

Analysis of Forest-Based Tornadoes Using Treefall Patterns

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ABSTRACT: Many tornadoes occur in rural forested regions of the world where traditional damage indicators are often unavailable to determine, or may underestimate, a tornado's true intensity. Future versions of the enhanced Fujita (EF) scale are expected to include guidelines for treefall pattern matching to determine tornado intensity. This study explores the reliability and uncertainty of using tornado treefall patterns as a method for assessing the maximum 3-s gust speed and swirl ratio of tornadoes in forested regions. Through mathematical analysis, treefall patterns are determined to depend primarily on the ratio of the tornado's radial, tangential, and translational speeds, as well as the critical tree failure speed. Moreover, four typical types of tornado treefall patterns are differentiated based on vortex–tree failure locations relative to the tornado's radius of maximum wind speed. As a result, when estimates for the critical tree failure and tornado translation speeds are known, treefall patterns can be consistently linked to an estimate of a tornado's maximum wind speed and swirl ratio. The damage paths of four tornadoes, including the previously analyzed Alonsa, Manitoba, EF4 tornado, are analyzed using custom software implementing a Monte Carlo simulation for treefall pattern matching to estimate the maximum 3-s gust speed and swirl ratio, as well as the associated uncertainty. Of the three newly analyzed events, two are estimated to have higher EF-scale ratings than those suggested by the current Canadian EF scale.

SIGNIFICANCE STATEMENT: Current methods in the Canadian enhanced Fujita (EF) scale are often unable to rate tornadoes above EF2 when considering only tree damage. However, previous studies have shown that treefall pattern matching has the potential to provide higher ratings. Building on previous works, this study explores the reliability and uncertainty in using treefall pattern matching for estimating a tornado's maximum 3-s gust speed and swirl ratio. Through the use of a Monte Carlo simulation approach, improved estimates of the range of tornado wind speeds are obtained.

KEYWORDS: Tornadoes; Algorithms; Remote sensing; Numerical analysis/modeling; Damage assessment; Software

1. Introduction

Canada is home to 270 million hectares of boreal forest—over 60% of Canada's land cover (Brandt 2009)—much of which is frequently hit by tornadoes. The Northern Tornadoes Project (NTP), a program run by the Canadian Severe Storms Laboratory, has the goal of assessing and documenting every tornado that occurs in Canada. Figure 1 shows the locations of tornadoes from 2017 to 2024 that have occurred in the Canadian boreal zone (NTP 2020). This analysis shows that 26% of tornadoes recorded by the NTP have occurred in the Canadian boreal zone. Butt et al. (2024) also found that these northern forested areas tend to be sparsely populated with the only observable indication of damage often being snapped or uprooted trees. Overall, considering the frequency of tornadoes in forested regions of Canada, properly assessing tree damage is critical for accurately determining Canada's tornado climatology. Moreover, this is also important for remote forested areas of the United States and northern Europe (Karstens et al. 2013; Shikhov and Chernokulsky 2018).

The intensity of tornadoes in Canada is assessed using the enhanced Fujita (EF) scale, which rates tornadoes on a scale from EF0 to EF5 based on their estimated maximum

wind speed (McDonald and Mehta 2006; Sills et al. 2014). The Canadian EF scale (NTP 2024), which is a modified version of the U.S. EF scale, estimates wind speeds based on 31 damage indicators (DIs), mostly representing different structures, as well as trees. Each DI includes degrees of damage (DOD) that outline the sequential damage stages observed. Every DOD is associated with upper-bound (UB), lower-bound (LB), and expected (EXP) wind speeds. In damage surveys, the worst failure mode is identified and linked to a DOD category, and a determination is made on whether the upper-bound, lower-bound, or expected value is more appropriate based on guidance in the document related to construction style, quality, and age. These factors help determine the estimated wind speed responsible for the damage.

Currently, the Canadian EF scale (NTP 2024) has a DI for trees that differs from the tree DIs in the U.S. EF scale. Whereas the U.S. EF scale provides wind speed estimates for individual (single) hardwood and softwood trees, in the Canadian EF scale, DODs are based on the percentage of mature trees snapped or uprooted in a given area of the tornado's damage track. These percentages are estimated using a method referred to as the “Scalable Box Method” that was developed by researchers at the NTP (Sills et al. 2020). Godfrey and Peterson (2017), among others, have also aimed to relate the percentage of trees downed in fixed-sized boxes as a function of wind speed. Table 1 shows the degrees of damage for trees, along with the guidance provided for this damage indicator. Notes for Table 1 are as follows:

- To estimate the percentage of trees snapped and/or uprooted, use the NTP Scalable Box Method.

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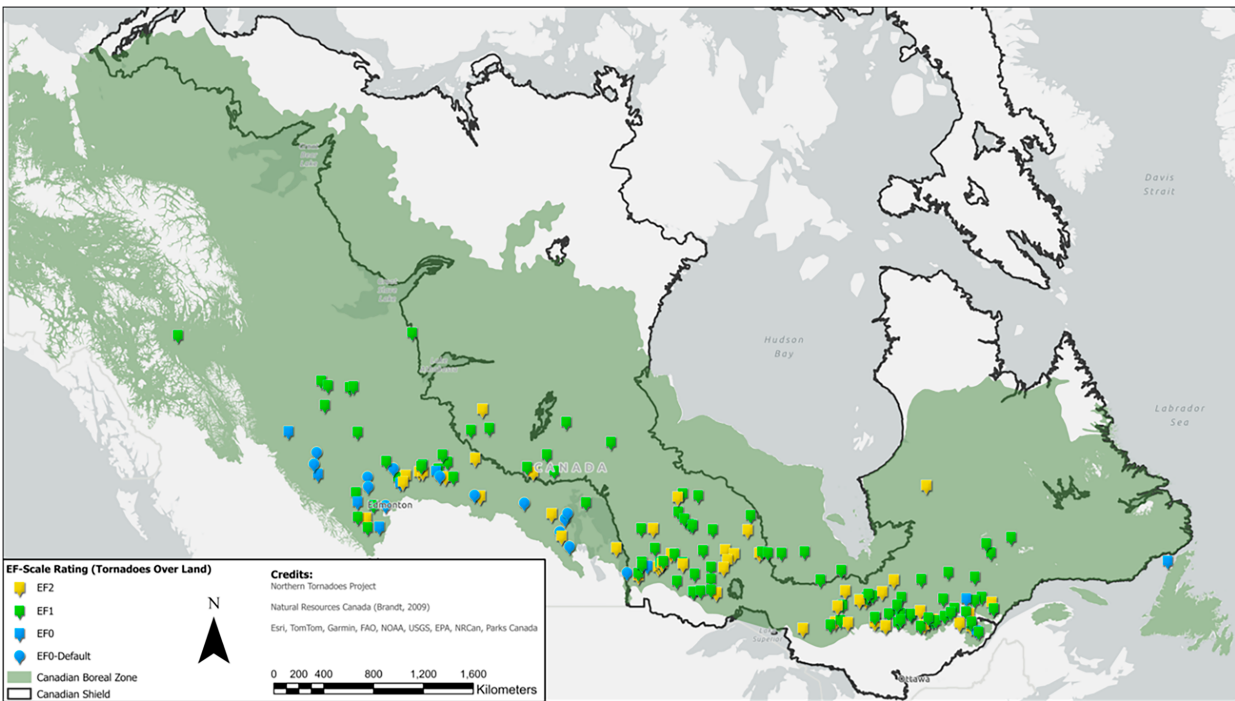


FIG. 1. A map of Canadian tornadoes (over land) from 2017 to 2024 that occurred in the Canadian boreal zone, along with a reference to the location of the Canadian Shield.

- For satellite-based assessments of forest damage (having limited imagery resolution, lack of tree health/species information, lack of plantation/age information), the NTP defaults to the lower-bound wind speed—with the following exceptions:
 - DOD6, deep soil and close to 100% treefall (EXP – 20 km h⁻¹)
 - DOD5, deep soil and close to 80% treefall (EXP – 20 km h⁻¹)
 - No leaves on trees in spring or fall (EXP)
- For all other assessment types, the NTP defaults to the expected wind speed—with the following exceptions:
 - Very shallow soil (LB)
 - Poor tree health (disease/infestation, broken at base of trunk due to girdling, etc.), shallow root balls, even-aged monoculture plantation (LB)
 - Most trees snapped in area without deep soil (EXP – 20 km h⁻¹)
 - Forests or woodlots composed of mature, deep-rooted red oak, red maple, beech, hemlock or white cedar (EXP + 20 km h⁻¹)
 - No leaves on trees in spring or fall and very shallow soil (EXP)
 - No leaves on trees in spring or fall and soil between very shallow and deep (EXP + 20 km h⁻¹)
 - No leaves on trees in spring or fall and deep soil (UB)

Of note in Table 1 are restrictions that potentially prevent the accurate assessment of EF3+ tornadoes. In areas of shallow soil, the default is to use the lower-bound wind speed. The Canadian Shield is a geological area of Canada with notably shallow soil (Government of Canada 2020). As seen in Fig. 1,

TABLE 1. DOD descriptions and wind speed estimates for the Canadian Tree DI, along with the DI notes, as adopted by the NTP (2024).

DOD	Description of damage	Wind speed estimates [m s ⁻¹ (km h ⁻¹)]		
		LB	EXP	UB
1	Small limbs broken (up to 5-cm diameter)	15.3 (55)	19.4 (70)	23.6 (85)
2	Large limbs broken (greater than 5-cm diameter)	18.1 (65)	25 (90)	30.6 (110)
3	Up to 20% of mature trees snapped and/or uprooted	22.2 (80)	31.9 (115)	41.7 (150)
4	More than 20% of mature trees snapped and/or uprooted	29.2 (105)	41.7 (150)	52.8 (190)
5	More than 50% of mature trees snapped and/or uprooted	40.3 (145)	52.8 (190)	63.9 (230)
6	More than 80% of mature trees snapped and/or uprooted; numerous trees may be denuded/debarked by missiles with only stubs of largest branches remaining.	52.8 (190)	65.3 (235)	76.4 (275)

TABLE 2. Summary of previous research using damage patterns to trees and forests.

Authors	Events analyzed	Description
Letzmann (1923) ; review and English translation by Peterson (1992)	—	Pioneering work linking treefall damage swaths to tornado wind fields Utilizes Rankine vortex model; demonstrates how treefall patterns change for different vortex parameters
Holland et al. (2006)	—	Presents framework combining Letzmann's model with a simplified treefall model to produce systematic treefall patterns for different vortex parameters and critical tree failure speeds
Beck and Dotzek (2010)	Milosovice, Czech Republic (2001)—F3	Uses a method similar to Holland et al. to manually match treefall swaths for estimating tornado wind fields.
Karstens et al. (2013)	Castellcir, Spain (2006)—F2 Joplin, Missouri, U.S. (2011)—EF5 Tuscaloosa–Birmingham, Alabama, U.S. (2011)—EF4	Estimates uncertainty using a range of critical tree failure speeds Used aerial imagery to acquire individual treefall directions Presents a more efficient simulation method, similar to Holland et al. to manually match treefall damage swaths and patterns
Lombardo et al. (2015)	Joplin, Missouri, U.S. (2011)—EF5	Compared treefall-based and structural-based methods for wind field estimation of the Joplin tornado
Rhee and Lombardo (2018)	Naplate, Illinois, U.S. (2017)—EF3 Tuscaloosa–Birmingham, Alabama, U.S. (2011)—EF4 Sidney, Illinois, U.S. (2016)—EF2	Utilized a grid-search approach to automatically find the best-matching treefall patterns. Analyzed both tree and crop damage
Chen and Lombardo (2019)	Joplin, Missouri, U.S. (2011)—EF5	Presents an analytical method using numerical optimization to more efficiently find the best-matching patterns
Stevenson et al. (2023)	Alonsa, Manitoba, Canada (2018)—EF4	Compared the method of Rhee and Lombardo (2018) to structural damage

many of these forested tornadoes also occur in the Canadian Shield, leading to many of these tornadoes being rated at the lower-bound wind speed. Another problem related to the accurate assessment of EF3+ tornadoes is that the wind speed at which a given tree will fail, referred to as the tree's critical failure wind speed ([Karstens et al. 2013](#); [Quine and Gardiner 2007](#)), is difficult to determine and is generally low relative to the wind speeds of EF3+ tornadoes.

With these restrictions, current methods for assessing tree damage in tornadoes often have the limitation of being unable to estimate wind speeds above EF2, which could lead to the potential underrating of many forest-based tornadoes in Canada and other regions of the world. Assessing the true maximum wind speeds in tornadoes is of critical importance to better design safety measures for communities, create better weather forecasting models, develop a broader understanding of tornado behavior, as well as update building codes and engineering standards. Recently published studies on wind speeds in tornadoes have also noted bias in tornado wind speed estimates ([Lombardo et al. 2023](#); [Dahl et al. 2017](#); [Miller et al. 2024](#)). Overall, this leads to the need for alternative methods of assessing tornado treefall damage ([Edwards et al. 2013](#)), particularly in forested regions with few, if any, other potential damage indicators.

The first work to examine this was [Letzmann \(1923\)](#), who noted that forest-based tornadoes tend to leave specific treefall patterns along the tornado's path and developed a simple analytical method using the Rankine vortex model for reconstructing similar patterns. Since then, significantly

more research has been conducted into simulating tornado wind fields and reconstructing treefall patterns as a method to estimate the maximum wind speed of tornadoes. [Table 2](#) provides a summary of the papers that have advanced the approaches for identifying and using tornado damage patterns to trees and forests to estimate tornado wind speeds.

As a high-level overview, current treefall pattern matching methods work by simulating a tornado vortex traveling over the same location and in the same direction as the observed tornado ([Karstens et al. 2013](#); [Rhee and Lombardo 2018](#)). A simulated treefall pattern is calculated using analytical models of the tornado wind field and tree failure mechanics, with treefall occurring at the first instance that the critical wind speed is exceeded for every tree. From there, the observed treefall pattern is compared to the simulated pattern, with the similarity between these patterns taken as proportional to the similarity between the characteristics of the observed and simulated tornado–vortex wind field. After simulations of many patterns, the best matching patterns can be utilized to estimate the wind speeds and characteristics of the observed tornado.

[Holland et al. \(2006\)](#), [Beck and Dotzek \(2010\)](#), and [Karstens et al. \(2013\)](#), building on the work of [Letzmann \(1923\)](#), demonstrated the use of analytical vortex models for simulating treefall patterns, with [Karstens et al. \(2013\)](#) and [Beck and Dotzek \(2010\)](#) applying them to analyze various tornadoes throughout the United States and the European Union, respectively. These works laid the foundation for utilizing treefall pattern matching as a method for estimating tornado

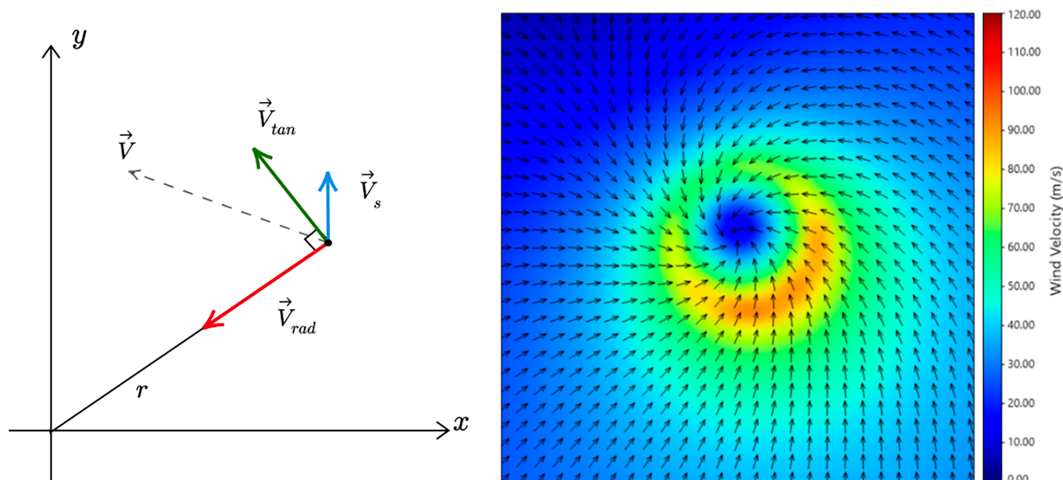


FIG. 2. A diagram depicting the components of (left) the two-dimensional vortex wind velocity and (right) a generated two-dimensional vortex field showing an example vortex field.

wind fields and maximum wind speeds. Furthermore, these works generally found consistent EF-scale ratings between structural and treefall-based wind speed estimates. For validation of treefall pattern-based methods, comparison between structural and treefall estimates for the Joplin, Missouri, tornado of 2011 was performed by Kuligowski et al. (2014) and Lombardo et al. (2015). Similarly, Stevenson et al. (2023) applied the treefall pattern matching methodology from Rhee and Lombardo (2018) to the Alonsa, Manitoba, EF4 tornado, which produced similar estimates to those of the observed structural damage upon which the EF4 rating was based.

There have been many recent improvements to algorithms for implementing treefall pattern matching methods. Rhee and Lombardo (2018) developed a grid search approach giving more accurate results for estimating vortex parameters based on the best matching patterns. Chen and Lombardo (2019) proposed an analytical method for solving treefall patterns (in contrast to simulation) for two distinct tornado wind field models—the Rankine and Burgers–Rott vortices (Burgers 1948; Rott 1958)—and utilized a numerical optimization approach to fit best-matching treefall patterns. This method is significantly faster than the simulations of Rhee and Lombardo (2018). Additionally, it can consider multiple transects when performing numerical optimization in a piecewise approach, to better fit the overall extent of the treefall damage. Generally, these methodologies are limited in their ability to assess the uncertainty and variability in their results.

In general, state-of-the-art techniques for wind speed estimation now tend to consider the variability of parameters by creating fragility curves, often using Monte Carlo simulations. Examples include Ellingwood et al. (2004), Amini and van de Lindt (2014), Roueche et al. (2016), and Gavanski and Kopp (2017) for wood-frame houses. Godfrey and Peterson (2017) used an approach which considered the fraction of trees down within a particular zone (but not combined with a tornado wind field model). Miller et al. (2024) used tornado wind field

models to assess the flight of large debris by combining wind field model parameters in a Monte Carlo simulation to estimate the range of tornado vortex parameters that could lead to the observed flight distances. Analysis of treefall patterns, as described herein, falls into this same type of approach; however, there have been no studies to date that have utilized the Monte Carlo simulation—fragility curve approach. One advantage of this type of framework is that it allows new knowledge to be incorporated as it becomes available in straight-forward ways, allowing the variation to be modeled and accounted for.

The objective of this study is to analyze tornado treefall patterns and assess their uncertainty in determining maximum wind speeds, through the use of Monte Carlo simulations that consider the variation due to different wind field models, critical wind speeds for treefall, vortex translational speeds, and location and scale of treefall pattern transects. Additionally, novel analysis of analytical treefall pattern solutions provides a greater understanding of how the patterns are related to their tornado wind fields, creating insight into damage observations. Sections 2 and 3 discuss and examine the analytical vortex models and the relationships between vortex parameters and types of treefall patterns,

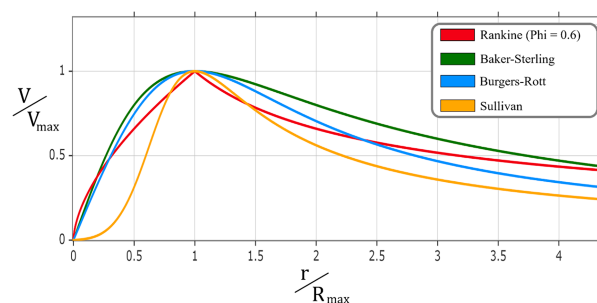


FIG. 3. Normalized, unitless, modified Rankine, Baker–Sterling (Bjerknes), Burgers–Rott, and Sullivan profiles.

building off the work of the previously mentioned studies. Furthermore, using a Monte Carlo simulation, a novel and more computationally efficient matching methodology is constructed. This methodology, discussed in [section 4](#), is better suited to assessing uncertainty. Then, in [section 5](#), the resulting method is applied to four Canadian forest-based tornadoes to examine the outcomes of the approach.

2. Tornado wind field models

Tornado wind field models can range from simple analytical vortex models like the Rankine vortex, to more intricate models such as simplified solutions of the Navier–Stokes equations ([Burgers 1948](#); [Rott 1958](#); [Baker and Sterling 2017](#)) and the semiempirical Twisdale model ([Twisdale et al. 2023](#); [Dunn and Twisdale 1979](#)). These are used in a range of applications beyond assessing tornado damage to trees and forests. For example, the Twisdale model is the basis for the tornado wind speed maps in ASCE 7–22 ([ASCE 2022](#)). The Baker–Sterling model has been used to fit the data for tornado–vortex simulator wind loading results ([Brusco and Kopp 2024](#)). These models represent the state of the art for such varied analyses, although there is recognition that they are significant simplifications and more work is needed ([Haan et al. 2024](#)).

a. Vortex field definition

For the purposes of treefall patterns, a tornado vortex is simulated as a two-dimensional projection of the overall vortex field near ground level due to the lower height of trees relative to the overall height of a tornado vortex ([Karstens et al. 2013](#)). The two-dimensional projection of a tornado vortex field is defined at any point as the sum of the radial ($\mathbf{V}_{\text{rad}}$), tangential ($\mathbf{V}_{\text{tan}}$), and translational ($\mathbf{V}_s$) velocities ([Chen and Lombardo 2019](#)). For the purpose of computing a treefall pattern, the vortex is assumed to translate in a constant direction and with constant parameters for a short duration over a chosen transect of the tornado’s damage path. For simplicity, translation in the positive y direction was chosen, in common with [Karstens et al. \(2013\)](#), but by rotating, any other direction can also be used. The strengths of the radial and tangential components are calculated by multiplying the unitless radial and tangential velocity profile functions (P_r , P_t) by maximum radial and tangential velocity constants (V_r , V_t). Due to the biomechanics of tree failures being mostly bending-moment-based overturning (uprooting) or snapping, the vertical velocity component of the vortex is assumed to be a negligible contribution to the failure of a tree in this model. Generally, single-core vortex velocity profile functions are assumed to be symmetric about any rotation and depend only on the distance from the center of the vortex ([Kim and Matsui 2017](#)):

$$\frac{V}{V_{\text{max}}} = P\left(\frac{r}{R_{\text{max}}}\right). \quad (1)$$

The unitless version of these profiles, as shown in [Eq. \(1\)](#), specifies the ratio of velocity to maximum velocity (V/V_{max}) as a function of radial distance from the origin to the radius at which the maximum velocity occurs (r/R_{max}). [Figure 2](#) shows

an example of a generated two-dimensional vortex field along with a diagram of the velocity components.

From here, the radial, tangential, and translational unit vectors can be calculated as

$$r = \sqrt{x^2 + y^2}, \quad (2)$$

$$\hat{\mathbf{V}}_{\text{rad}} = \left[\frac{-x}{r}, \frac{-y}{r} \right], \hat{\mathbf{V}}_{\text{tan}} = \left[\frac{-y}{r}, \frac{x}{r} \right], \hat{\mathbf{V}}_s = [0, 1]. \quad (3)$$

Using the sum of the vectors, the overall wind velocity vector ($\mathbf{V}$) at any given point, (x, y) , can be calculated as

$$\mathbf{V} = \mathbf{V}(x, y) = \mathbf{V}_{\text{rad}} + \mathbf{V}_{\text{tan}} + \mathbf{V}_s, \quad (4)$$

$$\mathbf{V} = P_r V_r \hat{\mathbf{V}}_{\text{rad}} + P_t V_t \hat{\mathbf{V}}_{\text{tan}} + V_s \hat{\mathbf{V}}_s, \quad (5)$$

$$\mathbf{V} = \left[-\frac{P_r V_r x + P_t V_t y}{r}, \frac{P_t V_t x - P_r V_r y}{r} + V_s \right]. \quad (6)$$

b. Single-core vortex profiles

For this model, the vortex profiles utilized are single-core, axisymmetric, unitless, and normalized such that their maximum of 1 occurs when $r = R_{\text{max}}$. As shown in [Fig. 3](#), normalized profiles start at zero and are increasing on the interval $0 < rR_{\text{max}}^{-1} < 1$ and decreasing on the interval $rR_{\text{max}}^{-1} > 1$. A commonly used profile is the modified Rankine vortex profile, [Eq. \(7\)](#), originally proposed for tornadoes by [Letzmann \(1923\)](#) and utilized in numerous other studies including [Karstens et al. \(2013\)](#), [Rhee and Lombardo \(2018\)](#), and [Chen and Lombardo \(2019\)](#):

$$P_t = P_r = \begin{cases} (rR_{\text{max}}^{-1})^\varphi, & \text{if } r \leq R_{\text{max}} \\ (r^{-1}R_{\text{max}})^\varphi, & \text{if } r > R_{\text{max}} \end{cases}, \quad 0.5 \leq \varphi \leq 1. \quad (7)$$

As noted above, other vortex profiles exist. For example, a more recently proposed vortex profile is the Baker–Sterling model ([Baker and Sterling 2017](#)), which simplifies to the Bjerknes vortex profile, [Eq. \(8\)](#), when normalized and converted to be two dimensional ([Bjerknes 1921](#)):

$$P_t = P_r = \frac{2rR_{\text{max}}}{r^2 + R_{\text{max}}^2}. \quad (8)$$

The Burgers–Rott profile, [Eq. \(9\)](#), is based on the Burgers–Rott vortex ([Burgers 1948](#); [Rott 1958](#)), which is an exact solution of the Navier–Stokes equations. Unlike the Rankine and Bjerknes models, the Burgers–Rott radial and tangential profiles differ. The Burgers–Rott radial profile is assumed to scale linearly indefinitely, which is not indicative of a tornado and, as such, can be replaced for tornado modeling with either its tangential profile or the linear Rankine profile where $\varphi = 1$:

$$P_t = \frac{k_1[1 - \exp(-k_2 r^2 R_{\text{max}}^{-2})]}{2\pi r R_{\text{max}}^{-1}}, \quad k_1 = 8.7836, \quad k_2 = 1.2564. \quad (9)$$

An extension of the Burgers–Rott profile is the Sullivan profile, Eqs. (10) and (11) (Sullivan 1959). Like Burgers–Rott, the radial profile is assumed to scale linearly indefinitely and can be similarly replaced. Figure 3 gives an overview of the graphs for each mentioned profile, all of which are utilized in the methodology of this study:

$$P_t = \frac{k_1}{rR_{\max}^{-1}} H(k_2 r^2 R_{\max}^{-2}), \quad k_1 = 0.029\,890, \quad k_2 = 6.2381, \quad (10)$$

$$H(x) = \int_0^x \exp\left[-t + 3 \int_0^t \frac{1 - \exp(-s)}{s} ds\right] dt. \quad (11)$$

c. Tornado translational speed estimation

The tornado translation speed (V_s) can be estimated from observed storm characteristics, typically from available radar data (Beck and Dotzek 2010; Karstens et al. 2013; Rhee and Lombardo 2018) but is difficult to determine without time-stamped visual evidence. However, it can be reasonably assumed that a tornado will move at the same speed as its parent mesocyclone. If the tornado occurred within the range of a weather radar station where Doppler radial velocity data are available, then such velocity data can be used to track the movement of the center of the mesocyclone over the time intervals that the tornado was present. In cases where radial velocity data are not available, the presence and location of the mesocyclone can be inferred from reflectivity features, such as the “hook echo” caused by the mesocyclone.

In the current work, the center of the mesocyclone is estimated at multiple points in separate radar scans which are then used to calculate the distance that the mesocyclone traveled. By assuming the tornado traveled along a quasi-linear path, the total distance traveled is then divided by the total time between radar scans to estimate the average translation speed.

d. Maximum velocity and 3-s gust speed

As previously described, the maximum wind velocity ($V_{\max}$) occurs when $r = R_{\max}$. When summing a pair of vectors, the magnitude of their sum will be maximized if both vectors are in the same direction. Using these facts, finding the point of maximum velocity is the same as finding the point on the circle, $x^2 + y^2 = R_{\max}^2$, where $\mathbf{V}_{\text{rad}} + \mathbf{V}_{\text{tan}}$ is in the same direction as $\mathbf{V}_s$. Since, for this model, $\mathbf{V}_s$ is in the positive y direction, it is implied that the x component of $\mathbf{V}_{\text{rad}} + \mathbf{V}_{\text{tan}}$ must equal to 0 and the y component must be positive. From there it follows that $V_{\max}$ occurs at the point:

$$x^* = \frac{V_t R_{\max}}{\sqrt{V_t^2 + V_r^2}}, \quad y^* = -\frac{V_r R_{\max}}{\sqrt{V_t^2 + V_r^2}}. \quad (12)$$

Furthermore, $V_{\max}$ can be shown to be a function of V_r , V_t , and V_s as

$$V_{\max} = V_s + \sqrt{V_t^2 + V_r^2}. \quad (13)$$

By examining the swirl ratio, $S = V_t V_r^{-1}$, using the Baker and Sterling (2017) definition, and Eq. (12), the location of $V_{\max}$

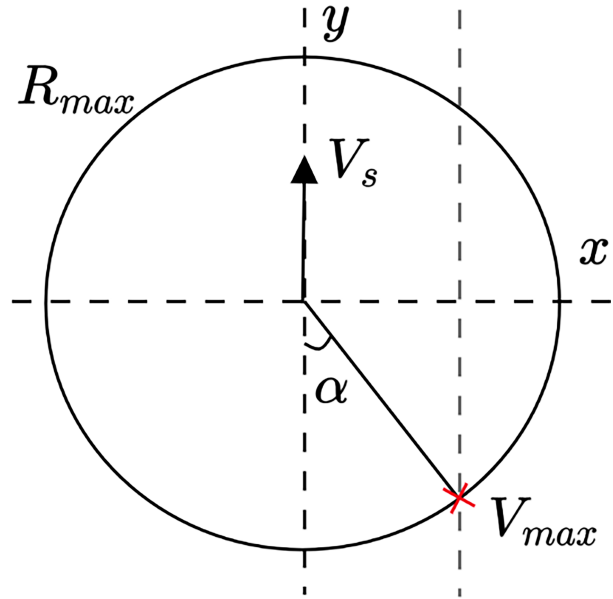


FIG. 4. A diagram of the location of maximum wind velocity ($V_{\max}$), as an angle offset from the y axis along the $R_{\max}$ circle, where α is calculated using Eq. (14).

can be expressed as an angle offset (α) from the y axis, along the $R_{\max}$ circle as shown in Fig. 4. Notably, this angle offset (α) is also the angle between the radial and the sum of the radial and tangential velocity components as discussed in Letzmann (1923), Holland et al. (2006), and Rhee and Lombardo (2018). Generally, this implies that the maximum wind velocity does not occur along the central axis of the vortex. In the literature, there are different definitions for the swirl ratio; however, this definition was used due to the two-dimensional vortices considered in this study and based on the discussion in Haan et al. (2024) (see also Twisdale et al. 2023; Dunn and Twisdale 1979):

$$\alpha = \tan^{-1}(S). \quad (14)$$

Generally, the wind speed estimates for damage given by the EF scale are based on a 3-s-average gust speed, as opposed to an instantaneous wind speed (McDonald and Mehta 2006). As such, the maximum 3-s gust speed can be approximated by integrating over a 3-s window centered around the location of maximum velocity and then dividing by the window's area, similar to that used by Miller et al. (2024):

$$V_{3-\max} = \frac{\int_{y^*-1.5V_s}^{y^*+1.5V_s} \int_{x^*-1.5V_s}^{x^*+1.5V_s} V(x, y) dx dy}{(3V_s)^2}. \quad (15)$$

3. Computing analytical treefall patterns

a. Critical tree failure speed estimation

One of the important parameters in the analysis of treefall patterns is the critical tree failure wind speed (V_c). Similar to

Chen and Lombardo (2019), as a simulated vortex translates over a simulated forest of trees, the trees are assumed to fail (snap or uproot) on average at a specified critical tree failure wind speed. Mechanistic models used to calculate the critical tree failure wind speed are generally based on assessing the balance between the destabilizing wind forces on the above-ground elements of trees and the combined resistive forces of the soil, roots, and stem. The destabilizing forces are dependent on the wind environment, the location of the tree within the forest canopy, the crown characteristics [e.g., mass, size, and any streamlining (which is the reconfiguration/bending of the branches and leaves to reduce wind resistance, Haller 1990)], and the stem (trunk) characteristics (e.g., shape, height, and mass). The resistive forces depend on the stem characteristics (e.g., diameter and wood strength) and the root-plate morphology, soil type, and state, and the water-table location (Quine and Gardiner 2007; Mansour et al. 2024). Moreover, the resistances of trees to overturning (also known as uprooting or windthrow; Sagi et al. 2019) and stem breakage failure (also known as snapping) are commonly based on empirical relationships found from field static tree pulling and laboratory timber strength tests (e.g., Nicoll et al. 2006).

The current method used to calculate V_c assumes tree overturning since most of the trees in the field study (described below) were observed to have failed through this mode. The resistance to overturning is based on correlations between the bending moment required to overturn trees and the stem weight or root-soil plate weight (Levy et al. 2004; Nicoll et al. 2006). Thus, the critical wind speed ($V_{c-\text{over}}$) at the forest canopy top was found using the relationship of Gardiner et al. (2000):

$$V_{c-\text{over}} = \frac{1}{k \times D} \left(\frac{C_{\text{reg}} \times \text{SW}}{\rho \times G \times d} \right)^{1/2} \left(\frac{1}{f_{\text{edge}} \times f_{\text{CW}}} \right)^{1/2} \ln \left(\frac{h-d}{z_0} \right), \quad (16)$$

where k is the Von Kármán's constant (0.4); d (m) is the zero-plane displacement; z_0 (m) is the aerodynamic roughness; D (m) is the average spacing between trees; G is an empirically derived gust factor based on bending moment; h (m) is the tree height; C_{reg} is a regression constant dependent on the tree species, soil, and rooting depth; SW (kg) is the stem weight of the tree; and ρ (1.226 kg m^{-3}) is the air density. Factors f_{edge} and f_{CW} account for the tree position relative to the forest edge and additional loads due to the overhanging weight of the crown under bending.

Another important parameter in calculating the critical tree failure speed is the empirical gust factor G . This captures in a single term the complex influence of the turbulent wind structure in a forest canopy and the dynamic response of trees to fluctuating winds. Although G has been estimated using field and wind tunnel studies for synoptic wind fields (Gardiner et al. 1997), equivalent studies for rotating tornadic winds do not exist. A similar approach to Savory et al. (2001) was adopted, who modeled tornado loading of lattice transmission towers, and a unity value of G was selected, thus assuming a quasi-static response by the trees. This seems reasonable given the expected

duration, size (relative to the trees), and frequency of tornadic gusts, and the natural frequency, porosity, and very high damping ratio of trees, which is in broad agreement with ASCE 7-22 (ASCE 2022). Finally, the values of the factors f_{edge} and f_{CW} were also set to unity, assuming the majority of damaged trees were distant from the forest edge and experienced little bending during failure.

b. Analytically solving vortex-tree failure locations

In this section, we develop our analytical approach. In this approach, when trees fail, the propagation effects and interactions between trees are ignored, with the underlying assumption that these effects will average out to trees falling in the direction of the wind at the instance of failure. Analytically, this assumes that simulated trees will fail at the first encountered position in the vortex field, where the magnitude of the wind velocity is greater than the critical tree failure velocity, referred to in this study as the “vortex-tree failure location.” (In the polar equations of Chen and Lombardo 2019, this is the “critical wind speed curvilinear trace.”) This can be solved as

$$\|\mathbf{V}(x, y)\| = V_c. \quad (17)$$

Substituting in Eq. (6) for $\mathbf{V}$ yields

$$0 = \left(\frac{P_r V_r x + P_t V_t y}{r} \right)^2 + \left(\frac{P_t V_r x - P_r V_t y}{r} + V_s \right)^2 - V_c^2. \quad (18)$$

Often, for vortex profiles, Eq. (18) can only be expressed implicitly as there exist multiple values of y for each value of x , where the magnitude of the wind velocity is equal to the critical tree failure speed. However, trees are assumed to fail at the first encountered location, where $\|\mathbf{V}\| = V_c$. Since the vortex is traveling in the y direction, trees will fail at the greatest y value that satisfies Eq. (18) for a given x value. As a result, the vortex-tree failure locations are modeled as a function of x and solved explicitly for the greatest y value that satisfies Eq. (18). Mathematically,

$$y = f(x) = \max(\mathcal{R}), \quad (19)$$

where $\mathcal{R}$ is the set of real roots for a given x value and the set of (constant) parameters, V_r , V_t , V_s , V_c , and R_{max} , as well as selected profiles P_r and P_t . For example, with the Baker–Sterling (Bjerknes) model, the vortex-tree failure location equation can be expressed as finding the greatest real root of a quartic equation in terms of y in Eqs. (20) and (21). In this case, polynomial equations are desired since their roots can be quickly and reliably solved using numerical algorithms such as the one presented by Yuksel (2022) or using functions in common software packages such as the “roots” function in MATLAB (2024) or the Python NumPy library (Harris et al. 2020). An example of a vortex-tree failure location function is depicted in Fig. 5:

$$0 = \left[\frac{2R_{\text{max}}(V_r x + V_t y)}{r^2 + R_{\text{max}}^2} \right]^2 + \left[\frac{2R_{\text{max}}(V_r x - V_t y)}{r^2 + R_{\text{max}}^2} + V_s \right]^2 - V_c^2, \quad (20)$$

$$\Rightarrow \mathcal{R} = \text{roots}(a_4 y^4 + a_3 y^3 + a_2 y^2 + a_1 y + a_0). \quad (21)$$

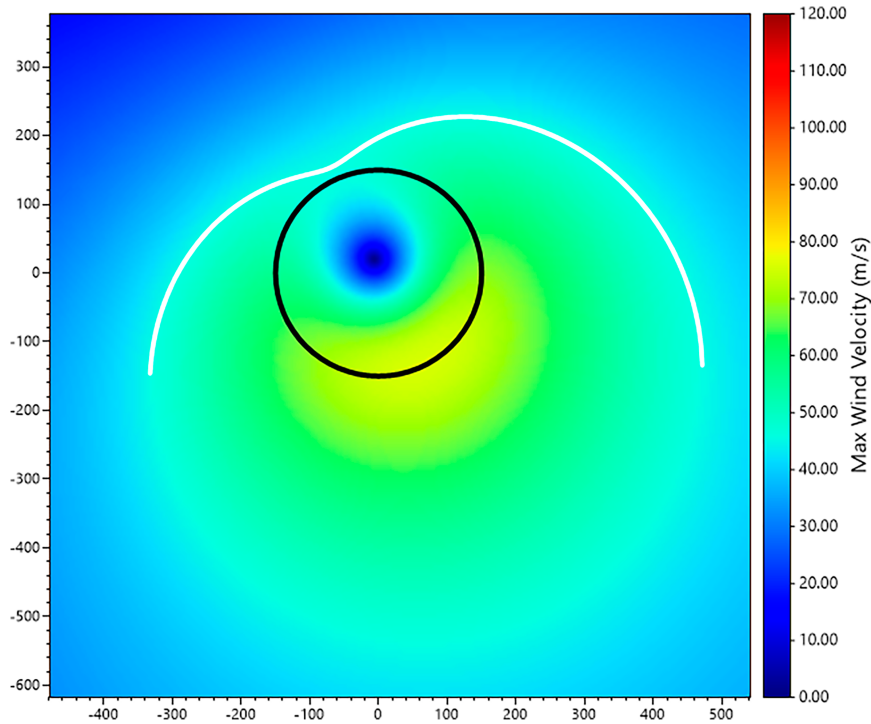


FIG. 5. A graph of the vortex-tree failure locations (white curve) using the Bjerknes model with, $V_r = 55 \text{ m s}^{-1}$, $V_t = 25 \text{ m s}^{-1}$, $V_s = 15 \text{ m s}^{-1}$, $V_c = 45 \text{ m s}^{-1}$, and $R_{\max} = 150 \text{ m}$ with the $r = R_{\max}$ circle in black.

Unfortunately, with other profiles like the modified Rankine (for arbitrary φ), Burgers–Rott, and Sullivan profiles, the vortex-tree failure location, defined by Eq. (19), cannot always be expressed as a polynomial. By investigation of Eq. (18) and the Bjerknes profile, it can be concluded that any profile that is a rational polynomial in $rR_{\max}^{-1}$, where the numerator and denominator polynomials contain only odd and even powered terms, respectively, will yield a polynomial for Eq. (19). As such, the Burgers–Rott and Sullivan tangential profiles are approximated using numerically optimized function fitting as

$$P_t = \frac{k_1 r R_{\max}^{-1} + k_3 r^3 R_{\max}^{-3}}{k_0 + k_2 r^2 R_{\max}^{-2} + k_4 r^4 R_{\max}^{-4}}, \quad (22)$$

where $k_0 = 1.8242$, $k_1 = 3.1115$, $k_2 = 1.5189$, $k_3 = 1.0$, $k_4 = 0.76843$, and $k_0 = 1.1180$, $k_1 = 0.060702$, $k_2 = -1.0$, $k_3 = 2.2901$, $k_4 = 2.2327$, for the Burgers–Rott and Sullivan profile approximations, respectively. These approximate profiles have a worst-case error of approximately 0.01 and 0.02 when compared to the Burgers–Rott and Sullivan profiles, respectively. Moreover, they produce degree 8 and 10 polynomials for Eq. (19), when the radial profile of the Burgers–Rott and Sullivan models is replaced by their tangential profile and the Rankine profile, respectively.

In the case of the modified Rankine profile, when $\varphi = 1$, the vortex-tree failure location equation is a circle whose roots are solved from a quadratic, as described by Letzmann (1923).

However, as φ decreases toward 0.5, the shape of the vortex-tree failure location equation deforms from a circle to an elliptical-like shape, which for an arbitrary φ cannot be expressed explicitly with y as a function of x . Moreover, for an arbitrary value of φ , the specific form cannot always be accurately approximated using the rational polynomials described above, without leading to Eq. (19) being a higher-degree polynomial (20+), which can create significant floating-point errors and be considerably slower (Yuksel 2022). Alternatively, the Rankine profile can be solved in polar form, where r is a function θ (Chen and Lombardo 2019), followed by some form of interpolation to approximate y for a given x value. However, for the purposes of this study, it should be noted that although generally slower, Eq. (19) can be solved for the Rankine profile (and any other profile functions) using numerical root-finding algorithms. For example, Brent’s root finding method (Brent 2013) can be reliably used provided that the roots are bracketed based on their locations relative to the $R_{\max}$ circle, as further discussed below.

c. Solving for a simulated treefall pattern

Once the vortex-tree failure location function has been determined, it can be discretely sampled at evenly spaced intervals, as shown in Fig. 6, consistent with the spacing of the observed treefall pattern, (Δx), discussed in section 4b. Then, the pattern can be solved by computing the unit vectors at the corresponding locations in the vortex field. However, as discussed in Rhee and Lombardo (2018), to ensure alignment

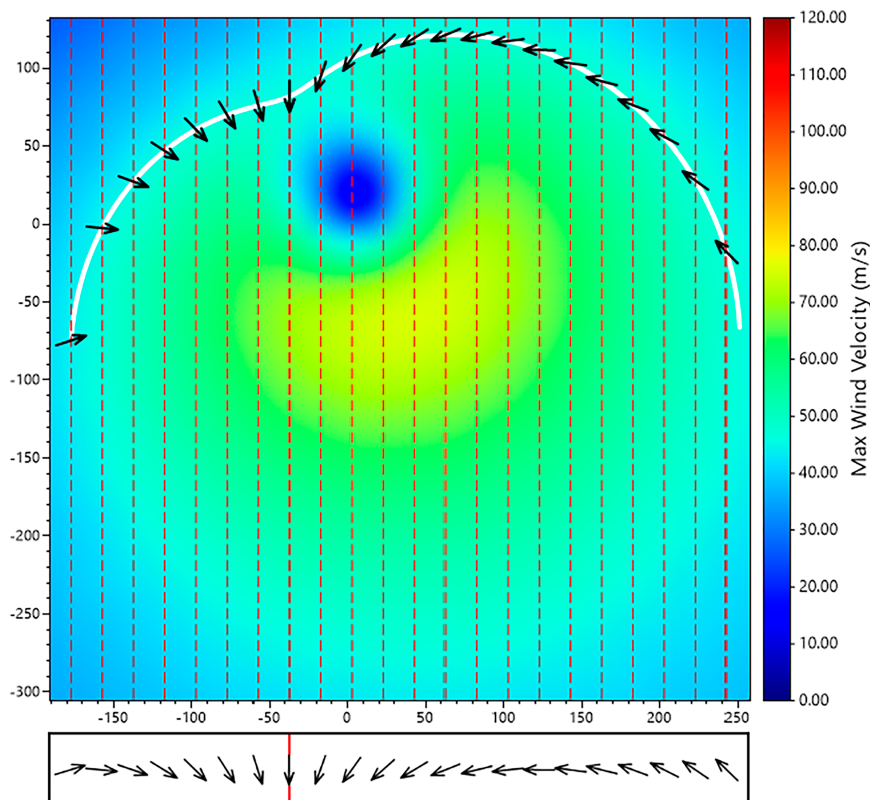


FIG. 6. A treefall pattern produced by discretely sampling the vortex-tree failure location function shown in Fig. 5 (with $R_{\max} = 80$ m instead of 150 m). The red line on the pattern indicates the axis of convergence, x_c .

between the observed and simulated patterns, the vortex-tree failure location function samples must be offset from the axis of convergence of the pattern's vectors and only on the interval, where the vortex-tree failure location function has real solutions. The axis of convergence x_c can be precomputed by solving for the x value, where the vortex-tree failure location function produces vectors whose x coordinate transitions between positive and negative. This can be modeled as a numerical root-finding problem that can be solved efficiently using algorithms such as the previously discussed Brent's method (Brent 2013). Similarly, the length of the pattern can be precomputed by determining the interval, $[a, b]$, over which real solutions exist to the vortex-tree failure location function. This can be solved using a binary (bisection) search over the two intervals, $(-\infty, x^*)$, (x^*, ∞) , as any solutions outside the interval, $[a, b]$, will be complex. Equation (23) demonstrates the sampling values of x over the required interval. The values of L_a and L_b represent the lengths of the treefall pattern on either side of the axis of convergence:

$$x = x_c + k\Delta x, \quad a \leq x \leq b, \quad k \in \mathbb{Z}, \quad (23)$$

$$L_a = x_c - a, \quad L_b = b - x_c. \quad (24)$$

Additionally, by translating a vortex with constant parameters, the trees will continue to fail in the same directions,

repeating the same pattern, as shown by Holland et al. (2006) and Karstens et al. (2013). As a result, the translated treefall pattern vectors can be projected into a single one-dimensional treefall pattern as shown in Fig. 6, similar to an observed treefall pattern created from a transect as shown in Rhee and Lombardo (2018).

d. Nondimensionality of the vortex-tree failure location function

As can be seen by examining Eq. (18) for different unitless profiles, Eqs. (7)–(11), changing $R_{\max}$ causes a proportional stretch to the vortex size and resulting pattern length, but it does not affect the underlying shape of the profile or vortex-tree failure location function. Therefore, if the same number of vectors in the pattern is maintained for different $R_{\max}$ values, the directions of the pattern's vectors will remain the same, but the overall pattern length will vary. As a result, the same pattern in terms of the number of vectors and their directions can be constructed at any length by changing the $R_{\max}$ value.

Additionally, by examining Eq. (18), a simultaneous proportional change to the velocity components, $V_r, V_t, V_s, V_c \rightarrow \lambda V_r, \lambda V_t, \lambda V_s, \lambda V_c$, would cancel out, having no effect on the shape of the vortex-tree failure location function. Such a change would affect the pattern vector magnitudes but not the directions

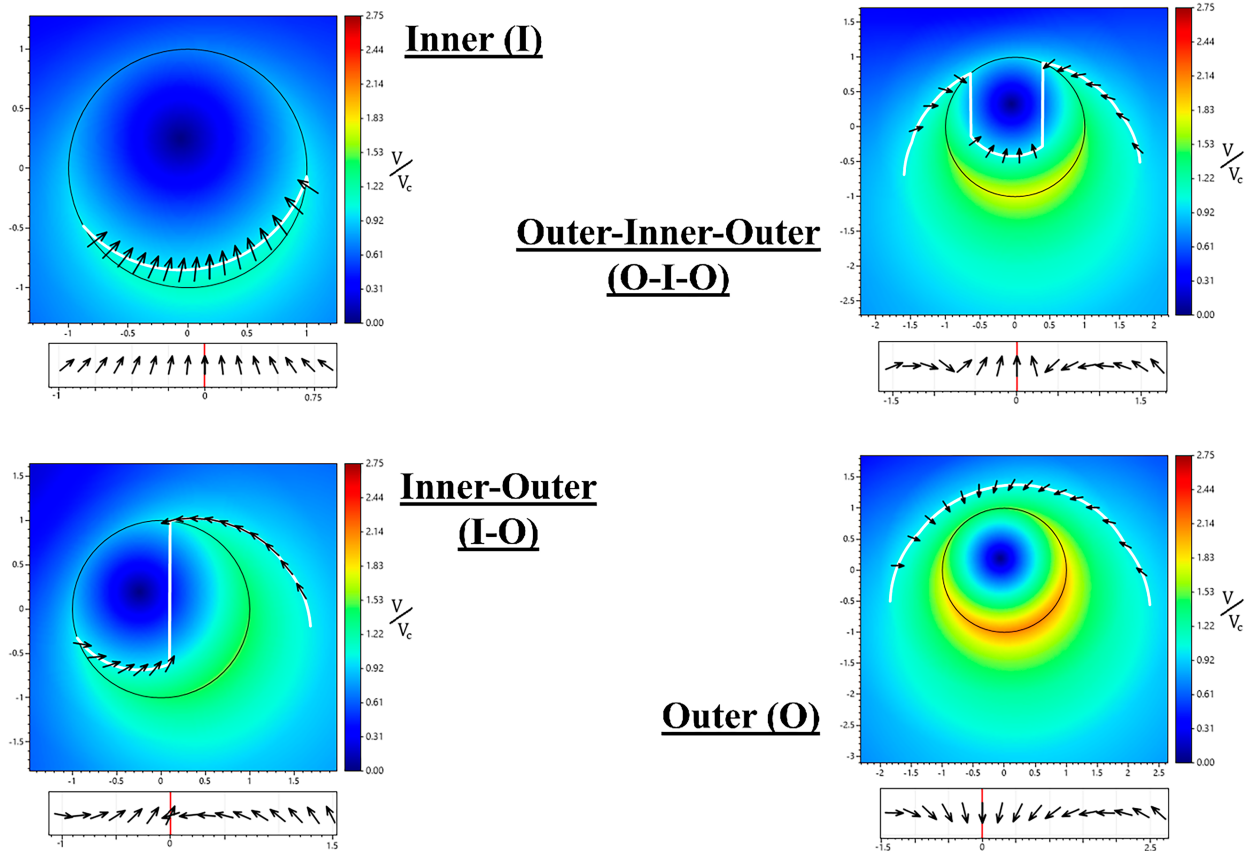


FIG. 7. Examples of the four types of patterns which can be classified by vortex-tree failure locations relative to the vortex's $R_{\max}$ circle. Inner and Outer represent solutions inside and outside the $R_{\max}$ circle, respectively. The black circle in each graph represents the $R_{\max}$ circle. The white curves in each graph represent all vortex-tree failure locations. The red line on each pattern indicates the axis of convergence, x_c .

and, since the treefall pattern is made up of unit vectors, does not affect the produced pattern. Overall, this indicates that a simulated pattern's directions depend only on the various ratios of $V_r:V_t:V_s:V_c$. To accurately estimate a dimensional value of $V_{\max}$ [which, from Eq. (13), depends on V_r , V_t , and V_s], estimates for V_c and V_s are required. Specific examples and further illustrations of the importance of these ratios can be found throughout the literature. Most notably, α , mentioned previously, and $G_{\max} = \sqrt{V_r^2 V_s^{-2} + V_t^2 V_s^{-2}}$, shown by Letzmann (1923) and discussed in Holland et al. (2006), as well as $\eta = V_c V_s^{-1}$, discussed in Chen and Lombardo (2019).

e. Discussion of analytical vortex-tree failure patterns

In this section, we examine the typical solutions of Eqs. (18) and (19) and the implied treefall patterns. By examining the vortex-tree failure locations relative to the $r = R_{\max}$ circle, we can classify solutions to the vortex-tree failure location function, Eq. (18), as “Inner” or “Outer” depending on whether they occur inside or outside the $R_{\max}$ circle, respectively. Moreover, patterns can be distinguished by discontinuous transitions between Inner and Outer solutions, described as “Inner-Outer” and “Outer-Inner-Outer” types based on the

transitions from left to right in the pattern. Figure 7 shows the four main types of patterns separable by these classifications, which align similarly to the types of patterns first described by Letzmann (1923). Additionally, for single core, counterclockwise-rotating (cyclonic in the Northern Hemisphere) vortices, only certain combinations of Inner and Outer solutions are possible with the models utilized in this study. For example, the reverse “Outer-Inner” pattern could only occur if clockwise (anticyclonic) rotation was utilized.

After analyzing the Inner and Outer partitions for the profiles discussed in this study, it appears that generally Inner vectors rotate counterclockwise, while Outer vectors rotate clockwise when comparing adjacent vectors from left to right. Moreover, if the axis of convergence happens during an outer partition, the converging treefall vectors will be directed opposite to the translation direction. Additionally, in the case of Inner-Outer patterns, the axis of convergence is taken as the axis where the discontinuity between Inner and Outer solutions occurs and is denoted in Fig. 7 with two vectors on either side of the discontinuity. Importantly, their rotation and convergence directions can be utilized to visually distinguish Inner and Outer partitions in observed treefall patterns.

When examining the modeled $V_{\max}$ for fixed estimates of V_c and V_s , several observations can be made. For $V_{\max} < V_c$, obviously, no pattern will be produced since no trees will be downed. As shown in Fig. 8, once $V_{\max} > V_c$, trees will fail. By considering an increasing value of $V_{\max}$, an Inner (I) type pattern will develop first. As $V_{\max}$ is increased further, the pattern transitions from Inner to one of the combinational type patterns, Outer–Inner–Outer (O–I–O), or Inner–Outer (I–O), and finally to the Outer (O) type pattern. Additionally, increasing the swirl ratio S increases the offset of the pattern's axis of convergence from the center, as shown in Figs. 4 and 8. As a result, generally greater swirl ratios tend to produce Inner–Outer over Outer–Inner–Outer patterns, but the specific values that are required vary based on the vortex profiles used. Overall, this suggests that different patterns are a good indicator of $V_{\max}$ and swirl ratio values, when V_c and V_s are known. Additionally, seeing these transitions between pattern types or shifts of the axis of convergence in observed patterns is an indication of changing vortex wind speeds or critical tree failure speeds, and swirl ratio, respectively, as described (in part) by Holland et al. (2006) and Rhee and Lombardo (2018).

However, for Outer patterns, further increase to $V_{\max}$, eventually results in a convergence of the treefall pattern to a specific Outer-type pattern based on the swirl ratio, with only the pattern's length increasing, as can be seen in Fig. 8. This is due to the $V_r:V_t:V_s:V_c$ ratio discussed previously becoming dependent on V_r and V_t as $V_r, V_t \gg V_s, V_c$ for a fixed V_s , and V_c . Furthermore, as previously discussed, decreasing the $R_{\max}$ value decreases the pattern's length while maintaining the pattern's vector directions. As such, for Outer patterns, often increasing $V_{\max}$, but decreasing $R_{\max}$ results in the same pattern. Therefore, in cases where the observed pattern matches closely with an Outer pattern, no upper bound on $V_{\max}$ can be obtained without further restrictions imposed on vortex parameters such as a good estimate for $R_{\max}$ to limit the simulated pattern's length. Estimating $R_{\max}$ can be accomplished using structural damage (Kuligowski et al. 2014; Lombardo et al. 2015). Nevertheless, when only tree damage is present, this problem of matching Outer patterns often limits a practical estimate of $V_{\max}$ for Outer-type patterns to the minimum required speed for simulating a similar pattern. This can be problematic for estimating the wind speed of EF4 or EF5 tornadoes, as Outer-type patterns require the highest overall wind speeds compared to the other types of patterns for fixed, estimated V_c and V_s values.

Although there is no upper bound on $V_{\max}$ for Outer-type patterns, a lower bound can be found by examining when the vortex–tree failure locations transition between Inner and Outer types. Under the assumption that the vortex–tree failure location function, Eq. (19), is continuous for Outer-type patterns, this problem can generally be reformulated as determining when the minimum wind speed along the $R_{\max}$ circle exceeds V_c . This assumption holds for the profiles considered in this study when excluding unlikely conditions such as high swirl ratios ($S \gg 1$) or as $V_s \rightarrow V_c$, further discussed below. Using a similar logic to the calculation for maximum wind speed, it can be shown that Outer-type patterns only occur when

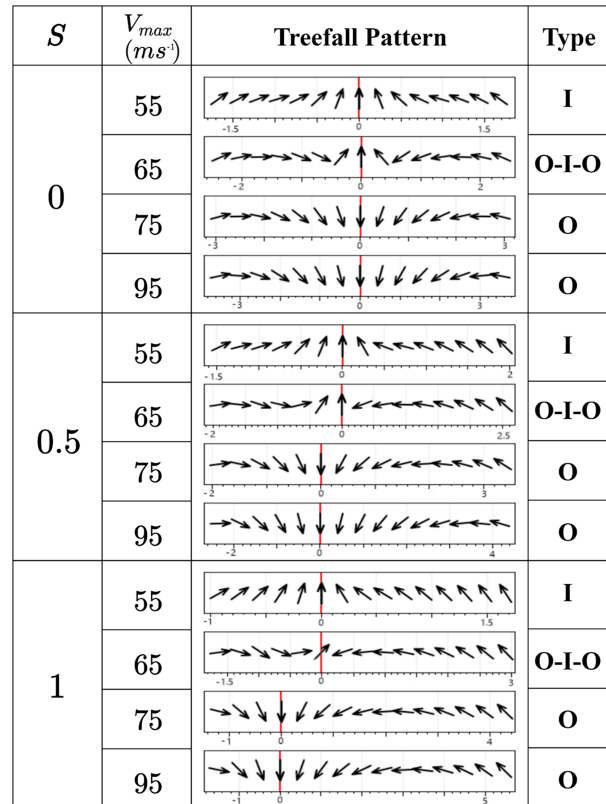


FIG. 8. Treefall patterns produced using the Baker–Sterling (Bjerknes) model for different swirl ratios (S) and maximum wind speeds ($V_{\max}$), given a constant $R_{\max} = 1$ m, $V_c = 40$ m s $^{-1}$, and $V_s = 15$ m s $^{-1}$. For consistency, the spacing between vectors (Δx) for a pattern was chosen to create 15 vectors each. The letters “I” and “O” represent Inner- and Outer-type vortex–tree failure location solutions, respectively.

$$V_{\max} \geq V_c + 2V_s. \quad (25)$$

Overall, this indicates the importance of having accurate estimates of V_c and V_s , when estimating $V_{\max}$ for Outer-type patterns.

Another notable issue occurs as $V_s \rightarrow V_c$. In this case, the trees can fail solely based on and in the direction of $\mathbf{V}_s$, with little influence from V_r or V_t , potentially causing a pattern with little to no convergence. Furthermore, although unlikely, if V_s exceeds V_c , the model breaks down completely as the vortex–tree failure locations become the entire real x – y plane. A potential solution to this problem could be to use decaying translational speeds farther out from the center of the vortex similar to the radial and tangential profiles, as discussed in Lombardo et al. (2023). This is not considered in the current study.

4. Treefall pattern matching

a. Defining similarity between patterns

When comparing observed and analytical patterns, an error metric must be chosen to define how similar the patterns are to each other. In the simplest case, the average of the

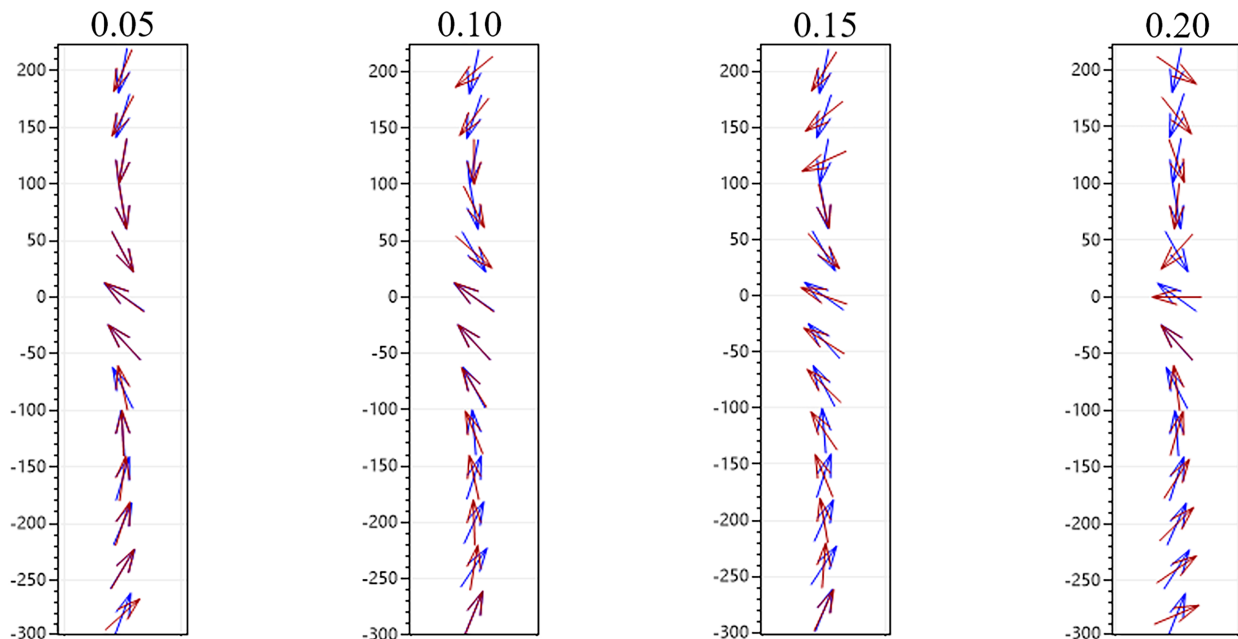


FIG. 9. Comparison of four different simulated treefall patterns (red) to the same observed pattern (blue), with increasing error (pattern dissimilarity). The errors (0.05–0.2) between patterns are calculated using the weighted average of vector angle differences normalized between 0 and 1.

differences in angles between the vectors can be compared either directly, or using their dot product (Rhee and Lombardo 2018), with lower averages (error) indicating a better match. In addition to comparing the directions of individual pattern vectors, the overall length and individual lengths on either side of the axis of convergence must be compared to ensure the observed and simulated patterns and corresponding tree damage are consistent in size. This can be accomplished by adding a penalty related to the difference in pattern lengths, as discussed by Rhee and Lombardo (2018). However, for computational efficiency, only comparing vortices with parameters that generate patterns with closely matching lengths can be performed by precomputing the lengths of patterns. Additionally, there is the question of whether all pattern vectors are equally important. As implied by the four types of patterns in Fig. 7, often the vectors closer to the axis of convergence give a better indication of the type of pattern. For example, when comparing Outer and Outer–Inner–Outer patterns, often the only difference occurs with the vectors closer to the axis of convergence. Moreover, the wind speed of tornadoes becomes weaker farther out from the center of the vortex, leading to potentially less reliable average treefall vectors, as fewer trees fail. As such, a linear weighting scheme, $w(x)$, based on distance from the axis of convergence can be utilized, with

$$w(x) = \begin{cases} 1 - \frac{x_c - x}{\Delta x + L_a}, & x \leq x_c \\ 1 - \frac{x - x_c}{\Delta x + L_b}, & x > x_c \end{cases}. \quad (26)$$

In practice, when comparing the best matching pattern to other close matching patterns, there is often a negligible

difference in the pattern error metrics, but some significant differences in vortex characteristics including $V_{\max}$. Often this can be caused by a pattern depending on the various ratios of $V_r:V_s:V_c$, with different values producing similar ratios. As a result, selecting any of these patterns may yield a different but plausible representation of the observed vortex characteristics. This uncertainty should be considered in tornado damage assessments. To do this, the distribution of tornado wind field parameters which produce patterns that match with errors below a particular cutoff threshold can be utilized. This distribution can then be analyzed and taken into account when rating the tornado. However, as discussed previously, using the minimum required wind speed for simulating a similar pattern is effectively required for Outer-type patterns when only tree damage is available. Therefore, in the current study, the minimum required wind speed of all plausible patterns must be used.

Determining an ideal cutoff threshold depends heavily on the similarity metric utilized for pattern comparison, as well as human judgment. Figure 9 demonstrates four different pattern matches with increasing pattern error (i.e., decreased similarity) when compared to the same observed pattern using the weighted average of vector angle differences described above, normalized between 0 and 1 by dividing by π . As can be seen in Fig. 9, an error of 0.1 or less tends to empirically yield closely matching patterns; however, with errors around 0.2, the simulated pattern no longer produces a reasonable match as the observed and simulated patterns often differ in types (in this case, Outer versus Inner–Outer). Furthermore, if the best-matching simulated patterns do not match with errors below the threshold, then either the observed pattern was poorly chosen, or the observed pattern cannot be reasonably modeled

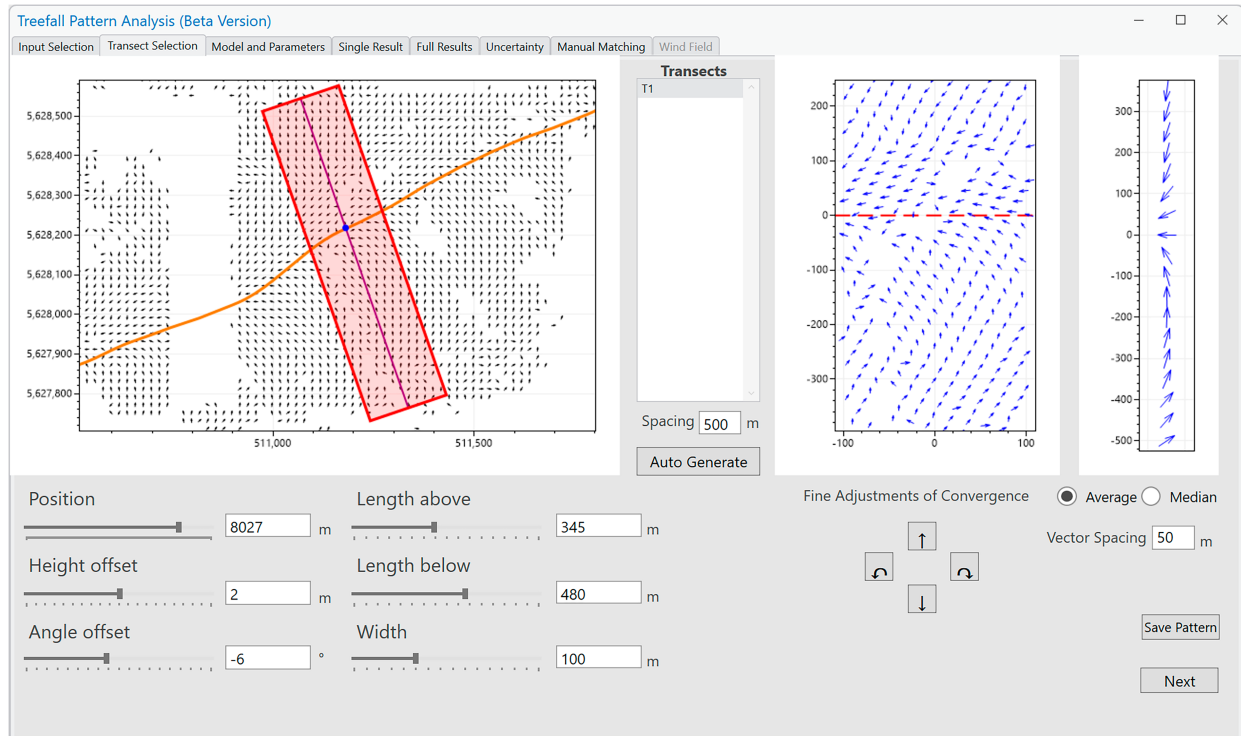


FIG. 10. Treefall patterning analysis and matching software, used to find and match treefall patterns. The orange curve is the convergence line, and the red box outlines the selected treefall pattern transect. The graph on the far right shows the area-averaged treefall pattern.

by the analytical single core vortices, indicating that this method may not be suitable for the tornado in question. It is proposed that this could occur when the underlying assumptions do not hold, for example, in the treefall of multivortex tornadoes with high swirl ratios, tornadoes with rapidly changing direction or parameters, sections with combined tornadic and downburst damage, or sections with little to no convergence of treefall vectors. Particularly, the case of little to no convergence as the treefall vectors are all falling in the same direction, can occur with weak Inner-type patterns, or where V_s approaches the speed of V_c , as described previously. Moreover, by extension, seeing a clear treefall pattern similar to those that can be simulated indicates that the assumptions likely hold, given the earlier published validations of the overall approach.

b. Treefall pattern matching software

Using custom treefall pattern matching software designed by the Canadian Severe Storms Laboratory, with a screenshot

shown in Fig. 10, an observed treefall pattern can be extracted and automatically matched to simulated patterns. The software allows for the placement and adjustment of a transect fit perpendicular to a section of the convergence line. Adjustments include the vector spacing (Δx), transect width, length above and below the convergence line, as well as the height and rotation offsets to adjust the transect relative to the underlying section of the convergence line if it is not fit perfectly. As adjustments are made, the treefall vectors inside the transect are shown, along with the corresponding area-averaged treefall pattern given a user-specified treefall pattern vector spacing. A transect is placed and adjusted until the observed treefall pattern is similar to one of the types shown in Fig. 7. Moreover, the transect must be fit to the extent of the full length of the observed treefall damage, and with a width ranging generally between 100 and 200 m. Furthermore, the vector spacing (Δx) should be selected to create a pattern with around 10–20 vectors. Generally, fewer than 10 vectors may not fully capture the underlying

TABLE 3. Parameter ranges and discrete sampling spacing used by the treefall pattern matching software.

Parameter	Range	Discrete spacing
V_r	20–80 m s^{-1}	1 m s^{-1}
V_t	1–50 m s^{-1}	1 m s^{-1}
$R_{\max}$	0.1–0.5 $\times$ observed pattern length	5 m
ϕ (Rankine)	0.50–1.00	0.05

TABLE 4. List of randomized transect parameters and ranges for a Monte Carlo–style simulation.

Randomized transect parameter	Offset range
Vector spacing (Δx)	$\pm 25\%$
Transect lengths (L_a , L_b)	$\pm 10\%$
Transect width	$\pm 10\%$
Transect height offset (from convergence line)	$\pm \Delta x$
Transect angle offset (from convergence line)	$\pm 5^\circ$

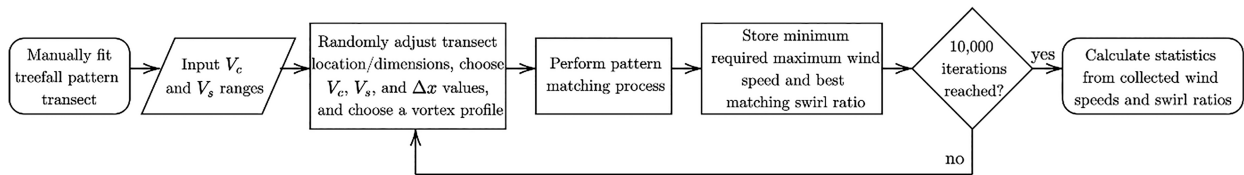


FIG. 11. Flowchart describing the Monte Carlo-style simulation utilized to measure uncertainty in treefall pattern matching.

pattern, and more than 20 are generally unnecessary. Notably, in the software, these patterns are rotated 90° clockwise from those discussed previously (and shown in the earlier figures).

Once a transect is fit, and an observed pattern determined, the user enters the range of parameters (V_r , V_b , V_s , V_c , $R_{\max}$, ϕ) for which corresponding simulated patterns will be generated. For this study, the ranges for V_s and V_c are specified for each event in Tables 6 and 7. Table 3 lists the range and discrete spacing utilized for each other parameter. These ranges were selected to ensure coverage of a wide range of treefall patterns while reducing the required computational time. The range of $R_{\max}$ values was selected in common with Miller et al. (2024), based on analysis done by Twisdale et al. (2023). To find the plausible matches, every combination of these parameters is first checked by precomputing the sets of parameters that will produce a pattern with lengths within a one vector spacing of the observed pattern's lengths. Then, for each of these sets of parameters, a simulated pattern is produced, and its error relative to the observed pattern is calculated. Sets of parameters with errors less than the chosen threshold of 0.1 are recorded. Once all these sets of parameters are compared, the overall best matching parameters, as well as the minimum $V_{3-\max}$ needed to produce a similar pattern, can be determined.

c. Accounting for uncertainty

During the process of finding and matching an observed treefall pattern, there are five main sources of uncertainty:

- 1) The treefall pattern matching error function and weighting scheme
- 2) The threshold of error for a reasonably well-matching pattern
- 3) The placement and dimensions of the transect
- 4) Estimates for critical tree failure and translational speed parameters (V_c , V_s)
- 5) Differences between vortex profiles (wind field models)

Although different error functions and weighting schemes for comparing treefall patterns have been utilized in other studies, the current study utilizes the average angle difference and linear weighting scheme for the reasons previously mentioned. Along

the same lines, although the threshold for a reasonably well-matched pair of patterns could be changed from 0.1, as shown in Fig. 9, 0.1 tends to correspond to reasonably well-matched patterns, while airing on the conservative side in comparison to higher values such as 0.2. Notably, using a lower threshold yields a subset of the matches from a higher threshold.

Along a tornado's damage path through a forest, there will be multiple locations where distinct treefall patterns appear. These can be used to develop contours of estimated wind speed or EF-scale rating (Rhee and Lombardo 2018). As for structural damage, estimates for the maximum wind speeds from treefall patterns are based on the location of damage with the highest associated wind speed estimate. (We note that, while structural damage is a point estimate, the current method uses tornado wind field parameters that consider an entire transect of path.) As such, all-distinct treefall patterns must be tested to ensure the highest wind speed estimate is found. Then, for each distinct region where a different treefall pattern is observed, manual changes to the size and orientation of the transect can change the pattern, adding uncertainty to the estimated wind speed. Most notably, as seen in Fig. 8, changes to the pattern lengths can result in significant changes to the best-matching swirl ratios.

As well, the ranges of estimated V_c and V_s values, along with the use of different vortex profiles (models), yield additional uncertainty. To assess the uncertainty of sources 3–5, a Monte Carlo style simulation is utilized in this study to compare 10 000 random variations to transect location/dimensions, vortex profiles, and V_c/V_s values for each analyzed tornado. For each of the 10 000 pattern-matching processes previously described, the transect is randomly manipulated, with a fixed V_c/V_s value selected from the ranges in Tables 6 and 7 and a vortex model selected from those discussed in section 2b. Moreover, fixing V_c and V_s for each run of the Monte Carlo simulation ensures only unique $V_r:V_b:V_s:V_c$ ratios are tested, improving computational efficiency by avoiding comparing duplicate patterns as discussed above. Table 4 lists the parameters used to randomly adjust the transect in the Monte Carlo simulation and their associated ranges. Figure 11 depicts a flowchart of the overall Monte Carlo simulation

TABLE 5. List of tornado events selected for treefall pattern analysis in this study.

Event name (location)	Date	Pathlength (km)	Max path width (m)	EF rating (from NTP)
Alonsa, Manitoba	3 Aug 2018	15.7	1200	EF4
Lake Traverse, Ontario	15 Jul 2021	13.3	530	EF2
Dwight, Ontario	15 Jul 2021	7.1	400	EF2
Lac Gus, Quebec	5 Sep 2018	11.4	450	EF2

TABLE 6. List of estimated V_s values and data sources for each tornado event analyzed.

Event	Radar station	Data type	Total time (s)	Total distance (m)	Radius of uncertainty (m)	Estimated V_s (m s^{-1})
Alonsa, Manitoba	XWL Woodlands, Manitoba	Radial velocity	1200	13 600	1500	11 ± 2
Lake Traverse, Ontario	WBI Britt, Ontario	Reflectivity	1800	33 700	3000	19 ± 2
Dwight, Ontario	CASKR King City, Ontario	Radial velocity	720	10 200	1500	14 ± 3
Lac Gus, Quebec	WMN Ste-Anne de Bellevue, Quebec	Reflectivity	1200	18 700	4500	16 ± 5

methodology used to estimate a tornado's parameters and the associated uncertainty.

5. Application to observed tornado events

a. Overview

For this study, four Canadian forest-based tornadoes were selected for analysis, as listed in Table 5. Events were selected which met the following criteria. First, the events must be primarily forest based, with a rating of EF2 based on 80% of mature trees snapped or uprooted in the area of worst damage. This is to ensure that enough trees were damaged to warrant the use of treefall patterns. Second, there must be visible treefall patterns similar to those of Figs. 7 and 8; otherwise, the assumptions made may not be valid. Third, a preference was given to events with Outer-type patterns as they tend to produce the highest wind speeds, when V_c and V_s have been estimated. For each event, all sections of the damage track with distinct treefall patterns were examined. Only the sections with the highest wind speed estimates are presented here. Additionally, for comparison with the study by Stevenson et al. (2023), the Alonsa, Manitoba, tornado was included.

All of these events were previously analyzed by the NTP using their standard procedures. Large-scale aerial imagery of the tornado's track and surrounding area using aircraft is collected (Sills et al. 2020). The collected imagery is $5 \text{ cm} \times 5 \text{ cm}$ per pixel in resolution or better. Next, Treefall Identification and Directional Analysis (TriDA) maps are created, showing a vector field of the treefall directions like those automatically produced using the software in Butt et al. (2024). A tornado convergence line (curve) is then fit along the path, where the treefall vectors converge. Finally, the tornado is rated using the Scalable Box Method (Sills et al. 2020). Ratings are included in Table 5. Additionally, V_s and V_c must be determined for each event to use the treefall methodology. Table 6 provides the estimates related to V_s , while Table 7 provides the estimates related to V_c .

To determine V_s , the available radar data and their resolution are examined. A radius of uncertainty is estimated for each selected point used to determine the center of the mesocyclone,

with its variance calculated as this radius squared. The radius of uncertainty was estimated at 1500 and 3000 m for Doppler radial velocity data and reflectivity data, respectively. For the Lac Gus tornado, due to the lower quality of available reflectivity data, an additional 1500 m of uncertainty was added. This uncertainty is assumed to be independent between the selected points, and as such the overall standard deviation of uncertainty can be calculated as the square root of the sum of the estimated variance at each point. Notably, this radius of uncertainty also attempts to account for potential deviations of the actual translational speed from the average translational speed over the short duration of a treefall pattern transect. From both radar and treefall convergence, it is clear that the tornadoes in the events considered traveled along quasi-linear paths, without looping. Table 6 gives a summary of the estimated V_s values and uncertainty (standard deviation) for each event.

To determine V_c , ground surveys were conducted for each event to determine the dominant tree species and collect soil samples. Additionally, values of diameter at breast height (DBH) and h were determined using drone and aerial imagery of each event location, by sampling 50–100 trees around the locations of worst damage. Specifically, trees which were unobstructed and clearly visible were selected to ensure accurate measurements. This revealed that balsam fir (*Abies balsamea*) and paper birch (*Betula papyrifera*) were dominant in the damaged areas, and the parameters used in the analysis reflect the relative proportions of each species. Values for D were estimated by taking the square root of the average area around each tree using

$$D = \sqrt{An^{-1}}, \quad (27)$$

where A is the area and n is the number of trees in the fitted treefall pattern transect with the highest estimated wind speed for each event.

The values of SW for each tree species were estimated using the tree taper equation of Honer (1967), with the appropriate shape parameters ($b_0 = 2.14$ and $b_1 = 301.63$ for BF and $b_0 = 2.22$ and $b_1 = 300.37$ for PB) and the wood density values ($\rho_{\text{wood}} = 761$ and 866 kg m^{-3} for BF and PB, respectively)

TABLE 7. List of estimated V_c values and associated tree parameters for each analyzed tornado event.

Event	Dominant species	Average height (m)	Average DBH (m)	Average D (m)	Estimated V_c (m s^{-1})
Lake Traverse, Ontario	Balsam fir	23 ± 3	0.39 ± 0.08	3.7	44 ± 8
Dwight, Ontario	Paper birch	19 ± 3	0.31 ± 0.09	3.6	39 ± 10
Lac Gus, Quebec	Balsam fir/paper birch (50:50)	$14 \pm 3/16 \pm 3$	$0.31 \pm 0.09/0.40 \pm 0.10$	3.9	31 ± 8

TABLE 8. Results for the tornadoes analyzed. Results are listed as median $\pm$ one standard deviation.

Event	V_c (m s^{-1})	V_s (m s^{-1})	S	$V_{3-\text{max}}$ (m s^{-1})	Treefall pattern rating	Canadian EF-scale rating
Alonsa, Manitoba, 2018	48 ± 12	11 ± 2	0.13 ± 0.04	75 ± 9	EF4	EF4
Lake Traverse, Ontario, 2021	44 ± 9	19 ± 2	0.29 ± 0.1	78 ± 7	EF4	
Dwight, Ontario, 2021	39 ± 10	14 ± 3	0.01 ± 0.01	67 ± 7	EF3	EF2
Lac Gus, Quebec, 2018	31 ± 8	16 ± 5	0.44 ± 0.1	57 ± 8	EF2	

were based on average green heartwood and sapwood moisture contents (Ross 2010). The C_{reg} was estimated using data from Ruel et al. (2000) for balsam fir growing in freely draining mesic till (189 Nm kg^{-1}) and Krišāns et al. (2022) for birch growing in drained mineral soils (190 Nm kg^{-1}). Well-known analytical expressions for vegetated surfaces (Raupach 1994) were used for d/h (0.8) and z_o/h (0.09), as a function of forest canopy height and leaf area index (LAI). The LAIs for balsam fir and paper birch were estimated from field and remote sensing studies of boreal mixed-wood forests in Ontario and Newfoundland (Hunt et al. 1999; Pope and Treitz 2013) and were assumed lie between 1.5 and $3.5 \text{ m}^2 \text{ m}^{-2}$. Notably, all events were below 500 m in elevation.

Table 7 gives a summary of the characteristics and tree statistics for each event, as well as the estimated V_c values and uncertainty using the methodology described in section 3. Notably, these values match closely to the upper and lower bound wind speeds of 73 – 113 mph (32 – 51 m s^{-1}) provided by Wind Science and Engineering Center (2006) for the overturning of softwood trees in the U.S. EF scale and represent 86% – 95% of separately calculated stem break critical wind speeds for each of the sampled trees (based on the relevant equation from Gardiner et al. 2000). Additionally, for the Alonsa, Manitoba event, the V_c value and uncertainty of $47.5 \pm 12.5 \text{ m s}^{-1}$ are taken from Stevenson et al. (2023) for comparison, which used a similar critical tree failure estimation methodology.

b. Results

The results for this study are listed in Table 8 and Figs. 12–15. For each event, the estimated minimum required $V_{3-\text{max}}$ as well as the best matching swirl ratio (S) are given as the median result with one standard deviation of uncertainty. These values are based on 10000 runs of each associated Monte Carlo simulation. The median was chosen over the mean as it is more resistant to outliers and due to the distributions being slightly skewed from symmetric normal distributions, as can be seen in Figs. 12–15 for the four analyzed events.

Figure 16 shows the selected treefall patterns for each event compared to the best-matching simulated pattern. As can be seen, all selected treefall patterns were of the Outer type and are matched closely by the simulated patterns, below the 0.1 weighted average threshold described previously. For the Alonsa event, the median $V_{3-\text{max}}$ of 75 m s^{-1} matches the current rating of EF4 based on structural damage; however, it is approximately 10 m s^{-1} lower than the treefall pattern estimates from Stevenson et al. (2023), indicative of the more conservative nature of this study caused by the utilization of the minimum required $V_{3-\text{max}}$, instead of directly estimating the instantaneous maximum wind speed. Nevertheless, two of the other three newly analyzed tornadoes produced estimated ratings above their current rating of EF2. Furthermore,

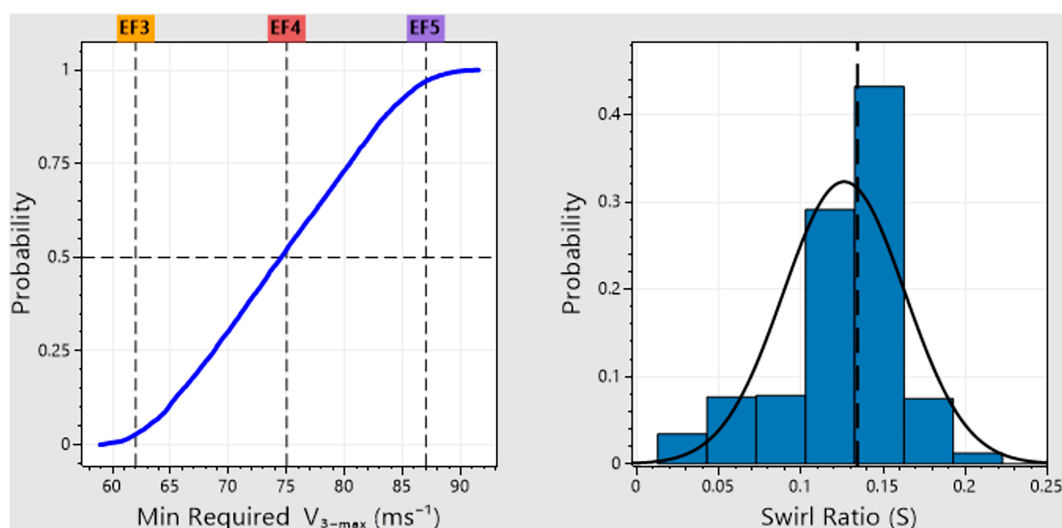


FIG. 12. Results from 10000 runs of the treefall pattern matching Monte Carlo simulation for the Alonsa, Manitoba, tornado. For the swirl ratio histogram, the dashed line represents the median result, and the solid line is a fit normal distribution.

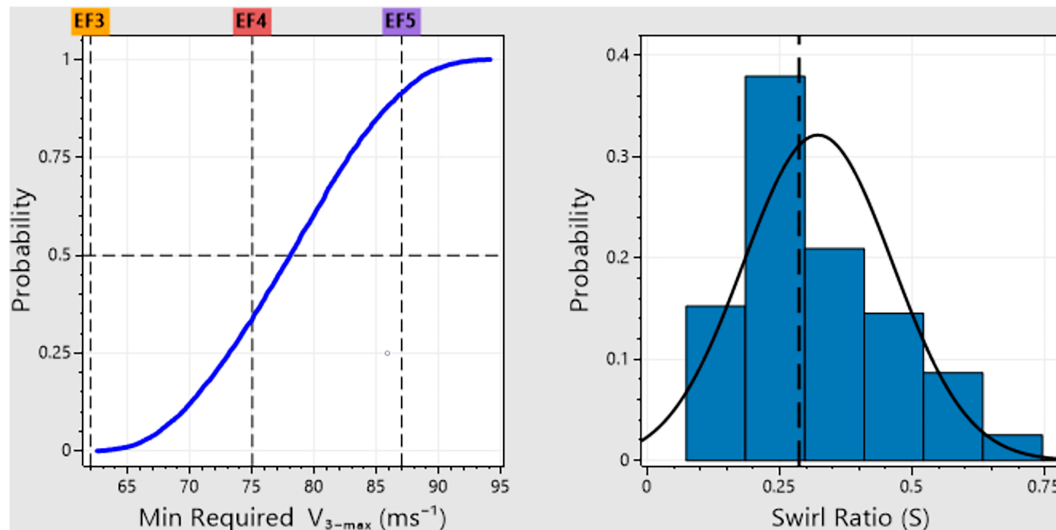


FIG. 13. Results from 10 000 runs of the treefall pattern matching Monte Carlo simulation for the Lake Traverse, Ontario, tornado. For the swirl ratio histogram, the dashed line represents the median result, and the solid line is a fit normal distribution.

in the case of the Lake Traverse tornado, every run of the Monte Carlo simulation required a minimum $V_{3-\max}$ above the threshold for EF3. This suggests a possible explanation is that many current Canadian EF2 tornadoes in forested areas are underrated due to insufficient higher-end damage indicators, but further research using this methodology will be required to assess this conclusively.

6. Conclusions

This study developed and assessed analytical solutions of tornado treefall patterns and their uncertainty for estimating

maximum 3-s gust speeds and swirl ratios. Through mathematical analysis, treefall patterns were determined to depend primarily on the ratio of the radial, tangential, translational, and critical tree failure speeds. As a result, when an estimate for the critical tree failure and tornado translation speeds are known, treefall patterns can be consistently linked to an estimate of a tornado's maximum wind speed and swirl ratio. Four typical types of tornado treefall patterns are differentiated based on vortex–tree failure locations relative to the radius of maximum wind speed. It was found that Outer-type patterns, which have convergence in the opposite direction of the translation direction, correlate to the highest wind speeds

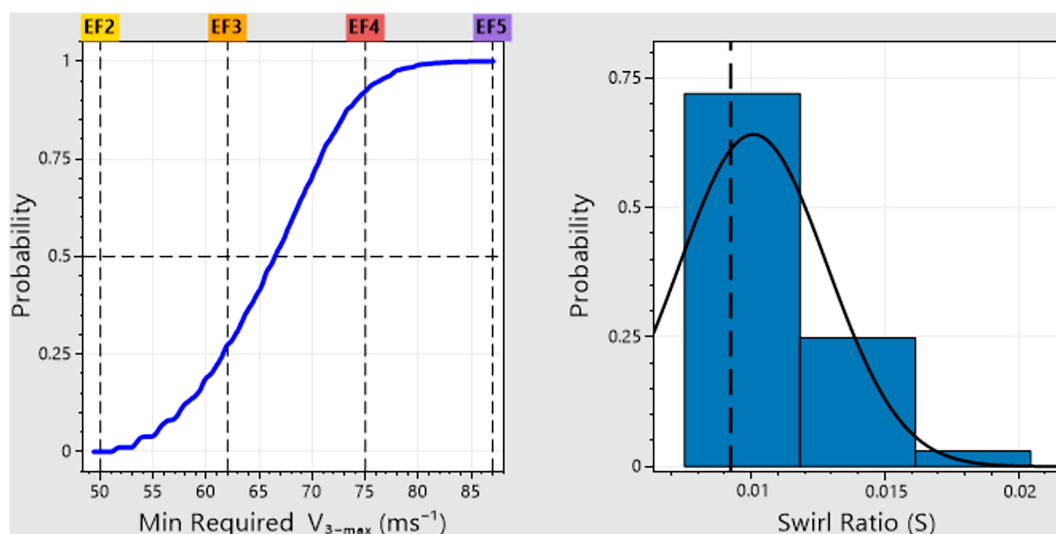


FIG. 14. Results from 10 000 runs of the treefall pattern matching Monte Carlo simulation for the Dwight, Ontario, tornado. For the swirl ratio histogram, the dashed line represents the median result, and the solid line is a fit normal distribution.

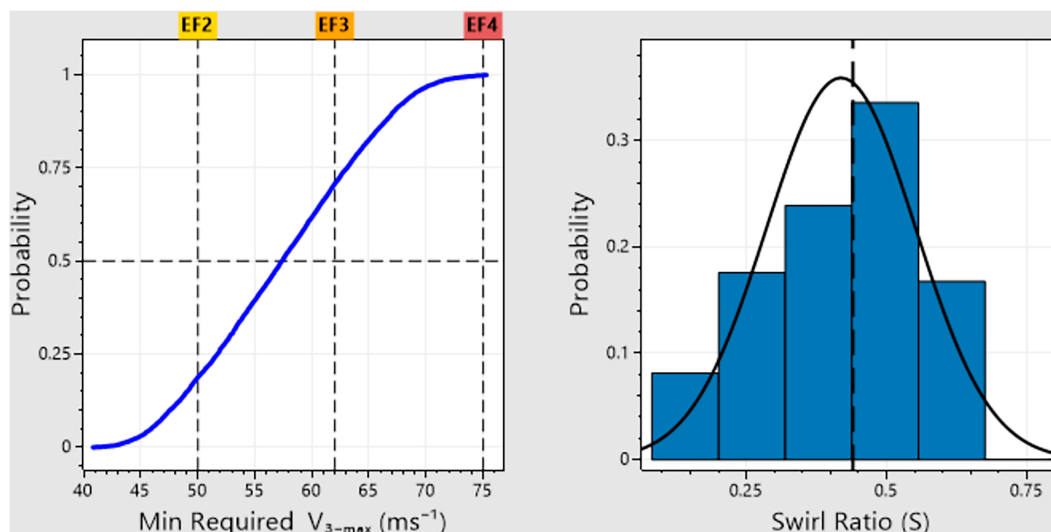


FIG. 15. Results from 10000 runs of the treefall pattern matching Monte Carlo simulation for the Lac Gus, Quebec, tornado. For the swirl ratio histogram, the dashed line represents the median result, and the solid line is a fit normal distribution.

compared to the other types of patterns for known critical tree failure and translational speed values. However, potential limitations exist for high wind speeds (EF5) due to the discussed Outer pattern convergence, fast traveling tornadoes due to the translational speed approaching or exceeding the critical tree failure speed, and multivortex tornadoes whose profiles differ from those discussed in this study.

Four forest-based tornado events, including the previously analyzed Alonsa EF4 tornado, were selected with

assessments of their critical tree failure and translation speeds values performed. By utilizing the Monte Carlo simulation methodology, two of the three newly analyzed events were estimated to have higher EF-scale ratings than those suggested by the Scalable Box Method currently used in the Canadian EF scale. Future work will apply this methodology to all Canadian forest tornadoes with significant treefall damage since it has the potential to change the ratings for many higher intensity tornadoes.

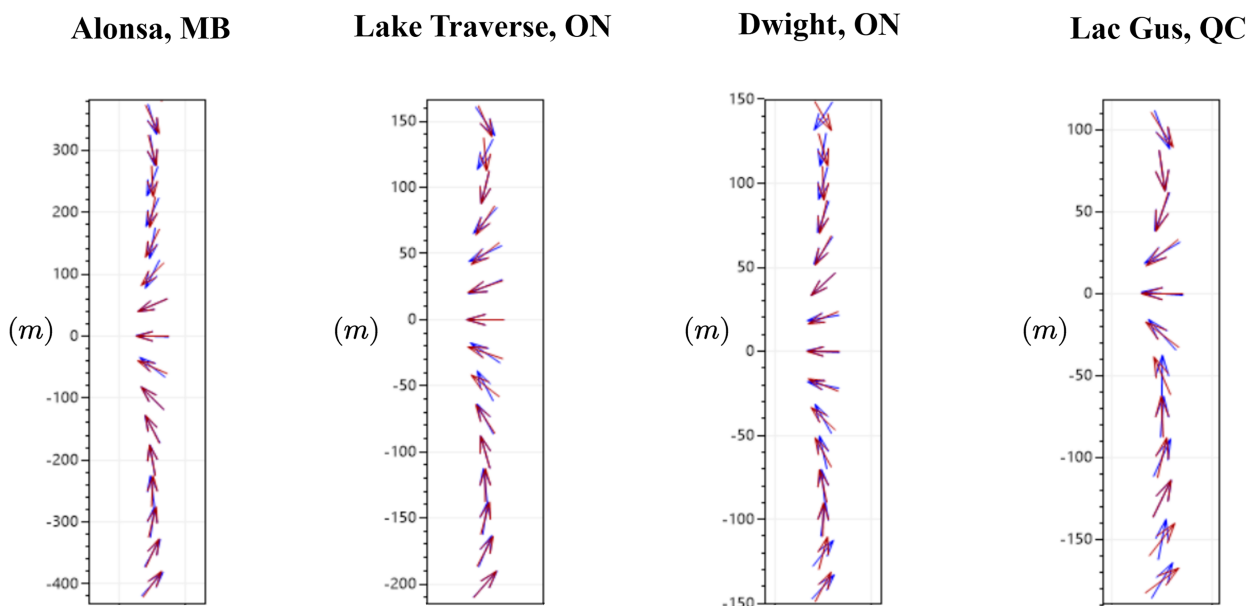


FIG. 16. (from left to right) Observed (blue) vs simulated (red) treefall patterns for the Alonsa, Manitoba; Lake Traverse, Ontario; Dwight, Ontario; and Lac Gus, Quebec events.

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Data availability statement. All the open-access data used in this study can be obtained from the Northern Tornadoes Project website (www.uwo.ca/ntp). An ArcGIS Pro add-on along with the code used in the study can be found in our GitHub repository (https://github.com/Canadian-Severe-Storms-Laboratory/Treefall_Pattern_Analysis).

REFERENCES

- Amini, M. O., and J. W. van de Lindt, 2014: Quantitative insight into rational tornado design wind speeds for residential wood-frame structures using fragility approach. *J. Struct. Eng.*, **140**, 04014033, [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000914](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000914).
- ASCE, 2022: *Minimum Design Loads and Associated Criteria for Buildings and other Structures*. American Society of Civil Engineers, 975 pp.
- Baker, C. J., and M. Sterling, 2017: Modelling wind fields and debris flight in tornadoes. *J. Wind Eng. Ind. Aerodyn.*, **168**, 312–321, <https://doi.org/10.1016/j.jweia.2017.06.017>.
- Beck, V., and N. Dotzek, 2010: Reconstruction of near-surface tornado wind fields from forest damage. *J. Appl. Meteor. Climatol.*, **49**, 1517–1537, <https://doi.org/10.1175/2010JAMC2254.1>.
- Bjerknes, V., 1921: *On the Dynamics of the Circular Vortex: With Applications to the Atmosphere and Atmospheric Vortex and Wave Motions*, Vol. 2. Ikommission hos Cammermeyers bokhandel, 89 pp.
- Brandt, J. P., 2009: The extent of the North American boreal zone. *Environ. Rev.*, **17**, 101–161, <https://doi.org/10.1139/A09-004>.
- Brent, R. P., 2013: *Algorithms for Minimization without Derivatives*. Courier Corporation, 195 pp.
- Brusco, S., and G. A. Kopp, 2024: Streamline curvature effects generated by tornado-like flows on the aerodynamics of a low-rise structure. *J. Wind Eng. Ind. Aerodyn.*, **253**, 105865, <https://doi.org/10.1016/j.jweia.2024.105865>.
- Burgers, J. M., 1948: A mathematical model illustrating the theory of turbulence. *Adv. Appl. Mech.*, **1**, 171–199, <https://doi.org/10.1016/j.jweia.2024.105865>.
- Butt, D. G., A. L. Jaffe, C. S. Miller, G. A. Kopp, and D. M. Sills, 2024: Automated large-scale tornado treefall detection and directional analysis using machine learning. *Artif. Intell. Earth Syst.*, **3**, e230062, <https://doi.org/10.1175/AIES-D-23-0062.1>.
- Chen, G., and F. T. Lombardo, 2019: An analytical pattern-based method for estimation of a near-surface tornadic wind field. *J. Wind Eng. Ind. Aerodyn.*, **194**, 103999, <https://doi.org/10.1016/j.jweia.2019.103999>.
- Dahl, N. A., D. S. Nolan, G. H. Bryan, and R. Rotunno, 2017: Using high-resolution simulations to quantify underestimates of tornado intensity from in situ observations. *Mon. Wea. Rev.*, **145**, 1963–1982, <https://doi.org/10.1175/MWR-D-16-0346.1>.
- Dunn, W. L., and L. A. Twisdale, 1979: A synthesized windfield model for tornado missile transport. *Nucl. Eng. Des.*, **52**, 135–144, [https://doi.org/10.1016/0029-5493\(79\)90015-3](https://doi.org/10.1016/0029-5493(79)90015-3).
- Edwards, R., J. G. LaDue, J. T. Ferree, K. Scharfenberg, C. Maier, and W. L. Coulbourne, 2013: Tornado intensity estimation: Past, present, and future. *Bull. Amer. Meteor. Soc.*, **94**, 641–653, <https://doi.org/10.1175/BAMS-D-11-00006.1>.
- Ellingwood, B. R., D. V. Rosowsky, Y. Li, and J. H. Kim, 2004: Fragility assessment of light-frame wood construction subjected to wind and earthquake hazards. *J. Struct. Eng.*, **130**, 1921–1930, [https://doi.org/10.1061/\(ASCE\)0733-9445\(2004\)130:12\(1921\)](https://doi.org/10.1061/(ASCE)0733-9445(2004)130:12(1921)).
- Gardiner, B. A., G. R. Stacey, R. E. Belcher, and C. J. Wood, 1997: Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry*, **70**, 233–252, <https://doi.org/10.1093/forestry/70.3.233>.
- , H. Peltola, and S. Kellomaki, 2000: Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecol. Modell.*, **129**, 1–23, [https://doi.org/10.1016/S0304-3800\(00\)00220-9](https://doi.org/10.1016/S0304-3800(00)00220-9).
- Gavanski, E., and G. A. Kopp, 2017: Fragility assessment of roof-to-wall connection failures for wood-frame houses in high winds. *ASCE-ASME J. Risk Uncertainty Eng. Syst.*, **3A**, 04017013, <https://doi.org/10.1061/AJRUA6.0000916>.
- Godfrey, C. M., and C. J. Peterson, 2017: Estimating enhanced Fujita scale levels based on forest damage severity. *Wea. Forecasting*, **32**, 243–252, <https://doi.org/10.1175/WAF-D-16-0104.1>.
- Government of Canada, 2020: The atlas of Canada—Physiographic regions. Accessed 30 September 2024, <https://atlas.gc.ca/phys/en/>.
- Haan, F. L., Jr., J. Wang, M. Sterling, and G. A. Kopp, 2024: Experimentally estimating wind load coefficients for tornadoes—An alternative perspective. *J. Wind Eng. Ind. Aerodyn.*, **251**, 105811, <https://doi.org/10.1016/j.jweia.2024.105811>.
- Haller, J. M., 1990: Aerodynamic features of the tree. *Arboric. Urban For.*, **16**, 244–252, <https://doi.org/10.48044/jauf.1990.056>.
- Harris, C. R., and Coauthors, 2020: Array programming with NumPy. *Nature*, **585**, 357–362, <https://doi.org/10.1038/s41586-020-2649-2>.
- Holland, A. P., A. J. Riordan, and E. C. Franklin, 2006: A simple model for simulating tornado damage in forests. *J. Appl. Meteor. Climatol.*, **45**, 1597–1611, <https://doi.org/10.1175/JAM2413.1>.
- Honer, T. G., 1967: Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. Canadian Department Forestry Rural Development, Forest Management Research and Service Institute Rep. FMR-X 5, 21 pp., <https://ostrnrcan-dostrnrcan.canada.ca/handle/1845/251147>.
- Hunt, E. R., Jr., M. B. Lavigne, and S. E. Franklin, 1999: Factors controlling the decline of net primary production with stand age for balsam fir in newfoundland assessed using an ecosystem simulation model. *Ecol. Modell.*, **122**, 151–164, [https://doi.org/10.1016/S0304-3800\(99\)00135-0](https://doi.org/10.1016/S0304-3800(99)00135-0).
- Karstens, C. D., W. A. Gallus Jr., B. D. Lee, and C. A. Finley, 2013: Analysis of tornado-induced tree fall using aerial photography from the Joplin, Missouri, and Tuscaloosa–Birmingham, Alabama, tornadoes of 2011. *J. Appl. Meteor. Climatol.*, **52**, 1049–1068, <https://doi.org/10.1175/JAMC-D-12-0206.1>.
- Kim, Y. C., and M. Matsui, 2017: Analytical and empirical models of tornado vortices: A comparative study. *J. Wind Eng. Ind.*

- Aerodyn.*, **171**, 230–247, <https://doi.org/10.1016/j.jweia.2017.10.009>.
- Krišāns, O., L. Čākša, R. Matisons, S. Rust, D. Elferts, A. Seipulis, and A. Jansons, 2022: A static pulling test is a suitable method for comparison of the loading resistance of silver birch (*Betula pendula* Roth.) between urban and peri-urban forests. *Forests*, **13**, 127, <https://doi.org/10.3390/f13010127>.
- Kuligowski, E. D., F. T. Lombardo, L. T. Phan, M. L. Levitan, and D. P. Jorgensen, 2014: Final report, National Institute of Standards and Technology (NIST): Technical investigation of the May 22, 2011, tornado in Joplin, Missouri. National Construction Safety Team Act Rep. NIST NCSTAR 3, National Institute of Standards and Technology, 21 pp., <https://doi.org/10.6028/NIST.NCSTAR.3>.
- Letzmann, J., 1923: *Das Bewegungsfeld im Fuss einer fortschreitenden Wind-oder Wasserhose*, Vol. 6. Mattiesen, 136 pp.
- Lombardo, F. T., D. B. Roueche, and D. O. Prevatt, 2015: Comparison of two methods of near-surface wind speed estimation in the 22 May, 2011 Joplin, Missouri tornado. *J. Wind Eng. Ind. Aerodyn.*, **138**, 87–97, <https://doi.org/10.1016/j.jweia.2014.12.007>.
- , Z. B. Wienhoff, D. M. Rhee, J. B. Nevill, and C. A. Poole, 2023: An approach for assessing misclassification of tornado characteristics using damage. *J. Appl. Meteor. Climatol.*, **62**, 781–799, <https://doi.org/10.1175/JAMC-D-22-0197.1>.
- Levy, P. E., S. E. Hale, and B. C. Nicoll, 2004: Biomass expansion factors and root: Shoot ratios for coniferous tree species in Great Britain. *Forestry*, **77**, 421–430, <https://doi.org/10.1093/forestry/77.5.421>.
- Mansour, M. A., T. Newson, and C. J. Peterson, 2024: Windthrow resistance of trees: Geotechnical engineering approach. *Trees*, **38**, 373–391, <https://doi.org/10.1007/s00468-024-02488-8>.
- MATLAB, 2024: MATLAB version: 24.1 (r2024b). The MathWorks Inc., <https://www.mathworks.com>.
- McDonald, J. R., and K. C. Mehta, 2006: A recommendation for an enhanced Fujita scale. Wind Science and Engineering Center, Texas Tech University, 95 pp., <https://courses.washington.edu/cee517/ef-ttu.pdf>.
- Miller, C. S., G. A. Kopp, D. M. L. Sills, and D. G. Butt, 2024: Estimating wind speeds in tornadoes using debris trajectories of large compact objects. *Mon. Wea. Rev.*, **152**, 1859–1881, <https://doi.org/10.1175/MWR-D-23-0251.1>.
- Nicoll, B. C., B. A. Gardiner, B. Rayner, and A. J. Peace, 2006: Anchorage of coniferous trees in relation to species, soil type, and rooting depth. *Can. J. For. Res.*, **36**, 1871–1883, <https://doi.org/10.1139/x06-072>.
- NTP, 2020: Open data for the Northern Tornadoes Project. Accessed 30 September 2024, <https://ntpopendata-westernu.opendata.arcgis.com/>.
- , 2024: Enhanced Fujita scale damage indicators and degrees of damage (Canadian implementation). Western University, 28 pp., https://www.uwo.ca/ntp/docs/EFscale_DI-DOD-Guide_Revision3b_15Apr2025.pdf.
- Peterson, R. E., 1992: Johannes Letzmann: A pioneer in the study of tornadoes. *Wea. Forecasting*, **7**, 166–184, [https://doi.org/10.1175/1520-0434\(1992\)007<0166:JLAPIT>2.0.CO;2](https://doi.org/10.1175/1520-0434(1992)007<0166:JLAPIT>2.0.CO;2).
- Pope, G., and P. Treitz, 2013: Leaf area index (LAI) estimation in boreal mixedwood forest of Ontario, Canada using light detection and ranging (LiDAR) and WorldView-2 imagery. *Remote Sens.*, **5**, 5040–5063, <https://doi.org/10.3390/rs5105040>.
- Quine, C. P., and B. A. Gardiner, 2007: Understanding how the interaction of wind and trees results in windthrow, stem breakage, and canopy gap formation. *Plant Disturbance Ecology: The Process and the Response*, Academic Press, 103–155.
- Raupach, M. R., 1994: Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. *Bound.-Layer Meteor.*, **71**, 211–216, <https://doi.org/10.1007/BF00709229>.
- Rhee, D. M., and F. T. Lombardo, 2018: Improved near-surface wind speed characterization using damage patterns. *J. Wind Eng. Ind. Aerodyn.*, **180**, 288–297, <https://doi.org/10.1016/j.jweia.2018.07.017>.
- Ross, R., 2010: Wood handbook: Wood as an engineering material. General Tech. Rep. FPL-GTR-190, USDA Forest Service, Forest Products Laboratory, 509 pp., https://www.fpl.fs.usda.gov/documnts/fplgtr/fpl_gtr190.pdf.
- Rott, N., 1958: On the viscous core of a line vortex. *Z. Angew. Math. Phys.*, **9**, 543–553, <https://doi.org/10.1007/BF02424773>.
- Roueche, D. B., F. T. Lombardo, and D. O. Prevatt, 2016: Development of empirically-based fragilities of residential damage in the 2011 Joplin, Missouri, tornado. *Geotechnical and Structural Engineering Congress 2016*, American Society of Civil Engineers, 1283–1294.
- Ruel, J.-C., S. Meunier, C. P. Quine, and J. Suarez, 2000: Estimating windthrow risk in balsam fir stands with the forestGales model. *For. Chron.*, **76**, 329–337, <https://doi.org/10.5558/tfc76329-2>.
- Sagi, P., T. Newson, C. Miller, and S. Mitchell, 2019: Stem and root system response of a Norway spruce tree (*Picea abies* L.) under static loading. *For.: Int. J. For. Res.*, **92**, 460–472, <https://doi.org/10.1093/forestry/cpz042>.
- Savory, E., G. A. R. Parke, M. Zeinoddini, N. Toy, and P. Disney, 2001: Modelling of tornado and microburst-induced wind loading and failure of a lattice transmission tower. *Eng. Struct.*, **23**, 365–375, [https://doi.org/10.1016/S0141-0296\(00\)00045-6](https://doi.org/10.1016/S0141-0296(00)00045-6).
- Shikhov, A., and A. Chernokulsky, 2018: A satellite-derived climatology of unreported tornadoes in forested regions of northeast Europe. *Remote Sens. Environ.*, **204**, 553–567, <https://doi.org/10.1016/j.rse.2017.10.002>.
- Sills, D. M. L., P. McCarthy, and G. Kopp, 2014: Implementation and application of the EF-scale in Canada. *27th Conf. on Severe Local Storms*, Madison, WI, Amer. Meteor. Soc., 16B.6, https://www.yorku.ca/pat/research/dsills/papers/SLS27/SLS2014_Sillsetal_EF-Scale_ExtendedAbstract_Final2.pdf.
- , and Coauthors, 2020: The Northern Tornadoes Project: Uncovering Canada's true tornado climatology. *Bull. Amer. Meteor. Soc.*, **101**, E2113–E2132, <https://doi.org/10.1175/BAMS-D-20-0012.1>.
- Stevenson, S. A., C. S. Miller, D. M. L. Sills, G. A. Kopp, D. M. Rhee, and F. T. Lombardo, 2023: Assessment of wind speeds along the damage path of the Alonsa, Manitoba EF4 tornado on 3 August 2018. *J. Wind Eng. Ind. Aerodyn.*, **238**, 105422, <https://doi.org/10.1016/j.jweia.2023.105422>.
- Sullivan, R. D., 1959: A two-cell vortex solution of the Navier-Stokes equations. *J. Aerosp. Sci.*, **26**, 767–768, <https://doi.org/10.2514/8.8303>.
- Twisdale, L. A., Jr., and Coauthors, 2023: Tornado wind speed maps for building design: Research and development of tornado risk assessment methodology. NIST Tech. Note NIST TN 2242, National Institute of Standards and Technology, 701 pp., <https://doi.org/10.6028/NIST.TN.2242>.
- Wind Science and Engineering Center, 2006: A recommendation for an enhanced Fujita scale. Texas Tech University, 95 pp., <https://courses.washington.edu/cee517/ef-ttu.pdf>.
- Yuksel, C., 2022: High-performance polynomial root finding for graphics. *Proc. ACM on Computer Graphics and Interactive Techniques*, Vol. 5, Association for Computing Machinery, 1–15, <https://dl.acm.org/doi/10.1145/3543865>.