International Journal of Applied Earth Observation and Geoinformation 51 (2016) 76–90

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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

Dynamics and controls of urban heat sink and island phenomena in a desert city: Development of a local climate zone scheme using remotely-sensed inputs

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ARTICLE INFO

Article history:
Received 22 November 2015
Received in revised form 23 April 2016
Accepted 14 May 2016
Available online 24 May 2016

Keywords:
Urban heat sink
Urban heat island
Local climate zones
Urban geometry
Land cover
Dubai

ABSTRACT

This study aims to determine the dynamics and controls of Surface Urban Heat Sinks (SUHS) and Surface Urban Heat Islands (SUHI) in desert cities, using Dubai as a case study. A Local Climate Zone (LCZ) schema was developed to subdivide the city into different zones based on similarities in land cover and urban geometry. Proximity to the Gulf Coast was also determined for each LCZ. The LCZs were then used to sample seasonal and daily imagery from the MODIS thermal sensor to determine Land Surface Temperature (LST) variations relative to desert sand. Canonical correlation techniques were then applied to determine which factors explained the variability between urban and desert LST.

Our results indicate that the daytime SUHS effect is greatest during the summer months (typically ~3.0 °C) with the strongest cooling effects in open high-rise zones of the city. In contrast, the night-time SUHI effect is greatest during the winter months (typically ~3.5 °C) with the strongest warming effects in compact mid-rise zones of the city. Proximity to the Arabian Gulf had the largest influence on both SUHS and SUHI phenomena, promoting daytime cooling in the summer months and night-time warming in the winter months. However, other parameters associated with the urban environment such as building height had an influence on daytime cooling, with larger buildings promoting shade and variations in airflow. Likewise, other parameters such as sky view factor contributed to night-time warming, with higher temperatures associated with limited views of the sky.

1. Introduction

The term “Urban Heat Island (UHI)” is mostly associated with air temperature data collected from mobile traverses or weather stations up to two meters above ground level (Emmanuel and Kruger, 2012; Pichierri et al., 2012). However, with the advent of thermal infrared (TIR) remote sensing technology, more studies have investigated surface UHI (SUHI) effects based on differences in land surface temperature (LST) between urban and rural areas measured by various space-borne TIR sensors. Data from space-borne TIR sensors cover larger spatial extents and retrieve temperature measurements for each pixel much more rapidly and cost-effectively than conventional ground-based measurements. Furthermore, remotely-sensed TIR data is particularly useful in areas where the weather stations are sparse or absent altogether (Knight et al., 2010). Although LST is not identical to air temperature, as the former is usually higher than the latter (US EPA, 2008; Yuan and Bauer, 2007), a study by Coutts and Harris (2012) revealed that trends in LST derived from remotely sensed imagery were similar to trends in air temperature, albeit with differences in absolute values.

While many factors affect the formation of a SUHI and its intensity, such as local weather conditions and geographical location, a key contributor is urbanization where the natural land cover is replaced by impervious surfaces (e.g. Imhoff et al., 2010; Rhee et al., 2014; Weng, 2001). As a consequence of urbanization, the evapotranspiration, thermal properties and wind flow of the landscape is altered, which can lead to an increase in surface temperatures in cities (Kato and Yamaguchi, 2005; US EPA, 2008). The increase in impervious surfaces leads to the increase of absorption of solar energy and its conversion to sensible heat rather than latent heat.

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http://dx.doi.org/10.1016/j.jag.2016.05.004
0303-2434/

This is evident when compared to rural areas through the increase of heat storage in urban areas from the combination of two properties: thermal conductivity and heat capacity (Gartland, 2008; Obiakor et al., 2012).

For cities in desert environments, a SUHI has been observed during the night while a surface urban heat sink (SUHS) has been observed during the day, where urban areas exhibit lower temperatures than rural areas (Frey et al., 2007; Lazzarini et al., 2013). Previous remote sensing studies in desert cities have focused on investigating the direct relationship between land surface temperature and surface cover (i.e. impervious surface and vegetation) from a two-dimensional perspective (Frey et al., 2007; Lazzarini et al., 2013). However, no research has thoroughly examined the effects of the three-dimensional urban geometry on the formation of SUHS and SUHI phenomena in desert cities. Indeed, urban geometry is considered a significant factor in determining the temperature distribution within cities (Unger, 2009; Voogt and Oke, 2003). This investigation into the effects of urban geometry and land cover type on surface temperature variation is motivated by previous studies in desert cities which have found that even areas lacking vegetation and being largely composed of impervious surfaces exhibit lower day time surface temperatures than surrounding rural areas (Frey et al., 2007; Imhoff et al., 2010). Furthermore, proximity to large water bodies has not been considered in previous studies of SUHS and SUHI phenomena in coastal desert cities (Frey et al., 2007; Lazzarini et al., 2013) in spite of its recognized importance (e.g. Coseo and Larsen, 2014).

1.1. Local climate zones in the urban environment

Stewart and Oke (2012) developed a climate-based classification system called 'Local Climate Zones' (LCZs) in order to standardize the classification and sampling of field sites in urban heat island studies and facilitate the comparison between several sites within the urban landscape. Typically, the study area is classified into a number of LCZs, each with a diameter ranging from hundreds of meters to several kilometres that share relatively similar geometry and land cover characteristics

A recent study by Stewart et al. (2014) based on three temperate cities concluded that thermal contrasts do exist among different LCZs and are governed primarily by urban geometry, tree heights and proportion of pervious surfaces. Thus, the LCZ system was deemed useful to investigate the UHI among various locations within the cities. Several UHI studies have adopted the LCZ classification system based on air temperature measurements using fixed or mobile weather stations (Alexander and Mills, 2014; Leconte et al., 2015; Siu and Hart, 2013). Others have proposed various methods to classify the urban environment into LCZs and map their distribution across a study site using inputs from remote sensing and other spatial data using GIS techniques (e.g. Bechtel and Daneke 2012; Lelovics et al., 2014), although this was done for different reasons than the research presented in this paper. This study uses a similar approach to classifying and mapping LCZs by using the available spatial data for the study site and developing and applying an appropriate classification method to this data. The boundaries of the mapped LCZs were then used to explore the spatial and temporal differences in LST measured from remotely-sensed TIR data.

1.2. Aim and objectives

The aim of this study was to elucidate the dynamics and controls of SUHS and SUHI phenomena in the desert city of Dubai. In order to achieve this aim three objectives were addressed: (i) to develop a technique to categorize the urban environment of Dubai into LCZs in accordance with the LCZ classification system; (ii) to study the diurnal and seasonal dynamics of the SUHS and SUHI in the LCZs using remotely-sensed thermal imagery; and (iii) to investigate the impact of different physical variables (related to urban geometry, proximity to the Arabian Gulf and land cover properties) on the temporal dynamics of the SUHS and SUHI phenomena.

2. Study area

Situated on the Arabian Gulf, Dubai emirate (25° 16′N, 55° 20′E) is considered one of the fastest growing cities in the Middle East and has been transformed into a city of global stature (Elsheshtawy, 2010). The total administration area of the emirate before the development of the islands was 3885 km^2 and the population reached 2,213,000 inhabitants in 2013 (Dubai Statistical Centre, 2013).

Dubai Creek divides the city into Deira to the east and Bur Dubai to the west forming bi-central districts comprised of high-density buildings. Bur Dubai is generally known for its modern high-rise buildings, however, low-rise to mid-rise building blocks are spreading in both directions from the Creek. In the last two decades, the physical size of the urban area has grown dramatically both horizontally and vertically and the desert has been transformed into residential, commercial, sports and tourism projects. The total urban area has increased horizontally to approximately 560 km^2 in 2011 (Nassar et al., 2014) while vertically, 96 buildings in Dubai are greater than 150 m in height. In 2011, approximately 14% of the Emirate was covered by impervious surfaces (buildings, roads, walkways and parking lots) and 1.1% by vegetation (Nassar et al., 2014).

Due to the diversity of building heights in Dubai and the systematic urban planning process, large discrete blocks of different urban land use types and building heights have been created, making this an interesting study site for investigating the impact of urban geometry on SUHS and SUHI effects. For example, residential areas are usually comprised of low to midrise buildings; mixed land use areas (commercial and residential combined) are usually comprised of mid to high-rise buildings while industrial areas are comprised of low-rise buildings.

Dubai is built upon flat terrain and experiences a hot and arid climate. Desert sand is the main land cover type in the Emirate. The warmest months in Dubai are July and August with an average maximum temperature of 43 °C and an average minimum of 33 °C, while the coldest months are January and February with an average maximum of 26 °C and an average minimum of 16 °C (Dubai Statistical Centre, 2014).

Our specific study area covers the main urban areas in Dubai which consist of a variety of urban structures, configurations and land cover types covering an area of 450 km^2 (Fig. 1). The study area was also chosen based on the availability of building footprint data for the city which were used to compute urban geometry parameters. It has also been designed to exclude the coastal strip (1 km) in order to avoid the problem of mixed pixels (land-water) in the remotely-sensed imagery which is a confounding factor in thermal studies of coastal regions (Lazzarini et al., 2013).

3. Materials and methods

To achieve the aim and objectives of the study, the following steps were taken: (1) derivation of urban geometry and land cover parameters from several datasets, (2) selection of LCZs based on the derived parameters according to the LCZ classification system, (3) LST retrieval using Dubai's LCZs based on day and night-time satellite imagery, (4) investigation of the SUHS and SUHI magnitudes diurnally and seasonally for each LCZ, and (5) determination of the relationships between different physical variables and the seasonal