Summary of Key Findings: Experimental Study of the Boundary Layer Beneath a Tornado-Like Vortex

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Introduction

This study experimentally investigated the boundary layer beneath a laboratory-simulated tornado vortex. Tornadoes exhibit peak wind speeds near the ground, yet direct field measurements are challenging [9]. Laboratory simulations provide a controlled environment to study these critical near-surface dynamics. Using high-resolution Particle Image Velocimetry (PIV), this work aimed to:

- Develop an experimental apparatus for applying PIV to characterise the boundary layer across a range of Reynolds numbers.
- Assessing the applicability of existing analytical models through comparison with experimental data.

The findings contribute valuable comparative data for numerical models of tornado near-surface flow and enhance understanding of tornadic wind loading.

Experimental Setup

A cylindrical tank generated a Rankine-like vortex in water via an array of annular turning vanes. PIV was used to measure the in-plane velocity field. Tracer particles within the water were illuminated by a vertical pulsed LED light sheet, and their motion was captured by a high-speed camera. Particle displacements between frames allows for the quantification of the velocity field in order to resolve flow structures with high precision.

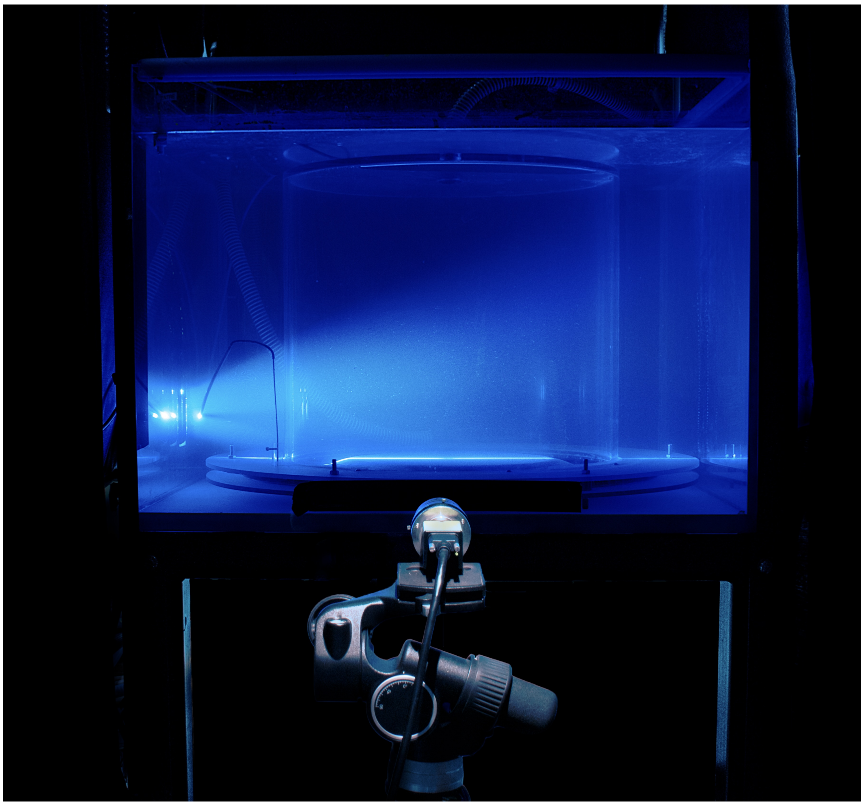

Figure 1: The vortex chamber for laboratory tornado simulation.

PIV Results and Laminar Structure

At moderate Reynolds numbers ($Re \approx 2000$), the flow was consistently laminar and axisymmetric. Figure 2 displays the PIV velocity field, showing clear radially inward flow near the base. This flow then turns sharply upward at the vortex core, defining the basic structure of the boundary layer. The laminar nature of this regime allowed for direct comparison with analytical solutions.

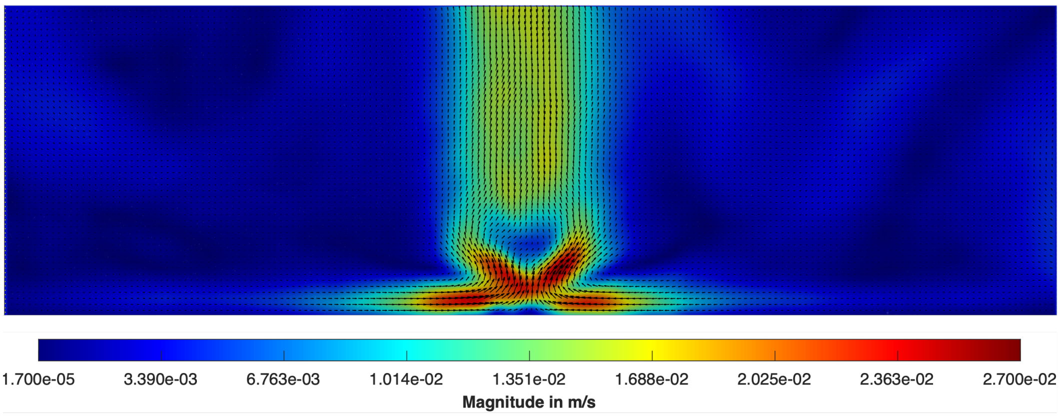

Figure 2: PIV velocity field in the laminar regime. Flow is radially inward near the base, then turns upward at the vortex core.

Radial Velocity Profiles

Radial velocity profiles (u_z) were obtained from three independent experimental runs—taken several minutes apart—to assess repeatability. Example results for the low Reynolds number case (Re_1) are shown in Figure 3, with each set of curves corresponding to a different radial location. In this figure, radius decreases from left to right, illustrating the radial acceleration of the flow toward the vortex core. The clarity of these profiles represents a significant improvement over previous experimental arrangements, with well-resolved boundary layers now observable across all positions. Plotting the data as discrete points highlights both the resolution of the measurement system and the exceptional agreement across independent runs.

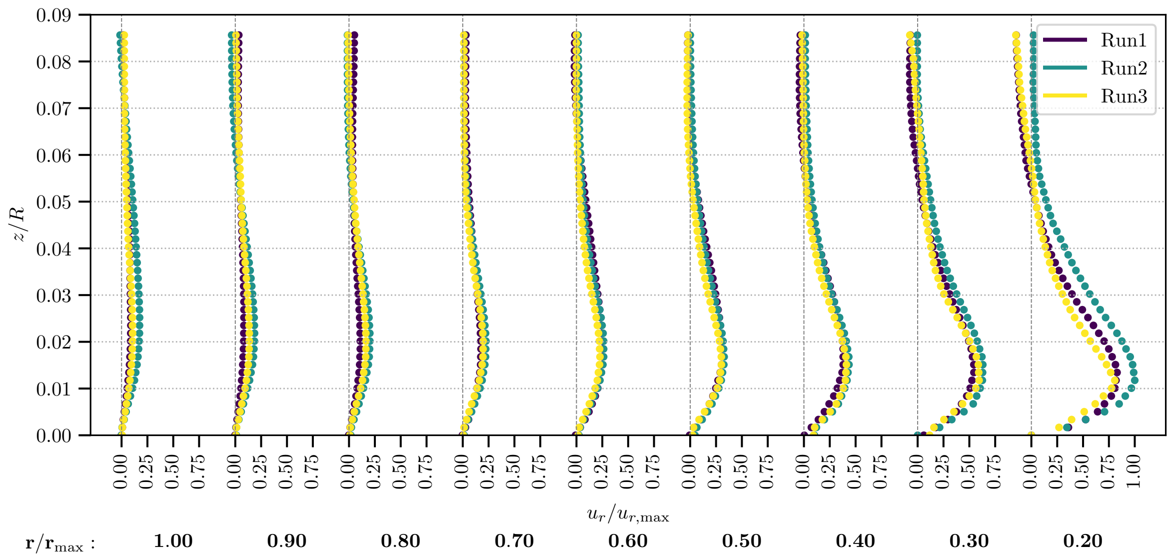

Figure 3: Left: Raw radial azimuthal velocity profiles at various heights. Right: Self-similar collapse after non-dimensionalisation, confirming theoretical expectations.

Comparison with Theoretical Models

Using measured circulation values, the radial velocity measurements were converted into their self-similar form via the transformation $f(\eta) = u_r \cdot 2\pi r/\Phi$, allowing direct comparison with the analytical inner-layer solution. The transformed profiles are presented alongside the theoretical trace of $f(\eta)$ in Figure 4. The observed self-similar structure strongly aligns with Burggraf's (1970) [2] analytical model for the boundary layer beneath an axisymmetric line vortex, for which the governing equations are:

$$\begin{aligned} \eta f'(\eta) &= h'(\eta) \\ hf' - \eta ff' - f^2 + (1 - g^2) &= f'' \\ (h - \eta f)g' &= g'' \end{aligned}$$

Here, $f(\eta)$ represents radial velocity, $g(\eta)$ azimuthal velocity, and $h(\eta)$ vertical velocity, all non-dimensionalised by the similarity variable η. The experimental radial velocity profiles ($f(\eta)$) show excellent agreement with this theoretical solution (Figure 4) within a thin *inner-layer*. This provides significant empirical evidence for Burggraf's model in the laminar regime.

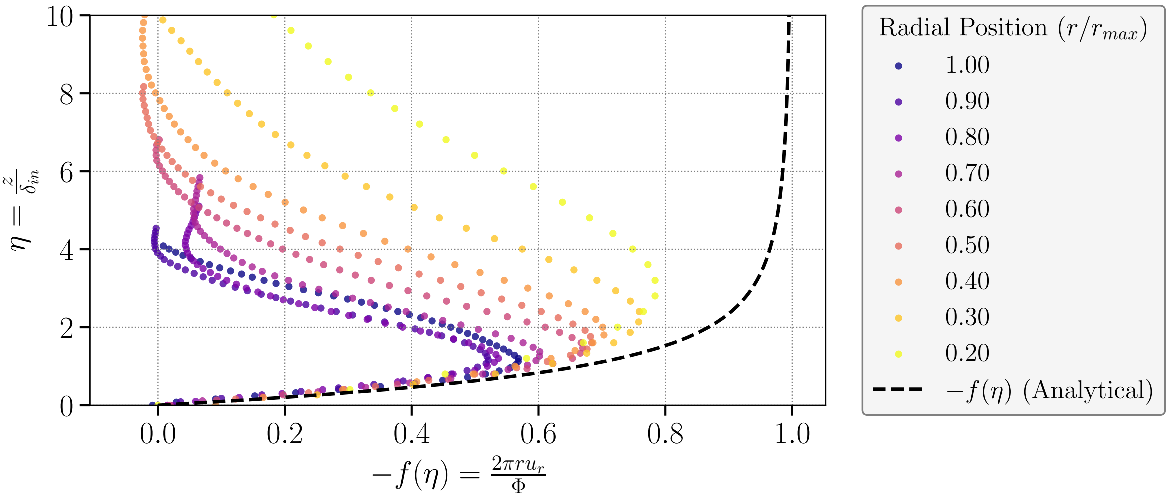

Figure 4: Comparison of the experimentally derived non-dimensional radial velocity profile with the analytical solution from Burggraf (1970).

Discovery of Axial Downflow

A significant experimental finding was the consistent measurement of a weak **downward** axial flow near the vortex centreline within the boundary layer. This behaviour, which can be anticipated through theoretical mass conservation arguments, challenges the classical assumption of uniform upward mass detrainment from classical vortex boundary layers. The data clearly show inward radial motion coexisting with weak axial downflow, before the flow turns sharply upward at the vortex core. This more nuanced picture of axial flow is critical for accurate 3D modelling of the near-surface tornado structure.

Conceptual Model of Tornado Boundary Layer

Figure 5 summarises the overall flow structure inferred from this study. It depicts a thin, laminar boundary layer with pronounced inward radial flow and confirmed downward axial motion within the boundary layer. This conceptual model summarises the experimental results, in agreement with mathematical models, providing a clearer understanding of near-surface tornado dynamics.

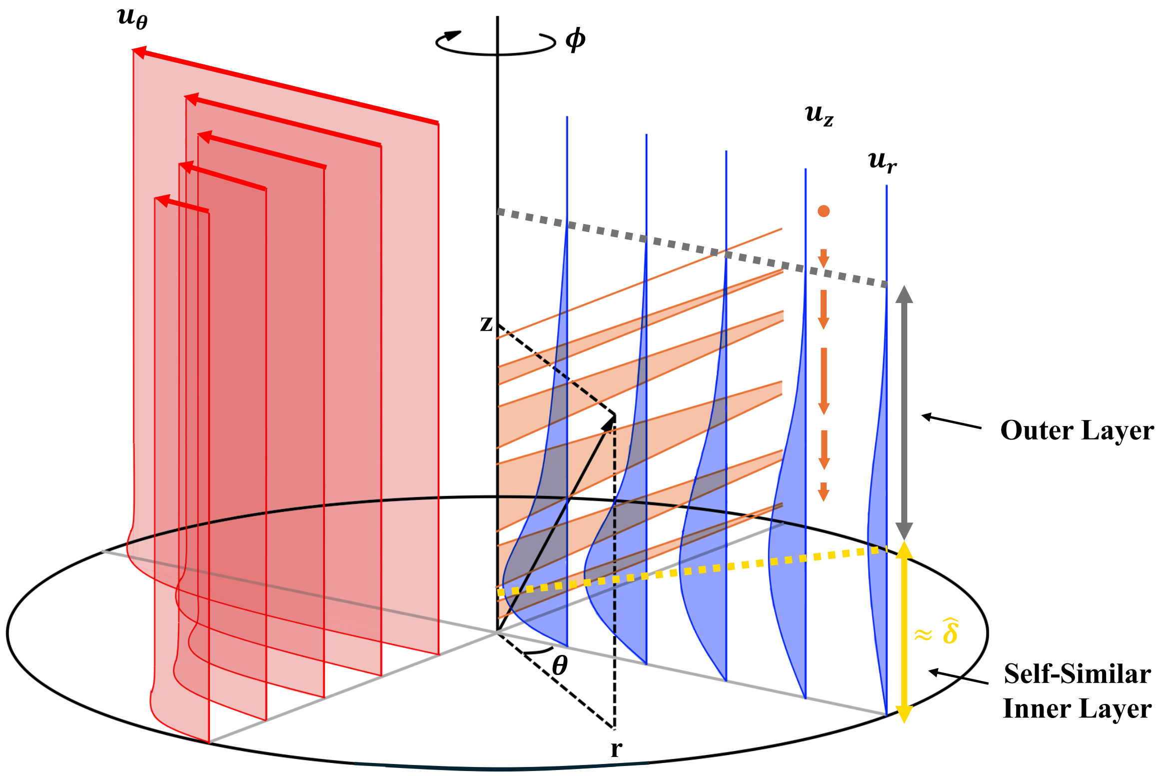

Figure 5: Summary of the tornado boundary layer structure based on experimental data: inward radial flow, subtle downward axial flow, and sharp updraft at the core.

Conclusion

This study provides robust experimental evidence for key features of the laminar boundary layer beneath a tornado-like vortex:

- Strong radial self-similarity within the laminar boundary layer.
- Excellent agreement between experimental azimuthal velocity fields and Burggraf's (1970) similarity solution.
- Confirmation of downward axial flow within the boundary layer, consistent with theoretical mass conservation.

These findings enhance fundamental understanding of near-surface tornado dynamics, offer valuable validation data for numerical models, and contribute to improved predictions of tornadic wind loading and hazard mitigation strategies.

References

1 Davies, L. (2025). *Experimental Study of the Boundary Layer Beneath a Tornado-Like Vortex*. IIB Final Project Report, University of Cambridge.

2 Burggraf, O. R. (1970). Analytical solutions for the viscous flow beneath a tornado-like vortex. *Tellus*, 22(3), 323-328.

9 N. Oceanic and A. A. (NOAA). U.s. billion-dollar weather and climate disasters, 1980 - present.