ON THE INTERACTIONS BETWEEN MEAN SHEAR AND NATURAL CONVECTION IN TURBULENT MIXED CONVECTION

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In many systems involving turbulent flows, both mean shear and natural convection have relatively strong effects in such a way that one cannot be neglected compared to the other. In this situation, the interplay between shear and buoyancy-driven convection brings the system into a new flow configuration known as unstably stratified pressure-driven flows or mixed convection. Under particular conditions, this type of multi-physics flows can eventually organize as horizontal convective rolls aligned with the mean flow direction (see Figure 1a)).

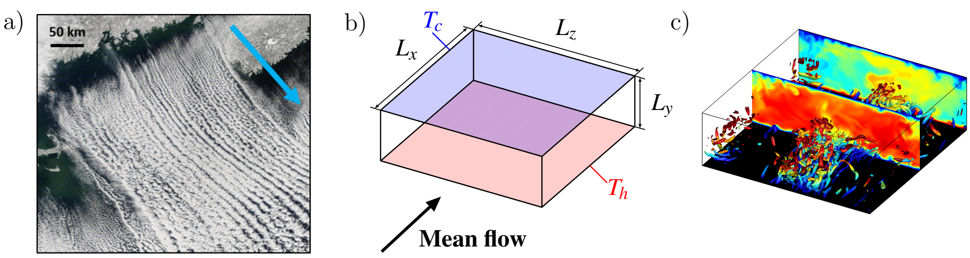

Figure 1. a) Horizontal convective rolls in the atmospheric boundary layers also known as cloud streets. The blue arrow indicates the direction of the mean wind. b) Simulation setup. c) Three-dimensional views of an instantaneous flow field for $\mathrm{Re}_\tau = 180, \mathrm{Ri}_\tau = 6.25$ and $\mathrm{Pr} = 0.71$. Isosurfaces of Q-criterion colored by their distance from the bottom wall (blue being the wall and red being the channel centerline) are shown for a volume corresponding to the bottom half of the channel. The front slice shows the streamwise velocity distribution u/u_τ in a cross-flow plane whereas the rear one shows the temperature field T/T_w.

Although several relevant studies have been conducted to investigate specific aspects of the horizontal convective rolls dynamics, the physical mechanisms driving the flow and their consequences on the turbulent transport remain poorly understood. For instance, it is still unclear how interactions between mean shear and unstable stratification modify the spatial distribution of momentum and heat. Can the bulk velocity increase under unstable stratification? How do stresses organize at statistically-steady equilibrium? Does the large-scale vortical motion create or convey turbulence? How and at which scale is energy transferred between potential, mean kinetic and turbulent kinetic energies? These are among the key questions we try to answer in the present work.

Fully resolved direct numerical simulations of unstably stratified pressure-driven flows are performed in the computational domain depicted in Figure 1b) and flow fields are post-processed to extract relevant flow features. The domain is doubly periodic along the stream-wise and span-wise directions whereas no-slip and isothermal conditions are applied to the channel walls. The Navier-Stokes equations are solved under their incompressible form jointly with an advection-diffusion equation for the temperature. The coupling between the two is achieved using the Boussinesq approximation. The aspect ratios of the computational domain are $\Gamma_{xz} = L_x/L_z = 1$ (square box) and $\Gamma_{xy} = L_x/L_y = \pi$. We consider two Reynolds numbers associated to the turbulent mean flow, $\mathrm{Re}_\tau = 180, 395$ and two different Prandtl numbers, $\mathrm{Pr} = 0.71, 7.0$. The relative magnitude of the buoyancy compared to the mean shear is measured by the Richardson number $\mathrm{Ri}_\tau = \mathrm{Ra}_\tau / \left(\mathrm{Re}_\tau^2 \mathrm{Pr}\right)$ which span from 0 to 80 to explore the interactions for different level of buoyant activity. Instantaneous fields of velocities/temperature and isosurfaces of Q-criterion are visualized to provide a qualitative description of the dynamics (see Figure 1c)). In addition, cross-flow two-dimensional steady-state statistics of various quantities such as mean momentum, temperature, turbulent stress or energies are reported to measure the effects of multi-physics interactions. Finally, spectra of velocity/temperature fluctuations are evaluated at different locations to evaluate how the spatial scales are affected. The study results show that the the bulk velocity can either increase or decrease depending on the flow conditions. An enhanced flow rate is observed for moderate Richardson numbers when the Reynolds number of the pressure-driven flow and the Prandtl number are low enough to feed a strong and coherent rotational mean motion of rolls that efficiently transport turbulence further from the channel boundary layer. The flow rate decreases for all the other flow conditions considered. The combination of both forced and natural convection increases the Nusselt number for every case. The way turbulence is created and transported drastically changes under strong mean shear/buoyancy interactions. The dynamical effects of these interactions are discussed based on the spatial distribution of the different terms of the energies budgets and spectral density distributions.