# Laboratory Experiments on the Low-Level Flow Environment for Tornadogenesis in a Supercell

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**SUMMARY**
The present study aimed to experimentally investigate the influence of the flow environment on tornado formation in supercells near the ground. Our original supercell simulator reproduces the rotational updraft of a mesocyclone and the forward- and rear-flank downdrafts (FFD and RFD). Moreover, it can move linearly to reproduce the inflow from the front. Various flow parameters of these flow elements are varied systematically. The flow conditions of tornado-like vortices are investigated using flow visualization. As a result, we confirm that cyclonic vortices at various locations and a counter-rotating vortex pair are generated in addition to cases with no vortex. Vortex morphology and intensity were found to depend primarily on the bottom height of the mesocyclone and the orientation of the RFD. These results deepen our understanding of the local airflow conditions necessary for tornado genesis and are expected to contribute to improved tornado-warning accuracy through observational and numerical forecast validation.

*Keywords: Supercell, Flow environment, Laboratory experiment, Tornadogenesis*

## 1. INTRODUCTION

Supercell is a major source of violent tornadoes. Because supercells have mesocyclones, the typical vortical pattern in Doppler velocity observed by radar is used to issue tornado warnings. However, almost 75 % of supercells are nontornadic (Barnes et al., 2007). Therefore, research on supercell tornadoes is still being conducted intensively. Major approaches are observational studies (e.g., Bluestein et al., 2007, Adachi, 2019) and numerical studies (e.g., Noda and Niino, 2005; Mashiko, 2016). These studies have focused on individual events, and the flow conditions for tornadogenesis are still not understood. The present experimental study aims to clarify the flow conditions of tornadic supercells near the ground.

Four principal flow elements of supercells are the rotational updraft of a mesocyclone, the forward and rear -flank downdrafts (FFD and RFD) and warm moist inflow from the front. The gust fronts are formed between the warm moist inflow and cold outflows from FFD and RFD. They are a source of vertical and horizontal vorticity near the ground. Our supercell simulator is designed to reproduce such flow structures.

## 2. EXPERIMENTAL METHOD

The supercell simulator used in this study consisted of three units: a mesocyclone simulator with 18 vanes, an FFD simulator, and an RFD simulator as shown in Figure 1. The mesocyclone simulator can control rotational intensity and updraft velocity by varying the attack angle of the vanes and the speed of a fan on the upper section, respectively. The FFD and RFD are reproduced by dense mist generated by ultrasonic humidifiers through ducts. The supercell simulator can be moved linearly in order to simulate the forward inflow. Experimental parameters are listed in Table 1. We examined updraft velocities, rotational intensity and bottom height as the characteristics of a mesocyclone. We also changed the locations and directions of the RFD. In this figure, the RFD is located at the center and points directly downward. Ordinarily location of the RFD is the righthand side as shown by Lemon and Doswell (1979). Totally 96 variations of flow situations are examined.

Flow structures are visualized using two laser sheets projected horizontally at $Z$=10mm, with the mist serving as tracer particles. Temporal flow patterns that generate tornado-like vortices are recorded with a video camera and a high-speed camera. Each experiment was repeated more than 10 times in order to check reproducibility.

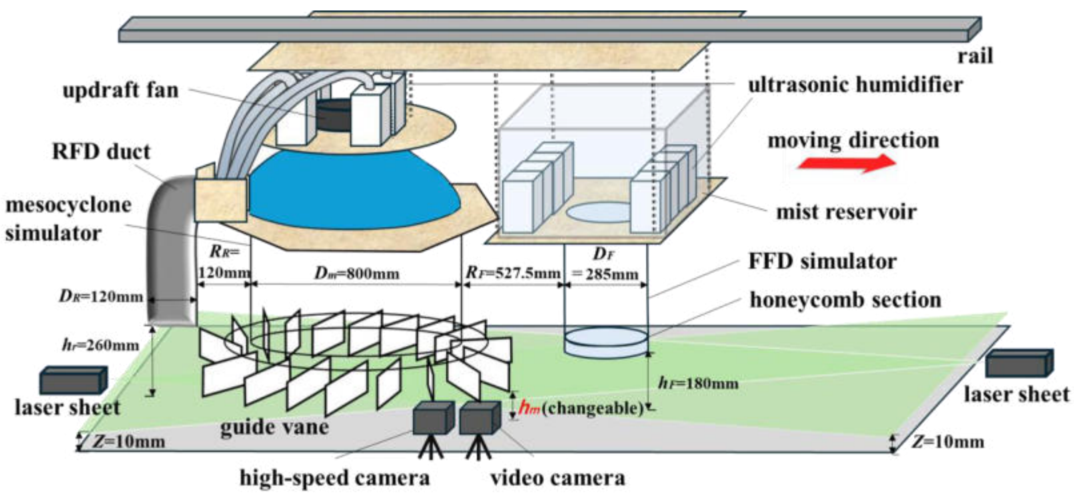



**Figure 1.** Schematic diagram of the experimental apparatus

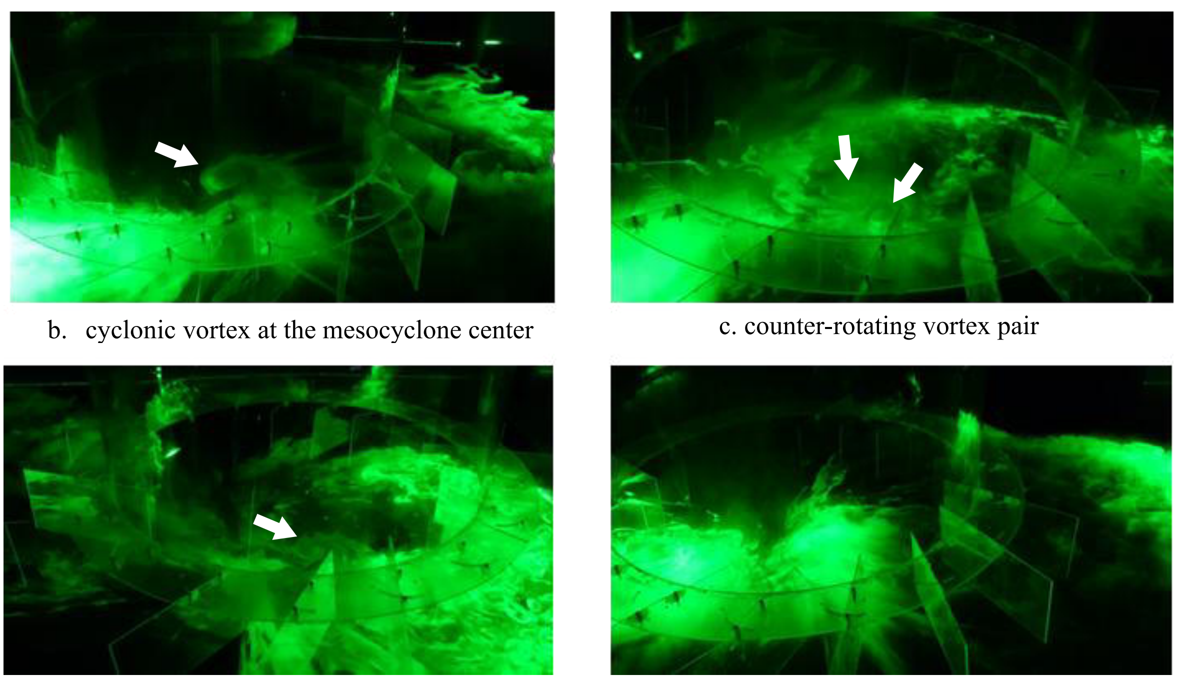
**Table 1.** Control parameters used in the present experiment

| Flow element | Parameter | Symbol | Conditions |
|---|---|---|---|
| Mesocyclone | Updraft intensity (Fan voltage) | $\boldsymbol{E}$ | 10 V, 12 V |
| | Height of mesocyclone base | $\boldsymbol{h_m}$ | 40 mm, 60 mm |
| | Rotation strength (Guide vane angle) | $\boldsymbol{\theta}$ | 30°, 60° |
| FFD | Position | – | Center |
| RFD | Downdraft direction | – | Toward mesocyclone center, directly downward |
| | Position (relative to storm motion) | – | Center, Righthand side, Lefthand side |
| Warm moist air | Translation speed of the system | $\boldsymbol{V_s}$ | 0.13 m s$^{-1}$, 0.17 m s$^{-1}$ |

## 3. RESULTS AND DISCUSSION

Typical flow patterns are shown in Figure 2. The most common major flow pattern is a cyclonic tornado-like vortex that occurs near the center of the mesocyclone, as shown in Fig. 2a. In this case, the outflow from the RFD is found to form the tornado-like vortex. The location of the tornado-like vortex varies depending on flow conditions. Figure 2b shows the case in which the tornado-like vortex occurs at the right portion of the mesocyclone. The counter-rotating vortex pair sometimes forms when the narrow cold outflow penetrates the mesocyclone as shown in Fig. 2c. Same situation is observed in actual supercell (Bluestein et al. 2007). Such a vortex is formed by the stretching of positive and negative vertical vorticity concentrated on both sides of the cold outflow. When the rotation of the mesocyclone is weak and the RFD points directly downward, the background positive vertical vorticity and the horizontal shear at the gust front between the inflow and the cold outflow become weak due to the weak penetration of the cold outflow. In this case, the tornado-like vortex dose not form, as shown in Fig. 2d.

The flow regime for the case in which the bottom of mesocyclone is relatively high ($hm$ = 60 mm) is shown in Figure 3. The upper two figures show the case of weak updraft velocity ($E$=10V) and the bottom ones show the stronger updraft case. Overall trend is that the tornado-like vortex forms more stably when the updraft velocity and the rotation intensity of the mesocyclone are stronger. The higher moving velocity is also important factor for stable vortex formation. The counter-rotating vortex pair is likely to appear when the RFD is located at the center position and the duct outlet of the RFD points mesocyclone center. This is because the cold outflow becomes narrow. The RFD is located on the righthand side in actual supercell (Lemon and Doswell 1979). However, such a situation is not necessarily suitable for tornado-like vortex formation. In the case of relatively low mesocyclone base, the tornado-like vortex becomes more stable, although the figure is not shown here.



b. cyclonic vortex at the mesocyclone center

c. counter-rotating vortex pair

a. cyclonic vortex at the right portion of mesocyclone

d. no vortex

**Figure 2.** Various flow patterns observed in the experiments. White arrow shows the location of tornado-like vortex.

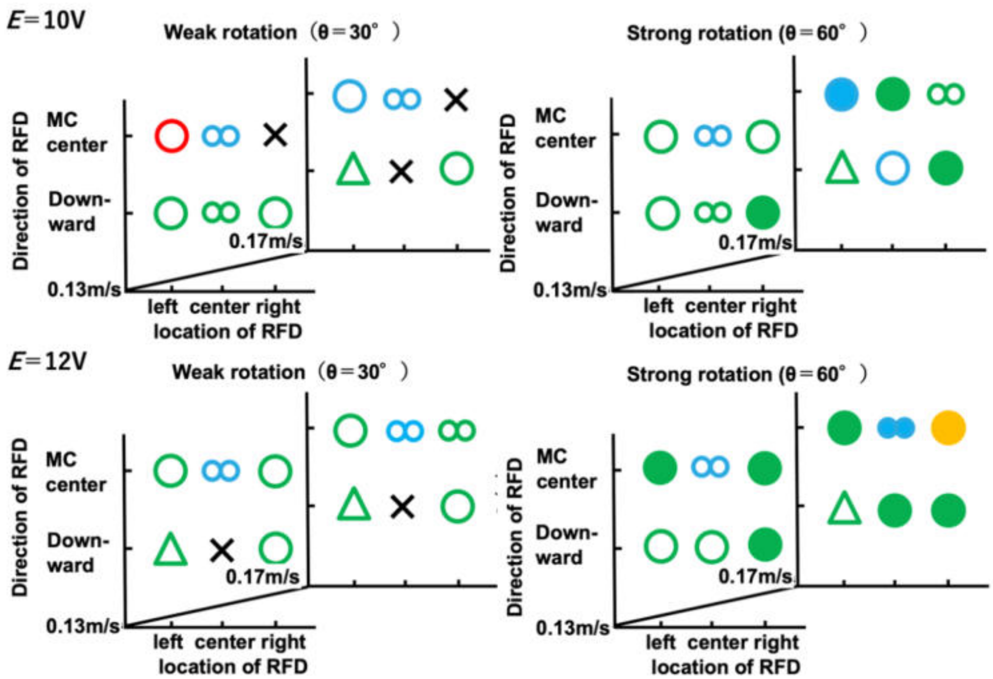



**Figure 3.** Regime diagram of vortex formation for *hm*=60 mm. Open circle and rigid circle show unstable and stable cyclonic vortex. Double circle denotes counter-rotating vortex pair. Triangle is the vortex formed FFD only. Cross shows no vortex. Coler shows the location of vortex, red: front portion of mesocyclone, green: center of mesocyclone, blue: right portion of mesocyclone, yellow: rear portion of mesocyclone.

## 4. CONCLUSION

This study experimentally demonstrated that a variety of vortex morphologies occur depending on the flow condition of supercells near ground. Major factors of tornado genesis are found to be the bottom height of mesocyclone and the position and orientation of the RFD. Such knowledges will contribute to revise the method of tornado prediction.

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