P1.25 COMPARISON OF NUMERICAL MODEL AND LABORATORY SIMULATOR TORNADO WIND FIELDS WITH RADAR OBSERVATIONS OF THE SPENCER, SOUTH DAKOTA TORNADO

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1. INTRODUCTION

A simulator has been designed at Iowa State University that produces the largest translating tornado in the country (with respect to a ground plane) for wind tunnel model testing of the interaction of tornado-like vortices with the built environment. To validate how well the laboratory tornado wind fields compare to those observed in nature, comparisons are made between laboratory measurements and radar observations of the Spencer, South Dakota tornado of 30 May 1998, and with numerical simulations of tornado winds that used these radar data as boundary conditions. In addition, extensive sensitivity tests were performed with a numerical model to better understand the impact of some assumed parameters in the design of the model domain, and the impact of surface roughness on vortex structure.

2. LABORATORY SIMULATOR DESIGN

Planning for a moving tornado simulator began in 1997, and five different design concepts were tested between 2001 and 2003. The final prototype design matches loosely observations during the VORTEX project that suggested a rear-flank-downdraft (RFD) nearly encircles the region of low-level enhanced vorticity around the time of tornadogenesis at the surface. Figure 1 shows the simulator in action, with dry ice being supplied to visualize the vortex. A circular duct 18 feet in diameter and 11 feet high is suspended from a 5 ton track crane so that it can move along a 34 foot ground plane. Within this 1 foot wide duct, a downdraft is simulated and some vorticity is imparted to this flow through the use of vanes at the top. This downdraft diverges upon hitting the ground, and a sizeable portion of the flow moves inward beneath a large fan (maximum flow rate of 125,000 cfm) that acts as an updraft.

The vorticity present in the low-level inflow is stretched beneath the updraft, forming a tornado that travels along the ground plane as the entire fan/downdraft-producing mechanism translates. This design permits a maximum tornado diameter of 4 ft., with a maximum tangential velocity of 60 miles per hour. The maximum swirl ratio achievable is 1.0, and the translation speed of the vortex can reach up to 2 ft/sec. The vortex height can vary from 4 to 8 feet by adjusting the ground plane upward or downward. In the path of the vortex, models of structures scaled to 1/150 and 1/300 are placed so that measurements can be made of the pressures/loads on them.

Velocity fields in the simulator were measured using a spherical 18-hole pressure probe (PS18 Omniprobe from Dantec). The pressures from the probe were measured with a Scanivalve zoc33/64

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Figure 1: Tornado simulator with vortex highlighted through the use of dry ice.

Px electronic pressure scanner. The 18-hole probe is conceptually organized to form a network of five-hole configurations (some ports/holes are shared by two groups). Because of this network, the probe can measure flow angularity up to 165 degrees with respect to the probe axis. The calibration software supplied with the probe uses a local least square fit with this network of 5-hole configurations to provide accuracy of 2% for velocity magnitude and 1.5 degrees for velocity angle.

Velocities were measured at several different levels from the ground plane. For all of these measurements, the ground plane was fixed at 45.7 cm (18 in.) below the exit of the outer duct and the fan speed was fixed at 20 Hz (1/3rd of the full speed, $Q_{1/3}$= 16.5 m^3). Measurements were done for vane angles of 35, 45 and 55 degrees. Data were sampled at the rate of 78 Hz for 26 seconds. The measurements were made with a stationary tornado, and the swirl ratio was estimated to be 0.78 (current definition) for the 55 degree vane angle setting.

3. RADAR OBSERVATIONS OF NEAR-GROUND WINDS

The primary observational radar data we used in our numerical simulation are from a violent tornado that passed through Spencer, South Dakota at 0134 UTC 30 May 1998, which was observed by the Doppler-On-Wheels (DOW) mobile radars (Alexander et al. 2005). The tornado center was closest in its approach of DOW-3 at this time. The core radius of the second tornado increased from 125 m early in its life eventually to 200 m by 0141 UTC and then decreased in size slowly.

Figures 2 and 3 show the instantaneous tangential and radial velocity profiles in the Spencer, South Dakota tornado as measured by Doppler velocity observations. The original data were fitted into an axisymmetric model constrained by the radar data to eliminate some higher wavenumber perturbations such as multiple vortices. This model incorporates the tornado wind field components of axisymmetric rotation and translation. The model domain covered a 2 km by 2 km area with 20 m horizontal grid spacing. The radar-scan time for each elevation was around 5 seconds which makes the effective scan frequency approximately 10 Hz. A least squares minimization of the Doppler velocity observations was applied to estimate the azimuthally averaged (axisymmetric) radial and tangential wind speed components in 40 m wide annuli at successive 20 m intervals moving out from the tornado center. These estimates are tornado-relative and do not include the translation speed. To obtain the stationary, axisymmetric rotation speed, the translational motion was subtracted from the observed wind speed.

The radar data analyzed contains the tangential velocity from 20 m to 660 m above ground and radial velocity within 1000 m from the center of the tornado. The tangential velocity (Fig. 2) along a radius has one peak value which defines the core radius. The core radius gradually increases with height from 120 m to 250 m so that the tornado vortex has a funnel shape. However, the maximum tangential velocity decreases from low levels to higher levels. The core radius in the radar data shows a sudden broadening from around 120 m at both 20 m and 50 m elevations to more than 200 m at elevations of 80 m and above. In addition, the magnitude of the maximum tangential velocity at 20 m and 50 m elevations is larger (≈20%) than that at higher elevations.

Radial velocity profiles as a function of height at different distances from the center of the tornado are shown in Fig. 3. Negative values represent inflow. At 1000 m radius, inflow is present at all levels below 400 m, but the depth of the inflow layer gradually decreases closer to the center of the vortex. The maximum radial velocity is located at

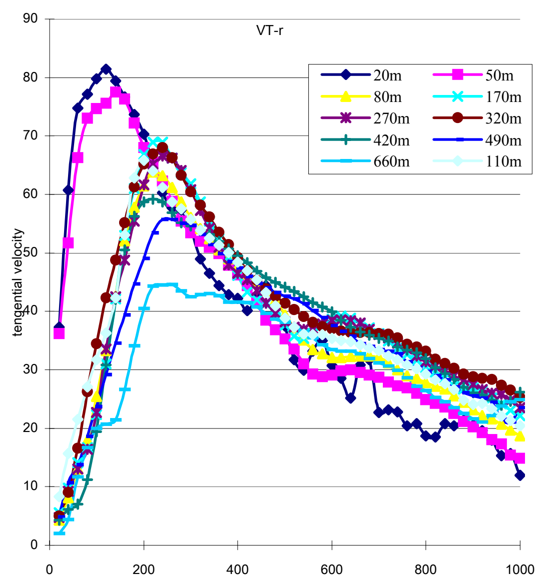

Figure 2: Radar-observed tangential velocity profiles in m/s (averaged azimuthally) as a function of radial distance (meters). Different colored curves show profiles at different elevations (m) above ground.

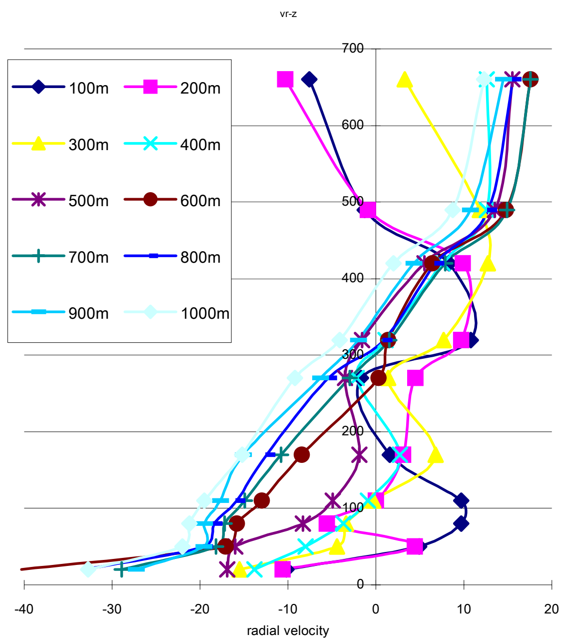

Figure 3: Radar-observed radial velocity profile (m/s) averaged azimuthally as a function of height (in meters). Different curves refer to different radial distances (m) from the center of the vortex.

20 m above ground, which is the lowest level for which data are available. Numerical simulations by Lewellen et al. (1997; 1999) indicate that strongest inflow is found in the lowest few tens of meters above the ground, potentially in a layer only 10-20 m above the ground.

The radar data at 0134:23 UTC were chosen as the inflow condition for all of our numerical simulations because the vortex was closest to the radar at this time, allowing data to be obtained closer to the ground than at any other time. The lowest elevation of the Doppler analysis is at 20 m because the bean centerlines were as low as 20-50 m AGL (Dowell, et al. 2005)**.** It should be noted, however, that radar data in three other volume sets at every one minute after 0134:23 UTC were also analyzed, and it was found that the wind distribution in the tornado changed rapidly. In the comparisons of numerical simulation results, laboratory results, and radar observations that follow, it should be noted that the radar data used in the axisymmetric model were acquired over a finite length of time. Thus, the radar observations presented here have essentially been time averaged, and calculated on the basis of an axisymmetric vortex. The FLUENT numerical simulations that yield a steady-state velocity structure within the vortex are based on a fixed boundary and initial conditions, as specified by the user, but the tornado in nature is subject to unsteady boundary conditions which could be one of the reasons that a violent tornado is a rare event (e.g. Lewellen 1999). Because of this discrepancy, the numerical simulations and laboratory results cannot be expected to match the radar observations exactly.

4. LABORATORY SIMULATOR MEASUREMENTS

Measurements have been taken of radial, tangential, and vertical velocity components within the laboratory simulator for several different vane angles. Figure 4 shows the flow (in ft/sec) for a case with a vane angle set to 35 degrees. It should be noted that the cross-section likely did not pass through the center of the vortex, but missed the center by a small distance, explaining the negative "radial" velocities (not truly radial) around r=0. With the fan speed at 20 Hz, the peak tangential velocity (contoured in color) was roughly 35 ft/sec and confined to an area within 5 inches of the ground. This maximum in tangential flow was found at increasingly smaller radii toward the ground, implying a funnel shape similar to that in the radar data. The core radius appeared to roughly double between the 2 inch height and 5 inches, with a further small increase aloft. Radial velocities were directed inward throughout the region sampled. Upward motion begins within 60-70 inches of the core of the vortex, with downward motion outside this radial distance.

5. NUMERICAL SIMULATION DESIGN

Because radar observations are unable to be made within the lowest 20-50 meters of the ground due to beam angle and obstructions, a CFD model was used to get an idea of wind in the lowest levels of the troposphere. For this purpose, FLUENT was used. The geometric model used here (Fig. 5), which was created to resemble the laboratory simulator, consists of three cylinders, an inflow cylinder at the bottom, an outflow cylinder at the top and a control domain cylinder outside the outflow cylinder at the top. In order to generate an axisymmetric vortex, axisymmetric and simple boundary conditions were applied to the domain. An initial sheared inflow enters the bottom cylindrical domain with radial and tangential velocity components. The flow can exit from the big cylinder only through the small central cylinder at the top boundary. The radius of the bottom cylinder (r1) represents the inflow radius where the initial inflow condition is defined. The radius of the top outflow cylinder (r2) might be thought of as representing the radius of the deep thunderstorm updraft.

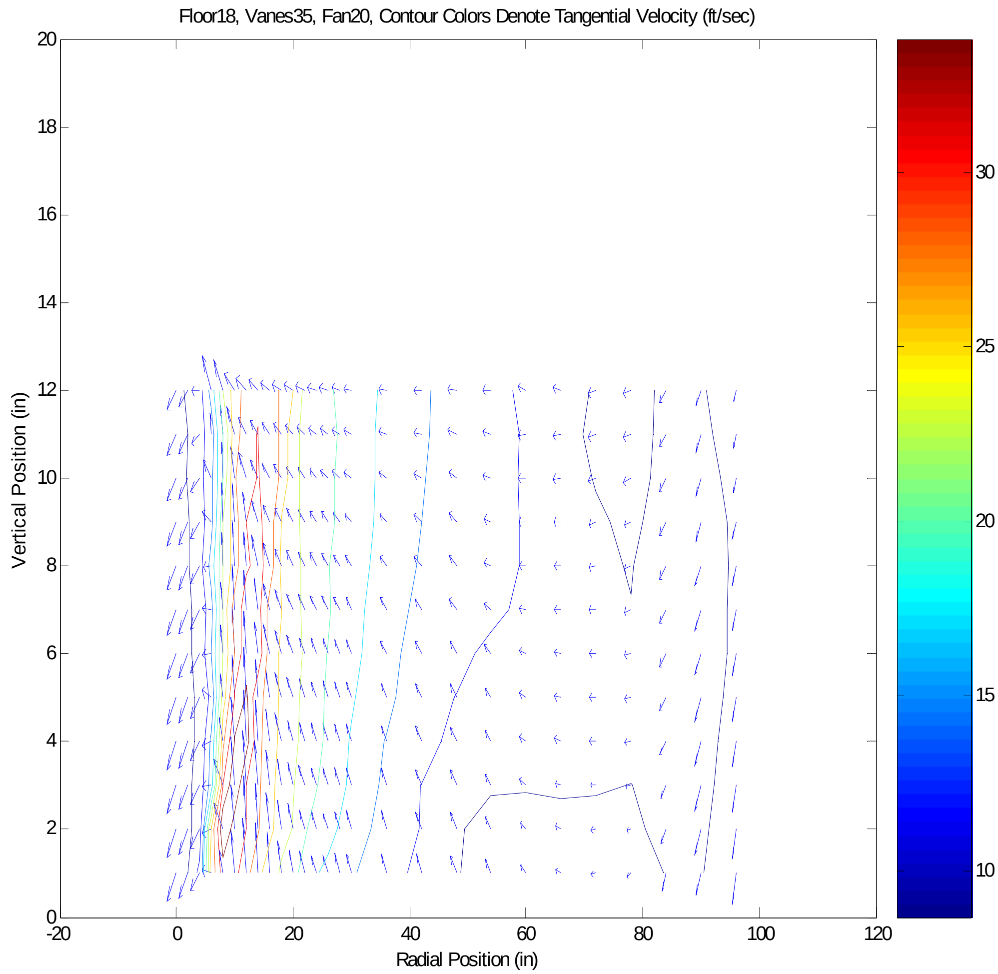

Figure 4: Measurements of velocity within the laboratory simulator with a 35 degree vane angle used, the fan running at 20 Hz, and the ground plane 18 inches below the bottom of the downdraft duct. Tangential velocities are contoured based on color scale at right.

For the design of the numerical model domain in FLUENT, one of the foremost considerations was at what radial distance the inflow data should be defined for the simulations. Next, an appropriate mesh size had to be determined – one that was small enough to accurately depict wind variations within the tornado close to the ground but large enough to allow the simulation to run with limited computational resources. Since the primary concern was the surface-layer wind profile (as opposed to flow higher up), the mesh size at near-ground levels was chosen to be finer than at higher levels. Although radar data was provided to an elevation of 660 m, no observational information was available to indicate the width of the updraft cloud base. A radius for the strong thunderstorm (or outflow) affecting the tornado or the height of the updraft had to be assumed for the design of the model domain. Without observational evidence for a specific radius, our approach was to test several different radii based on generally reasonable values for outflow width to see which radius resulted in a simulated tornado agreeing most closely with the radar observations. A similar procedure was followed for the depth of control domain cylinder (h2). Finally, the impact of surface roughness was investigated by putting rings of finite height on the ground in the model domain.

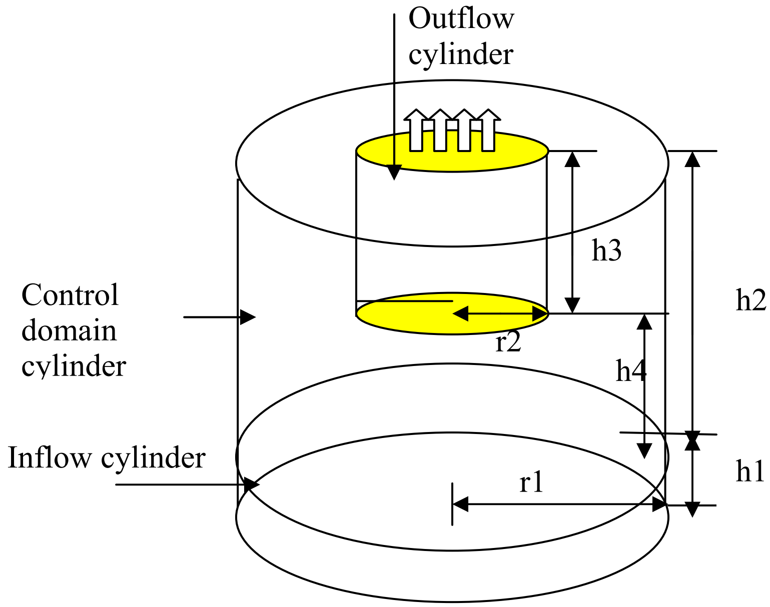

Figure 5: Geometry of the numerical model domain

In all of the simulations except the one considering the effect of surface roughness, a smooth ground plane was assumed. Therefore, the decay rate of the tangential velocities outside of the core region and the magnitude of the peak tangential velocity are not expected to match with those inferred from the radar observations. The comparison of tangential velocities between numerical simulations and radar observations would be considered a reasonable match if the radius of the vortex core and the angular velocity of the vortex within the core region compare well in the lower elevations (≤ 50 m). Furthermore, it has been proved that the measurement errors could be caused by the differences between the air motion and the object motion (Dowell, et al. 2005). As Doppler radars sample the motion of objects within the tornado instead of the actual airflow and it was found that objects move outward relative to the air and more slowly than the air in tangential direction, the Doppler radar data are very likely to be smaller than the real wind velocity (Dowell et al. 2005).

6. NUMERICAL MODEL SENSITIVITIES

Although the Doppler-on-Wheels radar dataset provided some information about the flow near the tornado at relatively low levels, the dataset was incomplete and some assumptions had to be made in the design of the numerical study. One of these assumptions concerned the distance away from the center of the tornado where the radar data would work best as prescribed inflow. Data were available outward to a distance of 1000 meters from the center of the tornado. There would be an advantage of taking the 1000 m data to represent inflow into the idealized numerical model domain since this distance would be farthest from the tornado itself, and the model would have the greatest freedom to simulate a tornado with minimal influence from the boundary conditions. However, the farther the inflow from the vortex core, the greater the influence of the ground roughness on the flow simulation. Since it is relatively difficult to model the terrain roughness in Fluent, this would favor the use of the radar observations as inflow for the numerical model relatively close to the tornado. However the boundary conditions then might influence the simulation adversely.

Based on the above issues, sensitivity tests were performed using the radar data at 800 m (case 1) and 1000 m (case 6) away from the tornado center as the inflow conditions prescribed on the outer cylinder of the model domain. 800 m was chosen because it matched the 90 inch radius in the lab model where the flow is nearly horizontal while 1000 m was the farthest away for which data were available. Recall that the vortex represented in the radar observations had a maximum core radius of around 250 m so this range of values is a distance at least twice the core radius away from the main vortex. The other geometric parameters used in all sensitivity texts are shown in Table 1. Since the primary focus of this study was the flow near the surface, a mesh size of 5 m at elevations below 70 m in the inflow cylinder and a much coarser mesh of 50 m above this level were used in all domains.

The two tests showed that the maximum tangential velocity was stronger in case 1 with smaller inflow radius than case 6 but the core radius was smaller in case 1 than case 6 (see Table 2), a result that may be counterintuitive since one might expect the smaller domain to result in a narrower vortex. A larger inflow radius may create a wider but relatively weaker vortex, while a smaller inflow radius generates a narrower but stronger vortex. The core radii were too small and the peak tangential speeds too large compared with the radar data. These problems may reflect errors in other parameters used in the model.

Mesh size would be another important factor that would likely affect the magnitude of the velocity simulated in the numerical model. Because radar observations are lacking below 20 m above ground, and there are no other wind observations available within tornadoes near ground, numerical simulations of the wind profile near the ground are very important for further study of tornado wind loads on structures. Our control experiments used a 5 m grid mesh at elevations below 70 m. To test sensitivity to mesh size, an additional test was performed increasing the mesh size to 20 m and 40 m at elevations below 70 m (case 2 and 3). All other parameters were the same as in case 1 above. The sensitivity test results show that a larger mesh size decreases the peak values of the tangential velocity at 20 m levels and increased the core radius. The lack of sensitivity at higher levels likely reflects the fact that the mesh size was not changed above 70 m (Table 2). The simulated core radius with the coarsened mesh did not change at 110 m elevation and still did not match the radar data profile particularly well. Further tests need to be performed.

As discussed earlier, radar observations showed the core radius increased from 120 m at 20 m elevation to about 250 m at 660 m elevation (Fig. 1). However, the simulations discussed so far showed a core radius only ranging from 78 m to 131 m. Sensitivity tests were performed to diagnose the impact of the outflow cylinder radius on the simulated tornado, particularly its core radius. In the tests, the radius of the outflow cylinder was changed from 300 m to 350 m (case 4) while other parameters were set the same as in the original case 1. The tests show that an enlargement of the outflow radius increases the core radius while at the same time weakening the vortex at all levels (Table 2). Case 5 has the same ratio between outflow radius and inflow radius as case 1 but the results showed that the vortex of case 5 is weaker and wider than case 1. It could be concluded that with the same ratio between outflow radius and inflow radius, a wider and weaker vortex is generated when a larger inflow and outflow radius is assumed. The magnitude of the peak tangential velocity is still stronger than observed radar data at low elevations. It must be pointed out that the tests described so far all used a smooth lower boundary. Tornadoes in the real world affect a surface with some roughness. Differences in the surface characteristics between the simulations and the Spencer tornado must be taken into account before concluding that the parameters tested so far best correlate with those present during the Spencer tornado.

Both numerical and laboratory studies (Lewellen et al 1997) have shown the interaction between the surface and the tornado-like vortex is primarily through the surface roughness. These studies have shown that an increase in surface roughness leads to a lower swirl flow behavior. Laboratory simulations of the surface roughness effects on vortices have been performed in air by Dessens (1972) and in water by Wilkins et al (1975). Both of these studies agreed that surface friction caused an increase in vortex size and a decrease in maximum tangential wind under the condition that all other parameters were unchanged.

In order to consider the impacts of surface roughness in our simulations, we built three rings at radii of 600, 400 and 200 m with height of 3 m (case 7), 5 m (case 8 and 9) and width of 10 m. This choice of geometry was a trade off between grid generation and computational requirements. As Fluent can only simulate directly the ground roughness of very small scale particles (e.g. sand), objects had to be placed near the ground to generate the larger roughness values present in the real world. For our simulations of the Spencer tornado, it appeared that roughness lengths between 20 and 40 cm were likely representative of areas (Simiu and Scanlan 1996). The aerodynamic roughness length is defined to be the height where the wind velocity

Case	Test Parameter	Surface Roughness	Outflow Radius r2 (m)	Inflow Radius r1 (m)	Mesh Size (m)	Inflow Depth h1 (m)	Length of Control Domain Cylinder h2 (m)	Length of Outflow Cylinder h3 (m)	Note
Doppler Radar Velocity Input at 800 m or 1000 m from the Vortex Center									
Case 1	**Original Case**	Smooth	300	800	5	270	1100	500	VD1
Case 2	**Mesh Size**		300	800	20	270	1100	500	
Case 3			300	800	40	270	1100	500	
Case 4	**Outflow Radius**		350	800	5	270	1100	500	
Case 5			375	1000	5	400	1100	500	VD2
Case 6	**Inflow Radius**		300	1000	5	400	1100	500	
Case 7	**Surface Roughness**	Rough 2	300	800	5	270	1100	500	VD1
Case 8		Rough 3	300	800	20	270	1100	500	
Case 9		Rough 3	300	800	5	270	1100	500	
Case 10		Rough 4	300	800	5	270	1100	500	
Laboratory Velocity Input at 800 m (90 in. in laboratory scale) from the Vortex Center									
Case 11	**Input**	Smooth	300	800	5	113	800	500	VL
Case 12		Rough 1	300	800	5	113	800	500	

Table 1: Parameters of the Numerical Domain for Case Studies. Scale of 1:330 is used for Laboratory Simulator versus Spencer 98 Tornado based on R_c at 80-400 m. For roughness tests, Rough 1 indicates 3 rectangular rings 1 m high and 10 m wide at 200 m spacing starting at r = 200 m, Rough 2 = 3 rectangular rings 3 m high and 10 m wide at 200 m spacing starting at r = 200 m, Rough 3 = 3 rectangular rings 5 m high and 10 m wide at 200 m spacing starting at r = 200 m; Rough 4 = 7 rectangular rings 5 m high and 10 m wide at 100 m spacing starting at r = 100 m. Other notations include: VD1 = radial and tangential velocities at 800 m radius from observed radar data up to 270 m elevation; VD2 = radial and tangential velocities at 1000 m radius from observed radar data up to 400 m elevation; VD3 = VD2 except doubled radial velocity; VD4 = VD2 except halved radial velocity; VD5 = VD2 except doubled tangential velocity; VD6 = VD2 except halved tangential velocity; VD7 = VD2 with doubled radial and tangential velocities; VD8 = VD2 with halved radial and tangential velocities; VL = radial and tangential velocities at 800 m radius from laboratory data up to 113 m elevation.

	Core Radius r_c (m)		Maximum Tangential Velocity V_t (r_c) (m/s)		Angular Velocity of the Core ω		Decay Rate n $VR^n = C$	
Z =	20 m	110 m	20 m	110 m	20 m	110 m	20 m	110 m
Radar Data, S=0.19	120	200	81	65	0.40	0.32	0.85	0.72
Case 1, S=0.17	68	107	176	122	2.24	0.48	0.95	0.76
Case 2, S=0.17	95	107	124	123	1.03	0.37	0.92	0.72
Case 3, S=0.17	105	107	69	121	0.41	0.59	0.81	0.77
Case 4, S=0.15	74	107	157	111	2.15	0.51	0.93	0.69
Case 5, S=0.11	72	131	141	88	2.12	0.34	0.98	0.69
Case 6, S=0.11	78	131	141	90	1.96	0.34	0.99	0.70
Case 7, S=0.17	81	107	159	123	2.10	0.68	0.95	0.76
Case 8, S=0.26	230	246	66	60	0.25	0.22	0.93	0.58
Case 9, S=0.21	181	213	74	63	0.40	0.27	0.97	0.69
Case 10, S=0.20	182	213	71	61	0.37	0.26	0.95	0.55
Case 11, S=0.50	112	147	100	65	0.94	0.31	0.94	0.99
Case 12, S=0.72	133	173	85	67	0.62	0.35	1.05	1.12

Table 2: Numerical Simulation Results

decreases to zero. Many experiments have been done to study the relationship between roughness elements and the roughness length (Lettau 1969, Kondo and Yamazawa 1986).

Our tests suggest that the tangential velocity close to the ground was greatly reduced by the rough floor. The reduction in velocity was concentrated near the ground. Comparing case 1 with case 8, the peak tangential velocities decreased from 176 m/s to 74 m/s at 20 m elevation, 7 m/s smaller than observed by radar (Table 2). At a higher level, 110 m, the decrease due to surface roughness was reduced to 63 m/s. Furthermore, increased surface roughness expanded the core radius at low elevations. Assuming conservation of angular momentum, the reduced tangential velocities must be accompanied by an enlarged core radius. In case 9, seven rings were built at every 100 m in the radial direction in order to generate a greater surface roughness. In this test, 20 m winds were reduced an additional 3 m/s from those present in case 8 and 110 m winds were reduced an additional 2 m/s by the increased surface roughness. The Fluent simulations of the Spencer tornado agree with earlier studies in showing surface roughness to decrease peak tangential velocities at low levels and slightly increase the core radius. Also of note, some small-scale turbulence was generated at distances of 400 to 800 m away from the center of the tornado at low levels. Similar turbulent effects were present in the radar data (Fig. 1). These results agree with Leslie (1977) who showed that surface roughness makes the flow more turbulent. m away from the center of the tornado at low levels. Similar turbulent effects were present in the radar data (Fig. 1). These results agree with Leslie (1977) who showed that surface roughness makes the flow more turbulent.

Since the lab simulation is a relative small scale simulation, it is difficult to compare directly with the observed radar data. In addition, it would be expensive to make all changes necessary to the laboratory simulator to investigate sensitivity in the lab to the various parameters discussed above. However, if numerical simulations resemble well both the observed radar data and the lab data, then it is likely reasonable to use the numerical results to compare the lab and radar datasets. To do this, a length scale of 1:330 was applied for the lab simulation data to transform it to be full scale. Thereafter, the velocity at the 800 m radius was used as the inflow in the numerical simulation of case 11 (smooth floor) and case 12 (rough floor). Figure 5 shows that the numerical simulation results match very well with the lab profiles at an elevation of 110 m, especially in case 11 which corresponds to the smooth floor. On the other hand, case 12 matched better with the radar data, which makes sense since it includes roughness effects that would be present in some degree in the real world.

7. DISCUSSION AND CONCLUSIONS

Radar observations taken by the DOW radars for the Spencer, South Dakota tornado of 30 May 1998 were compared to wind information from a laboratory tornado simulator and numerical model results where the radar information was used as boundary condition input. In addition, numerous sensitivity tests were performed with the numerical model to determine the impact from changing some assumed parameters in the domain design, along with the effects of surface roughness.

In general, the numerical model and laboratory simulator generated vortices that agreed well with the radar observations. The numerical model was shown to produce a vortex agreeing well with the lab simulator results at most levels, likely a result of both using a smooth lower boundary. When roughness effects were added to the numerical model, the agreement with radar observations, already reasonable at most levels away from the surface, improved.

In sensitivity tests, the core radius of the tornado decreased as the inflow conditions were defined using radar data increasingly far from the center of the tornado. Although the simulated tornado became too narrow when the inflow conditions were defined at these relatively far distances, the vertical profiles of tangential velocity agreed best with radar observations, showing strongest velocities at the levels closest to the ground, and an increase of core radius with elevation. The mesh size used in the model also impacted the simulations, with larger mesh size reducing the magnitude of the tangential velocity. Thus, it appears to be important to use the smallest mesh size possible within the constraints of limited computational resources. The radius of the outflow cylinder was found to control both the size and intensity of the vortex. Enlarging the outflow radius increased the core radius while reducing the tangential velocities at all levels. Surface roughness was found to decrease peak tangential velocity, which occurs at low levels, but had a reduced effect at higher levels. Surface roughness enlarged the vortex core radius as it reduced tangential velocity, a result agreeing with previous studies. Furthermore, it was found that another impact of surface roughness was to make flow more turbulent so that greater eddy exchange of momentum occurred. The more turbulent vortex could be more destructive because the speed and directions of the wind would fluctuate rapidly (Leslie 1977).

The general agreement between radar, numerical simulation, and laboratory simulator results suggest that tests performed in the Iowa State simulator to determine tornado loads on built structures should reasonably approximate what is observed in nature, potentially leading to cost effective ways to improve the ability of built structures to withstand the winds from most tornadoes.

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