The organization of boundary layer turbulence and objective momentum transport barriers

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Abstract. Uniform momentum zones (UMZs) have become a prominent avenue with which to investigate and explain fluid behavior in turbulent boundary layers. UMZs are, however, non-material observer-dependent characterizations of one-dimensional momentum projections dependent on the size and resolution of the flow domain, as well as the choice of statistical methods employed. The present research harnesses recent mathematically-proven definitions of momentum-flux-minimizing surfaces to identify three-dimensional momentum transport barriers in turbulent boundary layer and channel flows. Our definition has the unique advantages of being frame-invariant, based on physics, and is not sensitive to UMZ definition ambiguities. As well, this same method can extract coherent vortical structures that block linear momentum transport. Organizing boundary layer turbulence with our objective momentum transport barriers shows great promise for advancing answers to classic questions of structure in fluid dynamics.

Introduction

Characterizing structures in turbulent boundary layers (TBL) has been a focus of fluid dynamics for many decades. Modern visualizations with PIV and DNS data sets have led to many theories describing the roles and generation of seemingly predominant flow-features for TBL. Typical methods to extract these turbulent structures, however, often rely on frame-dependent (non-objective) descriptors (e.g. velocity contours and vorticity magnitude, or λ_2, Q, and Δ criteria), and are not materially coherent. One such theoretical framework is the description of Uniform Momentum Zones from velocity contours to describe the organization of separate, non-interacting regions in boundary layers. Though based on a physical intuition of fluid dynamics, the interfaces defined by common UMZ approaches do not actually behave as barriers to linear momentum transport [1]. In the presented research, we adopt recent theoretical developments on momentum and vorticity transport barriers for unsteady flows to aid in the visualization of TBL structures in an objective and mathematically-rigorous way.

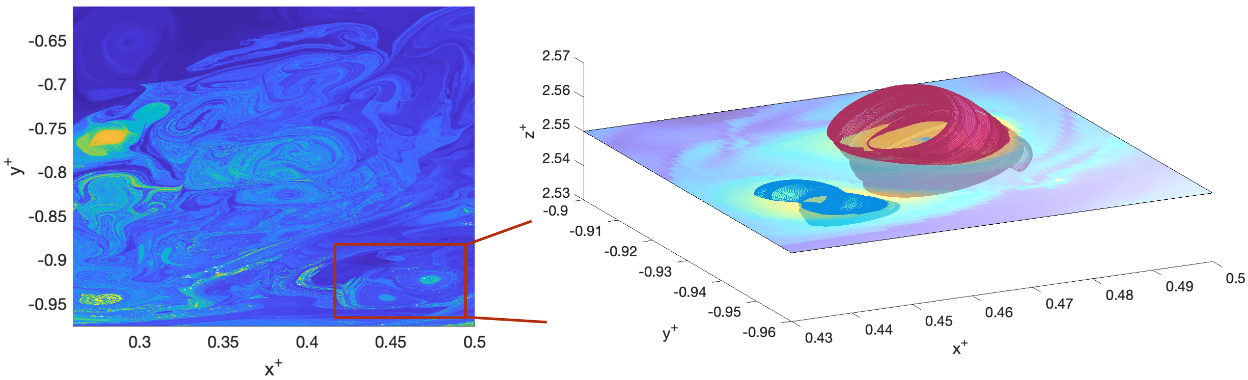

Figure 1: Two-dimensional intersection of linear momentum barrier field structures and three-dimensional extraction of two near-channel-wall vortices.

Results and Discussion

From the recently derived barrier field equations for momentum transport [1], we have developed a method for extracting both cores of vortical momentum-blocking structures and quasi-planar momentum-transport-limiting interfaces separating both regions of different turbulence intensity and clusters of vortices. This method has been applied to the three-dimensional, time-resolved, Re=1000, turbulent channel flow DNS from the public Johns Hopkins Turbulence Database [2]. These rigorously-defined structures were then compared with classic non-objective metrics. Additional simplifications of the method have shown great potential to also extract close approximations of these rigorous flow features as isosurfaces of appropriate metrics. This further reduces the computational burden for their extraction and aids in the automation of TBL structure analysis.

References

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[2] Y. Li, E. Perlman, M. Wan, Y. Yang, R. Burns, C. Meneveau, R. Burns, S. Chen, A. Szalay & G. Eyink. "A public turbulence database cluster and applications to study Lagrangian evolution of velocity increments in turbulence". Journal of Turbulence **9**, No. 31, 2008.