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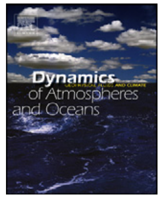

A diapycnal diffusivity model for stratified environmental flows

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ABSTRACT

The vertical diffusivity of density, K_ρ, regulates ocean circulation, climate and coastal water quality. K_ρ is difficult to measure and model in these stratified turbulent flows, resulting in the need for the development of K_ρ parameterizations from more readily measurable flow quantities. Typically, K_ρ is parameterized from turbulent temperature fluctuations using the Osborn–Cox model or from the buoyancy frequency, N, kinematic viscosity, ν, and the rate of dissipation of turbulent kinetic energy, ε, using the Osborn model. More recently, Shih et al. (2005, J. Fluid Mech. 525: 193–214) proposed a laboratory scale parameterization for K_ρ, at Prandtl number (ratio of the viscosity over the molecular diffusivity) $Pr = 0.7$, in terms of the turbulence intensity parameter, $Re_b = \varepsilon/(\nu N^2)$, which is the ratio between the destabilizing effect of turbulence to the stabilizing effects of stratification and viscosity. In the present study, we extend the SKIF parameterization, against extensive sets of published data, over $0.7 < Pr < 700$ and validate it at field scale. Our results show that the SKIF model must be modified to include a new Buoyancy-controlled mixing regime, between the Molecular and Transitional regimes, where K_ρ is captured using the molecular diffusivity and Osborn model, respectively. The Buoyancy-controlled regime occurs over $10^{2/3}Pr^{-1/2} < Re_b < (3\ \ln\sqrt{Pr})^2$, where $K_\rho = 0.1/Pr^{1/4}\nu\ \ Re_b{}^{3/2}$ is Pr dependent. This range is shown to be characteristic to lakes and oceans and both the Osborn and Osborn–Cox models systematically underestimate K_ρ in this regime.

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1. Introduction

Geophysical flows, such as lakes and oceans, are strongly affected by density stratification. One of the consequences is anisotropic turbulent mixing, where the vertical diffusivity is limited by the stratification. The vertical diffusivity is a key parameter in stratified flows as it governs a wide range of processes, ranging from local contaminant distributions to the global heat budget of oceans. Since the first basin-scale mixing estimates in the ocean by Munk (1966), the question of how much mixing occurs is still debated (Ivey et al., 2008).

The turbulent kinetic energy equation leads to a definition of the vertical diffusivity of density K_ρ as the ratio between the buoyancy flux, b, and the vertical density gradient (Osborn, 1980)

$$K_\rho = \frac{b}{N^2} = \frac{-g\overline{\rho' w'}/\rho_0}{N^2} \tag{1}$$

where $N = \sqrt{(-g/\rho_o)(\partial\rho/\partial z)}$ is the buoyancy frequency, ρ_0 a reference density and ρ' and w‘ are the fluctuating components of the turbulent density and vertical velocity fields, respectively. The overbar indicates a temporal averaging of the turbulent quantities. Attempts to directly obtain b have been made, but such estimates remain difficult to interpret and require careful examination due to: (i) the non-stationary and intermittent nature of the turbulence, and (ii) the difficulty in separating non-reversible from reversible along-gradient mixing (Moum, 1990; Fleury and Lueck, 1994; Yamazaki and Osborn, 1993; Ivey et al., 2008; Saggio and Imberger, 2001). Given the difficulties in directly estimating b, as the ratio between a scalar flux and its gradient, indirect methods have been developed to parameterize K_ρ.

In contrast, the turbulence intensity, often characterized by the rate of dissipation of turbulent kinetic energy, ε, has benefited from spectacular improvement in the accuracy with the development of new sensors and instruments, such as temperature and velocity microprofilers or pulse coherent acoustic Doppler profilers (e.g., Ruddick et al., 2000; Lueck et al., 2002; Wiles et al., 2006; Steinbuck et al., 2009).

The objective of this paper is to develop a functional parameterization of K_ρ that is easy to implement and use with data collected from instruments commonly deployed in the field. More specifically, we need to correctly calculate diffusivities from temperature microstructure to quantify environmental fluxes, such as vertical oxygen transport under low turbulence conditions. The parameterizations will be tested against an extensive set of such data. The remainder of the paper is organized as follows. In Section 2, the different parameterizations proposed in the literature are discussed. Given the lack of validated field parameterizations for K_ρ, we focus on existing laboratory and numerical work. We then infer a practical parameterization for field measurements from a new analysis of the laboratory and numerical data (Section 3). Lakes represent an ideal field laboratory to test parameterizations at the oceanic scale (Wüest et al., 1996) and this new parameterization is tested against the existing parameterizations using field data from Lake Erie (Section 4). Limitations of the proposed parameterization are presented in Section 5.

2. Existing parameterizations for K_ρ

Analytical models and experiments suggest that irreversible diascalar mixing depends on the time evolution of the turbulence (Ivey and Imberger, 1991; Barry et al., 2001; Smyth et al., 2005; Shih et al., 2005), the stratification (Gargett et al., 1984; Rehmann and Koseff, 2004; Shih et al., 2005), and the molecular diffusivity ($\kappa_T \sim 10^{-7}$ m^2 s^{-1} and $\kappa_S \sim 10^{-9}$ m^2 s^{-1} for heat and salt, respectively; Stretch et al., 2010; Nash and Moum, 2002). In the following, we discuss the parameterizations resulting from these assumptions.

2.1. Parameterization inferred from the turbulent kinetic energy equation

The fundamental assumption driving the most commonly used K_ρ parameterization is that turbulent fluxes are dominated by the motion from the largest eddies and irreversible mixing occurs at a rate consistent with the large-scale turbulent production. Developed by Osborn (1980) and extended by