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The research has dealt with the interaction of turbulence and stratification in a three layer system and the nature of shear-free turbulence near sharp interfaces. Summaries of the research projects are given in the final report.

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Final Technical Report

WAVE-TURBULENCE INTERACTION AT AN INVERSION LAYER

by

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and

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1.0 Introduction

The structure of turbulence within and near inversion layers as well as the motion within the interior of an outer stratified layer are of interest in understanding the communication between stratified and turbulent layers. Such an understanding is imperative in predicting the penetration of a turbulent layer into a contiguous stratified region (entrainment phenomena) and the dispersion of species in the turbulent layer. A stunning example in this context is the fluid motion in the lower atmosphere generated by convective turbulence. Here the stratification consists of three layers; the bottom layer near the surface is well mixed by convective turbulence and the outer weakly stratified layer is separated from the bottom layer by a strong, stable, somewhat thin layer called the inversion layer. The height of the bottom layer is referred to as the mixing height. Thus the buoyancy frequency profile in the lower atmosphere can be approximated as

$$
\begin{aligned}
N(z) &= 0 \text{ for } 0 < z < h_l \\
&= N_i \text{ for } h_l < z < h_l + h \\
&= N_u \text{ for } h_l + h < z < h_l + h + h_2
\end{aligned}
$$

where z is the vertical coordinate measured from the ground, h_l the mixing height, N_i the buoyancy frequency within the inversion layer of thickness h, and N_u ($< N_i$) the buoyancy frequency above the inversion. It has been demonstrated that mean wind effects such as shear production of turbulence can be neglected except very near the ground (Deardroff 1980) and hence the forcing of the inversion can be treated as due to shear-free turbulence. This is somewhat different from the oceanic case, where, albeit a three layer stratification consisting of an upper mixed layer, a thermocline and a deep weakly stratified layer can be identified, the turbulent production at the base of the mixed layer is significant.

The work reported here deals with the interaction of turbulence and stratification in a three layer system similar to that described above and the nature of shear-free turbulence near sharp interfaces. Summaries of the two projects are given below.

2.0 Experiments with Three-Layer Stratified Fluids

The experiments were carried in a traditional mixing box similar to that used by Turner (1968). For experimental convenience, the upper layer was maintained turbulent and the layers below were stably stratified. Shear free turbulence induced by mechanical means (an oscillating grid) was used to drive the upper turbulent layer. A schematic of the experimental apparatus is shown in Figure 1(a) and the stratification used is shown in Figure 1(b). Based on linear internal wave theory, one expects that waves generated at the inversion layer will have frequencies satisfying $\omega < N_i$ and the waves radiated into the outer layer will have frequencies $\omega < N_u$. Since $N_i > N_u$, one further expects that waves in the inversion satisfying $N_u < \omega < N_i$ will be trapped inside that layer and, owing to the build up of energy, break thus dissipating energy. During the wave breaking, turbulence is generated which leads to localized mixing within the inversion, reduction of the buoyancy gradient within the interface and growth of the mixed layer.

A three layer stratification was set up in the experimental apparatus using conventional techniques. The laser-induced fluorescence (LIF) technique and conductivity measurements were used to examine the wave activity within the stratified layers. A two-dimensional image processing technique was developed to probe interfacial mixing events. Although a laser-based local Richardson number probe was used to detect waves in the stratified layers, measurement of wave parameters using this method was difficult owing to the low wave activity in the stratified layers.

The LIF flow visualization revealed the existence of different mixing mechanisms in different Richardson number (*Ri*) ranges. Here the Richardson number is defined as $Ri = N_i^2 h_I^2 / u_H^2$, where L_H and u_H are the length and velocity scales of the (undistorted) turbulence, respectively. At low *Ri*, say $Ri < 25$, the interfacial mixing takes place owing to the scouring of the interface by the energetic turbulent eddies in the mixed layer. As Ri increases, wave breaking becomes important and, at $Ri > 40$, mixing is dominated by the breaking of internal waves. At very high Ri, the interface was found to be rather calm and non entraining; here the interface is dominated by molecular diffusive processes.

The maxima of the internal wave energy spectra lie between the buoyancy frequencies of the inversion layer N_i and the weakly stratified layer N_u; resonant trapped waves within the inversion could be identified. Measurements of these wave frequencies showed good agreement with a theory due to Carruthers and Hunt (1992). The interfacial layer thickness was measured using two techniques. The conductivity measurements showed that the normalized interfacial layer thickness is a slowly varying function of the Richardson number; i.e., $d/L_H \sim Ri^{-3/4}$. The concentration measurements, on the other hand, showed a much more rapid decrease with Ri; i.e., $d/L_H \sim Ri^{-5/3}$. The r.m.s. amplitude of the normalized interfacial-wave distortions was found to decrease with Ri as $\left(\overline{\zeta^2}\right)^{1/2}/L_H \sim Ri^{-1}$ and the energy spectrum of the interfacial distortions showed the existence of a region with a -2 slope, in accordance with the predictions of Moffatt (1984) and Fernando & Hunt (1992). The r.m.s. fluctuation of normalized interfacial vertical velocity was found to be a decreasing function of Ri as $\left(\overline{w^2}\right)^{1/2}/u_H \sim Ri^{-1/2}$.

Complete description of the experiment and the experimental results will be given in Perera, Fernando & Boyer (1992).

3.0 Modelling of Turbulence Near Sharp Interfaces

A model for turbulent mixing across sharp density interfaces subjected to homogeneous turbulence was developed in this study. The analysis was essentially based on the rapid distortion theory approach of Hunt (1984), which reckon on the empirical observation that the dissipation rate of turbulent kinetic energy above an interface is independent on the height. The homogeneous turbulence was modelled using the classical von Karman spectra and the interfacial motions were assumed to be governed by the linear internal-wave equations. It was further assumed that the first mode of internal waves governs the interfacial motions, thus simplifying the interfacial boundary conditions; the latter has been a major bottleneck in modelling fluid motions near sharp density interfaces.

Two configurations, namely, (i) a turbulent fluid layer separated from a non-turbulent heavy fluid layer by a density interface (single-sided stirring) and (ii) a density interface sandwiched between two layers of equal turbulent intensities and length scales (double-sided stirring), were considered. The former case is applicable to situations of mixed layer deepening in stably stratified fluid masses due to convective stirring or wave breaking whereas the latter is important in analyzing the interfacial migrations in density step structures. Detailed measurements on the interfacial structure for the case (i) have been made by Hannoun & List (1988), when the interface is forced by oscillating-grid induced shear-free turbulence. These results were effectively utilized to obtain a physical insight for the problem and for the validation of the model.

The existence of resonant modes at the interface was identified when $\omega < Ri/2$; the waves at or near resonant frequencies amplify during the evolution and break down owing to local shear instabilities to form isolated, intermittent, patches at the interface (here Ri is based on the buoyancy jump at the interface). The patches act as energy sinks, as a result of mixing and dissipation, and are responsible for the maintenance of internal-wave energy at a finite level. Such breaking events cannot be described by linear theory; modelling based on physical and mathematical reasoning was introduced to close the problem. Based on the experimental observation that the time-traces of the interfacial displacement at a given location has discontinuities, the following spectral form was proposed for the vertical velocity:

$$\psi_{33}(\omega,o) = \begin{cases} I(\omega) & \text{for } \omega > \omega_c \\ I(\omega_c) & \text{for } \omega < \omega_c \end{cases} ,$$

where $I(\omega)$ is the spectral form predicted by the linear theory and ω_c is the frequency below which non-linear breaking of waves becomes important. The cut off frequency ω_c was evaluated using the physical argument that the ratio of the energy G contained in the vertical velocity spectra in non-linear and linear regimes is constant; this assumption led to the condition $m_c = Ri/2\omega_c$ is a constant, independent of the Richardson number.

It was found that the vertical velocity data give excellent agreement with the predictions for case (i), if $m_c = 0.5$ (corresponding to $G = 1.25$) is chosen. The calculations for various quantities were carried out using $m_c = 0.5$ for both cases (i) and (ii). In calculating the displacement spectra using the modelled spectra, the low frequency end near $\omega \simeq 0$ behaves as ω^{-2}, and thus the existence of a low frequency cut off, dictated by the lowest frequency of the motion in the mixed layer, was suggested. The proposed form of the displacement spectra was

$$\psi^d(\omega,0) = \begin{cases} \psi_{33}(\omega,0)/\omega^2 & \text{for } \omega > \omega_0 \\ \psi_{33}(\omega_0,0)/\omega_0^2 & \text{for } \omega < \omega_0 \end{cases}$$

Based on previous work, the non-dimensional ω_0 was selected as 0.18. Using the above spectral forms with $m_c = 0.5$, $\omega_0 = 0.18$ and the standard von Karman form of spectra for homogeneous turbulence, the Richardson number Ri dependence of non-dimensional r.m.s. vertical velocity $\left(\overline{w^2}\right)^{1/2}$, displacement $\left(\overline{\zeta^2}\right)^{1/2}$ and pressure-velocity correlation $\overline{\Delta pw}$ at the interface were calculated as follows:

Single-Sided Stirring

$$\left(\overline{w^2}\right)^{1/2} = 1.8\ Ri^{-0.33}$$
$$\left(\overline{\xi^2}\right)^{1/2} = 3.2\ Ri^{-0.83}$$
$$\overline{\Delta pw} = 5.0\ Ri^{-0.49}$$

Two-Sided Stirring

$$\left(\overline{w^2}\right)^{1/2} = 3.0\ Ri^{-0.33}$$
$$\left(\overline{\xi^2}\right)^{1/2} = 5.4\ Ri^{-0.83}$$
$$\overline{\Delta pw} = 16.7\ Ri^{-0.49}$$

However, it was pointed out that the form of joint-wave number frequency spectra $\chi_{ij}(k,\omega)$ of homogeneous turbulence used in the present work, which is an essential input to the modelling, does not yield an Eulerian frequency spectra, consistent with the experimental observations, upon integration over the wave number space. Calculations performed with appropriate modifications showed that the predictions based on the assumption G = 1.0 (i.e., $m_c = 0.36$) also give a good agreement with the experimental data. The resulting predictions are as follows:

<u>Single-Sided Stirring</u>	<u>Two-Sided Stirring</u>
$\left(\overline{w^2}\right)^{1/2} = 1.8\ Ri^{-0.33}$	$\left(\overline{w^2}\right)^{1/2} = 3.2\ Ri^{-0.33}$
$\left(\overline{\xi^2}\right)^{1/2} = 3.2\ Ri^{-0.83}$	$\left(\overline{\xi^2}\right)^{1/2} = 4.9\ Ri^{-0.83}$
$\overline{\Delta pw} = 5.0\ Ri^{-0.49}$	$\overline{\Delta pw} = 11.8\ Ri^{-0.49}$

An entrainment model was developed to calculate entrainment rates across density interfaces. The model predictions were found to be in good agreement with the entrainment data obtained in previous oscillating-grid experiments such as Turner (1968) and E and Hopfinger (1986). Turner (1968) conjectured that the entrainment rates for single and double-sided cases ought to be the same. One of the important findings of the present analysis is that these two cases are different and the different entrainment rates observed by Turner (1968) can be real. The differences arise from the fact that the profiles of buoyancy flux and the interfacial velocities within the interface are dissimilar for the two cases; however, the power law dependencies of various quantities on the Richardson number Ri were found to be similar.

The present analysis is more complete than the previous theories on turbulent mixing across interfaces. Hannoun and List (1988) used the analysis of Phillips (1977), based on first mode of internal waves at sharp interfaces, to interpret their results but the latter does not take into account the effects of turbulence on the interface which lead to resonant breaking of waves. Mory (1990) assumed that Kelvin-Helmholtz instabilities resulting from the sloshing motion of the eddies on the interface leads to mixing. An approximate analysis indicates that such a mechanism is unlikely to play an important role in mixing, except at small Ri.

4.0 References

Carruthers, D.J. and Hunt, J.C.R. 1992. Waves, turbulence and entrainment near an inversion layer. Submitted for publication.

Carruthers, D.J. and Moeng, C-H. 1987. Waves in the overlying inversion of the convective boundary layer. *J. Atmos. Sci.*, **44**, 1801-1808.

Deardorff, J.W. 1980. Stratocumulus capped mixed layers derived from a three-dimensional model. *Boundary-layer Meteor.*, **18**, 495-527.

E, X., Hopfinger, E.J. 1986. On mixing across an interface in stably stratified fluid. *J. Fluid Mech.*, **166**, 227-244.

Fernando, H.J.S. and Hunt, J.C.R. 1992. Modelling of turbulent mixing across shear free density interfaces, to be submitted to *Journal of Fluid Mechanics.*

Hannoun, I.A. and List, E.J. 1988. Turbulent mixing at a shear-free density interface. *J. Fluid Mech.*, **189**, 211-34.

Hunt, J.C.R. 1984. Turbulence structure in thermal convection and shear-free boundary layers. *J. Fluid Mech.*, **138**, 161-184.

Moffatt, H.K., 1984. Simple topological aspects of turbulent velocity dynamics. *Proc.* IUTAM Symp. on Turbulence and Chaotic Phenomena in Fluids (ed. T. Tatsumi), Elsevier.

Mory, M. 1990. Models of turbulent mixing at a density interface including the effects of rotation. *J. Fluid Mech.*, **223**, 193-207.

Perera, H.J.S., Fernando, H.J.S. and Boyer, D.L. Wave-turbulence interaction at an inversion layer, to be submitted to *Journal of Fluid Mechanics.*

Phillips, O.M. 1977. Dynamics of the Upper Ocean. Cambridge Univ. Press, 2nd ed.

Turner, J.S. 1968. The influence of molecular diffusivity on turbulent entrainment across a density interface. *J. Fluid Mech.*, **33**, 639-56.

5.0 Publications Resulting from the Contract

Noh, Y. and Fernando, H.J.S., The sedimentation of a particle cloud, to be submitted to *Physics of Fluids*.

Fernando, H.J.S. and Hunt, J.C.R. Modelling of turbulent mixing across shear free density interfaces, to be submitted to *Journal of Fluid Mechanics*.

Perera, H.J.S., Fernando, H.J.S. and Boyer, D.L. Wave-turbulence interaction at an inversion layer, to be submitted to *Journal of Fluid Mechanics*.

Fernando, H.J.S. and DeSilva I.P.D., 1991, Mixing in a stratified turbulent patch. *AIChE annual meeting*., Los Angeles.

DeSilva, I.P.D., Montenegro, L., Brandt, A., and Fernando, H.J.S., 1991 Experiments on the critical-layer absorption phenomena in stratified fluids, *Bull. Am. Phy. Soc.*, 36(10), 2703

Fernando, H.J.S., Hunt, J.C.R., Perera, M.J., and McGrath, J. 1991 Modelling of mixing across shear-free density interfaces, *Bull. Am. Phys. Soc.*, 36(10), 2667.

Hunt, J.C.R., Carruthers, D.J. and Fernando, H.J.S., 1991 Interfaces between different atmospheric and oceanic layers, *SIAM meeting*, Washington D.C., July 06-10.

6.0 Reports of Inventions

none

7.0 Participating Scientific Personnel

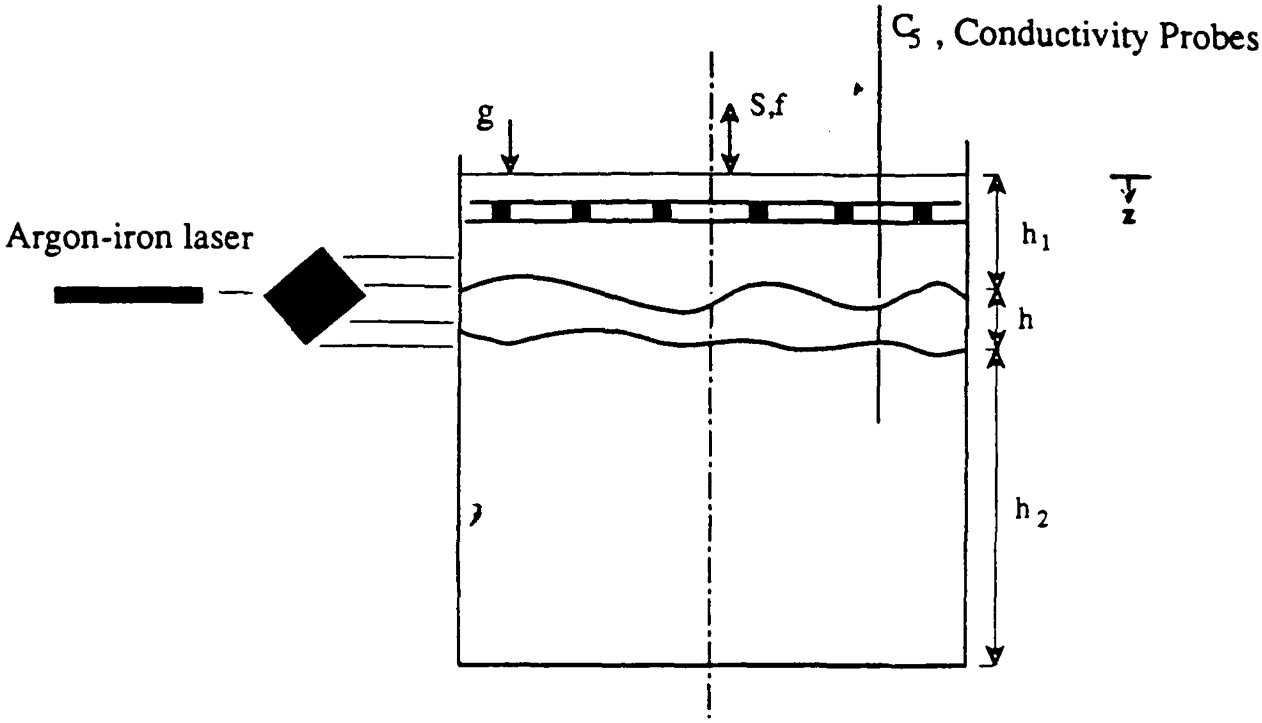
H.J.S. Fernando, Principal Investigator

D.L.Boyer, Co-Principal Investigator

M.J.M.Perera, Graduate Student

C.Y.Ching, Graduate Student

(a)



(b)

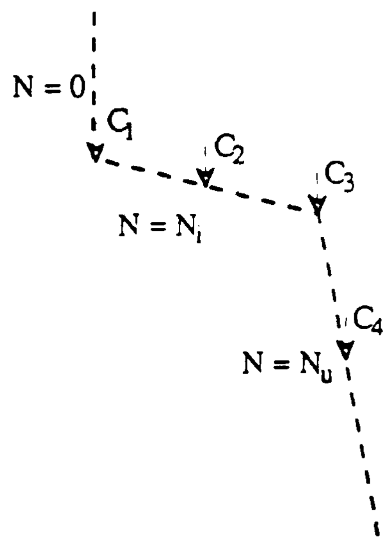


Figure 1. (a) A schematic of the experimental apparatus (b) the three layer stratification used for the experiment. The positions of the conductivity probes are given by C_1, C_2, C_3 and C_4 and the traversing conductivity probe is represented by C_5.