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13. ABSTRACT *(Maximum 200 words)*
A comprehensive research program was carried out to investigate turbulence, waves and mixing in oceanic surface and benthic boundary layers, with special emphases on the generation, sustenance, diffusion and decay of turbulence in such layers. The research was mainly laboratory experimental, supplemented by analytical and numerical developments. The penetration of a shear-generated turbulent layer into a stably stratified non-turbulent layer, with applications to the oceanic surface-layer deepening, was the theme of the first part of the research program; the rate of turbulent-layer propagation, energetics, diffusion of mass, momentum and turbulent kinetic energy and small scale processes were the studied in detail. The applicability of results to oceanic situations, especially for surface-layer modeling, was also evaluated. The second part of the investigation dealt with oscillatory, surface-wave boundary layers, mimicked in the laboratory by an oscillatory bed underlying either a quiescent fluid layer or a mean current. The aim was to measure the diffusivities of momentum, mass and turbulent kinetic energy in such layers and to use the results to verify commonly used parameterizations in predictive models for coastal oceans.

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TURBULENT MIXING IN OCEANIC SURFACE AND BENTHIC BOUNDARY LAYERS

Final Report of the ONR Contract No.
N00014-97-0070

by

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Introduction

The long-term goal of our research program is to understand, using laboratory experiments, numerical modeling and theoretical analysis, small-scale mixing processes occurring in oceanic surface and benthic boundary layers. The knowledge so gained will be used to develop sound closure parameterizations for oceanic predictive numerical models. The objectives of the specific effort being reported were to improve the fundamental knowledge of turbulent mixing and diffusion processes occurring in oceanic boundary layers, with special emphases on the surface mixed layer and the wave-current boundary layer in coastal oceans. In the studies of surface mixed layers, the focus was on the penetration of a mixed layer (say, driven by the wind) into a density stratified bottom layer while transporting momentum and mass vertically. Also of interest were the effects of such transports on large-scale circulation patterns and air-sea coupling. Studies on the wave boundary layer are expected to verify the accuracy of currently used bottom boundary layer parameterizations of coastal ocean models.

During the contract period, the principal investigator H.J.S. Fernando, graduate students Rajka Krstic and Eric Strang, post-doctoral fellows Andrew Folkard and Heather Earnshaw, and visiting scientists Professors Eliezer Kit (Tel Aviv University) and J.C.R. Hunt (U.K. Meteorological Office) worked on several problems related to turbulent mixing in stably stratified fluids and coastal-ocean bottom boundary layer. The results of completed studies are outlined below and the resulting publications are listed at the end of this report.

Turbulent Mixing in Stably Stratified Shear Flows

A major part of the study on the penetration of a surface mixed-layer into an underlying stratified layer was laboratory experimental. The experiments were performed in a recirculating water channel, whereby an upper turbulent layer was driven over a stagnant denser layer to mimic the development of upper-ocean mixed layer. A uniquely designed disk pump was used to drive the flow, and special precautionary measures were used to ensure one-dimensional growth of the mixed layer. Detailed measurements using the laser-Doppler, hot film and particle-image velocimetry techniques as well as flow imaging using the laser-induced fluorescence (LIF) method were used for flow diagnostics. The measurements included the production of turbulent kinetic energy, buoyancy flux, rate of dissipation, internal wave radiation, integral-scales of turbulence and the local Richardson number with a resolution of 2.5 mm (using a specially designed probe). The experiments were conducted by Dr. Eric Strang as a part of his Ph.D. thesis and the P.I., in collaboration with Prof. J.C.R. Hunt of the University of Cambridge, U.K, carried out a rapid-distortion-theory based analysis of the problem.

Efforts to quantify buoyancy and momentum transports through stratified shear layers using our controlled laboratory experiments revealed some interesting features. It was found that these transport rates are primarily governed by the bulk Richardson number $Ri_B = \Delta bD/\Delta U^2$, where ΔU and Δb are the velocity and buoyancy jumps across the shear layer and pycnocline, respectively, and D is the depth of the mixed layer overlying the sheared density interface. This bulk parameter, however, was closely related to the mean local gradient Richardson number $Ri_g = N^2/du/dz)^2$, where N is the local buoyancy frequency at the base of the mixed layer and du/dz is the local shear. When $Ri_B < 5$ (or $Ri_g < 1$), turbulent mixing at the shear layer was dominated by energetic Kelvin-Helmholtz billows, the breakdown of which produced strong, intermittent buoyancy transport episodes. Mixing in the stratified shear layer appears to be most efficient, with a mixing efficiently of $Ri_f = 0.4$, at the critical Richardson number of $Ri_g = 1$ (or $Ri_B = 5$). The range of flux Richardson numbers Ri_f observed ($0.05 < Ri_f < 0.4$) is consistent with that of $Ri_f = 0.15$ commonly employed in the Osborn dissipation model and those found in various oceanic data, namely, $Ri_f \sim 0.15$ -0.2 in turbulent patches within the main thermocline (Moum & Osborn 1986, J. Phys. Ocean. 16, 1250) and $Ri_f \sim 0.4$ in turbulent tidal fronts (Gargett & Moum 1995, J. Geophys. Res., 81, 1180). Correspondingly, the dissipation flux coefficients (the ratio of buoyancy flux to the dissipation rate) measured in our experiments showed an excellent agreement with those obtained in turbulent tidal fronts and a reasonable agreement with data obtained from oceanic (turbulent) surface layers.

Above the critical value of $Ri_g > 1$, the mechanism responsible for turbulent mixing transitions from K-H to intermittent breaking of interfacial (internal) waves and secondary shear (Holmboe) instabilities. Crossing to this new regime is associated with a dramatic reduction of the entrainment rate, almost by an order of magnitude. The laboratory observation of a critical Richardson number ($Ri_g = 1$) is consistent with limited ocean observations available (Moum et al. 1992, J. Phys. Ocean. 22, 1330). Furthermore, it is in fair agreement with mixing shut-off criteria employed in some integral mixed-layer models (Price et al. 1986, J. Geophys. Res., 91, 6411).

Measurements performed vertically across the stratified shear layer were used to estimate the eddy diffusivities of density and momentum, K_ρ and K_m, respectively. When properly scaled, comparisons of these values with those deduced by oceanic microstructure measurements and several expressions used for oceanic mixing parameterizations indicate a fair agreement. Laboratory data, however, were typically larger than upper bounds of these estimates. When mixing is active, $Ri_B < 5$ (or $Ri_g < 1$), K_ρ was found to be approximately equal to K_m; this assumption is commonly used in numerical models at all Ri_B, although our data show that, at large Ri_B, the momentum transfer coefficients are higher than its buoyancy transfer counterpart.

Formation of Step Microstructure in Stratified Turbulent Flows

Numerous oceanic and atmospheric observations have provided evidence for widespread occurrence of microstructure in regions where overall stratification is stable. This microstructure can take the form of either ragged density profiles or a series of well-mixed turbulent layers separated by sheet-like density interfaces (step microstructure). No single mechanism can be attributed to all of the microstructure observations, and to this end several plausible mechanisms have been proposed. The purpose of this part of the work was to describe yet another mechanism that has not been proposed before. It was argued that turbulent mixing in a non-linearly stratified fluid or an isolated mixing event in a linearly stratified fluid can lead to the formation of step microstructure because of the merger of disparate mixing fronts. This concept is demonstrated using a simple laboratory experiment and an associated theoretical model.

Experiments on Collapsing Turbulent Regions in Stratified Fluids

Laboratory experiments were carried out to investigate the properties of a collapsing turbulent patch generated within a linearly stratified fluid by a sustained energy source and its longtime evolution in the presence of lateral boundaries. An oscillating grid spanning the width of the experimental tank was used as the turbulence source. Initially, the patch grows rapidly, as in an unstratified fluid, until the buoyancy forces arrest its vertical growth. Thereafter, the patch collapses to form horizontally propagating intrusions at its equilibrium density level. The fluid lost from the patch into the intrusion is replenished by return currents generated at the top and bottom edges of the patch. The nose of the intrusion propagates with a constant average speed ("initial spreading regime") determined mainly by the horizontal pressure gradient forces and the resistance induced by upstream propagating, low-frequency, columnar internal waves. Although the intrusion propagation speed is independent of viscous effects, they cause the development of a slug of fluid pushed ahead of the intrusion. When this slug reaches the endwall, strong upstream blocking occurs, causing the intrusion to decelerate ("blocked regime"); the intrusion nose, however, eventually reaches the endwall. The thickness of the patch is found to be approximately constant during the initial spreading regime and slowly growing in the blocked regime. At large times (t) both the patch and the "fully blocked" intrusion begin to grow vertically with a power law of the form $t^{1/5}$. A simple mixing model was advanced to explain this observation. Various turbulent and internal-wave parameters pertinent to collapsing patches were also measured, and their properties were compared with those of non-collapsing patches.

An Analysis of Turbulent Motions in and Around a Differentially Forced Density Interface

The Rapid-Distortion-Theory based analysis proposed by Fernando & Hunt [J. Fluid Mech., 347, 197, 1997] was extended to study the nature of turbulence in and around a density interface sandwiched between turbulent layers with dissimilar properties. It was shown that interfacial motions consist of low-frequency, resonantly excited, non-linear internal waves and high-frequency, linear internal waves driven by background turbulence. Based on the assumptions that (i) all resonant waves and some non-resonant waves having frequencies close to the resonant frequencies grow rapidly, break and cause interfacial mixing, (ii) the spectral amplitude of the vertical velocity in the wave-breaking regime is constant, and (iii) kinetic energy is equipartitioned between linear and non-linear breaking wave regimes, the r.m.s. vertical velocity at the interface and the turbulent kinetic energy flux into the interface were calculated. The migration velocity of the interface was calculated using the additional assumption that the buoyancy flux into a given turbulent layer is a fixed fraction of the turbulent kinetic energy flux supplied to the interface by the same layer. The calculations were found to be in good agreement with the entrainment data obtained in previous laboratory experiments in the parameter regime where the interface is dominated by internal wave dynamics.

Studies on Turbulent Oscillatory (Wave) Boundary Layers

Two approaches were used to study the physics and transport properties of wave boundary layers. In the first approach, a purely oscillatory turbulent boundary layer, generated by an oscillating bottom in a deep fluid layer, was used to mimic the oscillatory flow under waves. This work was performed by Ms. Rajka Krstic as a part of her Ph.D. thesis project. In the second study, carried out by Dr. Heather Earnshaw, an actual wave boundary layer produced by a periodic train of waves traveling on a sloping beach was investigated in a large wave tank of dimensions 104.5 x 3.5 x 6 (ft). In both studies, the parameters of interest are the mean velocity profiles, integral length and velocity scales of turbulence and the upward diffusion of turbulent kinetic energy, momentum and mass. Particle-image, particle-tracking and laser-Doppler velocimetry are used for flow diagnostics.

Flow visualization studies during the oscillatory boundary layer work elicited the mechanism of vortex formation surrounding roughness elements, which occurred at the end of each half-cycle. Vortices so formed interacted with surrounding vortices within the boundary layer, causing violent exchange of the mass and momentum in the vertical direction. Turbulent kinetic energy was found to be maximum near the bed, and its distribution followed the numerical calculations of Justensen (1988, Coastal Engineering, 12, 257) reasonably well. Measurements over two-dimensional planes enabled the calculation of autocorrelation functions of velocity at different distances from the bed for different phases of flow oscillations. Comparison of eddy viscosity measurements with the theoretical model of Trowbridge and Madsen (1984, J. Geophys. Res., 89, 7989) and the integral length scale measurements with the model of Grant & Madsen (1979, J. Geophys. Res., 80, 5109) elicited successes and failures of these models. For example, integral length-scale measurements agreed fairly well with the predictions of Grant & Madsen, usually within 10%, indicating their suitability to parameterize lengthscales in numerical models. As a continuation of this work, experiments are now being conducted on wave-current boundary layers. A specially designed apparatus, capable of superimposing a steady (mean) current on the oscillatory motion is being used for this purpose. This study is expected to yield important new information on the modification of current (mean velocity, shear stresses, roughness length and integral velocity and lengthscales) by the oscillatory component of the boundary layer. The results will be compared with the theoretical model of Grant & Madsen.

List of Publications

Journal Papers

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Papers Submitted

Strang, E.J. and Fernando, H.J.S. "Turbulence and Mixing in Stratified Shear Flows," *Journal of Fluid Mechanics* (under revision).

Neves, J. and Fernando, H.J.S., "Behavior of a Sediment-Laden Vertical Turbulent Jet," *Journal of Fluid Mechanics* (under revision).

Lozovatsky, I. and Fernando, H.J.S., "Observations of Turbulence in Marine Stratified Layers," *Journal of Geophysical Research* (under revision).

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