ARTICLE IN PRESS

Urban Climate xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

# A modeling study of the sensitivity of urban heat islands to precipitation at climate scales

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ARTICLE INFO

*Keywords:*
Urban heat island
Precipitation
Urban canopy model
CONUS

ABSTRACT

The impacts of urban surface characteristics on urban heat islands have been extensively studied. However, the influence of local climate on the urban heat island intensity remains elusive. This study aims to quantify the influence of precipitation on the urban heat island intensity over the Continental United States (CONUS) at climate scales. Results from numerical experiments show that across the CONUS, the urban heat island intensities are positively correlated with the precipitation amounts in summer but not in winter. The sensitivity of urban heat island intensity to precipitation varies spatially and seasonally. In summer, the urban heat island intensity in mid-south CONUS is particularly sensitive to changes in precipitation and the sensitivity shows a generally negative correlation with the precipitation amount. The sensitivity is found to largely come from the rural temperature rather than the urban temperature, and is mostly controlled by the partition of available energy to sensible and latent heat fluxes. In winter the albedo effect is also important. This study highlights the climatic conditions as important controls on the urban heat island intensity, and thus climate change has significant implications for the urban thermal environment even if urban surface characteristics remain the same.

## 1. Introduction

The urban heat island (UHI) effect refers to a microclimatic phenomenon that cities are typically hotter than the surrounding rural areas (Oke, 1982; Arnfield, 2003; Grimmond, 2007; Mills, 2008). It has important implications for energy consumption (Akbari et al., 2001), human health (Anderson and Bell, 2009), air pollution (Sarrat et al., 2006), and biogeochemical cycles (Grimm et al., 2008). Given the fact more than half of the global population lives in cities now and the continued urbanization (United Nations, 2014), it becomes important to fully understand the causes of, and contributors to, UHIs, which will pave the way for developing strategies for mitigating heat in cities (Rizwan et al., 2008; Rosenzweig et al., 2010; Stone, 2012).

Studies on the UHI effect can be broadly separated into three categories: theoretical, experimental, and numerical studies. Theoretical studies often focus on the scaling of urban heat island intensity (UHII) (Fernando et al., 2010; Hidalgo et al., 2010; Fan et al., 2016; Theeuwes et al., 2017), which is often defined as the difference between urban and rural near-surface air (or surface) temperatures, with respect to city size (Oke, 1973), canyon geometry (Oke, 1981), wind speed (Li et al., 2016), urban-rural contrasts of water availability (Li and Bou-Zeid, 2013), and related parameters. Experimental studies often focus on quantifying the UHII using in situ and/or remotely sensed observational data and exploring their correlations with urban-rural contrasts of various biogeophysical factors (Schatz and Kucharik, 2014; Zhou et al., 2016) and hydroclimatic factors (Hoffmann et al., 2012; Wiesner et al., 2014). Over the last two decades, numerical studies have become popular and many urban models have been proposed to simulate

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https://doi.org/10.1016/j.uclim.2017.12.001
Received 12 April 2017; Received in revised form 7 October 2017; Accepted 8 December 2017

the urban thermal environment (Grimmond et al., 2010; Grimmond et al., 2011; Best and Grimmond, 2015). These models allow investigations of the sensitivity of UHII to a wide range of factors such as urban morphologies, surface materials, vegetation coverage and types, and anthropogenic activities (Loridan et al., 2010; Ryu et al., 2011; Wang et al., 2011).

Although it is well acknowledged that the UHII varies across different climatic conditions (Arnfield, 2003), a systematic investigation of how different climatic factors affect the UHII is lacking. Nonetheless, understanding the influence of climatic factors, in addition to the influence of surface characteristics, is important for capturing and forecasting the UHII under climate change. A recent study by Zhao et al. (2014) demonstrated strong contributions of background climate to urban heat islands by showing that the annual mean daytime UHII across the North America is strongly and positively correlated with the annual mean precipitation amount. However, their study did not compare directly the influence of precipitation on the UHII to the influences of other climatic variables. In addition, they did not examine the seasonality of the sensitivity of UHII to precipitation. These remaining questions motivate our study.

Using offline land simulations with the Geophysical Fluid Dynamics Laboratory (GFDL) land model coupled with a newly developed and validated urban canopy model (Li et al., 2016a), this study analyzes the influence of atmospheric forcing, especially precipitation, on simulated urban heat islands over the Continental United States (CONUS). The specific questions we aim to answer in this paper include: 1) how important is the influence of atmospheric forcing, particularly precipitation, in controlling the simulated UHII in different seasons? 2) Does the sensitivity of UHII to precipitation differ between regions and seasons?

The rest of the paper is organized as follows: Section 2 describes the model and methodology; Section 3 presents the main results; and Section 4 summarizes the findings and discusses the implications.

## 2. Model and methodology

The model used in this study is the land component (called LM3) of GFDL global climate and earth system models, coupled with a newly developed and validated urban canopy model (UCM). Details about the LM3 (Shevliakova et al., 2009; Milly et al., 2014) and the LM3-UCM (Li et al., 2016a), including model validation, have been described elsewhere. Here only the key features are introduced. LM3 represents each grid-cell's surface heterogeneity as a collection of tiles (Shevliakova et al., 2009; Milly et al., 2014). Each tile has its own energy and water balances throughout the vegetation-soil column and its own exchange coefficients with the atmosphere. The fluxes of each tile are aggregated at the bottom atmospheric layer so that the atmosphere only receives the area-averaged fluxes. The principle land cover types in LM3 include natural vegetation, grassland, pasture, secondary vegetation, and urban. The LM3-UCM is built on the urban canyon concept and includes two major components: roof and canyon (Li et al., 2016a). It solves the surface energy balance for different urban facets, including roof, wall, impervious ground, and pervious ground. It considers radiation processes in the urban canyon including radiative trapping, shadow effects, and multiple reflections between walls and ground surfaces. It parameterizes turbulent exchanges between the atmosphere, the canopy air, walls and ground surfaces through a resistance approach. It also incorporates hydrological and biological processes associated with vegetation within the urban canyon.

In this study, the LM3 is driven by atmospheric forcing from large-scale climate model outputs or gridded data sets that are primarily based on observations and reanalysis fields to simulate the UHII. The forcing variables for all experiments include downward shortwave radiation, downward longwave radiation, air temperature, specific humidity, pressure, wind speed, and precipitation. In the first experiment (see Table 1), outputs at the bottom level of the atmospheric component from coupled land-atmosphere-ocean earth system model simulations for the Coupled Model Intercomparison Project Phase 5 (CMIP5) are used. Specifically, ESM2Mb model outputs (Dunne et al., 2012; Dunne et al., 2013; Malyshev et al., 2015), with a spatial resolution of 2 by 2.5° and a temporal resolution of three hours, are used to conduct long-term simulations (from 1700 to 2100) over North America (20°N–55°N, 130°W–60°W). This is identical to the simulation presented in Li et al. (2016b). In the second experiment (Exp. 2), the LM3 is also driven by a 50-yr (1949–2000), 3-hourly, 1-degree data set developed by Sheffield et al. (2006) (hereafter called Princeton forcing), which is based on a combination of observational and reanalysis data. We apply the first 30-yr forcing to the period of 1700–1948 in order to spin-up the model. Given the difference in the resolution of the two forcing data sets, both are then interpolated to a grid of resolution of 50 km for a consistent comparison. In all the experiments, we focus on the period from 1981 to 2000.

To examine the role of precipitation in controlling the UHII across the North America, we also design a third experiment (Exp. 3), in which the model is driven by atmospheric forcing used for Exp. 1 except that the precipitation data are replaced by those from Exp. 2. While we acknowledge that mixing the two forcing data sets may introduce inconsistency between precipitation and other forcing variables, this issue should be alleviated at the temporal scale that we are interested in (i.e., the long-term scale). Given that the precipitation from Exp. 2 is corrected by observations, our third experiment is essentially similar to many previous studies, including

**Table 1**
The list of numerical experiments.

| Experiments | Key features |
|---|---|
| 1 | ESM2Mb forcing; |
| 2 | Princeton forcing; |
| 3 | ESM2Mb forcing except that precipitation is from Princeton forcing; |