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The effect of multi-dimensional indicators on urban thermal conditions

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A B S T R A C T

Urban heat island (UHI) studies have recognized ten factors as increasing the inner-city temperature compared with that of the surrounding suburbs. The UHI effect is a leading cause of heat-related diseases and mortality in many nations. However, there are still two main shortcomings. First, the effect of UHI is not well recognized in arid and semi-arid regions. Second, the association of multi-dimensional information with surface temperature in urban areas must be examined. This study focuses on the height-related aspects of urban geometry in an arid region. A range of multispectral and spatial vector data were used to derive the surface temperature and two-dimensional (2D) and three-dimensional (3D) information of the study area. All information was aggregated into a grid with common spatial resolution to create a homogeneous dataset. The machine learning statistical model of a boosted regression tree (BRT) was used to reflect the relative influence of 2D and 3D indicators with land surface temperature. Our results showed a cooler surface temperature in the city than in the surrounding area, leading to the question of whether the established UHI definition encompasses all types of cities. In addition, the thermal band was able to distinguish different spatial structures in the study area. The BRT analysis demonstrated that both multi-dimensional 2D and 3D indicators affect the surface temperature. In particular, the 3D indicators play a more important role than 2D indicators in shaping the surface temperature at different urban geometries of the study area. This new method can help urban planners identify the most influential 2D and 3D indicators that affect the surface temperature in different districts of a city.

1.Introduction

Human society is becoming increasingly urbanized. Projections by the United Nations suggest that the world's urban population is expected to increase by 66 percent by 2050 (United Nation, 2014). The associated expansion of urban area will also accelerate the destruction of the natural environment (Chun and Guldmann, 2014). Replacing natural environment with urban structures leads to significant higher temperatures, known as the urban heat island (UHI) effect (Weber et al., 2014). The UHI effect is a distinct micro-climate condition whereby temperatures in urban core areas are higher than in the surrounding suburban and rural areas (Oke, 1982). Generally, there are two main groups of factors that affect the formation and intensification of heat islands in urban areas. The first group includes climatological factors such as climatic region (incoming solar energy), season, time of the day and wind regimes (Tomlinson et al., 2010). This means bio-physical factors that are independent from human presence and activities. The second comprises factors related to the urban built environment, and thus human induced and influenced, such as the topography of the city, size of the urban area, population density, inhabitant activity, type of building materials, vegetation structure, and physical form of the urban landscape (Wienert and Kuttler, 2007). Both groups of factors act simultaneously and differ in terms of the possibility to influence them.

The human stress caused by UHI can directly (Harlan et al., 2006; Lafortezza et al., 2009) and indirectly (Stafoggia et al., 2008) affect city inhabitants' daily lives and individual health

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(Schuster et al., 2017). Currently, 10 factors are well known to play a major role in the formation of urban heat. An abundance of urban vegetation cover has been shown to decrease urban heat through leaf evapotranspiration (Kjelgren and Montague, 1998). Bodies of water in urban areas also cause a cooling island effect (Du et al., 2016). Surface characteristics and configuration also play a role (Amiri et al., 2009). Urbanized areas, in contrast to sprawling areas, affect the heat storage capability (Kato and Yamaguchi, 2007). Urban geometry (spacing between buildings) affects the heat distribution (Chun and Guldmann, 2014). The sky view factor indicates the amount of solar radiation absorption onto the surface (Bottyán and Unger, 2003). Wind flow and air circulation help reduce the temperature (Grimmond, 2007). Finally, a building's height and shape manipulate the surface albedo (Giridharan et al., 2004).

Generally, there are two shortcomings in previous UHI studies. First, most UHI research has been conducted in mid-latitude regions (Ana-Maria et al., 2016). The UHI effect has been rarely studied in arid and semi-arid regions. Second, the temperature intensity in UHI studies has been mainly associated with a single dimension, such as the effect of UHI on public health (Pantavou et al., 2011; Huang et al., 2013; O'Neill et all., 2003; Gosling et al., 2009), increased energy demand for cooling infrastructure (Arifwidodo and Chandrasiri, 2015), increased global temperature (Teuling et al., 2010), the cooling effect of urban vegetation (Weng et al., 2004), and the association of horizontal land cover classes with surface temperature (Alavipanah et al., 2016). Using individual dimensions usually leads to homogenous scaled outputs (Wong and Lau, 2013).

However, urban environments are multi-dimensional settings for which a multi-dimensional approach is undoubtedly needed to measure several horizontal (2D) and vertical (3D) dimensions in a city at the same time. UHI studies that assess several dimensions at once are largely absent, although there are a few exceptions (Nicholand and Wong, 2005; Matejicek et al., 2006; Unger, 2006; Noori-kakon and Mishima, 2009; Wu et al., 2013; Wong and Lau, 2013). Previous studies have argued that it is difficult to measure diversity on a homogenous scale; therefore, to capture the complexity of the urban environment, we must engage with multi-dimensional information and respective indicators (Alavipanah et al., 2016).

This study focuses on the spatial distribution of temperature in an urban context. In particular, the height-related aspects of urban geometry are addressed. The objective of this paper is to assess the association of urban multi-dimensional (two- and three-dimensional) indicators on urban surface temperature. Therefore, this study examines the city of Yazd due to the presence of two very different urban geometries in the city.

The remainder of the paper as organized as follows. Section 2 and 3 describes the study area and data source. Section 4 describes the method used to retrieve the surface temperature, mapping the land cover classes, modeling the three-dimensional structure of the built-up environment, data integration and statistical model of the study area. The results of the relative spatial effect of urban multi-dimensional indicators (2D and 3D) on surface temperature are shown in Section 5. Section 6 discussed the remaining issues and areas to be studied in future research. Section 7 concludes the paper.

2. Study area

The study region is situated in central Iran (31.8974° N, 54.3569° E) (Fig. 1, left panel). Continuously inhabited since the Proto-Elamite period (3400–2500 BC) (Carter and Mathew, 1984), Yazd is known as the world's largest adobe brick city and second-oldest city (Potts, 1999). The city of Yazd is the capital and largest city of the province of Yazd. The United Nations Educational, Scientific and Cultural Organization (UNESCO) has added the city of Yazd to its list of world heritage since July 2017. As home to almost half a million inhabitants in 2015, Yazd stretches over a relatively flat area of approximately 240 km^2 at 1200 m above sea level. With an average annual rainfall of only 60 mm and a summer temperature that is frequently above 40 °C, Yazd is the driest major city in Iran. Yazd is clearly affected by its arid and dry surrounding and is considered to have a hot desert climate (BWh) by the Köppen-Geiger climate classification.

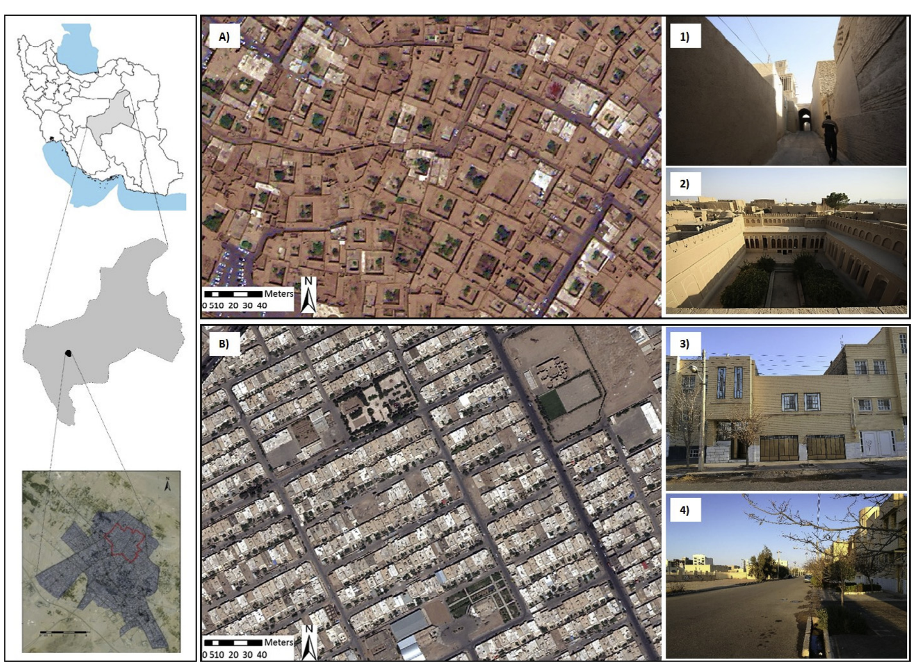

Fig. 1. The left panel shows the geographical location of the study area. The red border depicts the location and orientation of the historic district in the city of Yazd. A) The urban structure of the historic district (picture 1 and 2). B) Newly structured urban area (picture 3 and 4).