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Reproducing tornadoes in laboratory using proper scaling

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ABSTRACT

Experimentally simulated tornado-like vortices are related to field tornadoes in order to: (i) establish proper kinematic and dynamic scaling and (ii) attempt to determine a relationship between laboratory parameters and the Enhanced Fujita Scale (EF-Scale). Data from recent in-situ Doppler radar campaigns are analyzed using the Ground-Based Velocity Track Display (GBVTD) method and a unique dataset of three-dimensional axisymmetric tornado flow fields is generated. In parallel, Particle Image Velocimetry (PIV) results of the most recent experimental simulations of tornado vortices performed in the model WindEEE Dome (MWD) are analyzed and then compared with the GBVTD-retrieved full-scale data. Based on these comparisons, the swirl ratio of the full-scale tornadoes, as well as the length and velocity scaling ratios of the simulated tornadoes are identified. It is concluded that the MWD apparatus can generate tornado-like vortices equivalent to EF0 to low-end EF3 rated tornadoes in nature.

1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) reported that in 2011 tornadoes killed 553 people in the United States with approximately $10 billion in damage. These recent catastrophes have led researchers to investigate the characteristics of this phenomenon in more depth. Despite the significant number of analytical, experimental and numerical studies and advances in measurement methods, investigation of the wind loading effects on structures and buildings in tornadic flows has been very limited.

Mishra et al. (2008a) placed a 1:3500 scaled cubical building model (edge length of 30 mm) in the path of a simulated single-celled vortex and measured the surface static pressures. They observed a clear difference between the pressure distribution over the building in tornadic winds compared to atmospheric boundary layer flows. In another attempt, a single-story, gable roof building was modeled in the Iowa State University (ISU) tornado simulator and the tornado wind-induced loads were measured by Haan et al. (2010). Using the length scale of 1:100, the model building was 91 mm × 91 mm × 66 mm ($L \times D \times H$). They concluded that wind load coefficients generated in tornadic winds are greater than the ones produced by straight boundary layer flows in an open terrain.

The shortage of tornado wind loading studies is mainly attributed to an unidentified relationship (i.e. geometric and velocity scales) between simulated and real tornadoes. In order to conclude that a simulated tornado-like vortex is a valid representation of a tornadic flow in nature, it is important that the geometric, kinematic and dynamic similitudes are analyzed. The difficulty with the case of tornadic flows originates in the definition of the main non-dimensional number governing the flow, i.e. the swirl ratio (S). The velocity ratio between the far-field tangential (V_θ) and radial (V_r) velocities is termed as swirl ratio, $S=(1/2a)V_\theta/V_r$, where a, namely the aspect ratio, is the ratio between the inflow height (h) and the updraft radius (r_0). Swirl ratio is defined based on the geometry and boundaries of a simulator and is location dependent. Therefore, it is nearly impossible (or very subjective) to calculate the swirl ratio for a real tornado as there is no clear definition of inlet/outlet boundary conditions in a field tornado. Therefore, to simulate tornado-like vortices either numerically or experimentally and study the damage associated with them, it is important to search and establish a relationship between the laboratory swirl ratio and the full-scale Fujita or Enhanced Fujita Scale (F-Scale or EF-Scale, respectively). This way, scaling parameters may be identified for each simulation and can be used for modeling different types of tornadic winds.

Baker and Church (1979) measured the maximum average core velocity (V_m) and the mean axial velocity at the updraft ($V_{z,m}$) for various swirl ratios in Purdue University vortex simulator which was 1.5 m in diameter and 0.6 m in height at the convergence zone. Since the ratio between these two velocities remained constant through a wide range of swirl ratios, they suggested that $V_m/V_{z,m}$ can be used as a scaling parameter. However, recent full-scale investigations by Nolan (2012) have shown that radial/axial velocities deducted from single-Doppler radar data using the Ground-Based Velocity Track Display (GBVTD) method are not

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Nomenclature

Q	volumetric flow rate per unit axial length
Re_r	radial Reynolds number
S	swirl ratio
V_D	Doppler velocity
V_m	maximum average velocity (average of axial, radial and tangential components) in the core region
V_r	radial velocity
V_T	translational velocity
V_z	axial velocity
$V_{z,m}$	average axial velocity at the updraft
V_θ	tangential velocity
$V_{\theta,max}$	tangential velocity at the core radius
a	aspect ratio
h	inflow height
r	radial distance
r_c	core radius
$r_{c,max}$	radius corresponding the overall maximum tangential velocity
r_0	updraft radius
ν_t	terminal velocity of hydrometeors and debris
z	height above the ground surface
z_{max}	height corresponding the overall maximum tangential velocity
z_{min}	minimum height scanned by Doppler radar
Γ_∞	maximum vortex strength
Υ	mathematical angle in GBVTD analysis
θ	vane angle
θ_T	direction of the mean wind flow (V_T)
ν	kinematic viscosity of the fluid
λ_l	geometric scaling ratio
λ_t	time scaling ratio
λ_v	velocity scaling ratio
φ	elevation angle of the radar beam
ψ	mathematical angle in GBVTD analysis

accurate for tornadoes rated F2 or less. The GBVTD method (Lee et al., 1999) is the most established mathematical model for retrieving the velocity field of tornadoes from single Doppler radar data. As a result, using $V_m/V_{z,m}$ as a scaling parameter is not a practical approach for the most occurring tornadoes.

Mishra et al. (2008b) determined the length scale of their simulation using the core radius of the vortex near the ground. They calculated the core radius of a single-celled tornado-like vortex simulated in Texas Tech University simulator using surface pressure data and compared the results with that of the May 1998 Manchester, SD tornado obtained through cyclostrophic momentum balance. Mishra et al. showed that using this length scale, the surface pressure profiles of the simulated and Manchester tornadoes are well matched and therefore, this particular simulation can be used for studying wind loading on scaled models. However, there is no evidence of a match between radial profiles of tangential velocities. It is important that the radial profiles of tangential velocity at various heights also be compared and matched in order to conclude that the simulated tornado is a valid representation of a single-celled tornado in nature. It should also be noted that obtaining pressure data from a real tornado is rare and more challenging than capturing velocity fields using radars.

Haan et al. (2008) validated the ISU simulator through quantitative and qualitative comparisons between full-scale and simulator flow fields. They compared, qualitatively, the non-dimensional contour plots of simulated tornado corner flow structures at two different swirl ratios with that of Spencer (Wurman and Alexander, 2005) and Mulhall (Lee and Wurman, 2005) tornadoes and inferred that the overall structure matches well. Also, they compared the azimuthally averaged tangential velocity profiles (hereinafter referred to as tangential velocity profile) of their simulated tornado at different swirl ratios with that of Spencer and Mulhall tornadoes at various heights and showed that the graphs match very well and collapse on each other. However, it should be noted that there are at least two geometric parameters of importance in a tornado-like vortex: the core radius at which the maximum tangential velocity happens and the height above the surface corresponding this maximum. By using non-dimensionalized graphs based on only the maximum tangential velocity and core radius, the radial profiles of tangential velocity are forced to collapse on one single graph but the height information is missing. Also, it seems that the geometric scaling of the ISU simulator is primarily determined based on the scale of the building model being used (Haan et al., 2008) and not on the scaling of the flow fields between real and simulated tornadoes.

Kuai et al. (2008) numerically simulated the flow field of the ISU tornado simulator using Doppler radar data and laboratory velocity field measurements as boundary conditions. They evaluated the performance of a Computational Fluid Dynamics (CFD) model in capturing near ground flow field characteristics of a full-scale and experimentally simulated tornado and compared the results of specific cases of numerical simulations with the tangential velocity field of the F4 rated 1998 Spencer, SD tornado (Wurman and Alexander, 2005). In this comparison, the geometric and velocity length scales of the simulation were selected based on the inflow radius and maximum tangential velocity, respectively. However, there is no discussion about the similarity of the flow structure between the simulated tornado and the radar data.

Karstens et al. (2010) investigated the swirl ratio and structure of the vortex qualitatively using surface pressure data as well as visual evidences. However, no attempt has been made to quantify the swirl ratio corresponding to each event. Two cases are studied by Karstens et al. (2010) in which a low swirl ratio with single-celled vortex structure OR a medium swirl ratio with a two-celled vortex structure are suggested for an F4 rated event. Yet, given the measurement/visual uncertainties in both cases, the discussion is inconclusive regarding the vortex structure and swirl ratio.

Zhang and Sarkar (2012) resolved the near ground structure of a simulated tornado vortex using Particle Image Velocimetry (PIV) and compared the tangential velocity profile of the simulated tornado with that of an actual tornado. In this work, Zhang and Sarkar acknowledged inherent uncertainties in the comparison approach and suggested that an extensive field database of tornadoes of various intensities and structures can overcome the existing problem in tornado simulations.

An attempt to determine a flow field relationship between simulated and full-scale tornado was made in 2008 by Hangan and Kim (2008). They proposed that by determining the overall maximum tangential velocity for a given swirl ratio and matching it with full-scale Doppler radar data, a velocity scaling could be approximated and a relationship between swirl ratio and Fujita Scale may be obtained. Hangan and Kim compared radial profiles of the tangential velocity for numerically simulated vortices with various swirl ratios to that of the Doppler radar full-scale data from the F4 tornado, in Spencer, SD on May 30, 1998 (Wurman and Alexander, 2005). They have considered the scaling of both the core radius and the height at which the maximum tangential velocity occurs. Hangan and Kim observed that the best fit between their tangential velocities at various heights and the