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Shear-Dominated Turbulence in a Vertical Buoyancy Layer

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1. INTRODUCTION

Natural convection boundary layers on vertical heated surfaces are ubiquitous in geophysical and industrial settings and have consequently been the subject of extensive research for several decades. However, a comprehensive understanding of the turbulent structure remains incomplete. We address this knowledge gap by analysing a series of direct numerical simulations (DNS) of a vertical buoyancy layer, a canonical model for natural convection immersed in a stably stratified ambient medium [1]. These simulations were conducted at a constant Prandtl number of $Pr = 0.71$ and cover a Reynolds number range of $800 \leq Re \leq 2800$. The Reynolds number is defined as $Re = (g\beta\Delta T\delta_l^3)/(2\nu^2)$, where $\delta_l^2 = 2(\nu\alpha)^{1/2}/N$, ν is the kinematic viscosity, α is the thermal diffusivity, N is the buoyancy frequency, g is the acceleration due to gravity, β is the coefficient of thermal expansion and ΔT is the temperature difference between the heated wall and the ambient. Figure 1 shows a representative visualisation of the instantaneous flow structure. In this work, we synthesise the findings from our multi-year DNS campaign and show that despite the flow being solely driven by buoyancy, the turbulence production, structure, and scaling are governed by mechanisms analogous to canonical shear-dominated flows.

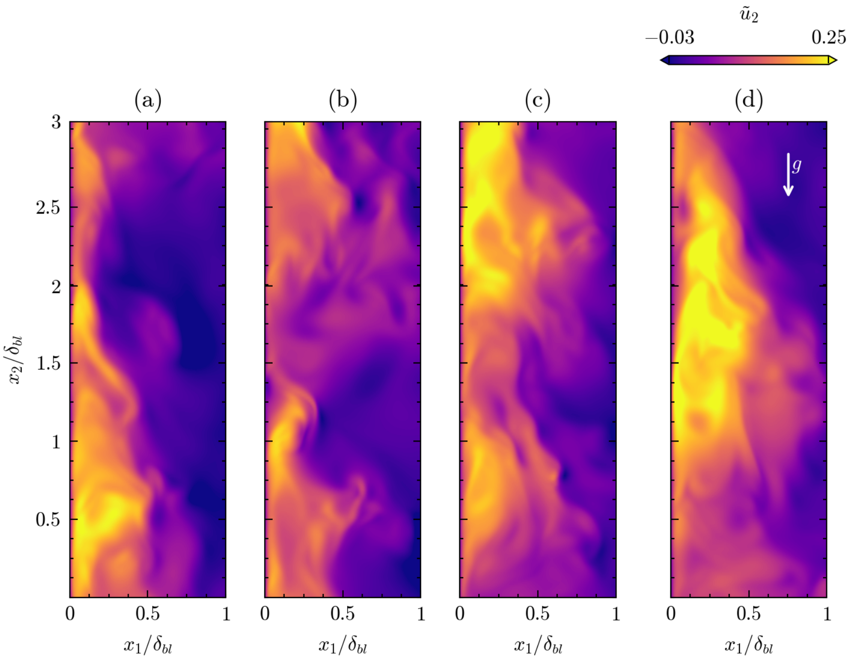

Figure 1. Instantaneous snapshots of the streamwise velocity field, $\tilde{u}_2$, across a streamwise–wall-normal ($x_2 - x_1$) plane at $Re = 800$. Gravity, g, acts downwards, and the fluid flows upwards. Coordinates are normalised by the boundary-layer thickness, δ_{bl}, as defined in [2]. The heated wall is at $x_1/\delta_{bl} = 0$. Only a portion of the entire domain is shown.

2. THE TURBULENT STRUCTURE

The outer layer (the wall-normal region beyond the velocity maximum) of the turbulent buoyancy layer is populated by energy-containing Large-Scale Motions (LSMs) of streamwise velocity fluctuations. These meandering structures exhibit significant streamwise and wall-normal coherence, all characteristic of canonical wall turbulence (e.g., in pipes, channels and zero-pressure-gradient flat-plate boundary layers) [2].

In the 'classical regime', i.e., at moderate Reynolds numbers, the inner layer (the wall-normal region between the heated wall and the velocity maximum) does not exhibit the organised streaks found in canonical wall turbulence. Despite this, turbulence is sustained locally by autonomous and self-sustaining 'Self-Contained Bursts' of Q2-Q4 Reynolds shear stress events (a local cycle of sweeps and ejections), a mechanism fundamental to canonical wall turbulence [3]. This near-wall cycle is autonomous and persists even without the outer bulk flow. It is also largely insensitive to the thermal boundary condition imposed at the wall (constant temperature versus constant heat flux) [4].

The prevalence of statistical structures and dynamics of canonical wall turbulence in the inner and outer layers suggests that the turbulent vertical buoyancy layer should adhere to the universal statistical laws governing shear-dominated turbulence. We confirm this by examining the longitudinal structure functions of the flow. While individual longitudinal structure functions are not universal, their relative scaling, quantified by the energy ratio, exhibits a universal, sub-Gaussian behaviour. This is characterised by a phenomenological model that links the energy-containing range to the anomalous scaling exponents of the inertial subrange [5]. All the above observations, therefore, indicate that the turbulence (its structure, dynamics, and scaling) in a vertical buoyancy layer is largely governed by the principles of shear-driven flows across most of the boundary layer.

These structural and statistical similarities lead us to argue that the primary role of the buoyancy field is not to modify the turbulence structure directly, but rather to establish a mean shear profile that sustains it. Consequently, the influence of buoyancy can be encapsulated within global scaling parameters such as the Richardson and friction Reynolds numbers [6], reducing its role to that of a scaling variable, at least to a first-order approximation. This perspective allows us to unify certain aspects of buoyancy-driven boundary layers with shear turbulence, opening up new avenues for modelling and prediction.

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