

# Geothermal Heat Flux and its Influence on the Oceanic Abyssal Circulation and Radiocarbon Distribution

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Geothermal heating of abyssal waters is rarely regarded as a significant driver of the large-scale oceanic circulation. Numerical experiments with the Ocean General Circulation Model POTSMOM-1.0 suggest, however, that the impact of geothermal heat flux on deep ocean circulation is not negligible. Geothermal heating contributes to an overall warming of bottom waters by about 0.4 °C, decreasing the stability of the water column and enhancing the formation rates of North Atlantic Deep Water and Antarctic Bottom Water by 1.5 Sv (10%) and 3 Sv (33%), respectively. Increased influx of Antarctic Bottom Water leads to a radiocarbon enrichment of Pacific Ocean waters, increasing  $\Delta^{14}\text{C}$  values in the deep North Pacific from  $-269\text{‰}$  when geothermal heating is ignored in the model, to  $-242\text{‰}$  when geothermal heating is included. A stronger and deeper Atlantic meridional overturning cell causes warming of the North Atlantic deep western boundary current by up to 1.5 °C.

## 1. Introduction

Geothermal heating through the seafloor adds only a very small contribution to the oceanic energy budget. The average geothermal heat flux currently entering the oceans is estimated to be between 93 to 101  $\text{mW m}^{-2}$  ( $1 \text{ mW} = 10^{-3} \text{ W}$ ) (Pollack *et al.* [1993]). In comparison, sea surface turbulent and radiative heat fluxes can be hundreds to thousands of times larger (Huang [1999]). Geothermal heating is also a seemingly lesser player from the point of view of the oceanic mechanical energy budget. Of the 2 TW ( $1 \text{ TW} = 10^{12} \text{ W}$ ) of mechanical energy injected into the ocean by winds and tides, approximately 0.4 TW are directly available for turbulent mixing, that increases the available potential energy of the ocean and partly fuels the Meridional Overturning Circulation, or MOC (Huang [1999]; Kuhlbrodt *et al.* [2007]). In comparison, Huang [1999, 2002] found that the potential energy geothermal heating can generate is almost 10 times smaller: 0.05 TW. In spite of the small energies associated with geothermal heating, geothermal heat fluxes might have a measurable effect on the large-scale circulation and tracer distribution (Adkins *et al.* [2005]; Huang and Jin [2002]; Mullarney *et al.* [2006]; Roussenov *et al.* [2004]). The reason for this is that, unlike surface heat fluxes, geothermal fluxes, however small, are unidirectional, always contributing towards increasing the buoyancy of the deep ocean. In addition, geothermal heat sources are situated at the bottom, while buoyancy losses occur at the surface, a configuration which, according to Sandström's Theorem (Huang [1999]), supports a closed MOC.

Numerical studies with ocean circulation models of various complexities have found that oceanic geothermal heating can create bottom waters several tenths of a degree warmer than would exist in its absence, and help maintain a vigorous abyssal circulation (Mullarney *et al.* [2006]; Huang and Jin [2002]; Adcroft *et al.* [2001]). It has also been argued by Roussenov *et al.* [2004] that, since oceanic concentrations of natural radiocarbon, notably in the Pacific Basin, are strongly controlled by the export rate of Antarctic Bottom Water (AABW), geothermal heating should affect the global distribution of  $\Delta^{14}\text{C}$ .

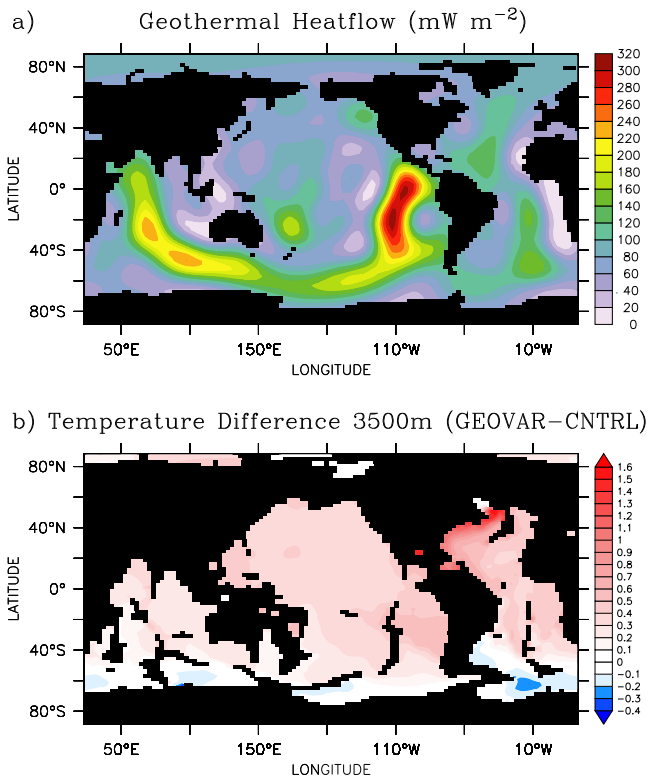
Adcroft *et al.* [2001] investigates the impact of geothermal heating on the simulated MOC of a global ocean general circulation model (OGCM) with realistic topography. They found a 25 % increase in the amount of AABW that enters the Indo-Pacific Ocean upon application of a uniform geothermal heat flux of  $50 \text{ mW m}^{-2}$ . In their study, the deep North Pacific region experiences the most pronounced warming, with a temperature rise of up to 0.4 °C. The study of Adcroft *et al.* [2001] used a spatially uniform geothermal heating source. However, geothermal heat fluxes vary considerably in space. The global compilation of geothermal heat fluxes of Pollack *et al.* [1993] shows that maximum values of up to  $325 \text{ mW m}^{-2}$  occur along the geologically young crests of the ocean ridges (Fig. 1(a)) and that, as the oceanic crust ages away from the ridges, geothermal heat fluxes decline to a background value of about  $50 \text{ mW m}^{-2}$ . According to this data set, the global mean of the geothermal heat flux through the seabed is  $101 \text{ mW m}^{-2}$ , which is about twice the value used by Adcroft *et al.* [2001].

In this article, we revisit the problem of assessing the impact that geothermal heating has on the MOC and the oceanic distribution of  $\Delta^{14}\text{C}$ . We use a global ocean climate model and compare results from experiments with and without geothermal heat fluxes.

These results of our study mainly confirm the findings made by Adcroft *et al.* [2001], reach, however, beyond them. Besides the circulation and temperature changes we obtain, which tend to be larger than theirs, we find an intensification of the Atlantic MOC by 10 % accompanied by a deepening of the NADW cell by up to 500 meters and a warming of the deep North Atlantic western boundary current by up to 1.5 °C. The most striking feature in our simulations is a cooling of the deep Weddell Sea by up to 0.3 °C caused by the geothermally enhanced convection in the Southern Ocean.

## 2. Model and experimental design

The model is an ocean-sea ice general circulation model coupled to an anomaly model of the atmospheric energy-moisture balance (Hofmann and Maqueda [2006]). The ocean model is the Modular Ocean Model, version 3.0, featuring a number of modifications outlined in Hofmann and Maqueda [2006]. Henceforth, this model will be referred to as the Potsdam version of MOM, version 1.0 (POTSMOM-1.0). The horizontal model grid has a uniform resolution of  $3^\circ \times 2^\circ$ . In the vertical, the grid consists of 29 levels with



**Figure 1.** (a) Geothermal heat fluxes of *Pollack et al.* [1993] (in  $\text{mW m}^{-2}$ ) and (b) Temperature difference at 3500 m between experiments GEOVAR and CNTRL averaged over the last 200 years of integration (in  $^{\circ}\text{C}$ ).

thickness increasing from 10 m at top to 405 m at the bottom. The model includes an empirical parameterization of bottom-enhanced vertical mixing (*Hasumi and Sugimotohara* [1999]), with a low background diffusivity of  $0.1 \text{ cm}^2 \text{ s}^{-1}$ . Isopycnic Redi stirring is set to  $1.25 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$ , while Gent-McWilliams thickness diffusivities vary between 0.275 and  $0.55 \times 10^7 \text{ cm}^2 \text{ s}^{-1}$ . The ocean model tracers are potential temperature, salinity and radiocarbon (*Toggweiler et al.* [1989]).

Three 5000-year experiments were run with this model. First, the control run (CNTRL) ignores geothermal heating. In the second run (GEOVAR), the non-uniform geothermal heat distribution of *Pollack et al.* [1993] (GEOVAR), shown in Fig. 1(a), was used. To test the effect of a homogeneous forcing a third experiment (GEOCONST) was conducted with a spatially uniform geothermal heat flux of  $101.0 \text{ mW m}^{-2}$ , the global average of the geothermal flux in GEOVAR. Results from the last 200 years of integration are presented here.

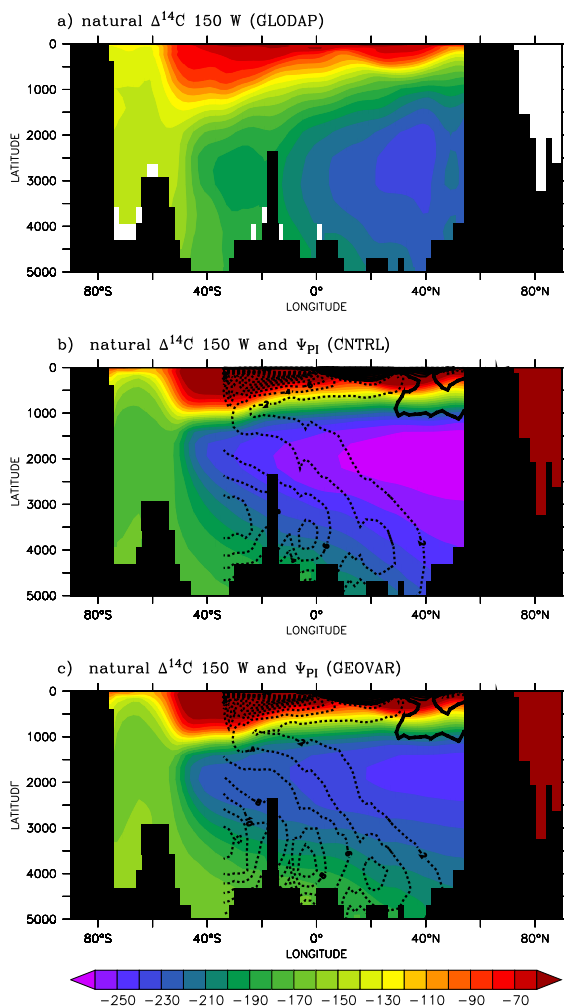
### 3. Results

In accord with the results of *Adcroft et al.* [2001] and the idealized experiments of *Scott et al.* [2001], our simulations show that, on global average, geothermal heating leads to a warming of waters below the main thermocline by a few tenths of degree Celsius ( $0.26 \text{ }^{\circ}\text{C}$  for GEOVAR and  $0.22 \text{ }^{\circ}\text{C}$  for GEOCONST). Parts of the cold newly formed AABW leave the deep Antarctic Circumpolar Current (ACC), move northward and enter the Atlantic and Indo-Pacific Basins at about  $40^{\circ}\text{S}$ . As this bottom water masses flow further

north, they gradually gain heat from the geothermal sources at the sea floor.

At a depth of 3500 m, the warming in the Pacific Ocean and in the eastern Atlantic Ocean simulated by GEOVAR amounts to 0.3 to 0.4 degrees (see Fig. 1(b)). Far away from the strong geothermal sources of the mid-ocean ridges, the warming patterns calculated in experiment GEOCONST are very similar to those of GEOVAR. This is explained by the fact that geothermal warming is an integrative process: whether it occurs progressively, as a result of a uniform heat flux (GEOCONST), or discontinuously, as waters move throughout hot and cold spots (GEOVAR) is immaterial, as long as the total heat absorbed is the same in both cases.

Results from GEOVAR and GEOCONST qualitatively depart from those discussed in *Adcroft et al.* [2001] in two remarkable ways. Firstly, the deep Southern Ocean, with the exception of the Amundsen and Bellingshausen Seas, experiences a cooling of up to  $-0.3 \text{ }^{\circ}\text{C}$ . Secondly, the deep western boundary current in the North Atlantic warms by between  $0.9 \text{ }^{\circ}\text{C}$  and  $1.5 \text{ }^{\circ}\text{C}$ . Salinity changes of about  $-0.1$



**Figure 2.** (a) Observed natural  $\Delta^{14}\text{C}$  (in  $\text{‰}$ ) at  $150^{\circ}\text{W}$  from the Global Ocean Data Analysis Project, GLODAP (*Key et al.* [2004]). (b) Color: as in (a) but simulated in CNTRL. Contours: 200-year mean of Indo-Pacific meridional overturning transport north of  $34^{\circ}\text{S}$  (in Sv) in CNTRL. The contour interval is 2 Sv. (c) As in (b) but simulated in GEOVAR.

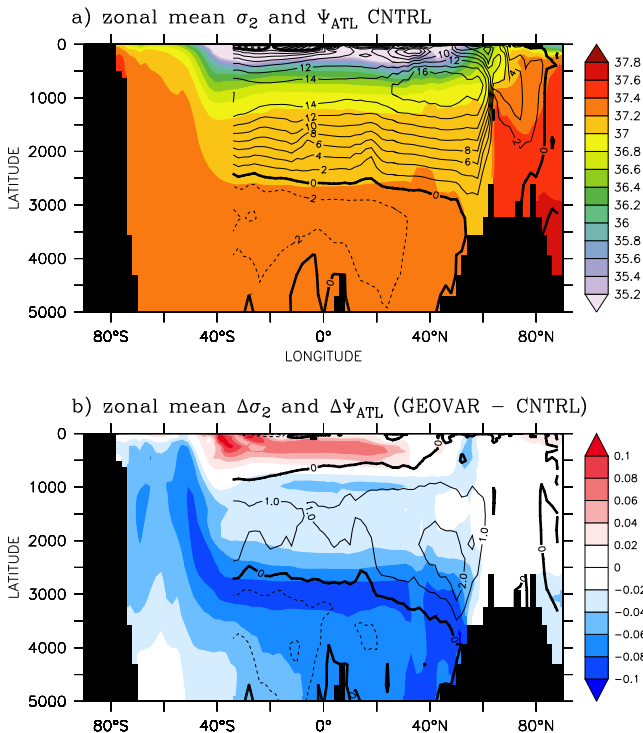
psu in the Southern Ocean and +0.1 psu in the North Atlantic accompany these temperature changes (not shown).

The seemingly paradoxical cooling of the deep Southern Ocean in GEOVAR and GEOCONST is caused by an intensification of open ocean deep convection in these simulations. In all three model experiments, the occurrence of open ocean deep convection in the Southern Ocean is a prevailing feature. The main area of convection, with winter mixed layers often stretching down to the seafloor, sits astride the eastern limb of the Weddell Sea Gyre, and is centered around the Greenwich Meridian at 65°S. Smaller convection areas occur over the Cosmonaut Sea and the western Ross Sea, off Cape Adare. The convective activity in the Weddell Sea exhibits a striking inter-decadal variability. Experiment CNTRL repeatedly reveals the occurrence of open deep convection covering a maximum area of about  $6 \times 10^5$  km<sup>2</sup> and lasting for about 20 years followed by a convection free period for about 30 years. In case of GEOCONST and GEOVAR the area of this intermittent deep convection almost triples, while the time period of the convective activity increases by a factor of two (not shown). We do not yet fully understand the factors that control the frequency and intensity of the intermittent convection events, but, clearly, the more intense deep convection in GEOVAR and GEOCONST gives rise to higher rates of formation and export of AABW (Fig. 2 b and c). Convection episodes are associated with strong sea ice melt and the formation of embayments in the sea-ice cover that, in the Weddell Sea, occasionally close into a polynya, a feature also captured in the modeling study of *Goosse and Fichefet* [2001], although their polynya reappeared every winter. While the formation of recurrent polynyas in the Weddell and Cosmonaut Seas is well documented (e.g.,

*Moore et al.* [2002], *Geddes and Moore* [2007]), the decadal cyclicity of the simulated polynyas and associated convection episodes is probably unrealistic, however, can not be entirely excluded because of the paucity of observational data.

The impact of geothermal heating on AABW circulation is most prominent in the Indo-Pacific Ocean. In CNTRL, the northbound flow of AABW at 30°S is 10 Sv, while in GEOVAR and GEOCONST this flow increases by about 40 % thus leading to a more vigorous ventilation of the deep North Pacific compared to CNTRL (Fig. 2 b and c). This result is in qualitative agreement with *Adcroft et al.* [2001], who, with a mean geothermal heat flux equal to roughly half ours, reported an increase of 25% in deep AABW flow into the Indo-Pacific. A larger export of AABW is expected to decrease the age of North Pacific waters, and this is borne out by the fact that the deep  $\Delta^{14}\text{C}$  minimum of  $-269$  ‰ in CNTRL, increases in GEOVAR to  $-242$  ‰ (Fig. 2 b and c), a value that compares well with recent observational data *Key et al.* [2004] (Fig. 2 a).

The warming of the deep western boundary current shown in Fig. 1(b) is the manifestation of a deepening of the North Atlantic Deep Water (NADW) overturning cell by 300 to 500 m, which also causes an increase in salinity and in  $\Delta^{14}\text{C}$  (by up to 14 ‰ not shown). This deepening results from the increased contrast between the density of newly formed NADW and that of the AABW reaching the North Atlantic, which is as much as  $0.1$  kg m<sup>-3</sup> lighter in GEOVAR than in CNTRL (Fig. 3b). Ultimately, upwelling of this lighter water in the Southern Ocean creates a stronger meridional density contrast in GEOVAR compared to CNTRL, and a concomitant increase of 1.5 Sv (10 %) in the strengths of the Atlantic MOC maximum and 30°S outflow.



**Figure 3.** (a) Color fill of 200-year mean of zonally averaged  $\sigma_2$  (in kg m<sup>-3</sup>) and contours of 200-year mean of meridional overturning transport (in Sv) in the Atlantic Ocean north of 34 S for CNTRL. (b) As in (a), but difference between GEOVAR and CNTRL.

## 4. Conclusions

Numerical experiments with a coarse resolution ocean-sea ice model indicate that geothermal heat fluxes are a non negligible forcing of the ocean circulation, substantially strengthening the AABW and NADW overturning cells. Geothermal heating stimulates convective activity in the Southern Ocean and, consequently, increases the rate of formation and export of AABW by 33 %. While the recurrent open ocean convection that produces most of the AABW in the model has rarely been observed, there is indirect evidence that sporadic thermobaric convection could indeed substantially contribute to the formation of AABW (*McPhee* [2003]). This enhanced production of AABW leads to a better representation of the distribution of natural  $\Delta^{14}\text{C}$ . In a recent study, *Matsumoto and Key* [2004] pointed out that, in ocean models with vertical diffusivities as low as observed, such as ours, the deep ocean will become less ventilated, and natural  $\Delta^{14}\text{C}$  values will thus be underestimated. Here we have shown that the inclusion of geothermal heat fluxes can partly correct this pathological behavior. We have also reason to believe that the simulation of CFCs (e.g. *Broecker et al.* [1999]), and maybe other tracers, will as well be improved thanks to the enhanced ocean ventilation afforded by the inclusion of geothermal heat fluxes. Geothermal heat fluxes also intensify by around 10 % both the maximum of the Atlantic MOC and the outflow of NADW into the Southern Ocean, while the penetration depth of NADW in the North Atlantic is increased from 2500 m to a more realistic 3000 m.

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