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Numerical Simulation of the Evolution Law of Tornado Wind Field Based on Radar Measured Data

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ABSTRACT

This paper studies the formation mechanism and evolution law of tornado wind field by means of CFD numerical simulation method. Flow field of the tornado vortex is generated by a full-scale numerical simulator, which modeled by the radar measured data of the Spencer tornado (1998) as the inlet boundary condition and the effect of roughness is considered. The distribution of the tangential velocity along radial direction and the wind pressure profile at different heights are studied in detail; and the present results are compared and validated with the radar measured data of Spencer tornado. The research results of this paper lay a solid foundation for the study on the tornado-induced wind load characteristics and the damage mechanisms of buildings.

1. INTRODUCTION

Tornado is a small scale weather system but with great destructive power. It has the characteristics of small scale, short duration, fast moving and so on. At present, many researchers study the formation mechanism and characteristics of tornado wind field by performing the field measurement, laboratory simulation and numerical simulation.

With the development of computational fluid dynamics, numerical simulation has been conducted extensively to study the tornado-vortex structure. (Lewellen and Lewellen 1997, 2007) used LES turbulence model to study the formation conditions of tornado-like vortex and the mechanism of high-speed rotation and translation speed. (Wicker and Wilhelmso 1995) simulated and analyzed the development and decay of tornado by using the three-dimensional supercell thunderstorm. (Kuai et al. 2008) changed the grid and geometry sizes of model to study parameter sensitivity for the flow field of a laboratory-simulated tornado. There are also some researches in changing the swirl ratios to obtain different typical tornado-like vortices by using LES turbulence model and compare the simulated tornadoes with field measurements in nature (Ishihara et al., 2011; Liu and Ishihara, 2015).

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Most of numerical simulations were performed on smooth ground, in order to study the effect of ground roughness on tornado, in numerical simulation, (Lewellen and Lewellen 2000) uesed LES turbulence model to study the influence of local swirl ratio and interaction of the surface roughness. (Natarajan and Hangan 2009) attempted to address the effect of surface roughness on tornado-like flows for a large range of swirl ratios (0.1~2.0), and found that the radial, axial and tangential velocities are increased inside the core region because of considering the roughness. Again, (Natarajan and Hangan 2012) simulated the translation by employing a moving-wall boundary condition and surface roughness by physical modeling of roughness element blocks. (Liu and Ishihara 2016) added an appropriate momentum source in the Navier-Stokes equation to simulate the ground roughness, and explored that the ground roughness can expand the size of the core, but reducing the core size when swirl ratio was small. However, some researchers have different conclusions. (Zhang and Sarkar 2008) studied the effects of ground roughness on tornado by using the PIV technique and observed differences in velocity and turbulence characteristics. (Diamond and Wilkins 1984) simulated the effects of translation and roughness on tornado in a modified Ward simulator, they found that the core radius is increased with the increase of swirl ratio and decreased with the increase of surface roughness.

This paper studies the generation methods of tornado-like vortex based on the measured data of Spencer tornado by using the CFD numerical simulation, and the effect of vegetation roughness on tornado wind field is performed by adding source terms to the momentum equation. The distribution of the tangential velocity in radial directions and the wind pressure profile at different heights are obtained and compared with the radar measured data.

2. NUMERICAL MODEL

2.1 Numerical Simulator of Tornado

Based on the study of the steady-state structure of the tornado wind field, only considering the influence of decisive factors on wind field structure after the wind field is stable, to make the following simplifying assumptions for the numerical simulation:

(1) Because of the $Ma < 0.3$, the wind field is considered as a incompressible flow;

(2) Simulating the full development state of the tornado, the wind field is considered as a steady wind field;

(3) The change of temperature and humidity in the atmosphere is not considered, and the wind field is considered as a constant temperature adiabatic flow field.

(4) The effect of gravity and buoyancy of air molecules is ignored.

In this study, the full-scale numerical simulator of tornado is designed to correspond with a laboratory simulator (Dessens 1972), which consists of a convection region and a convergence region as shown in Fig. 1. The lower side of cylinder is set as the inlet of wind speed, which height is H1, and the radius of the updraft hole is R2, which are respectively 320 m and 200 m. The height of the convection region is 800 m. The physical parameters of numerical tornado simulator in this study are listed in Table 1. The inlet surface is set as a velocity-inlet boundary condition, where the radial velocity and tangential velocity on the inlet are specified using the radar measured data of the Spencer tornado (1998), and the axial velocity is assumed to zero.

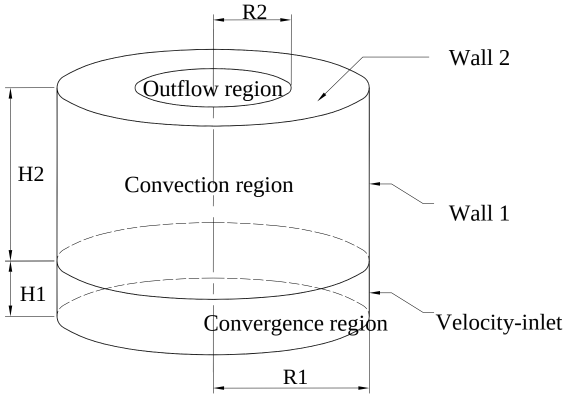


Fig. 1 Schematic diagram of the numerical tornado simulator

Table 1 Physical parameters of numerical tornado simulator (m)

Height of the inlet layer(H1)	320
Radius of the convergence region (R1)	900
Radius of the convection region (R1)	900
Height of the convection region (H2)	800
Radius of exhaust outlet (R2)	200

2.2 Inlet Boundary Condition

For the inlet, the profiles of the radial velocity and the tangential velocity are specified as the radar measured data of the Spencer tornado (Alexander and Wurman 2005) as follows:

Tangential velocity:

$$V_t(z) = 17.910\left(\frac{z}{20}\right)^{0.17} \tag{1}$$

Radial velocity, below 20m:

$$V_r(z) = -27.302\left(\frac{z}{20}\right)^{0.1732} \tag{2}$$

Radial velocity, 20m to 320m:

$$V_r(z) = 6.326\left(\frac{z}{20}\right)^{0.5341} - \quad 3 \tag{3}$$

2.3 Vegetation Roughness Model

In order to considering the influence of the ground roughness on the tornado flow field, the vegetation roughness model is adopted in this study, which is according to the model expressions recommended by (Mochida et al. 2008):

$$S_u = -\eta C_f \alpha U \sqrt{U^2} \tag{4}$$

$$S_k = US_u \tag{5}$$

$$S_\varepsilon = \frac{\varepsilon}{k} C_{p\varepsilon 1} S_k \tag{6}$$

This model as the source terms is added to the equations of the momentum, the turbulent kinetic energy and the dissipation rate. The additional source terms contain four parameters, where $C_{p\varepsilon 1}$ is the model coefficient, η is the fraction of the area covered with trees, α is the leaf area density, C_f is the drag coefficient. As model coefficients in turbulence modeling for prescribing the time scale of the process of energy dissipation in the canopy layer, $C_{p\varepsilon 1}$ is given to its appropriate value in this study. However, η, α and C_f are the parameters required to be determined according to the real conditions of trees. (Mochida et al. 2008) calculate the results by using the canopy model when $C_{p\varepsilon 1}$ is 1, 1.5, 1.8, 2, and then compare the predicted results with the measurement data. It is found that the results with $C_{p\varepsilon 1} = 1.8$ are in good agreement with the measured data.

A theoretical method is used to derive the model of additional source term S_ω. Based on the relationship between ε and ω: $\varepsilon = C_\mu \omega k$ (C_μ is turbulence parameter), which is taken into the ε equation of the standard $k-\varepsilon$ turbulence model, through the expansion and linear transformation and subtracting k equation, and then compared with the ω equation of the $k-\omega$ turbulence model. The relation formula of the additional source terms of the ω equation is obtained as follows:

$$S_\omega = \left(\frac{S_\varepsilon}{C_\mu \omega} - S_k\right)\frac{\omega}{k} \tag{7}$$

Substituting S_ε and S_k into the model, the expression of S_ω is obtained:

$$S_\omega = \eta C_f \alpha (C_{p\varepsilon 1} - 1)\frac{\omega}{k} U^3 \tag{8}$$

2.4 Boundary Conditions and Solution Settings

The boundary conditions are set as follows: the side of the convergence region is a *velocity-inlet* with measured tangential and radial velocity of Spencer tornado; the bottom of convergence region and the side of convection region are set as a no-slip *wall*, and the *outflow* boundary is adopted in the outflow region.

The commercial CFD code “Fluent” was employed to perform 3-D simulations of evolution law of tornado field. The Pressure-Based steady solver is used for the present simulations. The SIMPLE algorithm is used to calculate the coupling between the pressure and velocity fields (Ferziger and Peric, 2002). The turbulence flow in the tornado is calculated by SST k-ω turbulence model. The first-order upwind scheme is employed for the momentum discretization because of it is able to better match the accuracy of the radar, and the pressure space discrete format is adopted PRESTO! format.

3. RESULTS and Discussion

The vegetation, hills and other obstacles on the ground will affect the movement route and speed of wind. According to the characteristics of landscape, supposing that the leaf density of vegetation α is 0.05, the degree of density is 7% of real rough ground in Spencer town.

3.1 Tangential Velocity Distribution

The contour of tangential velocity at the vertical section (y=0) in tornado field is shown in Fig. 2. It can be clearly found that the profile of the tangential velocity in the region near left and right inlet is increased gradually with increasing the height. The tangential velocity reached its minimum value, which is close to 0, in the core region of the tornado. With the increase of radius, the tangential velocity is increased firstly and then decreased. The maximum tangential velocities at different heights are between 100 meter and 200 meter, thus, the core radius can be determined. Below the height of 400 meters above the ground, the maximum tangential velocity at different heights is decreased gradually with the increase of the height, and the core radius increase with the increase of height, and the core radius is increased with the increase of height.

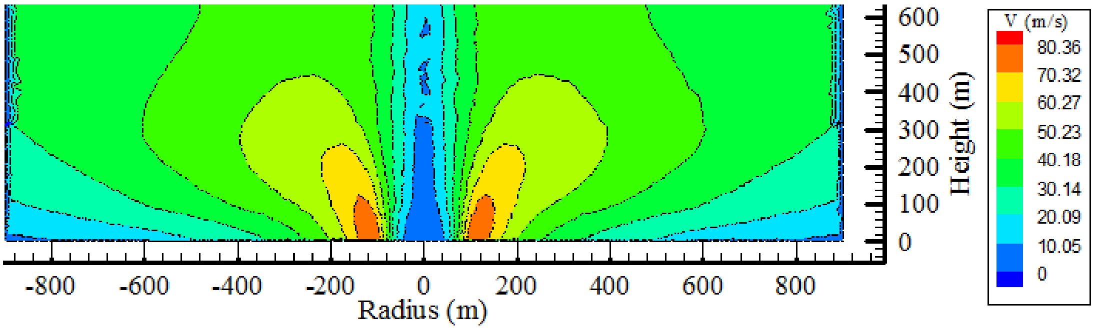
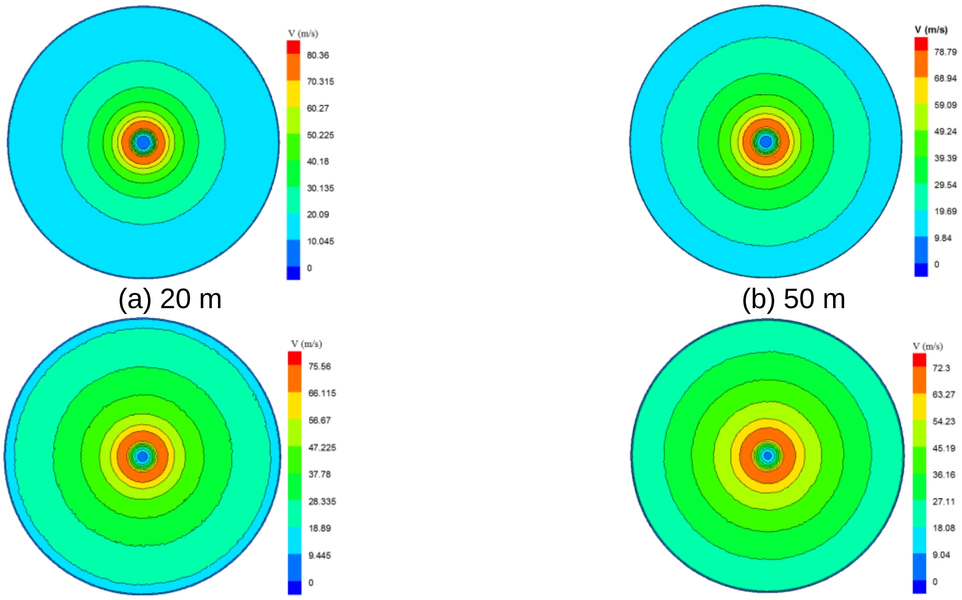
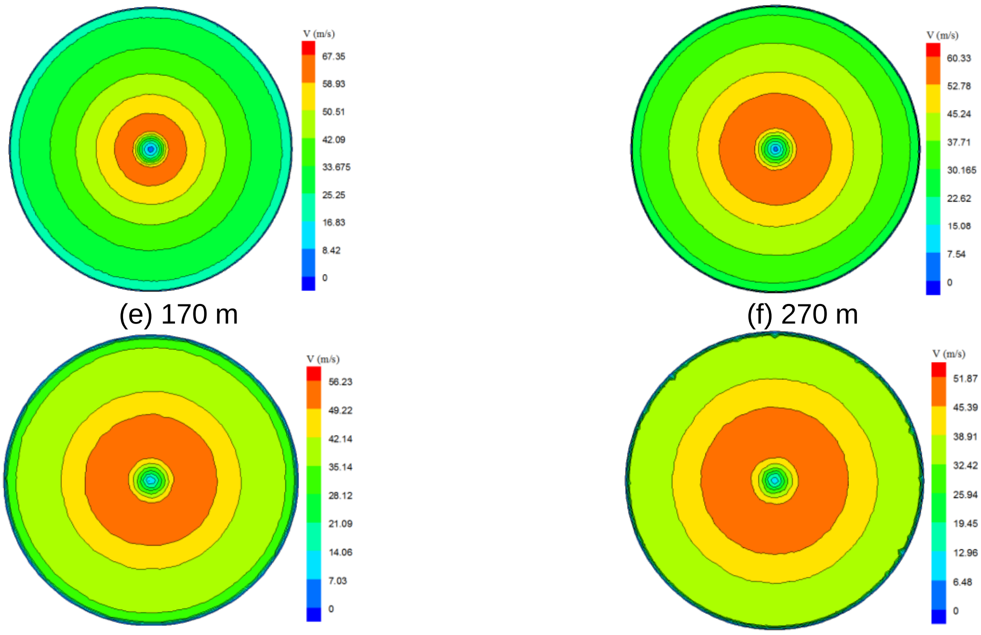


Fig. 2 Contour of tangential velocity at vertical section (y=0)

The contours of tangential velocity at different heights are shown in Fig. 3. It can be seen that the tangential velocity is increased from the center of the wind field to the core radius, and then decreased with increase of the distance out of core radius. At the same time, the maximum tangential velocity at different heights is shown a clear trend of decrease with increase of the height.


(a) 20 m
(b) 50 m
(c) 80 m
(d) 110 m



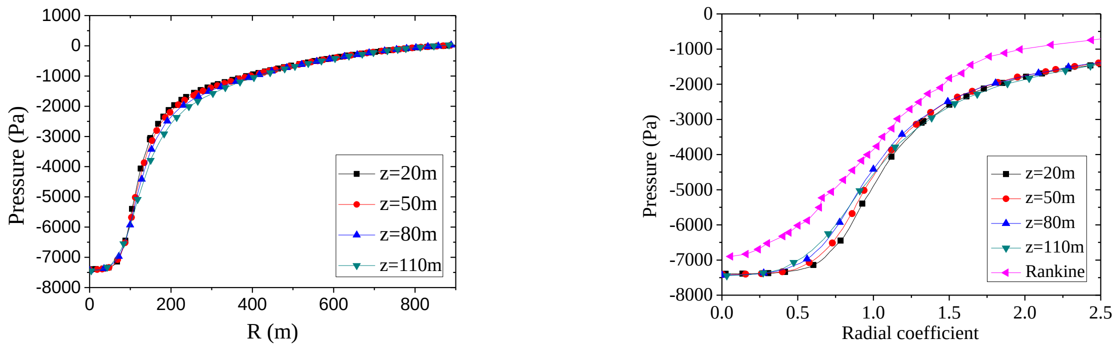
(e) 170 m (f) 270 m

(g) 320 m (h) 420 m

Fig. 3 Contour of tangential velocity at different heights above the ground

3.2 Pressure Distribution

The change of pressure along with the radius is given in Fig. 4(a). As seen in the figure, the larger negative pressure exists in the core region of the tornado, and the pressure distribution at each height is not quite different. When radius $R < 70\,\text{m}$, the pressure did not change significantly and kept at about 7400 Pa. When the radius increases to 200 m, the negative pressure is decreased sharply to about -2000 Pa, and as the radius is further increased, the negative pressure is decreased gradually and finally is closed to about -500 Pa. From the view of pressure versus radial coefficient, which is ratio of the radius to the core radius of different height, it is found that the pressure is changed significantly within 2 times of the core radius. Compared with the pressure calculated by the Rankine vortex theory, the difference of pressure in the center of core region is less than 6%, see Fig. 4(b).

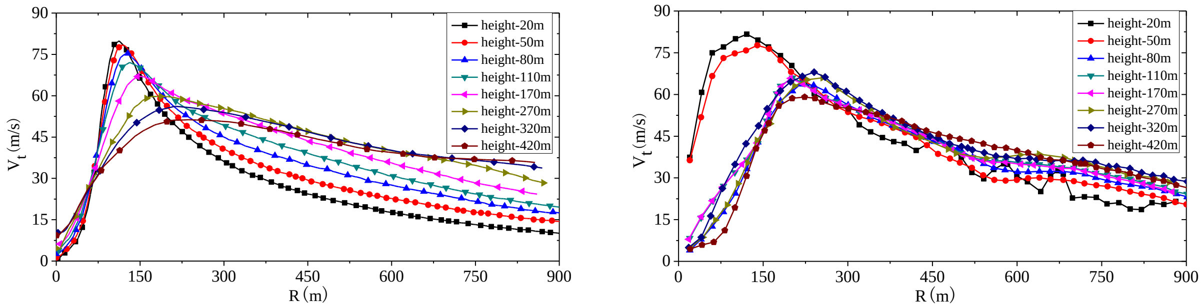


(a) Pressure versus radial (b) Pressure versus radial distribution

Fig. 4 Pressure at different heights in radial directions

3.3 Comparison of Numerical Results and Radar Measured Data

Fig. 5(a) and (b) present the radial profile of tangential velocity at different heights of numerical simulation and radar measurement. At height of 20 meter and 50 meter, the maximum tangential velocity and the core radius are in agreement with the measured data as shown in Tab 2. With the increase of the height, the core radius is gradually increased, while the tangential velocity is become smaller. The present maximum tangential velocity is consistent with that of the radar measurement as shown in Fig. 6. The result shows good consistency between the numerical simulation results and radar measurement.

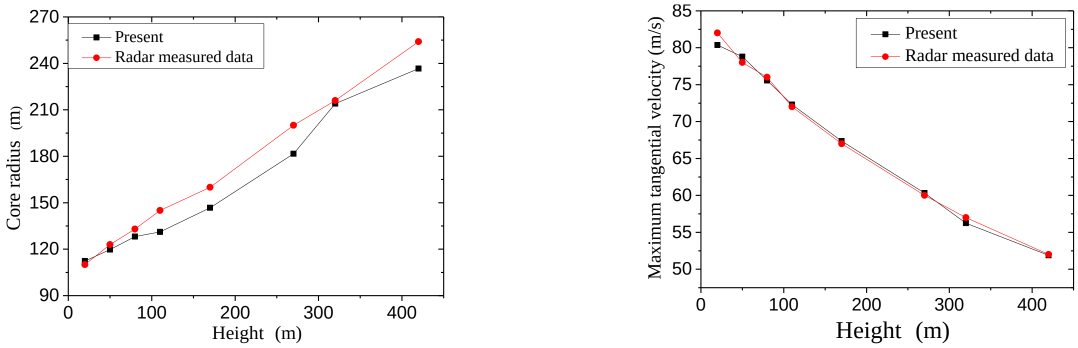


(a) Present (b) Radar measurement

Fig. 5 Comparison of radial profile of tangential velocity between present simulation and the measured data of Spencer tornado

Table 2 Comparison between present results and radar measured data

Height (m)	Core radius of present (m)	Maximum tangential velocity of present (m/s)	Core radius of Radar measurement (m)	Maximum tangential velocity of Radar measurement (m/s)
20	112.33	80.36	110	82
50	119.77	78.79	123	78
80	128.11	75.56	133	76
110	131.17	72.30	145	72
170	146.78	67.35	160	67
270	181.60	60.33	200	60
320	213.95	56.23	216	57
420	236.61	51.87	254	52



(a) Core radius (b) Tangential velocity

Fig. 6 Comparison between numerical results and radar measured data

4. CONCLUSION

In this study, the tornado-like vortex is generated by a numerical simulator and the effect of ground roughness on the tornado flow field is studied using SST k-ω turbulence model. The following conclusions are summarized.

The effect of vegetation roughness on tornado is performed by adding source term in equation. The tangential velocity and core radius of numerical results are in good agreement with the radar measured data of the Spencer tornado since considering the influence of the roughness. It follows that the structure of tornado-like vortex is affected by the ground roughness. When considering the actual geographical characteristics of the ground, the present full-scale numerical simulator can be used to accurately obtain the wind field characteristics of a tornado.

References

Alexander C R, Wurman J. The 30 May 1998 Spencer, South Dakota, storm. Part I *the structural volution and environment of the tornadoes[J]. Monthly Weather Review*, 2005, **133**(1): 72-97.

Dessens Jr J. Influence of ground roughness on tornadoes: A laboratory simulation *[J]. Journal of Applied Meteorology,* 1972, **11**(1): 72-75.

Diamond C J, Wilkins E M. Translation effects on simulated tornadoes*[J]. Journal of the atmospheric sciences,* 1984, **41**(17): 2574-2580.

Ferziger J, Peric M, 2002. Computational Method for Fluid Dynamics, *3rd ed. Springer, Berlin.*

Ishihara T, Oh S, Tokuyama Y. Numerical study on flow fields of tornado-like vortices using the LES turbulence model*[J]. Journal of Wind Engineering & Industrial Aerodynamics,* 2011, **99**(4): 239-248.

Kuai L, Haan Jr F L, Gallus Jr W A, et al. CFD simulations of the flow field of a laboratory-simulated tornado for parameter sensitivity studies and comparison with field measurements *[J]. Wind and Structures,* 2008, **11**(2): 75-96.

Lewellen D C, Lewellen W S, Xia J. The Influence of a Local Swirl Ratio on Tornado Intensification near the Surface*[J]. Journal of the Atmospheric Sciences,* 2000, **57**(4): 527-544.

Lewellen D C, Lewellen W S. Near-surface intensification of tornado vortices*[J]. Journal of the Atmospheric Sciences,* 2007, **64**(7): 2176-2194.

Lewellen W S, Lewellen D C, Sykes R I. Large-Eddy Simulation of a Tornado's Interaction with The Surface*[J]. Journal of the Atmospheric Sciences,* 1997, **54**(5): 581-605.

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

Liu Z, Ishihara T. Study of the effects of translation and roughness on tornado-like vortices by large-eddy simulations*[J]. Journal of Wind Engineering and Industrial Aerodynamics,* 2016, **151**: 1-24.

Mochida A, Tabata Y, Iwata T, et al. Examining Tree Canopy Models for CFD Prediction of Wind Environment at Pedestrian Level*[J]. Journal of Wind Engineering and Industrial Aerodynamics,* 2008, **96**(10-11): 1667-1677.

Natarajan D, Hangan H. Numerical study on the effects of surface roughness on tornado-like flows*[C]//11th Americas Conference on Wind Engineering (11ACWE).* 2009.

Natarajan D, Hangan H. Large eddy simulations of translation and surface roughness effects on tornado-like vortices*[J]. Journal of Wind Engineering and Industrial Aerodynamics,* 2012, **104**: 577-584.

Wicker L J, Wilhelmso R B. Simulation and Analysis of Tornado Development and Decay Within a Three-Dimensional Supercell Thunderstorm*[J]. Journal of the Atmospheric Sciences*, 1995, **52**(15): 2675-2703.

Zhang W, Sarkar P P. Effects of ground roughness on tornado like vortex using PIV. In: *Proceedings of the AAWE Workshop. Vail, Colorado,* 2008.