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Wind Shear Effects on the Structure and Dynamics of the Daytime Atmospheric Boundary Layer

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The daytime atmospheric boundary layer (ABL), in which the positive buoyancy flux at the surface creates convective instability and generates turbulence, has been a subject of extensive research during the last century. However, fewer studies have considered wind shear in detail and most of them are single-case studies. So most of the available theories and parameterizations have not been sufficiently tested over a wide range of atmospheric conditions. Moreover, since previous numerical studies were mostly carried out by large eddy simulation, a complete understanding of the physics of the problem is still missing due to the lack of information about the small-scale dynamics. Specifically, despite the consensus in the community that wind shear enhances the entrainment process, the amount of enhancement is still matter of contention.

In order to investigate the effects of wind shear on the structure and dynamics of the ABL in detail, direct numerical simulations are used in this study. Shear is prescribed by a height-constant velocity in the troposphere and the simulation runs until a fully turbulent, quasi-equilibrium regime is observed. Despite the simplification of neglecting the Coriolis force, our configuration reproduces the main features observed in the previous studies, which had taken the Coriolis force into account. As a novelty compared to previous single-case studies, we introduce a dimensionless parameter that allows us to study systematically any combination of surface buoyancy flux, buoyancy stratification, and wind shear; We refer to this dimensionless number as shear number. Seven simulations with shear numbers ranging from 0 (no wind) to 20 (moderate wind) are conducted; this range of shear numbers corresponds to wind strength from 0 to 15 m/s in the free troposphere for typical midday atmospheric conditions.

In general, we find that shear effects are negligibly small when the shear number is below 10, and for larger values the effects remain constrained inside the entrainment zone and surface layer. This critical shear number is justified by scrutinizing the turbulence regimes (convective and mechanical) within the entrainment zone in the sense that, for this shear number, the turbulence transport of turbulence kinetic energy inside the entrainment zone equals the shear-production rate. Following this analysis a critical flux Richardson number of 0.6 inside the entrainment zone is found. In particular, we observe the following: First, the mean buoyancy and total buoyancy flux inside the mixed layer remain invariant under a change of shear number and they follow the free-convection scaling laws. Second, the height of minimum buoyancy flux increases due to shear effects, but just moderately (less than 5%). Nevertheless, this increment represents a growth of entrainment zone's thickness by 50% for shear numbers of the order of 20. Third, we observe that for shear numbers larger than 10, the entrainment flux ratio grows by up to 50% in an early state of ABL development. We provide explicit parameterizations of all these shear effects.