

Turbulent variances approaching free convection in the atmospheric boundary layer

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1. INTRODUCTION

In the atmospheric boundary layer, the scaling of turbulent variances transitions from dependence on shear-based parameters under near-neutral conditions to dependence on a global convection parameter in the limit of free convection. The shear regime is typically described by the local stability parameter $\zeta = z/L$, while the convective regime is characterised by the bulk parameter $-z_i/L$, where z_i is the depth of the boundary layer and L is the Monin–Obukhov length. The local stability parameter $\zeta = z/L$ is effective in weak instability, while buoyant turbulence in deeper convective layers is typically normalised by the convective velocity scale w_* . Recent theoretical work has refined the asymptotic forms of variance scaling in wall-bounded turbulence extended into adiabatic, high-Reynolds regimes [1]. Large-eddy simulation (LES) studies now offer sufficient resolution to examine variance transitions directly, and recent work has shown how departures from Monin–Obukhov similarity appear well below the classical limits of the surface layer [2]. Redistribution of turbulent kinetic energy is governed by pressure–strain effects, and its variation with increasing convection is expected to reflect changes in eddy topology, transitioning from roll-dominated structures to cellular convection.

This study presents LES results for 13 cases of the dry convective boundary layer that span a bulk instability range of $-z_i/L = 2.6$ to 5686.3 (with case 13 employing zero mean wind), focussing on how the normalised streamwise (u), spanwise (v) and vertical (w) variances evolve with instability.

2. APPROACH

The simulation suite was performed on homogeneous terrain with fixed surface heating. Geostrophic wind was varied to modulate shear, while maintaining identical surface heat flux conditions. The resolved variances were combined with subgrid (SGS) contributions extracted from the three-dimensional output. The SGS energy contribution follows similarity-based formulations that account for unresolved scales in the surface and mixed layer [3]. The velocity components were rotated into the mean wind direction at the surface. Variance profiles are evaluated relative to the convective velocity scale w_* , allowing consistent comparison across weak to nearly free-convective regimes. Variance budgets are also analysed to diagnose the role of pressure–strain redistribution in anisotropy.

3. RESULTS

The LES ensemble confirms three interlinked behaviours, all illustrated in Figure 1. The figure presents variance profiles scaled by height z/z_i . Figure 1a shows the normalised streamwise variance $\langle u'^2 \rangle / w_*^2$. At weak instability, the surface layer reveals a logarithmic decay with height, consistent with attached-eddy asymptotics [1]. This trend is gradually eroded as $-z_i/L$ increases, with the profiles at $0.5z_i$ displaying a monotonic reduction in amplitude. The absence of collapse to a universal form highlights the continued influence of shear even in regimes where buoyant forcing dominates.

Figure 1b presents the normalised spanwise variance $\langle v'^2 \rangle / w_*^2$. Unlike the streamwise component, it does not exhibit a clear logarithmic decay in the surface layer for weakly convective cases. With increasing instability, its amplitude at $0.5z_i$ decreases, but in intermediate and strongly convective regimes, the spanwise variance exceeds the streamwise variance. This reversal of the conventional

ordering points to roll-driven organisation of turbulence and enhanced lateral motions. Budget analysis indicates that pressure–strain redistribution acts as a sink in the streamwise variance equation and a source in the spanwise and vertical components. This mechanism is consistent with turbulence theory on Reynolds stress anisotropy [4] and with LES-based budget studies in heterogeneous boundary layers documenting non-canonical redistribution [5].

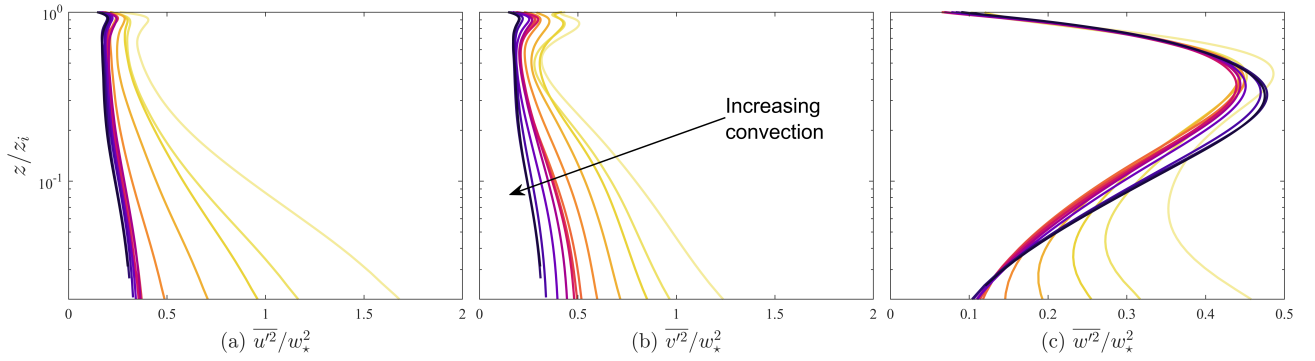


Figure 1. Normalised variance profiles relative to the convective velocity scale for all 13 LES cases. Colours indicate increasing convective intensity with case number.

Figure 1c illustrates the normalised vertical variance $\langle w'^2 \rangle / w_*^2$. At $0.05z_i$, the variance first decreases with increasing instability, before rising again and peaking in the three most convective cases (11–13). This behaviour contrasts with the quasi-universality of vertical variance profiles reported in earlier convective boundary layer studies [6]. The enhanced variance aloft corresponds to increases in near-surface vertical transport as shear effects vanish from the dominant cell organisation.

Together, these behaviours define a coherent transition across stability regimes: shear-dominated anisotropy at weak instability, spanwise dominance at intermediate regimes, and vertical dominance near free convection. Importantly, variance ordering is not a passive reflection of buoyant scaling but is the result of competing influences of shear production, buoyancy production, turbulence transport, and pressure redistribution.

The integration of asymptotic theory, SGS similarity treatment, and LES-based budgets provides a refined continuum linking surface-layer similarity to mixed-layer buoyant turbulence. These results reinforce the need to adopt frameworks that capture transitional behaviour across regimes of increasing instability, with the potential to develop into new canonical universal profiles.

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