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IMPACTS OF TORNADIC SUPERCELLS ON THE CENTRAL BUSINESS DISTRICT OF OKLAHOMA CITY

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1. INTRODUCTION

A previous misconception was that tornadoes could not strike cities. Elsom and Meaden (1982) showed that in fact tornadoes could and did strike cities, but mostly on the urban fringe, not the central business district (CBD) locations. With a few exceptions (e.g. the Miami tornado in 1997), most of the tornado events to impact urban areas have been on the outer reaches of the city. Some recent examples of cities with tornado touchdowns were Nashville, Salt Lake City, Birmingham, and Oklahoma City (multiple times). While the probability of tornadoes in the CBD of cities was small given the very limited spatial extent of the locations as well as the relatively small size of tornadoes, the impact of other features of the parent thunderstorm (e.g. rear-flank downdraft and forward flank downdraft) were more frequent and widespread.

On 8 and 9 May 2003, two tornadic supercells struck portions of Oklahoma City. While it was not a surprise that supercells or tornadoes could impact large urban areas (especially in ‘tornado alley’), it was very unlikely that two similar events could occur approximately thirty hours apart. Due to the Oklahoma Mesonet, the proximity of the National Weather Service (NWS) operational Doppler radar, and urban meteorological instruments (installed during a preliminary study for Joint Urban 2003), these unique events were recorded with great detail. Fortunately no fatalities and few injuries were reported during both events even though significant damage occurred along each storm path.

Because of the size of Oklahoma City (land area) and location, many supercells (not all tornadic) have impacted the city. A tornado climatology, compiled by Brooks et al, (2003), showed that for any given year, central Oklahoma would experience 1.25 tornado days. Furthermore, Branick (2003) demonstrated that, on average, a tornado hit the Oklahoma City metropolitan area each year.

While the CBD of Oklahoma City was spared by the tornadoes produced on 8 and 9 May 2003, features of the supercell that directly impacted the CBD of Oklahoma City were the forward-flank and rear-flank downdrafts. Quantitative comparisons between urban and rural variables measured were conducted and this study presents the relative difference between thermodynamic and dynamic parameters inside and outside of the city during events.

2. BACKGROUND

2.1 *Instruments and Data*

Numerous instrument platforms collected data during the 8 and 9 May 2003 events including observations from the Twin Lakes WSR-88D (KTLX) radar, Automated Surface Observing System (ASOS) data from Will Rogers World Airport (KOKC) and Wiley Post Airport (KPWA), the Oklahoma Mesonet, and Portable Weather Information and Display System (PWIDS) stations were greatly examined for quantitative results.

The Oklahoma Mesonet, an automated network of 115 permanent meteorological stations dispersed across the state of Oklahoma (Brock et al., 1995), was used to determine ambient atmospheric conditions at the surface in locations outside of Oklahoma City. Each Mesonet Site measured solar radiation, air pressure, precipitation, wind speed and direction at 10 meters, temperature and relative humidity at 1.5 meters, and bare soil and sod temperatures at 10 centimeters depth (Brock et al., 1995). A majority of sites also measured temperature at 9 meters, net radiation, and numerous soil properties at various depths (Brock et al., 1995). For this study observations of wind speed, wind direction, temperature, and relative humidity recorded by Mesonet Sites surrounding Oklahoma City (Figure 1). The measurements of these parameters were collected at five-minute intervals and analyzed.

As part of a preliminary study for Joint Urban 2003, PWIDS sites were installed in and near the CBD of Oklahoma City for nearly a year beginning in June 2002. The PWIDS sites measured wind speed, wind direction, temperature, and relative humidity. Most sites were mounted atop street light/traffic light poles, approximately ten meters

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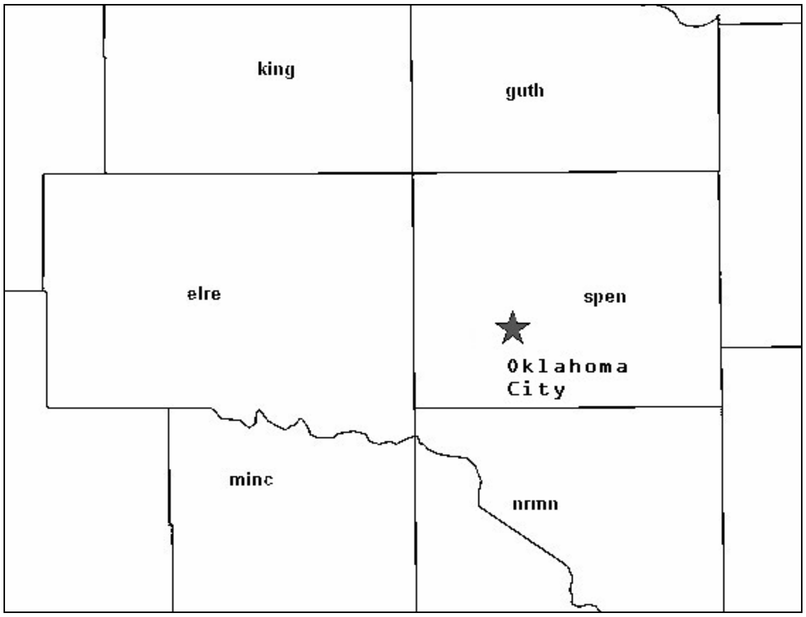

Figure 1. Station identifiers for Central Oklahoma Mesonet Sites relative to the central business district of Oklahoma City (indicated by a star).

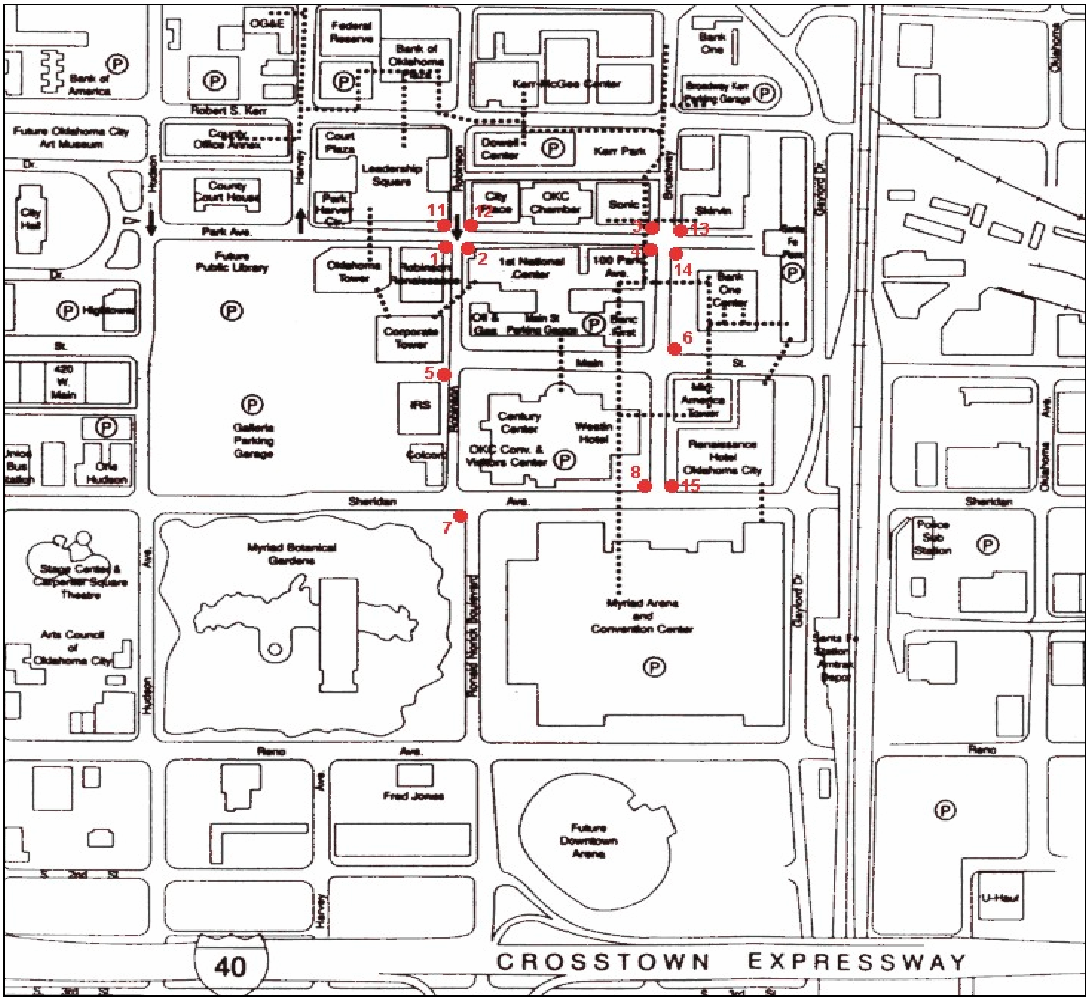

Figure 2. Locations of PWIDS sites within the CBD of Oklahoma City. Streets and building footprints were displayed on this figure.

above ground level. Thirteen of the PWIDS Sites (P1-P8 and P11-P15) were used for this study, all within four blocks of each other (Figure 2). Unlike the Mesonet Sites, PWIDS recorded data every ten seconds during this study.

2.2 *Basic Features of a Supercell Thunderstorm*

Figure 3 illustrates the Lemon and Doswell (1979) conceptual model of a supercell thunderstorm. Besides the tornado, two downdraft regions and one updraft region were apparent in this model. "One downdraft is located in the precipitation cascade region downwind of the updraft. The other downdraft lies immediately upwind of the updraft" (Lemon and Doswell 1979). In the model, the updraft region supplies the storm with an inflow of warm moist air, while the downdraft regions consist of precipitation and air cooled by evaporation. As the hydrometeors are transported away from the central updraft region, gravity overcomes the upward acceleration, causing the hydrometeors to fall. Thus, the forward-flank downdraft (FFD) of the supercell tends to be cooler and more moist than the surrounding environment (Lemon and Doswell 1979). Conversely, the rear-flank downdraft (RFD) was drier than the ambient conditions and cooler than ambient temperatures but warmer then the FFD (Markowski 2002b). As either the FFD or RFD reach the surface, the air spreads outward in all directions, hence the radial distribution of streamlines from each downdraft in Figure 2. Further information about supercell thunderstorms and RFDs could be found in Lemon and Doswell (1979) and Markowski (2002a and b).

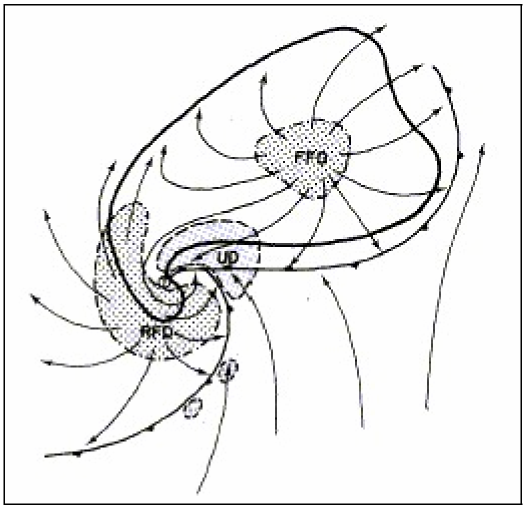

Figure 3. Idealized view of a supercell thunderstorm. Bold lines denoted outline of radar echoes, arrows displayed surface wind flow. Storm motion was to the upper right. Adapted from Lemon and Doswell (1979).

3. EVENTS

3.1 *8 May 2003*

Synoptic scale conditions were extremely favorable for isolated supercell development in Oklahoma on 8 May 2003. At 1200 UTC on 8 May 2003, an upper level jet streak was present over northern New Mexico oriented from southwest to northeast and had speeds in excess of 60 meters per second. This jet streak pushed out into the central plains, and thus, Oklahoma was under southwesterly flow at 300 mb level by late afternoon.

Meanwhile a strong 850 mb low moved from eastern Colorado into Nebraska, which led to strong southerly flow over most of the central plains area. South of the 850 mb low, a surface low pressure center propagated from eastern Colorado into central Kansas. In response to the surface low, south-southeasterly winds were present over Oklahoma. This surface low advected adequate amounts of surface moisture needed for severe thunderstorm development. Additionally, an eastward moving dryline extended south, from the surface low, into central Texas and provided the low-level forcing needed for storm initiation.

By 2100 UTC on 8 May, thunderstorms began to develop southwest of Minco, OK. Over the next thirty minutes one thunderstorm developed into a supercell thunderstorm while a second, weaker thunderstorm passed over the CBD of Oklahoma City ahead of the main supercell at 2140 UTC. From 2145 to 2200 UTC the FFD of the main supercell passed through the CBD of Oklahoma City. The mesocyclone of the supercell, and the coincident tornado, translated eastward just ten kilometers south of the CBD (Figure 4). While no in situ instruments were installed to measure rain in the CBD, radar observations clearly revealed that heavy precipitation fell on the CBD during the same time span. By 2225 UTC the supercell had passed out of the CBD.

3.2 *9 May 2003*

The synoptic conditions for 9 May were little changed from the previous day. The 300 mb trough axis remained along the western side of the Rocky Mountains. East of the trough was another jet streak oriented the same as the previous day and extended from southern Arizona, through New Mexico, into the Texas and Oklahoma Panhandles. By 0000 UTC 10 May, southwesterly upper level flow was present over Oklahoma. A new 850 mb low developed over New Mexico, which provided strong southerly flow at low-levels. In addition a new surface low propagated east from the Rocky Mountains into the Texas Panhandle by 0000 UTC. Again a dryline moved from west Texas through western Oklahoma.

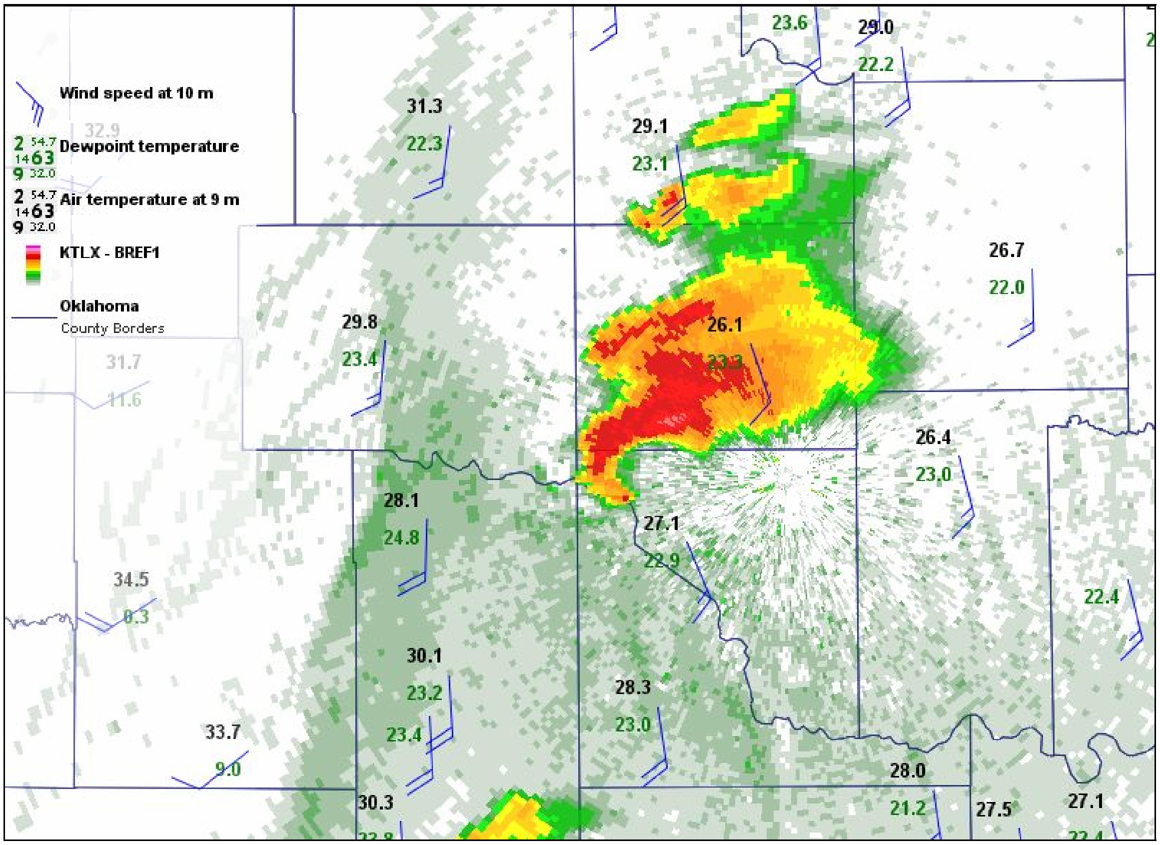

Figure 4. Conditions in Central Oklahoma 8 May at 2205 UTC. Wind barbs denote wind speed and direction at each Mesonet Site. Nine-meter temperature (top number) and surface dewpoint (bottom number) indicated as well. Map also displayed radar base reflectivity. Forward flank of the supercell was completely over the CBD of OKC.

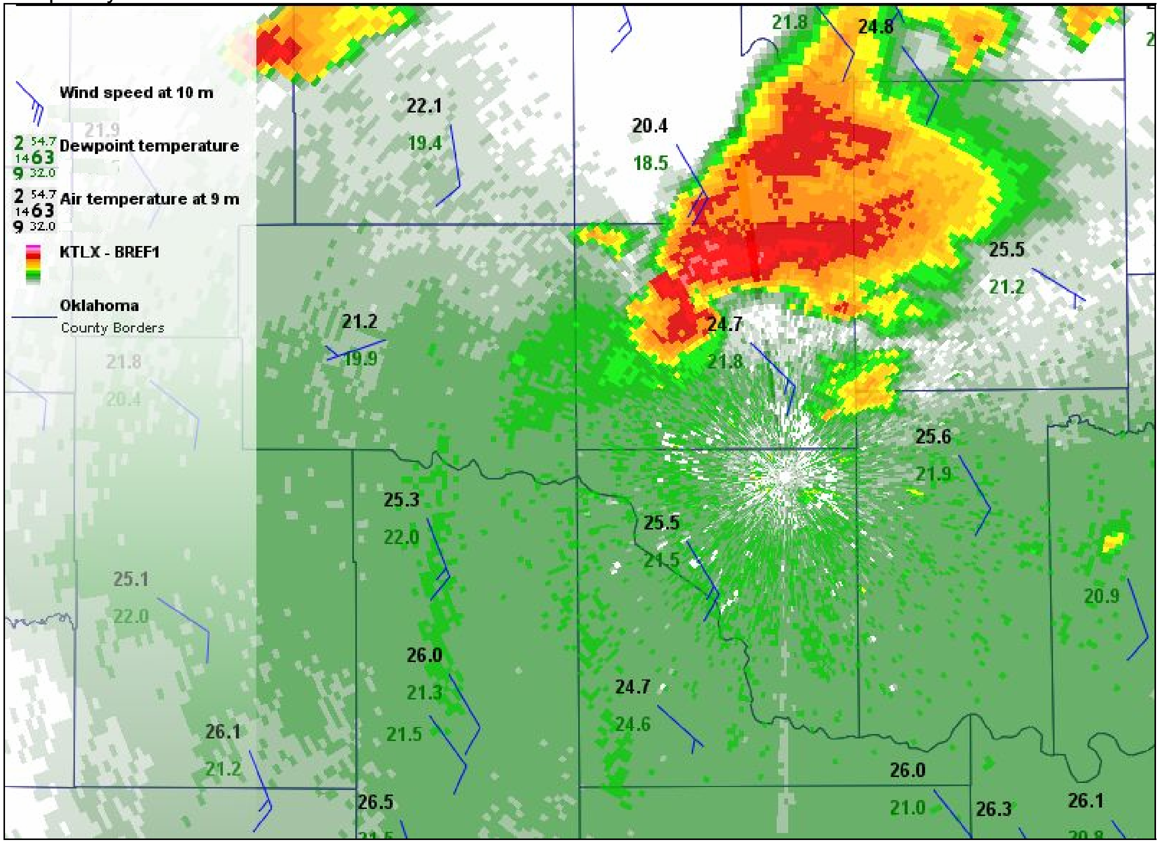

Figure 5. Same as Figure 3 except on 10 May (9 May supercell) at 0340 UTC.

The dryline initiated several thunderstorms during the day on 9 May. By 0125 UTC the main supercell approached central Oklahoma, and by 0220 UTC the leading edge of the supercell was over western Oklahoma City. For most of the event the CBD was skirted with rain (doppler estimated) because as the storm passed north of the CBD, downtown Oklahoma City remained in the inflow region of the supercell until approximately 0340 UTC when the RFD passed through (Figure 5). At its closest point, the mesocyclone and adjoining tornado was six kilometers to the north of the CBD from 0310 to 0330 UTC, and by 0400 the supercell was no longer over the CBD.

4. Discussion

Time series data from the PWIDS sites were examined and compared to Mesonet site measurements for both events. As such, the differences between the ambient (rural) and CBD conditions were analyzed, which provided the magnitude of perturbation the storms created over the urban and rural areas.

4.1 *Time Series of the Tornadic Supercell Events*

4.1.1 *8 May 2003*

Prior to the supercell approaching Oklahoma City, temperatures measured within the CBD varied between 29 to 30 degrees Celsius. However, when the anvil approached and reduced the downwelling solar radiation temperatures cooled and less variability was observed. As the FFD approached and passed, precipitation increased, and the cooling rate increased substantially. Most sites converged to nearly the same temperature value, and remained at the value until the influence of the supercell passed. While in the FFD, temperature measurements decreased to 21 degrees Celsius. However, after passage of the thunderstorm, temperatures increased to nearly 29 degrees Celsius with increased variability. Table 1illustrates the magnitude of temperature decrease at each PWIDS and central Oklahoma Mesonet sites during this event. While Spencer (SPEN) was the closest Mesonet site to be impacted by the supercell, the site did not measure the same temperature decreases that were observed within the CBD.

The variability in wind direction was quite large during the 8 May supercell event. One example was P11, where nearly 180 degrees in wind direction change was observed before and after the thunderstorm passed over the city. The variation was mostly dependent on the north-south and east-west orientation of the streets and the entry flow into the city. However, when the supercell passed over the city, the wind direction variation decreased to approximately sixty degrees. Conversely, P1 had little variation in wind direction (less than thirty degrees) during most of the period. However, there was considerable backing of the flow, nearly 180 degrees, at this site when the thunderstorm passed over the city.

Additionally wind speed had great disparity between PWIDS sites. However, unlike the wind direction, the general patterns of the wind speeds were similar. As the impacts of the FFD intensified, wind speeds increased in the CBD. Most peak winds were recorded during this time, and then decreased significantly. However, once the supercell thunderstorm moved away from the city, wind speeds increased to pre-storm levels. Table 1 illustrates the peak winds measured inside and outside the CBD of Oklahoma City.

Temperature Decrease		Wind Gusts
Location	(Celsius)	(Meters per Second)
ELRE	3.5	12.6
GUTH	4.5	14.6
KING	4.6	14.4
MINC	4.9	15.6
NRMN	1.2	13.4
SPEN	7.8	14.9
P1	8.2	11.2
P2	8.3	6.9
P3	8.7	7.5
P4	8.3	9.9
P5	8.5	10.5
P6	8.7	11.7
P7	9.0	10.3
P8	9.4	4.9
P11	8.6	7.5
P12	8.4	7.4
P13	8.3	13.9
P14	8.4	9.0
P15	9.3	6.7
KOKC	-	14.4
KPWA	-	14.4

Table 1. Decrease in temperature and peak winds during the 8 May 2003 supercell event for PWIDS, central Oklahoma Mesonet, and ASOS sites.

4.1.2 *9 May 2003*

Similar to the 8 May event, temperatures within the CBD were relatively similar (within a half degree Celsius of each other). Two factors could have contributed to the smaller degree of variance: 1) a small rain shower occurred over the city prior to the approach of the updraft/inflow and RFD, 2) over two hours has passed since the sun had set yielding less differential heating. Nonetheless, temperatures measured at each site decreased as the RFD passed through the CBD. A curious feature, which was measured by most of the PWIDS sites, was a temperature spike of nearly one degree Celsius around the time of the RFD passage resulting from a 'warm' RFD passage, or a warm inflow into the supercell. However, when the rain cooled air moved through the city, temperatures rapidly decreased. Once the supercell had passed, the temperatures returned to pre-storm levels, as in the 8 May case. Table 2 displays the magnitude of temperature declines for the 9 May event.

Observations of wind directions for all PWIDS sites yielded less deviation than the 8 May event. For example, P11 observed only a ninety degree variation before the supercell passed by the city, while P1 had less than fifty degrees of variation. For this case winds tended to become more sporadic at sites after the outflow from the storm went through the CBD. As mentioned before, this could have been due to the approach angle of the entry winds. For most sites the winds veered as the RFD moved across the CBD and wind speed variation was similar to 8 May. As the storm approached, increased variability of wind speed was observed followed by a peak wind around the time of the RFD passage. Once the storm passed, wind conditions returned the ambient flow. Table 2 illustrates the peak wind measured at different locations.

Temperature Decrease		Wind Gusts
Location	(Celsius)	(Meters per Second)
ELRE	2.9	16.4
GUTH	3.4	15.6
KING	3.7	9.2
MINC	0.9	15.4
NRMN	0.4	11.8
SPEN	2.8	8.2
P1	2.4	9.87
P2	2.6	8.94
P3	2.5	10.97
P4	2.3	10.9
P5	2.3	11.9
P6	2.1	10.94
P7	-	-
P8	-	-
P11	2.4	8.56
P12	2.6	5.27
P13	2.4	11.27
P14	2.5	8.56
P15	-	-
KOKC	-	11.8
KPWA	-	-

Table 2. Decrease in temperature and peak winds during the 9 May 2003 supercell event for PWIDS, central Oklahoma Mesonet, and ASOS sites.

4.2 *Comparison between urban and rural measurements*

4.2.1 *8 May 2003*

It was not surprising to see that the average temperatures within the CBD deviated substantially from the ambient environment as the supercell tracked across the city. Rain cooled air dominated the city, leading to a seven degree Celsius difference. What was surprising about the 8 May event was the rapid return to the ambient temperature experienced in the CBD. Figure 6 displayed the change in temperature difference over time for both the CBD (averaged from all PWIDS) and SPEN. Prior to the supercell event there was little difference between the ambient environment and the CBD. When the core of the FFD passed through the city, at approximately 22:05 UTC (see also Fig. 4), the temperature perturbation increased significantly. SPEN experienced a similar decrease in temperature fifteen to twenty minutes later as the supercell passed over. However, the maximum temperature difference within for the CBD was more abrupt than for SPEN.

Wind speeds measured within the CBD were less than the ambient speeds for this time span. Additionally, SPEN experienced below average wind speeds during the entire supercell event. Figure 7 displays the change of wind speed differences over time, which reveals a lull in near-surface flow within the CBD. Conversely, SPEN did not experience as strong or as long of increase in wind speed differences when the storm passed over.

Differences were again apparent between ambient and CBD conditions, this time with regards to dewpoint depressions (Fig. 8). Prior to the supercell passage, the CBD began with a greater dewpoint depression (less moist air) than the surrounding environment. As the storm approached the city, the CBD became more moist than the surroundings. Again, as the FFD and associate precipitation propagated through the city, the air within the CBD became more moist. After the storm left the city, there was a brief decrease in air moisture, relative to the surrounding environment. On the other hand, SPEN was more moist than ambient conditions for the entire event.

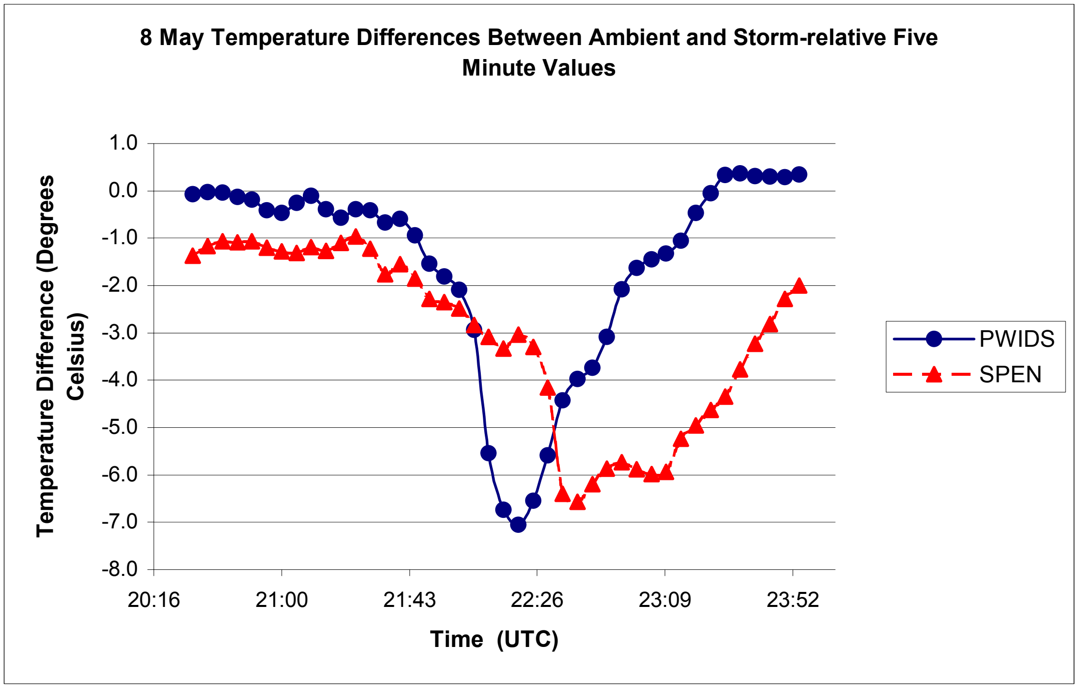

Figure 6. Comparison between ambient and storm-relative temperatures on 8 May 2003. Ambient temperatures were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative temperatures referred to either the average temperature computed from the PWIDS sites or the recorded temperature at SPEN. Negative values depicted cooler storm-relative temperatures.

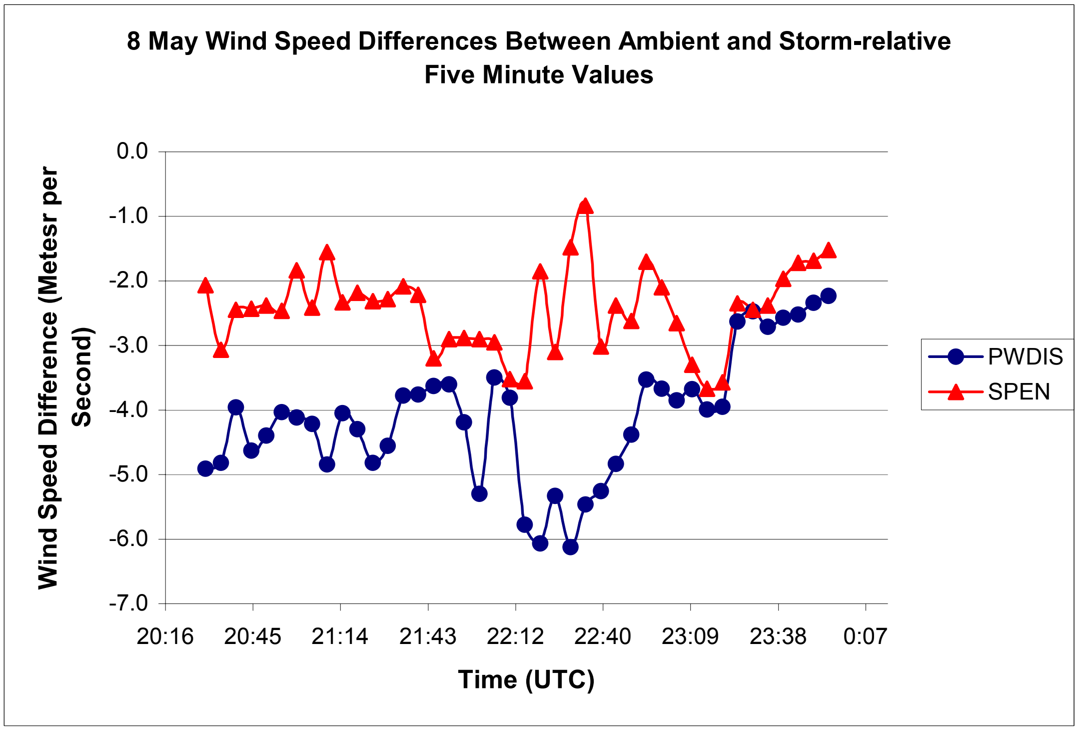

Figure 7. Same as Figure 6 only for wind speed. Ambient wind speeds were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative wind speeds referred to either the average wind speed computed from the PWIDS sites or the recorded wind speed at SPEN. Negative values depicted slower storm-relative wind speeds.

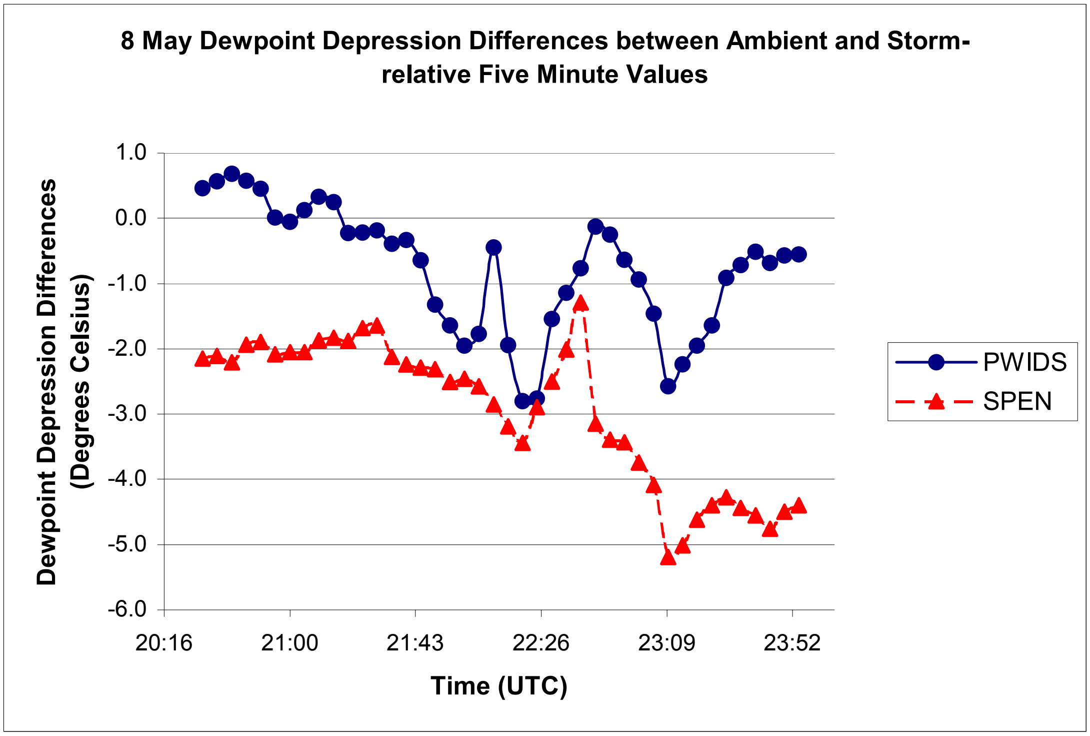

Figure 8. Same as Figure 7 only for dewpoint depressions on 8 May 2003. Ambient dewpoint depressions were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative dewpoint depressions referred to either the average dewpoint depressions computed from the PWIDS sites or the recorded wind speed at SPEN. Negative values depicted lower storm-relative dewpoint depressions (more moist conditions).

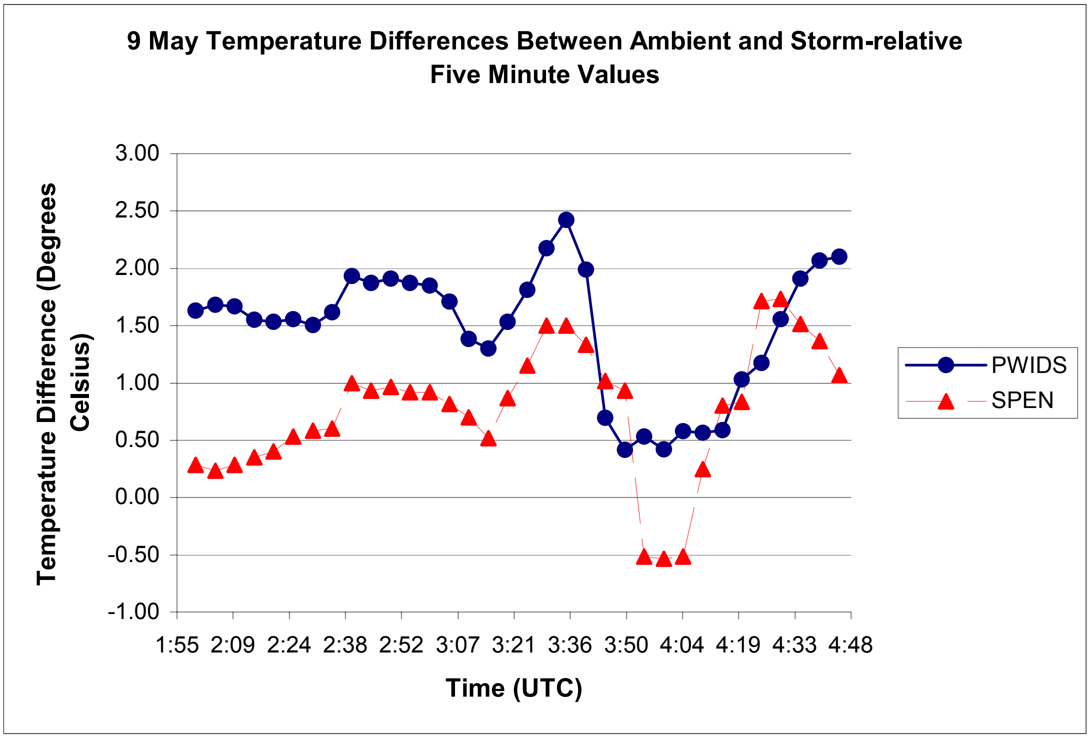

Figure 9. Comparison between ambient and storm-relative temperatures on 10 May 2003 (the 9 May event). Ambient temperatures were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative temperatures referred to either the average temperature computed from the PWIDS sites or the recorded temperature at SPEN. Negative values depicted cooler storm-relative temperatures.

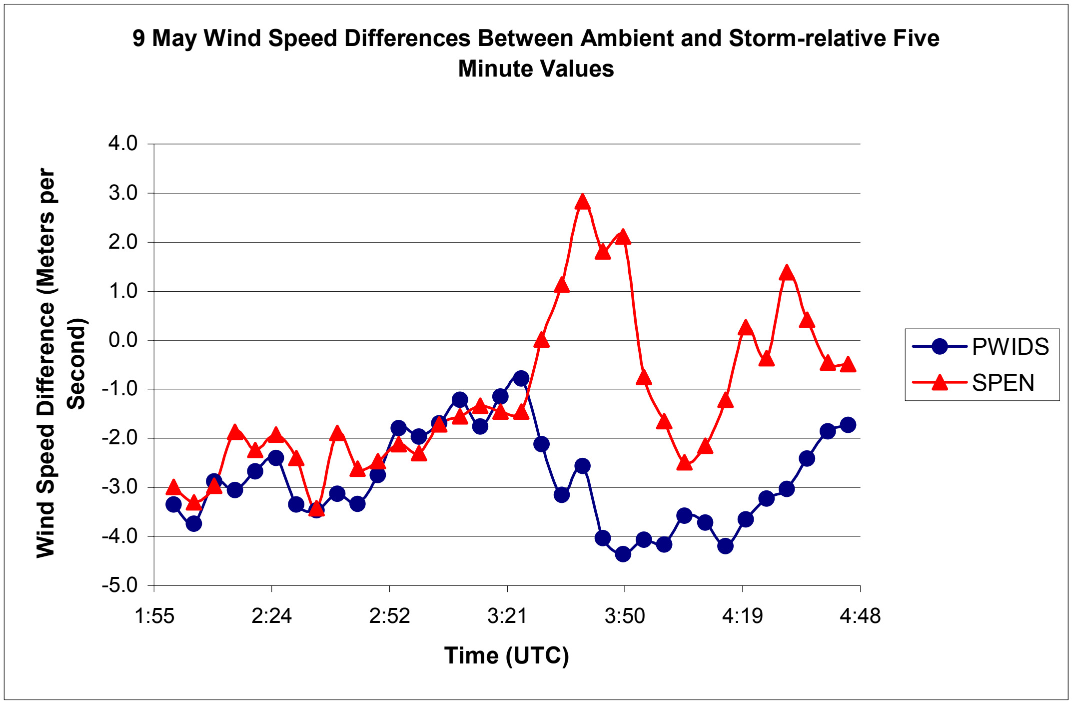

Figure 10. Same as Figure 9 only for wind speeds on 10 May 2003 (9 May event). Ambient wind speeds were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative wind speeds referred to either the average wind speed computed from the PWIDS sites or the recorded wind speed at SPEN. Negative values depicted slower storm-relative wind speeds.

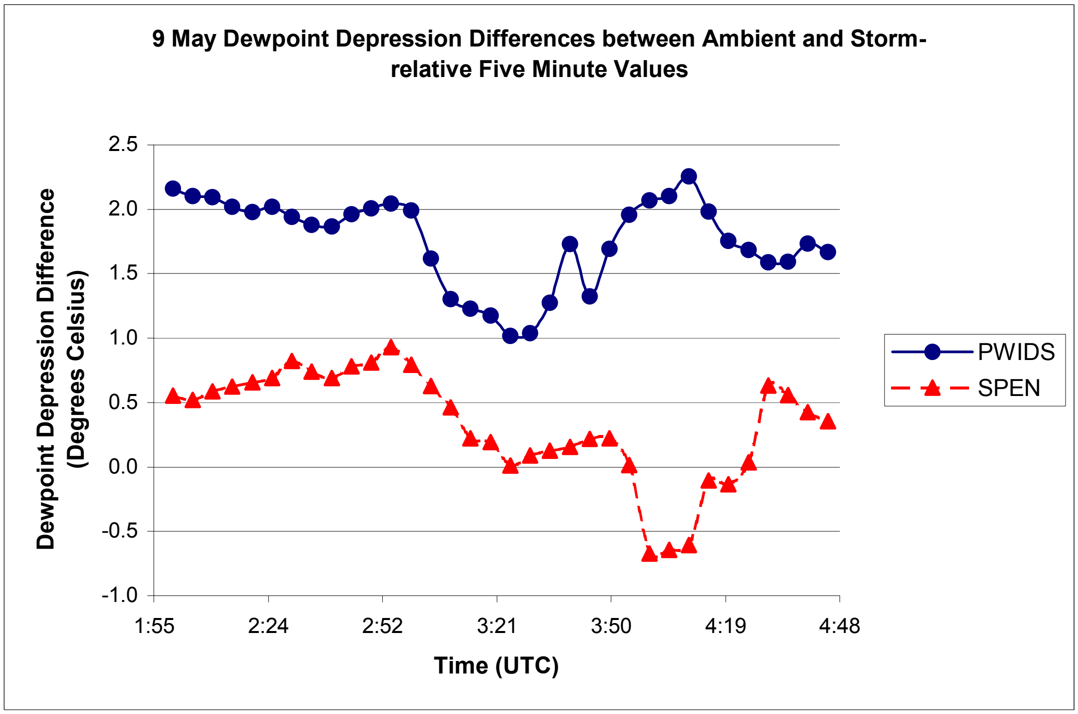

Figure 11. Comparison between ambient and storm-relative dewpoint depressions on 8 May 2003. Ambient dewpoint depressions were calculated by averaging the six surrounding Mesonet sites during the entire period. The storm-relative dewpoint depressions referred to either the average dewpoint depressions computed from the PWIDS sites or the recorded wind speed at SPEN. Negative values depicted lower storm-relative dewpoint depressions (more moist conditions).

4.2.2 *9 May 2003*

The tornadic supercell event on 9 May yielded different results from the previous day. Temperature differences for the CBD had nearly an identical trend when compared to SPEN (Fig. 9). The only disparity was the magnitudes of temperature differences. The CBD was always warmer then ambient conditions, but approached surrounding temperatures as the RFD and precipitation associated with it progressed through the city. Once the storm passed, the difference in ambient to CBD temperature increased. At one point SPEN was cooler than ambient conditions because the RFD and associated precipitation impacted the site. One final note, it took the city nearly five times longer than SPEN to return to ambient conditions.

Once again, wind speeds within the city were lower than the ambient wind speed. Conversely, SPEN experience wind speeds up to three meters per second higher than the ambient conditions. Figure 10 displays the wind speed perturbation over time for the 9 May event. As the core of the storm approached the CBD, wind speed difference reduced, but never was greater than ambient conditions. When the storm moved away from the city, the CBD experience a lull (indicated on Figure 10 by the minimum values after 0350 UTC). SPEN recorded a similar lull, but the duration was not as long.

Air moisture conditions within Oklahoma City were drier than the surrounding environment. Figure 11 illustrates that prior to the supercell event, the difference between dewpoint depression in rural versus urban areas did decrease over time within the CBD, and hence it approached ambient dewpoint depression values. However, after the storm passed through the city, the magnitude of dewpoint depression difference in the CBD increased (the city was more dry than the ambient environment). As for SPEN, the dewpoint depression remained slightly larger than the environment, then reduced after the storm passed.

5. CONCLUSION

The tornadic supercells of 8 and 9 May 2003 had an impact on the CBD of Oklahoma City. The FFD and RFD of two separate storms passed through the CBD on subsequent days. Each event was unique despite a storm track that only varied by 25 kilometers.

It was determined that homogeneous outflow passed through the CBD for each event. On 8 May the outflow resulted from the forward-flank downdraft, while on 9 May the outflow was associated with the rear-flank downdraft. Temperatures within the city were somewhat varied prior to the downdrafts, but became uniform during the events. Hence, the outflow from the storms masked any urban thermodynamic effects. After supercells left the urban area, temperatures rebounded to pre-storm values. Also, winds had high directional variability prior to events, but for many locations there was a significant decrease in wind variability when the thunderstorm outflow passed through the city.

The RFD from the 9 May supercell infiltrated the CBD of Oklahoma City and was “dry” (i.e. lacked precipitation). There was a slight dewpoint depression increase (drier air) as the RFD passed through the CBD. Also, the RFD may have been ‘warm’ (i.e. the temperature perturbations were above the ambient values). It was found that a small increase in temperature accompanied the passage of the RFD. Average wind speeds within the CBD were less than those locations north and west of the CBD. Unfortunately, the wind measurements at Wiley Post Airport were not available during the tornadic event. Because both the tornado and RFD directly hit the airport it would have given an extremely useful measurement of the magnitude of wind speed to compare to the CBD.

It should be noted that some of the results could have been a product of the relatively small area covered by the PWIDS sites, and distance to nearby Mesonet sites. Also, the proximity of the PWIDS sites to buildings results in increased surface roughness may have skewed the wind speed decrease within the city. It is often observed in cities that winds can be accelerated through openings in the urban canyon. Only the integration of a permanent urban micronet and future storm passage could resolve these concerns. Regardless, the measurements that were taken on 8 and 9 May 2003 offered interesting details into both mesoscale and urban scale meteorology.

6. ACKNOWELDGEMENTS

This study was made possible, in part, by funding from the Defense Threat Reduction Agency. The authors would like to thank Donny Storwald for providing the PWIDS Data. Additional thanks go to Mark Shafer, Rachael Sigler, and Danny Cheresnick for their assistance in acquiring and viewing the radar data.

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