Experimental and Numerical Studies of Non-Equilibrium Stratified Turbulence Relevant to Oceanic Currents

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LONG-TERM GOAL

Our long-term goal is to understand and parametrize the influence of complex shear and stratification patterns observed in the ocean on small-scale transport processes with particular application to coastal flows and fronts

SCIENTIFIC OBJECTIVES

The objective of the numerical component of past year’s research was to investigate the effect of an additional horizontal shear component on vertically sheared, vertically stratified flow. This study was motivated by observations of intense mixing generated by horizontal shear in tidal convergence fronts [1], shallow seamounts [2] and sidewalls of channels. In addition, quantitative comparisons with same initial spectra were conducted between the laboratory and numerical results of vertically sheared, vertically stratified flow for mutual validation. The main objective of the experimental component was to design and build a rapid vertical traversing system in order to make measurements using the same type of sampling most often employed in ocean measurements. The basic anisotropy of turbulence in stably stratified flows demands that such measurements be made and compared with those made in the ocean with vertical profilers. Our current student, Kurt Keller, was courageous enough to attempt such laboratory measurements. We hope to be able to use our results to assess and evaluate the many ocean microstructure measurements that are made in this way. Perhaps we can eventually shed some light using our experimental and numerical results on the large disparity in measured dissipation rates as estimated from large scale balances versus microstructure measurements .

APPROACH

A rapid vertical traverse was built and tested. The traverse is driven by a computer controlled stepper motor to assure smooth acceleration and deceleration, allowing the fragile hot-wire and cold wire sensors to survive the rapid excursions of the traverse. Two components of the velocity and the temperature are measured by the probe sensor

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array. The traverse is sufficiently fast so that all scales of the turbulence and internal wave fields are essentially frozen during the duration of the measurement.

The numerical study involved DNS of the Boussinesq form of the three-dimensional, unsteady Navier-Stokes equations. A spectral collocation method was used for the spatial discretization and a third-order, Runge-Kutta scheme for the temporal advancement. The instantaneous velocity, density and pressure fields obtained from the simulation were processed to obtain all terms in the transport equations for Reynolds stress and buoyancy flux, as well as spectra and two-point correlations**.** The statistics were also used to evaluate turbulence transport models.

WORK COMPLETED

A complex shear flow with vertical shear given by $dU/dz = S\cos\theta$ and horizontal shear $dU/dy = S\sin\theta$ was simulated. The limiting cases of $\theta = 0$ and $\theta = \pi/2$ correspond to purely vertical shear and purely horizontal shear, respectively. The influence of horizontal shear was studied by systematically increasing the inclination angle θ in the range $0 < \theta < \pi/2$ keeping S, the *magnitude* of shear, as well as the Vaisala frequency N and other parameters constant. The angle variation study was conducted for two values of gradient Richardson number $Ri = N^2/S^2$, a small value $Ri = 0.2$ and a large value $Ri=2.0$. The high-order spatial and temporal accuracy of our numerical algorithms allowed simulations at turbulence Reynolds number up to $Re_t = 10{,}000$ on the largest grid. The cases with large horizontal shear and large Ri were the most computationally intensive because of the development of internal waves that required a domain with large streamwise extent with up to 512x256x256 points for resolution. A parallel code suitable for the Cray T3E was developed to allow such large-scale computations. The DNS data base which is available to any other interested research group was used to evaluate the effect of horizontal shear on the density and momentum transport coefficients, dissipation and buoyancy scaling as well as investigate qualitative differences in the behavior at small and large values of gradient Richardson number. The study of nonvertical shear has been submitted for publication [3] and new results emphasizing the behavior of the case with purely horizontal shear are to be presented in the upcoming Ocean Sciences meeting in Feb. 1998 and the APS Fluid Dynamics meeting in Nov. 1997.

Some initial results for rapidly sampled vertical temperature profiles have been obtained during the testing of the rapid vertical traversing system. These preliminary data will be reported at the November meeting of the Division of Fluid Dynamics of the American Physical Society as well as the Ocean Sciences Meeting in Feb. 1998. The resolution of the system looks excellent, and the signal to noise ratio is high. High frequency noise due to the stepper motor has been eliminated by the use of line filters. Due to current sampling rate limits of our present A-D converter we have not been able to simultaneously measure the two velocity components. A much faster A-D board has been ordered and we expect it to arrive this November. The flow facility has been further improved by adding a much larger blower on the tunnel level on the lower wall where the velocity is highest. This has increased the attainable shear rate by a factor of 2, with a corresponding increase of the

Richardson number range attainable. With the ongoing refinements in the flow facility and in the DNS, the experimental and DNS results in the vertically sheared case are now converging very well.

RESULTS

Fig. 1 clearly shows that when the shear angle increases from $\theta=0$ (and, correspondingly, the horizontal shear $dU/dy = S\sin\theta$ increases from a zero value) there is a rapid increase of the growth rate of turbulent kinetic energy. Indeed, the case with purely horizontal shear ($\theta = \pi/2$) shows asymptotic growth of turbulence compared to the asymptotic decay seen for purely vertical shear($\theta=0$). The change in growth rate is especially significant for small angles of θ implying that a relatively small amount of horizontal shear can cause a large increase in turbulent transport. Following the rapid increase, the turbulence growth gradually approaches a value which is *smaller* than the unstratified case (Ri = 0), suggesting that vertical stratification has a residual stabilizing effect even when the shear is completely in the horizontal plane. The nondimensional value of ε/SK is relatively invariant to the angle θ which implies that the turbulent dissipation rate ε also increases strongly with horizontal shear. A simple model that accounts for the presence of horizontal shear was developed by parametrizing its effect in terms of an ‘‘effective’’ Richardson number which decreases as a function of increased strength of horizontal shear. Such a model can be easily incorporated in Richardson number-based parametrizations of small-scale transport used in ocean climate calculations. An interesting observation is that, although the net production P of turbulent kinetic energy increases with the shear inclination angle θ, the flux Richardson number $Ri_f = B/P$ where B is the buoyancy flux remains relatively invariant. The cases at low Ri = 0.2 have an asymptotic value of $Ri_f = 0.2$ for all shear inclination angles studied here while the cases with high Ri = 2.0 have an asymptotic value of approximately $Ri_f = 0.3$. The DNS results suggest that B/ε does not remain invariant when the relative magnitude of horizontal shear increases.

The influence of horizontal shear on vertical diffusivity of mass, $D_\rho = -B/(d\rho/dz)$, is shown in Fig. 2. The diffusivity which is normalized with its value for purely vertical shear increases sharply with an increasing horizontal shear component and eventually becomes a factor of 20 larger in the case with purely horizontal shear ($\theta= \pi/2$).

The simulations at large Richardson number Ri=2 have been completed. The potential energy evolution and 3-D flow visualization shows significant wave motion with frequencies close to the Vaisala frequency superposed on high frequency turbulent motion. The high Ri data base is the subject of ongoing analysis.

Temperature spectra measured with the vertical traverse look much different than those we have measured earlier with fixed point Eulelrian measurements. They look, in fact, very much like data obtained with ocean microstructure profilers, i.e. there is a low frequency wave-like range in which the spectral slope is constant and a high frequency range which exhibits a turbulence-like spectrum with an increasingly steep fall off. This behavior appears consistent with some vertically spaced multi-point (8) measurements we made earlier with fixed temperature probes, which show turbulent overturning behavior for low Richardson number and internal wave-like undulations for large Richardson number.

IMPACT/APPLICATIONS

The numerical simulations have demonstrated that a small amount of horizontal shear can result in a large increase in turbulent dissipation rates as well as vertical transport of mass in a stably stratified medium. The implication is that horizontal shear associated with side and bottom topographic features can lead to energetic small-scale mixing. A model that gives an ‘‘effective’’ Richardson number as a function of shear angle was also developed for direct implementation in ocean climate codes that are based on Richardson number parametrizations of small-scale transport.

Our vertically sampled laboratory measurements will allow a critical study of the process of vertical sampling using ocean microstructure profilers, which has been done extensively over the past 25 years in many ocean expeditions. We will be able to assess the effects of the rate of convergence of statistics obtained in turbulent patches in the ocean, lack of statistical stationarity, and degree of anisotropy.

RELATED PROJECTS

The microstructure measurements being made by many groups, e.g. at Oregon State University and the University of Washington, are a strong motivating factor for our experiments, and are scientifically closely related, as are many other studies of small scale mixing of the ocean and associated parameterizations needed for computational studies**.** The numerical investigation of the effect of horizontal shear components on ocean microstructure and its parametrization is tied to the measurement of large dissipation rates and mixing events in the vicinity of tidal fronts and side/bottom topography by the groups at the University of Washington and the Institute of Ocean Sciences in British Columbia.

[1] D. M. Farmer, E. A. D’Asaro. M. V. Trevorrow and G. T. Dairiki, ‘‘ Three-dimensional structure in a tidal convergence front,’’ *Continental Shelf Research,* **15**, 1649-1673 (1995).

[2] R. G. Lueck and T. D. Mudge, ‘‘Topographically induced mixing around a shallow seamount,’’ *Science*, **276** (no.5320), 1831-3 (1997).

[3] F. A. Jacobitz and S. Sarkar, ‘‘The effect of nonvertical shear on turbulence in a stably stratified medium,’’ *Phys. Fluids,* pp. 17, submitted (1997).

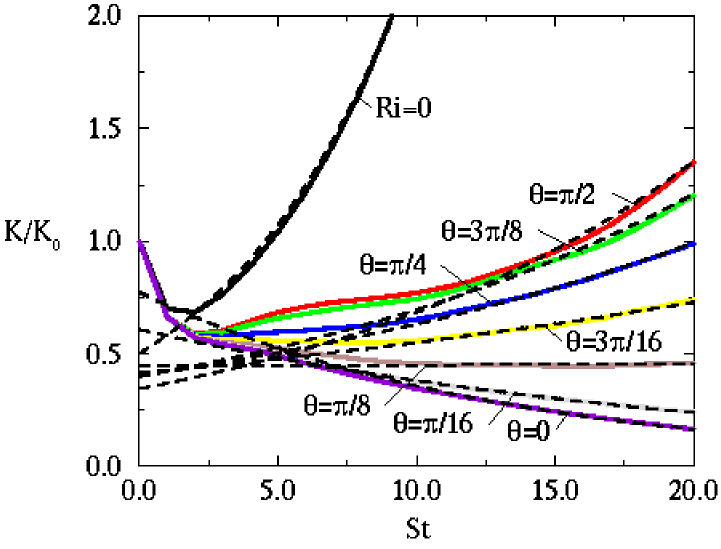

Fig. 1: The evolution of turbulent kinetic energy as a function of time for various shear inclination angles θ. The vertical shear is $dU/dz = S\cos\theta$ and horizontal shear is $dU/dy = S\sin\theta$. The Richardson number based on shear magnitude is $Ri = N^2/S^2 = 0.2$. The limiting cases of $\theta = 0$ and $\theta = \pi/2$ correspond to purely vertical shear and purely horizontal shear, respectively. The unstratified case, $Ri = 0$, is also shown.

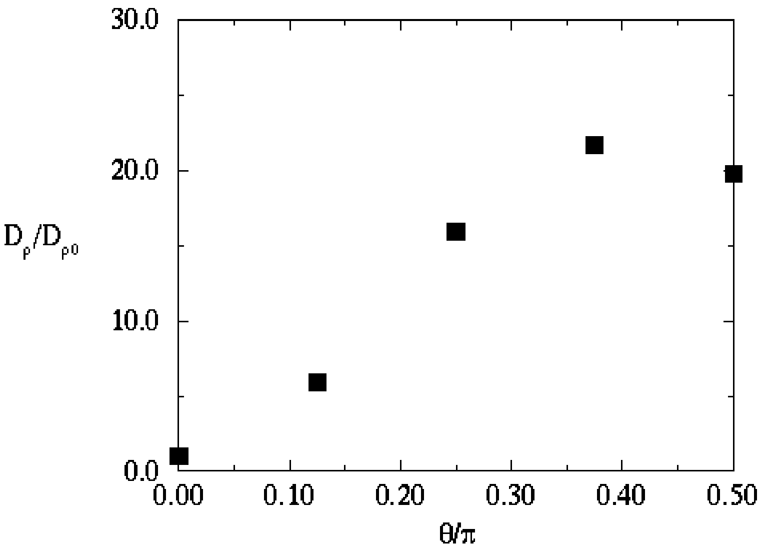

Fig. 2: The variation of vertical turbulent diffusivity D_ρ of mass normalized by its value for the case with purely vertical shear . The value of $Ri = 0.2$.