Impact of spanwise surface temperature heterogeneity on a steady stably stratified Ekman layer: buoyancy-induced secondary circulations with Coriolis effects

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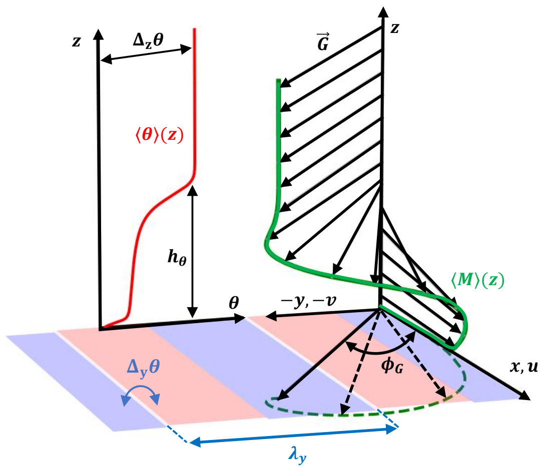
Several recent studies have demonstrated that large streamwise-aligned secondary circulations are generated by thermally heterogeneous surfaces with spanwise length scales in the order of the boundary layer depth, both in unstably[1] as well as stably[2] stratified channel flow configurations. These mean secondary flow structures significantly affect surface fluxes and mean profiles in turbulent boundary layers. In the atmospheric boundary layer, large-scale motions are influenced by Coriolis effects. Consequently, the mean wind direction changes with height, forming an Ekman layer, which is particularly relevant in the stable boundary layer (SBL). The impact of Coriolis effects and the associated mean-wind rotation on surface-induced secondary flows remains largely unexplored.

To address this issue, large-eddy simulations (LES) of a stably stratified Ekman layer were performed, with spanwise varying surface temperature as illustrated in Figure 1 (left). The stable boundary layer is subjected to synoptic-scale atmospheric subsidence, which leads to a steady state where the surface cooling is balanced by subsidence heating.[3] This facilitates easy and formal comparison of cases with different surface temperature configurations, such as varying strip width ($\lambda_y = 100 - 800$ m) or surface temperature difference ($\Delta_y\theta = 1.5 - 12$ K).

LES results indicate that the Coriolis force acts to enhance secondary vortices rotating in one direction, while suppressing those in the other, resulting in an asymmetric mean flow field. As depicted in Figure 1 (right), the secondary motions and the associated high- and low momentum pathways are tilted. Both a larger surface temperature contrast and increasing strip width result in stronger secondary circulations and dispersive fluxes, increased near-surface gradients, elevated SBL depth and low-level jet, and reduced mean surface heat flux. Based on the generated LES dataset, novel correlations between characteristics of the surface heterogeneity and their impact on the mean SBL structure are suggested.



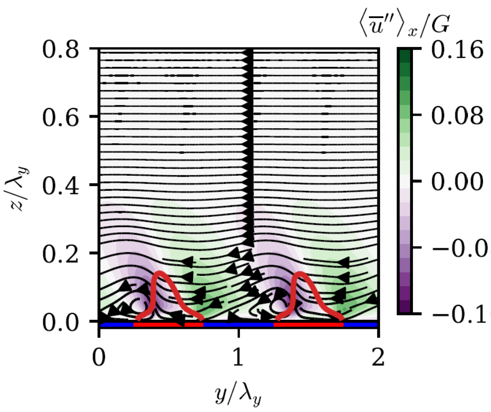


Figure 1: Left: schematic figure of the studied stably stratified Ekman layer with heterogeneous surface temperature. Green and red lines: mean profiles of horizontal wind speed $\langle M\rangle$ and potential temperature $\langle\theta\rangle$. G: geostrophic wind vector, ϕ_G: geostrophic angle. h_θ: thermal boundary-layer depth, $\Delta_z\theta$: vertical temperature difference of the SBL. Red and blue strips: high- and low-temperature patches, with surface temperature contrast $\Delta_y\theta$ and wavelength λ_y. Right: streamwise- and time-averaged dispersive streamwise velocity fluctuation $\langle\overline{u}'\rangle_x = \langle\overline{u} - \langle\overline{u}\rangle_{xy}\rangle_x$. Streamlines indicate direction of in-plane velocity. Thick red contours trace the points where the temperature gradient is 0.

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[1]Salesky et al., *Journal of Fluid Mechanics* **934**, A46 (2022)
[2]Bon and Meyers, *Journal of Fluid Mechanics* **933**, A57 (2022)
[3]Bon et al., *Boundary-Layer Meteorology* **190**, 42 (2024)