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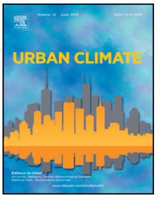

Spatio-temporal rainfall patterns around Atlanta, Georgia and possible relationships to urban land cover

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ABSTRACT

Spatio-temporal patterns in mean and extreme rainfall are examined around the city of Atlanta, Georgia using the Multi-sensor Precipitation Estimates (MPE) and ERA-Interim reanalysis datasets. The analysis spans the period 2002 to 2015 and employs a 9-cell gridded framework centered on downtown Atlanta. Statistically significant anomalies in daily precipitation were found over and downwind (predominately east to northeast) of Atlanta. The pattern of rainfall anomalies is most evident in the early evening hours of the day and is hypothesized to be related to the evolution of the skin or surface urban heat island (UHI), rather than the canopy layer UHI. The study formally proposes the term "flow regime dependent" downwind anomaly regions. Like previous results, the study reveals that downwind anomaly regions can vary as a function of prevailing wind regime. Using a metric called the Wet Millimeter Day (WMD), the study also finds that there is a tendency for extreme rainfall to cluster in the climatological downwind area of Atlanta. The work builds upon previous findings while employing different datasets to provide novel additional contributions related to the temporal evolution of the "urban rainfall effect" and the patterns of extreme rainfall.

1. Introduction and motivation

Rainfall, in terms of frequency and intensity, can vary spatially, temporally, and seasonally. Flooding associated with extreme rainfall events is increasingly a stressor on society and the geophysical system (Shepherd

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et al., 2011; Andersen and Shepherd, 2013). More frequent and intense extreme hydroclimate events (DeGaetano, 2009; Hirsch and Archfield, 2015; Powell and Keim, 2015; NAS, 2016) have been projected due to a warming climate system. Throughout 2016, for example, Louisiana, Texas, West Virginia, and Maryland experienced significant flooding, which elevated the discussion on linkages between flooding and climate change (Van der Weil et al., 2017; NAS, 2016).

However, internal atmospheric variability (i.e., weather) is also a significant driver of precipitation variability. Primary modes that have been associated with extreme precipitation in the southeastern United States include cut-off lows (Shepherd et al., 2011), tropical cyclones (Schumacher and Johnson, 2006; Shepherd, 2012), frontal and damming systems (Gamble and Meentemeyer, 1997; Srock and Bosart, 2009), warm season convection (Mote et al., 2007; Hand and Shepherd, 2009), and atmospheric rivers (Mahoney et al., 2016).

Several studies have identified key predictor variables associated with extreme precipitation (Maddox et al., 1979; Doswell et al., 1996; Konrad, 1997; Schroeder et al., 2016). Konrad (1997) identified five major synoptic types associated with extreme rainfall in the Southeast. Using a clustering analysis, he found that the following variables were associated with all five types: Precipitable Water (PW), 700 hPa mixing ratio, 850 hPa warm advection, and K-Index (i.e., a measure of thunderstorm potential based on lapse rate and the vertical extent of the moisture content in the lower atmosphere). Some variables (500 hPa PVA, BL convergence, and 200 hPa divergence) were synoptic type-dependent. Schroeder et al. (2016) noted the role of PW and warm cloud depth (i.e., layer between Lifted Condensation Level (LCL) and -10 °C level).

Even within non-mountainous, relatively homogeneous physiographic regions, the hydro-meteorological processes that control the seasonality and intensity of precipitation can exhibit substantial intra-regional variability. In the Piedmont Atlantic Megaregion (i.e., the urbanizing corridor from Atlanta to Charlotte), floods exhibit bimodal seasonality at gaged locations (Lecce, 2000a, 2000b; Gamble, 1997; Gamble and Meentemeyer, 1997). In summer and early fall, floods tend to be generated by thunderstorms and tropical cyclones. Analyses of streamflow gages suggests that floods generated by thunderstorms are dominant in basins <100 km^2, but the frequency of summer/fall flooding relative to the frequency of winter/spring flooding in Atlanta is greater than the relative frequency of summer/fall floods in Charlotte (Lecce, 2000a, 2000b; Gamble, 1997; Gamble and Meentemeyer, 1997).

One element that is increasingly understood is the roles of urbanization, suburbanization, and exurbanization in hydrometeorological processes. As society continues to urbanize (Burian and Shepherd, 2005; Shepherd et al., 2013; Ashley et al., 2014), the juxtaposition of rainfall variability, extreme events, and societal impacts increases. According to the National Weather Service (NWS, 2015), floods are currently the second deadliest and third costliest weather-related hazard in the United States. Estimates show that flood fatalities surpassed 3000 cases in the United States, and property losses totaled over $270 billion during the period 1980–2014 (U.S. National Weather Service, 2015). Ashley and Ashley (2008) found that 58% of weather-related fatalities could be attributed to flash flooding.

1.1. Background on urban rainfall studies in Atlanta

Literature dating to Horton (1921) has suggested that urban areas modify precipitation and convective activity. The next generation of investigations such as Project METROMEX (Huff and Changnon, 1973) continued to provide evidence of urban initiation or enhancement of rainfall, though certain methodological questions were raised by scholars. Lowry (1998) provides a summary of these major concerns. This study, given the methodology applied, addresses concerns related to legitimate controls, stratification schemes, and merging effects between different synoptic weather systems. Since the focus was exclusively on Atlanta, there was no need to address Lowry's concern about replication in multiple urban areas, though other studies by Niyogi et al. (2017), Ashley et al. (2012), and Shepherd et al. (2002) have done so.

More recent work (Niyogi et al., 2011; Niyogi et al., 2017; Seino et al., 2016) continues to provide evidence that urban impervious surfaces initiate or enhance precipitating systems, adding further complexity to the system. The body of literature (Mitra and Shepherd, 2016) is fairly conclusive that urban environments alter the spatio-temporal distribution of precipitation under certain conditions. Several studies have identified spatio-temporal patterns in rainfall around Atlanta (Bornstein and Lin, 2000; Shepherd et al., 2002; Dixon and Mote, 2003; Diem and Mote, 2005; Mote et al., 2007; Ashley et al., 2012; Haberlie et al., 2015).

Bornstein and Lin (2000) used convective models to simulate the effect of the urban heat island on summer convection in Atlanta. Their case studies emerged from the comprehensive Project ATLANTA work