Urbanization Impacts on the Summer Heavy Rainfall Climatology over the Eastern United States

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ABSTRACT: The relationship between rainfall characteristics and urbanization over the eastern United States was examined by analyzing four datasets: daily rainfall in 4593 surface stations over the last 50 years (1958–2008), a high-resolution gridded rainfall product, reanalysis wind data, and a proxy for urban land use (gridded human population data). Results indicate that summer monthly rainfall amounts show an increasing trend in urbanized regions. The frequency of heavy rainfall events has a potential positive bias toward urbanized regions. Most notably, consistent with case studies for individual cities, the climatology of rainfall amounts downwind of urban–rural boundaries shows a significant

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increasing trend. Analysis of heavy (90th percentile) and extreme (99.5th percentile) rainfall events indicated decreasing trends of heavy rainfall events and a possible increasing trend for extreme rainfall event frequency over urban areas. Results indicate that the urbanization impact was more pronounced in the northeastern and midwestern United States with an increase in rainfall amounts. In contrast, the southeastern United States showed a slight decrease in rainfall amounts and heavy rainfall event frequencies. Results suggest that the urbanization signature is becoming detectable in rainfall climatology as an anthropogenic influence affecting regional precipitation; however, extracting this signature is not straightforward and requires eliminating other dynamical confounding feedbacks.

**KEYWORDS:** Atmosphere–land interaction; Climate change; Hydrometeorology; Mesoscale processes; Regional effects; Climate variability

1. Introduction

A number of recent studies have noted an increase in heavy or extreme rainfall events over many parts of the globe (Brunetti et al. 2004; Zhai et al. 2005; Goswami et al. 2006; Allan and Soden 2008; Zou and Ren 2015). Many studies (Groisman et al. 2005; Min et al. 2011) found empirical evidence from observations or model projections showing that a greenhouse-enriched atmosphere may be associated with an increased probability of intense precipitation events. More quantitatively, Karl and Knight (1998) analyzed long-term rainfall data during the period 1910–55 and found that the frequency of heavy precipitation events had increased over the United States by about 7% during said period.

The change in heavy rainfall frequency has been primarily attributed to increasing greenhouse gases (Meehl et al. 2000). Additionally, regional land-use/land-cover changes (LULCC) can also affect rainfall by altering mesoscale convection (Pielke et al. 2007, 2011). Urbanization, in particular, can affect thunderstorms (Bornstein and Lin 2000; Schroeder et al. 2016). As early as the 1920s, Horton (1921) noted that some cities in the northeastern United States might be more likely to spawn thunderstorms. The Metropolitan Meteorological Experiment (METROMEX; Huff and Changnon 1972) helped demonstrate the mechanisms of increased rainfall downwind of urban landscapes. Since then, their single city studies have been verified by several studies (Shepherd et al. 2002; Hand and Shepherd 2009; Niyogi et al. 2011; Kishtawal et al. 2010; Smith et al. 2012; Yeung et al. 2015; Haberlie et al. 2015).

Studies such as Pielke et al. (2011) document recent efforts in understanding the climatic impacts of LULCC. In general, the LULCC impact on rainfall is attributed to dynamic mesoscale boundaries such as changes in atmospheric convergence zones (Rozoff et al. 2003; van den Heever and Cotton 2007; Lei et al. 2008) and aerosol impacts (Rosenfeld 2000; Storer et al. 2010; Carrió et al. 2010).

While individual case studies or single city–based studies are available in the literature, the objective here is to provide observational evidence to add to assessments related to the increase in heavy rainfall over a 50-yr period with the intent to identify an urbanization signature as a detectable regional climate forcing.

2. Data and method

To assess urbanization impacts on summer rainfall, the eastern United States was the area of focus. This choice was motivated by the availability of rainfall datasets
and widespread urbanization over the eastern United States compared to the western United States. Moreover, the absence of significant topographic features (the Appalachians are excluded in this study) over the eastern United States are beneficial for analysis and interpretation of the results. Rainfall data were analyzed over different subregions of the eastern United States evaluating both the amount and frequency of heavy rainfall events (Figure 1; Vose et al. 2014) (printer-friendly grayscale files for all figures in this paper can be found in the online supplementary material). The topography-corrected Parameter-Elevation Regressions on Independent Slopes Model (PRISM)-based monthly rainfall datasets (Daly et al. 1994) were used to estimate the change in rainfall amounts over the last two decades (1990–2008). PRISM uses point measurements of precipitation, temperature, and other variables to produce estimates of precipitation on a monthly time scale at 4-km grid spacing. PRISM was selected over the precipitation datasets to explicitly account for topographical impacts that can confound the urbanization signal (Diem and Brown 2003).

Figure 1. The study domain with different subregions over the eastern United States. The colors indicate the population density in 1990 (unit: log N; N: people per square kilometer).
Urbanization was quantified based on population data from the Gridded Population of the World, version 3 (GPWv3), and from the Global Rural–Urban Mapping Project (GRUMP). These are two recent products rendering a human population distribution in a common georeferenced framework. The spatial population map shows the distribution of human population across the globe. Corresponding to available rainfall data, the 1990 and 2010 population data for the eastern United States were used to assess urban landscape and urbanization conditions. The population distribution map and the national land-cover datasets (NLCD) map show a qualitative match particularly for urban grids and is a reasonable proxy for marking urban boundaries [e.g., Figure 2 for the state of Indiana and Sutton et al. (2001)]. The population data only consider population distribution, while different urban morphological characteristics are not considered. However, population density and its changes are easier to quantify than other factors related to urbanization (e.g., infrastructure), and the population density was used to define the intensity of urbanization in the numerical analysis in the present study. Population and PRISM rainfall data have the same spatial grid spacing (≈4 km). Note that the urban effects on rainfall are likely an aggregate of the different effects identified in literature (splitting, intensification, urban heat island–induced convection, aerosol interaction, etc.).

Additionally, daily rainfall data were obtained from the National Climatic Data Center (NCDC) for the 4593 weather stations covering the eastern United States from 1958 to 2008. To avoid topographical effects, stations with elevations less than 500 m were chosen to exclude stations in mountainous terrain. As a result, the Appalachian Mountains were excluded from the analysis. Stations with fewer than 2000 total rainy days (approximately 25 years) were excluded to remove those with

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Figure 2. (a) Example image for Indiana urban landscape from NLCD 2001 (all urban categories) and (b) Indiana population distribution map (>400 people per square kilometer) using gridded world population version 3 (unit: log(population number per square kilometer)).
large gaps in the record. Moreover, because hurricanes and tropical storms influence daily heavy rainfall amounts (Barlow 2011; Kellner and Niyogi 2015), tropical cyclone/hurricane-related heavy rainfall events were also excluded. Daily rainfall was excluded if there were landfalling tropical cyclones or hurricanes 1 or 2 days prior to the rainy day according to the Atlantic basin NHC “best track” hurricane database (HURDAT; Jarvinen et al. 1984). This criterion is chosen considering the balance between the decreasing intensity of landfalling hurricanes (Knight and Davis 2007) and retaining more available data for analysis. Daily precipitation was categorized as heavy rainfall events (the 90th percentile), very heavy rainfall events (the 98th percentile), and extreme rainfall events (the 99.5 percentile). From this quantity, the change in event frequency over time was analyzed. The trend in heavy rainfall frequency was determined using a least squares regression. Based on the model assumptions, a linear distribution regression was found to be acceptable. The regression line represents the long-term trend and determines whether the number of extreme events has or has not increased over the time period.

3. Results and analysis

3.1. PRISM rainfall data analysis

Figure 3 shows the population densities for 1990 and 2010 and their difference. The high-value areas in Figure 3c denote a large population increase in several locations indicating rapid urbanization during this period. In the Midwest, notable population growth was seen in existing urban centers like Minneapolis, Minnesota; Chicago, Illinois; Milwaukee, Wisconsin; Indianapolis, Indiana; Columbus, Ohio; and St. Louis and Kansas City, Missouri. Southern cities showing urbanization included Houston, Dallas, and Austin, Texas. Most coastal areas in the northeastern United States experienced continued population growth as well, especially New York City, New York; Baltimore, Maryland; and Washington, D.C. While in the southeast subregion, Raleigh and Charlotte, North Carolina; Atlanta, Georgia; and Tampa, Orlando, and Miami, Florida, all showed increased urbanization.
PRISM-based monthly precipitation data over the eastern United States were analyzed from 1990 to 2008. The data were averaged for the summer season spanning from May to August. The difference between 1990–99 and 2000–08 is shown in Figure 4. The Boston, Washington, D.C., Baltimore, Tampa, and Houston regions showed significant rainfall increases (~30%) in their surrounding areas. Furthermore, these areas also experienced continued urbanization as previously discussed. Midwestern cities like Chicago, Illinois; Indianapolis, Indiana; Cleveland, Ohio; Detroit, Michigan; St. Louis, Missouri; and Pittsburgh, Pennsylvania, also saw a 10%–20% increase in precipitation. Reviewing the changes, it was found that the northeastern and some southern areas (particularly parts of Texas) experienced increases of more than 30%. Rural stations within Iowa, Minnesota, Nebraska, South Dakota, and Kansas show decreases (~20%) in summertime rainfall in the last 20 years.

To isolate the likely modification of the rainfall climatology by urbanization, the rainfall change over urban areas was compared with the changes across rural areas. According to the U.S. Census Bureau, an urban area consists of at least 400 people per square kilometer. Using this criterion, the grids were divided into urban and rural subsets. The spatially averaged rainfall change over the whole domain was a 0.36-mm increase between the two subperiods (1990–99 and 2000–08). While over urban areas, there was a 4.17-mm increase in summer rainfall with a 0.86-mm decrease over the rural areas. To better explore this feature and normalize spatial patterns, the rainfall probability distribution function (PDF) was computed over the urban and rural areas (see Figure 5). The urban grids have a positive bias when compared to rural grids, which shows that heavy rainfall may have an urban association. Using a two-sample Friedman test, with the rural and urban points, the
urban grids in Figure 5 were shown to be significantly ($p = 1.8 \times 10^{-4}$) different than the rural grids, with a distinct positive bias.

After analyzing the rainfall changes over urban versus rural landscapes for the eastern United States, a more detailed analysis over different subregions was undertaken to better explore the spatial differences in the rainfall changes. The subregions (Figure 1) are useful for dividing the different data and also for putting current climate anomalies into a historical perspective (Vose et al. 2014). Furthermore, the subregions are known to have different local feedbacks on regional climate due to synoptic conditions. Figure 6 shows the probability distribution functions for the five subregions across the eastern United States: Northeast, East North Central, Central, Southeast, and South. The PDF confirms the finding for the broader region but also shows regional features. Consistent with the different observations, the PDFs indicate that the region has experienced more rainfall in last 20 years. The shapes of the curves provide additional information regarding rainfall changes in the urban versus rural areas. Using the Friedman test, all regions except the Northeast, were shown to have a statistically significant urban positive bias and to represent distinct modes of precipitation. The Northeast is an exception in that the results indicate slightly more positive rainfall changes over the rural areas. However, it is also notable that there are more urban grid cells than rural grid cells over the Northeast and, as a result, the increasing rainfall near urban–rural boundaries will also contribute to the rural areas and can confound the results.

### 3.2. Heavy rainfall downwind of urban areas

The higher rainfall anomaly seen downwind of urban areas has been documented by different studies (Shepherd 2005). To assess the downwind region in the monthly rainfall dataset, the North American Regional Reanalysis (NARR) wind fields at 32-km grid spacing and the winds at 850-mb level from 1990 to 2006 were used to match the rainfall amount data. The NARR data were interpolated to match the spacing of the population grids. Daily wind field patterns were obtained to determine the downwind direction, and the fields were averaged over the summer period (May–August) to derive a wind map. Note that while individual thunderstorm and rainfall cells would certainly vary for each storm, the 850-mb field was
chosen to approximately capture the “boundary layer winds” for the entire region. Based on the wind information, higher rainfall adjacent to some cities rather than over the cities themselves was noted (Figure 7).

To better visualize rainfall changes downwind of the urban area, for all urban grids, the downwind precipitation was considered as the representative rainfall for further analysis. These results help show rainfall changes over urban areas versus downwind urban areas more clearly. Prior research (Huff and Changnon 1972) suggests a 50-km distance from the downwind direction would be appropriate. Note that this distance is likely a function of storm speed as analyzed in Schmid and Niyogi (2013), but the single value is reasonable for the regional analysis. For an urban grid, the grid cell was located 50 km downwind of the NARR climatological wind direction at 850 mb, and the urban rainfall change value was replaced with the downwind grid’s rainfall change value (i.e., convolved). The choice of the
threshold for downwind distance was also based on tests with different values (30–80 km, with a 10-km interval), and the strongest anomaly signal was noted for 50 km. Each city and every individual storm can have a different downwind maxima effect location, and this general threshold has only been used to conduct the climate assessment. Figure 8 shows the areas of increasing population threshold with the rainfall change with and without this convolution over the last 20 years, along with the number of stations in the area. Figure 8a shows the change in rainfall for different population thresholds without convolution. Here, the change of the rainfall decreases monotonically from a positive value of 2.7 mm at 0 threshold to −300 mm corresponding to the extreme case of 7500 people per square kilometer, while the critical point of rainfall change from positive to negative is at 2750 people per square kilometer. Considering the number of stations for different population thresholds, the number of grids that have more than 2560 people per square kilometer population density is only 300. This corresponds to about 1% of the total area representing dense urban centers over the eastern United States. Therefore, while an overall increase in rainfall occurred over the last 20 years, the dense urban centers (2750+ people per kilometer) show a decrease.

After convolving the urban grids with downwind grids (Figure 8b), the rainfall remained the same for the 0 to 900 people per square kilometer threshold. An increase in rainfall is noted with the population threshold above 6250 people per square kilometer. The rainfall then decreases, corresponding to the low rainfall amounts observed over select locales (e.g., very large cities). Figure 8b also demonstrates that when the characteristic downwind region is decreased from 80 to 50 km, via the convolution function parameter, the field shows a monotonic increase in rainfall when regressed against the population increase. Climatologically,
rainfall decreases over the city center and generally intensifies over the downwind region some 50 to 100 km from the urban region. The urban–rural boundary is influenced significantly by urbanization, population density, and related land-cover changes. Shepherd et al. (2010) and Shem and Shepherd (2009) also found in numerical modeling studies that convergence is enhanced at the urban–rural interface.

3.3. Analysis of surface observations

3.3.1. Heavy rainfall event

The relationship between population density and heavy rain event frequency was analyzed by examining the slope of the trend lines of heavy rainfall frequency for each station (Figure 9). Most stations with a change of heavy rain event frequency have slopes ranging from −10% to 15% per 50 years. The histogram peak is...
between 0% and 5%. When considering population density, dense urban areas show higher variability with significantly more (15% per 50 years) or less (−15% per 50 years) heavy rainfall events. Areas that showed increases or decreases in heavy rainfall event frequency (>15% per 50 years or <−15% per 50 years) had population densities around 8000 people per square kilometer, and the number of impacted stations was low (~30). The effects of population density again suggest that the urban–rural boundary, especially the downwind area, has more heavy rainfall events than the city centers (Bornstein and Lin 2000; Niyogi et al. 2011). To further illustrate the downwind amplification of rainfall by urban areas, Figure 10a depicts all stations with more than an 8% slope value for rainfall changes. Cities within Massachusetts, New York, Pennsylvania, and Washington, D.C., are seen prominently throughout Figure 10. A number of Central threshold stations can be seen around Indianapolis, Cincinnati, Cleveland, Columbus, Louisville, St. Louis, Minneapolis, and Chicago. In the southern part of the study domain, only a few stations met this threshold. This spatial analysis is also confounded by urbanization because impacts are along the urban–rural boundaries.

Stations with a negative slope in heavy rainfall frequency (i.e., reduction) are shown in Figure 11a. Most stations in this category are not near major cities. In the northeastern United States and eastern parts of the Midwest as well as in southwestern areas over Texas, very few stations showed decreases in heavy rainfall frequency. However, many stations in the western section of the Midwest, such as in Wisconsin, Illinois, Iowa, Kansas, and Kentucky, showed decreases over rural regions. Similarly, many stations across Alabama, Georgia, and South Carolina showed similar trends.

3.3.2. Very heavy rainfall events

Similar results were found for very heavy rainfall events (Figure 10b). The pattern is similar to Figure 10a, showing that more stations in urban areas
experienced a higher frequency of very heavy rainfall events. While large cities had fewer events, the urban–rural boundary area had more instances of very heavy rainfall. From the spatial distribution map of stations with more than 3% per 50 years change in the very heavy rainfall events (Figure 10b), it was noted that the very heavy rainfall event frequency change is similar to the heavy rainfall event frequency change.

3.3.3. Extreme rainfall events

Generally, the extreme events in this category typically occur once or twice a year. The number of stations with positive slope and negative slope are almost equal. The stations with maximum population density show a slope of +7% per
50 years. This indicated that some big cities experienced more extreme rainfall events than others, but the sample size is small and hence the results are uncertain.

The map of stations shows a slope larger than +1% per 50 years for extreme rainfall events (Figure 10c). Most increases occur over the northern U.S. areas, with many locations showing urban influence. Urban area stations, such as Minneapolis, Chicago, St. Louis, Indianapolis, Houston, Miami, Pittsburgh, Boston, and Washington, D.C., had positive slope values of more than 1% per 50 years. This trend is notably different from both heavy rainfall and very heavy rainfall event conditions. Even though both the rainfall amount and the frequency of heavy rainfall events decreased over urban areas, more extreme rainfall events were found over big cities, especially in the northern United States. The mechanism for this phenomenon needs to be explored in a future study with higher spatial density of urban observations. Other regions with more than 1% slope are evenly distributed over the eastern United States.

Alternatively, in Figure 11c, areas with a negative slope of extreme rainfall events were relatively evenly distributed over rural areas. There were only a few over northern Houston and western New York City as well as Miami. There were also many instances over Alabama, northern Georgia, and South Carolina that were observed.

4. Conclusions

Several recent studies have suggested urban initiation-downwind translation or bifurcation/remerging as possible mechanisms for the urban–rural anomalies resulting in the urban modification of storms and resulting rainfall patterns. After analyzing different observations and rainfall characteristics relative to urban–rural boundaries, a number of general conclusions can be drawn related to the climatic signature of rainfall modification by urban areas.

In the last two decades, both the amount and frequency of observed summer rainfall in the eastern United States have increased. Results point toward an urbanization signature in the changes in the rainfall pattern. In particular, urban and rural areas show different patterns in their rainfall changes. Consistent with the case studies reported in the literature, locations in the periphery of urban areas exhibit a higher probability of heavy rainfall amounts in the last 20 years, while the urban centers have experienced a decrease in rainfall amounts. The urban–rural boundaries experienced significantly more rainfall in the summer, especially in the climatological downwind regions.

As a result of the rainfall amount changes, the frequency of heavy rainfall events and very heavy rainfall events also show a modest increase over urban–rural boundaries and a general decrease over city centers and rural areas. While one would expect heavy rainfall to decrease over urban centers because of thunderstorm splitting, extreme rainfall events showed an increasing trend. This needs to be reevaluated with a higher density of urban rainfall stations and possibly longer period of record.

Spatially, the rainfall changes over northeastern and central areas are more pronounced in comparison to the changes in the south. In the Northeast, results of both rainfall amount and frequency indicated a significant increase, while the Southeast shows a decreasing trend in the frequency of heavy rainfall events. These
results suggest that changes in thunderstorm and rainfall patterns around urban regions may now start to show a climatological signature but are also influenced by other local and large-scale processes that have not been explicitly identified in this assessment. Thus, this analysis suggests that the observed rainfall changes may have an urbanization-based signature in addition to the larger/global changes being documented.

This study also highlights the challenge that exists in identifying the impact of urbanization on regional rainfall patterns. While the temperature impacts of urbanization (urban heat islands) are relatively local, the impact of urbanization and temperature increase is collocated (Fall et al. 2011); the rainfall impacts need additional consideration of the dynamical and mesoscale processes. Thus, the urbanization impact is often at a different location as compared to where urbanization has occurred. When model results or gridded data products are being analyzed, the urban impact on rainfall will likely depend on the spatial resolution of the analysis undertaken. For example, for a fine grid (e.g., order of 1–5 km) high-density station network, the urbanization impact will likely be often noted as a downwind feature away from urbanization. For a coarse grid analysis (using climate model or reanalysis grids –30 km or more) it is likely that the impact would be over the grid itself since the urban feature would likely be a subgrid feature. As a result, spatial confounding or additional similar data processing is needed before making the conclusions about urbanization impacts. Also, it is not necessary that all urbanization-induced rainfall changes be downwind of the urban area. In fact, in a recent report (Seto et al. 2012), a synthesis presented includes scenarios where rainfall can increase upwind as well as downwind, while in some cases it can even increase over the city itself depending on the dynamical and regional heating rates.

Another feature to consider is the “definition” of urbanization itself. While a satellite imagery–based dataset can help identify the spatial domain, it is important to note that urbanization is more than just landform changes, and the human influence and activities that cause anthropogenic changes (e.g., transportation) also have an impact. As a result, the population threshold used in this study appears to be a good surrogate for urbanization. However it is not recommended to use only a single threshold, as a percentile basis would be more appropriate to capture the difference in density over different regions. This is consistent with the analysis of Kishtawal et al. (2010) where the urbanization signature as detected by satellite-based land cover and population density was evaluated for India. The dynamical processes affect many of the results, and their importance needs to be considered especially when analyzing future climate scenarios in conjunction with urbanization changes. When the dynamical aspects are not adequately considered, it is likely that incorrect conclusions related to the significance or lack of urbanization impacts on future rainfall climatology can emerge.

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