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Analyzing long-term spatio-temporal patterns of land surface temperature in response to rapid urbanization in the mega-city of Tehran

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ABSTRACT

Analyzing and monitoring spatial and temporal urbanization is vital for a better understanding of land surface temperature (LST) variations. Only a few studies have examined LST variations in mega-cities regarding long-term spatial and temporal scales. First, this study compared heat differences between urban and sub-urban areas (referred to hereafter as the regional scale) in the entire mega-city of Tehran and urban heat variation among 22 regions located within Tehran (referred to hereafter as the local scale) during last three decades. Second, we examined how land cover, climate and elevation data were correlated with urban heat for regional and local scales in the mega-city of Tehran. A series of six Landsat TM images of Tehran in 1986, 1991, 1994, 2001, 2008, and 2011 were classified into four land cover classes (built-up, crop, open space, and green lands). These images were also used to calculate land surface temperature (LST) and normalized difference vegetation index (NDVI). We used 30 m elevation data from the Shuttle Radar Topography Mission. We also downloaded 1 km climate data including temperature, precipitation, solar radiation, vapor pressure and wind speed from Global Climate. At the regional scale, we found that urbanization in the mega-city of Tehran doubled during last three decades increasing from 21% in 1986–43% in 2011. Moreover, the mean LST difference among various land cover classes was on average 5.70 °C in each time point. Furthermore, the mean LST for various land cover classes increased on average 6.46 °C from 1986 to 2011. We also found that mean NDVI, mean elevation and mean climate were more effective in reducing mean LST inside Tehran than outside Tehran. At the local scale, regions north of Tehran experienced the lowest mean LST values while regions south and southwest of Tehran experienced the highest mean LST values from 1986 to 2011. Moreover, the mean LST difference among the 22 regions in each time point observed was 6.77 °C on average. Furthermore, the mean LSTs for all regions increased on average 3.75 °C from 1986 to 2011. As the mean LST increased, the mean NDVI became a stronger factor in mitigating the mean LSTs in all 22 regions. Finally, mean NDVI, mean elevation and mean climate across 22 regions played significant role to control LST variations inside Tehran. We concluded that long-term spatial and temporal analysis can inform decision-makers for better planning to mitigate and control urban heat variations in the mega-city of Tehran.

1. Introduction

The complex structure of urban areas consists of infrastructures, biodiversity, and human organizations (Weng and Schubring, 2004; , 2010; , 2014). The economy in Iran has been growing steadily since the early 1980s, which initiated waves of urbanization across the mega-cities of Iran (Tayyebi et al., 2011a,b). Urbanization in Iran has been the primary cause of the conversion of vegetation areas to impervious surfaces such as buildings, roads, and paved surfaces (Shafizadeh-Moghadam et al., 2017a,b). The main consequence of land cover conversion due to urbanization is the creation of a phenomena called “urban heat island” (UHI; Oke, 1973), which describes the difference between sub-urban and urban temperatures (Arnfield, 2003). Such land cover conversion has significant impacts on local climates by increasing land surface temperatures (LST) (IPCC, 2014) and a variety of negative environmental consequences such as biodiversity loss (Higgins, 2007) and water scarcity (Barnett et al., 2005) as well as negative consequences on human life such as increasing heat-related mortality (Patz et al., 2005), increasing energy demand (Kikegawa et al., 2006), and increasing air pollution (Stone, 2005). Thus, it is vital to assess how

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urbanization affects LST variations across space and time in the long term (Grimmond, 2007).

Climate data (e.g., temperature, wind speed, water vapor, precipitation) have been used over last one hundred years a primary indicator to measure urban heat across space and time (Oke, 1973). Braganza et al. (2004) argued that T_{avg} alone is not as useful indicator of climate change as the trends in diel temperature range due to changes in either T_{max} or T_{min}, or relative changes in both. Other study showed that increased diel temperature range often reduce crop yields because the associated increase in T_{max} results in increased water stress (De Villalobos and Peláez, 2001) or reductions in T_{min} when freezing temperatures can result in crop injury (Krishnan et al., 2007). Within cities, increased T_{min} associated with heatwaves have been correlated with increased mortality (Kalkstein, 1992) and higher T_{max} is associated with greater energy use (Santamouris et al., 2001). Many climate models projected further significant changes in diel temperature range in future and indicators of diel temperature variation are an important component of climate studies (Holden et al., 2011).

LST is a function of surface properties such as construction materials and the structure of urban vegetation (Sobrino and Raissouni, 2000). Land cover, elevation, and climate conditions contribute to urban heat formation and LST patterns in mega-cities (Kalnay and Cai, 2003; Chen et al., 2006; Jenerette et al., 2007; Grimm et al., 2008; Zhou et al., 2011; Fu and Weng, 2016; Li et al., 2016). Increasing vegetation is an effective way to reduce urban heat because it has high evapotranspiration (Tomlinson et al., 2012). In a single mega-city study, Hawkins et al. (2004) found that urban heat variation in the mega-city of Phoenix, AZ, with its homogenous dry climate gradient, was up to 14 °C. In regional mega-city comparisons, Imhoff et al. (2010) found that the largest urban heat variation was 8 °C among 38 mega-cities in the continental United States where those cities were located in various climate gradients. Similarly, Tran et al. (2006) compared urban heat variations in 18 Asian mega-cities located in regions with both temperate and tropical climates and found large variations in the magnitude, intensity, and extent of urban heat across those cities.

The magnitude of urban heat varies during the day and according to the season (Buyantuyev and Wu, 2010; Haashemi et al., 2016). Impervious surfaces (e.g., concrete and buildings) absorb heat during the day and re-emit heat at night (Koch-Nielsen, 2013). Moreover, due to changes in the sun's intensity and ground cover, urban heat also varies according to the season (Zhou et al., 2014). Such heat transfer creates temperature differences between day and night as well as across seasons. For instance, a study by Morris et al. (2001) found that urban heat variations were higher in summer and spring as compared to autumn and winter. The maximum urban heat intensity was observed at night rather than in the day (Oke, 1973). Daily and seasonal variations correlated with vegetation and LST suggest a much stronger coupling during warmer seasons and at midday, respectively, than in cooler seasons and at night (Myint et al., 2013).

While existing studies provide an essential basis for a better understanding of the effects of urban heat across space and time, there were also some limitations. First, few studies have examined the spatial and temporal variations of LST within local scale (Huang and Cadenasso, 2016; Jenerette et al., 2016) in spite of its influence on the knowledge of environmental implications and public health planning practices; such information provides critical insights for decision makers and city planners. Second, at the local scale, the effects of land cover, especially the role of vegetation, on LST is less certain, and these are the scales appropriate for policies that can reduce environmental risks (Harlan et al., 2013). Resolving the microscale of an individual's interactions with the environment is critical in improving decision making by individuals and policy makers. Third, few studies have examined the spatial and temporal variations of LST as a result of rapid urbanization in the long term (Chaudhuri and Mishra, 2016; Fu and Weng, 2016), and fourth, although the interactions among land cover, climate, biophysical factors, and LST has been known, the interactions of these drivers with LST across space and time remain elusive (Buyantuyev and Wu, 2010). Thus, a better understanding of the effects of the biophysical and land cover conditions on LST in mega-cities needs to be further investigated.

Assessing the long-term effect of urbanization on LST has not been measured at the regional and local scales in the mega-city of Tehran across space and time. Tehran has undergone rapid expansion since the early 1980s due to economic growth in Iran. This study compared the heat difference between urban and sub-urban areas (the regional scale) in the entire mega-city of Tehran as well as heat variation among 22 regions located within the urban areas of Tehran during last three decades. The purpose was to 1) examine the long-term dynamics of urbanization from 1986 to 2011 at the regional and local scale, 2) assess the long-term dynamics of LST and NDVI variations across space and time at the regional and local scales, and 3) quantify the relationship between elevation, climate and land cover conditions on LST across space and time at the regional and local scales. The outcome of such analyses provides information helpful in the management of regional and local scales regarding spatial and temporal variations of urban heat.

2. Materials and methods

This paper proceeded according to the following steps to achieve its primary goals (Fig. 1). First, we downloaded and processed time-series Landsat TM images as well as climate data. Second, we classified time-series Landsat TM images according to various land cover classes using maximum likelihood function. Third, we calculated NDVI and LST using time-series Landsat TM images, and finally, we quantified the effect of biophysical, land cover and climate conditions on LST at regional and local scales.

2.1. Data source and data processing

The path and row of Landsat TM images for the mega-city of Tehran were 164 and 35, respectively. Landsat TM consists of seven spectral bands with a spatial resolution of 30 m for all bands except Band 6, which initially acquired at a spatial resolution of 120 m, but products were resampled to 30 m. The spectral range of Landsat TM bands vary from 0.45 μm to 12.5 μm. Each Landsat TM image covers the entire mega-city of Tehran as well as its sub-urban areas. These images were acquired through the United States Geological Survey (USGS) website (https://landsat.usgs.gov/landsat-data-access), which has been corrected for atmospheric, radiometric and geometrical distortions. The six Landsat TM images for the mega-city of Tehran were acquired in June of 1986, 1991, 1994, 2001, 2008, and 2011. The Landsat images had clear atmospheric conditions with less than 5% cloud cover, and were further rectified to a UTM zone 39N. The RMSE was found to be less than 0.5 pixels.

We also used monthly climate data at a very high spatial resolution (1 km × 1 km) from Global Climate Data (http://worldclim.org/version2; Fick and Hijmans, 2017). Climate data includes monthly temperature (minimum, maximum and average), wind speed, solar radiation, precipitation and vapor pressure, aggregated across a target temporal range of 1970–2000 using weather stations data (Fig. 1). We used climate data for the mega-city of Tehran in June.

2.2. Study area

Urbanization in the mega-city of Tehran has accelerated during last 30 years (Pijanowski et al., 2010). It has had one of the fastest growing economies in Iran with highest GDP ranking among the top 20 Iranian mega-cities (Tayyebi et al., 2011a, 2011b). The mega-city of Tehran is surrounded by mountains in the north and east where urbanization cannot occur (Shafizadeh-Moghadam et al., 2017b, 2017c). Tehran traverses from the older urban ring to the rapidly sub-urbanizing areas in the middle and rural fringe. Urbanization has caused significant land