Estimating wind speeds in tornadoes using debris trajectories of large compact objects

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ABSTRACT

Currently, the Enhanced Fujita scale does not consider the wind-induced movement of various large compact objects such as vehicles, construction equipment, farming equipment / haybales, etc. that are often found in post-event damage surveys. One reason for this is that modelling debris in tornadoes comes with considerable uncertainties since there are many parameters to determine, leading to difficulties in using trajectories to analyze wind speeds of tornadoes. This paper aims to develop a forensic tool using analytical tornado models to estimate lofting wind speeds based on trajectories of large compact objects. This is accomplished by implementing a Monte Carlo simulation to randomly select the parameters and plotting cumulative distribution functions showing the likelihood of lofting at each wind speed. After analyzing the debris lofting from several documented tornadoes in Canada, the results indicate that the method provides threshold lofting wind speeds that are similar to the estimated speeds given by other methods. However, the introduction of trajectories produces estimated lofting wind speeds that are higher than the EF-scale rating given from the ground survey assessment based on structural damage. Further studies will be required to better understand these differences.

1. Introduction

The Enhanced Fujita (EF) scale is currently used in several countries including Canada, the United States of America, and Japan to rate the intensity of tornadoes through observable damage indicators (DI). For each DI, there are varying degrees of damage (DOD), along with their associated wind speeds. These DODs range from the threshold of damage to total destruction of the DI (McDonald & Mehta, 2006). The overall EF-scale rating for the tornado is then assigned based on the maximum wind speed across all observed damage indicators (Mehta, 2013; Sills et al., 2014).

Damage surveys can be challenging when there is low population density, leading to sparse and intermittent infrastructure and damage observations. This can result in the underestimation of true tornado intensities. For example, if a tornado is observed but does not cause damage to a DI, it is rated as EF0-Default (or EF-Unknown), even if damage to a non-DI is apparent. This lack of damage indicators indicates a need for advanced analysis methods to help supplement damage indicators found in the EF scale (Edwards et al., 2013), such as the directional treefall...
method for estimating wind speeds in a tornado (Rhee & Lombardo, 2018). Although the DIs in the EF scale cover a wide range of structures, they (mostly) do not consider the wind-induced movement of various, non-structural objects. Some regional versions of the EF scale do contain some guidance for the wind-induced movement of different objects. For example, the Japanese EF scale (JMA, 2015) considers the overturning of light, ordinary, and large vehicles, although it does not provide guidance for a larger displacement or lofting of these vehicles.

Large compact objects such as vehicles, construction materials, and large appliances are often found to be lofted to a new location in the aftermath of damage surveys (Marshall et al., 2012; Kopp et al., 2016; Sills et al., 2020). For example, Figure 1 shows an example of farming equipment (combine harvester) weighing approximately 9800 kg that was thrown 80 – 100 m in the July 1, 2023, Didsbury, AB, EF4 tornado. Since there is no guidance in the EF scale on the wind-induced movement of such objects, these observations are currently not being utilized to provide additional estimates of the wind speeds.

Fig. 1. Photograph of a thrown combine from the ground survey of the July 1, 2023, Didsbury, AB EF4 tornado.

Previous studies have been performed on the wind-induced motion of vehicles, and how they correlate to the damage to various DIs in the vicinity. Haan et al. (2017) provides a recent review of the work done on these, as summarized in Table 1. Table 1 shows tornado intensity
estimates based on 1) the correlation between observed vehicle movements and nearby damage (Fujita, 1971; Schmidlin et al., 2002), 2) observations of vehicle movements along with estimated probabilities of vehicle motion from Paulikas et al. (2016), and 3) wind-tunnel and tornado-vortex testing done by Haan et al. (2017). Overall, these results indicate that the distinction between sliding, flipping, and lofting is crucial to the analysis of wind-induced movement of compact objects. Fujita (1971) discusses, quite generally, the distance vehicles are moved or thrown by the tornado, while the more recent works examine probabilities of the various types of wind-induced motion as a function of wind speed.

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<tr>
<td>F0 / EF0</td>
<td>-</td>
<td>-</td>
<td>10% of vehicles shifted laterally</td>
<td>-</td>
<td>29 – 38</td>
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<tr>
<td>F1 / EF1</td>
<td>Moving autos blown off road</td>
<td>72% of the vehicles were not moved by the wind and 96% were not tipped over</td>
<td>65% of vehicles did not move, 31% shifted laterally, and 4% were rolled or lofted</td>
<td>Sliding likely to occur</td>
<td>39 – 49</td>
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<td>F2 / EF2</td>
<td>Cars blown off highway</td>
<td>-</td>
<td>-</td>
<td>50 – 60</td>
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<tr>
<td>F3 / EF3</td>
<td>Cars lifted off the ground</td>
<td>50% [of vehicles sampled] were not moved by the wind and 82% were not tipped over.</td>
<td>36% of vehicles did not move, 48% shifted laterally, and 15% were rolled or lofted</td>
<td>61 – 74</td>
<td></td>
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<tr>
<td>F4 / EF4</td>
<td>Cars thrown some distance or rolled considerable distance</td>
<td>All vehicles were moved with 69% shifted laterally and 31% rolled or lofted</td>
<td>-</td>
<td>74 – 89</td>
<td></td>
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<td>F5 / EF5</td>
<td>Automobile-sized missiles generated</td>
<td>-</td>
<td>-</td>
<td>&gt; 89</td>
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Table 1. Wind-induced movement observations for vehicles (based on Table 1 from Haan et al. (2017)).

There has been limited research exploring the detailed use of different wind-borne debris elements, or their flight distances, as a tool for tornado wind speed estimation. Wills et al. (2002) presented a model for describing the damage done to buildings by wind borne debris and noted that loose-laid debris items are much more likely to roll rather than experience lofting. Kopp et al. (2011) used a failure analysis of complete roofs and worked out a method to use the observed flight distance of the roof to estimate the wind speed causing that failure and flight. However, both models used a straight-line wind field assumption, ignoring the importance of the role of the 3D tornado wind field on the angle of attack of the wind acting on large compact objects. In fact, while the number of studies on wind-borne debris, generally, is rather limited, it is more so for tornadoes. Some notable exceptions include the work of Twisdale et al. (1979) who developed a methodology for simulating the initial release

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conditions and subsequent motion of objects transported by tornadoes, Huo et al. (2020) who performed large eddy simulations of a tornado-like vortex to estimate the debris trajectories of spherical debris, as well as Huo et al. (2023) who examined the initialization of debris flight in these large eddy simulations of tornado-like vortices. Zhao et al. (2021) included a more detailed summary of previous analytical and experimental approaches to study wind-borne debris dynamics in both straight-line winds as well as tornadic wind fields.

The objective of this paper is to use an analytical model of a translating tornado, as well as observed debris trajectories from tornado damage surveys, to create a model for estimating wind speeds in tornadoes using debris trajectories of large loose-laid compact objects. To accomplish this, numerical simulations with a wind field model based on Baker & Sterling (2017) are developed. Aerial imagery or ground-survey observations that depict wind-induced movement are then used to determine the start and end points, as well as the characterization (weight, dimensions, etc.) of these objects. By analyzing the wind speeds required to create the necessary debris trajectories, the average critical wind speed for lofting and median trajectory will be determined. The motivation for this paper is to apply this method to thoroughly documented tornado events from available damage survey observations (NTP, 2020), and compare with the EF-scale ratings of those events.

2. Damage Survey Observations

a. Identification of Debris Lofting Cases

Thorough post-event damage surveys are important for the identification of debris lofting cases. The critical pieces of data come from ground observations (including the recollection of events from people who experienced the event), and remote sensing, which are all described in detail below.

First is the identification of the debris lofting cases. This usually occurs during the ground survey portion of the post-event damage survey, when large compact objects are visibly noted to be out of place. Some example signs that this occurred include improper orientation of the object (such as being flipped on its side) and being embedded in the ground. In addition to noting the final ending location of the debris, the other key piece of information that is obtained from ground surveys is the starting location of the debris. This often requires homeowner recollection of where the object was before the tornado occurred, which is supported by
markings on the ground (such as wheel marks, or dead grass) that indicate the starting position. Occasionally, for very large debris, it is also possible to view where the object started via high-resolution satellite imagery.

Next is the determination of whether the debris was lofted or rolled (or a combination of the two mechanisms), as well as an accurate measurement of the distance between the starting and ending location. To help with this, remotely piloted aircraft systems (commonly known as drones) and the associated collected imagery can be used. Drones have been used with increasing frequency during damage surveys to get overhead views of damage, get photos in unsafe areas, and detect tornado paths through crops and forests (Sills et al., 2020). Drones are useful for recording images and video on a neighbourhood scale (Womble et al., 2018), which means that unlike other remote sensing methods such as satellite imagery or aircraft, drone imagery remains clear and useful even in less-than-ideal conditions such as low cloud cover, or smoke / haze from wildfires or other environmental factors. Depending on the drone, photogrammetry equipment, and height that the drone is operating at, the current resolution of drone imagery ranges from under 1 cm / pixel to about 2.5 cm / pixel. Higher resolution drone imagery allows for detailed investigations of structural connections, tree species, directional analysis of treefall, and debris movements (Womble et al., 2018; Wagner et al., 2019; Sills et al., 2020). Aircraft imagery (from piloted flights) can also be used, but the typical resolution is lower than drone imagery at approximately 5 cm / pixel.

Once debris movement is noted from ground survey observations, a determination can be made about the type of movement that the debris experienced via aerial imagery. These movements are either classified as lateral movement (which encompasses any horizontal displacement including sliding, rolling, tumbling, etc.), or a lofting movement (which encompasses vertical displacement that exceeds the height of the object itself). This determination is made based on the ground markings surrounding the launch and landing area. As an example of how ground markings are used to determine whether lofting occurred, Figure 2 shows a section of the drone orthomosaic from the July 18, 2022, Medicine Hat, AB EF2 tornado that depicts damage to grain silos.
Fig. 2. Drone orthomosaic of the July 18, 2022, Medicine Hat, AB EF2 tornado. The starting point, ending point, and path of the debris element are noted by the white markings.

The starting point of the debris elements of the destroyed grain silos is noted as the white circle on the left side of Figure 2, which was based on the ground-to-silo connections. The ending points of the debris elements can be found scattered in the field to the east of the start point. Based on the crop markings in the field, which show the exact path the grain silo took through the field, it appears that the debris elements experienced lateral (rolling or sliding) movement rather than lofting movement. Measuring the horizontal length of the debris trajectory, the farthest debris element (noted as the white circle on the right side of Figure 2) travelled approximately 530 m. As an example of noted lofted debris movement, Figure 3 shows a section of the drone orthomosaic from the July 1, 2023, Didsbury, AB EF4 tornado that depicts a combine (previously shown in Figure 1) that was lofted.
Fig. 3. Drone orthomosaic of the July 1, 2023, Didsbury, AB EF4 tornado. The starting point, ending point, and path of the debris element are noted by the white markings.

An area of potential starting points of the combine are noted as the white circle on the left side of Figure 3. This starting point was provided by homeowner recollection and corroborated by daily satellite imagery. The ending point of the combine can be seen in the area as noted by the white circle on the right side of Figure 3. Based on the lack of ground markings around the combine, and the fact that the combine was partially embedded into the ground, it appears that the debris element experienced lofting movement rather than rolling movement. Measuring the horizontal length of the debris trajectory, the combine travelled approximately 90 m. Due to the inherent uncertainty of this measurement, and the large size of the analyzed objects, a tolerance of 10 m is added, so that during modelling a debris trajectory horizontal length of 80 – 100 m will be considered valid. The classification of lateral movement vs. lofting movement is critical, as this study only focuses on a method to calculate the wind speed based on the horizontal length of the lofting trajectory of an object, meaning that this method could not be used on the grain silos from the Medicine Hat, AB tornado, but could be used for the Didsbury, AB tornado.

Another critical component to determining an accurate trajectory is the effect of the terrain elevation. Specifically, the relative change in elevation between the starting and ending points of the debris. Figure 4 shows the digital elevation model (Digital Elevation Models, 2015)...
derived from the aerial orthomosaic from the July 1, 2023, Didsbury, AB EF4 tornado. The relative elevation is referenced to the take-off location of the drone, which is set as zero. Although this high-quality elevation model has been obtained from drone imagery, open-source elevation models with lower resolution would also be able to provide an estimate of the relative elevation change. For the following analysis, the change in elevation between the start and end points is defined as $\Delta$.

![Relative Elevation](image)

Fig. 4. Digital elevation model (DEM) obtained from the orthomosaic in Figure 3 for the July 1, 2023, Didsbury, AB EF4 tornado.

b. Identification of Debris Details

To analyze the debris trajectories noted in post-event damage surveys, details about the characteristics of the debris need to be identified during the ground survey. The most critical pieces of information are the weight of the object, as well as its length, width, and height. The dimensions are easy to obtain during ground surveys; however, the weight of the object generally requires some investigation. Most large compact objects, such as vehicles, and farming equipment often contain model numbers that are searchable online to obtain the weight and size. Alternatively, for objects without model numbers (such as the haybales presented in a later section), research papers or referenceable material for the typical range of weights for
that object are obtained. With that information, the following variables can be defined: \( \rho_o \) is the density of the object (assumed uniform throughout), and \( l \) is the characteristic dimension of the object.

Additionally, the various aerodynamic coefficients of large compact objects need to be well defined. These coefficients vary depending on whether the object is surface-mounted (when the object is in contact with the ground), or airborne (when the object is not in contact with the ground). \( C_D^{SM} \) is the drag coefficient of the object while surface-mounted (defined using the relative wind speed and direction of the trajectory), \( C_L \) is the lift coefficient (defined using the relative wind speed and direction perpendicular to the trajectory), and \( C_D^A \) (defined using the relative wind speed and direction of the trajectory) is the drag coefficient of the object while airborne. For the surface mounted drag coefficients \( (C_D^{SM}) \) and lift coefficients \( (C_L) \), research papers or referenceable material for the typical range of aerodynamic coefficients for that object are obtained. As a notable example, the vehicles used in this study are referenced from Heisler (2004). The airborne drag coefficients \( (C_D^A) \) are assumed to be “idealized” shapes for simplicity in the analysis, i.e., all vehicles are assumed to be prismatic, and haybales are assumed to be cylinders. The coefficients of these idealized shapes are referenced from Potter et al. (2016).

c. Identification of Tornadic Wind Field Parameters

To analyze the debris trajectories noted in post-event damage surveys, details about some of the characteristics of the tornadic wind field need to be identified during the ground survey. Based on the overall ground and drone survey, or through remote sensing, the maximum overall width of the tornado damage path, based on damage survey observations, at the point where the debris is lofted, defined as, \( W_{max} \) can be obtained. Additionally, \( V_T \), the translational speed of the tornado can be estimated via radar analysis of the motion of the tornado’s parent mesocyclone by calculating how far the mesocyclone traveled in between each radar scan. Different radars, located at different distances away from the mesocyclone, may give slightly differing answers for the translational speed of the mesocyclone, which is used to provide a range for the Monte Carlo simulation detailed later in this paper. Baker & Sterling (2017) provides some guidance on suitable parameters for the tornado wind field model. Typical values for \( \delta \), which is the ratio of the radial distance where the maximum radial velocity occurs to the vertical distance where the maximum vertical velocity occurs (which is a function of terrain roughness) can be found in Table 1 of Baker and Sterling (2017). Due to the difficulty
in determining the core radius, \( r_m \), the range of values is set to 10 – 50% of the maximum damage width of the tornado. \( U_m \) is the maximum radial velocity of a tornado, and \( S \) is the swirl ratio defined as the maximum value of the circumferential velocity to the maximum value of the radial velocity (\( S = \frac{V_m}{U_m} \)). These values are impossible to determine via the ground survey or through any remote sensing method. Therefore, these values are set to a wide range in the Monte Carlo simulation, detailed later in this paper.

3. Methodology

a. Tornado Wind Field Model

Tornadoes have complex wind fields due to the dependence on swirl ratio, ground roughness, and non-stationarity. Three-dimensionality, non-linear effects, and flow field instabilities and singularities need to be taken into account to properly model a tornado (Lewellen, 1993; Davies-Jones et al., 2001; Karstens et al., 2010; Gillmeier et al., 2018). Model-scale tornado generators (Haan et al., 2008; Hangan and Kim, 2008; Haan et al., 2017) as well as computational fluid dynamics (CFD) (Huo et al., 2020; Gairola et al., 2023) have become popular methods for simulating tornadoes. However, because the debris model presented in the next section uses an analytical model, an analytical wind field model was chosen for this study. Common models for tornado wind fields are the Rankine vortex model (Rankine, 1882), the Burgers-Rott model (Burgers, 1948; Rott, 1958), and the Sullivan vortex model (Sullivan, 1959). The simplest of these models is the Rankine vortex model, which is based on a rigid core inner vortex, and a free vortex outer region. The circumferential velocity field of the Rankine vortex model can be expressed as:

\[
V = \begin{cases} \frac{V_m r}{r_m} & \text{if } r < r_m \\ \frac{V_m r_m}{r} & \text{if } r > r_m \end{cases}
\]

where \( r \) is the radius, \( V \) is velocity, and \( V_m \) is the maximum velocity, located at radius \( r_m \). Another common model for tornadoes is that developed by Twisdale et al. (1979), which has three degrees of freedom to simulate dynamics in turbulent flow fields. However, this model was created using empirical relationships and was not set in a consistent analytical framework (Baker & Sterling, 2017).
The development of model-scale tornado-vortex generators (Haan et al., 2008; Hangan and Kim, 2008; Haan et al., 2017) as well as the collection of in-situ data (Refan et al., 2014) have added additional insight into the effect of tornado wind loads. Baker & Sterling (2017) used this available full-scale data for tornado and wind pressure fields to develop a simple analytical model to predict velocity time histories in order for debris trajectories to be calculated. Compared to the other analytical models referenced earlier, the Baker & Sterling (2017) model employs the use of a shape parameter, allowing for the circumferential velocity profile to be varied. Consequently, the Baker & Sterling (2017) model replicates radial inflow close to the ground to a more accurate degree (Gillmeier et al., 2018), which is critical for debris flight analysis. A summary of assumptions for modelling the wind field for a one-cell tornado, as laid out in Baker & Sterling (2017), is:

- A single cell vortex with radial inflow and vertical upflow.
- The radial inflow has a maximum in the radial direction at \( r = r_m \) and approaches zero at \( r = 0 \) and \( r = \infty \).
- The radial inflow has a maximum in the vertical direction at \( z = z_m \) and approaches zero at \( z = 0 \) and \( z = \infty \).
- The velocity and pressure fields are solutions of the Euler equations – the inviscid, high Reynolds number form of the Navier-Stokes equations.
- The tornado boundary layer is modelled by increasing the radial velocity from zero at ground level to a maximum at \( z = z_m \).
- Turbulence is neglected due to a lack of information available about turbulent eddies in the overall tornado structure in full-scale measurements.

The full derivation and discussion of this model can be found in Baker & Sterling (2017). Based on this derivation, the radial velocity normalized by the maximum radial velocity (\( \bar{U} = U/U_m \)), the circumferential velocity normalized by the maximum radial velocity (\( \bar{V} = V/U_m \)), and the vertical velocity normalized by the maximum radial velocity (\( \bar{W} = W/U_m \)) can be expressed as:

\[
\bar{U} = \frac{-4\bar{r}\bar{z}}{(1 + \bar{r}^2)(1 + \bar{z}^2)} \quad [2]
\]

\[
\bar{V} = \frac{2.88\bar{r}\ln(1 + \bar{z}^2)}{(1 + \bar{r}^2)} \quad [3]
\]
\[ \bar{W} = \frac{4\delta \ln(1 + \bar{z}^2)}{(1 + \bar{r}^2)^2} \]  

where \( \bar{r} \) is the radial distance from the centre of the vortex \( (r) \), normalized by the radial distance where the maximum radial velocity occurs \( (r_m) \), and \( \bar{z} \) is the vertical distance from the ground \( (z) \), normalized by the vertical distance where the maximum vertical velocity occurs. \( (z_m) \).

Figure 5 depicts the radial, circumferential, and vertical normalized velocity profiles of the model as a function of dimensionless radial distance. Although this model does not fully account for the complexities of the tornado boundary layer, the simplicity of the analytical expressions allows it to be easily adapted as an input for a debris trajectory model. For these reasons, it is used in this study. Of note for this single-cell model is that although multi-vortex tornado suction vortices may have higher wind speeds, they are excluded in this study due to no multi-vortex behaviour noted in the tornadoes presented in this paper (although it is worth noting that small-scale vortices could be present inside what appears to be a single-cell tornado, which is not accounted for in this study for simplicity). The three main assumptions that this model requires are the location of the maximum radial velocity, the ratio between the vertical and horizontal length scales, and the swirl ratio, which will be discussed in the model validation section. Finally, it is assumed that \( z = z_m \) at the ground level, and the debris starts at \( r = r_m \). This is to assist in finding the minimum lofting speed, as \( z = z_m \) creates the critical radial velocity at \( r = r_m \).
Fig. 5. Normalized radial, circumferential, and vertical velocities vs. dimensionless radial distance based on the Baker & Sterling (2017) vortex mode ($\delta = 0.1; S = 0.5; z = z_m$).

b. Debris Flight Modelling

Previous studies on wind-borne debris have generally classified debris into three types: compact, sheet (or plate-like), and rod-like (Wills et al., 2002). Compact debris is generally defined in Wills et al. (2002) as debris that does not meet the specialized geometry for sheet debris (like plywood or corrugated iron), or rod debris (like bamboo or metal poles). This study focuses on compact debris, since it can simplify the debris modelling by assuming the drag coefficient is the same for all orientations (Holmes, 2004). There are two approaches to modelling trajectories from wind-borne debris. The first approach is particle-based and obtains the trajectories from wind-borne debris. The first approach is particle-based and obtains the trajectories from wind-borne debris by solving the differential equations of motion. The second is a fluids-based approach, which involves solving debris motion using the Navier-Stokes equations with a CFD simulation (Huo et al., 2020, Zhao et al., 2021). For operational simplicity, the particle-based method is implemented in this study, combined with a model for the wind field.

Tachikawa (1983) developed a parameter, later named the Tachikawa number (Holmes, 2006), to describe the non-dimensional ratio of aerodynamic forces to gravity forces. The Tachikawa number, which has since been used widely in the calculation for compact, sheet, and rod wind-borne debris, can be expressed as:

$$K = \frac{\rho_a A U^2}{2mg}$$

[5]

where $\rho_a$ is the density of air, $A$ is the reference area of the object, $U$ is the wind speed, $m$ is the mass of the object, and $g$ is the gravitational acceleration constant.

For a tornadic 3D wind field, the dynamics of wind-borne debris can be described through a set of second-order differential equations of Newton’s 2nd law in a cylindrical coordinate system (radial, circumferential, and vertical directions). Figure 6 shows an example of an object in a cylindrical coordinate system, where $U$, $V$, and $W$ are the radial, circumferential, and vertical wind speed of the tornado vortex, respectively, and $u_o$, $v_o$, and $w_o$ are the radial, circumferential, and vertical speeds of the object, respectively.

The relative wind speed acting on the object is $\sqrt{(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2}$, with radial $(U - u_o)$, circumferential $(V - v_o)$, and vertical $(W - w_o)$ components. The
angles between the trajectory and the radial, circumferential, and vertical components ($\alpha, \beta, \gamma$, respectively) can be expressed as:

$$\alpha = \arccos \frac{(U - u_o)}{\sqrt{(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2}}$$  \[6\]

$$\beta = \arccos \frac{(V - v_o)}{\sqrt{(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2}}$$  \[7\]

$$\gamma = \arccos \frac{(W - w_o)}{\sqrt{(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2}}$$  \[8\]

Fig. 6. Definition sketch of the cylindrical coordinate system and velocity components for debris object flight.

Using this coordinate system, the equations that govern the initial motion for a loose-laid object on the ground can be written as:

$$\frac{d^2 u_o}{dt^2} = \frac{\rho_a}{2\rho_o t} \left( C_D^{SM} \cos \alpha - C_L \sin \alpha \right) [ (U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2 ] + \frac{v_o^2}{r}$$  \[9\]

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

\[
\frac{d^2 w_o}{dt^2} = \frac{\rho_a}{2\rho_o l} (C_{D}^S \cos \gamma + C_L \sin \gamma)[(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2] - g
\]

where \(\frac{d^2 u_o}{dt^2}\), \(\frac{d^2 v_o}{dt^2}\), and \(\frac{d^2 w_o}{dt^2}\) are the radial, circumferential, and vertical acceleration of the object, and \(r\) is the radial distance from the center of the vortex. Once airborne, the object under the compact-debris assumption is assumed to have a lift coefficient of zero, along with a different drag coefficient compared to when the object was surface-mounted. This effect of dramatically reduced lift while airborne has been demonstrated in tornado simulator experiments (Tang et al., 2022) This reduces the equations that govern the motion of the object while it is airborne to:

\[
\frac{d^2 u_o}{dt^2} = \frac{\rho_a}{2\rho_o l} (C_{D}^A \cos \alpha)[(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2] + \frac{v_o^2}{r}
\]

\[
\frac{d^2 v_o}{dt^2} = \frac{\rho_a}{2\rho_o l} (C_{D}^A \cos \beta)[(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2]
\]

\[
\frac{d^2 w_o}{dt^2} = \frac{\rho_a}{2\rho_o l} (C_{D}^A \cos \gamma)[(U - u_o)^2 + (V - v_o)^2 + (W - w_o)^2] - g
\]

To switch between these two sets of equations, and their associated drag and lift coefficient values, a determination must be made for when an object is considered airborne (lofted). For simplicity, an object is defined as being airborne after it reaches \(z = 1\) m above the ground. Between the heights of 0 m and 1 m, the drag and lift coefficients change based on a linear interpolation between the surface mounted values \((C_{D}^{SM}, C_L)\) and the airborne values \((C_{D}^{A}, C_L = 0)\).

These equations adequately describe the forces acting on a compact object in a 3D tornadic wind field, which allows for a calculation of the debris trajectories of a lofted object by solving the equations with a numerical method. Similar models for the acceleration of debris in a wind field have been commonly used in trajectory analysis in previous studies (Holmes, 2004; Baker, 2007; Baker & Sterling, 2017; Huo et al., 2020; Zhao et al., 2021). This model assumes that there is no rotation of the compact object while in the air, and therefore, there are no additional
lift forces due to the Magnus effect. This is a reasonable assumption due to the limited impact the effect has on large compact objects rotating relatively slowly (Holmes, 2004; Baker, 2007). To simplify the computational analysis of the trajectories, which uses a fourth-order Runge-Kutta method (Kutta, 1901), these accelerations are converted into Cartesian coordinates, i.e.,

\[
\begin{align*}
\frac{d^2 x}{dt^2} &= (\cos \theta - \sin \theta) \frac{d^2 u}{dt^2} \\
\frac{d^2 y}{dt^2} &= (\sin \theta \cos \theta) \frac{d^2 v}{dt^2} \\
\frac{d^2 z}{dt^2} &= \frac{d^2 w}{dt^2}
\end{align*}
\]  

[15]

where \( \theta \) is the angle between the radial axis in the cylindrical coordinate system to the x-axis in the Cartesian coordinate system, as shown in Figure 6.

c. Monte Carlo Simulation

Lofting trajectories estimated from damage survey observations are used to assist in a Monte Carlo simulation in order to account for the uncertainty in the tornado model and debris parameters. Figure 7 shows a flowchart of how this Monte Carlo simulation functions.

![Flowchart of Monte Carlo simulation and trajectory comparison process.](image)

Fig. 7. Flowchart of Monte Carlo simulation and trajectory comparison process.

To start, the tornado model parameters and debris parameters are selected randomly. The parameters modelled (described earlier in the paper) are \( r_m, V_T, \delta, S, U_m, \rho_o, l, C_{DSM}, C_D, \) and \( C_L \) which are all assumed to be a uniform distribution to reduce bias. Note that not all parameters are modelled through the Monte Carlo simulation every time. For example, the characteristic length \( l \) of a vehicle is well defined, so \( x_{\text{min}} = x_{\text{max}} \), which does not require a Monte Carlo simulation for that specific parameter. However, the characteristic length of a haybale may be variable, so adding that parameter to the Monte Carlo simulation is necessary.

File generated with AMS Word template 2.0
Due to the uncertainty of some of these parameters, namely the maximum radial wind speed, the swirl ratio, and the location of the core radius, the values have been given a wide range to ensure that the true, likely values are being captured within the range. Other values such as the translational speed, and the density of the object, which are easier to empirically determine, have been set to a tighter range. Once these random values have been selected, the trajectory that these random values produced is compared to the overall distance seen from the drone or aerial orthomosaic. If the overall horizontal displacement of the object matches the observed horizontal displacement of the debris, (with the caveat that the object is only considered to be lofted if it reaches 1 m in height), the random values and trajectory are saved as a “valid” trajectory. The simulation repeats until 10000 valid trajectories and parameter set combinations have been found. From there, statistical analysis of the parameters that cause lofting of a certain distance can be calculated, such as the median parameters, along with the associated trajectory. Although the EF scale uses wind speeds that represent the expected (mean) value, the median was chosen for this analysis as this is what is typically used for fragility curves where the distribution of the result is not defined. Since all parameters are assumed to be a uniform distribution (which is likely not true in reality for some of the parameters), a median value is the best choice for this analysis. Ideally, a multi-parameter optimization would be performed to determine the most likely set of valid parameters. However, this is currently impossible due to the lack of knowledge of which of the many parameters are the most critical, and, therefore, a weighting can not be assigned. Future work into the varying importance of tornado parameters may be able to improve this analysis in the future.

Of particular interest is the wind speed (defined as the vector addition of the radial, circumferential, vertical, and translational wind speeds) acting on the object that causes the initial lofting and eventually causes it to travel the observed distance. The instantaneous wind speed can be defined as the wind speed acting on the object at the moment when it experiences any sort of lofting ($z_{max} > 0$), henceforth referred to as the “lofting wind speed”. However, since this study aims to compare these lofting wind speeds to the EF scale (McDonald & Mehta, 2006), a conversion to a 3-second gust wind speed is necessary. To accomplish this, a spatial averaging based on the translational wind speed of the tornado is used to encapsulate the wind speeds in the tornadic wind field that are located 1.5 seconds in each direction (for a total of 3 seconds per side) at the point, and moment in time where the debris is initially lofted.
To calculate the 3-second gust wind speed, an area integral of the magnitude of the sum of the instantaneous radial, circumferential, vertical, and translational wind speeds at the point \((x, y)\), defined as \(V_0\), over the 3 second interval and then divided by the area of integration \((3V_T)^2\) can be calculated as:

\[
V_3 = \frac{\int_{y_0-1.5V_T}^{y_0+1.5V_T} \int_{x_0-1.5V_T}^{x_0+1.5V_T} V_0(x, y) \, dx \, dy}{(3V_T)^2}
\]

where \(V_3\) is the 3-second gust wind speed, and \((x_0, y_0)\) is the point of initial loft for the debris. Figure 8 shows a diagram of an example of a 3-second spatially averaged area for a tornado with a maximum width \(W_{\text{max}}\) of 640 m, and a translational speed \(V_T\) of 10 m/s (which are the maximum width and translational speed of the Didsbury, AB tornado that lofted the combine in Figures 1 and 3). For all cases tested in this study, the ratio of the averaging area to the overall area of the tornado is less than 5%, indicating that this method does not reduce the overall complexity of the tornado. However, this method should be used with caution for tornadoes with small widths along with high translational speeds. In those cases, averaging for a 3-second gust may cause an oversimplification of the tornadic wind field.
Fig. 8. Diagram depicting the circumference of a 640 m wide tornado, along with the 3-second spatial averaging box for a tornado with a translational speed of 10 m/s, along with the initial lofting location of the debris.

4. Trajectory Validation & Expected Trajectories

To ensure the trajectories being estimated from the methodology set out in the previous section are consistent with other analytical trajectory estimates, the methodology is applied and compared to the trajectories determined from Baker & Sterling (2017). The lift coefficient is assumed to be zero through the simulation, as lift coefficients were not considered in the Baker & Sterling (2017) model. In this simulation, Baker & Sterling (2017) defines a dimensionless buoyancy parameter, which can be defined as:

$$
\phi = \frac{0.5\rho A r_m}{M} C_D
$$

where $M$ is the mass of the debris, and $A$ is the reference area of the debris. Broadly speaking, this parameter specifies the effect that the debris parameters have on the trajectory. A low buoyancy number indicates debris that is heavy and unlikely to loft from the ground, whereas a high buoyancy number indicates lighter debris that has a higher chance of lofting. Figure 9 shows a comparison between the Baker & Sterling (2017) results (left), and the results from the current study (right) for the case with a buoyancy parameter of 50 (top), which results in a case where the debris remains airborne in the tornado; and for the case with a buoyancy parameter of 10 (bottom), which results in a case where the debris is lofted, but then is brought back down to the ground.

File generated with AMS Word template 2.0
Fig. 9. Comparison of trajectories for the Baker & Sterling (2017) model (left) to the current study modelling a one-cell vortex (right). Results shown are for debris with a high buoyancy parameter (top) and for debris with a low buoyancy parameter (bottom).

As Figure 9 shows, the models are a near-identical match, indicating that the alternative equations match with the Baker & Sterling (2017) model. To compare the analytical results with model-scale experiments, Bourriez et al., (2020) conducted a model-scale study of debris motion of styrofoam spheres in a vortex generator. The results were captured using high-speed cameras and compared to simulations using the Baker & Sterling (2017) model. Overall, Bourriez et al., (2020) showed that the Baker & Sterling (2017) model is in good agreement with experimental values, indicating that it is an appropriate model to use for this study.

Examining the effect that the buoyancy parameter has on trajectories can assist in the determination of the expected behaviour of differing large compact objects. Figure 10 shows a variety of trajectories as a function of the buoyancy parameter.
Fig. 10. Comparison of trajectories as a function of the buoyancy parameter.

Figure 10 provides some interesting insights into the physical role that a tornado has in lofting compared to straight-line winds. Depending on the buoyancy parameter, the object is lofted until the vertical lift is balanced out by gravity forces. It then remains airborne while the combined lift and drag forces exceed the force of gravity. As the object speeds up towards terminal velocity, the overall lift and drag forces decrease, leading to it falling towards the ground. This is very different from objects being lofted in a straight-line wind scenario, which relies on a strong temporal pulse of winds to temporarily allow for the drag and lift forces to become strong enough to loft the object, and then fall due to a lack of vertical velocity. This creates a trajectory similar to an object like a ball being kicked, a singular arc with limited vertical displacement.

The next section will present results from three different tornadoes. The range of buoyancy parameters will also be provided in that section for each debris element in that specific tornado. However, in general, the buoyancy parameters average around 0.5 across the varying large compact objects. When the buoyancy parameters are that low, the trajectories appear to be similar to straight-line wind trajectories due to the vertical velocities of the tornado not being strong enough to overcome the lack of buoyancy for very long.

5. Results

a. Didsbury, AB – EF4 Tornado – July 1, 2023

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On July 1, 2023, an EF4 tornado occurred in Didsbury, AB. As seen in Figures 1 and 3, a New Holland TR86 combine harvester was lofted. Based on the drone orthomosaic shown in Figure 3, the combine harvester was lofted and moved 80 – 100 m from its starting point. Ground survey observations also noted the width of the tornado at that point ($W_{\text{max}}$) as well as details about the combine harvester that were used to calculate $l$ and $\rho_m$. Finally, the translational speed of the tornado ($V_T$) was determined through the radar analysis of the mesocyclone motion over time. Table 2 shows the parameters used in the analysis of the Didsbury tornado, along with the Monte Carlo simulation results that show the median parameters across the probability distribution of results. Figure 11 plots the median trajectory of the combine (left) and the cumulative distribution function of the lofting wind speed of the combine (right). The trajectory reaches a maximum height of 1.26 m relative to its starting elevation. Appendix A shows the probability distribution of the parameters for the Didsbury, AB tornado in order to provide a detailed example of the analysis of this event.

<table>
<thead>
<tr>
<th>Variable</th>
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<th>$x$</th>
<th>Monte Carlo Median Results</th>
</tr>
</thead>
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</tr>
<tr>
<td>$r_m$</td>
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<td>64 – 320 m</td>
<td>212 m</td>
</tr>
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<td>$V_T$</td>
<td>NTP (2020)</td>
<td>6 – 10 m/s</td>
<td>8.41 m/s</td>
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<td>$\delta$</td>
<td>Baker &amp; Sterling (2017)</td>
<td>0.1 – 0.2</td>
<td>0.16</td>
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<tr>
<td>$S$</td>
<td>N/A</td>
<td>0.4 – 1.1</td>
<td>0.84</td>
</tr>
<tr>
<td>$U_m$</td>
<td>N/A</td>
<td>50 – 140 m/s</td>
<td>119 m/s</td>
</tr>
<tr>
<td>$l$</td>
<td>NTP (2020)</td>
<td>3.35 m</td>
<td></td>
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<td>$\rho_m$</td>
<td>NTP (2020)</td>
<td>72 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>$C_D^M$</td>
<td>Heisler (2004)</td>
<td>1.4 – 1.8</td>
<td>1.68</td>
</tr>
<tr>
<td>$C_D^A$</td>
<td>Porter et al., (2016)</td>
<td>1.8 – 2.0</td>
<td>1.84</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Heisler (2004)</td>
<td>0.3 – 0.5</td>
<td>0.40</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>NTP (2020)</td>
<td>-2 m</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>N/A</td>
<td>0.08 – 0.53</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Parameters used in the debris trajectory analysis, along with the median results of the Monte Carlo simulation of the combine harvester in the Didsbury, AB tornado.
On August 7, 2020, an EF3 tornado occurred in Scarth, MB. In this event, a Jeep Grand Cherokee (referred to as “SUV”), and a Chevrolet Silverado Z71 (referred to as “Truck”) were lofted considerable distances. The fact that they were lofted, and the approximate distances travelled, were based on the recollection of the occupants of the SUV as well as aerial photography showing impact marks in the crops during the post-event damage survey. Ground survey observations also noted the width of the tornado at that point ($W_{max}$) as well as details for the SUV and Truck that were used to calculate $l$ and $\rho_m$. Finally, the translational speed of the tornado ($V_T$) was determined through the radar analysis of the mesocyclone motion over time. Figure 12 shows an aerial orthomosaic from the post-event damage survey along with the estimated horizontal length of the trajectory of the SUV (30 – 50 m) in white, and the estimated horizontal length of the trajectory of the truck (80 – 100 m) in black. The vehicles had been removed from the area before the aerial orthomosaic was created, so they are not visible in the imagery. Table 3 and Table 4 show the parameters used in the analysis of the Scarth tornado, for the SUV and Truck, respectively, along with the Monte Carlo simulation results that show the median parameters across the probability distribution of results. Figure 13 plots the median trajectory of the vehicles (left) and the cumulative distribution function of the lofting wind speed of the vehicles (right). The trajectory of the SUV reaches a maximum height of 1.09 m relative to its starting elevation, and the trajectory of the Truck reaches a maximum height of 2.28 m relative to its starting elevation.
Fig. 12. Aerial orthomosaic of the August 7, 2020, Scarth, MB EF3 tornado. The estimated horizontal length of the trajectory of the SUV is denoted by a white arrow. The estimated horizontal length of the trajectory of the truck is denoted by a black arrow.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reference</th>
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<th>Monte Carlo Median Results</th>
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<td>$W_{\text{max}}$</td>
<td>NTP (2020)</td>
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<tr>
<td>$r_{\text{m}}$</td>
<td>N/A</td>
<td>139 – 695 m</td>
<td>436 m</td>
</tr>
<tr>
<td>$V_T$</td>
<td>NTP (2020)</td>
<td>4 – 6 m/s</td>
<td>5.51 m/s</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Baker &amp; Sterling (2017)</td>
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<td>0.14</td>
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<td>$S$</td>
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<td>0.4 – 1.1</td>
<td>0.82</td>
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<td>$U_m$</td>
<td>N/A</td>
<td>50 – 140 m/s</td>
<td>110 m/s</td>
</tr>
<tr>
<td>$l$</td>
<td>NTP (2020)</td>
<td>1.80 m</td>
<td></td>
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<tr>
<td>$\rho_m$</td>
<td>NTP (2020)</td>
<td>80 kg/m$^3$</td>
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<tr>
<td>$C_{D}^{M}$</td>
<td>Heisler (2004)</td>
<td>0.35 – 0.65</td>
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<tr>
<td>$C_{D}^{A}$</td>
<td>Potter et al., (2016)</td>
<td>1.1 – 1.3</td>
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<td>Heisler (2004)</td>
<td>0.3 – 0.4</td>
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<td>$\Delta$</td>
<td>NTP (2020)</td>
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<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>N/A</td>
<td>0.04 – 0.35</td>
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</table>
Table 3. Parameters used in the debris trajectory analysis, along with the median results of the Monte Carlo simulation of the SUV in the Scarth, MB tornado.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reference</th>
<th>$x$</th>
<th>Monte Carlo Median Results</th>
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<tr>
<td>$W_{max}$</td>
<td>NTP (2020)</td>
<td>1390 m</td>
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<tr>
<td>$r_m$</td>
<td>N/A</td>
<td>139 – 695 m</td>
<td>430 m</td>
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<tr>
<td>$V_T$</td>
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<td>4 – 6 m/s</td>
<td>5.14 m/s</td>
</tr>
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<td>$\delta$</td>
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<td>0.16</td>
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<td>$S$</td>
<td>N/A</td>
<td>0.4 – 1.1</td>
<td>0.81</td>
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<td>$U_m$</td>
<td>N/A</td>
<td>50 – 140 m/s</td>
<td>119 m/s</td>
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**Tornado Parameters**

**Debris Parameters**

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<td>$l$</td>
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<td>NTP (2020)</td>
<td>72 kg/m$^3$</td>
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<td>$C_D^{SM}$</td>
<td>Heisler (2004)</td>
<td>0.55 – 0.85</td>
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<td>Potter et al., (2016)</td>
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<tr>
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<td>Heisler (2004)</td>
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**Terrain Parameters**

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**Buoyancy Parameter**

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<td>$\phi$</td>
<td>N/A</td>
<td>0.05 – 0.42</td>
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Table 4. Parameters used in the debris trajectory analysis, along with the median results of the Monte Carlo simulation of the truck in the Scarth, MB tornado.

Fig. 13. Median trajectory (left) and cumulative distribution function of the lofting wind speed (right) for the Scarth, MB SUV & truck.
c. Alonsa, MB – EF4 Tornado – August 3, 2018

On August 3, 2018, an EF4 tornado occurred in Alonsa, MB. Further details on this tornado can be found in Stevenson et al. (2023). As noted in that paper, a common debris type found in the post-event damage survey was cylindrical haybales. Figure 14 shows drone photography of the haybales from the post-event damage survey. The starting point of the haybales is noted as the red circles on Figure 14. It was possible to tell the starting locations based on the dead grass imprints of where the haybales used to be. Several partially intact haybales were found washed up on the beach, which was then noted as the ending point, though the distance was likely greater since the haybales landed an unknown distance offshore then washed back onshore. A few haybales were lofted and ended up in the wooded area in between the field and the beach. From this information, it is estimated that the haybales would have had to travel at minimum 50 – 100 m, to their noted end point. Additionally, on the ground survey and from the drone photography, it was noted that there were few signs of hay debris in the fields, or signs that the haybales rolled before launching. It is also likely that the haybales would have had to travel over wooded areas and structures to reach the lake. Therefore, it appears that the debris elements experienced lofting movement rather than lateral movement. Ground survey observations also noted the width of the tornado at that point ($W_{\text{max}}$) as well as details about the haybales that were used to calculate $l$ and $\rho_m$. Finally, the translational speed of the tornado ($V_T$) was determined through the radar analysis of the mesocyclone. Since these haybales are relatively uniform in density, and have a simple shape, an equation for the threshold wind speed for lofting was used to assess the wind speeds in this event in Stevenson et al., (2023):

$$v_{\text{Threshold}} = \sqrt{\frac{2g\rho_m l}{\rho_a[C_D \sin \theta + C_L \cos \theta]}}$$

[19]
Fig. 14. Drone photographs (full photo – top; zoomed photo – bottom) of haybale debris that were lofted into Lake Manitoba by the tornado, along with its starting position, denoted by red circles.
To continue to build on the analysis done in Stevenson et al. (2023), the debris trajectory model was used with the goal of comparing to the values given in the simplified equation. Table 5 shows the parameters used in the analysis of the Alonsa tornado, along with the Monte Carlo simulation results that show the median parameters across the probability distribution of results. Figure 15 plots the median trajectory of a haybale (left) and the cumulative distribution function of the lofting wind speed of a haybale (right). The trajectory reaches a maximum height of 1.13 m relative to its starting elevation. Additionally, for a direct comparison to the instantaneous threshold lofting wind speed determined in Stevenson et al., (2023), the model is used to analyze trajectories from 0.1 – 1 m, to calculate the minimum lofting speed of the haybales. Figure 15 includes a cumulative distribution function for this threshold lofting as well. Overall, there is good agreement between the lofting wind speeds from the threshold equation method, and the lofting wind speeds from the current model when a threshold value of lofting is used for the minimum and maximum trajectory.

<table>
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<th>Variable</th>
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<th>Monte Carlo Median Results (Trajectory)</th>
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<td>$W_{max}$</td>
<td>Stevenson et al., (2023)</td>
<td>1600 m</td>
<td>1600 m</td>
<td>1600 m</td>
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<td>$r_m$</td>
<td>N/A</td>
<td>160 – 800 m</td>
<td>498 m</td>
<td>554 m</td>
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<tr>
<td>$V_T$</td>
<td>Stevenson et al., (2023)</td>
<td>10 – 14 m/s</td>
<td>11.9 m/s</td>
<td>12.2 m/s</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Baker &amp; Sterling (2017)</td>
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<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$S$</td>
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<td>0.88</td>
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<tr>
<td>$U_m$</td>
<td>N/A</td>
<td>50 – 140 m/s</td>
<td>87.9 m/s</td>
<td>127 m/s</td>
</tr>
</tbody>
</table>

Table 5. Parameters used in the debris trajectory analysis, along with the median results of the Monte Carlo simulation of haybales in the Alonsa, MB tornado.
Fig. 15. Median trajectory (left) and cumulative distribution function of the lofting wind speed (right) for the Alonsa, MB haybales, along with a comparison to the threshold equation results from Stevenson et al., (2023).

6. Discussion

Figure 16 combines the results of the cumulative distribution function of lofting wind speeds for the three examined tornadoes and compares them to the EF-scale rating given by the post-event ground surveys (based on available Dis). Additionally, the bounds of each EF-scale rating (based on the USA implementation of the EF scale) are provided for reference. Overall, the lofting wind speeds given by this model are higher than the rating based on the ground survey EF-scale assessment, which shows that there is an argument to be made that the wind speeds from these events were underestimated.
Fig. 16. Cumulative distribution functions of the lofting wind speeds, along with the EF-scale rating provided by the ground survey assessments.

These results imply that a large compact object being lofted more than 50 m horizontally is an indicator of an EF5 tornado. Fujita (1971), as mentioned earlier in Table 1, noted that “automobile sized-missiles may be generated” at F5 wind speeds. This was detailed further in Fujita (1981), where it was noted that F5 tornadoes can cause “automobile-sized missiles [to] fly through the air in excess of 100 m”. These descriptions of damage were based on aerial and ground photography of multiple tornado investigations although, notably, Fujita (1981) does not detail how the threshold value of 100 m was determined. Previous post-event damage survey from F5 / EF5 tornadoes have also noted this level of vehicle lofting (McCarthy et al., 2008).

Studies have also shown that tornado characteristics are challenging to capture due to the Enhanced Fujita scale relying on damage-based estimates for the wind speed of an event. Lombardo et al. (2023) showed that EF4 tornadoes are the most likely to be correctly identified through damage, but that ratings of EF5 tornadoes are biased low due to effects such as population density, and number of structures impacted, whereas ratings of EF3 tornadoes and lower are biased high for the same reasons. Wurman et al. (2021) also performed mapping of low-level winds in 120 tornadoes using a mobile Doppler radar and found that EF-scale ratings are 1.2 to 1.5 categories (an average of 20 m/s) lower than radar observations would suggest.
Stevenson et al. (2023) also suggested that the wind speed estimation of the EF4 Alonsa, MB tornado was limited by the quality of the construction of the DIs that were hit by the tornado. Alternate methods of estimating wind speeds in Stevenson et al. (2023) indicate higher wind speeds than those obtained from conventional EF-scale assessment. These studies suggest that the higher wind speed estimates from the current methodology may not be an overestimation, but a more accurate reflection of the true wind speeds of these tornadoes.

However, there are some limitations to this study that prevent this argument from being fully realized. An example of this is the potential overestimation in wind speed due to the importance of the initialization of debris lofting in tornadic wind fields (Huo et al., 2023). In this study, it was observed that while the presence of an updraft flow does not ensure that the debris will become airborne, the debris initialization correlated well with the vertical velocity component and resulted in an increased likelihood of lofting at the location of the core radius of the vortex (\(r = r_m\)). Notably, the current lift coefficients for vehicles used in this study are based on a purely horizontal wind speed, which generates a lift due to the difference in pressure created on the roof of the vehicle to the undercarriage below the vehicle as the surrounding air moves through it (Heisler, 2004). Therefore, there is a current disconnect in the lift coefficients used for the vehicles in this study, and the likely physics causing the initiation of lofting for these objects in a tornadic wind field. It seems likely that more realistic coefficients may decrease the lofting wind speed. However, there are no data available for lift coefficients of these objects in a tornadic wind field, which should be a topic of future research.

Another limitation is the uncertainty of the tornado wind field model at low heights. The Baker & Sterling (2017) model assumes zero vertical velocity at ground level, which is why this methodology assumed that \(z = z_m\) at the ground level in order to find the minimum lofting velocity, as \(z = z_m\) creates the critical radial velocity. Future work should examine the details of the tornadic wind field at low levels, especially the vertical velocity component.

Finally, it is recommended that this method should only be used for debris in large tornadoes where the flight of the object is significant (at least a 50 m trajectory). Many damage survey observations have shown cases where there are small overturning and/or lofting events of large compact objects with small trajectories that are correlated with lower EF-scale ratings. These cases with small trajectories are highly dependent on the initial conditions, and the overall distance that the debris travels may not be able to accurately determine the lofting wind...
speeds. In these cases, a threshold calculation could be used, such as the one demonstrated for the Alonsa, MB haybales.

7. Conclusions

A computational debris trajectory model was created by combining the Baker & Sterling (2017) tornado model, with the set of debris equations from Holmes (2004). The inherent uncertainties of the model were addressed by implementing a Monte Carlo simulation to vary the uncertain parameters and obtain cumulative distribution functions for the likelihood of debris lofting. The model shows adequate agreement with damage observations from Fujita (1981), and the threshold equation of lofting derived in Stevenson et al. (2023). This method was then used to analyze trajectories noted in post-disaster damage survey investigations by examining lofted debris in the Didsbury, AB EF4 tornado, the Scarth, MB EF3 tornado, and the Alonsa, MB EF4 tornado. It was noted that the lofting wind speeds given by this model are much higher than the rating based on the ground survey EF-scale assessment. This may be due to the current tendency to bias strong EF5 tornadoes lower than reality (as shown in Lombardo et al., 2023 and Wurman et al., 2021), or limitations in conventional EF-scale assessments (Stevenson et al., 2023). Alternatively, this could be an overestimation due to the issue of debris initialization in a tornadic wind field, and the effect that has on the lift coefficients of an object, which is still not yet fully resolved. Another potential issue is the accuracy of the wind field model at low heights, or the assumptions made about the location of the critical peak radial wind speed. Further studies will be required to resolve these differences.

Future versions of the EF scale are expected to include a chapter dedicated to the use of remote-sensing imagery in the study of tornado damage, and guidelines for alternative methods for determining the wind speeds in tornadoes (Marshall et al., 2022). This study provides a framework for a method to utilize observed debris trajectories as one of these alternative methods. A future goal for this work is to use multi-debris tracking to determine more detailed parameters of a tornado. The more debris items that are lofted in a small area from the same event, the more specific the tornado parameters become that induce lofting in that specific manner for those specific events. This may be able to tell us more than just the wind speed of an event. For example, parameters such as the swirl ratio ($S$) and the core radius of the vortex ($r_m$) may be identifiable from this type of analysis.
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Data Availability Statement.

All of the aerial imagery and debris information used for this study are openly available from the Northern Tornadoes Project Open Data Site as cited in NTP (2020). It is the intention of the authors to make the model available as an ArcGIS Pro add-on in the future.

Appendix A: Didsbury, AB Parameter Probability Analysis

This section details the Monte Carlo simulation results for the Didsbury, AB tornado. Figure A1 compares the probability distribution of the radius of maximum velocity ($r_m$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A2 compares the probability distribution of the translational wind speed ($V_T$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A3 compares the probability distribution of the ratio of the radial distance where the maximum radial velocity occurs to the vertical distance where the maximum vertical velocity occurs ($\delta$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A4 compares the probability distribution of the swirl ratio ($S$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A5 compares the probability distribution of the maximum radial velocity ($U_m$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A6 compares the probability distribution of the surface-mounted drag coefficient ($C_D^{SM}$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A7 compares the probability distribution of the airborne drag coefficient ($C_D^A$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis. Figure A8 compares the probability distribution of the lift coefficient ($C_L$) vs. the obtained distribution of valid trajectories from the Monte Carlo analysis.
Fig. A1. Modelled probability distribution of the radius of maximum velocity ($r_m$) vs. the obtained probability distribution from the Monte Carlo analysis.

Fig. A2. Modelled probability distribution of the translational wind speed ($V_T$) vs. the obtained probability distribution from the Monte Carlo analysis.
Fig. A3. Modelled probability distribution of the ratio of the radial distance where the maximum radial velocity occurs to the vertical distance where the maximum vertical velocity occurs ($\delta$) vs. the obtained probability distribution from the Monte Carlo analysis.

Fig. A4. Modelled probability distribution of the swirl ratio ($S$) vs. the obtained probability distribution from the Monte Carlo analysis.
Fig. A5. Modelled probability distribution of the maximum radial wind speed ($U_m$) vs. the obtained probability distribution from the Monte Carlo analysis.

Fig. A6. Modelled probability distribution of the surface-mounted drag coefficient ($C_{D,SM}^M$) vs. the obtained probability distribution from the Monte Carlo analysis.
Fig. A7. Modelled probability distribution of the airborne drag coefficient ($C_D^A$) vs. the obtained probability distribution from the Monte Carlo analysis.

Fig. A8. Modelled probability distribution of the lift coefficient ($C_L$) vs. the obtained probability distribution from the Monte Carlo analysis.
REFERENCES


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