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Idealised modelling of ocean circulation driven by conductive and hydrothermal fluxes at the seabed

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ABSTRACT

Geothermal heating is increasingly recognised as an important factor affecting ocean circulation, with modelling studies suggesting that this heat source could lead to first-order changes in the formation rate of Antarctic Bottom Water, as well as a significant warming effect in the abyssal ocean. Where it has been represented in numerical models, however, the geothermal heat flux into the ocean is generally treated as an entirely conductive flux, despite an estimated one third of the global geothermal flux being introduced to the ocean via hydrothermal sources.

A modelling study is presented which investigates the sensitivity of the geothermally forced circulation to the way heat is supplied to the abyssal ocean. An analytical two-dimensional model of the circulation is described, which demonstrates the effects of a volume flux through the ocean bed. A simulation using the NEMO numerical general circulation model in an idealised domain is then used to partition a heat flux between conductive and hydrothermal sources and explicitly test the sensitivity of the circulation to the formulation of the abyssal heat flux. Our simulations suggest that representing the hydrothermal flux as a mass exchange indeed changes the heat distribution in the abyssal ocean, increasing the advective heat transport from the abyss by up to 35% compared to conductive heat sources. Consequently, we suggest that the inclusion of hydrothermal fluxes can be an important addition to course-resolution ocean models.

1. Introduction

Geothermal fluxes through the ocean floor have only recently been considered as a significant factor influencing ocean circulation. The global average of the geothermal heat flux into the oceans is estimated by Davies and Davies (2010) to be 105.4 mW m^{-2}. At first glance it seems that neglecting these fluxes could be justified, as net heat fluxes at the surface can be a thousand times greater in magnitude. However, this is not an entirely meaningful comparison. The conductive component of the geothermal heat flux is always directed upwards (e.g. Adcroft et al., 2001; Hofmann and Morales Maqueda, 2009; Emile-Geay and Madec, 2009), whereas the surface fluxes can be positive or negative, leading to cancellations on a global scale. Additionally, the dense water masses acted upon by geothermal fluxes are rarely in contact with the surface of the ocean. The surface area of outcropping Antarctic Bottom Water, for example, is about one thousand times less than the seabed contact area, thus making surface integrals of heat fluxes at the upper and lower boundaries comparable (Emile-Geay and Madec, 2009).

An increasing interest in the impact of geothermal heating on the large scale circulation in recent years has led to the process being modelled at the global scale. It had previously been studied at regional and basin scales (e.g. Stommel, 1982; Joyce and Speer, 1987; Speer, 1989; Thompson and Johnson, 1996), but the companion papers of Adcroft et al. (2001) and Scott et al. (2001) were the first to consider geothermal heat fluxes as an influence on the global circulation. Their modelling experiments, using a uniform seabed heat flux of 50 mW m^{-2}, showed average abyssal temperature rising by 0.3 °C and a 25% increase in the Pacific meridional overturning. This result is reinforced by consistent findings in the experiments of Hofmann and Morales Maqueda (2009), Emile-Geay and Madec (2009), Urakawa and Hasumi (2009), Mashayek et al. (2013) and Downes et al. (2016). Hofmann and Morales Maqueda (2009) used spatially varying geothermal heat fluxes based on the dataset of Pollack et al. (1993) to obtain an average abyssal temperature rise of about 0.4 °C and a 33% increase in the formation rate of Antarctic Bottom Water. Emile-Geay and Madec (2009) followed a different method, using the formula of Stein and Stein (1992) relating heat flow to crustal age and the high-

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resolution dataset of crustal age from Müller et al. (1997), to produce similar results. In another modelling study (Piecuch et al., 2015) found that inclusion of geothermal heating raised the global mean sea level trend, showing that its effects can be seen throughout the entire water column.

The geothermal heat flux into the ocean has two components: conductive and advective (or hydrothermal). There is compelling modelling evidence to suggest that geothermal heating is an important contributor to global circulation, but all of the experiments mentioned above employ an entirely conductive heat flux. This is a potentially serious shortcoming since hydrothermal fluxes have a far from negligible contribution to the geothermal heating of the global ocean. The global flow of hydrothermal fluids in and out of the crust has been estimated at up to 0.35 Sv (Elderfield and Schultz, 1996). This is equivalent to one third of the global ocean's freshwater input from rivers and surface runoff, a process which, like hydrothermal activity, has a strong buoyancy signature. Towards the young crust on the flanks of mid-ocean ridges there is a discrepancy between predicted and observed geothermal heating (Anderson and Hobart, 1976), known as the heat flow anomaly. As the observational methods measure conductive heat, this discrepancy can be explained by the co-existence of conductive heating and hydrothermal circulations, the latter being dominant in areas where the crust is highly permeable and pathways exist which allow water to flow in and out of the ocean through the seabed (e.g. Harris and Chapman, 2004). Stein and Stein (1994) compare the heat flow model of Stein and Stein (1992) to observations and, by studying the heat flow anomaly, conclude that more than half of the geothermal heat flux through 10 million year old crust is advective in nature (i.e. hydrothermal) and that the proportion increases as the crust becomes younger. They estimate that 34% of global heat flow is hydrothermal, which is in agreement with the earlier estimate of Sclater et al. (1980) that one third of the total heat entering the ocean from below does so hydrothermally. It seems reasonable to conjecture that this amount of advective flux must have an impact on the abyssal circulation different from that of a purely conductive heat flux.

The purpose of the work presented here is to gain understanding, in a modelling context, of the importance of hydrothermal flows in geothermally driven circulations at the scale of an ocean basin. To this end, we have introduced a physically consistent formulation of hydrothermal fluxes in the primitive equation ocean model NEMO (Madec, 2008) and conducted a number of numerical experiments to characterise the relative importance of hydrothermal and conductive heat fluxes. To our knowledge, this is the first time such hydrothermal flows have been implemented in an ocean circulation model of this type.

The rest of the paper is organised as follows. In Section 2, we present an analytical model used to assess the impact of a neutrally buoyant flux through the seabed on an otherwise motionless bottom layer. We then move on to more complex, but still idealised, formulations that include heat fluxes in Section 3. In this section, we describe the implementation of conductive and hydrothermal fluxes in the NEMO model and how the net geothermal flux is partitioned between the two. In Section 4 results from a series of numerical experiments are presented and interpreted with a focus on the differences between the two extremes, where the heat source is either entirely conductive or entirely hydrothermal in nature. In Section 5, we discuss the findings of our experiments, their relevance to the real world and what implications our results may have on future modelling.

2. Motivation: circulation driven by vertical volume fluxes through the seabed

Mass or volume flux through the seabed has not been implemented in ocean modelling to date, so it is important to detail this process here. We take a simple first look at the effects of adding a flux of volume (imposed as a velocity per unit length) through the seabed using the linearised steady state shallow water equations. We assume that all properties in the y-direction are constant, so $\frac{\partial}{\partial y} = 0$. In the vertical, $z = 0$ coincides with a flat seabed and the undisturbed free surface of the abyssal mixed layer is located at $z = \mathscr{H}$, so that the thickness of the abyssal mixed layer is in general $h(x) = \mathscr{H} + \eta(x)$, where $\eta(x)$ is a small perturbation.

The system is then described by the frictional geostrophic equations

$$-fv = -Ru - g'\frac{\partial h}{\partial x} \tag{1a}$$

$$fu = -Rv \tag{1b}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0, \tag{1c}$$

with boundary conditions

$$w(x, h(x)) = u\frac{\partial h}{\partial x} \tag{2a}$$

$$w(x, 0) = w_b \tag{2b}$$

$$u, \eta \to 0 \quad \text{as } x \to -\infty, \tag{2c}$$

where u, v and w are the velocities in the x-, y- and z-directions, respectively. The constants R and g' are a Rayleigh friction coefficient and the reduced gravity in the layer, respectively. The prescribed function $w_b(x)$ describes the distribution of the vertical fluid velocities through the seabed boundary, and should be constructed so as to ensure that the domain conserves its volume (i.e. that the integral of w_b across the whole domain is zero).

Since the problem is linear, we arrive at the solutions for u, v, h and w being

$$u(x) = \frac{\int_{-\infty}^{x} w_b(\xi)\,d\xi}{h(x)} \tag{3a}$$

$$v(x) = -\frac{f}{R}u(x) \tag{3b}$$

$$h(x) = \sqrt{\mathscr{H}^2 - \frac{2(f^2 + R^2)}{Rg'}\int_{-\infty}^{x}\left(\int_{-\infty}^{\zeta} w_b(\xi)\,d\xi\right)d\zeta} \tag{3c}$$

$$w(x, z) = w_b(x) - \left(w_b(x) + \frac{(f^2 + R^2)u^2}{Rg'}\right)\frac{z}{h}. \tag{3d}$$

This solution shows that the flow, u, along the x direction results from the horizontal divergence caused by the discharge and recharge of water through the seabed (3a), while the horizontal cross flow, v, is a balance between the components of friction and the Coriolis force in the y direction (3b). Since we assume there is no stratification within the bottom mixed layer, the horizontal flow is vertically uniform (from the Taylor–Proudman theorem) and the vertical velocity varies linearly from its value at the seabed w_b to that at the top of the mixed layer, which is in general non-zero to ensure that there is no flow across this interface. The shape of the interface itself is determined by the shape of the velocity function w_b.

To illustrate the resulting solutions, we choose the function w_b to be symmetric, with an upwards flow centred at $x = 0$ flanked by two areas of downward flow. This is designed to mimic a hydrothermal vent field surrounded by porous seabed through which the water re-enters the crust. To avoid discontinuity in the boundary function and ensure volume is conserved, we set