DIRECT NUMERICAL INVESTIGATION OF THE STABLY-STRATIFIED EKMAN LAYER

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Abstract We study with DNS the stably stratified turbulent Ekman layer at moderately high Reynolds number, $1600 < Re < 2500$. Following the standard conventions, Re is defined with the laminar Ekman layer thickness $\delta_E = \sqrt{2\nu/f}$ and the geostrophic wind G . The stratification is quantified by the friction Monin-Obukhov lengthscale L^+, which varies from $L^+ = \infty$ down to $L^+ \approx 300$. In the case with the strongest stratification, laminar and turbulent patches in the form of inclined bands coexist in the flow whereas in cases with weaker stratification the turbulence is continuous but strongly affected by stratification. We present one-point and two-point statistics and investigate the influence of rotation and stratification on the length scales and boundary layer height.

INTRODUCTION

Atmospheric boundary layers which develops during nights with clear sky and/or over Arctic regions are subjected to strong cooling near the ground causing a stable stratification within the flow. Strongly stratified boundary layers are characterised by several specific phenomena such as the suppression of the vertical motions, the appearance of laminar patches, strong intermittency and the development of internal waves. The investigation of the effect of stratification in wall-bounded turbulence has recently been addressed in a number of numerical studies which have mostly considered canonical flow types as channel flow [5] and open-channel flows [7, 4, 3], not considering the presence of rotation. The first numerical simulations of a rotating boundary layer, the so-called Ekman layer, done by [1] at $Re = 400$ was recently extended to larger Re, reaching up to $Re = 2828$ [8]. The stably stratified Ekman layer has only been simulated at rather low Re (*e.g.* [2, 6]). In this study we simulate the stably stratified Ekman layer at higher Reynolds numbers than previously considered, $1600 < Re < 2500$, which gives rise to a larger scale separation in the flow and also allows us to introduce a stronger stratification, which was previously prevented by the flow relaminarization.

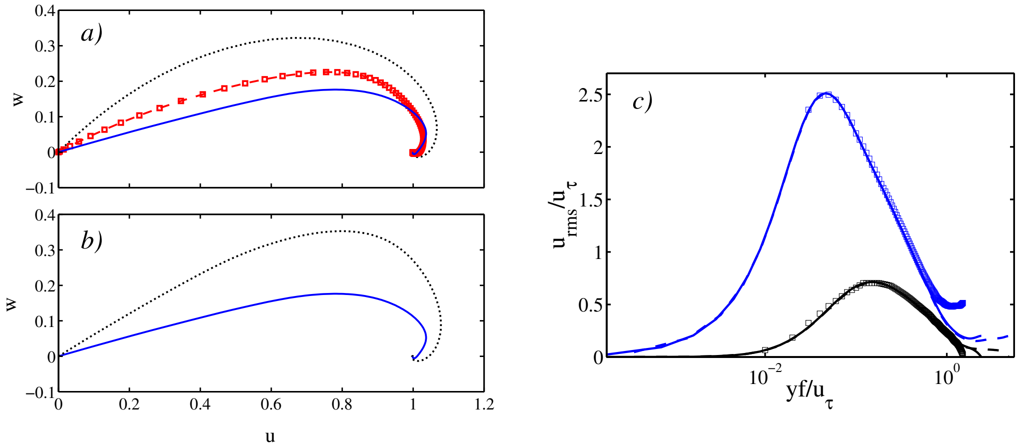

Figure 1. *a)* and *b)* Ekman spiral; *a)* unstratified simulations at ---- $Re = 400$ and —— $Re = 1600$ (presently only marginally resolved); □ [6] and ········ laminar spiral. *b)* Stratified simulations: —— $Re = 1600$ and $L^+ = \infty$; ········ $Re = 1600$ and $L^+ = 300$. *c)* horizontal and vertical rms velocity fluactuations at $Re = 400$. —— $Ly = 2.4$; ---- $Ly = 4.8$; □ [6]. Ly refers to the computational box height.

PRELIMINARY RESULTS

Fully resolved DNSs are carried out using a pseudo-spectral code. Fourier expansions are used in the horizontal directions, whereas half-Chebyshev polynomials are employed in the vertical direction in order to allow for a non-uniform grid with a clustering of points only at the lower boundary. For open channel flows, the latter proved to give a considerable speed-up compared to full-Chebyshev methods. The code has been validated for unstratified cases at low Re, both for non-rotating and rotating (Ekman) cases. Figure 1 shows the excellent agreement with reference simulations of Ekman layers [6]. We have observed that large scale structures develop nearby the low-level jet. Therefore, it is necessary to use larger boxes than previously used, $(L_x, L_z) = (6, 6)u_\tau/f$ with f being the Coriolis parameter, in order to resolve the largest naturally-appearing flow structures. Streamwise and spanwise resolution (defined with respect to the direction of the shear stress at the wall) of approximately 5 and 10 viscous units have been employed in order to resolve all the scales of the near-wall turbulent dynamics. Roughly one billion grid points are required to carry out a proper DNS at $Re = 1600$ with an adequate box size.

To initialise the runs, we start the simulations at a low resolution and then increase the resolution in steps. The following preliminary results are obtained from marginally-resolved simulations; the fully resolved DNSs are expected to be ready for the conference. Figure 1*a-b* shows the dependence of the Ekman spiral with the Re and the stratification. The flow direction tends to align closer to the geostrophic wind as Re increases. The angle between the shear at the wall and the geostrophic wind consequently decreases. On the other hand, stratification tends to increase this angle.

Figure 2*a)* shows the instantaneous velocity component aligned with the shear stress at the wall in a cross-flow plane for an unstratified Ekman layer. The variation in the mean velocity direction as well as a low-level jet pointing towards the right can be clearly seen in the picture. Figure 2*b)* shows a snapshot of the horizontal plane of a strongly stratified Ekman layer. The stable stratification suppresses the vertical motions and destroys turbulent kinetic energy. As a consequence, turbulence cannot be continuously sustained and laminar/turbulent patches appear in the flow in the form of bands inclined with an angle of about 30 degrees. Similar structures have been reported in a number of recent studies of internal flows, such as channels. Flores and Riley [4] suggest that relaminarization appear at $L^+ \approx 100$. However, as observed in this study, relaminarization is not an abrupt phenomenon, but a rather continuous process in which laminar patches progressively become larger, provided that the considered domain is large enough to support the continuous growth. This process seems to already start around $L^+ \approx 400$.

Our aim is to study the different length-scales of the flow, *e.g.* the viscous scale l^+, the integral length scale δ, the Ekman turbulent thickness u_τ/f and the Monin-Obukhov length L. We will investigate their dependence on the external stratification as well as the possible interaction between the turbulent structures characterised by certain scales. One-point and two-point statistics will be presented and analysed.

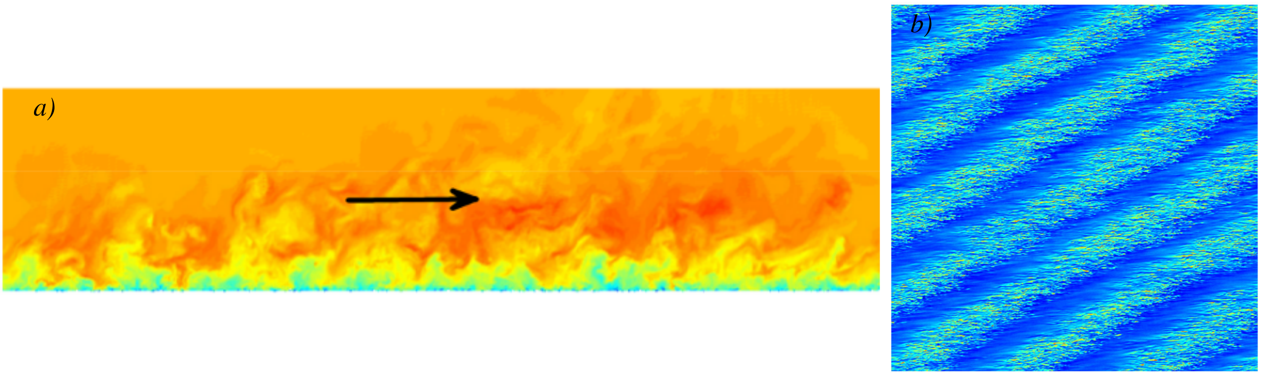

Figure 2. Instantaneous flow field of the velocity component aligned with the shear stress at the wall. $Re = 1600$. *a)* Cross-flow plane of an unstratified Ekman layer. The black arrow indicates the low-level jet and its direction. *b)* Horizontal plane for very high stability, $L^+ = 300$.

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