Landscape and Urban Planning 167 (2017) 198–211

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

The hysteresis effect on surface-air temperature relationship and its implications to urban planning: An examination in Phoenix, Arizona, USA

Jiyun Song[a,c,d], Zhi-Hua Wang[a,*], Soe W. Myint[b], Chuyuan Wang[b]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, USA
[b] School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287, USA
[c] Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK
[d] Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge, CB2 1PX, UK

ARTICLE INFO

Keywords:
Hysteresis effect
Remote sensing
Sensor network
Surface-air temperature relationship
Urban climate

ABSTRACT

Urban areas, with massive built-up landscapes and manmade structures, have different patterns of local microclimate as compared to natural terrains. A better understanding of the surface-air temperature relationship in urban environments is of significant importance in interpreting urban climatic characteristics and solving related environmental problems via sustainable landscape planning strategies. In this study, we analyse the ground-based in-situ measurements as well as remotely sensed thermal dataset in Phoenix, AZ. Prominent hysteresis effect manifests in correlating diurnal cycles of surface and near-surface air temperatures. In particular, a peculiar pattern of "8-shaped" surface-air temperature hysteresis is observed over concrete pavement especially in winters. Pearson's *r* values, measuring the strength of surface-air temperature coupling, show strong correlation with incoming solar radiation and wind speed, but are relatively insensitive to humidity. The hysteresis effect diminishes at climatic scale, such that the remotely sensed surface temperature can be approximated as linearly correlated to the near-surface air temperature.

1. Introduction

Rapid urbanization has significant influences on the dynamics of energy and scalar transport through the earth's surface due to land use change, landscape modification, emission of greenhouse gases, etc. (Kalnay & Cai, 2003; Song, Wang, & Wang, 2017). The urban land use land cover (LULC) changes, anthropogenic activities, and urban metabolism inevitably modify energy and water cycles, leading to regional and global changes through land-atmospheric interactions (Arnfield, 2003; Chrysoulakis et al., 2013; González, Donnelly, Jones, Chrysoulakis, & Lopes, 2013; Myint, Wentz, Brazel, & Quattrochi, 2013; Song & Wang, 2015a; Song & Wang, 2015b; Song & Wang, 2016a; Song & Wang, 2016b). One of the most remarkable impacts of urbanization on climate is the urban heat island (UHI) effect, manifesting the temperature difference between climate-based "urban" and "rural" sites (Landsberg, 1981; Oke, 1982), more specifically the thermal environment difference between different local climate zones (Stewart & Oke, 2012). The spatial scales of the effect of surface temperature (T_s) on air temperature (T_a) are related to the relative efficiency of surface energy partitioning (specifically between the sensible and anthropogenic heat fluxes) (Chrysoulakis et al., 2016), the vertical thermal structure and stratification of the atmospheric boundary layer (Kawashima, Ishida, Minomura, & Miwa, 2000), as well as the influence of turbulent source areas regulated by wind direction, atmospheric stability and cross-wind turbulence (Schmid, 1997; Stewart & Oke, 2012). A better understanding of urban $T_s \sim T_a$ relationship is therefore of critical importance for characterizing urban climate idiosyncrasies and solving urban environmental problems via landscape planning (Stoll & Brazel, 1992).

In this study, we focus on the Phoenix metropolitan area in Arizona as our study area (see Fig. 1) for investigating the relationships between surface and air temperatures over different types of surfaces and analysing the landscape and meteorological determinants of variable surface-air correlation. The primary reason of this selection of study area is that Phoenix has emerged as a hub of urban environmental studies due to a number of contributors, including (a) extensive LULC change, especially the conversion from agricultural to built areas, during recent decades, (b) constant clear skies and light winds accentuating the climatological impacts of urbanization, (c) elevated water and energy demands associated with the desert setting of the city, and (d) a compilation of a rich field measurement dataset over the last few decades (Stoll & Brazel, 1992; Chow, Brennan, & Brazel, 2012). Currently, as a

---

* Corresponding author.
E-mail addresses: zhwang@asu.edu, wzh.wang@gmail.com (Z.-H. Wang).

http://dx.doi.org/10.1016/j.landurbplan.2017.06.024
Received 9 January 2017; Received in revised form 28 June 2017; Accepted 30 June 2017

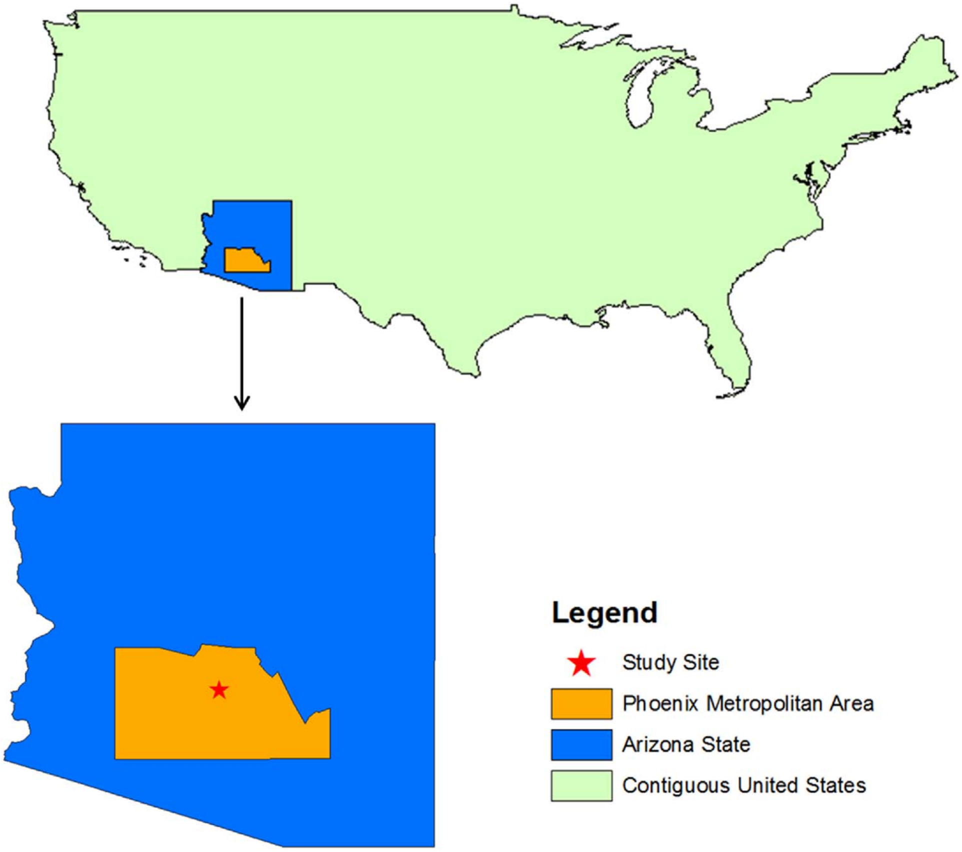

Fig. 1. The location of study area (red star) within the State of Arizona and contiguous United States. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dwelling place of approximately 4.3 million people, Phoenix ranks as the 13th largest metro area by population in the United States (U.S. Census Bureau, 2013). Located at the heart of the emerging Arizona's Sun Corridor and in the northeast of the Sonoran Desert, Phoenix has a subtropical desert climate with long hot summers and short cool winters. According to the 30-year records from 1981 to 2010, there are 107 days annually with daytime high temperature greater than 38 °C in summer (NOAA, 2011). Precipitation is scarce in this area with an average annual value of 203 mm, mostly from winter storm events and the summer monsoon season (Zheng, Myint, & Fan, 2014). At regional scales, the LULC changes in the Phoenix metropolitan region, especially since 1945, have contributed significantly to the formation of emergent regional climate patterns, such as forming a warmer and drier American Southwest (Chow et al., 2012). In addition, there are abundant clear and calm synoptic weather conditions that foster the development of severe UHI.

The continuous and increasing interest in Phoenix's urban environmental problems has led to the collection and archive of a rich and valuable dataset, including atmospheric, geographic, meteorological, ecohydrological, and socio-economic records. Sources of these data products vary widely from ground-based measurements to high-resolution satellite imagery, and from intense field campaigns to extensive stakeholder surveys. For example, the long-term analysis of annual climatic data from 1948 to 2014 at the Phoenix Sky Harbor International Airport station shows that air temperature has a monotonous significant increasing trend with a mean increasing rate of 0.06 °C per year, as shown in Fig. 2. In particular, during the selected period of 67 years, monthly maximum and minimum temperature has increased by 1.7 °C and 6.2 °C respectively, indicating a continuous urban warming more prominent at nighttime.

To find solutions to the extreme heat stress and other environmental challenges in the study area, numerous partnerships have been developed among academic institutes, private sectors, and local and state agencies. Together, a wide variety of urban landscape planning and UHI

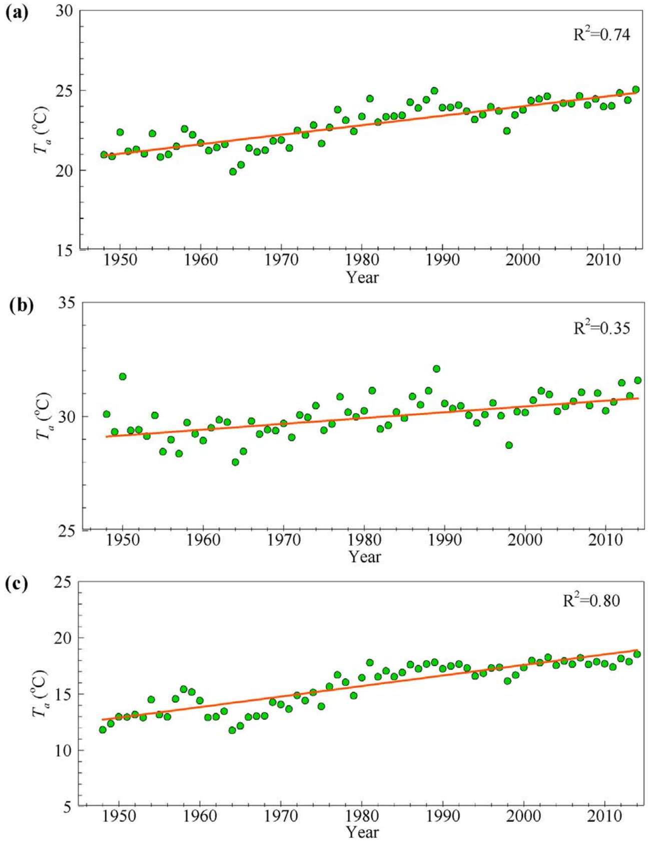

Fig. 2. Temporal trends of yearly (a) mean, (b) maximum, and (c) minimum air temperatures in the Phoenix metropolitan area from 1948 to 2014.