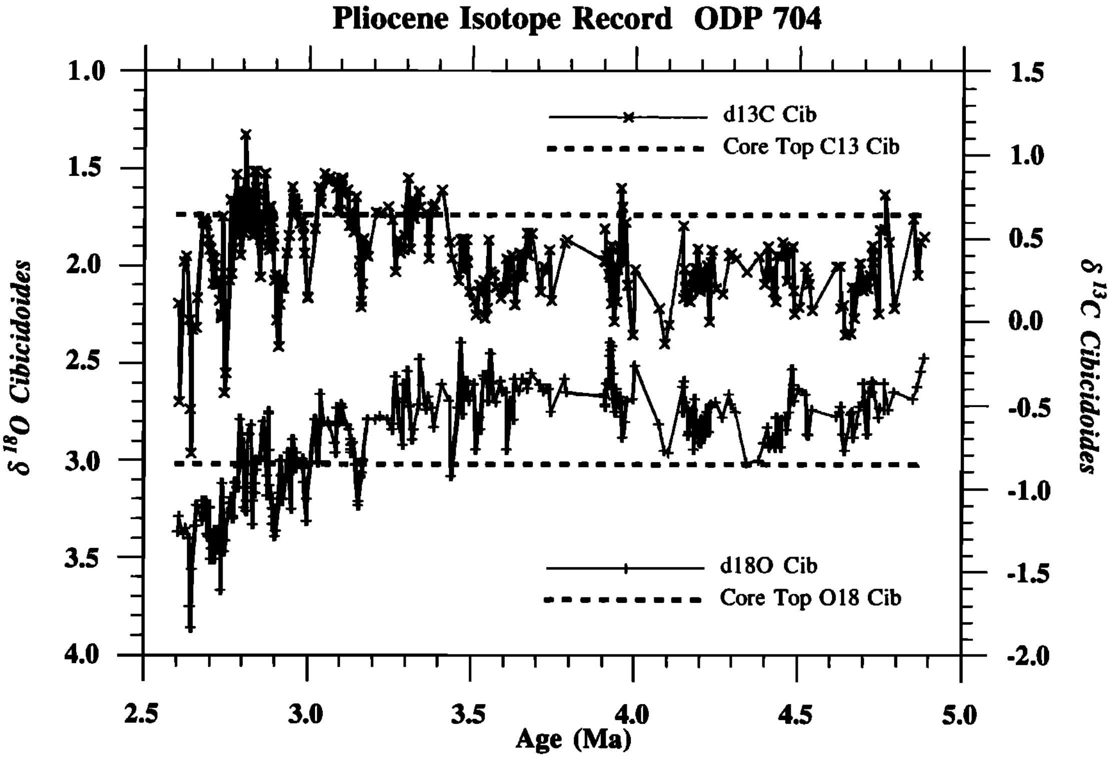

Figure 1. Isotopic records of $\delta^{13}C$ and $\delta^{18}O$ at 7°E, 47°S during the Pliocene. Dashed line represents the core top records. Data are from *Hodell and Venz* [1992]. More positive $\delta^{13}C$ values between 2.7 and 3.4 Ma can be interpreted in terms of more northern component water in the SO.

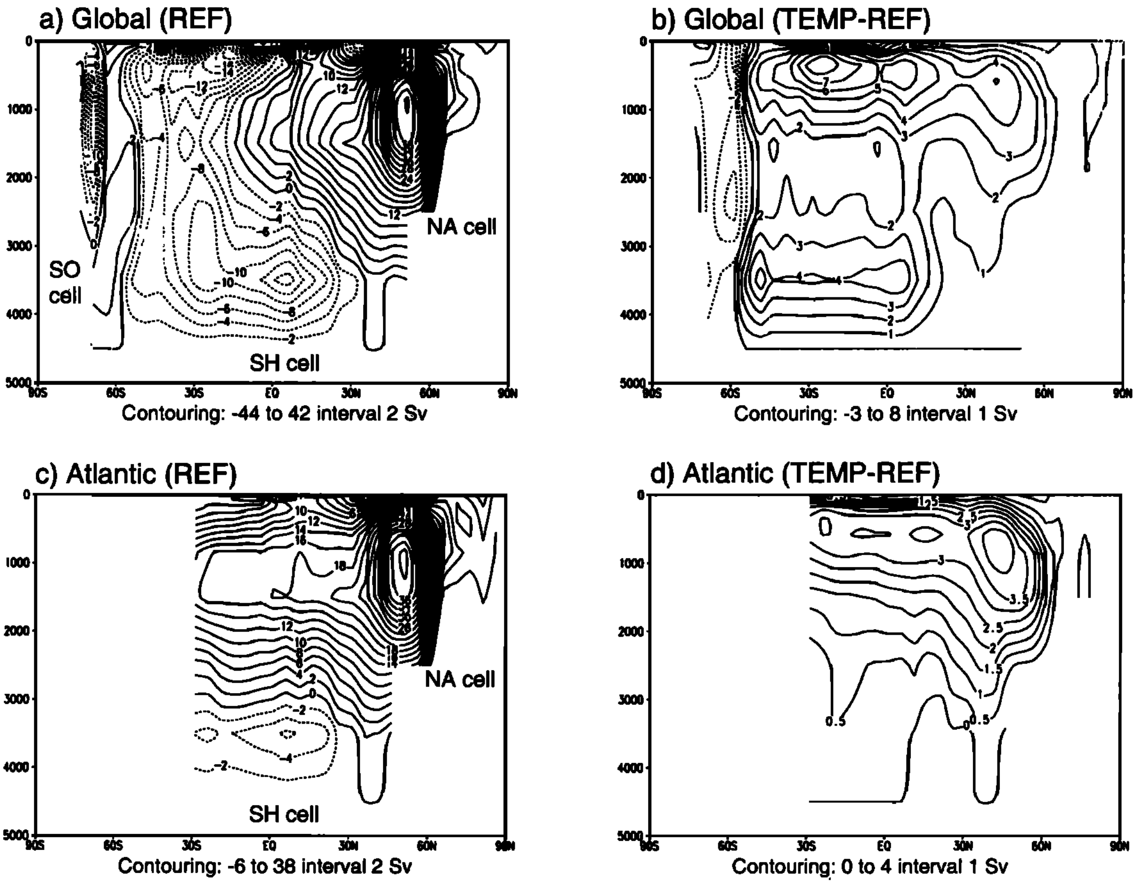

Figure 2. Annual mean global and Atlantic meridional overturning circulation of REF (Figures 2a and 2c), and its difference from TEMP (Figures 2b and 2d). By convention, positive values in difference fields refer to more North Atlantic Deep Water above 3000 m and less Antarctic Bottom Water outflow below 3000 m. Units are in Svedrups.

3. Results

With the increased SO surface temperature, Antarctic sea ice decreased by >60% (4.7 x 10^3 km^3 in REF versus 1.5 x 10^3 km^3 in TEMP). This change increases the amount of meltwater and reduces the amount of brine release due to sea ice formation, which eventually decreases SO convection and AABW outflow toward low latitudes. Figure 2 shows the zonally integrated global and Atlantic meridional overturning stream function of REF and its difference to experiment TEMP. Detailed descriptions of the overturning circulation related to the production of NADW, AABW, and the outflow of AABW are found in previous studies [*Stössel et al.*, 1998; *Kim and Stössel*, The impact of subgrid-scale convection on global thermohaline properties and circulation, submitted to *Journal of Physical Oceanography*, 1999].

One of the distinct features registered in TEMP is the increase of NADW overturning in the Atlantic and outflow in all ocean basins (Figure 2). In the Atlantic Ocean, NADW outflow increases by ~20% at 30°S, and the overturning increases by ~10% (Figures 2b and 2d). A significant decrease in AABW outflow by ~30% is registered in the global overturning, while there is relatively little change in the Atlantic basin (note that by convention the positive values below 3000 m around the equator represent decreased AABW outflow). Since we did not modify the boundary conditions over the North Atlantic, the increased NADW must be related to some changes in the SO. As discussed above, an increase of NADW outflow and overturning can be caused by pole-to-pole changes in the density difference between North Atlantic and the SO. Figure 3 shows annual mean sea surface topography. In the Southern Hemisphere, sea surface is higher in TEMP than REF because the decreased AABW production reduces water density in the SO. The enhanced low pressure at depth in the SO means there is less "resistance" to NADW penetration; this in turn leads to an overall strengthening of the conveyor until a pressure balance is restored in the SO. This feature had been shown by theoretical approaches by *Stommel* [1961] and *Rooth* [1982] and studies by *Marotzke and Willebrand* [1991] and *Stocker et al.* [1992] with ocean models of intermediate complexity. A similar response has been found due to seasonal change in SO forcing by orbital insolation variations [*Kim et al.*, 1998].

The change in meridional overturning circulation is reflected in meridional heat flux, which plays a significant role in the global climate system. Figure 4 shows the annual mean meridional heat flux globally and for the Atlantic and Pacific basins. Southward heat flux decreases for the global cross section, especially in the Southern Hemisphere, while northward heat flux significantly increases in all ocean basins. The decreased southward heat flux in the Southern

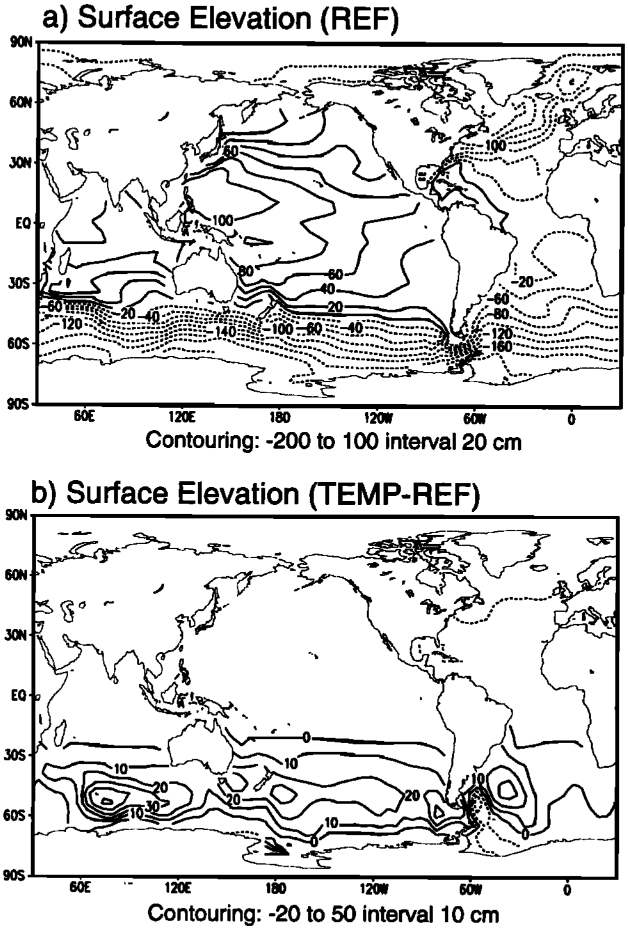

Figure 3. (a) Annual mean sea surface topography of REF and (b) its difference from TEMP. Units are in centimeters

Hemisphere, mainly contributed by the Pacific basin, is due to the decreased AABW outflow to the low latitudes (more positive values at 3000 m in Figure 2b) and consequently decreased upper layer return flow to the south (Figure 4c). The increased northward heat flux, especially in the Atlantic (~20% at 20°N), is driven by the increased NADW outflow and consequently increased upper layer return flow to the north. Such a response could explain the pattern of warming in the subpolar North Atlantic, which has been interpreted as indicating greater ocean heat transport in this basin [*Dowsett et al.*, 1996]. The North Atlantic warming response is not manifested in our run because the atmospheric forcing over the North Atlantic was kept the same as in the control.

4. Discussion and Conclusions

Using a realistic estimate of the atmospheric forcing changes with a fully three-dimensional OGCM, we investigated a possible reason why NADW overturning and outflow increased during the Pliocene by applying the concept that pole to pole density difference causes a change in the global thermohaline circulation. Although the modeled Pliocene response of the North Atlantic circulation is similar to the observed, our approach still begs the question of what causes the SO to change. For this we have to hypothesize a different sensitivity of North Atlantic and SO circulation to the inferred increase in Pliocene CO_2 levels from 350 to 400 ppm. It is reasonable to assume that the largest response to such a small CO_2 perturbation occurs in regions sensitive to snow and sea ice albedo. Since the SO has the largest area of sea ice in the world, the response to the CO_2 change may therefore be greatest in this region. This rationale justifies why the modification of the surface temperature was limited to the Southern Hemisphere in our experiment.

In previous studies, NADW overturning was simulated to decrease with increased CO_2 [*Mikolajewicz et al.*, 1990; *Manabe et al.*, 1991]. Southern Hemisphere overturning increased [*Manabe et al.*, 1991]. However, the data and our model results imply that this latter response did not occur in the Pliocene. Further greenhouse gas simulations with a different coupled model [*Hirst et al.*, 1996] suggest that *Manabe et al.*'s [1991] results are sensitive to parameterization of diffusion in the ocean model; that is, high latitude Southern Hemisphere warming occurs with the more

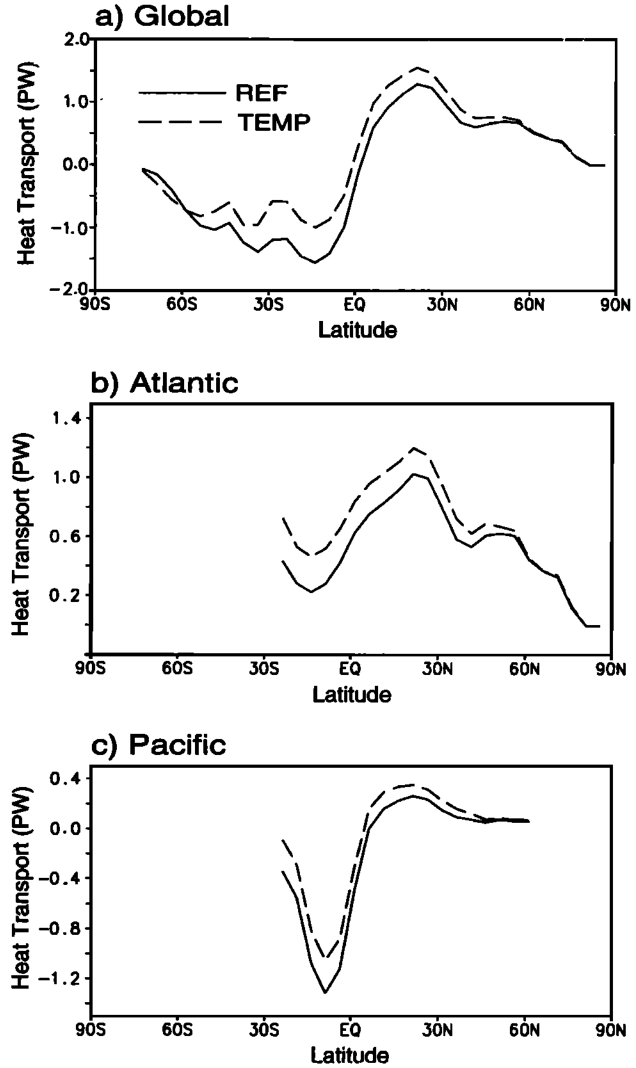

Figure 4. Zonally integrated meridional heat transport in (a) all ocean basins, (b) Atlantic basin, and (c) Pacific basin simulated in REF and TEMP. Units are in PW (1 x 10^{15} W).

realistic Gent and McWilliams parameterization [*Gent and McWilliams*, 1990]. Therefore, we do not consider *Manabe et al.*'s [1991] results from a transient CO_2 run as necessarily at variance with results that might be obtained for equilibrium runs with different model parameterizations. Although more work is obviously called for on this intriguing problem, our results suggest that there may be a relatively straightforward explanation for the enhanced overturn of NADW during the mid-Pliocene.

In conclusion, the increase of NADW production could be a consequence of Pliocene warming rather than a primary cause, because the rate of NADW overturning and outflow and consequent meridional heat transport are affected by changes in the SO. Although the temperature response to inferred higher Pliocene changes would occur everywhere, we postulate that the SO is most sensitive to the CO_2 changes because of the greater area of sea ice in this region. Although the model results require further testing (as do the pCO_2 data), this study provides insight into a plausible physical explanation for the observed increase in North Atlantic overturn in the mid-Pliocene.

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