RECONSTRUCTION OF NEAR-SURFACE TORNADO WIND FIELDS FROM FOREST DAMAGE

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(Dated: 15 September 2009)

I. INTRODUCTION

Tornado intensities are usually determined according to the damage produced. Here, a method for the reconstruction of tornado near-surface wind fields and their intensity from forest damage is described. Forest damage due to tornadoes has already been documented by Wegener (1917), Letzmann (1923, 1925), Budney (1965) and Fujita (1985) while Holland et al. (2006) (cf. Dotzek et al., 2008) and Bech et al. (2009) focused on the simulation of forest damage patterns by using a simple vortex model similar to ours. We present a model based on the analytical tornado wind field model of Letzmann (1923) and a mechanistic tree model of Peltola and Kellomäki (1993) to simulate real tornado forest damage patterns. From the comparison of the simulated and real forest damage patterns, conclusions on the tornado intensity and important parameters of the tornado near-surface wind field can be drawn. Full details are given by Beck (2008), Beck et al. (2008) or Beck and Dotzek (2009).

II. ANALYTICAL TORNADO MODEL

Letzmann (1923) developed a three-dimensional analytical tornado model with a linear velocity increase in the tornado core and hyperbolical velocity decay in the tornado mantle. The equations for the tangential and radial velocity component (v_θ and v_r) are similar to those of a Rankine vortex with R_{max} indicating the radius of the tornado core.

A constant translation speed v_{trans} of the tornado in y-direction is assumed. The radial v_r and tangential velocity components v_θ of the vortex depend on the three parameters v_{trans}, G_{max} and α. Here, G_{max} indicates the ratio between circular v_{cir} and translation velocity component v_{trans} of the tornado wind field, and α is the angle between the direction of the wind and the pressure gradient at the point of maximum velocity. Letzmann (1923) discussed a variation of the angle α within the velocity field and defined a tornado core to be "genuine" (outflow from the vortex centre and inflow from the outside, a two-cell vortex) or "false". According to Letzmann (1923), during a tornado life cycle the behaviour of a tornado core changes from a false core to a genuine core at its mature stage.

Letzmann (1923) derived theoretical tree damage patterns for different values of the parameters α and G_{max} depending on the critical intensity for stem breakage of the trees. He introduced an angle ψ indicating the deviation of the fall direction of the trees from the direction of tornado translation. Letzmann (1923) showed that a tree with $\psi = 0°$ indicates either a converging or a diverging line, while a tree with $\psi = 180°$ characterizes a converging line. A tree with $\psi = 180°$ is only found for values of G_{max} greater than 2.0, however. Based on this, Letzmann (1923) classified the theoretical tree damage patterns into four main swath types.

III. STRUCTURE OF THE MODEL

The model for the simulation of tree damage patterns consists of a wind field model for a tornado near-surface wind field and a tree model for the calculation of the critical velocity for tree stem breakage. The structure of the model is outlined in Fig. 1.

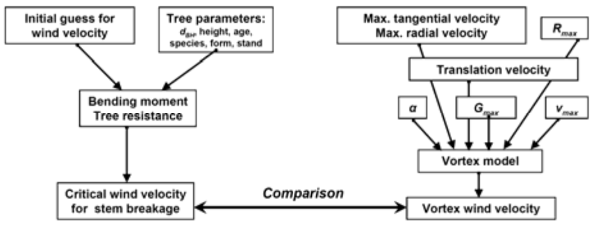

FIG. 1: Structure of the model consisting of the tree model for the calculation of the critical velocity for stem breakage and the wind field model giving the instantaneous wind vector at each grid point.

The analytical tornado model of Letzmann (1923) serves as wind field model. In the first part of the model, the critical velocity for stem breakage is derived from the mechanistic HWIND model of Peltola and Kellomäki (1993). Here, either a random or homogeneous distribution of trees can be used. The bending moment and the tree resistance are calculated from several tree parameters with an initial velocity guess, and the values are compared. If the bending moment exceeds the tree resistance, the iteration ends. Otherwise the velocity is incremented by 0.5 m s^{-1} steps.

The calculations are done for a 400 m 400 m domain with a grid size of 10 m. The wind field model produces an instantaneous velocity at each grid point which is compared to the critical velocity for stem breakage. If the instantaneous velocity exceeds the critical velocity for stem breakage the tree is considered to be broken and the falling direction is assumed to be the instantaneous direction of the wind field at the corresponding point.

IV. FOREST DAMAGE ANALYSIS

The F3-tornado of Milosovice, Czech Republic, occurred on 31 May 2001 with a path width of 400-500 m and a path length of 4.5 km (www.chmi.cz/torn/cases/20010531/-20010531.html). Besides the main vortex (1), three smaller vortices were observed. From radar observations, the translation speed of the thunderstorm cell producing the tornado is estimated as 16.5 ± 1.0 m s^{-1}.

The damage patterns of the individual vortices were analyzed by different parameters. First, an estimation of the angle α is made by analyzing if the damage pattern is convergent or divergent. Then, the value of G_{max} has to be derived from the damage patterns as well as the sense of rotation of the vortex. Also the radius R_{max} and the type of the tornado core follow from comparison of simulated damage patterns with the real damage patterns by varying the single parameters. From these parameters, the near-surface wind fields of the vortices can be reconstructed.

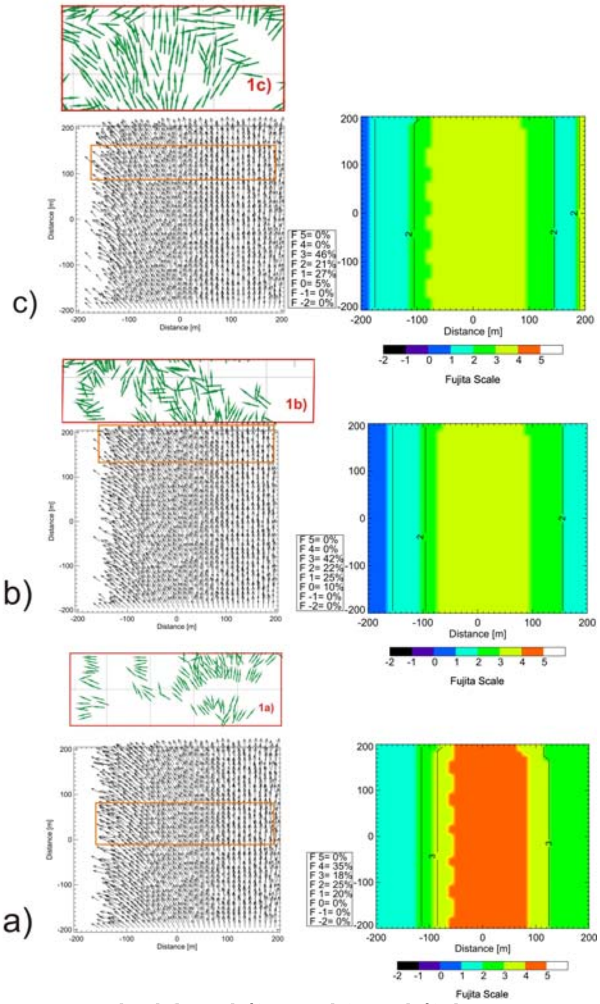

FIG. 2: Simulated (lower left) vs. real (upper left) damage patterns of the main Milosovice tornado. On the right, the distribution of the Fujita-scale for the simulated damage pattern is shown.

The Fujita-scale distribution in Fig. 2a even indicates an F4 zone amid the damage path and verified a widespread F3 zone for this tornado. Other derived parameters are shown in Table I. Note that the uncertainty in v_{max} equals (G_{max} + 1) times the variability in v_{trans} (Beck, 2008; Beck and Dotzek, 2009), hence our approach can be very accurate.

	G_{max}	α	v_{trans}	v_{cir}	v_{max}
1a)	5.0	-140°	16.5 ± 1.	82.5 ± 5.	99.0 ± 6.
1b)	4.0	-140°	16.5 ± 1.	55.5 ± 4.	82.5 ± 5.
1c)	4.0	-150°	16.5 ± 1.	55.5 ± 4.	82.5 ± 5.

TABLE I: Parameters and velocity components (m s^{-1}) from the damage analysis of the main tornado vortex (1) in sub-regions 1a), 1b), and 1c), see Fig. 2. In addition, R_{max} = 80 m was derived.

V. CONCLUSIONS

The method presented here allows reconstruction of near-surface tornado wind fields from the analysis of actual forest damage patterns:

- Letzmann's analytical tornado model depending on G_{max}, α and v_{trans} is perfectly suited to determine these parameters from forest damage patterns;
- If the tornado translation speed is known, the damage pattern completely determines the wind field. Intensity can be inferred without requiring tree stand parameters;
- By consecutive simulations with varying parameters G_{max}, α and R_{max} to fit the observed damage patterns, the near-surface tornado wind fields and the location of the centreline of the tornado track can be determined;
- The convergence and divergence lines mentioned by Letzmann (1923) could be verified in the tree damage patterns, leading to a better damage classification;
- F-scale distribution along the path and the areal percentage of peak intensity may feed into risk models;
- The maximum velocity of the Milosovice tornado was determinable with an uncertainty of only 6.0 m s^{-1}, about a half-level of the F-scale. In general, the relation $\Delta v_{max} = (G_{max} + 1)\, \Delta v_{trans}$ holds.

Thus, the high accuracy of this model approach is encouraging, given that the main objective of the method was to reconstruct the tornado near-surface wind field *structure*.

VI. ACKNOWLEDGMENTS

This work was partly funded by the German Ministry for Education and Research (BMBF) under contract 01LS05125 in the project RegioExAKT (Regional Risk of Convective Extreme Weather Events: User-oriented Concepts for Climatic Trend Assessment and Adaptation, www.regioexakt.de).

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