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What controls the magnitude of the daytime heat sink in a desert city?

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ABSTRACT

The aim of this study was to increase knowledge of the causes of cooling in desert cities. We used a time-series of Landsat images to characterize the changes in daytime land surface temperature during the period of rapid urbanization in Dubai. Changes in land cover and albedo were also quantified from Landsat data and the development of different land use types and variations in urban geometry were characterized. The results demonstrate that urban growth has promoted a heat sink and that all urban land use types contributed to this effect. Vegetation generated the largest cooling effect per unit surface area but impervious surfaces dominated the urban environment and are responsible for the majority of the heat sink created by the city. Changes in albedo were not causally related to the urban heat sink, however, variations in urban geometry, particularly the amount of shading cast by buildings, had some influence on the magnitude of cooling. This study provides evidence that the expansion of the heat sink during urbanization in a desert environment is influenced by the forms of land cover transition, the type of urban land use that is developed, the thermal properties of construction materials used and the geometry of the city environment that is constructed. Future research should concentrate upon understanding these mechanisms in order to plan future developments which maximize cooling and reduce the environmental impacts of desert cities.

1. Introduction

Numerous studies have addressed the issue of the urban heat island (UHI) in different regions of the world, especially where urban areas have replaced natural vegetated surfaces in temperate and subtropical environments. The results of these studies have indicated that urban areas show higher land surface and/or air temperatures than surrounding rural areas, particularly at night-time (e.g. Coseo & Larsen, 2014; Hu & Brunsell, 2013; Zhang et al., 2013). However, in hot arid environments, where urban areas are replacing desert sands, urban heat sinks (UHS) can be detected, where urban land surface temperature (LST) is lower during the daytime than the surrounding desert (Frey, Rigo, & Parlow, 2007; Imhoff, Zhang, Wolfe, & Bounoua, 2010; Lazzarini, Marpu, & Ghedira, 2013).

The magnitude of the observed UHS in desert regions can depend on many factors including weather conditions and the timing of temperature observations, but it has been suggested that the characteristics of the urban land cover exert a major control on variations in land surface temperature (Carnahan & Larson, 1990). The UHS effect has been attributed to an increase in vegetated areas associated with urbanization which generate a cooling effect due to the increase in latent heat flux through evapotranspiration and a decrease in sensible heat relative to the desert surroundings (Lazzarini et al., 2013). However, other studies have shown that desert cities can still exhibit an UHS despite containing little vegetation and being primarily composed of impervious surfaces (Frey et al., 2007; Imhoff et al., 2010), although no evidence was provided to explain these findings. This disparity in the literature highlights the need for further research to understand the relationships between land cover and LST in desert cities.

The properties of the urban fabric can also influence the UHS; it has been suggested that highly reflective materials, or those with a low thermal conductivity, can contribute to urban cooling (Erell, Pearlmutter, & Williamson, 2011; US EPA, 2008). Some cities have made use of highly reflective materials on rooftops, roads and parking lots to increase albedo hence reduce the absorption of solar radiation and surface temperatures (Bretz, Akbari, & Rosenfeld, 1998). For example, Mackey, Lee, and Smith (2012) found that increasing the surface reflectivity in urban areas of Chicago had a

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stronger cooling effect than increasing the amount of vegetation cover. Similarly, increasing the specific heat capacity of urban materials has been shown to decrease daytime summer peak temperatures by postponing the release of stored heat (Hamdi & Schayes, 2009), although this is likely to contribute to an urban heating effect at nighttime. Moreover, urban water bodies can make a significant contribution to cooling due to their high specific heat capacity and ability to lose heat via evaporation (Omran, 2012). However, the overall contribution of variations in the thermal properties of different surface materials has received little attention in the context of the UHS phenomenon in desert cities.

Evidence concerning the impact of urban geometry on thermal conditions is somewhat unclear. Several studies have demonstrated that an increase in building height and density produces an increase in surface temperature (e.g. Martin et al., 2012; Wu, Lung, & Jan, 2013). Conversely, other research suggests that tall buildings and narrow streets generate shadow effects which decrease the absorption of solar energy at the land surface thus lowering temperatures (e.g. Kato, Matsunaga, & Yamaguchi, 2010; Littlefair et al., 2000). There is also evidence that variability in building height is important, with areas containing a diverse range of building heights generating an increase in wind speeds and natural ventilation at street level leading to a decrease in surface temperature (Johansson & Emmanuel, 2006). Given that these cooling mechanisms have been recognized, it is now important to determine the relative contribution of urban geometry to the overall UHS effect in desert cities.

Although the UHS effect in desert regions has been identified there is considerable uncertainty over the factors which generate this phenomenon. Hence, the aim of this study was to improve our understanding of the causes of cooling in desert cities. The study site was Dubai, United Arab Emirates (UAE), which has experienced rapid urbanization over the last 25 years. We used data from the Landsat image archive to address the following research objectives: (i) to characterize changes in land cover, land use and albedo that have taken place as a result of urbanization; (ii) to quantify the development of the UHS during urbanization; (iii) to examine whether variability in the magnitude of the cooling effect can be explained by the transitions in land cover, albedo and type of land use; and (iv) to evaluate the sensitivity of the UHS to variations in urban geometry.

2. Study area

Dubai Emirate (Fig. 1) is one of the fastest growing cities in the Middle East. The total area of the emirate is approximately 3885 km^2 and it is characterized as a hyper arid environment with an annual average rainfall of only 8 mm falling mostly in the late autumn and winter months (Dubai Airport, 2014). The warmest months in Dubai are May to September with an average maximum temperature of 40 °C and average minimum of 28 °C; the coldest months are December to February with an average maximum temperature of 25 °C and average minimum of 15 °C.

After the discovery of oil in the late 1960s, Dubai attracted a large overseas labour force. Consequently, the population increased from 183,187 in 1975 (National Bureau of Statistics, 2010) to 2,003,790 inhabitants in 2011 (Dubai Statistical Centre, 2011). The physical size of the urban area has grown dramatically over time as the desert has been transformed into residential, commercial, sports and tourism developments. This growth was a consequence of the strategic plan of the Emirate to diversify the economy by stimulating real estate marketing and developing tourism attractions. Indeed, the rapid pace of desert alteration in Dubai has attracted the attention of economists, environmentalists and urban planners.

According to the Skyscraper Center (2014), 180 buildings in Dubai are greater than 100 m in height in 2011, while there are also many other areas of low-rise urban development, making Dubai an excellent study site to investigate the effect of urban geometry on the UHS in desert cities. Furthermore, due to the strong and systematic urban planning process in Dubai, large discrete blocks of different urban land use types have been created, making this a useful study site for investigating the impact of land use on the cooling effect. The recently developed offshore islands (see Nassar, Blackburn, & Whyatt, 2014) were not included in the study area but the environmental impacts of the islands are being investigated in our ongoing work.

3. Materials and methods

Fig. 2 shows the main stages of data processing and details are provided in the following subsections.

3.1. Data acquisition and image pre-processing

Three Landsat scenes, acquired in August 1990, 2001 and 2011 (Table 1) were used to capture the main period of rapid urbanization in Dubai. Previously, the largest UHS effects have been observed during the daytime in the summer (e.g. Imhoff et al., 2010; Lazzarini et al., 2013) hence the Landsat scenes chosen for this study were the most appropriate for examining the variability of the UHS in Dubai over space and time. All the images were cloud free, which greatly helped in the land cover (LC) classification and retrieval of LST and albedo. All images were acquired as close as possible to the same Julian day in order to minimize the effects of variations in solar geometry.

Atmospheric correction for bands 1–5 and 7 was conducted using the Fast Line of Sight Atmospheric Analysis of Spectral Hypercubes module within ENVI and the original digital numbers were converted to surface reflectance (Kayadibi, 2011). The images were then co-registered with existing map data on a WGS 84 datum/Dubai Local Transverse Mercator projection using 57 ground control points which were distributed around the images to maximize registration accuracy (Jensen, 2005).

3.2. Land cover (LC) classification and derivation of land surface temperature (LST) and albedo

A hybrid classification method was applied to the atmospherically corrected Landsat images to derive LC maps for the three sample years (Fig. 3). This hybrid method of classification is based on a combination of unsupervised and supervised algorithms and exploits the advantages of both approaches to overcome their limitations (Lo & Choi, 2004). This method has previously proven effective for discriminating urban areas in desert environments (Nassar et al., 2014).

To assess the accuracy of the classified images, 60 stratified random samples (image and reference pairs) were collected for each class and these samples were independent from the data used for training to avoid bias (Verbyla & Hammond, 1995). The reference sample classes were identified through manual interpretation of high resolution imagery from Dubai Sat-1 (for 2011), IKONOS (for 2001) and aerial photography (for 1990). The overall accuracies for the three classified images ranged from 89 to 93% which exceeded the minimum 85% accuracy recommended by Anderson, Hardy, Roach, and Witmer (1976).

LST was obtained from the single thermal channel of Landsat TM/ETM+ using the methods of Weng (2001) for Landsat TM and Yuan and Bauer (2007) for Landsat ETM+. In both methods the emissivity effects were corrected using an approach developed by