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Sensitivity of contemporary sea level trends in a global ocean state estimate to effects of geothermal fluxes

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ABSTRACT

Geothermal fluxes constitute a sizable fraction of the present-day Earth net radiative imbalance and corresponding ocean heat uptake. Model simulations of contemporary sea level that impose a geothermal flux boundary condition are becoming increasingly common. To quantify the impact of geothermal fluxes on model estimates of contemporary (1993–2010) sea level changes, two ocean circulation model experiments are compared. The two simulations are based on a global ocean state estimate, produced by the Estimating the Circulation and Climate of the Ocean (ECCO) consortium, and differ only with regard to whether geothermal forcing is applied as a boundary condition. Geothermal forcing raises the global-mean sea level trend by 0.11 mm yr^{-1} in the perturbation experiment by suppressing a cooling trend present in the baseline solution below 2000 m. The imposed forcing also affects regional sea level trends. The Southern Ocean is particularly sensitive. In this region, anomalous heat redistribution due to geothermal fluxes results in steric height trends of up to ± 1 mm yr^{-1} in the perturbation experiment relative to the baseline simulation. Analysis of a passive tracer experiment suggests that the geothermal input itself is transported by horizontal diffusion, resulting in more thermal expansion over deeper ocean basins. Thermal expansion in the perturbation simulation gives rise to bottom pressure increase over shallower regions and decrease over deeper areas relative to the baseline run, consistent with mass redistribution expected for deep ocean warming. These results elucidate the influence of geothermal fluxes on sea level rise and global heat budgets in model simulations of contemporary ocean circulation and climate.

1. Introduction

Due to the conductive cooling of the oceanic lithosphere and turbulent convection over hydrothermal vents, the solid Earth imparts heat to the ocean at a rate of 35–36 TW (1 TW ≡ 10^{12} W) or ∼100 mW m^{-2} (1 mW ≡ 10^{-3} W) on average (Pollack et al., 1993; Davies, 2013). Whereas the oceanographic literature is replete with studies of the oceanic response to various types of surface forcing (e.g., Forget et al., 2015a), there have been far fewer works on the ocean's adjustment to the geothermal fluxes along its bottom boundary, which is surprising, since it is not small compared to the energy imbalance of the ocean (Wunsch and Heimbach, 2014) or the planet (Allan et al., 2014).

Earlier investigations focus on regional ocean processes about localized geothermal sources. Stommel (1982), Joyce and Speer (1987), and Speer (1989) consider the oceanic response to geothermal forcing by hydrothermal vents along the East Pacific Rise. They establish under what conditions the anomalous hydrothermal input behaves as a passive tracer, advected by background flow, or an active one, spreading westward as a "β plume".

Later papers target larger scales, considering geothermal forcing in the context of circulation and climate more broadly. Adcroft et al. (2001), Scott et al. (2001), and Emile-Geay and Madec (2009) use circulation models to explore the influence of geothermal flow on the abyssal circulation. These authors detail how geothermal fluxes impact the steady state meridional overturning circulation, deep stratification, and meridional transport of heat.

Motivated by the need to understand current trends and anticipate future changes in global sea level (important for adaptation efforts), recent studies have begun to account for geothermal fluxes in estimates of the global-mean steric sea level balance. Griffies and Greatbatch (2012), Hieronymus and Nycander (2013), and Palter et al. (2014) suggest that geothermal fluxes contribute 0.08–0.11 mm yr^{-1} to the steady state global sea level budget. These estimates are

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derived by averaging the product of the local thermal expansion coefficient and the rate of geothermal flow over the global ocean floor. Such values are not negligible compared to the rate of global-mean sea level rise (2.6–2.9 mm yr^{-1}) observed by satellite altimeters over the last couple decades (Watson et al., 2015).

The aforementioned studies elucidate the *steady state* ocean response to geothermal forcing. However, increasingly common are *transient* model simulations of contemporary ocean climate and sea level change that include geothermal forcing as a boundary condition (e.g., Griffies et al., 2014). Yet, to the best of our knowledge, there has been no systematic study exploring the impact of incorporating geothermal forcing in these relatively short (e.g., decadal) transient model runs, and so various questions remain, for example,

- What is the nature of the modeled ocean response to geothermal fluxes?
- Does the geothermal forcing affect regional patterns of sea level change?
- How is geothermal input redistributed by ocean transport processes?
- Is there any impact on surface heat and freshwater exchanges with the atmosphere?

We address these questions using two 20-yr model simulations that are identical in all respects (initial conditions, atmospheric state, internal model parameters, etc.) except that the first simulation (the *baseline*) does not include a geothermal flux boundary condition, whereas the second one (the *perturbation*) does incorporate this type of forcing along the ocean floor. We infer the impact of the geothermal fluxes by taking the difference between the two solutions. This study is distinct from previous work on the equilibrium response in that we consider transient behavior over a short interval. While we acknowledge that our results may be sensitive to the particular study period and that different conclusions might follow from consideration of longer periods, our findings are relevant to efforts to simulate global and regional sea level changes over the modern altimetric period (Griffies and Greatbatch, 2012; Storto et al., 2015).

The remainder of this paper is structured as follows: in Section 2, we outline our numerical model framework, introducing the two solutions to be compared; in Section 3, we present our main findings from the model intercomparison, including results from a passive tracer simulation designed to elucidate the transport pathways and the dynamical influence of geothermal fluxes; finally, in Section 4, we summarize our findings and discuss their implications.

2. Material and methods

2.1. Ocean state estimate and the baseline solution

Our framework is a dynamically and kinematically consistent estimate of the global ocean circulation and sea ice state over 1992–2011 produced by the Estimating the Circulation and Climate of the Ocean (ECCO) consortium (Wunsch et al., 2009; 2013; Forget et al., 2015a). Broadly speaking, the ECCO state estimates represent numerical solutions to an evolved formulation of the Massachusetts Institute of Technology general circulation model (Marshall et al., 1997), adjusted to myriad ocean data (e.g., Wunsch et al., 2013). Based on the adjoint model (Marotzke et al., 1999; Heimbach et al., 2005), iterative adjustments are made to initial conditions (i.e., temperature and salinity), surface boundary conditions (i.e., the atmospheric state), as well as internal model parameters (e.g., spatially varying diffusion coefficients; see Forget et al., 2015b) so as to minimize the misfit (or cost or objective function) between the model and data.

The state estimate used in this study (ECCO version 4, release 1; hereafter simply referred to as the baseline solution) differs from earlier ECCO configurations (e.g., Wunsch et al., 2009), for example, in terms of horizontal grid, vertical coordinate, parameterization choices, and surface boundary conditions. Forget et al. (2015a) and Forget and Ponte (2015) document the innovations in ECCO version 4 and the baseline solution in great detail, and so a brief description is sufficient in this paper. The model setup solves the primitive equations with a nominal horizontal spacing of 1° and 50 vertical levels. Also used are interactive dynamic and thermodynamic models for sea ice and snow (Losch et al., 2010) along with parameterizations for effects occurring on small spatial scales (Redi, 1982; Gaspar et al., 1990; Gent and McWilliams, 1990; Duffy et al., 1999). This Boussinesq solution employs a nonlinear free surface and real freshwater exchanges along with a rescaled (r^*) vertical coordinate (Adcroft and Campin, 2004; Campin et al., 2004, 2008). Bulk formulae (Large and Yeager, 2004) are used for the surface boundary conditions (except for the momentum equations where wind stress is specified directly). Atmospheric state variables are first taken from the Interim European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-Interim) described by Dee et al. (2011) and adjusted based on procedures outlined above. Note that, while it has been adjusted to observations through the iterative optimization, this estimate constitutes a freely running forward model solution. Also, given that the model is Boussinesq in formulation, we apply the spatially uniform, temporally varying Greatbatch (1994) correction to the sea level and bottom pressure fields. This post hoc correction consists of “adding back” to the diagnosed sea level and bottom pressure fields, where bottom pressure is converted to units of water thickness, the time series of the global mean steric height inferred from the estimated density field.

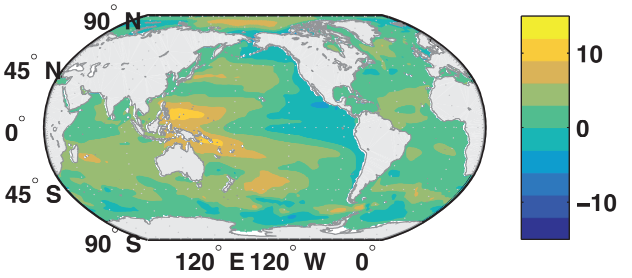

Fig. 1. Eighteen-year (1993–2010) trends in sea level η (mm yr^{-1}) from the baseline solution without geothermal forcing. Since the ocean model conserves volume rather than mass, the spatially uniform correction due to Greatbatch (1994) has been applied.

Fig. 1 shows a map of baseline sea level (η) trends over 1993–2010 as a context for what follows. While these trends and their correspondence to observations are discussed in detail elsewhere (Forget et al., 2015a; Forget and Ponte, 2015), we briefly consider some salient aspects. The baseline solution gives a global-mean η trend of 2.6 ± 0.4 mm yr^{-1}, which is in agreement with altimetric data that suggest that global-mean η rose at a rate of 2.6–2.9 mm yr^{-1} from 1993 to mid-2014 (Watson et al., 2015). Mass addition and thermal expansion give 2.1 ± 0.4 and 0.5 ± 0.1 mm yr^{-1} to the baseline trend, respectively (not shown); these contributions are similar to recent observational assessments for overlapping time periods (e.g., Church et al., 2013; von Schuckmann et al., 2014; Llovel et al., 2014; Purkey et al., 2014).

The estimate also shows regional deviations from the global-mean η trend of up to ± 10 mm yr^{-1} (Fig. 1). These spatial variations owe mostly to steric height (η_ρ) changes rather than bottom pressure (p_b) changes (not shown), in accord with Stammer et al. (2013), who show strong correspondence between η and η_ρ trend maps over 1993–2010 based on altimetric data and *in situ* measurements, respectively. (For clarity, we will quote p_b values in equivalent thickness units rather than the traditional pressure units.) Some of the most noteworthy regional η features along the western tropical Pacific and Indian Oceans are thought to reflect the baroclinic ocean response to wind stress by means of long Rossby waves (cf. Timmermann et al., 2010; Merrifield, 2011; McGregor et al., 2012; Forget and Ponte, 2015).