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Turbulent patches in a stratified shear flow

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Turbulence measurements within an artificially generated turbulent patch embedded in a stratified shear flow are presented. The results indicate that the enhanced patch growth that has been observed at background gradient Richardson numbers on the order unity can be attributed to the onset of shear-induced mixing at the patch boundaries rather than enhanced interaction between turbulence and shear that causes increased turbulence levels within the patch. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1949203]

In a recent paper, Fernando[1] described experimental observations on the interaction between a stratified shear flow and an artificially (oscillating-grid) generated turbulence patch within it. The vertical-patch-size measurements were conducted with and without shear, under otherwise identical conditions, and the patch size with shear was found to be significantly larger than its nonsheared counterpart when the gradient Richardson number of the background flow, $\mathrm{Ri}_g = N^2/(dU/dz)^2$, where N is the buoyancy frequency and (dU/dz) is the vertical shear, was smaller than a critical value Ri_c, which is on the order unity (more specifically $\mathrm{Ri}_c \approx 1.2$). Two mechanisms were proposed to explain the observed larger patch sizes for $\mathrm{Ri}_g < \mathrm{Ri}_c$: (i) enhanced interaction of patch turbulence with background shear that leads to additional turbulence generation, and thus higher turbulence intensities within the patch and (ii) onset of interfacial instabilities and turbulent mixing at the density interfaces bounding the patch (patch edges) due to enhanced shear across them. No turbulence measurements were available to investigate whether high levels of turbulence are tenable within the patch at $\mathrm{Ri}_g < \mathrm{Ri}_c$. Such measurements are presented in this paper to verify the hypothesis (i).

The experimental apparatus and procedure are described in detail in the work by Fernando.[1] The experimental flow configuration consisted of two counterflowing fluid layers of different densities and equal heights h_L, the lighter layer above the denser layer, so as to form a stably stratified shear layer between them. This layer was found to have approximately hyperbolic velocity and density profiles. The upper layer consisted of a water/alcohol mixture whereas carefully prepared saline water that has the same refractive index as the upper layer was in the lower layer. The spatial uniformity of refractive index permitted the use of optical (laser) techniques for flow diagnostics. The counterflow in the apparatus was created first and it was allowed to achieve a steady state. Then a turbulent patch was generated by oscillating a grid (made of wire mesh) at the center of the interface between two flowing layers. The velocity measurements were made using a two-component laser-Doppler velocimeter along a vertical line close to the center of the grid. The measurement locations were sufficiently away (2.5 cm) from the vertical oscillating rod (diameter 0.4 cm) that powered the grid. The density profiles were made using a traversing microscale conductivity probe. The grid forcing (oscillation frequency, amplitude) and the velocity difference ΔU between the layers were maintained approximately the same for all experiments, but the background Richardson number Ri_g was varied by changing the density difference (buoyancy jump) between the layers. The Reynolds numbers of the experiments $\Delta U h_L/\nu$, where ν is the kinematic viscosity, were on the order 7500. The horizontal turbulence intensities $\sqrt{u'^2}$ within the patch were measured at predetermined distances away from the center of the patch, and its value normalized by ΔU was used to evaluate whether there is an enhancement of turbulent kinetic energy production in the patch as $\mathrm{Ri}_g \to \mathrm{Ri}_c$. The rms measurements utilized 25 s velocity traces obtained at 150 Hz.

The properties of the turbulent patch within the stratified shear layer, generated by the grid (specified by the "action" parameter K), are expected to be a function of the thicknesses of the velocity shear layer δ_u and the density interfacial layer δ_b, overall density Δb and velocity ΔU jumps between the layers, grid action K, and the distance z from the grid plane. This means that quantities such as $\sqrt{u'^2}$ and the patch thickness h_p are functions of these parameters, viz,

$$\sqrt{u'^2} = \pi_1(K, \delta_u, \delta_b, \Delta b, \Delta U, z), \tag{1a}$$

$$h_p = \pi_2(K, \delta_u, \delta_b, \Delta b, \Delta U, z), \tag{1b}$$

where π_1, π_2, … are functions. From (1a) and (1b) it follows that

$$\sqrt{u'^2} = \pi_3(h_p, \delta_u, \delta_b, \Delta b, \Delta U, z), \tag{2}$$

which leads to the dimensionless form

$$\frac{\sqrt{u'^2}}{\Delta U} = \pi_4\left(\mathrm{Ri}_g, \frac{h_p}{\delta_u}, \frac{\delta_b}{\delta_u}, \frac{z}{h_p}\right). \tag{3}$$

Note that the grid action K was replaced by h_p to give a physical underpinning for dimensional analysis so that certain limiting cases can be evaluated. Given that the shear production of turbulent kinetic energy first feeds into the

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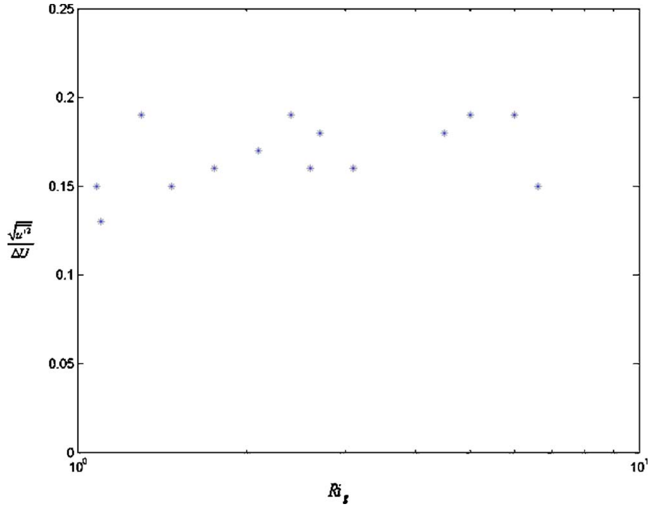

FIG. 1. A plot of normalized rms velocity in the patch at a distance $z/h_p \sim 0.75$ as a function of Ri_g.

horizontal component and then, via intercomponent energy transfer, to the vertical component, the emphasis was on $\sqrt{\overline{u'^2}}$. When $h_p/\delta_u \ll 1$, $\delta_b/\delta_u \approx$ constant and for a given z/h_p, (3) can be written as

$$\frac{\sqrt{\overline{u'^2}}}{\Delta U} = \pi_5(\mathrm{Ri}_g). \qquad (4)$$

Figure 1 shows a plot of $\sqrt{\overline{u'^2}}/\Delta U$ as a function of Ri_g for a given z/h_p (≈ 0.75). This particular selection of z/h_p was made as it is sufficiently close to the central region of the patch and also away from the grid plane (to avoid strong grid forcing effects). Other parameters of relevance were $0.25 < h_p/\delta_u < 0.6$, with an average h_p/δ_u of 0.36, and $\delta_b/\delta_u \approx 0.3-0.4$. The measurement error estimates are ±10% at low $\mathrm{Ri}_g(<3)$ and ±20% at high Ri_g. Note that there is no clear increase of $\sqrt{\overline{u'^2}}/\Delta U$ as $\mathrm{Ri}_g \to \mathrm{Ri}_c$. This, together with the fact that there was only a little variation of ΔU among different experiments, indicates that the marked growth of the patch size observed as Ri_g approaches unity could not be due to the increase of turbulent intensity as a result of enhanced turbulence-shear interaction. Further, if an increase in rms velocities causes the patch size h_p to grow according to the usual parametrization[1] $h_p \sim \sqrt{\overline{u'^2}}/N$, the ratio $h_p/\sqrt{\overline{u'^2}}/N$ is expected to be a constant, irrespective of Ri_g. As shown in Fig. 2, this is not the case, and a clear increase of this ratio can be seen as $\mathrm{Ri}_g \to 1$. Both of these results point to the possibility of the onset of shear (Kelvin-Helmholtz) instabilities-induced interfacial mixing at the upper and lower patch boundaries at $\mathrm{Ri}_g < \mathrm{Ri}_c$. The measurements presented herein resolve one of the key issues raised in our previous paper[1] with regard to the behavior of turbulence patches in stratified fluids.

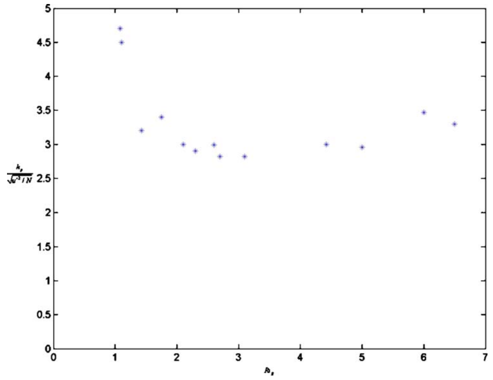

FIG. 2. A plot of normalized patch height $h_p/(\sqrt{\overline{u'^2}}/N)$ as a function of Ri_g.

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[1] H. J. S. Fernando, “Turbulent patches in stratified shear flows,” Phys. Fluids **15** 3164 (2003).