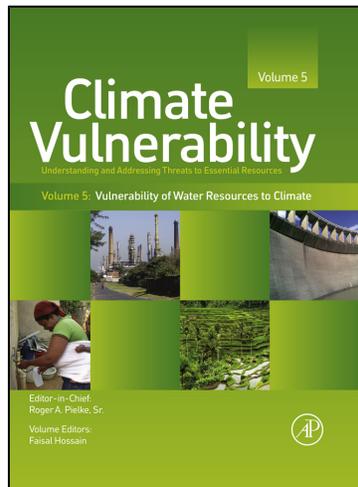


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5.07 Impacts of Urbanization on Precipitation and Storms: Physical Insights and Vulnerabilities

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5.07.1 Introduction

On January 19, 2011, an unusual weather event occurred. The National Weather Service Web site (http://www.crh.noaa.gov/news/display_cmsstory.php?wfo=ddc&storyid=62980&source=0) described the event in the following way: "the atmosphere was cold and moist with low clouds and fog preceding the formation of the snow. It appears that two slaughter plants and a power generating plant (upwind of the region) contributed to the snow as ice nuclei and copious amounts of water vapor were fed into the boundary layer. East/southeast winds carried the vapor and nuclei aloft into the lower clouds and then precipitated out as snow downwind (Figure 1) of the source. Snowfall of as much as 0.7" was reported in the snowfield with no snow observed at all outside of this area." The snowfall plume is apparent in Doppler radar images (Figure 2(a)) and satellite depictions of snow cover (Figure 2(b)).

Though unusual, this example illustrates how human activity in an urban environment affected a precipitation event. The scholarly literature continues to indicate that urbanization, deforestation, irrigated landscapes, impounded structures, and pollution can alter the frequency, intensity, or occurrence of precipitation (Mahmood et al. 2010). In fact, the Intergovernmental Panel on Climate Change (IPCC) (Trenberth et al. 2007) specifically mentioned an emerging interest in how urban environments—the focus of this discussion—modify hydrometeorological and climate system. While the climate discourse has been primarily centered around greenhouse gas emissions, urban climate effects are conclusively documented.

Seto and Shepherd (2009) stated that "the built environment characterized by urbanization is a significant forcing function on the weather-climate system because it is a heat

source, a poor storage system for water, an impediment to atmospheric motion, and a source of aerosols (e.g., pollutants)." Table 1 (adapted from Seto and Shepherd 2009) presents multiple ways that urbanization can impact hydro-meteorological and climate processes.

The most common manifestation of urban climate is the urban heat island (UHI). The UHI is typically characterized by warmer skin, surface, and canopy temperatures in urban landscapes due to heat-retaining materials (e.g., asphalt, concrete), lack of vegetation, and excessive anthropogenic heat sources. Surface geometry (e.g., as expressed by sky view factor) is also an important element of the UHI; surface geometry also increases the surface area for solar absorption, leads to multiple reflections and decreased albedo, and affects turbulent transport (sheltering effects). All of which impact the UHI. Grimmond et al. (2010) and Yow (2007) are excellent resources for information on the energetics, thermal properties, and dynamics associated with UHIs.

UHIs are somewhat common in both scientific and public vernacular. It is a conclusive example of human alteration to the Earth's climate system. However, the literature has also revealed that urban landscapes and associated pollution may also alter components of the water cycle, particularly clouds, precipitation, and land surface hydrology (Bentley et al. 2010; Niyogi et al. 2011; Grimmond et al. 2010; Hidalgo et al. 2008; Mills 2007; Shepherd et al. 2010a, 2011). The motivation herein is to review the theoretical and physical basis for how urbanization influences the spatiotemporal nature of precipitation and convective activity. This is particularly important for the following reasons:

1. For the first time in history, the majority of the world's population lives in urban environments (Hand and Shepherd 2009) and this number will increase to over 80%

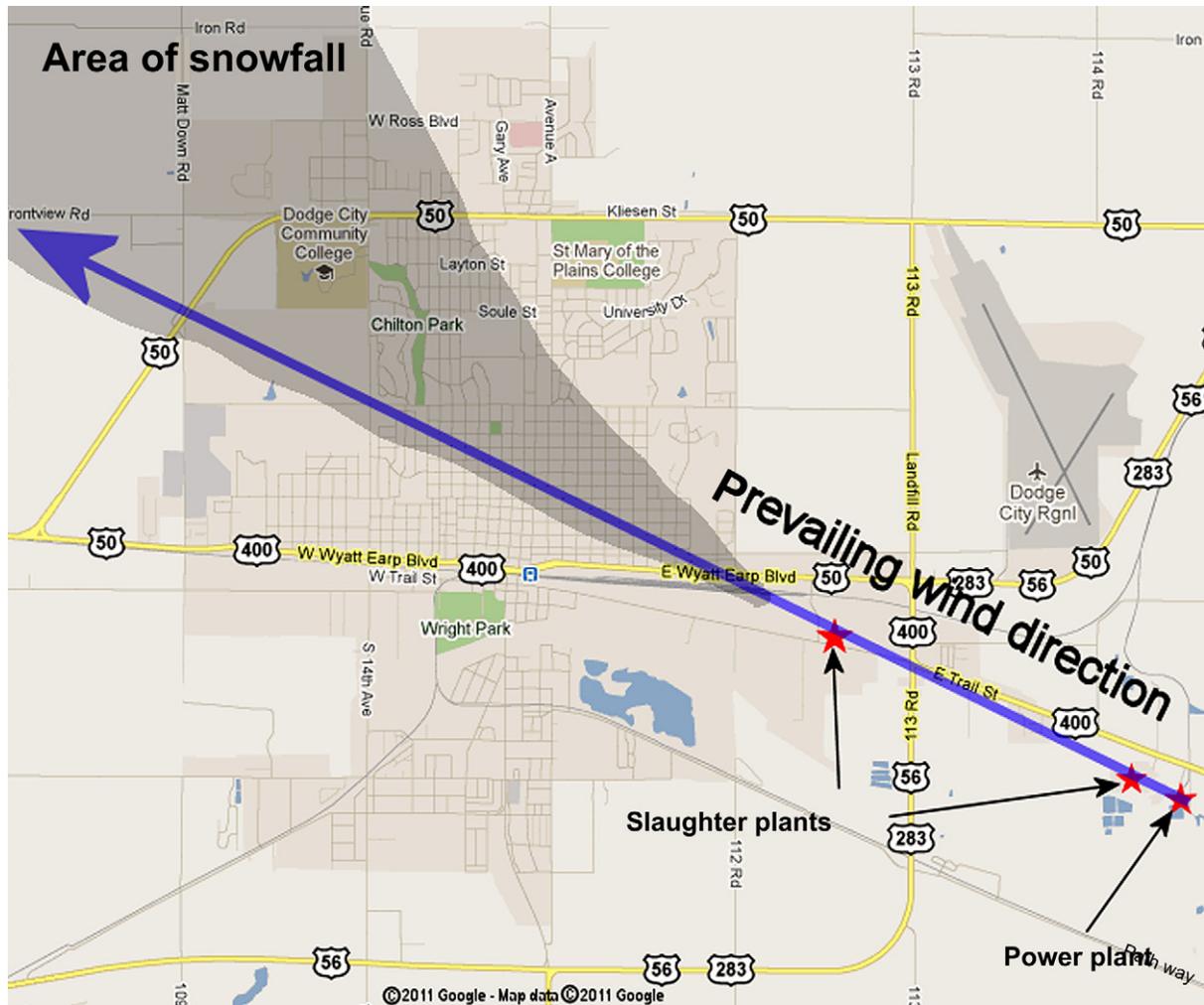


Figure 1 Dodge city, Kansas area and downwind region of unusual snow event. Source: National Weather Service; Shepherd J. M. and T. L. Mote, 2011: Can cities create their own snowfall?: what observations are required to find out? Earthzine, Special Urban Monitoring Theme Issue. [Available online at <http://www.earthzine.org/themes-page/urban-monitoring/>.]

by 2030 (UNFPA 2007) (Figure 3). This means that urban land cover and air quality degradation will continue to expand and expose more people to vulnerabilities associated with urban climates.

2. Convective processes and precipitation are critical components in the global water cycle and a key proxy for climate, but they exhibit variability at a range of scales from local to global.
3. Urban-hydrometeorological-atmospheric interactions have major societal implications for weather forecasting, climate diagnostics and prediction, flood management, water resource management, urban planning design, and agriculture.

5.07.2 Vulnerabilities in the Coupled Human Natural System

It is clear that the urban rainfall effect (URE) is of scientific interest because there are clear linkages to contemporary

research and forecast problems in meteorology, climatology, hydrology, and geography systems. However, precipitation in an urban setting is strongly coupled to key societal processes and decision trees. An array of vulnerabilities may be linked to urban precipitation climatologies and variability:

1. Urban flooding: Jurisdictions are increasingly interested in the complex interplay of the urban environment and the atmospheric and land surface components of the water cycle. Shepherd et al. (2011) raised important questions about whether storm water management, drainage systems (Burian et al. 2004), and urban planning consider the shifting precipitation regimes associated with large-scale climate and urban climate. For example, hydroclimate experts have warned that current urban flood assessment and storm water management are based on hydroclimate stationarity assumptions and outdated assumptions concerning rainfall intensity and frequency. Intensity, duration, and frequency resources and methodologies must be modified to reflect nonstationarity and new understanding of local-to-regional hydrometeorological forcing.

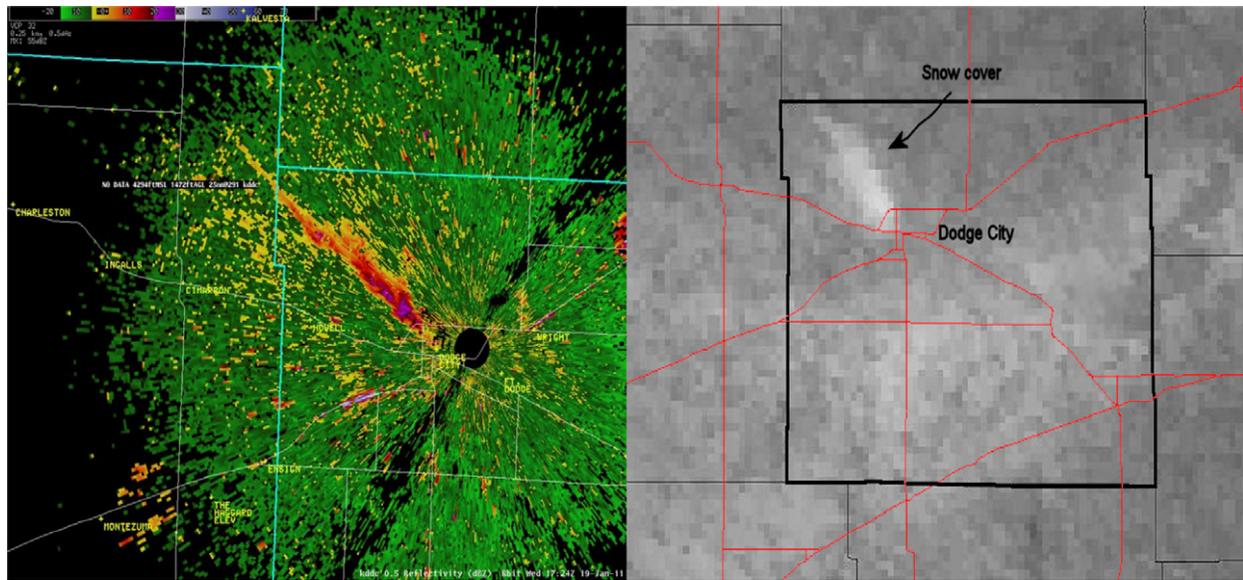


Figure 2 Dodge city snow event as captured by a (a) radar image at 1124 LST and (b) satellite image after the event. Source: National Weather Service; Shepherd J. M. and T. L. Mote, 2011: Can cities create their own snowfall?: what observations are required to find out? Earthzine, Special Urban Monitoring Theme Issue. Available online at <http://www.earthzine.org/themes-page/urban-monitoring/>.

Table 1 Alterations of surface and atmospheric processes by changes in urban land cover, urban aerosol loading in the atmosphere, and anthropogenic greenhouse gas emissions

<i>Weather or climate processes</i>	<i>Urban land cover</i>	<i>Urban aerosols</i>	<i>Anthropogenic greenhouse gas emissions</i>
UHI and mean surface temperature record	Surface energy budget	Insolation, direct aerosol effect	Radiative warming and feedback
Wind flow and turbulence	Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow	Direct and indirect aerosol effects and related dynamic/thermodynamic response, dispersion, and transport	Radiative warming and feedback
Clouds and precipitation	Surface energy budget, UHI destabilization, UHI meso-circulations, UHI-induced convergence zones	Aerosol indirect effects on cloud–precipitation microphysics, insolation effects	Radiative warming and feedback
Land surface hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud–microphysical and precipitation processes	Radiative warming and feedback
Carbon cycle	Replacement of high net primary productivity land with impervious surface	Black carbon aerosols	Radiative warming and feedback, fluxes of carbon dioxide
Nitrogen cycle	Combustion, fertilization, sewage release, runoff	Acid rain, nitrates	Radiative warming and feedback, NO _x emissions

Adapted from Seto, K., and J. M. Shepherd, 2009: Global urban land-use trends and climate impacts. *Curr. Opin. Environ. Sustain.*, doi:10.1016/j.cosust.2009.07.012.

- Urban planning: It is reasonable to consider how contemporary and future cities are planned. Stone et al. (2010) and Shepherd et al. (2010b) have shown that urban land cover is a significant driver of climate at the urban and associated regional scales. Such research is intriguing and raises questions about urban governance and the inclusion of urban hydroclimate science in policy and decision making. It is not unreasonable to consider the planning of an urban landscape with an eye toward mitigating or maximizing precipitation for a region’s agriculture or water supply needs.
- Public health: Urban precipitation climatology may be associated with an array of health issues, ranging from West Nile virus to asthma. Socioeconomics and public health

- practices are first-order factors, but it is plausible that areas which may experience more rainfall in an urban regime could be more susceptible to water-borne diseases (e.g., dysentery or cholera) or vector-borne diseases (e.g., malaria, dengue, and West Nile virus). Further, thunderstorms were associated with more hospital admissions for respiratory distress and asthma for metropolitan Atlanta, Georgia (Grundstein et al. 2008).
- Water resource management: In the face of increasing drought and the need for additional surface water supply, Shepherd and Mote (2009) have argued that future water supply reservoirs might be placed in urban rainfall anomaly regions to optimize recharge, particularly in the warm season. For example, Mote et al. (2007) noted that eastern



Figure 3 Defense Meteorological Satellite Program (DMSP)/Optical Line Scanner (OLS) data showing lights at night in the United States. Source: NASA (<http://www.nasa.gov/vision/earth/lookingatearth/NIGHTLIGHTS.html>). The lights, to a first order, are a proxy for urbanization.

suburbs of Atlanta (within 50–100 km) receive more warm season rainfall (more on this in later sections), yet **Figure 4** shows that this region has no new reservoirs planned.

5. Strategic systems management: The placement of new agricultural lands, sensitive electrical infrastructure, flood management, or industrial facilities might be informed by knowledge of urban lightning or precipitation anomalies.

Proposed Water Supply Reservoirs

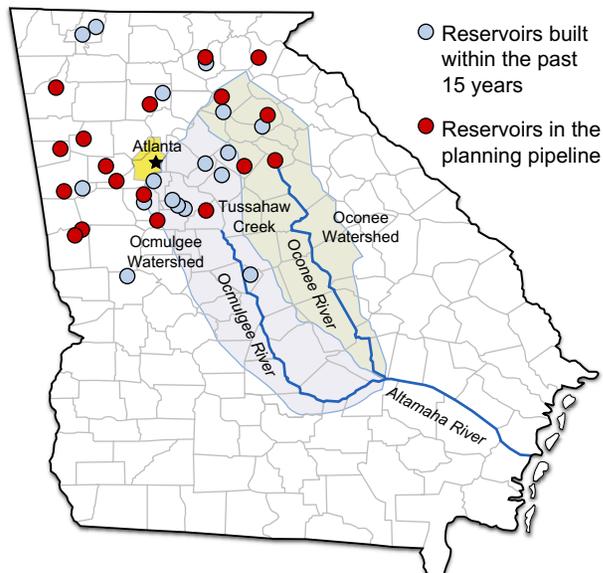


Figure 4 Proposed water supply reservoirs (courtesy of the Army Corps of Engineers). Red dots are planned reservoirs. Source: Shepherd, J. M., and T. L. Mote, 2009: Urban effects on rainfall variability: potential implications for Georgia's water supply. *Proceedings of the 2009 Georgia Water Resources Conference*, 6 pp.

Clearly, urban weather and climate are integrated in the economics of urban regions. Such costs might include flood damages, airport closures, health-insurance costs, or regional transportation infrastructure. Snowstorms in 2010 and 2011 crippled Washington, DC (i.e., 'Snowmageddon') and revealed cascading scales of vulnerability ranging from the poorest citizen of the District of Columbia to the President of the United States.

A rare tornado in the central business district of Atlanta, Georgia, in 2008 and the crippling tornado outbreak in Joplin, Missouri, in 2011 reveal potential infrastructure vulnerabilities and the need to consider severe weather in urban building codes. Thomas (2011) recently discussed the vulnerabilities of hospitals to severe weather in light of the Joplin event. She notes that "... extreme weather can cause building failures that ultimately lead to interruptions in the continuity of care. The impacts are not momentary. From post traumatic stress disorder to the costs of structural rebuilding, the affects can be long-lasting. Yet, structural mitigation, while not a full panacea, can offer some protection to keep buildings and people safe. The World Health Organization (WHO) calculates that the price for retrofitting the non-structural items (e.g., moveable carts, trays) costs as little as 1% of the value of a hospital, while possibly protecting up to 90% of the hospital's assets. According to FEMA, the most common points of hospital failure from storms are the elevator crankcases, windows and generators. Bolstering protection of these building assets costs magnitudes less than the cost to rebuild." While specific to hospital infrastructure, such recommendations are relevant to any urban building infrastructure facing the threat of increased storm activity or flooding.

While urban changes to the hydroclimate have been discussed herein, one must not overlook the coupled influenced and heightened vulnerability due to the background climate gases (Seto and Shepherd 2009). Reports, composed of international expertise, continue to call for renewed resources and

research to address urban hydroclimate interactions (Dabberdt et al. 2000; NOAA OFCM 2004; NRC 2012).

5.07.2.1 Controversy Over the Sign of Change

Though methods and data availability continue to improve, there is still uncertainty and scientific debate about whether urban environments increase rainfall, decrease rainfall, or have no effect on rainfall. The consensus in the literature suggests that some type of enhancement is the dominant sign change; however, other results are compelling (see Section 5.07.2). However, it is worth noting that there is some literature that finds conflicting results, albeit a relative minority of studies. Hughes (2006) found no statistical evidence supporting UREs in cities of the United Kingdom, although she did not rule them out either. Matheson and Ashie (2008) found in modeling simulations for Tokyo that rainfall was increased or decreased due to the inclusion of the city, as a function of the prevailing wind. However, their results do suggest that urban landscape can modify precipitating systems. Trusilova et al. (2008) coupled atmosphere–land surface (CAL5) model simulations of European climate sensitivity to urban land cover offered mixed results. Shepherd et al. (2010a) summarized their results by noting that they found “statistically significant increases (decreases) in winter (summer) precipitation in their urban simulations as compared to the pre-urban simulations.” This study was interesting but used fairly coarse model resolution (10 km) and cumulus (not explicit microphysics) parameterization for cloud–precipitation processes.

Kaufmann et al. (2007), using statistical and econometric models, found evidence of reduced precipitation after urban development throughout the Pearl River Delta of China. They suggested that reductions in surface hydrology could explain the changes. Guo et al. (2006) used a similar argument to explain decreased cumulative rainfall around Beijing. Zhang et al. (2009) showed that urban land cover in Beijing reduced ground evaporation and evapotranspiration, which was important for rainfall formation. One important factor that was missing in the studies describing precipitation suppression in Asia is aerosols or pollution.

Aerosols (e.g., pollutants) have been shown to suppress precipitation. This inverse relationship between aerosol load and precipitation has been summarized in Lin et al. (2011), Stjern et al. (2011), and Rosenfeld et al. (2008). Asia is a heavily polluted region and a thorough climatological assessment of precipitation change in the region must consider the recent trends in the spatiotemporal aerosol distribution. Recent studies (Rosenfeld et al. 2008; van den Heever and Cotton 2007) have explored the role of giant cloud condensation nuclei (CCN) (enhancement) and smaller CCN (suppression). However, the synergistic role of urban aerosols and land cover on precipitation is still not conclusive and requires additional study. It is likely that topography, meteorology, aerosol type, and continentality determine the order of influence of aerosols. For example, Jin and Shepherd (2008) argued that aerosol effects are more dominant on maritime cloud droplet formation. Stjern et al. (2011) found no statistical evidence that aerosols have affected drizzle or light rain climatologies in Europe. Lin et al. (2011) firmly established the inverse relationship between aerosols and precipitation.

5.07.3 Historical Evidence of the ‘URE’

While contemporary methods and studies have advanced knowledge of the URE, it is useful to consider the historical legacy of this field. Horton (1921) observed that thunderstorms seemed to develop over large cities. Kratzer (1937, 1956) further advanced the notion of urban alteration of precipitation. However, the pioneering text ‘The Climate of Towns’ by Helmut Landsberg (1956) elevated the possibility that large urban areas affect rainfall. Over the next several decades, more research emerged on the topic. Several studies were focused on a hypothesis that industrial, urban regions southeast of Chicago, Illinois, such as La Porte, Indiana, had enhanced cumulative precipitation due to urban or aerosol effects. Stout (1962) and Changnon (1968) led early investigations related to the ‘La Porte Anomaly’ although they were inconclusive (Lowry 1998). More importantly, these early studies stimulated the first golden age in research on the topic.

The prevailing hypothesis in early studies, many advanced by European scholars, was that rainfall was enhanced primarily over or downwind of urban areas (Landsberg, 1970; Huff and Changnon, 1972a,b). A major North American field program, the METROpolitan Meteorological EXperiment (METROMEX), was a large-scale effort to test such hypotheses and advance scientific understanding of urban precipitation climatologies and physical mechanisms. A key legacy of METROMEX is that it provided some of the earliest and most rigorous hypotheses about physical forcing of urban hydroclimate interactions. METROMEX employed many observational strategies including special rain gauge networks, balloon soundings, and weather radar. Shepherd et al. (2010a) summarized key findings from the series of scholarly publications from this multicity investigation:

1. Enhanced cumulative precipitation (see Figure 5 as an example) by urban effects are typically 25–75 km downwind of a city during warm season months (Changnon et al. 1977; Huff and Vogel 1978; Changnon 1979; Braham 1981),
2. Cumulative amounts were enhanced between 5 and 25% over background values (Changnon et al. 1981, 1991), and
3. The size of an urban area influenced the horizontal extent and magnitude of urban enhanced precipitation (Changnon 1992).

Lowry (1998) raised questions about the methodologies and research framework applied during METROMEX and post-METROMEX studies. He further hinted that such deficiencies could ‘create’ the anomaly regions. His recommendations, summarized below, would provide key guidance to contemporary studies on urban rainfall. Lowry (1998) recommended:

1. “Designed experiments—especially legitimate controls and, where appropriate, stratification schemes—in which explicitly stated hypotheses are tested by means of standard statistical methods.
2. Replication of the experiments in several urban areas.
3. Use of spatially small, and temporally short, experimental units reflecting the discontinuous nature of precipitating systems.
4. Disaggregation of standard climatic data to increase sample size and avoid merging effects between dissimilar synoptic weather systems.”

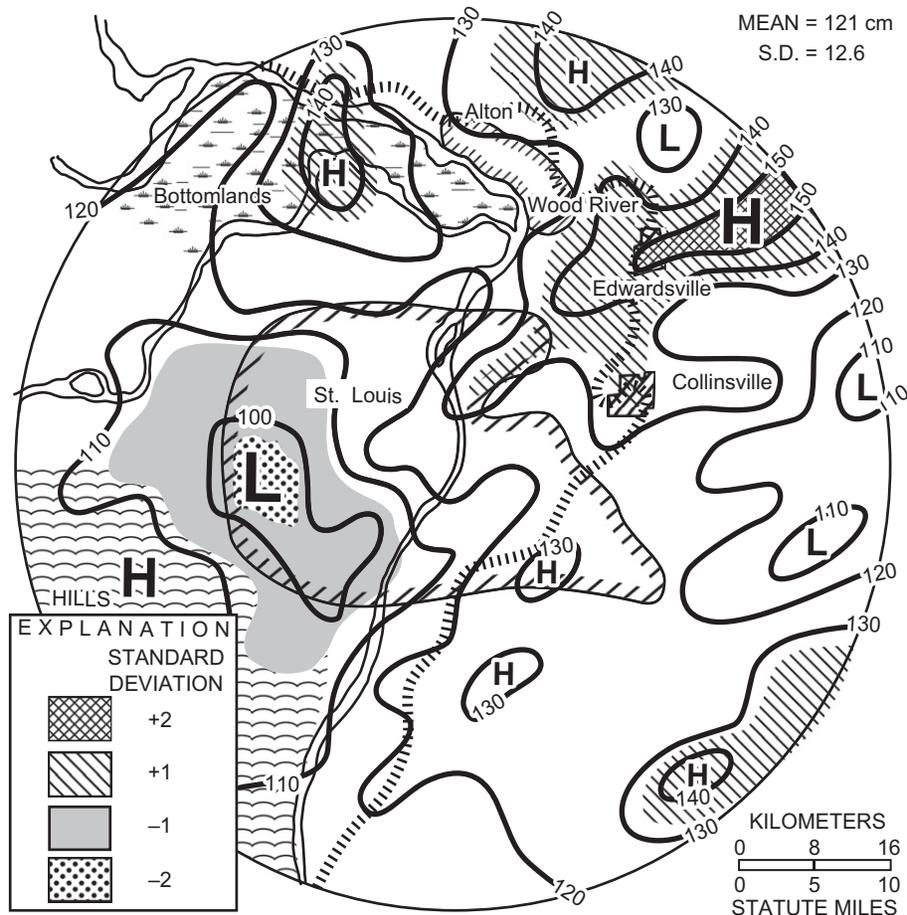


Figure 5 METROMEX, total summer rainfall (cm), 1971–75. Source: Changnon, S. A., F. A. Huff, P. T. Schickedanz, and J. L. Vogel. 1977. Weather anomalies and impacts: In summary of METROMEX Vol. I. Illinois State Water Survey Bulletin 62, 260 pp.

As noted earlier, the literature has found conflicting results to METROMEX. Tayanc and Toros (1997) found no evidence that four large Turkish cities had modified climatological rainfall patterns. Robaa (2003) argued that an inverse relationship may exist between urbanization and cumulative precipitation around Cairo, Egypt. In future sections, other recent findings that support or refute the METROMEX results are discussed. The text will also explore the physical mechanisms that link urbanization to precipitation changes. Aerosols – for example, their concentration, size, and to a lesser extent composition – have been shown to suppress or enhance precipitation and/or lightning (Rosenfeld et al. 2008). Regardless of the sign of the change, it is clear from the literature that urbanization alters the hydroclimate system in diverse ways.

5.07.4 Post-METROMEX Era Perspective

After METROMEX and the subsequent questions about the validity of its findings, momentum on the topic slowed. Balling and Brazel (1987) noted a greater frequency of occurrence of late afternoon thunderstorms around the Phoenix area. They attributed the increase in frequency to rapid urbanization in this otherwise arid region. Selover (1997) noted that moving

summer convective storms were altered by Phoenix. Later work by Diem and Brown (2003) and Shepherd (2006) corroborated the notion of a URE in the Phoenix area, particularly in the Lower Verde region of Phoenix. Shepherd (2006) hypothesized that urban-induced mesocirculations might interact with outflow boundaries from the mountain-forced convection to explain the location of the Lower Verde anomaly.

Jauregui and Romales (1996) found significant correlations between the daytime UHI and the intensity of rain showers during the wet season (May–October) in Mexico City, Mexico. They also argued that the frequency of intense rain showers had increased as a result of urban growth. Changnon and Westcott (2002) found a similar tendency toward more heavy rainstorms in recent decades for a selection of urban locations.

Bornstein and LeRoy (1990) were one of the first research groups to study the URE in a ‘megapolis’ city. Using weather radar, they found that maximum convective rainfall was found on the lateral edges and downwind of New York City. This study was important because it further demonstrated the value of weather radar to overcome limitations associated with the sporadic nature and point source availability of rain gauges. Precipitation, unlike temperature, is highly variable in space and time, which can be problematic for point source measurements. This study also solidified the notion that cities not only initiate

or enhance convection but also modify the structure and progression of storms. Recently, Niyogi et al. (2011), using Doppler radar data, found that the city of Indianapolis, Indiana, modifies a significant number of storms approaching the urban environment. Such studies indicate that the urban effect is not only apparent in the initiation of convection in weak large-scale forcing environments as previously argued, but it can also modify preexisting convection. Shem and Shepherd (2009) found similar results in their modeling simulations of moving convective systems in Atlanta, Georgia.

Shepherd et al. (2002) introduced a new approach for examining the URE. They used satellite-based instrumentation designed to measure precipitation from space. Space-borne estimates enabled the investigation of multiple cities simultaneously as opposed to one or two urban locations. This approach overcomes one of the limitations of earlier work identified by Lowry (1998). On the other hand, the satellite-derived rainfall estimates had relative coarse spatial resolution and well-known measurement biases. Shepherd et al. (2002), using a short 3-year period, found evidence of precipitation anomalies in the climatological downwind region of several major cities in the southeastern United States. Diem et al. (2004) and Shepherd (2004) had a scholarly discourse on the merits of the findings, appropriate scale, and methodologies in Shepherd et al. (2002). Souch and Grimmond (2006) noted that this paper may have 'reinvigorated' the urban climate community on the question of UREs.

Shortly after Shepherd et al. (2002) had published, Dixon and Mote (2003) presented evidence that in the moist environment of Atlanta, Georgia, some nocturnal convective storms might have been initiated by the urban landscape itself. During the same period of time, a Japanese paper, Fujibe (2003), stated that increased convective activity downwind of large cities like Tokyo may be due to the enhanced surface convergence in the urban environment (more in the following sections). Shepherd and Burian (2003) extended the satellite-based methodology to a large coastal-urban complex, Houston, Texas, and found that rainfall anomalies in the data were spatially consistent with lightning flash density anomalies described by Orville et al. (2001). Orville et al. (2001), and later Steiger and Orville (2003), attributed the lightning anomalies to urban landscape or industrial-urban aerosols. Further details are provided in the following sections.

In 2005, Shepherd reviewed the current literature related to urban convection and rainfall effects. While the review was a timely contribution to the literature, he also provided a set of recommendations to move understanding and predictive capability forward on the topic: The recommendations of Shepherd (2005) were as follows:

1. "New observing systems must be developed to monitor and track anthropogenic and natural aerosols, land cover/land use changes, cloud microphysics, and precipitation processes,
2. Modeling systems that explicitly resolve aerosols, cloud microphysics, complex land surfaces, and precipitation evolution so that a more conclusive understanding of the feedback and interactions can be attained,
3. Implementation of urban parameterizations at the local scale to resolve urban canyon, dynamics, and flux processes,

- particularly in terms of roughness, surface cover properties, low-level moisture associated with irrigation, and aerosols,
4. Field studies to validate satellite observations and modeling simulations of urban-precipitation processes and to extend basic understanding of the processes involved,
5. Climate modeling systems that adequately characterize the urban environment are required to understand the aggregate roles of global urban surfaces on the Earth's climate system, particularly the precipitation component of the water cycle under different growth and climate scenarios,
6. Assessment of the impact of urban-induced rainfall on societal applications."

Burian and Shepherd (2005) confirmed the satellite-based results of Shepherd and Burian (2003) by using historical gauge data to show that "urban area and the downwind regions of Houston, Texas (USA) had 59 and 30% respectively greater cumulative rainfall between noon to midnight in the warm season compared to the upwind region." As noted earlier, two studies (Diem and Brown 2003; Shepherd 2006) identified spatial anomalies around the northeastern suburbs and exurbs of Phoenix during the monsoon season. Shepherd (2006) results suggested that the anomaly regions had 12–14% more cumulative precipitation in the posturban (1950–2003) period as compared to the preurban (1895–1949) period. Shepherd argued that outflow boundaries from mountain thunderstorms might be interacting with the urban circulation to explain the location of the anomaly. Simultaneously, Chen et al. (2007) posed a similar hypothesis to explain a nocturnal anomaly around Taipei (Taiwan).

One of the most compelling studies to date is Mote et al. (2007). They employed a radar analysis to look at warm season (2002–06) composites of precipitation climatology. **Figure 5** (left panel) shows the greater rainfall totals expected in the Blue Ridge mountains of north Georgia and in the coastal plain to the south. More interestingly, there is an anomaly of higher rainfall amounts over and east of the Atlanta, Georgia, metropolitan area even though, climatologically, the entire area is similar. They found that this 'downwind area' receives up to 30% more warm season rainfall during the evening and early morning hours. It should be noted that this study stratified cased days to remove large-scale forcing, a key recommendation of Lowry (1998). This study is also compelling because it successfully establishes that the radar climatology strongly reveals the mesoscale and topographic signatures of rainfall in Georgia. Diem (2008) extended the epochal analysis of Diem and Mote (2005) to confirm, using long-term climatological analysis, that a rainfall anomaly exists in the northeast suburbs of Atlanta. Bentley et al. (2010) has extended the Mote et al. (2007) radar study and found that an array of downwind 'anomaly' regions may exist and, perhaps, some upwind anomalies as well. This is an important point to mention that, for a given day, upwind and downwind are a function of the prevailing wind such that a downwind anomaly for a given day may differ from the climatological downwind region, which is based on average flow conditions. In a compelling study, Ashley et al. (2012) conducted a climatological synthesis of urbanization effects on an array of cities in the southeastern US using a 10-year radar data analysis. They confirmed "positive urban amplification of thunderstorm frequency and intensity for major cities."

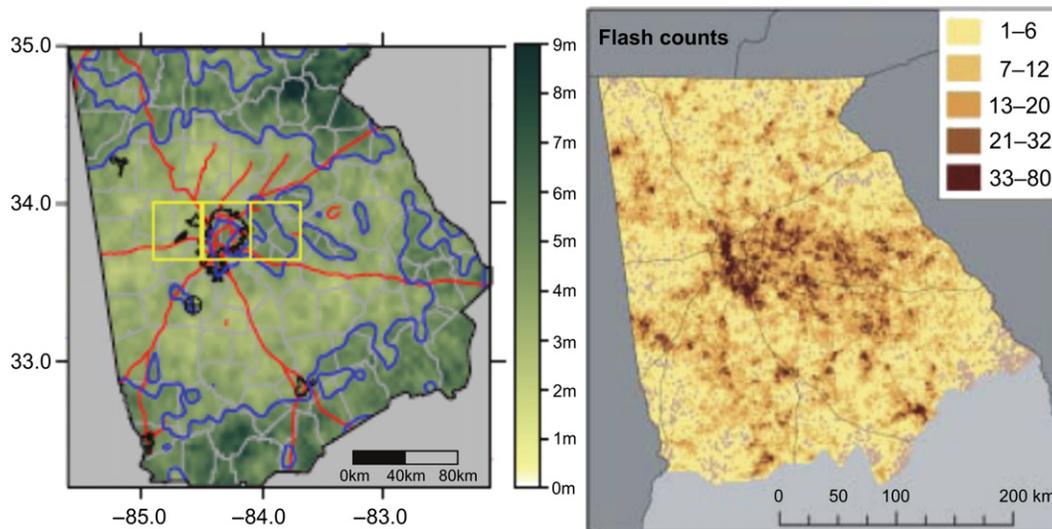


Figure 6 Average daily rainfall (shaded and units of millimeters) from Jun.–Aug. 2002 composited for days with weak atmospheric forcing. The 5-mm contour is shown in blue, and the yellow boxes represent the mean upwind (left), city (center), and downwind (right) regions (Left) and lightning flash anomalies (May–Sep. (1995–2003) on days dominated by weak atmospheric forcing) (right) in Atlanta, Georgia. See Mote et al. (2007) or Stallins and Rose (2008) for further information on methods and data.

5.07.5 Beyond Spatiotemporal Rainfall Climatology: Urban Effects and Other Related Hazards

5.07.5.1 Rainfall Intensity and Frequency

Since the URE is primarily associated with convection, it is logical that urban effects might be observable in other convective-related processes (e.g., heavy rainfall rates, lightning, and flooding). Rose et al. (2008) used cloud-to-ground (CG) lightning data and North American Regional Reanalysis (NARR) rainfall data set to reveal lightning enhancements in the same downwind anomaly region (Figure 6, right panel) identified by Mote et al. (2007). Stallins and Rose (2008) provided an excellent review of urban effects on lightning and highlight several global studies on the topic. The possible mechanism will be discussed later in the text.

Hand and Shepherd (2009) used a blended product called the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis and the Oklahoma mesoscale observational network to confirm not only a statistically significant rainfall anomaly in the north–northeast suburbs of Oklahoma City but also a tendency for heavier rainfall events to occur in the same region. This study was novel because it was the first application of a merged satellite product incorporating infrared, passive microwave, and rain gauge data rather than only satellite precipitation radar data. Consistent with Rose et al. (2008), Hand and Shepherd (2009) noted a fairly strong relation between prevailing wind and downwind anomaly regions. More importantly, Hand and Shepherd (2009) also established that such satellite-based estimates are relatively accurate when validated against ground-based rain gauge networks (at the appropriate scale) and can be useful in investigating rapidly developing urban regions around the globe. Basara et al. (2009) discussed a new fine-scale Oklahoma City micronet with observations in the central business district. Such measurements are rare and will enhance our research capacity going forward.

Kishtawal et al. (2009) used historical gauge networks and the TRMM precipitation radar to show that heavy rainfall events increased in urbanized regions of India compared to rural stations (Figure 7). Mitra et al. (2011) also used gauge data and satellite rainfall estimates to study the oft-neglected pre-monsoonal rainfall climatology of India. They found that urban stations in the region of Kolkata, India, have positive trends in pre-monsoonal rainfall. A forthcoming modeling effort by Mitra and Shepherd (personal communication) further confirms that ‘Nor’westor’ convective systems may interact with the urban landscape to affect the evolution of rainfall in the region.

Halfon et al. (2009) noted increased cumulative precipitation amounts downwind of Tel Aviv, Israel. Chang et al. (2009) noted the role that urban land cover played, through boundary layer and flux alterations, on a heavy rainfall event in Mumbai, India. Meng et al. (2007) also used ground radar-based analysis in an innovative study which presented evidence that the urban land cover associated with Guangzhou City (China) intensified thunderstorms associated with a tropical cyclone. Radar echoes were maximized over the urban area as also noted by Shem and Shepherd (2009) and Niyogi et al. (2011). Inamura et al. (2011) used ensemble simulations with a large number of members to investigate the effects of Tokyo’s landscape on heavy rainfall. They found that the urban effects of Tokyo modified the wind convergence and rainfall leeward of the urban area. Li et al. (2011) associated rapid urbanization in the Pearl River Delta region of China with an increase in strong precipitation and convective events. Miao et al. (2011) used a mesoscale model with high fidelity representation of urban canopy. Their results confirmed that Beijing can modify storms by splitting them or enhancing the amount of rainfall. They attributed the modification to thermal (sensible and latent heat) transport rather than momentum transport (more on mechanisms later). Zhang et al. (2010) noted in the Yangtze River Delta Economic Belt that urban areas experience 15%

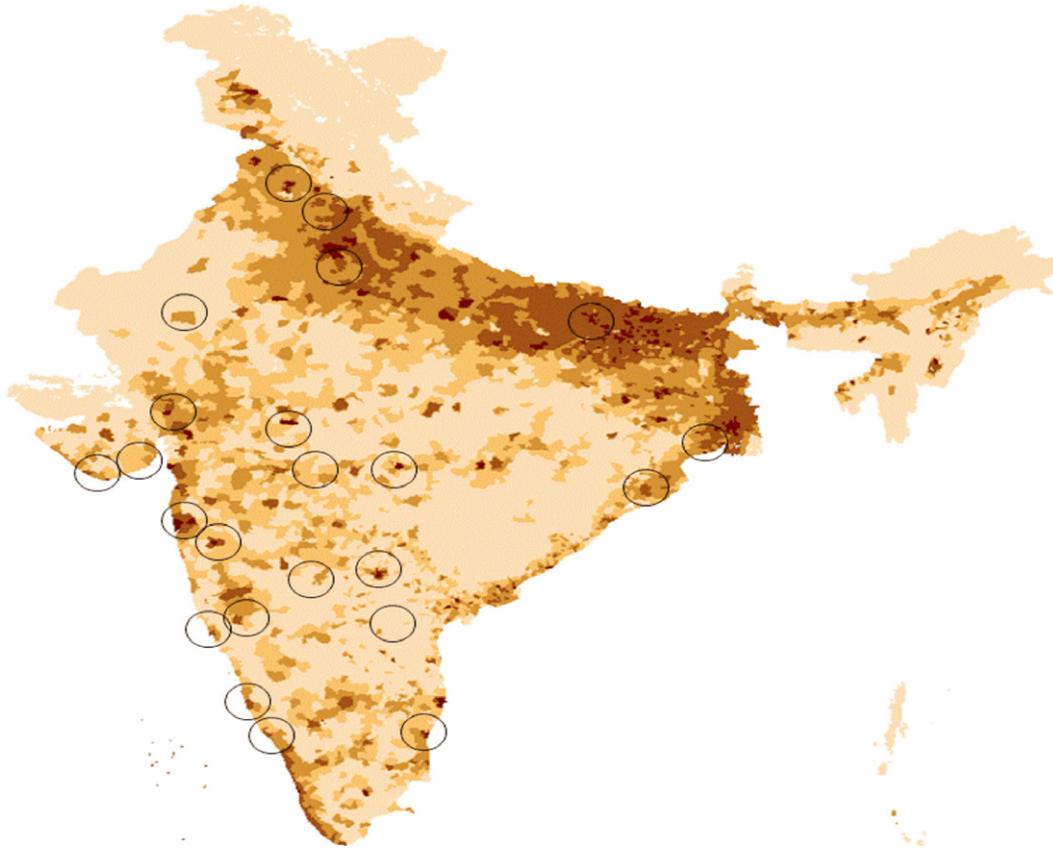


Figure 7 Circles represent the location of stations where the frequency of heavy precipitation events exhibits a positive trend with 99% confidence. The change in population density between 1990 and 2000 is shown in the background (from Kishtawal et al. 2009). Darker colors represent larger changes in population density. The darkest colors are indicators of cities.

more rainfall over the city and leeward, but that the effect was most prevalent during the summer.

5.07.5.2 Flooding

In 2010 and 2011, a number of cities worldwide experienced severe urban flooding. Ntelekos et al. (2007) showed that both the urban landscape and pollution may have assisted in priming the atmosphere for convection that led to flooding in the Baltimore—Washington area. Shepherd et al. (2011) argued that the urban landscape may have enhanced precipitation associated with a large-scale flooding event in Atlanta, Georgia. Though synoptic and mesoscale processes described the ‘big picture’ flooding event, localized regions of enhancements in the downwind part of the city may have been urban forced (Figure 8). They also confirmed that the urban landscape accelerated the land surface hydrological response. Shepherd et al. (2011) stated that “previous studies have noted the role that the urban environment has on the hydrologic cycle, including runoff, infiltration, evapotranspiration, and precipitation (see Reynolds et al. 2008, for a review). Reynolds et al. (2008) found that impervious surfaces in Houston distributed stormwater to conveyance systems with more volume over a shorter amount of time, which increases the risk of overwhelming the capacity of the system.” It is suggested that in considering urban effects on the urban hydrological cycle,

one must consider precipitation–urban interactions as carefully as they consider the evapotranspiration–urban or runoff–urban relationships, which tend to be more understood.

5.07.5.3 Lightning

Heavy convective activity and rainfall events are typically associated with lightning. Thus, it is not surprising that researchers have also identified a potential ‘urban lightning effect.’ The advent of ground-based and space-based lightning detection systems has advanced our ability to investigate this facet of the problem. Two overarching findings have emerged (Stallins and Rose 2008). They are summarized in Shepherd et al. (2010a): “(1) cloud-to-ground negative polarity flash densities increase, particularly downwind of the city center and (2) the percentage of positive polarity cloud-to-ground flashes decrease in the vicinity of cities.” The reader should consult Stallins and Rose (2008) for a summary of the range of geographic and climatological regimes that have experienced an urban CG lightning effect.

Studies have mainly noted higher negative CG flash densities and decreased positive flash production within 100 km of the urban center (Stallins and Rose 2008). Because lightning is inherently associated with convection, it is not surprising that lightning and rainfall anomalies around cities would be consistent. This is clearly evident in Figure 5, for example,

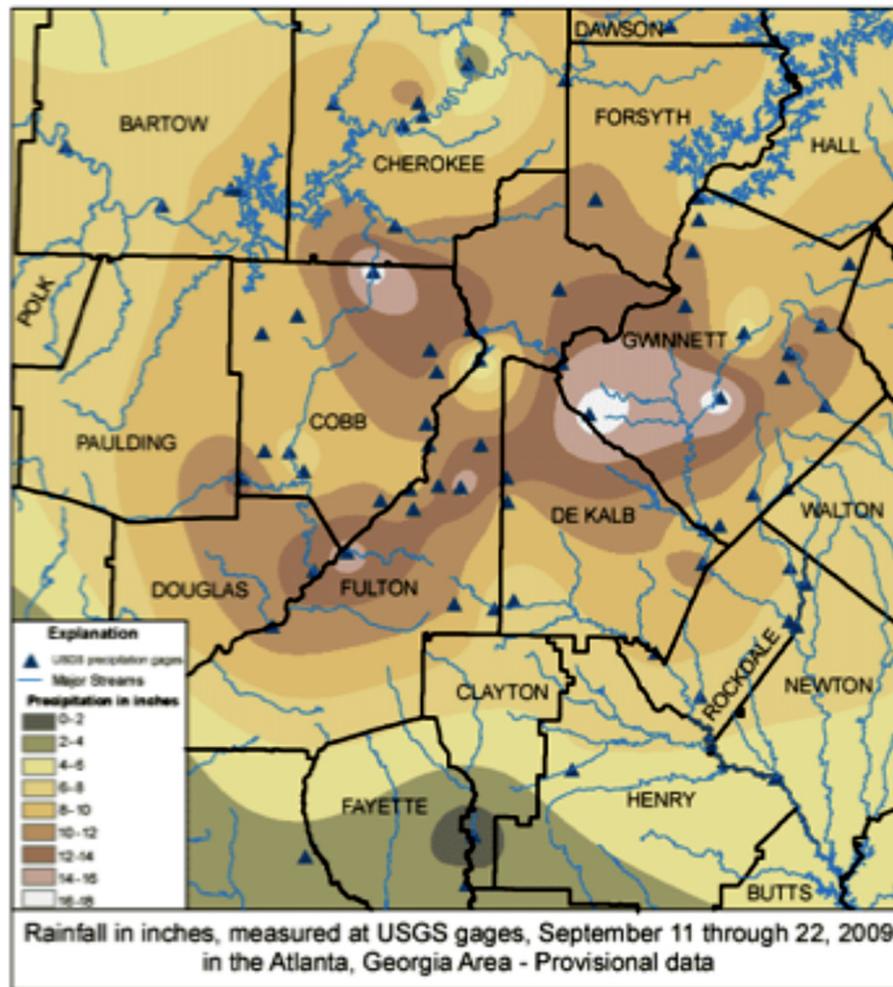


Figure 8 Cumulative rainfall totals around Atlanta, Georgia, during the September 2009 floods. Source: USGS.

around Atlanta, Georgia. More research and more robust hypotheses are required to explain how urban attributes contribute to the noninductive charge separation process (Yair 2008). In this process, graupel-ice crystal collisions in the presence of supercooled liquid water and vertical air currents allow for the accumulation and transfer of negative and positive charges throughout the cloud. Logical questions might center around how urban aerosols might delay the onset of precipitation and lead to a more invigorated, glaciated cloud, as Rosenfeld et al. (2008) argued, and how convective forcing associated with the roughness, UHI, and destabilized urban atmosphere increase the likelihood of convective activity. However, the role of aerosols is strongly supported by a few studies. Stallins et al. (2006) found smaller percentages of positive flashes downwind of long sections of major transportation arteries in Atlanta, Georgia. They argued that the aerosol effect may be detectable ~100 km downwind of the Atlanta central business district. Steiger and Orville (2003) observed higher flash densities and lower percentages of flashes in a Lake Charles-Baton Rouge Louisiana corridor. Of interest, this region has significant aerosol-producing refineries and chemical production facilities but not necessarily a centralized urban landscape footprint. For locales devoid of significant land cover, the spatial association among aerosols, increased flash

densities, and decreases in the percentage of positive flashes support a mechanistic role for atmospheric particulate matter.

5.07.5.4 Winter Precipitation

Though very limited and not contemporary, early research on urban effects on snowfall suggested that modified freezing rainfall and snowfall occur over and downwind major US cities because of the UHI (Landsberg, 1981; Changnon, 2003). Molders and Olson (2004) have suggested that snowfall anomalies in Fairbanks may be due to urban effects. Other studies of snowfall enhancement downwind of urban areas have been limited and generally focused on aerosol effects (e.g., Van den Berg 2008; Wood and Harrison 2009). Very little work on urban landscape shape and snowfall response exists because the vast majority of research in the physical geography and urban climate literature has posited that urban effects are most apparent during the warm season when smaller scale convective forcing is dominant (Shepherd et al. 2010a; Bentley et al. 2010; Mote et al. 2007). However, Shepherd and Mote (2011) recently argued that enough preliminary evidence is found in the literature to warrant new research on this topic. Clearly, the example quoted in the Section 1 establishes that humans can modify snowfall.

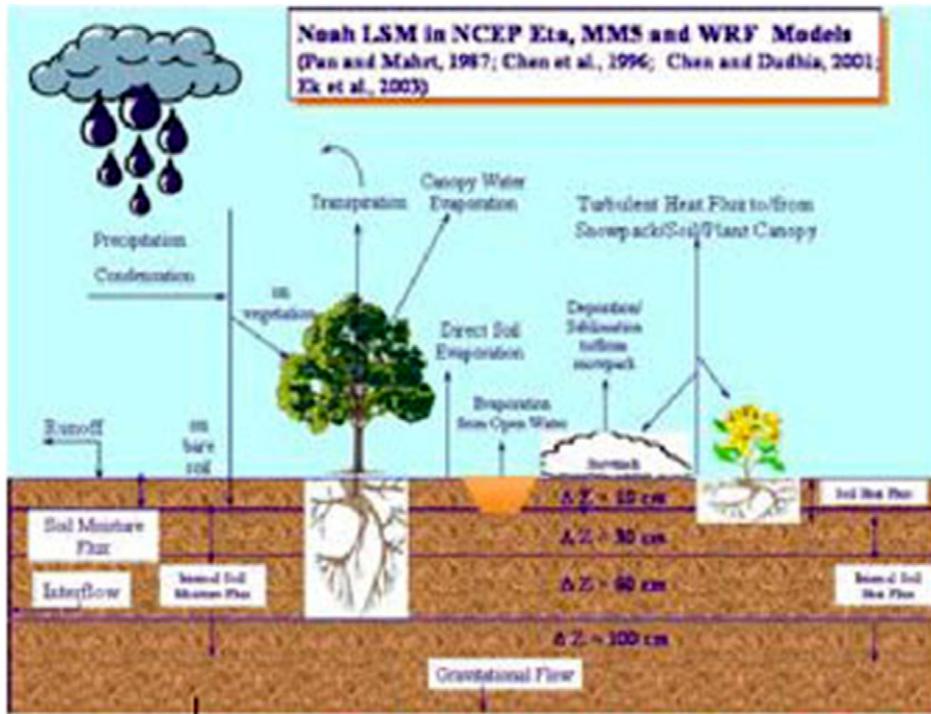
5.07.6 What Causes the URE?

Even with the uncertainties about the 'sign' of the change in precipitation due to urbanization, it is widely accepted that urban environments 'affect' rainfall processes. Shepherd et al. (2010a) stated that "though several plausible hypotheses for urban effects

on rainfall have emerged within the literature, there is no conclusive theory on what mechanisms, independently or synergistically, affect urban rainfall processes. A large body of literature has been devoted to pattern description and visualization. These methods are vital for generating and testing these hypotheses, but emphasis has now shifted to documenting

The Noah/UCM in WRF

Natural surface



Coupled through 'urban fraction'

Man-made surface

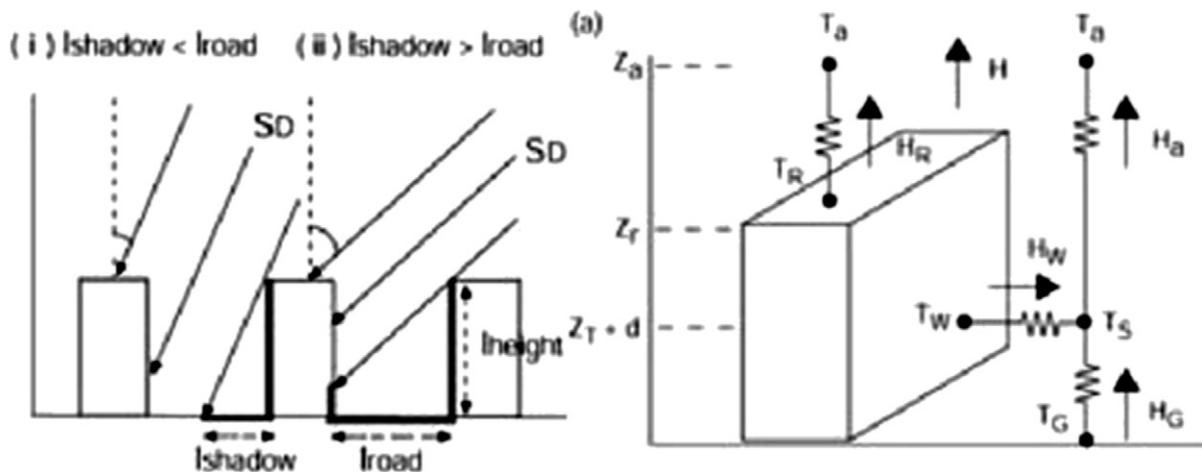


Figure 9 Example of a couple atmosphere-land-urban modeling systems. Source: UCAR.

mechanisms and elucidating relative contributions (Teller and Levin, 2008).” While some questions remain about the ‘URE’, the topic has received considerable attention recently.

While mechanistic studies have been precise for single case studies, a larger hydroclimatological perspective covering many years and processes is still needed (Shepherd et al. 2010a). However, it is still useful to highlight the leading hypothesis even though one cannot make generalizations about when they are most applicable.

5.07.6.1 Low-Level Dynamical and Flux Processes

Pielke et al. (2007) is a clear reminder that land cover can influence atmospheric processes. These processes are manifested at the surface, boundary layer (Oke 1987), and beyond. However as Lowry (1998) noted, controlled experiments are required. One of the most appropriate ‘laboratories’ for assessing mechanisms is the physically based CALS model. CALS enables a plausible way to remove or alter land surface, aerosol, topographic, or meteorological features to evaluate atmospheric responses under different scenarios. **Figure 9** summarizes how the CALS model interacts to characterize thermodynamic, dynamic, and moisture exchanges.

Post-METROMEX era model experiments provided early evidence that the URE was linked to urban-induced convergence, thermodynamic changes, and surface fluxes. **Table 2** summarizes some of the key findings from the period 1979 to 2011.

A common weakness of the studies in **Table 2** is the lack of representation of aerosols or pollution. This is somewhat

a function of the state of the modeling technology, but next-generation modeling systems are starting to address this deficiency. van den Heever and Cotton (2007) considered urban landscape and aerosol effects in their modeling study of St. Louis. More of these types of studies are required to determine the relative roles of aerosols in the URE.

5.07.6.2 Aerosol Roles

Aerosols are defined in Shepherd et al. (2010a) as “particles in the atmosphere, ranging from 0.01 μm to 10 μm . Urban regions usually have the highest concentration of aerosols, up to 108–109 particles per cc (Seinfeld and Pandis, 1998). Aerosols can be divided by size: fine mode and coarse mode particles. Coarse particles are composed of mechanical materials such as tire dust, sea salt and natural dust in urban areas. Fine particles tend to be produced locally by construction, air conditioning, transportation, and industry or by chemical interactions [in the atmosphere] involving sulfates, nitrates, ammonium and organics.”

Urban aerosols can vary in composition: black carbon, particulate matter, sulfates, nitrates, and others. The direct radiative effect of aerosols scatters or reflects solar radiation. Jin et al. (2011) recently presented evidence that aerosol direct effects can significantly reduce the magnitude of the urban skin temperature heat island, which may in turn affect precipitation processes. Some aerosols, mainly black carbon, may absorb and warm the atmosphere, which may have a large-scale stabilization effect on the atmosphere, thus suppressing cloud

Table 2 Key model studies over the period 1978 to 2011

<i>Authors</i>	<i>Key finding</i>
Vukovich and Dunn (1978)	Urban–rural gradients and boundary layer stability primarily describe UHI mesocirculations, which are conceptually similar to sea-breeze circulations
Huff and Vogel (1978) Hjelmfelt (1982)	Sensible heat fluxes and surface roughness associated with urban surfaces transport heat to the atmosphere Rising motion linked to St. Louis-induced low-level convergence/translation of the urban circulation by larger-scale advection. Bornstein and Lin (2000) later corroborated this finding by using a special observation network in Atlanta
Thielen et al. (2000)	Weak UHIs are associated with sensible heat flux, buoyancy, and convergence variations at a distance from heat source
Rozoff et al. (2003)	Nonlinear interactions associated with momentum drag, urban surface friction, and heating could induce downwind converge
Niyogi et al. (2006)	Applied urban canopy models embedded in the land surface model. Such models represent 3D urban morphology and heterogeneity rather than simple slab representations of urban surface. Their simulations demonstrated how the urban morphology affects temperature and wind flow
Gero and Pitman (2006)	Dynamical forcing (increased instability and convergent forcing) triggered a convective storm over urban land cover associated with Sydney, Australia
Ikebuchi et al. (2008)	Confirmed that urban land cover and anthropogenic heating altered the location and intensity of convective rainfall around Tokyo
Baik et al. (2007) and Han and Baik (2008)	Used numerical and analytical models to show that boundary layer destabilization leads to a region of intensified rising motion induced by the UHI. These studies also offered a plausible explanation for why urban convective effects can be apparent in the daytime even though UHI magnitude is greater in nocturnal hours (Arnfield, 2003). They reasoned that during daytime hours, stability conditions favor stronger UHI circulations. Han and Baik (2008) also found, using a 3D framework, an internal gravity wave field with a rising branch downwind of the theoretical heat source (e.g., the city)
Shem and Shepherd (2009)	Combined urban-induced convergence associated with urban circulation on the perimeter of Atlanta’s urban land cover and increased sensible heat flux contributed to enhancement of convection in Atlanta case studies
Shepherd et al. (2010b)	Enhanced sensible heat flux and low-level convergence associated with urban land cover interacts with sea-breeze circulation near Houston to create regions favorable for convective development. Carter et al. (2012), Lo et al. (2007), Yoshikado (1994), and Ohashi and Kida (2002) have found similar results for Houston, Hong Kong, and Japanese cities. Shepherd et al. (2010b) also used 2025 urban land cover projections to determine future precipitation changes as a function only of land cover change (no greenhouse gases)
Niyogi et al. (2011)	Indianapolis’ urban land cover modifies convective system structure, pathway, and intensity

development (Kaufman et al. 2005). However, this aspect of the urban rainfall problem warrants further study.

The indirect effect of aerosols (i.e., aerosols serve as CCN) on precipitation has received most attention in the literature. Twomey (1977) posited that under the condition of finite water vapor availability, more CCN will lead to more competition for water vapor in the cloud–droplet formation process. This process leads to smaller cloud droplets that are not able to grow efficiently or rapidly to produce raindrops. Jin and Shepherd (2008) employed satellite-derived cloud, aerosol, and precipitation properties to confirm the Twomey effect over regions of China and adjacent maritime regions.

The literature is rich with recent discussions on how aerosols affect precipitation (Rosenfeld and Lensky 1998; Rosenfeld 2000; Givati and Rosenfeld 2004; Kaufman et al. 2005; Jin et al. 2005; Lensky and Drori 2007; Rosenfeld et al. 2008; Jin and Shepherd 2008; Stjern et al. 2011; Lin et al. 2011). The prevailing understanding is that larger maritime aerosols enhance the collision–coalescence process, promote larger droplets, and

create earlier rainout. On the other hand, smaller aerosols over land counter the collision–coalescence process. This may delay rainout and invigorate the cloud to deeper convection (Rosenfeld et al. 2008). This scenario suggests that suppressed precipitation by urban aerosols (Lin et al. 2011) might be associated with increased electrification and rainfall intensification. Figure 10 presents a summary of such processes and illustrates how suppressed rainfall might lead to an invigorated convective cloud and more electrification. It should be noted, however, that many of the aerosol studies have not focused on urban aerosols and more work is required because there is still a great degree of uncertainty (Stjern et al. 2011).

5.07.6.3 Bifurcation and Other Dynamic Effects

As noted earlier, the presence of buildings, the thermodynamic UHI dome, or a combination of the two can modify local and regional circulations around cities. Both observational and modeling studies continue to confirm that convective cells can be redirected, bifurcated, or altered by the urban landscapes.

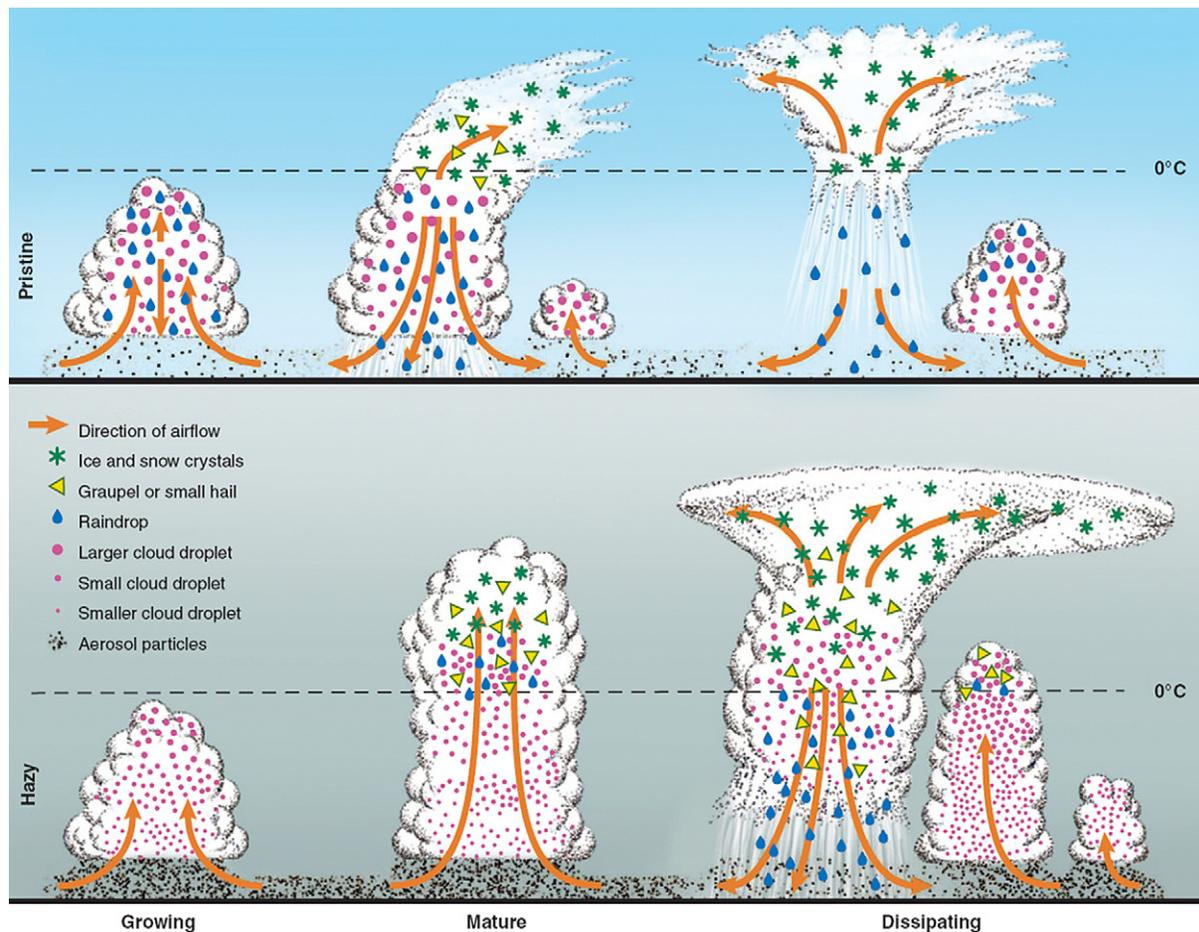


Figure 10 Evolution of deep convective clouds developing in the pristine (top) and polluted (bottom) atmosphere. Cloud droplets coalesce into raindrops that rain out from the pristine clouds. The smaller drops in the polluted air do not precipitate before reaching the supercooled levels, where they freeze onto ice precipitation that falls and melts at lower levels. The additional release of latent heat of freezing aloft and reabsorbed heat at lower levels by the melting ice implies greater upward heat transport for the same amount of surface precipitation in the more polluted atmosphere. This means consumption of more instability for the same amount of rainfall. The inevitable result is invigoration of the convective clouds and additional rainfall, despite the slower conversion of cloud droplets to raindrops. Reproduced from Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissel, and M. Andreae, 2008: Flood or drought: How do aerosols affect precipitation? *Science*, **321** (5894), 1309–1313.

Bornstein and LeRoy (1990) argued that the building barrier effect caused storms to bifurcate around New York City. Stallins and Bentley (2006) observed peaks in flash density in air mass thunderstorms on the periphery of the urban core, and the highest flash densities were associated with the urban core. Ntelekos et al. (2007) argued that the Baltimore–Washington, DC, corridor influenced the movement of storms and associated outflow boundary. Shear instability (i.e., turbulence related to differential wind velocity in the vertical) and diurnal heating can also force horizontal convective rolls in urban areas (Miao and Chen 2008). Niyogi et al. (2011) argued that storms were commonly altered by the urban landscape of Indianapolis, Indiana. Such structural changes included splitting, enhancement, and downwind mergers. Further research must shed light on whether a building, thermodynamic boundary layer, or combined barrier effects lead to such dynamical responses. It is even interesting to speculate on how the urban environment affects severe weather (e.g., tornadoes). Do such barrier effects explain the lack of tornado strikes in central business districts or is simply a function of scale? One might also posit whether the thermodynamic and moisture environments of a city can affect inflow at convective scales in severe environments (Jeff Basara, 2010, personal communication).

Bornstein (2011, personal communication, with modifications by S. Grimmond and M. Shepherd) attempted to provide a framework for understanding urban thunderstorm effects (Figure 11). This conceptual schematic is based on several years of research and captures some of our understanding. However, this schematic will evolve as our understanding improves.

5.07.7 Broader Context

An array of related studies continues to emerge related to urban rainfall processes. HYPERLINKvan den Heever and Cotton

(2007) important study noted that urban-induced wind convergence determined storm initiation in their simulations, but aerosols influenced the amount of cloud water and ice present in the clouds. Also, aerosols were important determinants of the updraft and downdraft intensities, their life span, and surface precipitation totals. Shepherd et al. (2001) investigated rainfall efficiency in sea-breeze thunderstorms and is a nice analog to the van Den Heever and Cotton study's discussion of integrated moisture convergence (initiating the storms) and mid-level moisture (affecting the rainfall efficiency). Such synergistic modeling/observational studies that capture aerosol and urban landscape sensitivities are critically needed. Bell et al. (2008) have presented evidence of a weekly precipitation cycle over the southeastern United States that may be linked to an anthropogenic aerosol cycle. However, other studies refuted the notion of a weekly cycle (i.e., DeLisi et al. 2001; Schultz et al. 2007; Lacke et al. 2009).

Several mitigating factors constrain the expression of aerosol, thermodynamic, and surface roughness mechanisms. Such factors include topography, aerosol concentrations, or seasonality. Studies must continue to detangle these influences from any attribution studies on the URE (Shepherd et al. 2010a). Other key mitigating factors are the shape, the form, and the size of cities. METROMEX suggested that large urban areas are more likely to be associated with the URE. Yet, there is very little research (observational or modeling) on threshold sizes for cities, optimal city shapes, and the role of morphology in relation to urban rainfall anomalies.

In summary, urban environments are clear examples of how the human system can modify the natural system in terms of weather and climate. The more this complex system is understood, the better the system and optimize interactions in the coupled system can be predicted. More importantly, the ability to anticipate and manage an array of natural and societal vulnerabilities can also be improved.

Urban areas have increased:

- Roughness
- Heating
- Aerosols

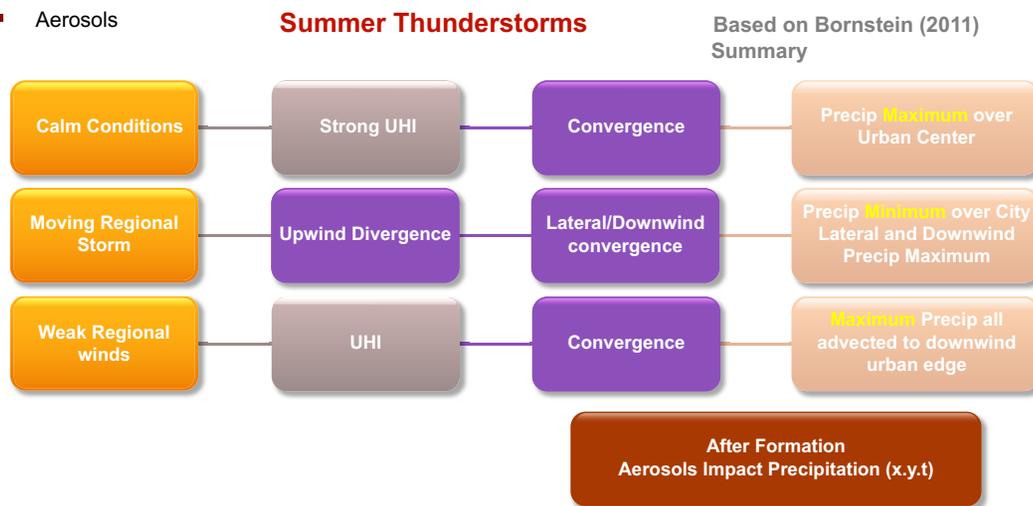


Figure 11 Summary of urban effects on thunderstorms (courtesy of B. Bornstein).

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