The Relationship between Severe Weather Warnings, Storm Reports, and Storm Cell Frequency in and around Several Large Metropolitan Areas

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ABSTRACT

The spatial distribution of storm-based severe weather warnings, local storm reports, and radar-detected storm cells around six large cities in the central United States is examined from October 2007 to May 2017. The cities are Columbus, Ohio; Cincinnati, Ohio; Indianapolis, Indiana; Louisville, Kentucky; Nashville, Tennessee; and St. Louis, Missouri. In all six cities, warning counts within 20 km of the city center are found to vary by 20%–40%. In every city except St. Louis, a maximum in warnings is located 5–15 km to the east (downwind) of the city center. Additional analysis reveals that the location of the warning maxima often varies with wind direction. Areas of enhanced convective activity are also evident in and around each city. Many of these areas are found to the east of the city center and are coincident with areas of increased warnings. This alignment could suggest that urban influences are creating areas of enhanced severe weather potential on the eastern side of large cities. However, there are also instances where the locations of maxima in warnings, local storm reports, and convective activity are spatially offset. In these locations, it is possible that other factors are impacting the distribution of one or more of these fields.

1. Introduction

Severe weather events such as large hail, strong winds, and tornadoes remain a large threat to life and property. An outbreak of large hail or damaging winds is capable of producing billions of dollars in damage (<https://www.ncdc.noaa.gov/billions/events.pdf>), while a single large tornado can result in hundreds of casualties and billions of dollars in damage (e.g., Brooks and Doswell 2001). From 1980 to 2011 severe local storms caused over \$90 billion in adjusted property damage in the United States (Smith and Katz 2013). Because of the strong societal

impact, it is important to understand the temporal and spatial distributions of damaging severe weather events.

The climatology of severe weather in the United States has been studied extensively. Tornadoes (and tornadic environments) are most frequent across the Great Plains (e.g., Brooks et al. 2003) while large hail events are most common in the High Plains region (e.g., Doswell et al. 2005; Cintineo et al. 2012). Weiss et al. (2002) found that damaging wind gusts are most often reported in the upper Midwest, Ohio valley, and Carolinas. Derechos are most common in the southern Great Plains (Bentley and Mote 1998), with a secondary maximum in the Ohio valley and along the shores of Lake Michigan (Ashley and Mote 2005). While the large-scale patterns of severe weather are well known, there may be smaller-scale variability embedded within that pattern due to the influence of local features. For example, significant topographic features have been found to produce preferred areas of convective initiation (e.g., Toth and Johnson 1985), and the Denver Cyclone has been associated with the frequent occurrence of nonsupercell tornadoes in northeast

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Colorado (e.g., [Szoke et al. 1984](#); [Wakimoto and Wilson 1989](#)). Surface characteristics may also be influential to severe weather formation. [Kellner and Niyogi \(2014\)](#) found that many tornadoes within Indiana touchdown near areas of land surface heterogeneity.

Another potential source of localized severe weather variability is large cities. It has been known for decades that large urban areas can influence regional precipitation. [Changnon \(1968\)](#) discussed the so-called La Porte weather anomaly—an area in northwest Indiana that received 30%–40% more rain and thunder than surrounding areas from the 1940s until the mid-1960s. This anomaly has been attributed to urban processes occurring within nearby Chicago, Illinois (e.g., [Changnon 1980](#)). The Metropolitan Meteorological Experiment (METROMEX) field project revealed that many large urban areas—St. Louis in particular—experience enhanced precipitation in areas downwind of their urban center (e.g., [Changnon et al. 1971](#); [Huff and Changnon 1973](#); [Changnon et al. 1976](#); [Braham et al. 1981](#)). More recently, the Atlanta, Georgia, metropolitan area has been found to contain regions of enhanced convective activity (e.g., [Bornstein and Lin 2000](#); [Dixon and Mote 2003](#); [Mote et al. 2007](#); [Shem and Shepherd 2009](#); [Bentley et al. 2012](#); [Stallins et al. 2013](#); [Haberlie et al. 2015](#)). Other cities have also been found to impact regional precipitation patterns. A 50-yr climatological study of the eastern United States showed an increasing trend in summertime precipitation events downwind of urbanized areas ([Niyogi et al. 2017](#)). [Burian and Shepherd \(2005\)](#) attributed increased precipitation amounts over and downwind of Houston, Texas, to rapid urbanization and growth. [Niyogi et al. \(2011\)](#) studied 91 different summertime convective events interacting with Indianapolis, Indiana, and found that more than half of the storms changed structure while passing over the city.

The degree to which precipitation is modified by urban environments seems to vary by location. Summarizing the results of METROMEX, [Huff and Changnon \(1973\)](#) note areas of enhanced precipitation in six of the eight cities studied. In addition, some of these cities only experience an increase in precipitation within the city limits while others experienced an increase both in the city and downwind. [Shepherd et al. \(2002\)](#) found enhanced rainfall rates downwind of five different U.S. cities, with the magnitude of the increase relative to the upwind side ranging from 15% to 51%. [Ganeshan et al. \(2013\)](#) studied multiple U.S. cities and found that the urban influence on rainfall anomalies varies by geography, with inland cities experiencing an increase in nocturnal convection and coastal cities experiencing an increase in afternoon convection. Using a suite of idealized numerical simulations, [Schmid and Niyogi \(2013\)](#)

found that city size can have a substantial impact on the magnitude of urban-induced precipitation modification.

Spatial variations in precipitation patterns around urban areas are often a result of changes to storm structure. [Huff and Changnon \(1973\)](#) suggested four mechanisms by which the urban environment can impact precipitation: destabilization via the urban heat island (UHI), an increase in low-level turbulence due to flow obstruction, microphysical modifications due to urban aerosol emissions, and modification of atmospheric moisture content. Subsequent work has yielded further insight into these four mechanisms. Numerous studies have found evidence of convergence zones caused by differences in land usage between urban and surrounding environments (e.g., [Hjelmfelt 1982](#); [Bornstein and Lin 2000](#); [Fujibe 2003](#); [Rozoff et al. 2003](#); [Niyogi et al. 2006](#)). These convergence zones can lead to areas of preferred convective initiation (e.g., [Braham et al. 1981](#); [Craig and Bornstein 2002](#); [Haberlie et al. 2015](#)). Modifications to aerosol size distributions via industrial pollution have also been shown to have an impact on urban precipitation (e.g., [Van den Heever and Cotton 2007](#); [Ochoa et al. 2015](#); [Schmid and Niyogi 2017](#)). While some have suggested that urban areas should experience reduced precipitation amounts because the added aerosols create smaller droplets and inhibit hydrometeor growth, numerous studies have found that urban areas (and areas downwind) actually experience enhanced precipitation amounts (e.g., [Jauregui and Romales 1996](#); [Changnon and Westcott 2002](#); [Hand and Shepherd 2009](#)). These findings may indicate that the impact of enhanced surface convergence dominates any detrimental effects due to modified aerosol size distributions (e.g., [Jin et al. 2005](#); [Van den Heever and Cotton 2007](#)). Urban moisture values appear to be significant as well. [Braham et al. \(1981\)](#) note that boundary layer equivalent potential temperature θ_e values tend to be several degrees smaller over St. Louis compared to surrounding regions due to decreased moisture over the urban center. They hypothesized that updrafts in urban clouds are “less energetic” due to the decreased θ_e values. [Rozoff et al. \(2003\)](#) found significant spatial variations in convective available potential energy (CAPE) in their simulations of a St. Louis thunderstorm. These variations were attributed to differences in latent heat fluxes as well as patterns of convergence and divergence.

Although it has been well established that large urban areas can modify the distribution of convective precipitation, it has yet to be determined if there is a similar impact on severe weather events. Before investigating the impact of large cities on severe weather, the overall distribution of severe weather events must be determined. One potential starting point would be to analyze local storm reports. However, as noted in several previous studies, storm report

data must be used with caution. Weiss et al. (2002) outline several issues associated with the use of local storm reports. The number of reports is influenced by the time of day of the event as well as the population distribution in the area of the event. Some reports may also be inaccurate or miscategorized due to human error. Trapp et al. (2006) found that the number of reports for a specific event is not necessarily representative of the magnitude of that event, with significant events sometimes having fewer reports compared to less significant events.

Another potential method would be to examine the distribution of severe weather warnings issued by the NWS. A fairly obvious deficiency of warnings is that they do not directly correlate with severe weather events, as is evident by the large fraction of tornado warning false alarms (e.g., Brooks 2004; Barnes et al. 2007; Simmons and Sutter 2009). Additionally, studies have shown that nonmeteorological factors such as population density can have a strong impact on warning distributions (e.g., Davis and LaDue 2004; Dobur 2005). White and Stallins (2017) analyzed warnings issued by 36 NWS offices and found that—in addition to political boundaries—median household income explained some of the variance in NWS warnings. That is, areas with higher household income tend to receive more warnings than areas with lower average income.

The purpose of this study is to investigate the distribution of severe weather events in and around large cities and identify potential areas of enhanced severe weather risk. Because of the complications mentioned above, analysis of a single dataset would be insufficient. To alleviate these issues, several different datasets are analyzed and compared. These include archived storm-based warnings issued by the National Weather Service, local storm reports, and a radar-based climatology of storm structure from the Severe Weather Data Inventory. Individually, these datasets all contain nonmeteorological sources of uncertainty. Consistent spatial patterns between two or more of these datasets may indicate an underlying physical cause.

2. Methodology

Six cities were chosen for analysis. These are Louisville, Kentucky; Indianapolis; Cincinnati, Ohio; Columbus, Ohio; St. Louis; and Nashville, Tennessee. These cities were chosen because they are relatively close to one another and experience roughly the same number of severe weather events per year.¹ All of these cities are also free of

any major² topographic features and for the most part they all have fairly well defined “edges” where the land use transitions to rural areas. Table 1 shows a summary of the cities included in the current study.

Archived shapefiles of NWS storm-based warning polygons were accessed from the Iowa Environmental Mesonet (mesonet.agron.iastate.edu). For each city, tornado and severe thunderstorm warnings³ issued by the nearest local NWS office were analyzed for the time period 1 October 2007–31 May 2017. The start date is coincident with a shift in NWS procedure from county-wide warnings to storm-based warnings. Storm reports from the NCEI Storm Events Database were examined from January 2007 through May 2017. Only reports of hail, thunderstorm wind gusts, and tornadoes were considered. The start date was chosen to approximately coincide with the date range used for NWS warnings, but extended slightly to include as many data points as possible. Beginning in 2007, the locations of storm reports could be recorded with four decimal digits of precision for latitude and longitude. However, many reports after 2007 contain only two decimal digits for latitude and longitude. It appears that the use of two decimal digits may be associated with recording reports at a “default” location. For example, on 1 April 2012, the Indianapolis Weather Forecast Office (WFO) recorded four reports at 39.78°N and 86.15°W, and then another eight reports on 21 September 2012 at this same exact location. Data were filtered to remove storm reports with identical latitude and longitude locations. This only impacts reports with two decimal digits of precision.

Data from the Severe Weather Data Inventory (SWDI; Ansari et al. 2009) were used to create a radar-based climatology of storm characteristics for comparison with severe weather reports and warnings. The SWDI dataset includes the level III WSR-88D “Storm Structure” product, which contains the location, maximum radar reflectivity, vertically integrated liquid water content, cloud base, cloud-top height, and cloud depth for each identified cell with a temporal resolution of 5 min. SWDI products from the nearest NWS radar to each city were analyzed from October 2007 through May 2017.

² Some cities—in particular Louisville, Columbus, and St. Louis—have nearby areas of relatively sharp elevation gradients; however, the maximum relief is less than 1000 ft.

³ The hail size threshold for severe thunderstorm warnings was altered during the time range of this study. Prior to January 2010, severe thunderstorm warnings could be issued if hail was forecasted to meet or exceed 3/4-in. diameter. This threshold was increased to a 1-in. diameter beginning on 5 January 2010.

¹ Based on data from the Storm Prediction Center (<http://www.spc.noaa.gov/climo/online/rda/>).

TABLE 1. List of metropolitan areas included in the current study. Population estimates are based on 2016 values from the U.S. Census Bureau. City center determination was based on Google maps. In all metropolitan areas listed, the city center was coincident with the most heavily developed downtown area.

Metropolitan area	Population estimate	City center lat (°N) and lon (°W)	Closest NWS sounding site	Closest NWS radar
Cincinnati, OH–KY–IN	2 165 139	39.1031, 84.5120	Wilmington, OH	KILN
Columbus, OH	2 041 520	39.9612, 82.9988	Wilmington, OH	KILN
Indianapolis, IN	2 004 230	39.7684, 86.1581	Wilmington, OH	KIND
Louisville, KY–IN	1 283 430	38.2527, 85.7585	Nashville, TN	KLVX
Nashville, TN	1 865 298	36.1627, 86.7816	Nashville, TN	KOHX
St. Louis, MO–IL	2 807 002	38.6270, 90.1994	Lincoln, IL	KLSX

Analysis techniques

Warning shapefiles were analyzed in several different ways. First, the warning polygons were evaluated on a $0.025^\circ \times 0.025^\circ$ grid overlaid on each metropolitan area. Each warning polygon was placed on the grid, and the number of grid points inside the polygon was counted. This process was repeated for each warning polygon to create a count of warning occurrences within each grid cell. A second analysis was done in which each warning was represented by its centroid point. The centroid for each polygon was calculated as

$$c_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \quad \text{and} \quad (1)$$

$$c_y = \frac{1}{6A} \sum_{i=0}^{n-1} (y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i), \quad (2)$$

where c_x is the east–west centroid location; c_y is the north–south centroid location; x_i and y_i are the longitude and latitude of each pair of vertices, respectively; and A is the area of the polygon. Representing warnings as a single centroid point allowed for an investigation into the number of warnings issued on different sides of each city and removes the influence of polygon size.

For point values such as storm reports or warning centroids, kernel density estimation was used to provide a smoothed estimate of the parameter’s spatial distribution. This was done using the “gaussian_kde” function in Python’s SciPy package. Latitude and longitude pairs for the point values were analyzed within a $100 \text{ km} \times 100 \text{ km}$ domain centered on each city. The so-called Silverman rule of thumb was used for bandwidth selection.

For some analyses, the data were subset to only include events where storms were traveling from a specified direction. NWS sounding data were accessed from NCEI’s Integrated Global Radiosonde Archive and used to estimate storm motion. The nearest sounding location to each city was used to calculate the pressure-weighted 0–6-km mean wind for each individual event. Sounding data from Nashville were used for Nashville

and Louisville, while data from Lincoln, Illinois, were used for St. Louis and data from Wilmington, Ohio, were used for Indianapolis, Cincinnati, and Columbus.

3. Results

Figure 1 shows the spatial distribution of storm-based warning counts within $0.025^\circ \times 0.025^\circ$ grid cells around each city. All six metropolitan areas show an asymmetric pattern around the downtown center. In five of the six, the warning maximum is on the eastern side of the city, typically within 20 km of the downtown center. This eastern maximum—noticeable in Columbus (Fig. 1a), Indianapolis (Fig. 1b), Nashville (Fig. 1c), Cincinnati (Fig. 1d), and Louisville (Fig. 1e)—can contain 20%–40% more warnings compared to areas on the western side of the city. Columbus (Fig. 1a), Indianapolis (Fig. 1b), and Louisville (Fig. 1e) have a second peak in warning count approximately 15–30 km west of the city center. This feature, combined with the eastern maximum, creates the appearance of a warning “hole” just west of the downtown area of these cities. The only city without a warning maximum to the east of its downtown area is St. Louis (Fig. 1f). Instead, the maximum is located northwest of downtown. This is particularly interesting because St. Louis’s impact on regional precipitation has been well documented (e.g., Huff and Changnon 1972; Rozoff et al. 2003). The area of maximum warnings shown in Fig. 1f does not align with the areas identified in previous studies as regions of enhanced precipitation.

In all six cities, the prevailing low-level winds are typically from the west and/or southwest. Thus, the eastern side of each of these cities roughly corresponds to the downwind side. Since warning polygons are often larger on the downwind edge, it is possible that the distributions shown in Fig. 1 are simply an artifact of that feature. To remove the potential influence of polygon shape, each warning polygon was represented by its centroid location. Figure 2 shows the distribution of warning centroids around each city smoothed by a kernel density estimate. Four of the six cities—Columbus (Fig. 2a), Nashville (Fig. 2c), Cincinnati (Fig. 2d), and

FIG. 1. Total warning counts within $0.025^\circ \times 0.025^\circ$ grid cells. Black lines represent major roadways, gray lines are state boundaries, and blue stars represent the city center of each metropolitan area. Warnings are from the period of October 2007–May 2017.

FIG. 2. Kernel density smoothed estimates of warning centroid locations. Units are number per unit area (10 km²). Black lines, gray lines, and blue stars are the same as in Fig. 1. The thick black outline represents the boundary of urbanized areas (U.S. Census Bureau). It encompasses areas with a population of 50 000 or greater.

Louisville (Fig. 2e)—have more warnings east of the city center, while St. Louis has a maximum on the western side (Fig. 2f). These results agree with those shown in Fig. 1. When considering warning centroid locations,

Indianapolis has a maximum nearly centered on the downtown area. This differs slightly from the warning distribution in Fig. 1b, which showed a maximum in warnings 5–10 km east of downtown Indianapolis.

FIG. 3. Total warning count within $0.025^\circ \times 0.025^\circ$ grid cells as a function of estimated storm motion around Nashville. Black lines, gray lines, and blue stars are the same as in Fig. 1.

If warning distributions are at all related to the urban modification of convective storms, the location of the warning maxima should vary with storm motion (i.e., wind direction). Figure 3 shows warnings around Nashville as a function of storm motion. When considering all wind directions, Nashville has a broad maximum in warnings extending along a north–south axis just east of its city center (Fig. 3a). When storm motion is mainly from the west (Fig. 3b), the warning maximum is concentrated to the northeast of the city. The vast majority of severe weather warnings occur when storms travel from the southwest (Fig. 3c), and this pattern closely resembles that shown for all storm motions. When storms travel from the northwest, the warning maximum is found southeast of the city (Fig. 3d).

Figure 4 shows the warnings around each of the six cities when storm motion is estimated to be from the

northwest. Louisville now has a maximum northwest of the city center, with a second peak to the southeast and a local minimum over the city center (Fig. 4e). In the Cincinnati area, the warning maximum is now concentrated in a small area approximately 20 km east of the city center (Fig. 4d). The distribution of warnings around Columbus, St. Louis, and Indianapolis does not appear to be substantially different from that shown in Fig. 1. Since the most common storm motion in each city is from the southwest, this analysis is limited by a much smaller sample size. The total number of warnings is roughly 10 times smaller when only considering storm motion from the northwest. Additionally, several cities (Louisville, Indianapolis, and Columbus) are located over 100 km from the nearest sounding site. Thus, the estimated storm motions in these three cities may contain larger errors than the estimates for Nashville, Cincinnati, and St. Louis.

FIG. 4. Total warning count within $0.025^\circ \times 0.025^\circ$ grid cells for estimated storm motions of 290° – 350° . Black lines, gray lines, and blue stars are the same as in Fig. 1.

To further investigate the impact of storm motion, the coordinate system was rotated and individual grid points were classified by their upwind–downwind distance relative to the city center. Only the grid points that fell within a “cone of influence” relative to the city center

were included. A schematic of this procedure is shown in Fig. 5. Figure 6 shows histograms of warning counts as a function of distance from the city center. There are two main features noticeable in Fig. 6. First, warning counts tend to decrease as the distance from the city center

FIG. 5. Schematic of the coordinate system rotation process used to categorize warnings as upwind or downwind of the city center. The minimum allowable θ is 45° .

increases. This means that, on average, large urban areas receive more warnings than outlying suburban/rural areas. Second, in every city except St. Louis, a maximum in the warning count is found roughly 5–15 km downwind of the city center. In some cities, the upwind–downwind discrepancy is confined to a relatively small range (e.g., Indianapolis; Fig. 6), while in other cities the difference is evident at distances of 40 km or more (e.g., Cincinnati; Fig. 6d). Several cities—Cincinnati, Indianapolis, and Louisville—exhibit a localized minimum in warning frequency within 5 km of the upwind edge of the city center. A Wilcoxon signed-rank test was used to determine if the differences in warning count on the upwind–downwind sides were statistically significant. Figure 7 shows the results of this analysis when considering locations ranging from 5 to 95 km from the city center. Between 30 and 60 km from the city center, each city except Louisville⁴ and St. Louis contains a region where the differences in warning counts are statistically significant at the 98% confidence interval.

⁴ Although differences in warning counts around Louisville are not statistically significant in an upwind–downwind reference frame, they are significant in an east–west reference frame (not shown).

Figure 8 shows the distribution of local storm reports around each city. In general, maxima in storm reports tend to be located closer to the city center than maxima in warnings. In Columbus, the warning maximum is roughly 10–15 km east of the city center (Fig. 1a) while the maximum in storm reports occurs much closer to downtown (Fig. 8a). Indianapolis shows a similar pattern, with the storm report maximum falling closer to the city center (Fig. 8b) than the warning maximum. In the St. Louis area, storm warnings are most frequent approximately 15 km northwest of the downtown center (Fig. 1f); however, the maximum in reports is approximately 5 km to the southeast of the area of maximum warnings (Fig. 8f). Nashville has a broad maximum in reports extending from its urban center to approximately 15 km to the northeast (Fig. 8c). The storm report maxima in Cincinnati (Fig. 8d) and Louisville (Fig. 8e) are also found to the east of the urban center and occur near areas with more frequent warnings (see Fig. 1).

SWDI storm structure data were used to create a regional climatology of storm cells around each metropolitan area. For this analysis, only cells with a maximum radar reflectivity of 50 dBZ or greater were considered. Figure 9 shows the number of storm cells within $0.05^\circ \times 0.05^\circ$ grid cells relative to the areal average. This quantity is defined as

$$z_{\text{rel}} = \frac{z_{50} - \bar{z}_{50}}{\bar{z}_{50}}, \quad (3)$$

where z_{50} is the number of occurrences of a storm cell having a radar reflectivity of 50 dBZ or greater within a grid cell, and $\bar{z}_{50}$ is the areal average of the same quantity taken over a $100 \text{ km} \times 100 \text{ km}$ domain centered on the city. Positive values of z_{rel} indicate areas with storm cell frequency greater than the areal average, while negative values indicate cell frequency less than the areal average.

One of the most noticeable—and expected—features in the distribution of convective cells is the dependence on radar range (Fig. 9). Around each city, the total cell count decreases with increasing radar range. This is most likely due to a reduction in radar resolution at increased distance. Table 2 shows values of the correlation coefficient between the radar range and cell count for each city. A strong negative relationship exists in the vicinity of each city. Despite this dominant signal, smaller-scale features are evident in several of the metropolitan areas. Columbus has a local maximum in convective activity 10–15 km east-northeast of downtown, just outside the Interstate Highway 270 (I-270) beltway (Fig. 9a).

FIG. 6. Average warning count within grid cells as a function of distance from the city center. Negative values are upwind and positive values are downwind.

Indianapolis (Fig. 9b) has a maximum in convective cell frequency just south of downtown and another maximum approximately 15 km east of downtown. Cincinnati has relatively large spatial gradients within the I-275 beltway (Fig. 9d). There is increased convective activity near downtown, 10–20 km southeast of downtown, and approximately 15 km northeast of downtown. Louisville appears to have a local minimum over the city center with a slight increase in convective activity

about 5–10 km east and southeast of the city center (Fig. 9e). St. Louis has a maximum in storm cell frequency 20 km to the northwest of the city center (Fig. 9f.), which is very near the KLSX radar site. There are also a few small areas 10–20 km east and southeast of downtown St. Louis with increased cell frequency. Nashville (Fig. 9c) has a broad maximum in convective frequency 15–20 km northeast of downtown, coincident with the KOHX radar site.

FIG. 7. The p values from a Wilcoxon signed-rank test comparing the upwind and downwind warning distributions for each city. Each point represents the comparison between the upwind–downwind distributions ranging from a radius of 0 km up to the radius specified at that particular point. The horizontal dashed lines represent p values of 0.05 and 0.01.

To reduce noise, the cell frequency data were smoothed using a kernel density estimate. The results of this analysis are shown in Fig. 10 and are very similar to the results shown in Fig. 9. Columbus has reduced cell frequency within the I-270 beltway and a region of increased frequency outside the beltway (Fig. 10a). Indianapolis has a broad maximum in convective activity just to the south of downtown and extending approximately 15 km southeast. Cincinnati has increased convective activity south/southeast of the downtown region (Fig. 10d). The downtown area of Louisville

has lower convective activity and increased activity extending around the southeast side of the city (Fig. 10e). The primary signals around Nashville (Fig. 10c) and St. Louis (Fig. 10f) appear to be dominated by radar range, with the maxima in these cities occurring very near the radar locations.

Similar to storm warnings, the area of most frequent convective activity is a function of storm motion. Figure 11 shows a kernel density estimate of convective cells around each city for storm motions ranging from 290° to 350° . When only considering storms moving from

FIG. 8. Kernel density smoothed estimates of local storm report locations. Units are number per unit area (10 km^2). Black lines, gray lines, and blue stars are the same as in Fig. 2.

the northwest, most cities show an increase in convective activity on the southeast side compared to that seen for all storm motions (Fig. 9), with the biggest changes being in Nashville (Figs. 9c and 11c), Cincinnati (Figs. 9d and 11d), and Louisville (Figs. 9e and 11e). The maximum

near Columbus also appears to shift slightly to the south (Figs. 9a and 11a), while the maximum near Indianapolis shifts approximately 20 km to the east of the city. For storms traveling from the northwest, there is good agreement between the location of the maxima in

FIG. 9. Relative frequency of convective cells with radar reflectivity of 50 dBZ or greater within $0.05^\circ \times 0.05^\circ$ grid cells (z_{rel}). Black lines, gray lines, and blue stars are the same as in Fig. 1. The black dots in (b), (c), (e), and (f) represent the locations of the nearest WSR-88D. The black arrows in (a) and (d) show the direction to the nearest WSR-88D (Wilmington; KILN), which appears out of the frame.

warnings and storm cell frequency on the east sides of Columbus (Figs. 1a and 11a), Nashville (Figs. 4c and 11c), and Louisville (Figs. 4e and 11e). However, the sample size for storms traveling from the northwest is

much smaller than the total distribution, so this result should be interpreted with caution.

Each city exhibits some degree of spatial alignment between maxima in warnings, reports, and convective

TABLE 2. Relationship between radar range and the frequency of cells with a radar reflectivity of 50 dBZ or greater.

Region	R	R^2
Cincinnati	-0.77	0.59
Columbus	-0.73	0.53
Indianapolis	-0.75	0.56
Louisville	-0.86	0.74
Nashville	-0.79	0.62
St. Louis	-0.58	0.34

activity. In general, warnings and convective frequency tend to have the closest alignment, with report maxima often found closer to the city center. In Columbus, warnings are most frequent on the eastern side of the city (Fig. 1a). It was also found that strong convective cells are more frequent east of downtown Columbus (Figs. 9a and 10a), while storm reports are most common closer to downtown (Fig. 8a). Cincinnati has increased convective activity just south of its downtown center (Figs. 9d and 10d). This area is also close to an area of increased warnings (Fig. 1d). Indianapolis has increased convective activity and a maximum in warnings approximately 15–20 km southeast of its downtown center (Figs. 1b, 9b, and 10b). Storm reports in the Indianapolis area are greatest close to downtown (Fig. 8b). In Louisville, the downtown center is coincident with a reduction in warnings and convective frequency compared to areas both west and east (Figs. 1e, 9e, and 10e). There is increased convective activity and a maximum in warnings approximately 10 km southeast of downtown. The relationship between warnings and convective activity in both St. Louis and Nashville is more difficult to interpret, due to the large cluster of increased cell frequency very near the radar sites (Figs. 9c,f). Both cities have distinct warning maxima on one particular side, and that maximum is spatially aligned with an increase in strong convective cells. However, this maximum in cell frequency may be strongly impacted by increased azimuthal resolution at small radar range.

4. Discussion

Five of the six cities studied have more warnings on their eastern side. From the analysis presented, the dominant mechanism responsible for this feature cannot be determined. It is possible that this area of increased warnings is associated with changes in storm structure, with existing storms weakening as they approach a city and restrengthening on the downwind side in a process similar to the bifurcation mechanism discussed by Bornstein and Lin (2000). It is also possible that some storms are initiated directly over urban areas due to the urban heat island (e.g., Haberlie et al. 2015). As these

storms mature and advect downwind, they could produce severe weather on the eastern edge of the city.

In some cities, at least a portion of the warning asymmetry could be a nonphysical by-product of the warning process itself. In several of the cities it appears that storm reports are strongly influenced by population density and distribution. It is possible that storm reports coming in from high-population areas on the western side of cities prompt NWS forecasters to issue severe weather warnings farther downwind (i.e., to the east). Polygon shape may also explain some aspects of the warning asymmetry. Storm-based warning polygons are typically larger on the downwind edge and represent uncertainty in the path of the storm. Since the majority of storms move roughly from west to east, it would stand to reason that a single warning near a city's center would be slightly larger on the eastern side due to uncertainty in storm progression. If this occurs regularly, it may have an impact on the gridded warning distributions shown in Fig. 1. However, our analysis using warning centroid locations (Fig. 2) mostly agrees with the analysis of gridded warning polygons (Fig. 1). The exception to this was Indianapolis, where the gridded analysis of warnings (Fig. 1b) reveals a maximum to the east of downtown while the centroid analysis (Fig. 2b) shows a maximum centered over downtown. Calculations of the polygon area (not shown) indicate that warning polygons are approximately 25% larger on the downwind side of Indianapolis compared to the upwind side. This is about twice as large as the size difference in the other cities and may explain the shift in warning maxima between Figs. 1b and 2b.

There is also the possibility that political boundaries are impacting the warning distribution. Several cities in this study—such as Louisville, Cincinnati, and St. Louis—are situated at the edge of county (and state) boundaries. Forecasters may choose to terminate warning polygons at political boundaries in order to delay the onset of emergency management procedures across the boundary until there is higher confidence in the threat. This may lead to a lower number of warnings near the political boundary compared to areas away from the boundary. There appears to be a sharp gradient in the number of warnings west of Louisville very near the Kentucky–Indiana border (Fig. 1e). The warning distribution around Indianapolis exhibits gradients to the east and south of the city that are oriented in straight lines (Fig. 1b). These gradients occur very near county boundaries.

Other factors may also impact the distribution of severe weather warnings around urban areas. Previous studies have shown that factors such as population density and median household income are statistically related to the

FIG. 10. Kernel density smoothed estimates of the frequency of convective cells with radar reflectivity of 50 dBZ or greater. Units are number per area (10 km^2). Black lines, gray lines, and blue stars are the same as in Fig. 2. Black dots and black arrows are the same as in Fig. 9.

number of warnings. That is, areas with higher household income tend to receive more warnings than areas with a lower income. Within the context of this current study, suburban areas tend to be characterized by higher household incomes than areas closer to the urban center. Several

of the metropolitan areas examined (Louisville, Cincinnati, St. Louis, and Nashville) appear to have more warnings in areas with larger household income. In all six cities, severe weather warnings are more frequent near areas with large populations with warning counts

FIG. 11. As in Fig. 10, but only showing cases when the estimated storm motion is from 290° to 350° .

decreasing toward rural areas. This finding is consistent with that of previous studies (e.g., White and Stallins 2017).

Finally, although each of the cities in this study is free of “major” topographic features, the role of topography cannot be completely disregarded. Even somewhat minor changes in topography may have an influence on

thunderstorm distributions and severe weather activity. For example, Parker and Kniewel (2005) found a minimum in thunderstorm activity around Grand Forks, North Dakota, with increases to the east and west of Grand Forks. These changes closely correspond to topographic changes within the Red River valley, despite the fact that the total

TABLE 3. Relationship between elevation and warning count. Correlation coefficients calculated using a Pearson correlation (R_{Pearson}) and Spearman rank correlation (R_{rank}). Topographic data are from the Shuttle Radar Topography Mission (NASA).

Region	R_{Pearson}	R_{rank}
Cincinnati	0.13	−0.09
Columbus	−0.23	−0.23
Indianapolis	−0.14	−0.17
Louisville	−0.18	−0.18
Nashville	−0.23	−0.19
St. Louis	0.04	0.05

change in elevation across the valley is typically less than 200 m over a horizontal distance of 100 km. Lyza and Knupp (2014) attributed deviations in certain Alabama tornado tracks to elevation changes as small as 200 m. Several cities in this study have nearby regions where the elevation changes by 100–200 m. For example, the area 15–25 km west of Louisville is approximately 100–150 m higher in elevation than the downtown center. This area of increased elevation aligns with an area of frequent warnings (Fig. 1e). Additionally, the region of increased warnings (Fig. 1a) and cell frequency (Fig. 9a) to the east of Columbus occurs very near the region's sharpest elevation gradient. The elevation 15–20 km east of downtown Columbus can be approximately 100–150 m greater than that in the urban center. Table 3 illustrates the relationship between warning counts and topography around each metropolitan area. In all cities except St. Louis, there exists a weak negative correlation between warning count and elevation, with the strongest relationships found in Nashville and Columbus. Figure 12 illustrates the relationship between convective cell frequency (previously shown in Fig. 9) and topography. In Columbus (Fig. 12a) and Indianapolis (Fig. 12b), the areas of increased convective cell frequency east of the city center occur in close proximity to an elevation gradient. In Louisville (Fig. 12e), the local minimum in cell frequency over the city center is associated with lower elevations. Although these patterns do not hold across all cities, it is possible that in certain cities at least a portion of the spatial variability is a result of local topographically induced circulations.

Regardless of the underlying cause, it is important to identify discrepancies between storm warnings, local storm reports, and areas of frequent storm activity. It may be useful for forecasters to know of potentially underserved areas where there are more reports than there are warnings and vice versa. Surplus warnings could lead to high false alarms and erode public trust, while surplus reports could indicate the potential for missed events. A comparison of storm reports to radar climatology may help identify potential underreporting zones within their county warning area.

5. Summary and conclusions

Several datasets were used to investigate the spatial distribution of severe weather in and around six large metropolitan areas in the central United States. The data used include NWS warnings, local storm reports, and the location and intensity of storm cells observed by the NWS radar network. In all six metropolitan areas there exists an asymmetric pattern in severe weather warnings, with warning counts varying by 20%–40% within 20 km of the downtown center. In five of the six cities—Louisville, Indianapolis, Nashville, Columbus, and Cincinnati—an increase in severe weather warnings is found 5–15 km east of the city center. When the coordinate system is rotated and storm motion is considered, it was shown that these five metropolitan areas experience more warnings on their downwind side than on their upwind side. In Columbus, Indianapolis, and Nashville, a maximum in warnings is located 5–10 km downwind of the city center. In Cincinnati and Louisville, the warning maximum is found 10–15 km downwind.

Asymmetric patterns are also seen in the distributions of storm reports and strong convective cells. In most cities, the location of maximum storm reports and maximum warnings are offset by approximately 5–15 km, with the maximum in reports occurring closer to the city center. Much closer alignment is seen between the areas of frequent warnings and enhanced convective cell frequency. In four of the six cities (Columbus, Cincinnati, Indianapolis, and Louisville), spatial variations in warning frequency are spatially aligned with variations in convective cell frequency. Additionally, when the warning and radar datasets were subsampled based on sounding-estimated storm motion, the maxima locations shifted. When only considering storm motion from the northwest, the frequency of strong convective cells to the southeast of the downtown area (i.e., downwind direction) increases around Columbus, Louisville, Nashville, Cincinnati, and St. Louis. In the Louisville and Nashville regions, the urban center receives less frequent warnings compared to areas 10–20 km downwind.

The spatial alignment between warnings and radar-detected cell frequency, combined with the finding that the spatial distribution of these fields shifts with wind direction, may indicate that the urban modification of convective cells produces preferred regions of severe weather activity within some metropolitan areas. However, there are also several examples of disagreement between the locations of maxima in warnings, reports, and/or convective cell location. Storm reports are most frequent near downtown Indianapolis, but warnings are most common 5–10 km east of this location. Both of these areas are associated with increased convective frequency. In St. Louis, warnings are most frequent 15–20 km northwest of the city center while reports with a maximum reflectivity of 50 dBZ or greater

FIG. 12. As in Fig. 9, but overlaid on elevation contours. Topographic data are from the Shuttle Radar Topography Mission (NASA). Lighter (darker) colors indicate lower (higher) elevations. High-resolution versions of each panel are available in the online supplemental material (Figs. S1–S6).

are most common 10–20 km southeast of the warning maximum. In Columbus, the maximum in storm reports is very close to the city center, but this is also an area of reduced convective activity. Cincinnati has a region of frequent storm reports just to the northeast of downtown but maxima in storm warnings and cell frequency occur to the south. This may suggest that other factors (e.g., topography, population density) are having some impact on the distributions of warnings and/or storm reports in these cities.

Additional work is necessary to determine the cause(s) of the variability in warnings, reports, and cell frequency around large cities. Simulations using the Weather Research and Forecasting (WRF) Model are currently being conducted to study the relative role of land usage, the urban heat island, and urban aerosols on changes to the structure and intensity of convective storms interacting with large cities and to determine how these factors may impact severe weather potential. Other potential avenues of exploration include multidisciplinary studies to examine any potential nonmeteorological factors for the variations in severe weather warnings and reports within large metropolitan areas.

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REFERENCES

- Ansari, S., M. Phillips, and S. Del Greco, 2009: NEXRAD severe weather signatures in the NOAA Severe Weather Data Inventory. *34th Conf. on Radar Meteorology*, Williamsburg, VA, Amer. Meteor. Soc., P6.19, https://ams.confex.com/ams/34Radar/techprogram/paper_156015.htm.
- Ashley, W. S., and T. L. Mote, 2005: Derecho hazards in the United States. *Bull. Amer. Meteor. Soc.*, **86**, 1577–1592, <https://doi.org/10.1175/BAMS-86-11-1577>.
- Barnes, L. R., E. C. Grunfest, M. H. Hayden, D. M. Schultz, and C. Benight, 2007: False alarms and close calls: A conceptual model of warning accuracy. *Wea. Forecasting*, **22**, 1140–1147, <https://doi.org/10.1175/WAF1031.1>.
- Bentley, M. L., and T. L. Mote, 1998: A climatology of derecho-producing mesoscale convective systems in the central and eastern United States. Part I: Temporal and spatial distribution. *Bull. Amer. Meteor. Soc.*, **79**, 2527–2540, [https://doi.org/10.1175/1520-0477\(1998\)079<2527:ACODPM>2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079<2527:ACODPM>2.0.CO;2).
- , J. A. Stallins, and W. S. Ashley, 2012: Synoptic environments favourable for urban convection in Atlanta, Georgia. *Int. J. Climatol.*, **32**, 1287–1294, <https://doi.org/10.1002/joc.2344>.
- Bornstein, R., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmos. Environ.*, **34**, 507–516, [https://doi.org/10.1016/S1352-2310\(99\)00374-X](https://doi.org/10.1016/S1352-2310(99)00374-X).
- Braham, R. R., Jr., R. G. Semonin, A. H. Auer, S. A. Changnon Jr., and J. M. Hales, 1981: Summary of urban effects on cloud and rain. *METROMEX: A Review and Summary*, Meteor. Monogr., No. 40, Amer. Meteor. Soc., 141–152.
- Brooks, H. E., 2004: Tornado-warning performance in the past and future. *Bull. Amer. Meteor. Soc.*, **85**, 837–843, <https://doi.org/10.1175/BAMS-85-6-837>.
- , and C. A. Doswell III, 2001: Normalized damage from major tornadoes in the United States: 1890–1999. *Wea. Forecasting*, **16**, 168–176, [https://doi.org/10.1175/1520-0434\(2001\)016<0168:NDFMTI>2.0.CO;2](https://doi.org/10.1175/1520-0434(2001)016<0168:NDFMTI>2.0.CO;2).
- , J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, [https://doi.org/10.1016/S0169-8095\(03\)00045-0](https://doi.org/10.1016/S0169-8095(03)00045-0).
- Burian, S. J., and J. M. Shepherd, 2005: Effect of urbanization on the diurnal rainfall pattern in Houston. *Hydrol. Processes*, **19**, 1089–1103, <https://doi.org/10.1002/hyp.5647>.
- Changnon, S. A., 1968: The La Porte weather anomaly—Fact or fiction? *Bull. Amer. Meteor. Soc.*, **49**, 4–11, <https://doi.org/10.1175/1520-0477-49.1.4>.
- , 1980: More on the La Porte anomaly: A review. *Bull. Amer. Meteor. Soc.*, **61**, 702–711, [https://doi.org/10.1175/1520-0477\(1980\)061<0702:MOTLPA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1980)061<0702:MOTLPA>2.0.CO;2).
- , and N. E. Westcott, 2002: Heavy rainstorms in Chicago: Increasing frequency, altered impacts, and future implications. *J. Amer. Water Res. Assoc.*, **38**, 1467–1475, <https://doi.org/10.1111/j.1752-1688.2002.tb04359.x>.
- , F. A. Huff, and R. G. Semonin, 1971: METROMEX: An investigation of inadvertent weather modification. *Bull. Amer. Meteor. Soc.*, **52**, 958–968, [https://doi.org/10.1175/1520-0477\(1971\)052<0958:MAIOIW>2.0.CO;2](https://doi.org/10.1175/1520-0477(1971)052<0958:MAIOIW>2.0.CO;2).
- , R. G. Semonin, and F. A. Huff, 1976: A hypothesis for urban rainfall anomalies. *J. Appl. Meteor.*, **15**, 544–560, [https://doi.org/10.1175/1520-0450\(1976\)015<0544:AHFURA>2.0.CO;2](https://doi.org/10.1175/1520-0450(1976)015<0544:AHFURA>2.0.CO;2).
- Cintineo, J. L., T. M. Smith, V. Lakshmanan, H. E. Brooks, and K. L. Ortega, 2012: An objective high-resolution hail climatology of the contiguous United States. *Wea. Forecasting*, **27**, 1235–1248, <https://doi.org/10.1175/WAF-D-11-00151.1>.
- Craig, K. J., and R. D. Bornstein, 2002: MM5 simulations of urban induced convective precipitation over Atlanta. *Fourth Symp. on the Urban Environment*, Norfolk, VA, Amer. Meteor. Soc., 5–6.
- Davis, S. M., and J. G. LaDue, 2004: Nonmeteorological factors in warning verification. *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., P2.7, https://ams.confex.com/ams/11aram22sls/techprogram/paper_81766.htm.
- Dixon, P. G., and T. L. Mote, 2003: Patterns and causes of Atlanta's urban heat island-initiated precipitation. *J. Appl. Meteor.*, **42**, 1273–1284, [https://doi.org/10.1175/1520-0450\(2003\)042<1273:PACOAU>2.0.CO;2](https://doi.org/10.1175/1520-0450(2003)042<1273:PACOAU>2.0.CO;2).
- Dobur, J. C., 2005: A comparison of severe thunderstorm warning verification statistics and population density within the NWS Atlanta county warning area. *Fourth Annual Southeast Severe Storm Symp.*, Starkville, MS, National Weather Association, <https://www.weather.gov/media/ffc/SEconf.pdf>.
- Doswell, C. A., III, H. E. Brooks, and M. P. Kay, 2005: Climatological estimates of daily local nontornadic severe thunder-

- storm probability for the United States. *Wea. Forecasting*, **20**, 577–595, <https://doi.org/10.1175/WAF866.1>.
- Fujibe, F., 2003: Long-term surface wind changes in the Tokyo metropolitan area in the afternoon of sunny days in the warm season. *J. Meteor. Soc. Japan*, **81**, 141–149, <https://doi.org/10.2151/jmsj.81.141>.
- Ganeshan, M., R. Murtugudde, and M. L. Imhoff, 2013: A multicity analysis of the UHI-influence on warm season rainfall. *Urban Climate*, **6**, 1–23, <https://doi.org/10.1016/j.uclim.2013.09.004>.
- Haberlie, A. M., W. S. Ashley, and T. J. Pingel, 2015: The effect of urbanisation on the climatology of thunderstorm initiation. *Quart. J. Roy. Meteor. Soc.*, **141**, 663–675, <https://doi.org/10.1002/qj.2499>.
- Hand, L. M., and J. M. Shepherd, 2009: An investigation of warm-season spatial rainfall variability in Oklahoma City: Possible linkages to urbanization and prevailing wind. *J. Appl. Meteor. Climatol.*, **48**, 251–269, <https://doi.org/10.1175/2008JAMC2036.1>.
- Hjelmfelt, M. R., 1982: Numerical simulation of the effects of St. Louis on mesoscale boundary-layer airflow and vertical air motion: Simulations of urban vs non-urban effects. *J. Appl. Meteor.*, **21**, 1239–1257, [https://doi.org/10.1175/1520-0450\(1982\)021<1239: NSOTEO>2.0.CO;2](https://doi.org/10.1175/1520-0450(1982)021<1239: NSOTEO>2.0.CO;2).
- Huff, F. A., and S. A. Changnon, 1972: Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor.*, **11**, 823–842, [https://doi.org/10.1175/1520-0450\(1972\)011<0823: CAOUEO>2.0.CO;2](https://doi.org/10.1175/1520-0450(1972)011<0823: CAOUEO>2.0.CO;2).
- , and —, 1973: Precipitation modification by major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220–1232, [https://doi.org/10.1175/1520-0477\(1973\)054<1220:PMBMUA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1973)054<1220:PMBMUA>2.0.CO;2).
- Jauregui, E., and E. Romales, 1996: Urban effects on convective precipitation in Mexico City. *Atmos. Environ.*, **30**, 3383–3389, [https://doi.org/10.1016/1352-2310\(96\)00041-6](https://doi.org/10.1016/1352-2310(96)00041-6).
- Jin, M., J. M. Shepherd, and M. D. King, 2005: Urban aerosols and their variations with clouds and rainfall: A case study for New York and Houston. *J. Geophys. Res.*, **110**, D10S20, <https://doi.org/10.1029/2004JD005081>.
- Kellner, O., and D. Niyogi, 2014: Land surface heterogeneity signature in tornado climatology? An illustrative analysis over Indiana, 1950–2012. *Earth Interact.*, **18**, <https://doi.org/10.1175/2013EI000548.1>.
- Lyza, A. W., and K. Knupp, 2014: An observational analysis of potential terrain influences on tornado behavior. *27th Conf. on Severe Local Storms*, Madison, WI, Amer. Meteor. Soc., 11A.1A, <https://ams.confex.com/ams/27SLS/webprogram/Paper255844.html>.
- Mote, T. L., M. C. Lacke, and J. M. Shepherd, 2007: Radar signatures of the urban effect on precipitation distribution: A case study for Atlanta, Georgia. *Geophys. Res. Lett.*, **34**, L20710, <https://doi.org/10.1029/2007GL031903>.
- Niyogi, D., T. Holt, S. Zhong, P. C. Pyle, and J. Basara, 2006: Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the southern Great Plains. *J. Geophys. Res.*, **111**, D19107, <https://doi.org/10.1029/2005JD006746>.
- , P. Pyle, M. Lei, S. P. Arya, C. M. Kishtawal, M. Shepherd, F. Chen, and B. Wolfe, 2011: Urban modification of thunderstorms: An observational storm climatology and model case study for the Indianapolis urban region. *J. Appl. Meteor. Climatol.*, **50**, 1129–1144, <https://doi.org/10.1175/2010JAMC1836.1>.
- , M. Lei, C. Kishtawal, P. Schmid, and M. Shepherd, 2017: Urbanization impacts of summer heavy rainfall climatology over the eastern United States. *Earth Interact.*, **21**, <https://doi.org/10.1175/EI-D-15-0045.1>.
- Ochoa, C. A., A. I. Quintanar, G. B. Raga, and D. Baumgardner, 2015: Changes in intense precipitation events in Mexico City. *J. Hydrometeorol.*, **16**, 1804–1820, <https://doi.org/10.1175/JHM-D-14-0081.1>.
- Parker, M. D., and J. C. Kniviel, 2005: Do meteorologists suppress thunderstorms?: Radar-derived statistics and the behavior of moist convection. *Bull. Amer. Meteor. Soc.*, **86**, 341–358, <https://doi.org/10.1175/BAMS-86-3-341>.
- Rozoff, C. M., W. R. Cotton, and J. O. Adegoke, 2003: Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *J. Appl. Meteor. Climatol.*, **42**, 716–738, [https://doi.org/10.1175/1520-0450\(2003\)042<0716:SOSLML>2.0.CO;2](https://doi.org/10.1175/1520-0450(2003)042<0716:SOSLML>2.0.CO;2).
- Schmid, P. E., and D. Niyogi, 2013: Impact of city size on precipitation-modifying potential. *Geophys. Res. Lett.*, **40**, 5263–5267, <https://doi.org/10.1002/grl.50656>.
- , and —, 2017: Modeling urban precipitation modification by spatially heterogeneous aerosols. *J. Appl. Meteor. Climatol.*, **56**, 2141–2153, <https://doi.org/10.1175/JAMC-D-16-0320.1>.
- Shem, W., and M. Shepherd, 2009: On the impact of urbanization on summertime thunderstorms in Atlanta: Two numerical model case studies. *Atmos. Res.*, **92**, 172–189, <https://doi.org/10.1016/j.atmosres.2008.09.013>.
- Shepherd, J. M., H. Pierce, and A. J. Negri, 2002: Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *J. Appl. Meteor.*, **41**, 689–701, [https://doi.org/10.1175/1520-0450\(2002\)041<0689:RMBMUA>2.0.CO;2](https://doi.org/10.1175/1520-0450(2002)041<0689:RMBMUA>2.0.CO;2).
- Simmons, K. M., and D. Sutter, 2009: False alarms, tornado warnings, and tornado casualties. *Wea. Climate Soc.*, **1**, 38–53, <https://doi.org/10.1175/2009WCAS1005.1>.
- Smith, A. B., and R. W. Katz, 2013: US billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Nat. Hazards*, **67**, 387–410, <https://doi.org/10.1007/s11069-013-0566-5>.
- Stallins, J. A., J. Carpenter, M. L. Bentley, W. S. Ashley, and J. A. Mulholland, 2013: Weekend-weekday aerosols and geographic variability in cloud-to-ground lightning for the urban region of Atlanta, Georgia, USA. *Reg. Environ. Change*, **13**, 137–151, <https://doi.org/10.1007/s10113-012-0327-0>.
- Szoke, E. J., M. L. Weisman, J. M. Brown, F. Caracena, and T. W. Schlatter, 1984: A subsynoptic analysis of the Denver tornadoes of 3 June 1981. *Mon. Wea. Rev.*, **112**, 790–808, [https://doi.org/10.1175/1520-0493\(1984\)112<0790:ASAOTD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1984)112<0790:ASAOTD>2.0.CO;2).
- Toth, J. J., and R. H. Johnson, 1985: Summer surface flow characteristics over northeast Colorado. *Mon. Wea. Rev.*, **113**, 1458–1469, [https://doi.org/10.1175/1520-0493\(1985\)113<1458: SSFCON>2.0.CO;2](https://doi.org/10.1175/1520-0493(1985)113<1458: SSFCON>2.0.CO;2).
- Trapp, R. J., D. M. Wheatley, N. T. Atkins, R. W. Przybylinski, and R. Wolf, 2006: Buyer beware: Some words of caution on the use of severe wind reports in postevent assessment and research. *Wea. Forecasting*, **21**, 408–415, <https://doi.org/10.1175/WAF925.1>.
- Van den Heever, S. C., and W. R. Cotton, 2007: Urban aerosol impacts on downwind convective storms. *J. Appl. Meteor. Climatol.*, **46**, 828–850, <https://doi.org/10.1175/JAM2492.1>.
- Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.*, **117**, 1113–1140, [https://doi.org/10.1175/1520-0493\(1989\)117<1113:NST>2.0.CO;2](https://doi.org/10.1175/1520-0493(1989)117<1113:NST>2.0.CO;2).
- Weiss, S., J. Hart, and P. Janish, 2002: An examination of severe thunderstorm wind report climatology: 1970–1999. *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 11B.2, https://ams.confex.com/ams/SLS_WAF_NWP/techprogram/paper_47494.htm.
- White, M. L., and J. A. Stallins, 2017: Nonmeteorological influences on severe thunderstorm warning issuance: A geographically weighted regression-based analysis of county warning area boundaries, land cover, and demographic variables. *Wea. Climate Soc.*, **9**, 421–439, <https://doi.org/10.1175/WCAS-D-15-0070.1>.