

Effects of Geometry and Flexibility on Canopy Turbulence

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ABSTRACT

Atmosphere-vegetation interactions are prominent in the exchange of momentum, mass, and energy across the land-atmosphere interface and therefore influence a wide range of environmental and societal processes, from ecosystem transport to wind hazards and infrastructure resilience. As extreme wind events pose significant risks to ecosystems and infrastructure, there is a growing need to understand how vegetation modifies turbulent flow and responds to aerodynamic forcing. However, predictive understanding remains limited because these systems involve strong coupling among multiscale geometry, structural flexibility, turbulent transport, and energy redistribution. This dissertation addresses that challenge by combining large-eddy simulation (LES) with physics-based analysis to develop a unified understanding of how flow interacts with flexible, vegetation-like systems.

This study investigates turbulent flow over fractal tree canopies, examining how canopy morphology, structural flexibility, spatial arrangement, and density affect mean flow and turbulent transport. It focuses on the turbulent kinetic energy budget and spectral energy distribution to identify how energy is produced, transferred, and dissipated across scales in the presence of multiscale flexible structures. These analyses evaluate and extend the emerging three-layer description of canopy turbulence, consisting of the canopy zone, mixing zone, and logarithmic-law zone. The goal is not only to characterize canopy flow behavior, but also to reveal the physical mechanisms by which vegetation geometry and deformation reorganize turbulent transport.

To extend the investigation from complex fractal tree canopies to more generalized vegetation-like structures, this dissertation considers simplified representations using stem arrays, tapered beams, and reversed tapered beams. These canonical models provide a systematic framework for examining how structural geometry and flexibility influence flow–structure interactions, with the aim of identifying physical mechanisms that extend beyond complex fractal tree geometries. This work contributes to both fundamental understanding and predictive capability for environmental flows involving complex vegetation, while providing a foundation for future reduced-order modeling of complex flow–structure systems.