On characterizing irreversible mixing and diffusivity in shear-induced stratified turbulent flows

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The characteristic behavior of irreversible diapycnal mixing efficiency ($\mathcal{E}$) as well as the associated diffusivities of mass (K_ρ) and momentum (K_m) have remained insufficiently understood for stratified turbulent flows. Based on idealized studies of homogeneous sheared and stratified turbulence of [1], in which the background density and stratification are forced to remain constant in time, it has been shown that K_ρ may be uniquely characterized by buoyancy Reynolds number defined as $Re_b = \varepsilon_k/(\nu N^2)$ (with ε_k and N denoting viscous dissipation and buoyancy frequency respectively). However, it has been unclear whether this characteristic behavior is exclusive to the specially designed model problem of [1] or whether it might also be realized in more realistic examples of stratified turbulent flow. In order to address this issue, we have performed an extensive series of Direct Numerical Simulations (DNS) of an evolving Kelvin-Helmholtz wave and have focused on the turbulence that is generated once the wave "breaks" [2, 3]. A fundamental problem arises in the course of such analysis concerning the need for an accurate representation of K_ρ, which requires isolation of irreversible mixing from reversible stirring. In order to address the latter issue, we have had to moderately revise the "diascalar" framework of [4] which has led us to derive an "Osborn-like" formula for K_ρ which critically depends on Re_b and $\mathcal{E}$ but involves none of the limiting assumptions of the original Osborn formula [5]. Our relationship is the following:

$$\frac{K_\rho}{\kappa} = \left(\frac{\mathcal{E}}{1-\mathcal{E}}\right) Pr Re_b, \tag{1}$$

in which κ is the molecular diffusivity, $\mathcal{E}$ is the irreversible mixing efficiency and Pr is the molecular Prandtl number. By employing this revised definition of K_ρ, we have been able to more generally establish the characteristic dependence of K_ρ on Re_b for a wide range of Re_b that is similar to [1] including the existence of a transition to a different regime of mixing at approximately $Re_b = \mathcal{O}(10^2)$ (see figure 1). It is interesting that the recent experimental investigation of [6] on stratified shear flows down an inclined duct also suggests a transition to a different regime of mixing at approximately $Re_b = 100$ based on length scales of the flow structures observed in their shadowgraph images.

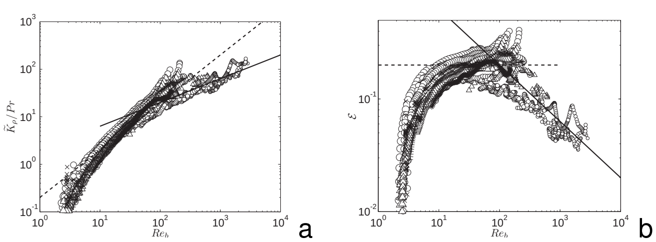

Fig. 1: An illustration of the Re_b-dependence of K_ρ/ν (a) and $\mathcal{E}$ (b) based on a compilation of all our DNS analyses.

In this talk, we will further elaborate upon the findings in [3] which also includes revised expressions for the eddy diffusivity of momentum K_m and turbulent Prandtl number $Pr_t = K_m/K_\rho$ as well as their characteristic dependence on both Re_b and the vertically-averaged gradient Richardson number Ri_b. Possible mappings between Re_b and Ri_b will be suggested for $Re_b > 100$ or $Ri_b < 0.2$.

References

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