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Research Paper

A scenario analysis of thermal environmental changes induced by urban growth in Colorado River Basin, USA

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ABSTRACT

Rapid urban population growth in the cities of South Western United States has led to significant modifications in its environment at local and regional scales. In this study, three densely populated cities in Colorado River Basin (CRB), viz. Phoenix, Las Vegas, and Denver are selected to capture the various dimensions of the impacts of land use changes on emergent hydroclimatic patterns in the entire CRB. We hypothesize that different modes of urban growth will lead to markedly different modification of the thermal environment as well as surface energy balance. To test the hypothesis, we adopted the mesoscale Weather Research and Forecasting model, incorporating the latest urban modeling system, for regional climate simulations. Projected future urban growth in the period 2010–2100 was obtained from Integrated Climate and Land Use Scenarios developed by the U.S. Environmental Protection Agency. The simulations of urban growth in CRB demonstrated significant nocturnal warming of about 0.36 °C, 1.07 °C, and 0.94 °C in near-surface temperatures in Phoenix, Denver, and Las Vegas respectively, with comparatively insignificant changes in daytime temperature. In addition, it was found that the thermal environment of Denver is the most susceptible to the projected future urban growth. Responses in urban surface energy budgets also differ in three cities due to the combined effect of local climatology and mode of urban growth.

1. Introduction

The world is urbanized rapidly, from one third of world population residing in urban areas in 1950 to more than half of world population in the urban settlements in 2014 (United Nations, 2015). With the global population projection to reach 9.7 billion by 2050, an increase of 2.5 billion more urban population is expected worldwide (United Nations, 2015). This continuously increasing urban population entails anthropogenically induced land use and land cover (LULC) changes, mainly the conversion of natural landscapes to build terrains. LULC changes associated with urbanization, in turn, lead to modification of surface radiation and moisture balance with significant consequences on air quality, natural resource management, and local and regional hydroclimate (Arnfield, 2003; Collier, 2006; Gober & Kirkwood, 2010). One well-known example is the urban heat island (UHI) effect that signals an elevated temperature in urban cores than rural surroundings (Oke, 1982, 1987). These urban-induced environmental changes, in turn, impose challenges to landscape planning and resource management (Song, Wang, Myint, & Wang, 2017; Yang & Wang, 2017), owing to their peculiar dynamic and thermodynamic characteristics of the built environment (Wang, 2014a; Wang, Zhao, Yang, & Song, 2016).

Urban landscape changes induced by population growth can be broadly classified into two modes: (1) the increase of housing density and building compactness in existing built up areas, often called urban sprawl with respect to its undesirable effect, and (2) the exurban growth or development of manmade (mainly residential) areas beyond the urban fringe (Theobald, 2005). Hereafter the two urban growth modes are referred to as *urban intensification* and *urban expansion*, respectively. The actual patterns of growth for individual cities depend on complex metrics embracing a variety of environmental, socio-economic, and political dimensions (Schneider & Woodcock, 2008). For example, historically Phoenix and Las Vegas have undergone similar and extensive urban expansion into surrounding deserts with abundant land availability (Auch, Taylor, & Acevedo, 2004). But the future urban growth of the two cities tends to bifurcate towards the end of the century: while the Phoenix metropolitan will continue its expansion into surrounding desert and/or agricultural lands, the current urban core of Las Vegas will be significantly intensified (US EPA, 2009), largely due to the constraints imposed by future climate changes on water resource management (Christensen & Lettenmaier, 2007; Gober & Kirkwood, 2010).

In this study, Colorado River Basin (CRB) is selected as our testbed.

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Table 1
Physical parameterizations schemes adopted in WRF-ARW model.

Physics in WRF	Physical Parameterization Schemes	References
Planetary boundary layer dynamics	Yonsei University scheme	(Hong, Noh, & Dudhia, 2006)
Microphysics	Thompson scheme	(Thompson, Field, Rasmussen, & Hall, 2008)
Shortwave radiation	Dudhia scheme	(Dudhia, 1989)
Longwave radiation	Rapid radiative transfer model	(Mlawer, Taubman, Brown, Iacono, & Clough, 1997)
Surface layer dynamics	MM5 similarity scheme	(Fairall et al., 2003)

Table 2
Classification of urban categories based on the impervious cover percentage.

Classification	Impervious surface percentage
Low Residential	20–39%
High Residential	40–64%
Commercial	64–100%

The basin is known as the life blood of the American southwest, and contributes to around 40 million people supporting seven states of United States, viz. Arizona, California, Colorado, New Mexico, Nevada, Utah and Wyoming (Boepple, 2012). Nevada and Arizona are the top two states with over one hundred percent increase in projected population for 2030 with Colorado making the top 15 with 34.7% increase (United Nations, 2015). Since the socioeconomic and ecosystem well-being of the Southwestern United States relies critically on the health of CRB, the assessment of the emergent regional hydroclimatic patterns, and its impact on the thermal environment, infrastructural management, and future sustainable development is crucial (Jayne & Campbell, 2011; Rasmussen et al., 2011).

Despite that numerous studies have been conducted on evaluating potential environmental changes in CRB, the direct assessment of the impact of urban landscape changes is largely missing. In particular, there is a lack of fine-resolution representation of different urban growth patterns (e.g. expansion vs. intensification), leading to inadequate representation of holistic climate change in this region due to urban landscape changes. In addition, the increase in population and urban development, coupled with the direct effects of climate change due to elevated greenhouse gas emission, have contributed to the uncertainty in the future development of CRB (Boepple, 2012). This underscores the importance of addressing potentially different environmental responses in growing cities under various geographical and socio-economic conditions.

To address these outstanding challenges, multiscale and multi-physics numerical modeling frameworks hold an important key. Among them, the Weather Research and Forecasting (WRF) (Skamarock et al., 2008) platform, integrated with urban canopy models (UCMs) is proved as a versatile tool, and has been widely adopted for urban climate modeling (e.g. Chen et al., 2011; Yang et al., 2015). In particular, the WRF-urban modeling system has undergone continuous improvements during the past decades (Kusaka, Kondo, Kikegawa, & Kimura, 2001; Wang, Bou-Zeid, & Smith, 2013; Wang, 2014b; Yang et al., 2015) for

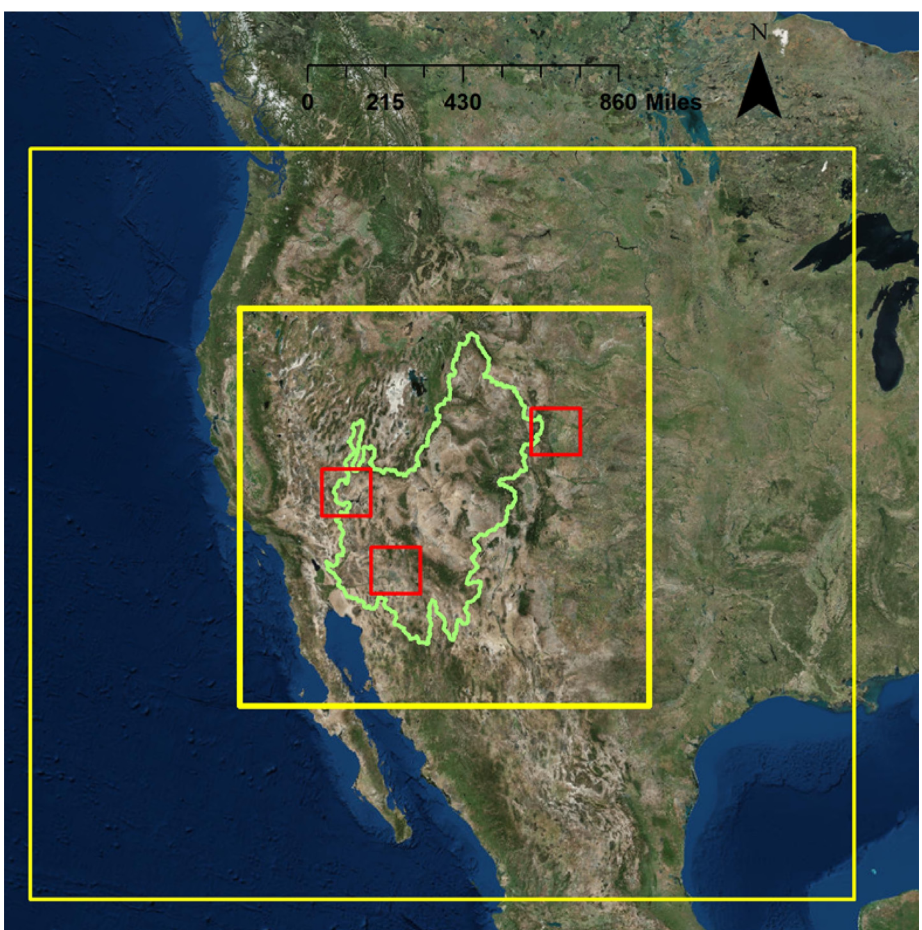

Fig. 1. Geographic representation of the five domains of the study with delineation of the CRB.