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Simultaneous assessment of debris trajectories to determine characteristics of the July 1, 2023 Didsbury, Alberta EF4 tornado

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Summary

The Enhanced Fujita scale is a useful assessment tool to determine wind speeds in tornadoes. However, it is a damage-based assessment which relies on the tornado hitting damage indicators whose wind loads have been well-documented and researched (such as houses, mobile homes, and trees). Additionally, the Enhanced Fujita scale is unable to tell the users any characteristics of the tornado beside the wind speed. The goal of this study is to further the development of a forensic tool for debris trajectories of large compact objects. This is done in order to demonstrate how debris trajectories noted in forensic damage assessments can be used to determine characteristics of a tornado that are normally impossible to ascertain from post-storm damage assessments, such as the swirl ratio and core radius of the tornado at the moment of debris lofting.

Keywords: *tornado, simulation, numerical methods, debris trajectories, damage surveys*

1 INTRODUCTION

Often when tornadoes go through populated areas, they encounter a wide variety of loose-laid objects including (but not limited to) trampolines, patio furniture, and plastic sheds (Northern Tornadoes Project 2017). Because these objects are not anchored to the ground, strong tornadoes are able to either slide, roll, or loft these objects. These debris flights are one of the leading causes of injury and death in tornadoes (Bohonos and Hogan 1999). In extreme weather events, it is common to see many loose-laid objects lofted great distances (Stevenson et al. 2023), including heavy compact objects such as vehicles, trailers, and farming equipment. A recent example of this in Canada is the July 1, 2023 Didsbury, AB EF4 tornado, where the post-storm damage survey assessment noted one property that contained vehicles, farm equipment, and trailers which were all lofted in various directions.

The Enhanced Fujita (EF) scale, used in countries like Canada and the United States, rates tornado intensity based on observable damage indicators (DIs). Each DI has various degrees of damage (DODs), each linked to specific wind speeds. Although the DIs in the EF scale cover a wide range of structures, they generally do not account for the wind-induced movement of various non-structural objects, which can result in the underestimation of true tornado intensities. The absence of sufficient damage indicators highlights the need for advanced analysis methods to supplement the existing EF scale (Edwards et al. 2013).

Miller et al. (2024) developed a forensic tool to account for the wind-induced movement of compact objects by combining the analytical tornado model from Baker and Sterling (2017) with debris equations similar to those used in previous studies on debris trajectory analysis (Holmes 2004; Baker 2007). This was achieved by utilizing a Monte Carlo simulation to randomly select parameters that govern the tornadic wind field and debris flight. However, all of the debris trajectories examined in Miller et al. (2024) were analyzed as single instances, and did not account for its relative position to the centreline of the tornado. With this in mind, the objective of this paper is to further develop the debris trajectory model introduced in Miller et al. (2024) by modelling multiple debris trajectories simultaneously to estimate characteristics of a tornado. To accomplish this, changes to the debris model are made to incorporate the relative location of multiple debris objects to the centreline of the tornado through GIS software. The motivation for this paper is to apply this method to the Didsbury, AB EF4 tornado, where a variety of large compact objects were found to have lofted on one property.

2 METHODS

2.1 Wind-borne debris trajectory analysis

This section provides a brief summary of the tornado wind field and debris equations used in both Miller et al. (2024) and the current study. More details on the wind field and debris equations, and how the Monte Carlo simulation is used to estimate debris trajectories can be found in Miller et al. (2024). The tornadic wind field used in this study is the Baker and Sterling (2017) model. Equations 1, 2, and 3 are the trajectory equations for radial, circumferential, and vertical motion, respectively, used to govern the initial motion of a loose-laid object on the ground.

$$\frac{d^2u_o}{dt^2} = \frac{\rho_a}{2\rho_o l}(C_D^{SM}\cos(\alpha) - C_L\sin(\alpha))[(U-u_o)^2 + (V-v_o)^2 + (W-w_o)^2] + \frac{v_o^2}{r} \quad (1)$$

$$\frac{d^2v_o}{dt^2} = \frac{\rho_a}{2\rho_o l}(C_D^{SM}\cos(\beta) - C_L\sin(\beta))[(U-u_o)^2 + (V-v_o)^2 + (W-w_o)^2] \quad (2)$$

$$\frac{d^2w_o}{dt^2} = \frac{\rho_a}{2\rho_o l}(C_D^{SM}\cos(\gamma) - C_L\sin(\gamma))[(U-u_o)^2 + (V-v_o)^2 + (W-w_o)^2] - g \quad (3)$$

where $\frac{d^2u_o}{dt^2}, \frac{d^2v_o}{dt^2}, \frac{d^2w_o}{dt^2}$ are the radial, circumferential, and vertical acceleration of the object, respectively, ρ_a is the density of air, ρ_o is the density of the object, l is the characteristic length of the object, C_D^{SM} is the surface-mounted drag coefficient of the object, C_L is the lift coefficient of the object, α, β, and γ are the angles between the trajectory and the radial, circumferential, and vertical components of the trajectory, respectively, U, V, and W are the radial, circumferential, and vertical wind speed of the tornado vortex, respectively, u_o, v_o, and w_o are the radial, circumferential, and vertical speeds of the object, respectively, and g is the gravitational constant. Once airborne, the object is modelled under the compact-debris assumption with a lift coefficient of zero and a modified drag coefficient relative to its surface-mounted state. This assumption matches findings from tornado simulator experiments, which have shown that lift forces acting on compact debris are significantly reduced once the object is no longer in contact with the ground (Tang et al. 2022).

2.2 Centreline tracking and multi-trajectory tracking

In order to simplify the simulation, the previous study assumed the debris started on the radius of maximum velocity. To increase the accuracy of the simulation and better assess the wind speeds acting on the object, this study simulated the tornado following a centreline. An estimated tornado centreline was found using aerial observations and traced as a series of connected line segments (polyline). The translation of the tornado is therefore given by the vector $\vec{V_T}$, travelling in the direction of the current line segment in the centreline with magnitude V_T. Once the tornado reaches the end of the current line segment, the direction of $\vec{V_T}$ changes to the direction of the next line segment in the centreline. By having the simulated tornado follow a centreline, the wind forces can be calculated at each time step based on the debris' relative location to the tornado's dynamic translation. Figure 1 gives an example overview of the simulated tornado travelling along a centreline.

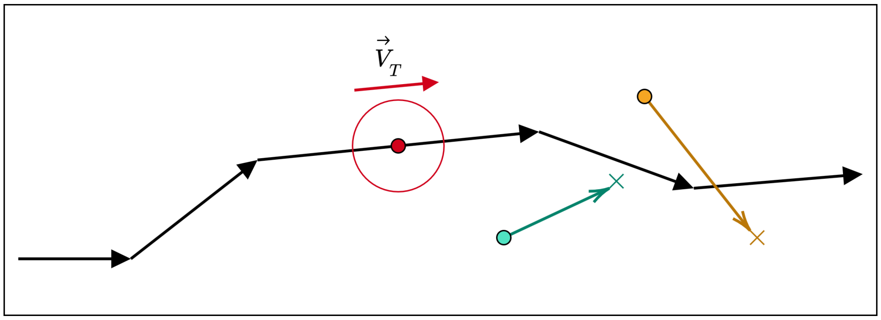

Figure 1: An example of the tornado centreline tracking. The line segments of the centreline are shown as black arrows. The tornado is shown as a red circle. Two example pieces of debris are shown with their trajectories in green and orange.

The multi-debris trajectory simulation is performed using the same algorithm for the previous single-debris trajectory study, by simulating each piece of debris in parallel. A Monte Carlo simulation is used to generate random tornado and debris parameters, followed by simulating the motion of the tornado and debris by numerically solving the previously described differential equations using the Runge–Kutta (RK4) method (Kutta 1901). A simulation is only considered valid if all pieces of debris are lofted and land in a satisfactory position within a determined distance threshold of their actual end positions, measured from aerial observation.

3 RESULTS

Figure 2 shows the Monte Carlo simulation outputs for the lofting of a combine during the Didsbury, AB EF4 tornado under two modelling approaches: (1) the previous single-trajectory method from Miller et al. (2024) without centreline tracking (grey) and (2) the updated multi-trajectory method incorporating centreline tracking (purple). The inclusion of centreline tracking introduces a noticeable shift in the distribution of estimated tornado parameters, particularly with the swirl ratio and core radius.

The most notable improvement occurs in the estimation of swirl ratio. The previous method produced values ranging from 0.4 to 1.2, which is quite a wide range of potential swirl ratios. In contrast, the centreline-based approach yields a thin distribution centred near 0.01 (noting that the swirl ratio graph in Figure 2 is on a logarithmic scale for better visualization of the results), aligning with studies that indicate that compact debris experience longer debris trajectories at lower swirl ratios (Huo et al. 2023). Similarly, the core radius estimates exhibit a dramatic reduction in uncertainty. Without centreline tracking, the distribution spans 50 to 350 m with no clear peak, reflecting poor constraint on vortex size. The updated method produces a sharp peak near 100 m, which is consistent with damage survey observations. For translational velocity, both methods produce similar ranges (approximately 6 to 10 m/s). Overall, these results demonstrate that integrating centreline tracking and multi-object analysis into Monte Carlo simulations substantially improves the accuracy and reliability of tornado parameter estimation, particularly for swirl ratio and core radius.

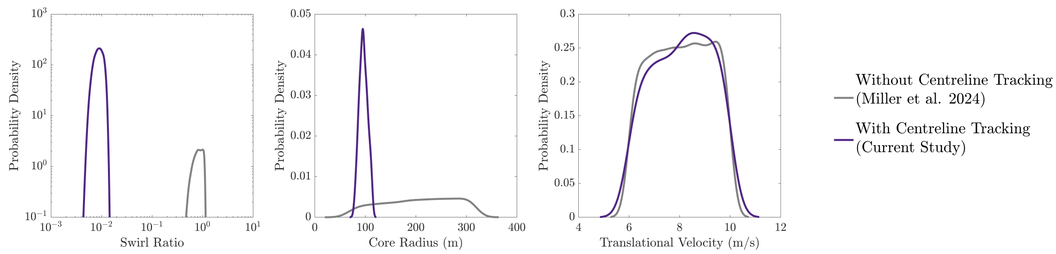

Figure 2: A comparison of the Monte Carlo simulation results when considering the lofting of a combine in the Didsbury, AB tornado without centreline tracking (grey) and with centreline tracking (purple).

4 CONCLUSIONS

Incorporating centreline tracking into the Monte Carlo simulations significantly improves tornado characterization by enabling direct estimation of swirl ratio and core radius, which are typically difficult to quantify. This approach also reduces positional uncertainty, leading to a more refined estimate for the lofting speed. A greater density of trajectories should reduce uncertainty and yield more precise estimates of key vortex parameters such as swirl ratio and core radius.

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