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Effect of topographic barriers on the rates of available potential energy conversion of the oceans

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ABSTRACT

Determining the energy budget of the oceans requires evaluating the rates of available potential energy conversion in the circulation. Calculating these conversion rates depends upon the definition of an appropriate "reference" state of the density field, but this definition is complicated in the oceans by the presence of bottom topography. The trapping of dense fluid by topographic barriers means that there are multiple definitions for the reference state. The approach taken in this paper is to examine the sensitivity of the available potential energy budget to several methods for defining the reference state. The first method makes allowances for restrictions imposed on the flow by topography, however it is computationally intensive. The second method is proposed as an inexpensive alternative to the first. These new methods are used to evaluate the energy budget of a model overturning circulation maintained by surface buoyancy forcing. The results are compared with those obtained from two existing methods; one which employs an adiabatic resorting procedure ignoring topography, and one which uses a reference profile developed from the horizontal average of the density field. In our model, the rates of available potential energy conversion are insensitive to the reference state definition providing the reference state is developed from an adiabatic resorting of the domain. These results suggest that any of the adiabatic resorting methods proposed here would be sufficient to evaluate the rates of energy conversion in the ocean.

1. Introduction

Topography in the oceans acts to constrain flows on a range of scales. One general effect is that horizontal density differences in the flow tend to be larger than in the absence of such topography (e.g., Stewart et al., 2011). Moreover, bottom topography acts to isolate water masses below the level of a connecting sill, and can thus support particularly large horizontal density differences at those levels (Bryden and Nurser, 2003). Hence topography can increase the potential energy of the water column, although some of this potential energy may not be available to the circulation due to topographic constraints. Current methods for calculating the energy budget of the oceans recognize the significant influence of basin hypsometry on volumes of different densities (e.g., Oort et al., 1994; Huang, 2005; Hughes et al., 2009; Roquet, 2013), but do not account for restrictions or barriers imposed on the circulation by topography. Here we ask the question of whether or not failing to account for topographic barriers affects the rates of energy conversion.

The meridional overturning circulation of the oceans, which serves as a motivation for this paper, is one example where an understanding of the oceanic energy budget generates valuable insight into the dynamics governing the flow. This overturning circulation, which contributes to the poleward transport of heat that maintains the thermal state of the climate system (Fasullo and Trenberth, 2007), is thought to result from an interplay between surface buoyancy forcing, wind-driven upwelling and turbulent mixing (Speer et al., 2000; Kuhlbrodt et al., 2007; Morrison et al., 2011). The forces that sustain the mean flow (buoyancy and surface wind stress) appear to supply mechanical energy (available potential energy and kinetic energy) at comparable rates (Oort et al., 1994; Saenz et al., 2012). A strong coupling of the forcing has inhibited the development of a consensus regarding the relative roles of wind and buoyancy in the momentum and energy balances of the oceans (Toggweiler and Samuels, 1998). In particular, there has been disagreement as to whether surface buoyancy fluxes can contribute to the mechanical energy budget and to

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driving large scale flow (Huang, 1999; Wunsch and Ferrari, 2004; Hughes and Griffiths, 2006). One element necessary in understanding the mechanical energy budget is to unambiguously define and evaluate the available potential energy, its rate of production and its rate of dissipation. A particular difficulty in this respect is the presence of bottom topography that forms barriers to flow between ocean basins, at least at the deeper levels in the water column. This difficulty introduces uncertainty in estimates of the rate of production of available potential energy and the role of buoyancy forcing.

Recent studies of the energetics of the overturning circulation (Hughes et al., 2009; Tailleux, 2009) have built on the framework proposed by Lorenz (1955), Oort et al. (1989, 1994) and Winters et al. (1995), by decomposing the total potential energy into the component that is available to drive motion (the available potential energy E_a), and the remainder that cannot be converted to kinetic energy of flow (the background potential energy E_b). The surface buoyancy fluxes produce available potential energy at the expense of background potential energy in a linear Boussinesq fluid (e.g., Hughes et al., 2009), although it has also been argued that internal energy plays an important role in this conversion (Tailleux, 2009). Furthermore, for a steady circulation, the rate of generation of E_a is necessarily balanced by the rate of irreversible mixing (in a linear Boussinesq fluid this results in the return of energy to E_b at a commensurate rate, Hughes et al., 2009). Calculation of these components and of the exchanges between them is dependent upon the definition of a background (or reference) state that is unable to generate motion. Defining a suitable reference state is made difficult by the presence of topography, specifically topographic barriers. To date, studies have either used single basin domains (e.g., Hughes et al., 2009), considered data from only the upper 1000 m of the water column (e.g., Oort et al., 1994), or simply ignored restrictions imposed on the circulation by topographic barriers (e.g., Huang, 2005). Acknowledging and accounting for these restrictions requires a specialized method to define a reference state.

Here we examine the influence that topographic barriers can have when evaluating the rates of available potential energy conversion of the oceans. Isolating the influence of topographic barriers using hydrographic datasets or realistic global ocean simulations is complicated by numerous factors including complex topography, nonlinearity and compressibility in the equation of state of seawater, the parameterization of subgrid processes and computational expenses. These complications introduce uncertainty to the findings and obscure the effects of topographic barriers. Additionally, such an approach does not afford a rigorous study of the influence of topographic barriers on the evaluation of the energy budget of the oceans. This calls for an idealized, process-based investigation. For this, we employ an overturning circulation maintained by surface buoyancy forcing with a linear equation of state in a range of idealized domains with and without topographic barriers, and discuss our results in an oceanographic context.

Previous work has not developed methods which allows the reference state definitions to take account of the presence of bottom topography. Therefore, in this study we examine two new methods that do so - in order to assess the sensitivity of the energy budget to such effects. The first method, referred to as the *Multi-Basin Relaxation* (MBR), makes allowances for restrictions imposed on the flow by topographic barriers. However, the MBR method is computationally expensive so we propose a second method, the *Capped Basin Resort* (CBR), as a ready alternative the MBR. The CBR is based on the assumption that dense waters trapped by topographic barriers are dynamically inert and can thus be ignored. We use the MBR and CBR methods to calculate and estimate, respectively, the potential energy reservoirs and, more importantly, the rates of conversion between them, and compare these with estimates obtained by existing methodologies which do not account for topographic barriers. In Section 2 we review the calculation of specific terms in the energy budget. In Section 3 we outline the existing and proposed reference state definitions, and in Section 4 test the influence these definitions have on the energy budget analysis of an idealized model overturning circulation driven by surface buoyancy fluxes. In this model, we find that although the calculated values of E_a and E_b are sensitive to the method used to define the reference state, the conversion rates of energy are not, providing an adiabatic resorting scheme is employed to generate the reference state. In Section 5 we discuss the physical interpretation of the idealized model results, and in Section 6 propose a practical methodology for energy budget calculations in real ocean basins.

2. Background

Potential energy reservoirs and their conversion rates

Following Winters et al. (1995), the total potential energy of a Boussinesq fluid with a linear equation of state is given by,

$$E_p = g\int_V \rho z\, dV, \tag{1}$$

where ρ is the density of the fluid, g is gravitational acceleration, V the volume of the domain and z is the vertical coordinate (defined as positive upwards relative to the deepest point of the ocean). The background potential is energy defined as,

$$E_b = g\int_V \rho z_*\, dV, \tag{2}$$

where z_* is the depth to which a fluid element will move if the entire domain is adiabatically resorted to be stably stratified and in a state of no motion. z_* satisfies the following equation,

$$\int_0^{z_*(\mathbf{x})} A(z')\, dz' = \int_V \mathrm{H}(\rho(\mathbf{x}') - \rho(\mathbf{x}))\, dV', \tag{3}$$

where H is the Heaviside step function and $A(z)$ is the area for depth z (see Huang, 1998, 2009). E_b, by definition, is changed only by diabatic processes (e.g. diffusion, mixing, heat fluxes, etc.). The available potential energy, defined as the difference between the total potential energy and background potential energy, is,

$$E_a = E_p - E_b = g\int_V \rho(z - z_*)\, dV, \tag{4}$$

and quantifies the amount of potential energy available for conversion to kinetic energy.

A complete understanding of the ocean's energy budget requires knowledge of both the magnitude of energy reservoirs, as well as conversion rates of energy between reservoirs. The conversion rates are more likely to provide information on the circulation, and so we outline here how to evaluate these conversions. Adopting the notation of Hughes et al. (2009), the only conversion rates that depend on the reference state are the surface buoyancy forcing, Φ_{b2}, and the irreversible mixing, Φ_d. These terms can be determined from the time-dependence of E_b, and can be evaluated using an evolution equation for density which we assume for now to be in a general form of a numerical model,

$$\frac{\partial \rho}{\partial t} = -\mathbf{u}\cdot\nabla\rho + \nabla\cdot K\nabla\rho, \tag{5}$$

where K is the eddy diffusivity. Then,

$$\frac{dE_b}{dt} = g\int_V \left(z_*\frac{\partial\rho}{\partial t} + \rho\frac{\partial z_*}{\partial t}\right) dV. \tag{6}$$