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Nocturnal propagating thunderstorms may favor urban "hot-spots": A model-based study over Minneapolis

Manisha Ganeshan [a,*], Raghu Murtugudde [b,c]

[a] Goddard Earth Sciences Technology and Research Studies and Investigations, Universities Space Research Association, Greenbelt, MD 20771, USA
[b] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA
[c] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA

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ABSTRACT

High-resolution WRF model sensitivity experiments are carried out (with and without urban land cover) to study urban impacts on nocturnal propagating thunderstorms over the city of Minneapolis. It is found that the storm spatial characteristics, especially the position of the storm cell, are appreciably altered by the presence of urban land cover. The most robust urban instability during stormy conditions is the enhanced surface convergence due to increased frictional drag. No urban impact is visible on the rainfall intensity simulated by the model. The frictional convergence, aided by the nocturnal Urban Heat Island (UHI), appears to be responsible for attracting propagating storms towards the urban center. Advanced modeling experiments are needed to quantify the mechanical and thermal influence along with similar studies in other cities to further investigate the urban impact on the frequency and trajectory of nocturnal propagating storms.

1. Introduction

It is well known that urban areas may influence weather and climate on a local scale. The Urban Heat Island or UHI, which refers to the anomalous warming of surface air temperature over urban land cover, has been commonly observed across several cities. Urban areas are also known to influence local precipitation, more evidently during the warm season (Changnon et al., 1977; Shepherd, 2005; Burian and Shepherd, 2005). The Metropolitan Meteorological Experiment (METROMEX), an observational campaign in the early 1970s, reported that warm season thunderstorms are invigorated as they propagate through the city (Changnon et al., 1977; Ackerman et al., 1977). The largest rainfall increase was found to occur over, as well as, downwind of the urban area (Changnon et al., 1977; Ackerman et al., 1977). This is because the UHI (along with the enhanced surface roughness of the urban land cover) produces a mesoscale convergence, resulting in deeper mixing heights in the daytime boundary layer, increased vertical velocity at cloud-base, and subsequent invigoration of propagating thunderstorms (Ackerman et al., 1977). Modeling and observational studies have widely considered this UHI-perturbed boundary layer to be the dominant cause for rainfall modification, especially downwind of cities (Vukovich and Dunn, 1978; Westcott, 1995; Shepherd et al., 2002; Shepherd, 2005; Shem and Shepherd, 2009). The diurnal variability of this phenomenon, however, is not fully explored. For instance, while boundary layer mixing is a maximum (minimum) during the day (night), the UHI is known to peak during nocturnal hours (Chandler, 1967; Oke, 1973; Shepherd, 2005). The urban processes (and related rainfall modification) may be different within the stable nocturnal boundary layer. During METROMEX, rainfall enhancement

* Corresponding author.
E-mail address: mganeshan@usra.edu (M. Ganeshan).

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also occurred in association with propagating thunderstorms during nighttime but the mechanisms were not investigated in detail (Changnon and Huff, 1986). Huff and Changnon (1973) observed an increase in the *frequency* of late night and early morning thunderstorms over cities such as St. Louis, Chicago, and New Orleans. The authors speculated that the UHI (which peaks during the night) and the related convergence were the leading cause, but did not carry out supporting analyses. If the nocturnal UHI does influence propagating thunderstorms, we know little about the nature of rainfall modification or the urban instability.

More recent observations over New York City and Atlanta report that during calm nights, the UHI leads to convergence and subsequent *development* of thunderstorms (Bornstein and LeRoy, 1990; Bornstein and Lin, 2000; Dixon and Mote, 2003). Analogous to a sea-breeze, a thermally direct circulation may be established causing air from surrounding rural regions to converge over the warm, low-pressure center of the urban area; thereby leading to rainfall initiation (Bornstein and Lin, 2000; Dixon and Mote, 2003). While such a direct feedback may easily produce air-mass type thunderstorms during calm regional flow, it is not known to influence propagating convective storms that are accompanied by windier conditions (Bornstein and LeRoy, 1990; Bornstein and Lin, 2000). Although in recent years competing urban mechanisms for rainfall impacts (such as aerosols, building barrier, and urban canopy effects) have received much attention, the influence of the UHI on propagating thunderstorms during the nighttime deserves further investigation. Since the nocturnal peak in the UHI is a widely observed phenomenon, it is important to fully examine its interaction with convective rainfall, especially, to investigate the cause for previously reported occurrence of more frequent nighttime propagating thunderstorms (Huff and Changnon, 1973; Ganeshan et al., 2013a).

For this purpose, land cover sensitivity simulations are carried out to study two nocturnal thunderstorms over the city of Minneapolis. Located in the northern Central Plains, this city is relatively isolated from topographic and coastal effects making it suitable for studying UHI-impacts. Based on the National Land Cover Dataset (Homer et al., 2012), Minneapolis is found to have an urban (impervious) surface area of around 1560 km^2 (see Ganeshan et al., 2013a). High-resolution Real-Time Mesoscale Analysis data (Manuel et al., 2011) suggests that the city has a significant UHI in the daytime (~1.1 °C) as well as nighttime (~2.1 °C) with corresponding rainfall anomalies observed during both periods (Ganeshan et al., 2013a). More specifically, a positive rainfall anomaly occurs over and downwind of Minneapolis during nocturnal propagating thunderstorms (Ganeshan et al., 2013a). These factors make the city ideal for investigating urban mechanisms responsible for nocturnal rainfall modification. Section 2 describes the methodology adopted, and Section 3 discusses the results, followed by major conclusions in Section 4.

2. Methods

2.1. Model configuration

The Advanced Research Weather Research and Forecast (WRF-ARW) model (version 3.3; Skamarock et al., 2008) is used to carry out high-resolution (0.5 km) urban land cover sensitivity simulations. The domain and nesting configuration over the Minneapolis-St. Paul region is shown in Fig. 1. The horizontal resolution of the outermost, middle, and innermost nested grids is 12.5 km, 2.5, and 0.5 km, respectively. Model output is analyzed over the innermost nested grid only. The North American Regional Reanalyses (NARR) data are used as initial and boundary forcing conditions (Mesinger et al., 2006). The model's vertical resolution consists of 45 levels in the terrain-following sigma coordinate system, with eight levels in the lowest 1 km and the remaining equally spaced up to 100 hPa.

The unified Noah Land Surface Model (LSM; Chen and Dudhia, 2001) is used for predicting heat and moisture fluxes from the surface to the atmosphere. The Mellor–Yamada–Janjic (MYJ) scheme (Mellor and Yamada, 1982) is selected for boundary layer and vertical diffusion processes while the Eta surface-layer scheme (Monin and Obukhov, 1954) is used to represent surface fluxes. The WRF Single-Moment 5-class (WSM5) scheme (Hong et al., 2004; Hong and Lim, 2006) is chosen for representing the microphysics. The Kain–Fritsch (KF) convective scheme (Kain, 2004) is activated at 12.5 km resolution, while convection is resolved explicitly at 2.5 km and 0.5 km resolutions (see Ganeshan et al., 2013b).

2.2. Urban physics in WRF model

In the WRF model, it is possible to simulate turbulent heat and momentum fluxes as well as other urban effects over developed land surfaces by coupling an urban canopy model with the Noah LSM. For this purpose, the performance of the Building Energy Parameterization (BEP) scheme (Martilli et al., 2002) and the Urban Canopy Model (UCM; Kusaka et al., 2001; Kusaka and Kimura, 2004; Chen et al., 2006) is evaluated by comparing the simulated skin temperature with observations from the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS skin temperature is derived from the split window algorithm developed by Wan and Dozier (1996). It is found that the nighttime skin temperature anomaly over Minneapolis is captured reasonably well by both urban schemes, but the observed daytime skin temperature increase is not adequately simulated by the UCM. This could be because the UCM is a comparatively less sophisticated, single-layer scheme, which assumes that building heights in the urban canopy do not extend beyond the lowest model level. The multi-layer BEP scheme, on the other hand, recognizes a three-dimensional (vertical) distribution of urban surfaces (such as walls, roofs) while calculating sources and sinks of heat, moisture and momentum in the urban canopy