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Effects of vertical variations of thickness diffusivity in an ocean general circulation model

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Abstract

The effects of a prescribed surface intensification of the thickness (and isopycnal) diffusivity on the solutions of an ocean general circulation model are documented. The model is the coarse resolution version of the ocean component of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3). Guided by the results of Ferreira et al. (2005) [Ferreira, D., Marshall, J., Heimbach, P., 2005. Estimating eddy stresses by fitting dynamics to observations using a residual-mean ocean circulation model and its adjoint. J. Phys. Oceanogr. 35, 1891–1910.] we employ a vertical dependence of the diffusivity which varies with the stratification, N^2, and is thus large in the upper ocean and small in the abyss. We experiment with vertical variations of diffusivity which are as large as 4000 $m^2\ s^{-1}$ within the surface diabatic layer, diminishing to 400 $m^2\ s^{-1}$ or so by a depth of 2 km. The new solutions compare more favorably with the available observations than those of the control which uses a constant value of 800 $m^2\ s^{-1}$ for both thickness and isopycnal diffusivities. These include an improved representation of the vertical structure and transport of the eddy-induced velocity in the upper-ocean North Pacific, a reduced warm bias in the upper ocean, including the equatorial Pacific, and improved southward heat transport in the low- to mid-latitude Southern Hemisphere. There is also a modest enhancement of abyssal stratification in the Southern Ocean.

Keywords: Ocean general circulation model; Mesoscale eddy parameterization; Vertically varying thickness diffusivity

1. Introduction

Mesoscale eddies contain most of the kinetic energy in the ocean yet cannot be routinely resolved by the global Ocean General Circulation Models (OGCMs) used in long climate simulations. A parameterization that has been widely used to represent their transfer properties in non-eddy-resolving OGCMs is the Gent and McWilliams (1990, hereafter GM90) isopycnal transport parameterization. In GM90, in addition to the diffusion of tracers along isopycnals (Redi, 1982) tracers are advected by the residual circulation, the

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sum of the Eulerian-mean and eddy-induced velocities. The eddy-induced velocity is assumed to be directly proportional to the isopycnal slope with the 'constant of proportionality' interpretable as a diffusivity coefficient – sometimes referred to as the thickness diffusivity. Typically, a constant value of $\mathcal{O}(1000)$ m^2 s^{-1} is used which does not vary in space and time, except near boundaries where 'tapering' recipes are employed for numerical stability. The choice of the constant value of the diffusivity is guided in part by the desire to obtain a model Antarctic Circumpolar Current (ACC) transport that matches observations – larger thickness diffusivity produces enhanced vertical momentum flux, thus supporting more drag with weaker ACC flow (Danabasoglu and McWilliams, 1995).

Estimates of the magnitude of the eddy diffusivity can be deduced from observations (from tracers, floats, drifters, altimetry, moorings, etc. – see e.g., Ledwell et al., 1998; Bauer et al., 1998; Sundermeyer and Price, 1998; Zhurbas and Oh, 2003; Marshall et al., 2006). These observations also tell us that the eddy diffusivity is not constant but exhibits considerable variability in space and time. Prescriptions for the computation of spatial dependencies of the diffusivities have been the subject of many numerical and theoretical studies. Marshall (1981), Treguier et al. (1997), Killworth (1997) and Treguier (1999) for example, focus on prescriptions for the vertical variation of the diffusivity guided by linear baroclinic instability theory and potential vorticity transfer. Danabasoglu and McWilliams (1995) explore the sensitivity of model solutions to an exponential decay of the diffusivities with depth to crudely represent the expected enhancement of mesoscale activity in the upper-ocean. The same exponentially decaying diffusivities are also tested in Jochum (1997). Held and Larichev (1996) and Visbeck et al. (1997) instead, attempt to understand gross horizontal variations of the diffusivity by relating it to the local Eady growth rate or typical eddy length and time scales that depend on some vertically integrated flow properties. A recent proposal by Griffies et al. (2005) takes into account a model's horizontal grid resolution and reduces the thickness diffusivity, particularly in regions of tropical grid refinement, assuming that eddies/tropical instability waves are (partially) resolved there. In addition to observations and theory, the output of eddy-resolving OGCMs have been utilized to estimate both the magnitude and spatial distributions of the thickness diffusivity (e.g., Rix and Willebrand, 1996; Bryan et al., 1999). These studies highlight the importance of the rotational component of eddy fluxes noted by Marshall and Shutts (1981) and Marshall (1984) (more often than not ignored in observational studies) as well as the need for long data sets to obtain robust estimates. Although the rotational component of the eddy flux does not need to be parameterized because it has no effect on the mean equations of motion, it introduces significant complications when diagnosing eddy fluxes in models and data and their association with diffusivities.

Despite the numerous above-mentioned studies, a common approach in the modeling community remains to ignore spatial variations altogether, unless it can be demonstrated that solutions of a particular model are 'improved', e.g., Griffies et al. (2005). This is perhaps because although there is an intellectual recognition that variations should be allowed, it is not at all obvious how one proceeds, there is insufficient observational and theoretical guidance and, often, only marginal improvements in the climatology of the model result when variations are allowed.

An alternative strategy to studying eddy parameterization was recently pursued by Ferreira et al. (2005) who used the adjoint of a large-scale global model – the MITgcm, Marshall et al. (1997a,b) – to fit it to observations by adjusting uncertain parameters. A residual-mean version of the model was used in which the effect of eddies appears in the momentum equations as the vertical divergence of an eddy stress. These eddy stresses were used as control parameters in an optimization procedure which minimized the model drift from observations. The implied eddy diffusivities showed a very substantial variability both in the horizontal and vertical, reaching as high as 4000 m^2 s^{-1} in the upper ocean (see Section 6a of Ferreira et al. (2005) for a more complete discussion, including the presence of (likely spurious) negative diffusivities in the tropics). Below the model thermocline, the model diffusivities are more than an order of magnitude smaller. They suggest that this vertical variation of diffusivity can be usefully captured by assuming that it varies in the same manner as the stratification, N^2. Ferreira et al. (2005) and Ferreira and Marshall (2006) show preliminary, promising results from simulations with the MITgcm using an N^2-dependent formulation for the eddy diffusivities. We note that both the magnitude, range, and surface intensification of the thickness diffusivity reported by Ferreira et al. (2005) have found recent support in Eden et al. (submitted) and Eden (2006) who diagnosed eddy fluxes from high resolution regional OGCMs, carefully taking into account rotational fluxes. In another recent study, Canuto and Dubovikov (2006) propose a diffusivity that varies in the vertical in the same manner as the