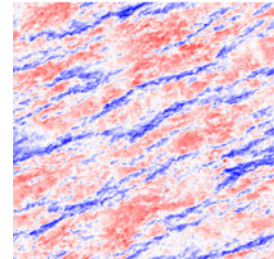


The anatomy of large-scale motion in atmospheric boundary layers

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The atmospheric boundary layer is the level of the atmosphere where all human activities occur. It is a layer characterized by its turbulent flow state, meaning that the velocity, temperature and scalar concentrations fluctuate over scales that range from less than a millimetre to several kilometres. It is those fluctuations that make dispersion of pollutants and transport of heat, momentum as well as scalars such as carbon dioxide or cloud-condensation nuclei efficient. It is also the layer where a ‘hand-shake’ occurs between activities on the land surface and the climate system, primarily due to the action of large energetic swirling motions or eddies. The atmospheric boundary layer experiences dramatic transitions depending on whether the underlying surface is being heated or cooled. The existing paradigm describing the size and energetics of large-scale and very large-scale eddies in turbulent flows has been shaped by decades of experiments and simulations on smooth pipes and channels with no surface heating or cooling. The emerging picture, initiated by A. A. Townsend in 1951, is that large- and very large-scale motions appear to be approximated by a collection of hairpin-shaped vortices whose population density scales inversely with distance from the boundary. How does surface heating, quintessential to the atmospheric boundary layer, alter this canonical picture? What are the implications of such a buoyancy force on the geometry and energy distribution across velocity components in those large eddies? How do these large eddies modulate small eddies near the ground? Answering these questions and tracking their consequences to existing theories used today to describe the flow statistics in the atmospheric boundary layer are addressed in the work of Salesky & Anderson (*J. Fluid Mech.*, vol. 856, 2018, pp. 135–168). The findings are both provocative and surprisingly simple.

Key words: shear layer turbulence, stratified turbulence, turbulent convection

1. Introduction

It is safe to state that the significance of turbulent flows in engineering and numerous branches of science is not in dispute. The equations describing turbulent flows, the Navier–Stokes equations, have been around since 1845 and yet the

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mathematical description of turbulence remains complex and often forbidding in practical situations. From the turn of the nineteenth century onwards, reliance on experiments became a necessity to arrive at usable expressions for conveyance in turbulent flows. By the middle of the twentieth century onwards, improved experimentation and data analysis tools (e.g. conditional sampling) began to reveal that aspects of turbulent fluctuations are not entirely irregular, and regularity has been detected in large-scale structures (Kovasznay, Kibens & Blackwelder 1970). Experiments have also shown that these large-scale structures dominate the energetics of the flow and contribute to momentum, heat and scalar exchanges (Monty *et al.* 2007; Marusic, Mathis & Hutchins 2010*a*). They also have provided tantalizing results about self-similarity in large-scale structures in certain situations (Marusic & Monty 2019). Undoubtedly, connecting such large-scale eddies to quantities required in practical turbulence problems such as momentum, heat and scalar exchanges between the flow and the underlying boundary refocused interest on the properties of large-scale motion (Hutchins & Marusic 2007; Marusic *et al.* 2010*b*). So, what is meant by large- and very large-scale motion (LSM and VLSM) here? How large is large? Do these LSM and VLSM impact turbulence near boundaries? And how can the properties of VLSM or LSM be used to ‘upgrade’ phenomenological theories being used in practice such as Monin–Obukhov surface layer similarity theory (MOST)? MOST was originally introduced to correct for the effect of thermal stratification on flow statistics in a stationary, planar-homogeneous atmospheric flow in the absence of mean vertical advection or Coriolis effects (Monin & Obukhov 1954). The desire to answer these questions has led to an ‘up-tick’ in experiments and simulation studies of boundary layer turbulence in highly controlled settings. Unsurprisingly, much of the qualified answers to these questions originate from studies of turbulent boundary layers over smooth walls at very high Reynolds numbers. Experiments have shown that, far from the boundary (a region referred to as the outer layer), the LSM has characteristic dimensions of boundary layer depth δ . Other measurements above the viscous sublayer but not too high up in the boundary layer (a region known as the inner layer) suggest that both LSM and VLSM are present. The size of VLSM appears to be commensurate with 10δ or larger. Beyond the niceties of smooth walls, does this emerging picture about LSM and VLSM hold for other situations, such as the atmospheric boundary layer where heating at the surface occurs? This is the essence of the problem considered in the paper by Salesky & Anderson (2018) (hereafter SA18).

2. Overview

From prior work, the velocity component most sensitive to the presence of LSM and VLSM is the longitudinal velocity component (Guala, Hommema & Adrian 2006). Shear or mechanical production in virtually all wall-bounded flows (e.g. smooth pipe or channel flows) injects energy from the mean flow into the streamwise or longitudinal velocity component of turbulence. The interaction between turbulent pressure and velocity gradients redistributes energy content across scales as well as across velocity components. If the pressure–velocity interaction is assumed to be efficient, then the turbulent energy content must attain an equipartitioned state. What prevents equipartitioning of turbulent energy is the presence of a physical wall that has a blocking effect on the energy-containing eddies in general. Anisotropy in energy distribution among components leads to speculations about possible geometric shapes (i.e. sizes and not just energy content) that maintain the aforementioned

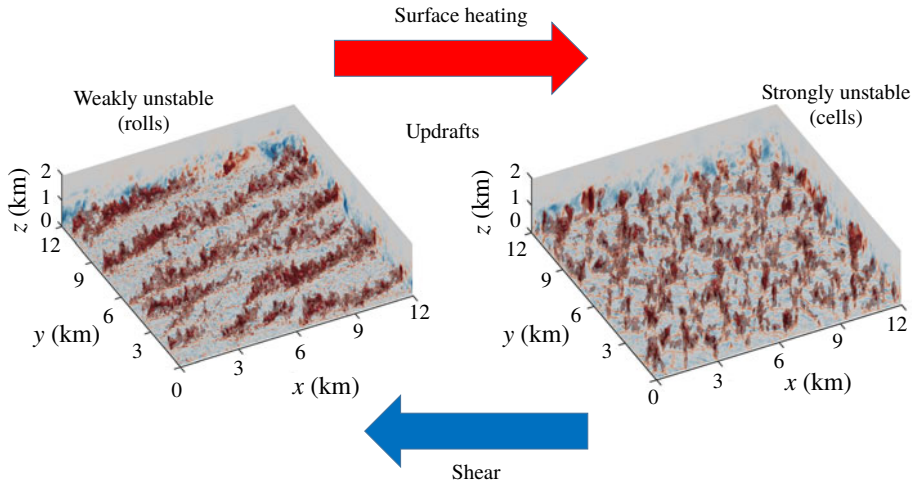


FIGURE 1. Updrafts (positive vertical velocity) in a mildly heated and strongly heated atmospheric boundary layer.

energy anisotropy while recovering the shape of the mean velocity profile and second-order flow statistics. A candidate shape was the hairpin vortex structure, which was presumed to be representative of attached eddies (i.e. eddies that sense the presence of the wall). In this picture, LSM forms due to streamwise coalescence of hairpin vortices formed near the surface, and the VLSMs form due to yet another streamwise coalescence of LSMs (hairpin vortex packets). Moreover, these structures appear to be self-similar, characterized by a population density that is inversely related to the distance from the boundary. These results are intriguing because a building block for large eddies that accommodates energy anisotropy, size anisotropy, inclination with the wall and some aspects of their rotational properties was found purely on phenomenological grounds and not from the Navier–Stokes equations. As a segue to atmospheric boundary layer flows, it is instructive to ask what happens to this ‘canonical’ picture in the presence of surface heating. It may be conjectured that surface heating alters the canonical picture in different ways. Buoyancy introduces another source of turbulent kinetic energy into the vertical velocity component. Depending on the relative strength of shear production of turbulent kinetic energy and surface heating (a quantity related to the so-called stability parameter put forth by MOST), the vertical velocity component may now become a source of energy for the longitudinal velocity component in the limit of large surface heating and weak shear. This view of two energy injection scales was the basis of early work on directional–dimensional analysis in turbulence research modifying MOST (Kader & Yaglom 1990). What SA18 explored is how this new source of energy arising from surface heating or buoyancy alters both the characteristic dimensions as well as the energetic scales commensurate with LSM and VLSM when this motion is sampled in both the inner and outer regions. What the simulation runs by SA18 reveal is that VLSM detected in the longitudinal velocity transitions from long, linear updrafts of size comparable to $\delta\delta$ to open cellular patterns analogous to turbulent Rayleigh–Bénard convection shown in figure 1. SA18 identified the properties of the two ‘end-member’ states of LSM and VLSM in the atmosphere based on a well-established atmospheric stability parameter routinely used to display experimental data. It showed that large and very large turbulence structures undergo a gradual

transformation from coalescent hairpin vortices to convection cells with increased instability parameter.

3. Future research directions

This topological picture of VLSM and attached eddies, and their gradual conversion to LSM due to increased surface heating, lends support to the existence of an intermediate ‘dynamic-convective’ regime proposed in directional–dimensional analysis (Kader & Yaglom 1990). That is, the daytime atmospheric boundary layer has a ‘dynamic’ (dominated by horizontal rolls formed from hairpin vortices), dynamic-convective (dominated by both horizontal rolls and ‘disordered’ convective cells) and free-convective (ordered convection cells) regimes each associated with differing scaling laws for their flow statistics with increased instability. That the transition from dynamic to convective is gradual (i.e. passing through dynamic-convective) has received support from other simulations and field experiments alike (Li & Bou-Zeid 2011; Salesky, Chamecki & Bou-Zeid 2017). Beyond dimensional and directional–dimensional analysis, a phenomenological model that is able to accommodate this switching can provide a reduced-order view of how LSM and VLSM are shaped by boundary conditions. Likewise, the role of stable stratification (i.e. surface cooling) in reshaping LSM and VLSM would be necessary to complete any new phenomenological model. Naturally, progress on these enquiries is necessary for a longer-term goal of modernizing MOST. This last line of enquiry may be one way for the results here to reshape large-scale atmospheric models currently used in weather forecasting, air pollution research and climate modelling.

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