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Validation criteria for the Baker and Sterling tornado debris flight model in a large-scale tornado simulator.

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SUMMARY

Validation criteria are examined for the Baker and Sterling tornado debris flight model in a large-scale tornado simulator. The goal is to develop a set of model validation test cases that can be safely run within the proposed NEWRITE facility at Iowa State University. A large-scale parametric search was conducted to establish a set of test cases. The search spanned the range of NEWRITE tornado wind, a broad range of debris types, different release locations. A set of test cases were established that satisfied the following criteria: (1) the trajectory stayed well within the confines of the facility, (2) the debris did not become permanently lofted into the tornado, and (3) the was lofted at some period during its flight. For each test case, large-scale stochastic simulations were run to capture the distribution of the landing location given uncertainty in the tornado properties, debris properties, and release location.

Keywords: *Tornado, debris, Tornado Simulator, model validation.*

1. INTRODUCTION

Windborne debris in tornadoes can cause significant damage to surrounding structures and can be a physical hazard for people unable to access shelter. It is, therefore, important to understand the physics of tornado-borne debris. There are several approaches to modeling debris flight in tornadoes including in small scale physical simulators, from analysis of post event debris distributions, and computationally. Computational studies fall into two basic categories depending on the method of calculating the wind field. Computational Fluid Dynamics simulations, such as Large Eddy Simulations, can provide detailed time varying wind field data that includes realistic turbulent fluctuations. The second approach is to use steady-state vortex models that capture the mean wind and pressure distribution in an idealized tornado vortex. While the second approach includes many, potentially unrealistic, simplifications, their computational cost is orders of magnitude lower than LES models.

Regardless of the approach used to simulate tornado-borne debris, there is still the open question of how to validate a given model. While there is extensive validation work done on debris flight in straight-line winds (e.g. Tohidi & Kaye 2017), the same is not true for tornado-borne debris. Unlike debris flight in straight line winds, tornado-borne debris flight will exhibit large horizontal curvature and could be influenced by large pressure gradients. Herein we examine how one would approach developing an experimental validation study using a large tornado simulator.

2. METHODOLOGY

In this study we adopt the tornado vortex model of Baker & Sterling (2017) to model the wind field in the proposed NEWRITE tornado simulator at Iowa State University. The goal is to establish a set of test cases and quantify the expected variability in landing location in terms of the uncertainty in test conditions.

The first step was to search for potential test cases. A parametric search was conducted across a broad range of potential parameters. Debris was assumed spherical with density ranging over $50 < \rho_p < 2500\ kg/m^3$ and radius ranging over $0.5 < r_p < 15\ cm$. The tornado parameters were the maximum radial wind speed ($30 < u_m < 74\ m/s$), maximum tangential wind speed ($40 < v_m < 90\ m/s$), core radius ($1 < r_m < 8\ m$), and height of maximum radial wind speed ($0.2 < z_m < 1\ m$). The particles were released at a horizontal distance from the core of $0.2\ r_m < x_0 < 2r_m$ and at a height of $0.1 < z_0 < 3\ m$. The search consisted of just over 1 million flight simulations systematically varying all the parameters.

The results of the search data were then used to identify potential test cases. The criteria for a valid test case were that (1) the debris stayed well within the facility structure, (2) the particle did not remain permanently lofted in the wind field, and (3) the debris was initially lifted upward by the tornado and did not simply fall out of the wind field. The remaining 69,000 possible test cases were reduced to a set of 15 test cases. These represents three cases from each of 5 particle densities. For each density, the three cases were established based on the longest flight time, the largest radial extent and highest trajectory peak.

Herein we examine the behavior of one of these cases, that of a wooden sphere with $r_p = 0.5$ cm and $\rho_p = 400\ kg/m^3$, $u_m = 30\ m/s$, and $v_m = 69\ m/s$. For this base condition a set of 12 cases were run in which different parameters. The first 8 cases ran simulations in which only one parameter is varied. Cases 9-11 varied all the debris, release, and tornado parameters respectively. Finally, case 12 was run varying all parameters. As the underlying uncertainty in these parameters was not known, each case was run 5 times with different ranges of uncertainty. Uncertainty varied from 2% to 10% for tornado parameters, radial release location (x_0), and debris density. Uncertainty ranged from 1% to 5% for the debris radius and vertical release location. Table 1 summarizes the parameters varied in each case.

Table 1: List of parameters and uncertainty range included in each test case

Type	Parameter	1	2	3	4	5	6	7	8	9	10	11	12
Debris	ρ_p (±10%)	✓								✓			✓
	r_p (±5%)		✓							✓			✓
Release Location	z_o (±5%)			✓							✓		✓
	x_0 (±10%)				✓						✓		✓
Tornado	z_m (±10%)					✓						✓	✓
	r_m (±10%)						✓					✓	✓
	u_m (±10%)							✓				✓	✓
	v_m(±10%)								✓			✓	✓

3. RESULTS

Results are presented for each test case (Table 1). The parameter uncertainty is quantified using a normalized uncertainty. This is defined as the uncertainty percentage divided by the maximum uncertainty modeled. This was done so to adjust for the fact that peak release location uncertainty was less than that for other parameters. Therefore, a normalized uncertainty of 1 corresponds to a

±5% for those listed in Table 1 as having ±5% uncertainty and ±10% uncertainty in all other parameters. All parameter uncertainty was assumed uniform. Figure 1(a) shows a sample of 20 trajectories for case 12 and a normalized uncertainty of 1. There is large variation in path and landing location. This is confirmed in the PDF of landing location for the same case but for 2,000 runs. See Figure 1(b).

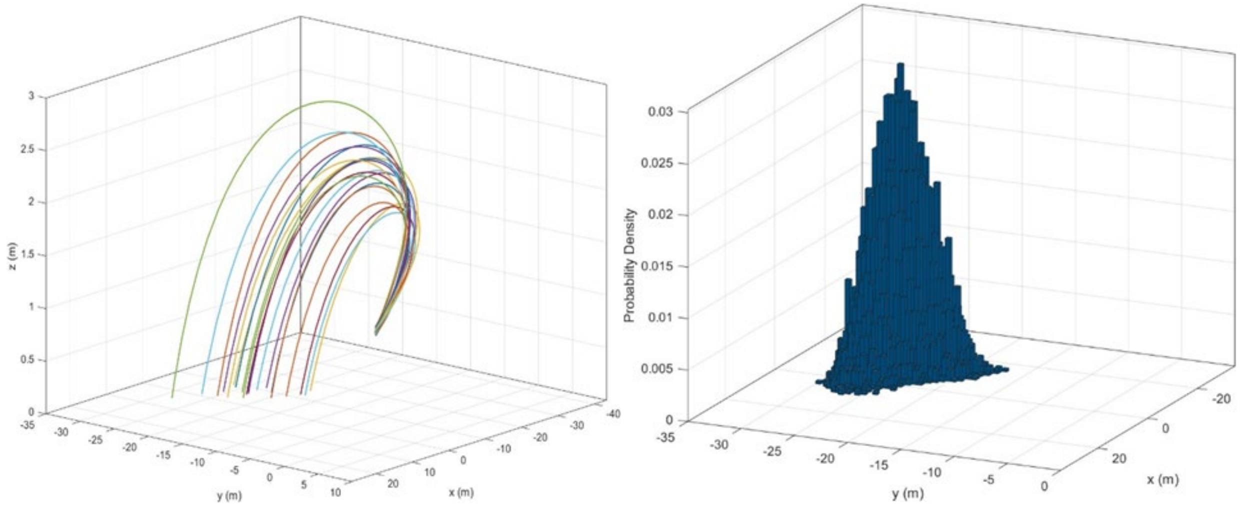

Figure 1. (a) A set of 20 sample trajectories for case 12 with a normalized uncertainty of 1. (b) PDF of landing location for case 12 with all uncertainty at ±6%.

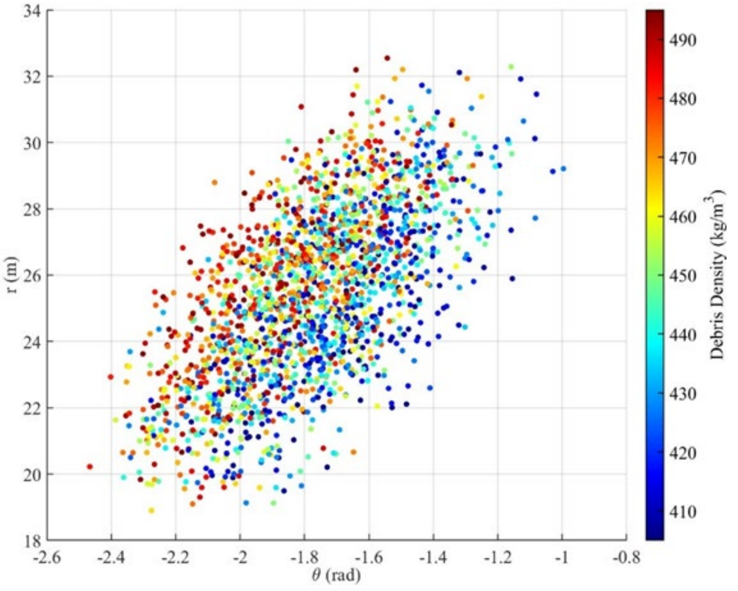

Figure 2. Landing locations in $r - \theta$ space for 2,000 runs of case 12 with normalized uncertainty of 1.

A scatter plot of landing location in polar coordinates is shown in Figure 2. The landing locations are color coded by particle density. Again, these data indicate considerable variability across both landing radius and landing angle. Quantification of the uncertainty is shown in Figure 3. This shows the coefficient of variation in landing radius (left) and angle (right) for each case as a function of normalized uncertainty. These plots indicate that uncertainty in the particle parameters

(Case 9) has only a small impact on the landing location variability compared to uncertainty in the tornado parameters (Case 11) and, to a lesser extent, the release location (Case 10). The largest individual parameter contribution to landing location uncertainty is tornado core radius (Case 6).

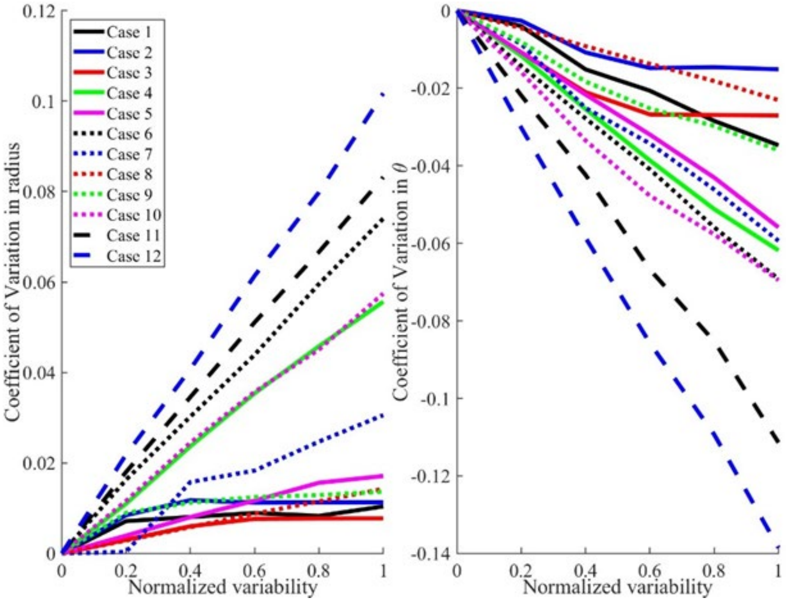

Figure 3. Coefficient of Variation for each case as a function of normalized variability.

4. CONCLUSIONS AND FUTURE DIRECTIONS

Herein we present results of a study of tornado-borne debris flight. The goal of this study is to establish potential model validation test cases for debris flight in the proposed NEWRITE large scale tornado simulator. 15 potential test cases have been identified based on safety and validity criteria. Results of a large set of simulations to model the impact of parameter uncertainty on landing location shows that the landing location is most sensitive to tornado parameters as opposed to debris or release location parameters. This suggests that, in order to undertake a validation study, the wind field must be well understood and including the mean tornado parameters and the variability of those parameters between test runs. Future work will include examining the variability statistics for the remaining 14 test cases, the development of detailed test protocols, and establishing statistical descriptions of flight properties that could be used for model validation.

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