Study on dense flying debris of tornado at different stages considering turbulence effects

Shuanglong Fan [1], Zhenqing Liu [2], Yiwen Cao [3], Xin An [4]

[1] *Huazhong University of Science and Technology, Wuhan, China, shuanglongfan@hust.edu.cn*
[2] *Huazhong University of Science and Technology, Wuhan, China, liuzhenqing@hust.edu.cn*
[3] *College of Civil Engineering, Hunan University, Changsha, China, caoyiwen@hnu.edu.cn*
[4] *Huazhong University of Science and Technology, Wuhan, China, anxin@hust.edu.cn*

SUMMARY:

Flying debris is an important factor influencing the destruction of buildings by tornadoes. However, research on tornado-borne debris remains limited. Thus far, the degree of this influence and methods to consider turbulence effects when predicting debris motion using the statistical information of wind velocities in tornadoes, have not been clarified. Therefore, in the present study, four methods for calculating debris motion based on the mean wind velocities and the root mean square of wind velocity fluctuations were examined. These four methods entailed (a) using only the mean wind velocities, (b) using Karimpour corrections, (c) assuming that the instantaneous flow fields of the tornado fluctuate as sinusoidal functions, and (d) assuming that the probability density functions of the instantaneous wind velocities follow Gaussian distributions. It was found that the debris concentration were sensitive to the turbulence in tornadoes. The Gaussian-distribution assumption afforded the best performances and could provide almost perfect predictions, except for the tornado-core regions.

Keywords: Tornado, compact debris, turbulence effects, wind velocities

1. INTRODUCTION

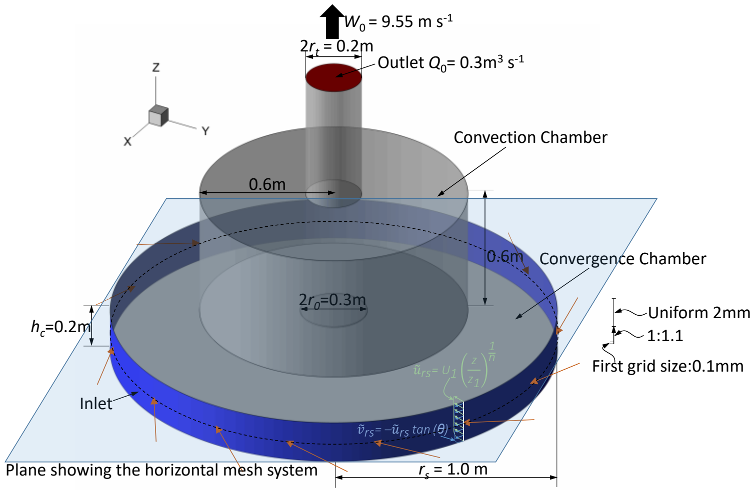
In the past decade, Crawford (2012) utilized the Iowa State University's tornado simulator to investigate the aerodynamics of windborne debris in tornadoes; specifically, the free-flight trajectories of spherical and cylindrical windborne debris were recorded using two cameras. Recently, using the University of Birmingham's tornado-like vortex generator, Bourriez et al. (2020) studied the trajectories of windborne debris in tornado-like wind flow fields initiated near a low-rise building. Numerical simulations were also conducted and compared with the experiments, which showed large similarities, indicating the high accuracy of the numerical model. Subsequently, Huo et al. (2020) used LES to model the debris in tornadoes with Tachikawa numbers between 0.6 and 2.5, and found that debris with a Tachikawa number of 2.5 were most likely to become wind-borne and travel for the longest time.

However, it was difficult to measure debris distributions in the aforementioned studies on the tornado-borne debris. Although numerical simulations can reproduce debris distributions, they require an extremely long computational time. Consequently, the objectives of this study are to develop a method that considers the turbulence effects during tornado-borne debris predictions and quantitatively clarifies the turbulence effects on tornado-borne debris.

2. LARGE EDDY SIMULATIONS FOR TORNADOES AND DEBRIS

2.1. Reproduction of full-scaled tornado by large eddy simulations

An identical numerical tornado simulator used in our previous study (Liu and Ishihara, 2015a; Liu et al., 2020b, 2021) was adopted in this study. Specifically, the Ward-type tornado simulator comprises a convergence chamber, a convection chamber, and an exhaust region, as shown in Fig. 1. All the numerical settings for reproducing the flow fields in the four tornadoes remain the same as those in the studies by Liu and Ishihara (2015a) and Liu et al. (2021).



λ_L – 1:1900, λ_V – 1:3.05

Figure 1. Configurations of the tornado simulator.

2.2. Simulation of debris in full-scaled tornado by large eddy simulations

The objects were released at a height of 10 m from the ground, as shown in Fig. 2. A square area with a width of 400 m was specified, wherein the objects were released. The objects were uniformly distributed in the area with a neighboring space of 20 m, indicating that a total of 441 particles were released at each time step (Δt_R = 0.1 s). The particle density was set to 500 kg·m^{-3} similar to that of wood, and two diameters (that is, d = 2 and 5 cm) were considered. Finally, a total of eight cases were simulated using LES with the detailed case settings listed in Table 1, similar to those in Liu et al. (2021).

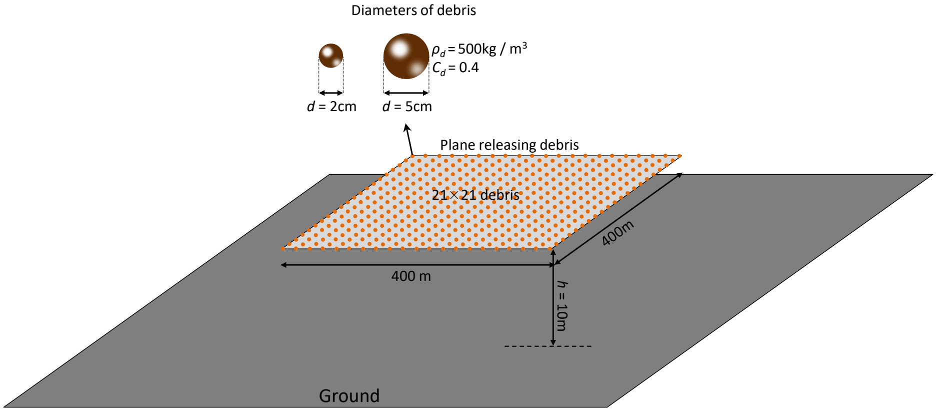


Figure 2. Schematic diagram of the debris.

Table 1. Representative parameters in the tornado.

Case number	Swirl ratio S	θ (°)	Elevation debris-released h (m)	Debris diameter d (cm)	Mass m_d (kg)	Tachikawa numbers T_a	Number of debris released at each time step	Time steps releasing debris	Drag force coefficient C_d
1	0.4	46.8	10	2	0.0021	32.1	21×21 = 441	5,000	0.4
2	0.4	46.8	10	5	0.0327	12.8			
3	0.6	58.0	10	2	0.0021	32.1			
4	0.6	58.0	10	5	0.0327	12.8			
5	1.0	69.4	10	2	0.0021	32.1			
6	1.0	69.4	10	5	0.0327	12.8			
7	3.8	84.4	10	2	0.0021	32.1			
8	3.8	84.4	10	5	0.0327	12.8			

3. PREDICTION METHODS FOR WIND VELOCITIES IN TORNADO

To utilize the available statistical information of the wind in tornadoes to quickly evaluate tornado-borne debris, a method involving the mean wind velocities and r.m.s. of the wind velocity fluctuations for determining the motions of the flying debris should be proposed. The wind velocities in tornadoes $v_{w,i}$ adopted to predict the debris motions. In Subsection 2, $v_{w,i}$ was directly determined by LES and was the baseline of the present study. However, in this study, $v_{w,i}$ is determined using the following four methods: (1) using only the mean wind velocities, (2) using Karimpour corrections (Karimpour and Kaye, 2012), (3) assuming that the tornado instantaneous flow fields fluctuate as sinusoidal functions, (4) assuming that the probability density function (p.d.f.) of the instantaneous wind velocities is consistent with the Gaussian distributions. The third and fourth methods are proposed in the present study.

4. PREDICTED RESULTS

The debris mean concentration φ value using Sinusoidal fluctuations (predicted by v_{wS}) and Gaussian distributions (predicted by v_{wG}) is shown in Fig. 3, where the motions of the flying debris were calculated based on instantaneous wind velocities v_{wR} in tornadoes modeled by LES. It can be found that as Δt_s increases, the debris is distributed more smoothly. When $\Delta t_s = 1.0$ s, the distribution of φ was almost identical to that predicted by v_{wM}. the concentration of debris observed in the break-down tornado center vanished. However, the regions covered by sparse debris were considerably less than those directly modeled by LES, indicating that the improvements resulting from using v_{wS} to predict the turbulence effects on the debris distribution are limited.

In addition, using v_{wG} to calculate the debris yielded almost the same debris distributions at a certain Δt_G, except for the tornado center. The instantaneous horizontal wind speed at the center of the mean flow fields in the tornadoes is not zero but a large and almost constant value. As a result, the debris penetrating the locations $r = 0$ m can hardly be thrown radially and concentrates at the tornado center when using a Gaussian distribution. In reality, the debris is always extremely sparse and its velocity is almost zero at the tornado center; hence, the debris here has very low destructive power. Therefore, the overestimation of φ by v_{wG} in the tornado center can be safely neglected.

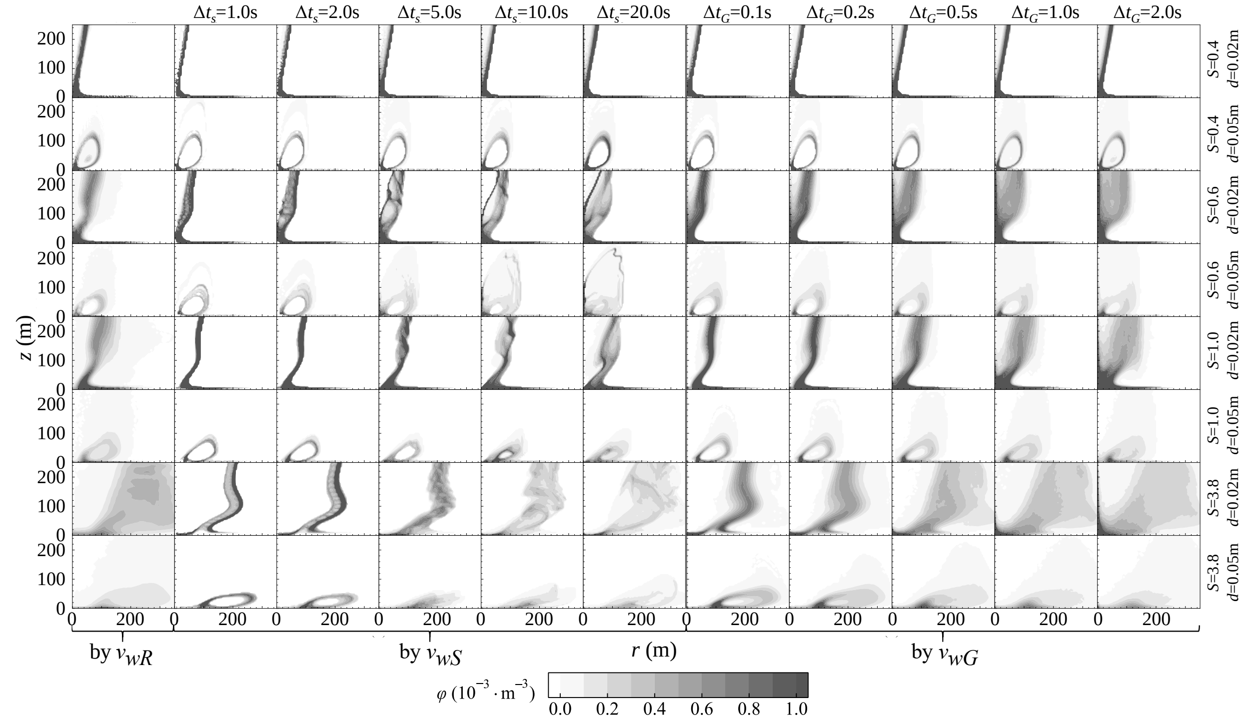


Figure 3. Contours of φ predicted by v_{wR}, v_{wS} and v_{wG}.

5. CONCLUSIONS

After adding sinusoidal fluctuations to the mean wind velocities, the flying debris covers a larger area, and the debris concentrations become smoother, indicating that the spectra of the wind velocities are also an important factor should be considered when predicting the flying debris in tornadoes. Trends and values of debris concentration can be perfectly predicted when the wind velocities in the tornado are assumed to be in line with Gaussian distributions. Debris concentration predicted by Gaussian distributions assumption shows large discrepancies in the tornado core region.

REFERENCES

Crawford, K., 2012. Experimental and analytical trajectories of simplified debris models in tornado winds. Iowa State University, Graduate Theses and Dissertations.

Bourriez, F., Sterling, M., Baker, C., 2020. Windborne debris trajectories in tornado-like flow field initiated from a low-rise building, Journal of Wind Engineering and Industrial Aerodynamics, 206, 104358

Huo, S., Hemida, H., Sterling, M., 2020. Numerical study of debris flight in a tornado-like vortex. Journal of Fluids and Structures, 99, 103134.

Liu, Z., Ishihara, T., 2015a. Numerical study of turbulent flow fields and the similarity of tornado vortices using large-eddy simulations. Journal of Wind Engineering and Industrial Aerodynamics, 145, 42–60.

Liu, Z., Cao, Y., Wang, Y., Cao, J., Hua, X., Cao, S., 2020b. Characteristics of compact debris induced by a tornado studied using large eddy simulations. Journal of Wind Engineering and Industrial Aerodynamics, in press, 104422.

Liu, Z., Cao, Y., Yan, B., Hua, X., Zhu, Z., Cao, S., 2021. Numerical study of compact debris in tornadoes at different stages using large eddy simulations, Journal of Wind Engineering and Industrial Aerodynamics, 210, 104530.

Karimpour, A., Kaye, N., 2012. On the stochastic nature of compact debris flight. Journal of wind engineering and industrial aerodynamics, 100(1), 77–90.