Mixing by Nonvertical, Uniform Shear in a Stably Stratified Environment

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1 Introduction

Mixing of water/air masses of different densities, natural or man-made discharges into the environment, life-supporting nutrients, as well as temperature and density contrasts is an important determinant of local and global features of the ocean/atmosphere climate and ecosystem. The additional effect of stratification induced by temperature and salinity gradients, as well as that of earth's rotation must be considered when mixing is studied in the context of geophysical and environmental flows. At scales of hundred meters or less, the effects of earth's rotation may often be neglected. The microstructure at these scales is thought to be related to a variety of mechanisms that include nonlinearly-breaking internal waves, shear layer instabilities, convective instabilities and boundary layer turbulence. Although diverse in their origin, mixing processes in the ocean often involve a competition between shear and stable stratification. Therefore, the role of stably-stratified shear flow in maintaining the ocean microstructure requires study. Flows with vertical shear, $\partial\overline{U}/\partial z$, have been the subject of numerous studies; however, the horizontal shear component $\partial\overline{U}/\partial y$ has received little to no systematic investigation. The influence of horizontal shear, $\partial\overline{U}/\partial y$, with emphasis on its comparison with the oft-studied case of vertical shear is the subject of this work.

It should be noted that, despite the preponderance of vertical shear in the open ocean, there are field measurements, for example, in coastal fronts [1] and straits [2] that indicate a significant $\partial\overline{U}/\partial y$ component. Flows over seamounts where greatly increased dissipation rates have been measured [3] as well as side- and bottom-boundary flows, most likely, have substantial horizontal shear components. To the best of our knowledge, there have been no theoretical or laboratory studies focussed on horizontally sheared, vertically stratified flow. However, laboratory experiments relevant by virtue of the presence of horizontal shear include the study of a front in a rotating, stratified fluid [4], the stratified wake of a sphere [5], and the stratified jet [6].

Figures 1(a)-(b) show schematics of the case with uniform vertical mean shear, $\partial\overline{U}/\partial x_3$, and uniform horizontal mean shear, $\partial\overline{U}/\partial x_2$, respectively. In both cases, there is uniform mean stratification, $d\overline{\rho}/dx_3 = S_\rho$, which is stable, $S_\rho < 0$.

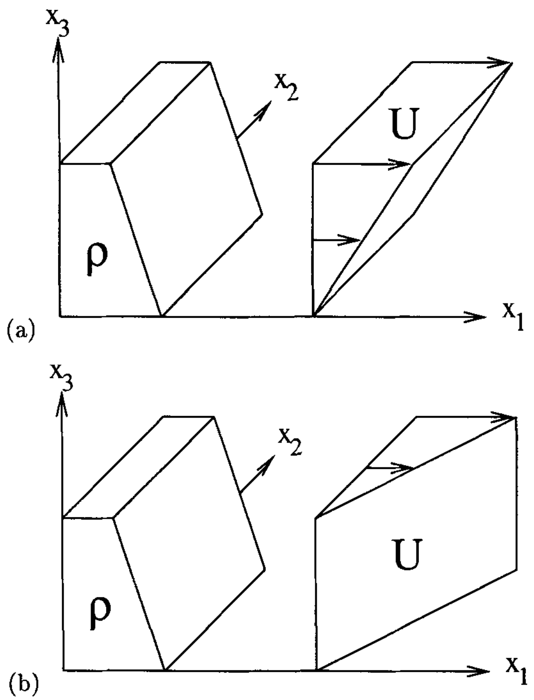

Fig. 1. Sketch of (a) vertically sheared flow and (b) horizontally sheared flow. There is a stable vertical density stratification in both cases

2 Approach

Since little is known from existing studies about the influence of horizontal shear on mixing in a vertically stratified fluid, direct numerical simulation (DNS) is an attractive approach that avoids the uncertain influence of turbulence models on the conclusions. In DNS, all dynamically important scales of motion are resolved which, given current computer hardware capabilities, limits the simulations to moderate Reynolds number. In the case of uniformly distorted flow, the appropriate Reynolds number $Re_\lambda = q\lambda/\nu$ is based on the rms velocity, $q = \sqrt{2K}$, and the Taylor microscale, $\lambda = \sqrt{5\nu q^2/\epsilon}$. Here K and ϵ denote the turbulent kinetic energy and dissipation rate, respectively. The value of Reynolds number is $Re_\lambda \simeq 100$ in the simulations reported here.

The unsteady, three-dimensional, Navier-Stokes equations with the Boussinesq approximation are numerically solved. A spectral collocation method is used for the spatial discretization and a third-order, low-storage, Runge-Kutta scheme for the temporal advancement in order to obtain high accuracy. The equations are solved in a reference frame that moves with the mean velocity [7] that, while introducing additional time-dependent terms in the gov-