Advances in Coherent Structures in Atmospheric Boundary Layer Turbulence (Postprint)

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Abstract

The discovery of turbulent coherent structures represents a major turning point in turbulence research, holding significant importance for understanding turbulence and the transport of mass, momentum, and energy. This paper first reviews the discovery process of turbulent coherent structures in the atmospheric boundary layer, then summarizes their morphological characteristics, compositional structure, flux contributions, and other features. Subsequently, it elaborates on the causes of their generation, detailing two typical formation mechanisms. The paper then discusses their practical applications, followed by a review of detection methods. Finally, it concludes with a summary of the entire paper and provides an outlook on future research trends.

Full Text

Preamble

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Abstract

The discovery of turbulent coherent structures represents a major turning point in turbulence research and is of great significance for understanding turbulence and the transport of matter, momentum, and energy. This paper first reviews the discovery process, then summarizes the morphological characteristics, compositional structure, flux contributions, and other features of turbulent coherent structures in the atmospheric boundary layer. The underlying causes are expounded, typical formation mechanisms are explained, practical applications are discussed, and detection methods are summarized. Finally, future research trends are prospected.

Keywords: atmospheric boundary layer; turbulent coherent structure; characteristic; formation cause; application; detection method

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1. Introduction

The discovery of turbulent coherent structures marked a revolutionary breakthrough in turbulence research. Following the pioneering work of Corino [11] and Smith [12] on low-speed streaks in the near-wall region, researchers have systematically investigated the structural characteristics of turbulent boundary layers. Since Reynolds' 1883 experiments on flow visualization [34], the study of coherent structures has become central to understanding turbulence dynamics.

Early theoretical contributions include the Boussinesq approximation [2], Prandtl's mixing length theory [3], Von Kármán's similarity hypothesis [4], and Taylor's vorticity transport theory [5]. By the mid-20th century, Kolmogorov's theory of locally isotropic turbulence [6,7] provided a statistical framework, while Townsend's attached eddy hypothesis [8] offered a structural perspective. Kline et al. [10] identified the characteristic "bursting" process, revealing that coherent structures are responsible for the majority of turbulent kinetic energy production and transport.

In atmospheric boundary layers, coherent structures manifest as ramp patterns, roll vortices, and cellular convection [24–26]. These structures dominate momentum and scalar transport, with ramp events accounting for up to 75% of the total flux [43]. The typical ramp pattern consists of a gradual rise followed by a sharp drop in scalar concentration, with an inclination angle of 18°–20° relative to the surface [27–28]. The characteristic timescale of these structures ranges from 2 to 40 seconds near the surface [70], with large eddies persisting for 3–6 minutes in the mixed layer [26,56,58].

Morphologically, coherent structures exhibit distinct features: elongated streamwise vortices in the surface layer, hairpin vortex packets in the buffer region, and large-scale rolls in the convective boundary layer. Adrian [29] demonstrated that these structures are spatially organized, with conditional averaging revealing their typical signatures. Smith [12] showed that low-speed streaks have characteristic spanwise spacing of $\lambda^+ \approx 100$ wall units and streamwise extent exceeding 1000 wall units.

The formation mechanisms involve shear instability, buoyancy forcing, and vortex merging processes. The Kelvin-Helmholtz instability plays a crucial role in generating large-scale structures at the interface between layers [37,41]. In unstable conditions, thermal plumes evolve into coherent updrafts and downdrafts, while in stable conditions, internal gravity waves can modulate turbulent patches.

Detection methods have evolved from visual identification to quantitative analysis. Wavelet transforms [97,101], empirical mode decomposition (EMD) [98–99], and conditional sampling techniques [37,102] are now standard tools. The Hilbert-Huang transform [98] and spectral analysis [107] enable multi-scale decomposition, while PIV measurements provide spatial structure information [20,21].

Applications include parameterizing turbulent fluxes in weather models, predicting pollutant dispersion, and optimizing wind energy extraction. The mixing-layer analogy [64] provides a framework for canopy flows, while Townsend's hypothesis [16] links coherent structures to surface roughness effects.

Future research directions involve: (1) high-resolution numerical simulations to capture structure dynamics, (2) multi-scale interaction studies, (3) development of structure-based turbulence closures, and (4) investigation of structure impacts on extreme weather events.

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Note: Figure translations are in progress. See original paper for figures.