ENTRAINMENT OF A TURBULENT PATCH IN A STRATIFIED FLUID

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Abstract Turbulent patches are localized events of turbulence, typically characterized by sharp differences between the flow characteristics across their interfaces. These localized events might add to the global mixing, heat exchange and mass transfer, playing a non-negligible role in the total energy balance in lakes or the ocean. This study takes a detailed look at the inner structure of a localized, mechanically forced patch in a linearly stratified ambient using laboratory experiments utilizing synchronized PIV and PLIF. The results point out that the role of the turbulent/non-turbulent interface at the edge of the patch could be significant in determining the growth rate and the maximum size of the patch.

INTRODUCTION

The localized turbulent mixing events in a stably stratified environment is a regularly recurring phenomenon in the deep ocean and other geophysical flows. The process concerns the penetrating of a turbulent region into a quiescent zone via turbulent entrainment. This process is typically quantified by two parameters, namely the entrainment coefficient, E and the turbulent buoyancy flux, $w'b'$. The entrainment coefficient E can be defined as a rate of penetration to the turbulent velocity fluctuations, for instance $E = d\delta/dt/\sqrt{q}$ where $q = \frac{1}{2}\langle u'^2 + w'^2\rangle$ is the turbulent kinetic energy and δ the mean vertical extent of the turbulent region. The turbulent buoyancy flux is denoted $\langle w'b'\rangle$ where w' and b' are the turbulent vertical velocity and buoyancy fluctuations, $b = g(\rho_0 - \rho)/\rho_0$ (ρ_0 is a reference density, g is gravity). Both parameters E and $w'b'$ describe how the diapycnal transport drives the mixing against the stabilizing effect of the ambient stratification. Studies of the wakes of self-propelled bodies [5, 7] and one/two-dimensional mechanically stirred patches [2, 3] provided detailed descriptions of the growth rates and report on a finite interval of growth of the patches. It was proposed that there is a time instant $Nt = 2 \div 4$, that depends on stratification and forcing (or a degree of mixing) at which the initial fast growth of the patch halts. After that time, if the patch is forced, it can grow slowly through a mechanism of zero-frequency horizontally propagating internal waves or if it is not continuously forced (like a wake), then it collapses and creates horizontal intrusions.

EXPERIMENTAL SETUP

The experimental setup introduces turbulence into the system using the vertical oscillation of a finite grid, the advantage being that it has been widely studies and characterised. The current study uses an experimental apparatus that isolates and catches the essence of turbulent mixing by generating a 3D finite localized turbulent patch in a linearly stratified fluid. The turbulence intensity is controlled by variation of the oscillation frequency of the grid.in the range of $3 \div 8$ Hz. Following McDougall [4], we matched the index of refraction of two different water solutions of Epsom Salts ($MgSO_4$) and sugar in order to create a stable stratification suitable for optical measurements. The experimental procedure allows to obtain a density difference of 20 kg/m^3 between the bottom of the aquarium and the free surface, keeping the maximum difference in the index of refraction at $\Delta n < 0.00001$. The degree of the stratification can be characterised by the Brunt-Väisäilä frequency N , which is defined as $N^2 = \frac{g}{\rho_0}\frac{d\rho}{dz}$, where ρ_0 is the density at mid-depth, and $d\rho/dz$ is the density gradient in the vertical direction. The linear density profile is confirmed to correspond to a buoyancy frequency of $N = 1 rad/s$ via a pycnometer. The grid was operated by an eccentric motor for 8 seconds and stopped, whilst the data was acquired continuously for a longer time. The Reynolds numbers based on the mesh size M and the r.m.s. of turbulent fluctuations in the patch were $Re = u'_{rms}M/\nu = 50 \div 150$ and the respective range of Froude numbers was $Fr = u'_{rms}/MN = 0.5 \div 1.50$. Optical measurements including synchronized Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) have been performed to capture the entire life cycle of the patch until it reaches a critical height followed by the eventual collapse.

RESULTS

The simultaneous capture of density and velocity fields allows the direct determination of 2-D fields of turbulent kinetic energy, enstrophy, buoyancy and buoyancy flux which can be related to the external parameters. The patch thickness was determined from the combined PIV/PLIF measurements in a variety of ways, using velocity, buoyancy or their derivatives. The turbulent/non-turbulent interface was identified using three different methods based on fixed thresholds

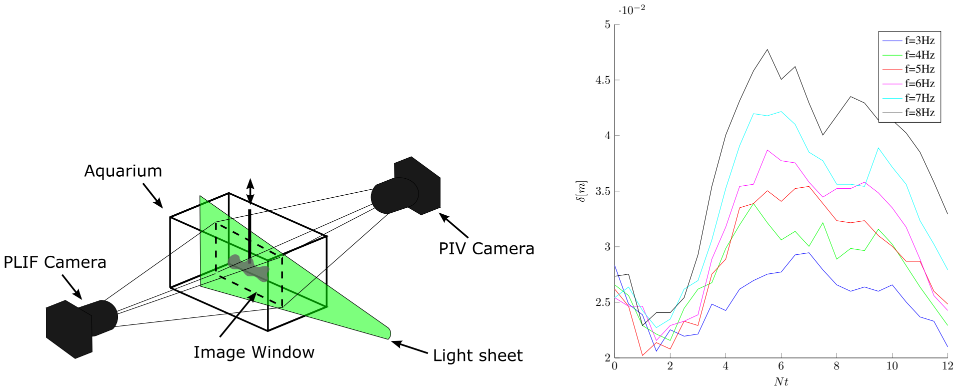

Figure 1. (left) Experimental setup scheme and (right) and mean vertical size of the patch varying the frequency.

of the vorticity magnitude, the velocity magnitude and the density [6]. Around the time of collapse, for $Nt = 4 \div 6$, the profile of the turbulent buoyancy flux changes sign (Fig.2a) from negative to positive, which is indicative of patch collapse. This statement is supported by the fact that the entrainment coefficient E peaks at a similar time as the sign inversion of $\langle w'b' \rangle$ (at $Nt \simeq 4$; see Fig 2.b). We note that $\overline{w}$ was much smaller than $\sqrt{TKE}_{max}$ and thus that E should be representative of turbulent processes. The patch growth slows down after $Nt \simeq 4$ and stops completely at $Nt \simeq 6$ when $E = 0$.

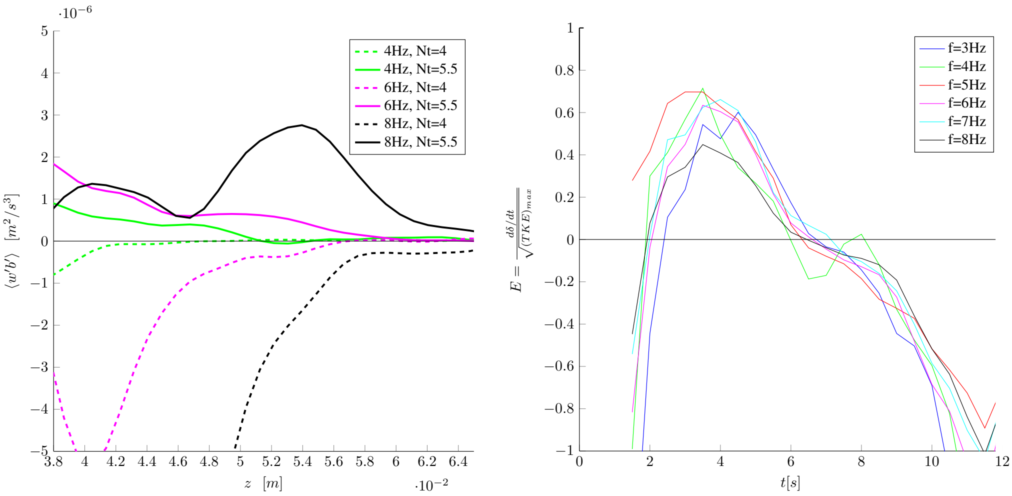

Figure 2. (left) Time evolution of the spatially averaged buoyancy flux, $\langle w'b' \rangle$ as a function of distance z from the grid, for time instants Nt for the case of 4,6, and 8 Hz. (right) Time evolution of the entrainment coefficient varying the frequency.

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