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Impact of Geothermal Heating on the Global Ocean Circulation

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Abstract. The response of a global circulation model to a uniform geothermal heat flux of 50 mW m^{-2} through the sea floor is examined. If the geothermal heat input were transported upward purely by diffusion, the deep ocean would warm by 1.2°C. However, geothermal heating induces a substantial change in the deep circulation which is larger than previously assumed and subsequently the warming of the deep ocean is only a quarter of that suggested by the diffusive limit. The numerical ocean model responds most strongly in the Indo-Pacific with an increase in meridional overturning of 1.8 Sv, enhancing the existing overturning by approximately 25%.

1. Introduction

The general circulation of the ocean in climate models is generally considered to be forced by wind stress, heat and freshwater fluxes at the sea surface. However, there are other sources of energy that can directly or indirectly lead to motion that are normally ignored or argued to be insignificant. For example, tidal forcing is normally neglected in climate models and yet tidal energy might be an important source for diapycnal mixing [Munk and Wuncsh, 1998].

Another neglected energy source is the geothermal heat flux through the sea floor. This trickle of heat, which is due to the slow cooling of the solid earth, is estimated to have a typical value of 50 mW m^{-2} (1 mW = 10^{-3} Watts) on abyssal plains and up to 200 mW m^{-2} on mid-ocean ridges [Sclater et al., 1980; Kadko and Baross, 1995; Stein et al., 1995; Murton et al., 1999]. Even these peak values are small compared to typical values of air-sea heat fluxes, which are of order 100 W m^{-2}. The consequences of the geothermal heat flux have been considered in process and regional scale studies and found to modify local water properties and circulation [Joyce and Speer, 1987; Hautala and Riser, 1989; Speer, 1989; Helfrich and Speer 1995; Thompson and Johnson, 1996]. It is less clear whether geothermal heating influences the large-scale ocean circulation. Joyce et al. [1986] used a scaling argument to suggest that the weak background geothermal heating is insufficient to affect the vorticity balance of the abyssal circulation. In a companion study, Scott et al. [2000] examine the response of an idealized sector ocean model to geothermal heating. Here we examine the response of a global circulation model to a simple representation of the geothermal heat flux. In both studies we find substantial modification of the meridional overturning circulation.

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2. Numerical model and experiments

We compare two realizations of a numerical global circulation model which are configured and forced in identical ways except that the perturbation experiment has a steady and uniform heat flux of 50 mW m^{-2} applied at the ocean bottom, independent of depth. By examining the difference between these two runs (perturbation - control) we establish how the geothermal heat flux can modify the ocean circulation.

The model [Marshall et al., 1997] has 15 levels, with an upper layer thickness of 50 m, and a uniform horizontal resolution of 2.8 ° in both latitude and longitude (128 × 64 grid points). The topography is realistic at this resolution except for the exclusion of the Arctic. In all other respects the model is standard (configured as in Danabasoglu and McWilliams [1995]) including the use of the Gent and McWilliams parameterization [Gent and McWilliams, 1990] with a thickness diffusion coefficient of 1000 m^{2}s^{-1} and forced by observed monthly averaged fluxes and restoring to monthly averaged Levitus data. We use asynchronous time steps of 1 day and 1 hour for the thermodynamic and the momentum equations, respectively. The model is integrated for 3000 years of thermodynamic time, at which point the deep ocean has equilibrated with the surface boundary conditions.

The resulting ocean state is similar to that obtained in other models at this resolution, with some typical deficiencies; the Antarctic Circumpolar Current (ACC) transport is weak, 95 Sv (1 Sv = 10^6 m^3 s^{-1}), and deep water properties are too cool (~1–2 °C). However, since we are examining the difference between perturbation and control experiments we assume that our results are not dependent on these aspects. The global meridional overturning and peak northward heat transports are 22 Sv and 1.5 *PW* (1 PW = 10^{15} Watts), respectively.

3. Results

Before presenting our model results, we consider a purely diffusive response in a hypothetical flat bottom ocean; this response represents an extreme limit where advection plays no role. If we add 50 mW m^{-2} at the bottom and diffuse the heat vertically with a diffusivity of 5×10^{-5} m^2 s^{-1}, then over a 5 km water column we obtain a temperature anomaly

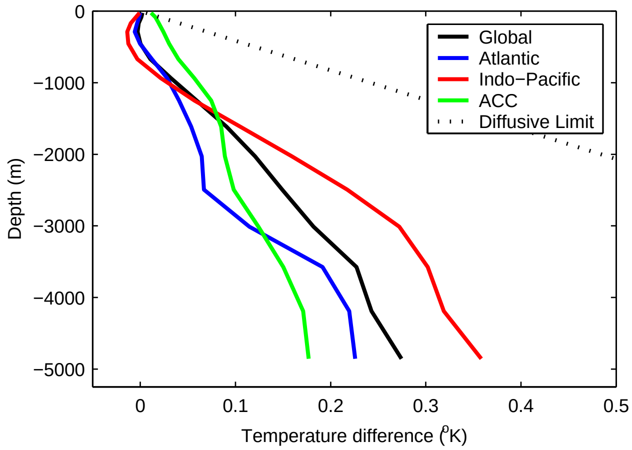

Figure 1. Horizontal mean temperature difference between geothermal and control runs. Shown are profiles for the global average, Atlantic basin and Indo-Pacific basins and the Southern Ocean (ACC). Also plotted, for comparison, is the theoretical profile in a purely diffusive limit.

that is linear with depth, approximately zero at the surface and +1.2°C at the bottom. In the context of deep water mass properties, this represents a substantial perturbation.

Fig. 1 shows the global horizontal mean temperature perturbation (solid black) obtained with the numerical model. The profile is close to linear, except for a slight minimum in the upper 300 m, and reaches a value of almost 0.3°C at 5000 m depth. This is only a quarter of the prediction from the diffusive limit (dotted curve, shown in part). Hence, the more significant portion of the heat transfer is accomplished through advection. There are regional variations in the perturbation temperature which we have measured by breaking the horizontal average into three non-overlapping regions: the Atlantic basin, north of the Cape of Good Hope, the Indo-Pacific basins, north of Cape Horn, and the Southern Ocean (the remaining model). The Indo-Pacific profile (red) has the largest perturbation, almost 0.4°C at the bottom, but is still far from the diffusive limit. The Atlantic (blue) has the most vertical structure, a narrow 1000 m band of high gradient accounting for most of the bottom temperature anomaly. The Southern Ocean (green) has the weakest perturbation with the most linear profile. These regional differences indicate that the circulation within these basins/regions responds differently, much as the regions play very different roles in the ocean circulation in general.

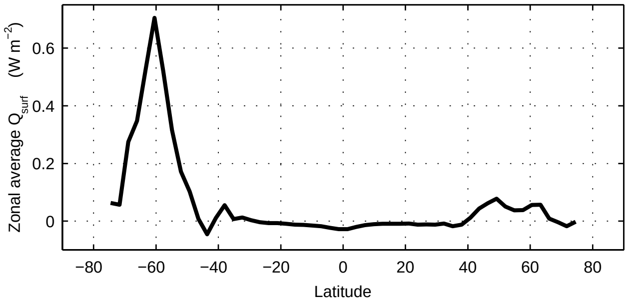

Figure 2. Zonally averaged surface flux anomaly. The global average is 50 mW m^{-2}, necessary to balance the geothermal heating.

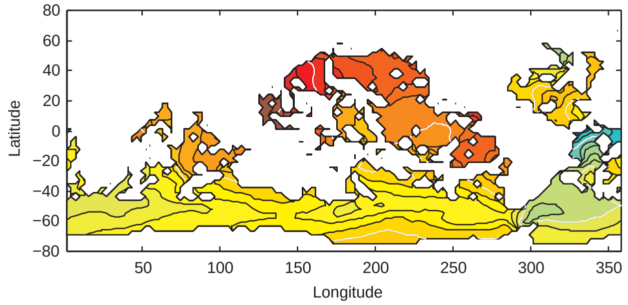

Figure 3. Difference map of potential temperature, θ, at a depth of 3010 m. Contour interval is 0.02°C. Peak value is North Pacific in 0.4°C.

All the profiles in Fig. 1 appear to approach zero at the surface. In our model the global mean SST anomaly is determined by the air–sea exchange coefficient (32 W m^{-2} K^{-1}), which balanced with the anomalous heat flux leads to a 1.5×10^{-3} °C warming. Fig. 2 shows the zonally averaged anomalous surface flux associated with the SST anomaly. Despite the uniformity of the applied geothermal heating, the majority of anomalous surface heat loss occurs in the Southern Ocean.

A horizontal map of temperature anomaly at a depth of 3010 m is shown in Fig. 3. The Pacific basin is clearly warmed the most with a peak of 0.5 °C and the entire ocean at this depth is generally warmer ($\sim$ 0.1 C°). There is, however, a region in the tropical Atlantic where the geothermal run is slightly cooler than the control. Later we will see that this is due to increased upwelling of cold water from depth.

Fig. 4 shows the anomalous meridional overturning circulation (MOC) for a) the globe, b) the Atlantic and c) the Indo-Pacific. The global anomalous MOC is dominated by the Indo-Pacific which shows a cross-equatorial transport of 1.8 Sv (1 Sv entering the Pacific across 35 °S), with southward flow above 3500 m and northward flow below. An overturning circulation acting in the presence of a large background temperature stratification transports heat meridionally. Here, deep anomalous flow transports cold water northward and anomalous mid-depth flow transports warmer water southward thus achieving an anomalous southward heat transport necessary to match the surface heat flux (Fig. 2).

The perturbation experiment must also transport heat vertically to connect the geothermal source to the surface. Fig. 5 shows vertical profiles of horizontally averaged vertical heat flux for a) the Indo-Pacific and Atlantic and b) the Southern Ocean. The contribution of the large scale circulation acting on the anomalous temperature difference (red curve) is upward in the Northern hemisphere; the upwelling Indo-Pacific water is anomalously warmed more than water at the same depth in the Atlantic. However, the contribution due to anomalous advection of a large-scale temperature distribution is downward (green curve) in the Northern hemisphere; this is due to the anomalous upwelling in the Pacific acting on the climatological temperature difference between Pacific and Atlantic. The net vertical heat transport is near zero in the upper layers (above 2000m) and downward in the deep layers.

The Southern Ocean is the primary region of upward anomalous heat transport (Fig. 5b) with an average net flux of around 200 mW m^{-2}, or four times larger than the geothermal heat flux. At depth (below 3000m), the anomalous circulation (green curve) accounts for most of the vertical heat transport. Despite the vigorous wind-driven overturning in the upper layers (above 2000m), the majority of vertical heat transport is due to parameterized fluxes; the strongly sloping isopycnals associated with the ACC allow the geostrophic eddy parameterization to efficiently transport anomalous heat vertically.

The overall picture, then, is one of net anomalous heat gain in the northern hemisphere due to little heat loss through the sea surface. A vigorous anomalous meridional overturning carries heat southward to the Southern Ocean where parameterized geostrophic eddies efficiently transport anomalous heat upward to the surface.

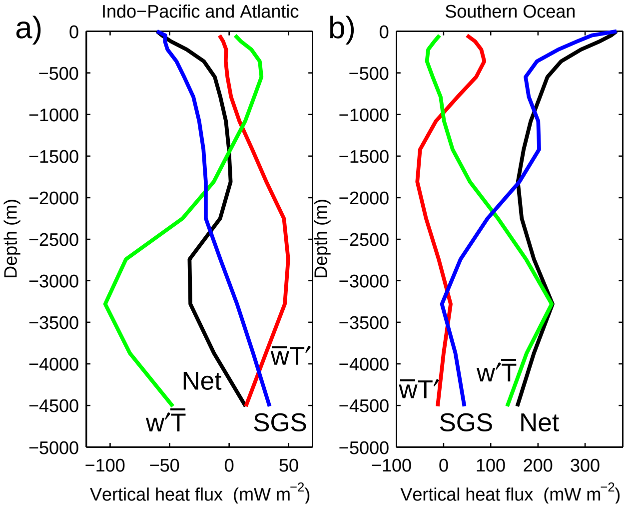

Figure 5. Horizontally averaged vertical flux anomaly for a) the Indo-Pacific and Atlantic and b) the Southern Ocean. In black is the net anomalous flux, in red is the component due to large scale advection of the temperature anomaly, $\overline{w}T'$, in green is the component due to anomalous advection, $w'\overline{T}$, and in blue is the component due to sub-grid scale parameterizations (SGS).

4. Discussion

We have shown that the addition of a uniform geothermal heat flux of 50 mW m^{-2} can lead to deep basin-scale temperature anomalies as large as 0.5 °C in the Indo-Pacific and on average about 0.3 °C. To explain this response we consider the direct effect of the background circulation on abyssal water that has been anomalously warmed. The properties of the water in the deep western boundary current (DWBC) in the far North Atlantic are dominantly set by surface boundary conditions. Water temperature rises as it passes near the bottom but the strong circulation leads to a relatively short residence time, essentially "flushing" the geothermally heated water out of the Atlantic at the depth of the deep western boundary current. In the Pacific, the deep inflow carries abyssal water that has already been anomalously warmed and hence has a warmer starting point before its more sluggish transit northward. This leads to an enhanced warming of the abyssal Pacific with respect to the other basins and also explains the vertical structure in the Atlantic (Fig. 1).

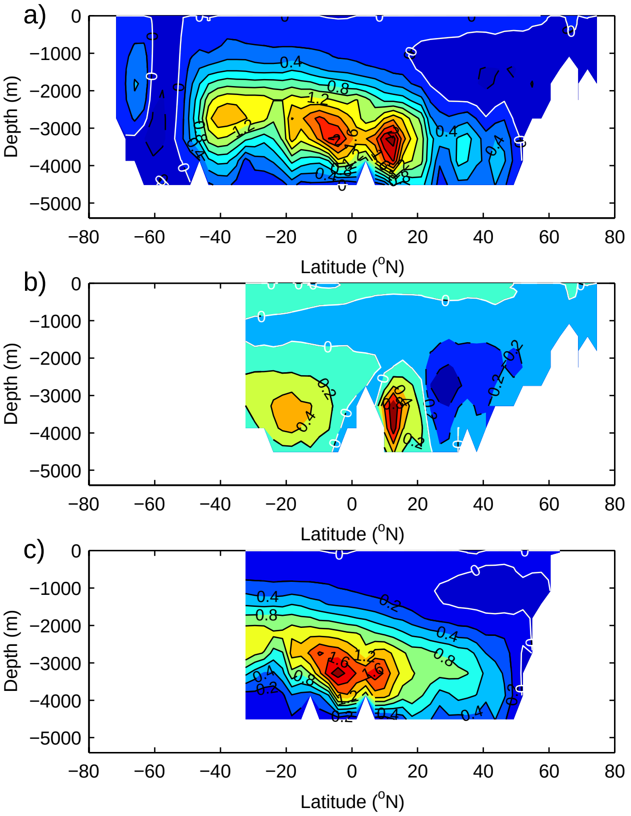

Figure 4. Difference in meridional overturning stream function for a) the globe, b) the Atlantic and c) the Indo-Pacific. Contour interval is 0.2 Sv. Positive numbers indicate clockwise circulation anomaly.

We also showed a strong meridional circulation anomaly in the Indo-Pacific basin essentially in the same sense as the existing circulation; that is, deep inflow and shallow outflow. This 1.8 Sv of transport constitutes a 25% increase in the Pacific overturning. It is not immediately obvious why the Pacific should respond so strongly, though we might speculate that it is connected to the sense of the thermohaline circulation; high latitude sinking in the North Atlantic and Antarctic and broad upwelling in the Pacific. The relatively sluggish northward flow in the deep Pacific allows the geothermal heat flux more time to act on water parcels. The Atlantic overturning has a much weaker and less coherent response. The North Atlantic Deep Water overturning cell is not influenced much by the geothermal heating partly due to the "flushing" mentioned above but also since it is generally disconnected from the bottom. The Antarctic Bottom Water cell is in contact with the bottom in all the basins and is therefore most influenced by the geothermal heating.

In the Southern Ocean, we noted a transition in mechanism for vertical heat transport. In contrast to the other oceans, the Southern Ocean is characterized by relatively large meridional gradients of temperature by virtue of wind-driven zonal channel dynamics. The combination of the meridional temperature gradients and the anomalous MOC results in particularly efficient vertical heat transport. Since this anomalous circulation does not reach the surface some other mechanism must achieve the vertical transport of anomalous heat in the upper water column. The wind-driven overturning in the ACC is associated with some of the strongest large-scale upwelling but in the absence of meridional gradients of anomalous temperature this circulation transports relatively little heat vertically. Instead, the geostrophic eddy parameterization [Gent and McWilliams, 1990] is able to efficiently flux anomalous heat upwards along the strongly tilted isopycnals.

The response that we describe is much larger than expected from naive comparisons of surface and geothermal heat fluxes, because heating a fluid from below is much more efficient in creating circulation than heating and cooling at the same level [Huang, 1999]. The changes in deep circulation have little impact on total meridional heat transport, but they might well influence the transports of carbon and other properties that have concentration maxima at depth. Changes in deep carbon and nutrient transports might lead to significant changes in outgassing rates and potentially in atmospheric CO_2 concentrations. Currently, model errors in deep temperature with respect to observations are probably larger than the changes reported here; nevertheless, the response in deep temperature is large compared to spatial and temporal variability. Moreover, the modifications in circulation change the temperature response qualitatively. We have used a uniform geothermal heat flux of 50 mW m^{-2} corresponding to the average flux away from ridges. Inhomogeneities in geothermal heat flux (for example, due to fast sea-floor spreading in the East Pacific) and enhanced fluxes along ridges could presumably lead to even stronger local responses.

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