5A.1 VISUALIZATION OF TORNADOES USING FUNNEL AND DEBRIS CLOUDS

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1. INTRODUCTION

To estimate the tornadic damage to structures and human beings, it is very important to investigate the characteristics of tornadoes. The main method to rate the intensity of tornadoes is the use of the Enhanced Fujita Scale, which is very reasonable if the degree of damage is clearly indicated (MacDonald, 2004). The Japanese Enhanced Fujita Scale was developed in April 2016 and has been used in Japan to estimate wind speeds from damage ever since (Okuda, 2015). This scale includes some damage indices not available in the American Enhanced Fujita Scale, such as automatic vending machines, power transmission line poles, and asphalt of roads (Noda, 2013). However, estimating the strength and scale of tornadoes is difficult if the amount of damage available for evaluation is not sufficient. Other methods that depend on the extent of damage involve direct observation, such as the VORTEX2 Project (Wurman, 1995). This is a very suitable method but it is difficult to use in Japan because of the challenge in moving observational equipment quickly and safely. Therefore, other methods are necessary to estimate characteristics of tornadoes quickly and safely.

One idea is to use images and movies uploaded to the Internet by the general public. The relationship between the maximum wind speed of tornadoes and the shape of funnel clouds was investigated, using a two-dimensional Rankine vortex (Dergarabedian, 1970). However, real tornadic vortices have three-dimensional structures. Therefore, the relationship between the characteristics of tornadoes and their funnel clouds should be investigated considering three-dimensional tornadic flows.

In this study, three-dimensional real-scale tornado-like vortices were produced using the Large Eddy Simulation in OpenFOAM. Moreover, funnel clouds for these flows were calculated assuming that only the temperature change is adiabatic. In this manner, the relationship between the characteristics of flows and shapes of their funnel clouds was investigated. Furthermore, debris clouds for these flows were obtained through the three-dimensional motion simulation of debris.

2. SIMULATION OF TORNADO-LIKE FLOW BY LES

2.1 *Calculation Configuration*

It is well known that a convergence flow and a horizontally rotating flow were required to produce a tornado-like flow. In this study, a simple rectangular numerical grid shown in Figure 1 was used. To generate a horizontally rotating flow, a horizontal shear flow was produced by a pair of data points, the wind speeds at the inlet and outlet1, with fixed uniform values u_0 and u_1, respectively, arranged as shown in Figure 1. The convergence flow was generated by the upwind to outlet2, placed at the center of the ceiling of the numerical region, and controlled by the difference in wind speed between inlet and outlet1. On the other hand, dimensions were given as real scales, because the conditions that control the scale of the tornadic vortex were unclear. This investigation was carried out under simple configurations, assuming incompressible flow and no heat transmission, because a tornado-like vortex can be produced experimentally.

These calculations were carried out by OpenFOAM based on the finite volume method. Table 1 shows the parameters for this calculation.

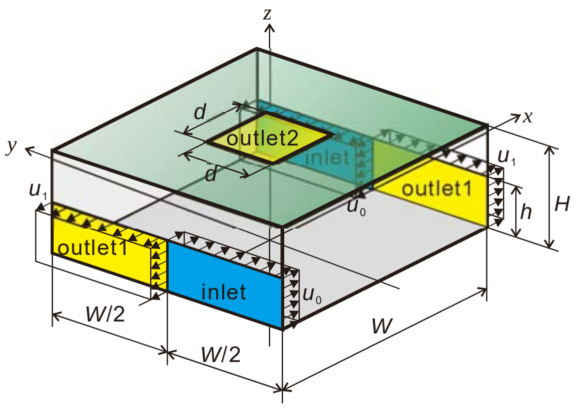

Figure 1 Numerical region and Boundary

Table 1 Parameters for this calculation

Inlet wind speed, u_0	**5 m/s**
Outlet 1 wind speed u_1	4 m/s
Height of Numerical Region, *H*	3 km
Width of Numerical Region, *W*	12 km
Width of Upwind hole, *d*	1.2 km (d/W = 0.1)
Height of Inlet, *h*	3 km (h/H = 1.0)

2.2 *Instant Flow Field*

Figure 2 shows the ensemble-averaged components of velocity in cylindrical coordinates—tangential, radius, and vertical directions—and pressure at the same distance from the vortex center of the instant flow field, z = 20 m, t = 30000 s. In this study, to quantitatively evaluate the strength and scale of the vortex, the core radius ε and the circulation Γ were obtained by fitting the Burgers-Rott vortex (Burgers, 1948) to this tangential wind speed distribution, as given by the

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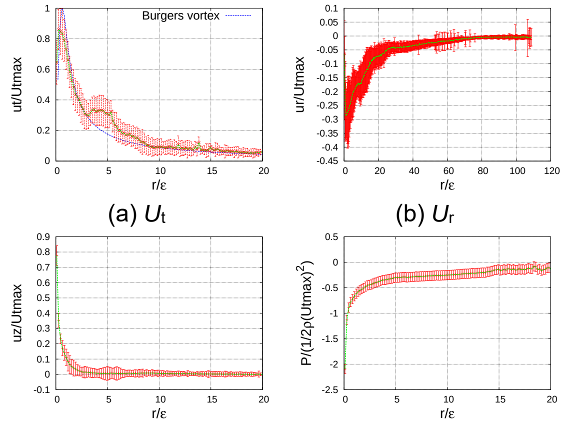
following formula:

$$U_t = \frac{\Gamma}{2\pi r}\left\{1 - \exp\left(-\frac{r^2}{\varepsilon^2}\right)\right\} \qquad (1)$$



(a) U_t (b) U_r

(c) U_z (d) p

Figure 2 Distributions of the wind velocity components and the pressure along the radius direction at z = 20 m

2.3 *Unsteadiness of Flow Field*

Figure 3 indicates the time histories of the core radius, circulation, and maximum tangential velocity given by the Burgers-Rott vortex distribution at the z = 20 m horizontal plane. The flow is unsteady, so the averaged values of the vortex parameters over dt = 1000 s were calculated at each height.

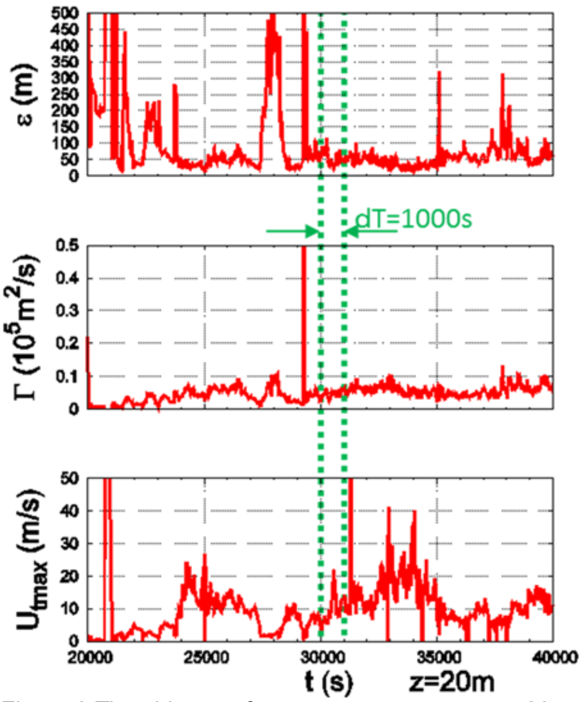


Figure 3 Time history of vortex parameters at z = 20 m

2.4 *Vertical Distribution of the Time-Averaged Flow Field*

Figure 4 indicates vertical distributions of vortex parameters averaged over a span of 1000 s. The green lines and red lines indicate the average value and width of the standard deviation, respectively.

The figure indicates that the core radius and circulation increase with altitude, but the maximum tangential wind speed remains nearly constant near the ground. This flow field was used in the visualization of tornado by funnel cloud, which is discussed below.

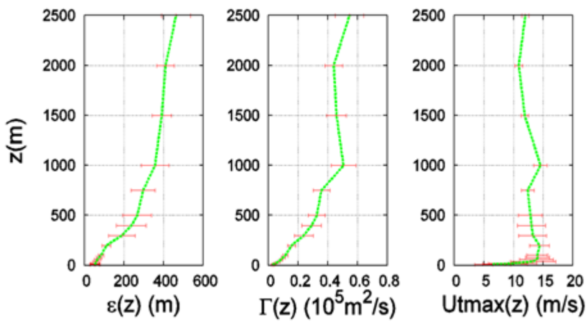


Figure 4 Vertical distributions of vortex parameters averaged over dt = 1000 s

3. VISUALIZATION OF TORNADO-LIKE FLOW BY FUNNEL CLOUD

3.1 *Definition of Funnel Cloud*

To investigate the relationship between the shapes of funnel clouds and the flow fields in this study, the funnel cloud was defined as the saturated water vapor surface. Assuming adiabatic change and incompressible flow, Teten's formula gives the saturated water vapor surface, as follows:

$$\frac{a_{s0}}{a_s} = \frac{T + 273.15}{T_0 + 273.15} \times 10^{\frac{7.5T_0}{T_0+237.3} - \frac{7.5T}{T+237.3}} \times RH \geq 1 \qquad (2)$$

where a_{s0} is a water vapor amount at the reference point. a_s is the saturated water vapor amount at the surface. T is the temperature at the surface and T_0 and RH are the temperature and the relative humidity at the reference point, respectively. These formulas indicate that the funnel cloud is controlled by the temperature and relative humidity. Moreover, the temperature is controlled by pressure field as described by the following formula:

$$T = T_0 + \frac{P_f - P_0}{C_p \rho} - \Gamma_d (z - z_0) \qquad (3)$$

where P_f is the pressure for tornado-like flow, P_0 is the reference pressure, C_p is the specific heat at constant pressure, and Γ_d is the dry adiabatic lapse rate. Therefore, as demonstrated, the funnel cloud is controlled by the pressure field and the relative humidity.

To construct the pressure field p_{target}, for the target maximum tangential wind speed $U_{tmax,target}$, the pressure of the tornado-like flow was modified to obtain the pressure field for an arbitrary maximum tangential wind speed, using the following formula:

$$p_{\mathrm{target}} = \left(\frac{U_{t\,\mathrm{max,target}}}{U_{t\,\mathrm{max,orginal}}} \right)^2 p_{\mathrm{original}} \qquad (4)$$

where $U_{tmax,orginal}$ and $p_{original}$ are the maximum tangential velocity and the pressure of the original flow field, respectively, produced by the calculation shown in the previous section.

Figure 5 shows an example of a funnel cloud produced under the condition of U_{tmax} = 105 m/s and *RH* = 60 % by this method.

Figure 5 An example of funnel cloud produced by the method described in section 3.1 (U_{tmax} = 105 m/s, *RH* = 60 %)

3.2 *Effects of Relative Humidity*

Figure 6 indicates how the shape of the funnel cloud changes by adjusting the relative humidity from 30 % to 70 % with a constant maximum tangential wind speed, U_{tmax} = 105 m/s. It is evident that the funnel cloud moves almost in parallel as the relative humidity is changed.

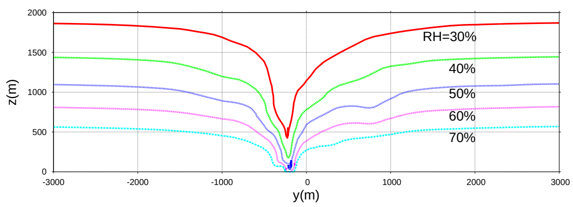


Figure 6 Effect of relative humidity on the shape of funnel cloud (U_{tmax} = 105 m/s)

3.3 *Effects of Maximum Tangential Wind Speed*

Figure 7 shows the relation between the shape of funnel cloud and the maximum tangential wind speed, assuming a constant relative humidity, *RH* = 60 %. This figure indicates that the funnel cloud stretches as the maximum tangential wind speed is decreased.

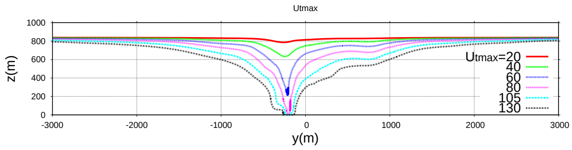


Figure 7 Effect of maximum tangential wind speed on the shape of funnel cloud

4. VISUALIZATION OF TORNADO-LIKE FLOW BY DEBRIS

4.1 *Equation of 3DOF motion of Debris*

In this study, it was assumed that the debris motion occurred only due to the drag forces. Therefore, the three-degrees-of-freedom equation of motion was used as shown below:

$$m\ddot{\mathbf{x}} = \frac{1}{2}\rho\left|\mathbf{U}(\mathbf{x}) - \dot{\mathbf{x}}\right|\left(\mathbf{U}(\mathbf{x}) - \dot{\mathbf{x}}\right)C_D A + m\mathbf{g} \qquad (5)$$

where m is the mass of debris, $\mathbf{x}$ is the vector of spatial coordinates of debris, ρ is the air density, $\mathbf{U}(\mathbf{x})$ is the wind speed vector at $\mathbf{x}$, C_D is the drag coefficient, A represents the area of debris, and $\mathbf{g}$ is the gravity acceleration vector. By normalizing this equation with the representative wind speed and gravity acceleration, the non-dimensional motion can be written as follows:

$$\ddot{\mathbf{x}}_* = C_D Ta\left|\mathbf{U}_*(\mathbf{x}_*) - \dot{\mathbf{x}}_*\right|\left(\mathbf{U}_*(\mathbf{x}_*) - \dot{\mathbf{x}}_*\right) + \mathbf{g}_* \qquad (5)$$

where Ta is the Tachikawa number, defined as the ratio of the aerodynamic force to the gravity force (Tachikawa, 1983). The index * indicates non-dimensional values. This equation indicates that non-dimensional motion is controlled by two parameters, the drag force coefficient, and the Tachikawa number.

In this study, C_D was set at 0.6 for a sphere, and the Tachikawa number *Ta* was adjusted to a range of values, from 1.6 to 2200, assuming different kinds of debris, such as Japanese roofing tile, solar panel, metal drum, pebble, and dust. Debris, with an initial vertical speed of 40 m/s, were launched randomly at 10000 shots per second from the ground, whose area was 500 m by 500 m, and the center was placed at the center of the tornado-like vortex.

4.2 *Results of Motion Simulation of Debris*

Figure 8 shows the debris cloud obtained for each *Ta*. The figure indicates that the flight distance and reachable altitude of debris increase with increasing Tachikawa number. This simulation was carried out for unsteady flow, so an investigation of the behavior of flying debris is necessary, taking into account this level of unsteadiness.

5. CONCLUSIONS

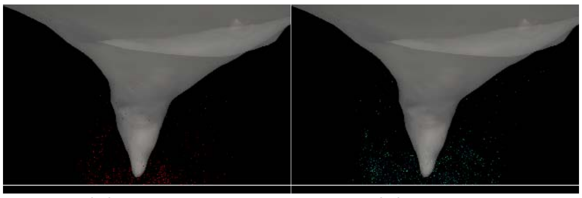
In this study, the following conclusions were obtained:

1) A field of tornado-like flow was generated numerically by a very simple numerical grid and set of boundary conditions, thus reproducing the

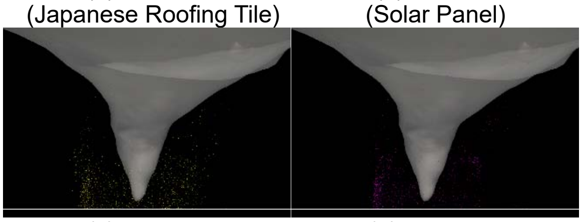
horizontal shear field.

2) Funnel clouds were generated numerically by a very simple condition, and the shape of funnel clouds was changed by changing the relative humidity and the maximum tangential wind speed.
3) Debris clouds for different Tachikawa numbers were generated numerically.

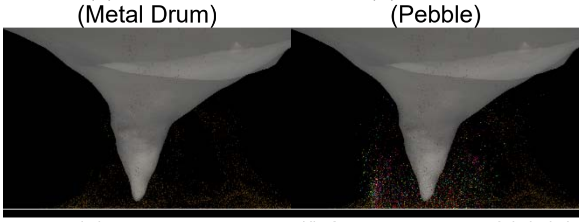
In the near future, the relationship between the characteristics of tornadoes and the shapes of funnel or debris clouds will be further investigated.



(a) *Ta* = 1.6 (Japanese Roofing Tile) (b) Ta = 5.0 (Solar Panel)



(c) Ta = 9.3 (Metal Drum) (d) Ta = 15.8 (Pebble)



(e) *Ta* = 2263 (dust) (f) Superposition of (a)-(e)

Figure 8 Debris clouds obtained for a variety of *Ta* values

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