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How does turbulence mix a stratified fluid?

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A principal topic of interest and importance in stably stratified flows is how turbulence irreversibly mixes the ambient density field. Because the density field is coupled dynamically to the velocity field through the stable stratification, this mixing affects the overall flow dynamics, and its accurate parameterisation has become a 'grand challenge' in environmental fluid mechanics (Dauxois *et al.*, *Phys. Rev. Fluids*, vol. 6, issue 2, 2021, 020501). In order to better understand the detailed kinematics of mixing in a stably stratified fluid, Jiang *et al.* (2022) perform experiments using a unique laboratory facility, capable of generating controllable stratified shear flows, and providing almost instantaneous density and three-component velocity measurements on a high-resolution, three-dimensional grid. Using three-dimensional data sets from the experiments, they employ the rortex–shear decomposition to identify the morphology of instantaneous rortices in the flow fields, leading to the interpretation of the motion of the rortices and ultimately to how the rortices cause irreversible mixing of the density field. This marks one of the first studies where, in a laboratory setting, full use has been made of somewhat high-resolution, three-dimensional near-instantaneous measurements; it demonstrates what can be accomplished in the laboratory, setting a new standard for future experiments.

Key words: stratified flows, stratified turbulence, turbulent mixing

1. Introduction

Understanding and predicting the nonlinear interplay between the velocity and density fields in turbulent stably stratified fluids is an important goal in geophysical fluid mechanics. The turbulence can irreversibly mix the density field, causing changes in its ambient structure, and thereby affecting the flow field and the turbulence itself. The stable stratification can not only inhibit the vertical transfer of chemical species, but also support the propagation of internal waves. And internal waves in turn often break down into turbulence, causing more mixing. So, for example, in ocean simulations, it is a 'grand challenge' to accurately parameterise the small-scale mixing in larger-scale

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models in order to improve predictions for the vertical transport of heat, carbon dioxide, salt and other scalars in the ocean (Dauxois *et al.* 2021). The accurate modelling of the turbulent mixing and resultant turbulent fluxes is important not only in predicting the overall ocean circulation (Jayne 2009), but also the effects of horizontal circulation, meridional overturning and poleward heat transport (Gregg *et al.* 2018).

There have been a number of studies addressing turbulence in stably stratified fluids, including field studies in the atmosphere and ocean, laboratory experiments and direct numerical simulations (see e.g. the reviews of Gregg *et al.* (2018) and Caulfield (2021) for discussions of many of these). Direct numerical simulations have addressed turbulent shear flows (e.g. Mashayek & Peltier 2013; Salehipour, Peltier & Mashayek 2015), homogeneous turbulence (e.g. Riley, Metcalfe & Weissman 1981; Shih *et al.* 2005) and stratified boundary layers (e.g. Garcia-Villalba & del Alamo 2011; Shah & Bou-Zeid 2014). Numerical simulations have the advantage that the entire flow field is known at each point in space and time, so that detailed evaluations of the dynamics, including local structures, can be examined. These simulations are limited, however, in terms of the range of the available parameters. For example, in numerical simulations of turbulence, because of resolution requirements, the Prandtl number, ν/κ, cannot be varied too far from the value of 1. Here, ν is the kinematic viscosity and κ the mass diffusivity of the fluid. A principal interest, however, is in flows with Prandtl numbers characteristic of the oceans and estuaries, where the main variation of density is often due to temperature (Prandtl number around 7) or to salt concentration (Prandtl number of several hundreds), or both. Theoretical analysis and numerical simulations have shown that even a modest variation of the Prandtl number can have a significant effect on turbulent mixing (Salehipour *et al.* 2015). Laboratory experiments of turbulence in stably stratified fluids, often using salt to vary the ambient density, have been used effectively to study turbulence. But these experiments are usually limited in Reynolds number and in the details of the flow to be explored, and are restricted to point-wise measurements, or more recently to planar measurements, and only snapshots are available rather than time-resolved measurements. The research presented by Jiang *et al.* (2022) reports on the use of a very advanced experimental facility to study stratified shear flows, the stratified inclined duct (SID). In addition to the systematic variation of two key non-dimensional flow parameters, allowing a broad range of dynamics for study, the facility allows for the measurement of the three-component velocity and the density fields in three dimensions, and with high spatial and temporal resolutions, essentially coming close to the capabilities of direct numerical simulation, but at Prandtl numbers characteristic of geophysical flows. In addition, the authors use the recently developed rortex–shear decomposition, enabling them to more accurately follow the structures that develop in their stratified shear flows, and ultimately determine how the fluids mix.

2. Overview

The authors use a SID, as shown in figure 1. An exchange flow takes place through a rectangular duct connecting two large reservoirs initially filled with aqueous salt solutions at densities $\rho_0 \pm \Delta\rho/2$; the inclined duct is at an angle θ with respect to the horizontal. The Prandtl number is approximately 700, the length of the duct is $L = 1350$ mm, while the height and width are both $H = 45$ mm.

Essentially, two non-dimensional parameters can be used to control the flow, the angle θ and the Reynolds number $Re \propto \sqrt{g(\Delta\rho/\rho_0)H}H/\nu$, where g is the acceleration due to gravity. The Reynolds number is primarily set by the density difference. The authors choose to address the Holmboe instability and resulting turbulence by a series

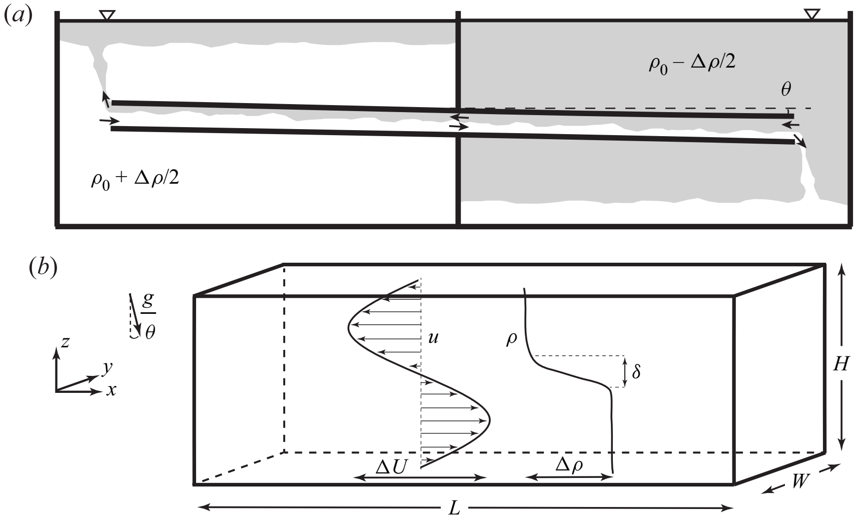

Figure 1. (*a*) Stratified inclined duct, in which exchange flow takes place through a rectangular duct connecting two reservoirs. (*b*) Notation. The x and z axes are, respectively, aligned with the horizontal and vertical of the duct, and $-z$ makes an angle θ with gravity, where $\theta > 0$ (from Lefauve & Liniden 2020).

of experiments of increasing strength. By varying Re and θ, the authors considered 15 data sets, with 4 in the Holmboe instability regime, 8 in the transitioning regime and 3 in the turbulence regime. Both symmetric and asymmetric Holmboe flows are considered. The authors employ the novel laser-sheet-scanning technique of Partridge, Lefauve & Dalziel (2019) in which particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) are performed in successive vertical planes, giving 'near-instantaneous' volumes of the three-dimensional velocity and density fields.

The research reported in the paper is essentially data driven, and the information obtained is mainly kinematic. It has the objectives of exploring how vortical motions, especially hairpin vortices, develop and evolve in flows from pre-turbulent to fully turbulent, and how the vortices interact with the density interfaces, participating in the interface overturning, stirring and ultimately mixing. In order to analyse and visualise the vortices, the authors use the recently developed rortex–shear decomposition (Gao & Liu 2018; Liu *et al.* 2018). This decomposition splits the vorticity field into a purely rotational part (the rortex vector), and a pure shearing part, and enables excellent identification of the vortical structures, especially the hairpin vortices.

The authors analyse the series of experiments in great detail, identifying the vortical structures, then presenting the detailed morphology of the rortices. Of special interest to the authors is the interactions of the vortices with the density gradients and density interfaces. Examples of some of their key results are synthesised in figure 2. This figure is from a case with higher values of θ and Re, and with stronger rortex–density interactions. At the point in time of the figure, the density field consists of a partially mixed layer bounded by two density interfaces. In the figure the position of several rortices is presented according to their positions in the layer, with rortices either on a density interface or within the partially mixed layer. The figure displays longitudinal rortices (in green and labelled RL) and transverse rortices (in magenta and labelled RT). The authors explain that a rortex across the interface, for example the rortex labelled 1 in figure 2(*a*), acts to lift the inner (premixed) denser fluid away from the upper interface and entrains outer lighter fluid into

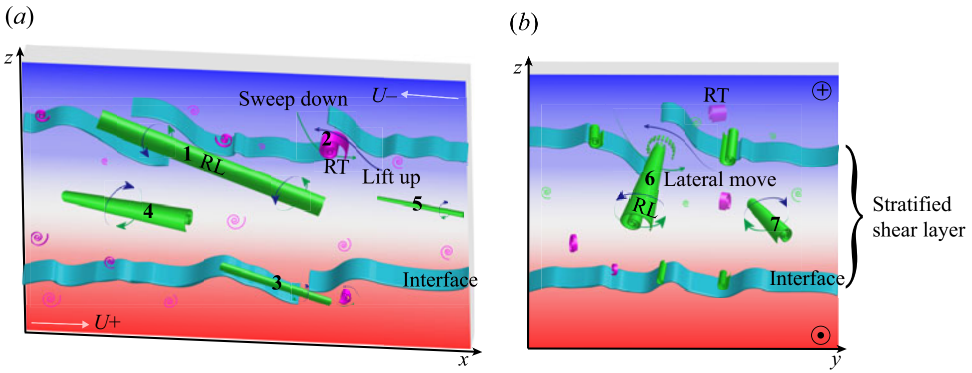

Figure 2. Schematic view of turbulent rortices near a density interface and within a partially mixed layer. (*a*) Side view (x–z plane). (*b*) Cross-sectional view (y–z plane). RL, longitudinal rortex (green) with R primarily along x; RT, transverse rortex (magenta) with R primarily along y (from Jiang *et al.* 2022).

the shear layer. Meanwhile the rortices within the shear layer, such as rortices 4 and 5, contribute little to the mixing of density. With detailed analysis of such structures, the authors are able to build a comprehensive morphology of how the turbulent shear layer mixes.

3. Summary

In this paper the authors present a carefully planned and executed series of laboratory experiments addressing stratified shear flows ranging from unstable flows, to transitioning flows to fully turbulent flows. The experiments resulted in several noteworthy advances: the successful utilisation of the SID facility with the implementation of PIV and PLIF to obtain high three-dimensional spatial resolution and nearly instantaneous temporal resolution of the density and the three-component velocity fields; the effective use of the rorticity–shear decomposition to analyse in depth the vortical character of the flow and, in particular, the interaction of the rortices with the density field; detailed, careful analysis and interpretation of the resulting flow fields. Their research leads to a comprehensive description of how the turbulence in the flows irreversibly mix the density field.

The information obtained in the paper is mainly kinematic. What awaits next for the authors is to continue with this sequence and examine the dynamical role that these vortices play in the overall turbulence energetics and mixing.

Declaration of interests. The author reports no conflict of interest.

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