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Convection Cells in the Atmospheric Boundary Layer

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In dry, shear-free convective boundary layers (CBLs), the turbulent flow of air is known to organise itself on large scales into coherent, cellular patterns, or superstructures, consisting of fast, narrow updraughts and slow, wide downdraughts which together form circulations. Superstructures act as transport mechanisms from the surface to the top of the boundary layer and vice-versa, as opposed to small-scale turbulence, which only modifies conditions locally. This suggests that a thorough investigation into superstructure properties may help us better understand transport across the atmospheric boundary layer as a whole.

Whilst their existence has been noted, detailed studies into superstructures in the CBL have been scarce. By applying methods which are known to successfully isolate similar large-scale patterns in turbulent Rayleigh-Bénard convection, we can assess the efficacy of those detection techniques in the CBL. In addition, through non-dimensional analysis, we can systematically compare superstructures in various convective regimes. We use direct numerical simulation of four different cases for intercomparison: Rayleigh-Bénard convection (steady), Rayleigh-Bénard convection with an adiabatic top lid (quasi-steady), a stably-stratified CBL (quasi-steady) and a neutrally-stratified CBL (unsteady). The first two are non-penetrative and the latter two penetrative.

We find that although superstructures clearly emerge from the time-mean flow in the non-penetrative cases, they become obscured by temporal averaging in the CBL. This is because a rigid lid acts to direct the flow into counter-rotating circulation cells whose axis of rotation remains stationary, whereas a boundary layer that grows in time and is able to entrain fluid from above causes the circulations to not only grow in vertical extent, but also to move horizontally and merge with neighbouring circulations.

Spatial filtering is a useful comparative technique as it can be performed on boundary layers of the same depth, defined from the surface to the height at which the turbulent kinetic energy (TKE) is zero (in non-penetrative cases) or less than 10% of its maximum value (in penetrative cases). We find that with increasing filter width, the contribution of the filtered flow to the total TKE in the middle of the boundary layer decreases much more rapidly in the penetrative cases than in the non-penetrative cases. In particular, around 20-25% of the TKE at this height comes from small-scale turbulence with a length scale less than or equal to 15% of the boundary layer depth in the CBL, whereas in Rayleigh-Bénard convection, it is just 6-7%. This is consistent with visualisations, which show that entrainment creates additional small-scale mixing within the large-scale circulations in the CBL. Without entrainment, large-scale organisation predominates.

Neither spatial nor temporal filtering are as successful at extracting superstructures in the penetrative cases as in the non-penetrative cases. Hence, these techniques depend not on the steadiness of the system, but rather on the presence of entrainment. We therefore intend to try other detection techniques, such as proper orthogonal decomposition, in order to make a rigorous assessment of which is most effective for isolating superstructures in all four cases.