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Quantifying of surface urban heat island intensity in Isfahan metropolis using MODIS\Terra\LST data

Majid MONTAZERI* and Seyed ABOLFAZL MASOODIAN

Department of Physical Geography, University of Isfahan, Isfahan, 8174673441, Isfahan Province, Iran.

*Corresponding author; email: m.montazeri@geo.ui.ac.ir

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RESUMEN

Las características de la isla de calor dependen del clima del lugar donde se encuentra la ciudad. Por lo tanto, se definió un índice para el área metropolitana de Isfahan con el fin de cuantificar la intensidad de la isla de calor urbana superficial. Este nuevo índice se basa en los píxeles representativos de las áreas urbanas y no urbanas. Con este fin se utilizaron datos del producto MODIS para estudiar el tipo de cobertura terrestre (MCD12Q1) con el fin de distinguir entre áreas urbanas y no urbanas. Además, los datos del producto MODIS/Terra para analizar la temperatura de la superficie terrestre (MOD11A1) de 2000 a 2018 se utilizaron durante el día y la noche para estudiar la intensidad de la isla de calor superficial. Luego, los pixeles representativos de áreas urbanas y no urbanas se identificaron utilizando el método de correlación espacial y se calculó el índice de isla de calor para el área metropolitana de Isfahan. El estudio mostró que la distribución de frecuencias para el índice de isla de calor durante la noche sigue una distribución normal y, a menudo, está entre 3.5 y 4º K por arriba de la temperatura de las áreas circundantes de la ciudad. La media flotante de 365 días de la isla de calor urbana superficial revela que este índice ha aumentado en los últimos años. La investigación del comportamiento temporal mostró que la intensidad de la isla de calor urbana superficial es alcanza su máximo en enero y se debilita en verano. La encuesta de comportamiento espacial mostró que el núcleo de la isla de calor urbana superficial se extiende hacia las áreas del centro de la ciudad, donde se encuentra la parte más antigua de ésta.

ABSTRACT

Heat island characteristics depend on the background climate of the site where the city is located. Therefore, an index was defined for the Isfahan metropolitan area to quantify the surface urban heat island intensity. This new index is based on the representative pixels of urban and non-urban areas. For this purpose, MODIS land cover type product (MCD12Q1) data were used to distinguish between urban and non-urban areas. Also, data from the MODIS/Terra land surface temperature product (MOD11A1) from 2000 to 2018 were utilized for daytime and nighttime to study the surface heat island intensity. Then, the representative pixels of urban and non-urban areas were identified using the spatial correlation method, and the heat island index was calculated for the metropolitan area of Isfahan. The study showed that the frequency distribution of the nighttime heat island index follows a normal distribution and is often 3.5 to 4º K above the temperature of the surrounding areas of the city. The 365-day floating mean of the surface urban heat island reveals that this index has increased in recent years. The research of temporal behavior showed that the intensity of the surface urban heat island reaches its maximum in January and becomes weaker in summer, while the survey of spatial behavior showed that the core of the surface urban heat island extends towards downtown areas, where the oldest part of the city is located.

Keywords: MODIS/Terra land surface temperature, surface urban heat island intensity, representative pixel method, Isfahan metropolis.

1. Introduction

The urban heat island (UHI) is one of the environmental phenomena that has emerged due to urbanization development and is often defined by the difference in air temperature of a weather station in the city center with that of a weather station outside the city (Stone, 2007), which is called air urban heat island (Arnfield, 2003; Peng et al., 2011). UHI is an anthropogenic climate modification that can affect the quality of urban life, including energy consumption, air, and water quality, as well as people's health (Peng et al., 2011).

Some researchers believe that four urban heat island types (urban boundary layer [UBL], urban canopy layer [UCL], surface, and subsurface) arise from differences in urban and rural cooling and warming rates at the surface, in the substrate, and in the air. Alterations to these rates are caused by changes to the surface energy balance. Besides, corresponding changes have been added to the energy balance of the urban crown layer, the air layers of the UBL, and the underlying substrate soil. Because of the similarity between the spatial patterns of the isotherms the term 'heat island' was coined for air temperature in the urban canopy layer and height contours of an oceanic island. The analogy is apt for the surface, boundary layer, and subsurface heat islands both by day and night, but for the UHI_{UCL} it usually only describes the nocturnal case (Oke et al., 2017).

Air temperatures from urban and suburban areas can be compared by different methods. Such heat island identification methods represent the traditional approach to studying the UHI. The studying methods for traditional UBL and UCL heat islands are based mainly on weather station data; however, remote sensing data has been increasingly used for the analysis of surface urban heat islands (Majkowska et al., 2016).

Using satellite data, the temporal and spatial structure of the land surface temperature (LST) can be revealed through a high spatial resolution, which can distinguish well between urban and suburban areas (Peng et al., 2011). Satellite data cover large areas with high spatial resolution, so they are a better tool for defining the surface UHI intensity (Jin, 2012). The heat island calculated from LST data derived from remote sensing is called surface UHI (Arnfield, 2003; Voogt and Oke, 2003). The surface UHI encompasses the patterns of LST in urban areas. The classical indicator to describe a surface UHI is the difference between urban and rural surface temperatures (Schwarz et al., 2011). Accordingly, the UHI intensity is the difference between the mean spatial temperature of urban and suburban/rural areas (Rizwan et al., 2008). However, there is no consensus among researchers as to whether the temperature difference between one urban district and another can serve as a basis for defining a heat island. While some researchers consider the difference between the temperature of fully urbanized and less urbanized areas of the city, others consider the difference between the two built-up areas (Rizwan et al., 2008).

Since the air temperature behavior is different from the LST, the time for measuring the temperature and the approach chosen to calculate the heat island index are both effective in the characteristics of the resulting heat island. In this case, the surface UHI reflects the difference in the LST patterns in different urban areas (Schwarz et al., 2011). The progress made over the past two decades show that the UHI is much more diverse than previously thought. Depending on where the temperature is measured (air or surface) and with which tool (station or satellite sensor), the resulting heat island will show different characteristics (Arnfield, 2003). In clear sky conditions, the higher the surface temperature, the higher the air temperature and the thicker the UBL. Since LST fluctuations during daytime are higher than in air temperature and there is a lag time between them, the surface heat island is stronger than the air heat island and its fluctuations are greater (Peng et al., 2011; Li et al., 2017). Although the LST measured by satellites is correlated to the air temperature measured at weather stations, the seasonal and diurnal variations are not necessarily identical, as the LST is linked to energy exchange processes on the land surface and has little dependence on its upper air column. As a result, the heat islands relying on LST are stronger during nighttime and daytime, but heat islands relying on air temperature are only strong at night (Jin, 2012). This is due to the shading of buildings, which is an important reason for the weak UHI in daytime (Li et al., 2019). However, the surface UHI, like the air UHI, relies on the temperature difference between urban and suburban areas.

Many indices have been proposed for quantifying the UHI using remote sensing data (Schwarz et al., 2011; Li et al., 2018, 2019). Although these indices allow to calculate the heat island intensity uniformly throughout the world, the credibility of these methods should be established for cities in arid regions (Jin, 2012; Li et al., 2018). This is mainly due to the fact that in arid regions there is a remarkable difference in the water budget between urban areas and the surrounding deserts. Therefore, in order to investigate the heat island in Isfahan, which is located in the arid biome, it is necessary to define a proper index based on the background climate characteristics of the metropolitan area of Isfahan, which is the main purpose of this research.

2. Data and methods

2.1 Study site

The Isfahan metropolis is the third largest city in Iran. The area of the city is about 231 km^2 with a population of more than two million people (Municipality of Isfahan, 2015). The Isfahan metropolis is in the central of Iran and lies between 32.60º-32.75º N and 51.58º-51.75º E (Municipality of Isfahan, 2015). The climate of Isfahan metropolis is warm and dry; however, its dominant background climate is hot and arid (Masoodian, 2011).

Since this research aims to investigate the surface heat island of the Isfahan metropolis, an area of 54 × 84 pixels (50051.68 × 77858.16 m) was extracted form the entire database, being Isfahan metropolis at its center (Fig. 1).

2.1 Data

Two categories of data were used in this study. First, the MODIS land cover type product (MCD12Q1) was used to distinguish between urban and non-urban areas. This product provides surface land cover type with a 500-m spatial resolution and annual temporal resolution. In MCD12Q1, surface land cover is ranked in 17 groups (Wang et al., 2007). Second, LST data from the MODIS sensor installed on two Terra/Aqua satellites was utilized. The MODIS sensor installed on these satellites has many products with different temporal and spatial resolution capabilities. The Terra satellite passes over Iran once between 10:00 to 12:00 LT during daytime and once between 21:00 to 23:30 LT during nighttime.

Among various temperature products of MODIS, the MOD11A1 was selected because it had the proper technical specifications for the period 2000-2018. The projection system of this product is the sinusoidal equivalent. The provided data are in the form of tiles with 10 geographical degrees (1200 × 1200 pixels) in HDF format and with a resolution of approximately 1000 m.

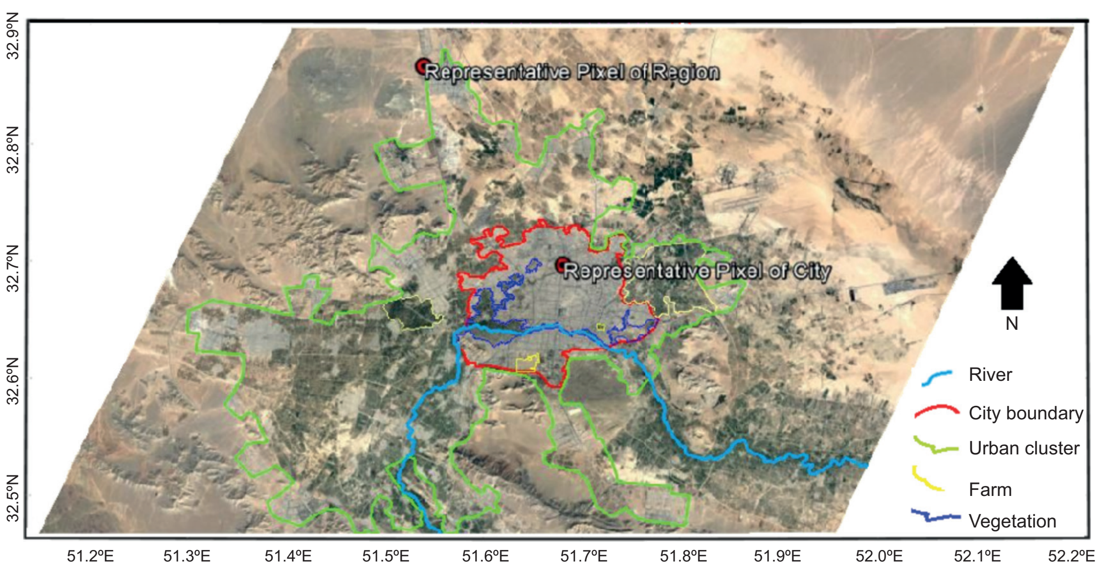

Fig. 1. Study area and surface land cover types.

To explore the city's impact on temperature, it is first necessary to separate urban and non-urban areas. Urban areas refer to parts of the land reported as urban and built-up in the MODIS land cover type product (13 code). Non-urban areas comprise all the land which is not reported as built-up. On the urban cluster scale, a range around Isfahan metropolis with the approximate dimensions of 50 × 80 km was considered (Fig. 1). Here, the boundary of the city is defined as all constructed areas on the latest Google Earth images.

2.2 Method

In this research, the UHI index is defined in terms of the LST difference between representative urban and non-urban pixels. To identify the representative pixel, the mean spatial correlation method was applied to LST data. The representative pixel in non-urban areas is a pixel where the average correlation coefficient of the LST with all other pixels within the non-urban region is maximum. The representative pixel of urban areas is a pixel for which the average correlation coefficient of LST with all other pixels within the urban areas is maximum.

The surface UHI intensity index was calculated by the following formula:

$$SUHII = LST_{UrbanRP} - LST_{Non-urbanRP} \quad (1)$$

where *SUHI* is the surface UHI index, LST_{UrbanRP} is the land surface temperature of the representative pixel of urban areas, and $LST_{\text{Non-urbanRP}}$ is the land surface temperature of the representative pixel of non-urban areas.

3. Results

3.1 Spatial analysis

The calculation of the LST spatial long-term mean during nighttime showed that in the administrative areas of the city, due to the difference in land cover, the LST shows significant spatial changes. At night, parts of the city are warmer, so that the core of the heat island in Isfahan's metropolitan area is extended over downtown, where the oldest part of the city is located (Fig. 2).

3.2 Temporal analysis

The LST difference between nighttime and daytime was separately calculated for urban and non-urban areas. The highest frequency of this LST difference in urban areas is 18º and 25º in non-urban areas (red and blue curves in Fig. 3, respectively). Daytime LST is higher in the dry lands around the city than in urban areas. In contrast, at night, the urban area traps the long wave radiation and is warmer than the surrounding deserts. As a result, the daily range of LST in urban areas is smaller than in non-urban areas, and the difference between daytime and nighttime LST in urban areas is much lower than that of non-urban areas (Fig. 3).

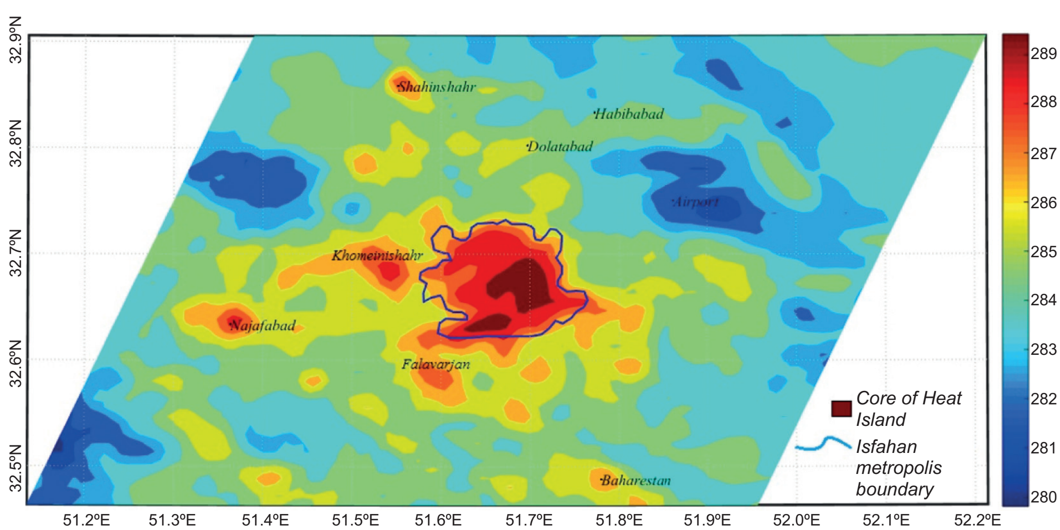

Fig. 2. Long-term mean LST (K^{o}) in the Isfahan metropolitan area, Terra nighttime.

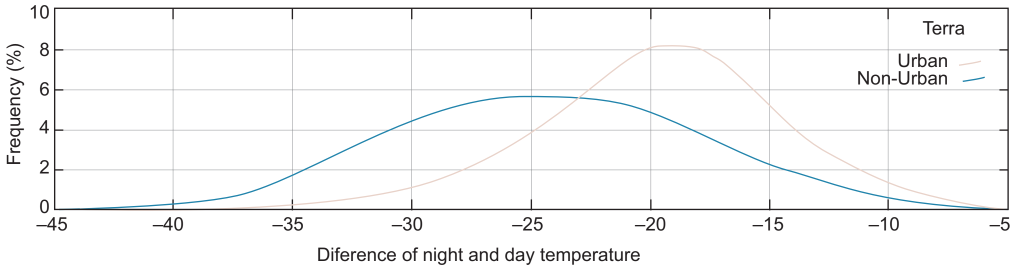

Fig. 3. LST difference between daytime and nighttime in urban and non-urban areas.

3.3 Urban heat island index

Given the temperature difference between urban and non-urban areas during daytime and nighttime, the effect of night heating can be assessed (Fig. 3). To investigate the heat island of Isfahan metropolis, the heat island index based on Eq. (1) was calculated and then drawn as a chart (Fig. 4).

Some nights urban temperature is lower than non-urban temperature; however, the heat island at night is nearly the dominant feature of the metropolitan area of Isfahan (Fig. 4). In other words, urban temperature at night is higher than non-urban temperature in more than 98% of the cases. The intensity of the nighttime heat island reached its maximum in 2007. Considering that the 2007 winter was very cold and snowy (Keikhosravi, 2016), the existence of anthropogenic thermal resources leads to the faster melting of snow in the city and its longest duration in the countryside, resulting in increased albedo and a decrease in countryside temperature. The stronger nighttime heat island intensity in that year shows the role of albedo and also the indirect impact of anthropogenic thermal resources in the formation of the heat island.

From the climate perspective, the question that should be answered about this heat island index is whether it is stable and if the statistical period is long enough to achieve a stable image of the heat island. The analysis of the floating mean shows that the 10-year data is sufficient to achieve a stable index of the nighttime heat island in the metropolitan area of Isfahan. In this case, since the length of the available statistical period is 1.5 times longer than the sufficient length, the length of the statistical period is not a factor that can limit the validity of the index. The floating mean is calculated by the following equation:

$$FM_i = \frac{1}{i}\sum_{j=1}^{i} LST_j \tag{2}$$

where FM_i is the ith floating mean value and LST_j is the land surface temperature at time j. The frequency

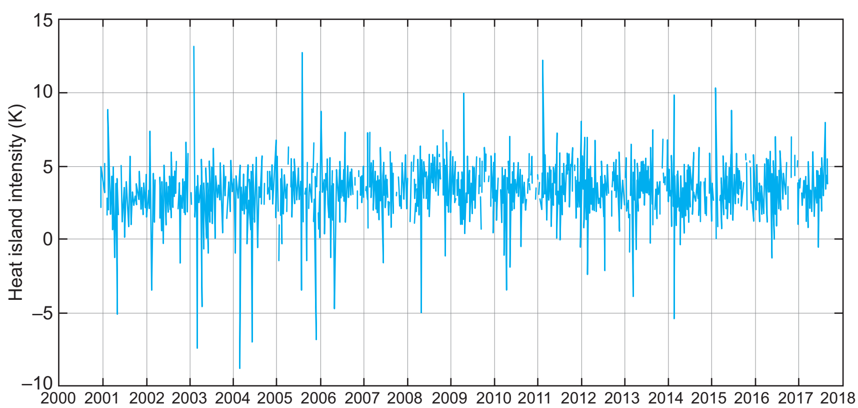

Fig. 4. Surface UHI intensity index in the Isfahan metropolitan area based on nighttime LST.

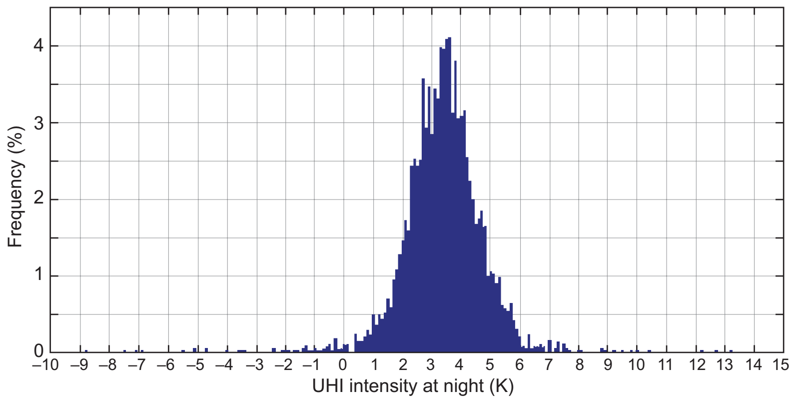

Fig. 5. Frequency distribution of the surface UHI index of the Isfahan metropolis (2000-2018).

distribution of the nighttime heat island index, which ranges from –9º to 14º K (Fig. 5), is normal in the Isfahan metropolitan area.

The median of the distribution index is 3.6 and the mean is 3.4º K. In other words, although in some rare cases (2% of nights) the city is colder than its surroundings, the temperature of the metropolitan area of Isfahan is often higher at night (from 3.5 to 4º K) than the temperature of suburban areas.

Ninety percent of the time, the nighttime temperature of the urban area is at least 2º K higher than its surroundings. Since there is no weather station data from the urban area and its surroundings, it is difficult to determine the mechanism of emergence of the nighttime heat island. However, the soil moisture and atmospheric humidity, and on the other hand anthropogenic heat and impervious surfaces, have the greatest effect on the heat island (Imhoff et al., 2010; Schatz and Kucharik, 2014; Du et al., 2016). The three-dimensional geometry of the city causes radiation to be trapped in the urban vertical walls, and the reduction of wind due to the presence of buildings also causes the nighttime heat island to be stronger. The greater the number of urban vertical walls that occupy land in larger areas of the city, and thus the proportion of vertical wall surfaces, the greater the impact of the city's three-dimensional geometry on the heat island (Ryu and Baik, 2012).

During the investigation period, the 365-day smoothed mean of the nighttime heat island index in the metropolitan area of Isfahan fluctuated between 2.5º and 4º K. (Fig. 6), which can be attributed to

Fig. 6. 365-day smoothed mean surface UHI of the Isfahan metropolis (2000-2018).

the increase in population and expansion of the metropolitan area. Recent studies have shown that the heat island buffer in the metropolitan area of Isfahan has increased from 3 km in 1985 to 10 km in 2015 (Madanian et al., 2018a) and the heat island ratio has increased from 0.16 in 1999 to 0.3 in 2018 (Shirani-Bidabadi et al., 2019). Also, impervious surfaces have increased from 15% in 1985 to 30% in 2015 (Madanian et al., 2018b).

The monthly long-term mean of the nighttime heat island index shows that the seasonal effect implies the weakening of the heat island during the warm season and its strengthening during the cold season (Fig. 7). Seasonal variations can be attributed to biophysical factors such as reduced solar energy and vegetation activity (namely evapotranspiration, increase of cloudiness, and albedo), and also to socioeconomic factors such as increased energy consumption and air pollution during winter.

4. Discussion

The urban land surface method was used here to study the surface UHI. Several studies have shown that the MODIS land surface temperature is highly correlated ($r = 0.97$) with air temperature in the Iranian meteorological stations (Moradi, 2016). Also, studies on gridded station data and MODIS land surface temperature data have shown that the average land surface temperature of Isfahan at noon is 39.7 ºC and its average air temperature is 31.1 ºC. The occurrence of higher temperatures on land surface than on the upper layers is reasonable, because the mechanisms affecting both are different. The land surface directly receives solar energy, while the 2-m air temperature is controlled by the thermal energy transfer of land surface.

In previous studies, different methods have been introduced to calculate the UHI indicators for remote sensing data, including the difference in mean LST between urban areas and cropland, the difference in mean LST between urban administrative areas and rural areas (buffer of 20 km²), the difference in mean LST between urban areas and all other areas, the difference in mean LST between urban areas and water surface, and the area with LST higher than the mean plus one standard deviation (Schwarz, et al., 2011). To calculate the indices for the metropolitan area of Isfahan, the region was first subdivided into several areas based on land cover type, including built-up areas, urban gardens, suburban farm areas, urban farm areas, river margin areas, urban clusters, and background areas (Fig. 1). Then, the long-term mean LST of each area was calculated (Table I).

Built-up areas encompass urban areas from which the vegetation such as gardens, farms, parks, green spaces, and barren lands are deducted. The background mainly covers arid and desert lands and comprises the entire area from which urban cluster areas are deducted.

This study shows that the urban built-up area is about 3.5º K warmer at night than the background

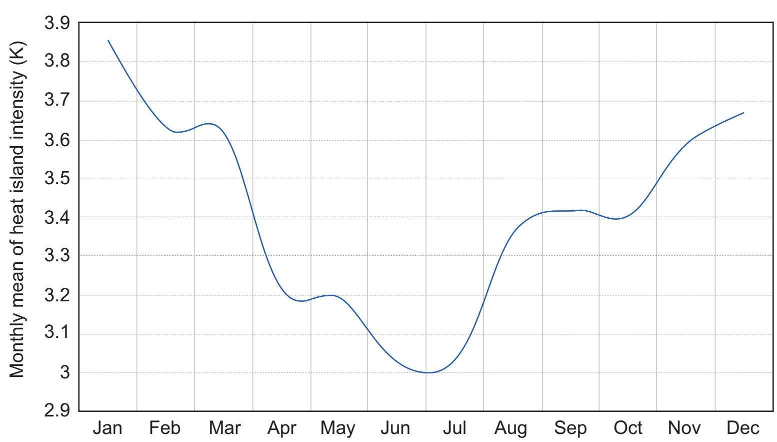

Fig. 7. Monthly long-term mean surface UHI of the Isfahan metropolis (2000-2018).

Table I. Long term mean LST at nighttime based on surface land cover type in the Isfahan metropolis.

Land cover type	Long term mean LST at nighttime
Built-up areas	10.7
Urban gardens	7.6
River margin areas	9.4
Farm areas outside the city (rural)	7.4
Farm areas inside the city	9.8
Urban clusters	8.5
Background areas	7.1

(non-urban) areas. The calculation of the UHI index based on the representative pixels of urban and non-urban areas shows a difference between 3.5 to 4° K. Therefore, it can be concluded that there is no significant difference between the results of the previously introduced methods and the representative pixel method, except that in the previous methods based on the average pixels of each area, the data of all pixels are always needed. However, in the representative pixel method based on the correlation matrix, the pixel that has the highest correlation coefficient with other pixels in urban areas is selected as the representative pixel of these areas. Also, the pixel that has the highest correlation coefficient with other suburban pixels is selected as the representative pixel of non-urban areas. Finally, only the data of two pixels in the urban and suburban areas are compared. Therefore, only the data of two pixels are needed to check the heat island index time series.

Based on the spatial distribution map of the average nighttime LST correlation coefficient in urban areas (Fig. 8), a pixel near the Kaveh passenger terminal represents the nighttime temperature of urban areas. The long distance to the Zayandehrood river, proximity to the interurban passenger terminal, a subway station, and the non-level intersection of the two main north-south and east-west highways of the city, as well as the dense texture of tall buildings, make this point one of the busiest places in Isfahan. Therefore, the placement of the representative pixel in this area of the city seems reasonable. About 99% of the average temperature variability of urban areas can only be explained by having the LST time series in this pixel, as shown in Table II, where n is the number of pixels and r is the correlation coefficient.

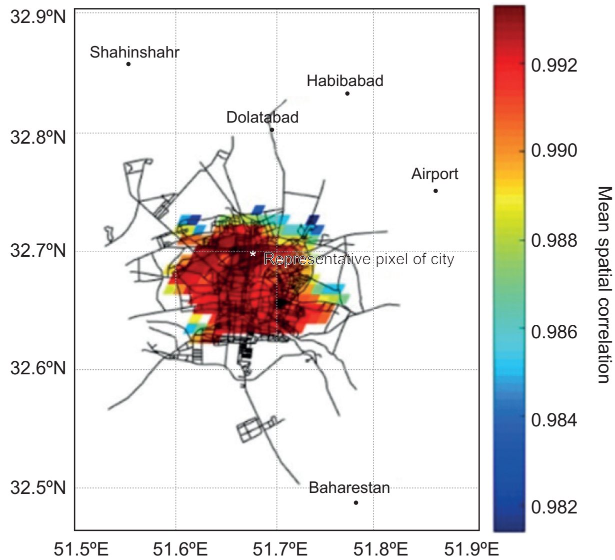

Fig. 8. Mean spatial correlation of LST during nighttime, based on Terra data in urban areas.

Table II. LST correlations of urban and non-urban representative pixels.

Parameters	Regression model	n	r
LST correlation of the urban representative pixel with the mean LST of urban areas.	y = 0.98x – 0.52	4216	0.9976
LST correlation of the non-urban representative pixel of with the mean LST of non-urban areas.	y = 0.96x + 0.32	4435	0.994
LST correlation of the non-urban representative pixel with the LST representative pixel of urban areas.	y = 0.96x + 3.8	4887	0.9881

The spatial distribution map of the average nighttime LST correlation coefficient in Figure 9 shows that a pixel in the northwest of Shahin Shahr represents the nighttime temperature of non-urban

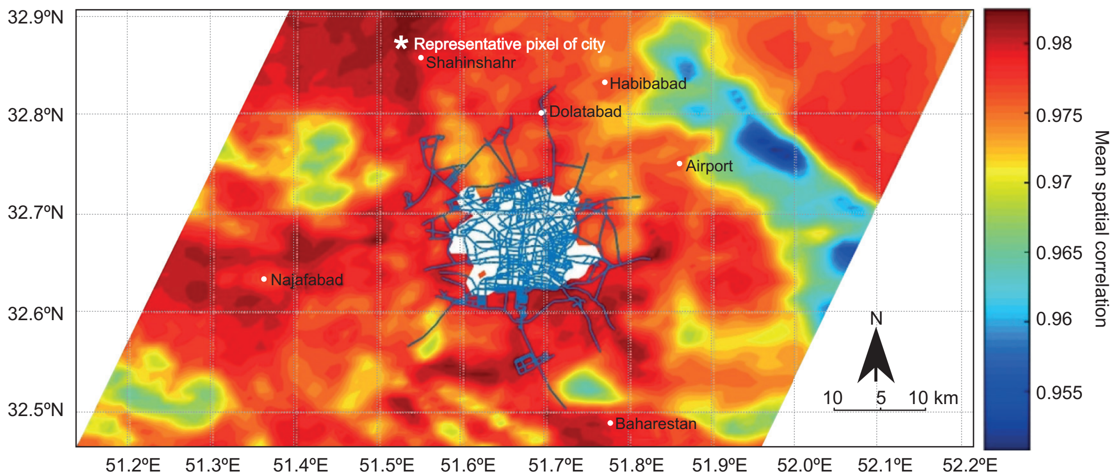

Fig. 9. Mean spatial correlation of LST during nighttime, based on Terra data in non-urban areas.

areas. This pixel is located on the dry lands outside the urban areas where vegetation cover is very sparse. These physical properties cause arid lands to easily absorb daytime heat and reflect it to the atmosphere in the nighttime as longwave radiation and to rapidly cool down the land. About 98% of the average temperature variability of non-urban areas can only be explained by having the LST time series at this point. Therefore, this point is a good representative of the climate of non-urban areas (Table II).

When there is a strong relationship between these two representatives of urban and non-urban areas, it is more likely to achieve a more reliable and consistent UHI index (Table II).

The advantage of the representative pixel method is that if the heat island index is calculated based on the average of pixels, the data of all pixels are always needed. If the representative pixel is selected, first, it represents an area and, second, only the data of one pixel is required to calculate the heat island index. If all pixels are required, it is very likely that cloud cover will prevent from recording the data for some pixels, hence the possibility of calculating the heat island is missed. As consistency is one of the characteristics of any climate index, it is not possible to calculate one day with a set of pixels and another day with another set of pixels. Thus, the use of all pixels results in decreased consistency of the index, while the representative pixel method ensures the index consistency. Besides, no data would be transmitted if the satellite mission ends. Therefore, if we only rely on the data of a single pixel to calculate the heat island, it is still possible to extract the data from this single pixel and continue monitoring the heat island.

5. Conclusion

The climatic background of the Isfahan metropolis has a warm and arid climate. The comparison of the urban area LST frequency distribution with that of the background area (suburbs) showed that the urban area is cooler during daytime and warmer at nighttime than the suburbs. This shows that an UHI is formed in Isfahan metropolis at nighttime. The UHI is defined based on the difference between air temperature of the weather station in the urban area and air temperature of the weather station in suburbs or rural areas adjacent to the urban area. There are difficulties in obtaining air temperature data for urban and suburban areas; therefore, satellite data of LST have been widely used recently to evaluate the UHI (assuming that the surface UHI is a measure of the atmospheric UHI). Several methods have been used to calculate the UHI intensity index, each of which has specific strengths and weaknesses. In this research, a new method was used to evaluate the UHI intensity in the Isfahan metropolis. This method is based on representative pixels. First, the studied area was divided into two parts, the built-up urban area and the background area. Then, based on the correlation of LST between pixels, the pixel with the highest correlation coefficient was selected as the representative pixel. Therefore, two representative pixels, one for the urban area and one for suburban region were obtained. Using the LST time series of these two pixels and based on the nighttime LST difference between urban and non-urban representative pixels, the Isfahan metropolis heat island intensity index was calculated. Investigations showed that at least 10 years of data are enough to achieve a stable UHI index, and the length of the statistical period is not a factor that can limit the validity of this index.

This study showed that nighttime UHI is almost the dominant characteristic of the Isfahan metropolis, and the LST of the built-up urban area at night is about 3.5º C warmer than the non-urban areas. The expansion of the core UHI in the central parts of Isfahan is in accordance with the ancient texture of the city. This can be attributed to the three-dimensional geometry of the city, which leads to the trapping of radiation in vertical urban walls and the reduction of wind due to the presence of buildings. In the studied period, the Isfahan metropolis UHI intensity index increased by about 1º C. On the other hand, the monthly surveys showed that this index weakens in the warm period of the year and intensifies in the cold period. In general, it can be said that despite the fact that there is no significant difference between the results of the previously introduced methods and the representative pixel method, in the previous methods (which are based on the average pixels of the urban and suburban areas) the data of all pixels must be accessed to update the UHI index. Meanwhile, in the representative pixel method, only the time series data of two representative pixels of the urban and suburban areas are necessary to update the UHI index. This is the most important advantage of the representative pixel method for calculating the UHI index compared to previous methods.

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