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An urban-based climatology of winter precipitation in the northeast United States

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ABSTRACT

Varying forms of precipitation during winter weather events cause disruptions to commercial operations and transportation networks, particularly in densely populated regions. Developing a better understanding of the characteristics surrounding these events may lead to better prediction and subsequent mitigation. This study constructs a 21-year cold season climatology of precipitation type over highly urbanized areas of the northeastern United States. By using quality-controlled station reports, a specific focus is placed on the influence of urbanization in precipitation processes. In events involving multiple precipitation types, the ambient atmospheric profile is very close to the freezing point in lower levels. The influence of the boundary layer urban heat island may play a role in increasing melting of hydrometeors. Statistically significant findings from linear regression modeling show that proximity to urban centers, as derived from mean road density, plays a role in the surface observation of mixed precipitation events. 21% of any mixed precipitation observation may be attributed to its distance from a high density urban area. Decreases in mean surface wind speed and direction during mixed precipitation events increase the likelihood of an intact boundary layer urban heat island and melting of hydrometeors when compared to stronger wind speeds during snowfall events.

1. Introduction

Cities are home to more than half of the world's population (United Nations, 2012). Alongside the population increase, the urban footprint on the planet increases. Accompanying high population densities facilitate a rise in societal and infrastructural vulnerability. As urbanization expands and, in many cases, merge with neighboring urban areas, the resilience of these cities to weather and climate phenomena has been a subject of much interest (Klein et al., 2003). This resiliency is especially tested during winter weather events that have paralyzed cities up to several days at a time. Examples in the United States extend from Atlanta, Georgia in January 2014 to Boston, Massachusetts in January 2015 to Washington, DC in December 2016 among many others. Whether due to snow and/or ice, transportation and commercial operations are severely impacted during winter weather events (Maze et al., 2006).

Urban climatology has produced an abundance of research detailing the effects of urbanization on local climate regimes. Seto and Shepherd (2009) summarize this research and find that increases in urbanization change local climates through many factors, including, but not limited to, precipitation distribution, circulation regimes, and the urban heat island (UHI). The heterogeneity of land cover and land use in contiguous urban areas, or urban clusters, may result in greater (and lesser) impacts within, between, and outside of traditional city boundaries. A better understanding of cities' abilities to modify precipitation patterns is of crucial importance to urban planning and resource management. Most studies on urban-precipitation interactions have predominantly focused

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on warm season impacts because the urbanized signal can more easily be discerned relative to periods dominated by larger-scale forcing (Mitra and Shepherd, 2016). Recent advances in regards to warm-season convection have further strengthened the literature (McLeod et al., 2017). Many mid- and high-latitude cities are also vulnerable to cold-season, winter weather events that potentially cause significant socioeconomic interruptions (Black and Mote, 2015). Climatological and meteorological studies have addressed prediction of winter precipitation. Very few, however, focused on the effects of urbanization on winter precipitation. Even fewer have addressed the role of urban clusters on transitional aspects of winter precipitation. Hereafter, *transitional* refers to any event where multiple precipitation types have been observed at the surface. Forecasting of transitional events remains difficult (Schuur et al., 2012). Compounding the difficulty, urban areas have the ability to alter the lower atmospheric temperature and moisture profiles through anthropogenic activities (Oke, 1995; Taha and Bornstein, 1999). Consequently, observed precipitation may not be consistent with the anticipated precipitation type considering the nearest observed or modeled atmospheric sounding profile.

Urbanization may not only lead to winter precipitation modification but also precipitation initiation or enhancement. Shepherd and Mote (2011) provide an example of this in a January 2011 case study in Dodge City, Kansas. Byproducts of local industrial activities (aerosols, excess water vapor, and heat) were advected by southeasterly surface winds into the lower atmosphere. The resulting plume served as a catalyst for snowfall downwind of the facilities into and northwest of the city.

This paper investigates the impact of urban clusters on precipitation type by constructing a winter season climatology and considering the urban morphology. Can urbanization alter the atmospheric profile enough to influence precipitation type at the surface? Do certain regions within a major urban cluster experience specific types of winter precipitation more or less frequently when compared to adjacent areas? Section 2 discusses the background and considerations made in addressing the objective. Section 3 outlines the data utilized throughout and the domain studied. Section 4 details the methodology and tools applied. Section 5 describes the findings and results, while Section 6 argues the significance of conclusions derived from the study and considers potential impacts and future investigations.

2. Background

Lower atmospheric temperature modifications are caused by urban land use and land cover change and the corresponding changes in the energy balance. The scales of vertical influence are categorized as the surface, canopy, and boundary layer heat islands (Arnfield, 2003). The surface UHI is observed in increased skin temperature primarily due to direct absorption of incoming shortwave and longwave radiation; the canopy UHI extends to roof level and is sustained through the reemission of longwave radiation from the surface and built environment. The urban boundary layer heat island begins above roof level and alters the atmospheric profile up to a kilometer above the surface and for several kilometers downstream (Oke, 1995). As hydrometeors fall through this environment, they encounter relatively warmer temperatures and lower humidity causing increased rates of melting and evaporation. Changnon (2003) found that UHI effects resulted in 0.5 to 2 fewer days on average of freezing rain reports in-city compared to surrounding rural environments in New York City and Chicago. The modification of freezing rain is caused by higher surface temperatures in cities. Clinton and Gong (2013) developed techniques using Moderate Resolution Imagining Spectroradiometer (MODIS) imagery to detect heat sources and sinks within the urban environment by deriving the surface skin temperature. The usefulness of satellite remote sensing like MODIS to obtain surface temperature is limited, however, by cloud cover during synoptic events. This drawback may be alleviated by the use of road sensor network data available through state and regional transportation departments. Measurement of the surface UHI is still useful, particularly for freezing rain, but is not effective for assessing modification of precipitation above the surface.

Stewart and King (1987) outline how precipitation type varies according to hydrometeor diameter, thickness of the freezing layer aloft, and the height of the freezing layer. Therefore, precipitation type prediction is possible if sufficient upper air observations are available. While assessing the viability of precipitation type algorithms designed to predict surface observations, Reeves et al. (2014) notes horizontal nonuniformity in crowd-sourced mPING observations of snow, ice pellets, and freezing rain may be due in part to UHI effects. The lack of upper atmospheric temperature and humidity observations limit the ability to apply implicit algorithms that assess precipitation type. Atmospheric sounding profiles provide data necessary to predict what we *should* observe at the surface then compare this to what actually *is* observed at Automated Surface Observing System (ASOS) sites. Sounding sites are typically on the order of several hundred kilometers apart and are collected every 12 h (Fig. 1b) (National Oceanic and Atmospheric Administration, 2017a). Use of this data is not suitable for spatial analysis on the urban scale nor for temporal analysis of transitional events. Reanalysis datasets, such as the North American Regional Reanalysis (NARR) which has a horizontal resolution of 32 km, 29 vertical levels, and three-hourly temporal resolution, provide acceptable temporal and spatial resolutions (Mesinger et al., 2006). Interpolation on this scale may be meaningful if data model quality is consistent with observations.

An assessment of the viability of NARR data for the purposes of this investigation is necessary. Preliminary analysis of a transitional event on 5 December 2009 highlights potential issues with this approach. Fig. 2 shows discrepancies between the NARR precipitation type algorithm and observed precipitation at ASOS stations. Furthermore, a statistical comparison of NARR data and atmospheric sounding data from two stations located within the affected domain (IAD and OKX, see Fig. 1b) is performed. NARR data is obtained from the grid points corresponding to the geolocation of the sounding stations. Air temperature, geopotential height, and wind speed are extracted from both datasets at 12 UTC on 5 December 2009. Nine standard vertical levels from 100 hPa to 1000 hPa are analyzed. Both, the NARR and sounding data are treated with the assumption of statistical dependence. This is based on principles related to Tobler's First Law of Geography (Tobler, 2004). The data are drawn from the same day and time, from locations < 500 km apart.

Table 1 shows the results of the traditional statistical measures performed. All variables either approached significance or were