Theoretical and Applied Climatology (2022) 147:891–907
https://doi.org/10.1007/s00704-021-03872-x

ORIGINAL PAPER

Changes in urbanization and urban heat island effect in Dhaka city

A. S. M. Shanawaz Uddin[1] · Najeebullah Khan[2] · Abu Reza Md. Towfiqul Islam[3] · Mohammad Kamruzzaman[4] · Shamsuddin Shahid[5]

Received: 20 April 2021 / Accepted: 15 November 2021 / Published online: 24 November 2021

Abstract
The study aimed to assess the changes in urban areas and UHI effects in Dhaka city, Bangladesh, from 2001 to 2017, using Moderate Resolution Imaging Spectroradiometer (MODIS) daily day- and nighttime land surface temperature (LST) data from 2001 to 2017. The expansion of the city was calculated using the city clustering algorithm (CCA). The temperature of the identified urbanized area was analyzed and compared with the adjacent regions. The changes in urban temperature were estimated using non-parametric statistical methods. The results showed that Dhaka city's land surface area has grown by 25.33% and its inhabitants by 76.65% during 2001–2017. Urban expansion and dense settlements caused an increase in average temperature in some areas of Dhaka city nearly 3 °C compared to that at its boundary. The day and night temperature differences at Dhaka city's warmest location and the coolest point outside the city were nearly 7 °C and 5 °C, respectively. The city's annual average day- and nighttime temperatures was increasing at a rate of 0.03 °C and 0.023 °C/year over the period of the last 17 years. The rising temperature would increase the UHI effect in the future, which, combined with high humidity, may cause a significant increase in public health risk in the city if mitigation practices are not followed.

1 Introduction

The rapid urban population growth due to the high influx of migrated population towards the cities caused a rapid unplanned urban expansion in the developing countries (Sidiqui et al. 2016; Elsayed 2007, 2012; Hossain 2006). The unplanned development of cities caused a noticeable higher temperature in urban regions than its surroundings or urban heat island (UHI) (Yang et al. 2015). The rising temperature due to global warming has further aggravated the effect of UHI (Khan et al. 2019a; Peng et al. 2011). Extensive removal of natural surfaces and higher heat retention materials used for urban development reduces heat evaporative and transformative rates; modifies the local climate, airflow, and atmosphere; and, thus, causes UHI (Karakuş 2019; Kaya et al. 2012). The UHI causes significant warming of urban atmospheric and surface temperatures and affects different urban sectors (Voogt and Oke 2003; Kovats and Akhtar 2008).

UHI causes an increased daytime temperature and reduced nighttime cooling leading to the elevation of many different diseases such as physical distress, breathing problem, tiredness, heatstroke, and heat-related death (Tan et al. 2010). The older populations, those suffering from various health problems, outdoor workers, and floating populations are at higher risks of these problems (Hsu et al. 2021; Tan et al. 2010). Besides, UHIs cause a high electricity consumption by increasing the demand for indoor cooling demand, which causes a feedback effect resulting in an increased land surface temperature (LST) in urban regions (Santamouris et al. 2015). In this context, UHI creation might be influenced by the sizes of urban areas. However, the characteristics of such a connection are not well understood.

✉ A. S. M. Shanawaz Uddin
asm.shanawaz@gmail.com

Shamsuddin Shahid
sshahid@utm.my

1 Department of Civil Engineering, Ahsanullah University of Science and Technology (AUST), 141 & 142, Love Road, Dhaka 1208, Bangladesh

2 Faculty of Engineering Science and Technology, Lasbela University of Agriculture Water and Marine Sciences (LUAWMS), Uthal, Balochistan 90150, Pakistan

3 Department of Disaster Management, Begum Rokeya University, Rangpur 5400, Bangladesh

4 Bangladesh Rice Research Institute, Gazipur 1701, Bangladesh

5 School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Bahru, Johor, Malaysia

Dhaka, the capital of Bangladesh, is the fastest developing area of the country. It is the 6th densely inhabited city on the globe. The city's population has grown drastically from 2.2 to 70 million during 1975-2015 (Hossain 2006). This massive rise in population resulted in removing the natural land cover over a vast area for urban expansion. The increased build-up areas and the reduction of natural land cover significantly increased the city's temperature (Dewan and Corner 2014). Several studies showed a positive correlation between the city's LST and impervious areas (Zhou et al. 2014; Kevern et al. 2012; Karakuş 2019). The heat variation can lead to disruptions in the health parameters of citizens in different regions of the city. These effects are also evident in Dhaka especially increased infectious diseases (Patz and Olson 2006; Shahid 2010), dengue fever (Hashizume et al. 2012), and typhoid fever (Dewan et al. 2013). Hence, a comprehensive study on UHI changes in Dhaka city with various climate and urban conditions is important for researchers and decision-makers.

Several studies have been conducted to evaluate the expansion of urbanization and UHI's effect in different cities of the world (Mensah et al. 2018; Shirani-Bidabadi et al. 2019; Bala et al. 2021; Holec et al. 2020; Ünal et al. 2020; Buo et al. 2020; Arshad et al. 2021). For example, Mensah et al. (2018) investigated urbanization impact on the temperature in Kumasi city, Ghana. They found 1.2°C increase in the average surface temperature of the city due to urbanization. Buo et al. (2020) estimated the expansion of urban areas and UHIs in Accra and Kumasi cities, Ghana, and showed their relationship. Arshad et al. (2021) evaluated the impacts of rapid urbanization on UHIs in Abha and Khamis cities of Saudi Arabia. However, the temperature increase due to rapid urbanization is not well documented in tropical cities. This is particularly true for the capital city, Dhaka, Bangladesh.

Despite large significance, studies related to UHI of Dhaka city is very limited. Raja and Neema (2013) analyzed LST and land cover (LC) of Dhaka city, estimated from Landsat TM/ETM+ data, for 1989–2010 and showed the city's LST related to LC changes. Trotter et al. (2017) estimated the effect of urbanization on LST of Dhaka using Landsat 5 TM data of only 3 years 1990, 2000, and 2011. They reported transformation of vegetation to the built-up area could increase the LST of Dhaka city by 2°C.

Monitoring of UHI can provide useful insights into urban thermal environmental changes due to urban growth. It is highly important for the implementation of UHI mitigation practices and ensures sustainable urban growth. Monitoring the urban thermal environment is traditionally based on air temperature collection at multiple locations in urban and its surroundings (Fortuniak et al. 2006). Traditionally, meteorological station records and mobile thermometers (Wong and Yu 2005) are used to monitor UHI. These data are insufficient to monitor the dynamic of urban LST with urban expansion due to their availability at limited locations especially in the developing countries (Yow 2007).

The advancement of thermal remote sensing offers a viable alternative to the shortcomings in traditional urban heat island monitoring (Pongrácz et al. 2010; Weng 2009). These techniques allow monitoring the distribution of urban thermal conditions and their intermittent and complex shifts quantitatively and effectively (Grimmond 2007). Therefore, remotely sensed data could be an alternative source for better studying UHI dynamics. Though LST provides an estimation of the surface UHI effect, it is widely used as a UHI proxy due to the strong relationships between near-surface air temperature and LST (Weng 2009; Zhou and Wang 2011).

Various satellite-based sensors, such as HCMM, Landsat TM/ETM+, AVHRR, MODIS, ASTER, and TIMS, have been developed to retrieve LST and emissivity for estimating UHI (Wong and Chen 2008; Sheng et al. 2017; Shirani-Bidabadi et al. 2019). Hossain (2006) proposed completely diverse methodologies to evaluate surface temperature from TERRA-MODIS (Moderate Resolution Imaging Spectroradiometer) images for analyzing UHI in eight megacities in Asia. He used MODIS maximum and minimum temperature separately for 2001–2003 for this purpose. Moreover, MODIS LST data have been used for studying UHI of 84 major cities of India (Shastri et al. 2017), urban temperature changes in 419 large global cities (Peng et al. 2011), and analyzing global temperature configuration (Clinton and Gong 2013). Unlike other datasets, the main advantage of MODIS data is its versatile usage, easy retrieve ability, estimation accuracy, and availability for a relatively long period (Benali et al. 2012). Therefore, the MODIS LST data has been utilized in this study.

The present research assessed the expansion of Dhaka and its effect on LST and UHI for the period 2001–2017 using MODIS day- and nighttime LST. Most of Dhaka city's population is under extreme health risk due to rising temperature and related changes in urban ecology, air quality, and other environmental changes. Assessment of UHI spatiotemporal changes in Dhaka city can provide a better insight of unsustainable urban development on the thermal environment and identify the measures to reduce its impacts.

2 Study area and data

2.1 Study area

Dhaka is situated in the centre of Bangladesh, as shown in Fig. 1. The city has flat, low-lying land with an elevation of 4 m (Azad and Kitada 1998; Alamgir et al. 2020). The city experiences a humid tropical climate with a mean temperature of 26.1°C (Trotter et al. 2017). Three broad

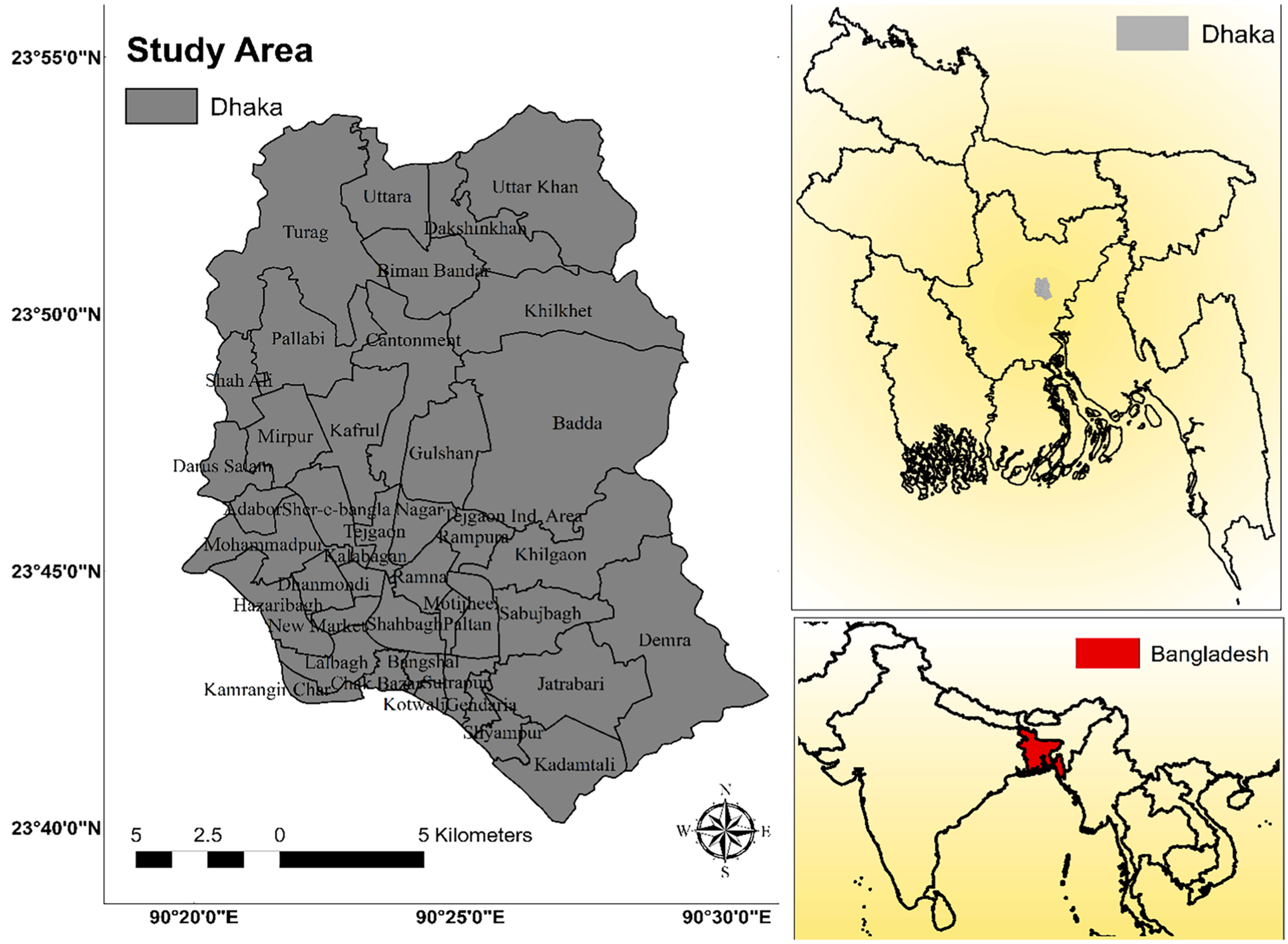


Figure 1 Location map of Dhaka city with corresponding latitude and longitude

seasons, a cool and dry winter (Nov–Feb), hot and dry summer (Mar–May), and a rainy monsoon (Jun–Oct), are experienced in the city (Tareq et al. 2013; Dewan and Corner 2014).

2.2 Data and sources

The daily LST (MOD11A1) was used for the estimation of UHI. MODIS-Aqua global daily LST data are available from February 2000, while the MODIS-aqua dataset is available since July 2002 (Klein et al. 2017; Khan et al. 2019b). MODIS terra was used in this study, considering the availability of data for a longer period. MODIS LST data has been extensively used in different climatic studies worldwide (Banerjee and Kumar 2018; Wong et al. 2012; Vancutsem et al. 2010; Duan et al. 2018; Kitsara et al. 2018; Aguilar-Lome et al. 2019). Studies reported MODIS LST as an identical product for temperature assessment (Cai et al. 2014; Justice et al. 2002; Friedl et al. 2002; Friedl et al. 2010; Wessels et al. 2004; Viña et al. 2008).

The yearly LC (MCD12Q1), estimated using MODIS surface reflectance data (Vermote et al. 2011; Sulla-Menashe and Friedl 2018), was used to estimate the city area. Unlike MODIS LST data, MODIS LC (MCD12Q1) data originates from MODIS Terra and Aqua images (Friedl et al. 2010). International Geosphere-Biosphere Product classifies 17 LC, which is used to classify MODIS LC data (Belward 1999). MODIS LC data has been used to produce global land use maps and assess global land use changes.

The MODIS estimates have uncertainty. Therefore, the reliability of the LST and LC data was evaluated using the quality control (QC) flag available in MODIS data. The average LST error in MODIS data is less than 1°C (Wan et al. 2004). The QC flag indicates any additional error in each pixel (Wan 2007). The LST data with an error within the range of ±2°C was only used in this study (Aguilar-Lome et al. 2019). The "Urban and Built-up Lands" pixels of LC data (MCD12Q1) (Peng et al. 2011) was used to identify the urban area. Population data of Dhaka city were collected from the statistical yearbook of Bangladesh (BBS 2018).

The population data were used to assess the changes in urban population density.

3 Methodology

The proposed study was conducted using the following steps

1. MODIS LST (MOD11A1) data having sufficient quality (LST error of less than 2°C) were extracted.
2. The "Urban and Built-up Lands" pixels of MODIS LC data (MCD12Q1) were extracted after assessing related information provided in the QC layer.
3. The city clustering algorithm (CCA) was used to identify Dhaka city's extent for different years from 2001 to 2017.
4. Urban temperature over the identified urban area was analyzed for different years from 2001 to 2017.
5. The effect of LST due to urban growth was analyzed based on both the day- and nighttime LST.
6. Statistical analysis was conducted to evaluate the significance of changes in urban temperature compared to surrounding non-urban temperature.

3.1 City clustering algorithm

The CCA, proposed by Peng et al. (2011), was utilized to identify the extent of Dhaka city, thus analyzing the growth of Dhaka city. The urban pixels, with a cell size of 1 km × 1 km, were queued as a baseline, the neighbourhood pixels obtained from the MODIS LC data set were added, and the pixels' queue was examined, whether urban or vegetated. If the queue is empty, return to the urban map and keep repeating adding pixels to verify urban pixels. Finally, the city C_i (t) of a cluster, i at time t is the sum of the cluster $n^j(t)$ and each cell j within it,

$$C_i(t) = \sum_{j=1}^{N_i} n^j(t) \tag{1}$$

3.2 Sen's slope estimator

Sen's slope method is used to identify the temperature change in our study area (Sen 1968). The slope, M, between two successive temperatures is,

$$M = \frac{A\left(t'\right) - A(t)}{t' - t} \tag{2}$$

Here, A (t') and $A(t)$ represent the temperature at time t' and t. The median of all M values is Sen's slope.

3.3 Mann-Kendall Test

Mann-Kendall (MK) test was used to estimate temperature change's significance (Mann 1945; Kendall 1948). For this purpose, each data is compared with successive data. If the latest temperature is greater than the earlier one, the MK test's statistical value (T) is increased by 1 and vice versa. The net temperature change is calculated as T,

$$T = \sum_{1}^{n-1} \left(\sum_{j=2}^{n} (sinxj - 1)\right) \tag{3}$$

where, n represents the number data, x is temperature at time of j, sin(xj-1)=1 when (xj-1)>0 and sin(xj-1)=0 when xj=1

The T is utilized to get the significance level Z,

$$Z = \frac{T - 1}{\sqrt{\sigma(T)}} \tag{4}$$

where σ (T) is the variance of temperature (T). In this study, the MK test was used to evaluate temperature trends at a 0.05 significance level (|Z|>1.96).

4 Results

4.1 Dynamic of city expansion

Figure 2 shows the changes in the area of Dhaka city over the period 2001 to 2017. The size of the city increased from 1128.5 km^2 in 2001 to 1458.6 km^2 in 2017, with a rate of 20.6 km^2/year. The highest expansion was between 2007 and 2008 when urban areas increased by nearly 6.1%. The annual change in the city is shown in Table 1. The table shows the total increase in city area by 25.33% during 2001–2017, while the population increase was 76.65% during the same period.

Figure 3 shows Dhaka city's spatial extend for the years 2001, 2005, 2010, and 2017. The figure shows that the city has expanded more on the northern side than the other side. There was a noticeable growth from 2005 to 2010 at around 24° North and 23°35′ South. This has been reflected in Figure 2 and Table 1, where a large increase in the urban area (6.1%) is reported during 2007–2008.

The increase in population faster than the expansion of urban areas caused an increase in the city's population density. The city's population density increased from 9481.6 people/km^2 to 12950.8 people/km^2, or the increase in population density was 76.59% during 2001-2017. It indicates a large increase in dense urban structures in Dhaka city over the study period. The large increase in urban structures increased heat retention and increased temperature in Dhaka city. The favorable investment

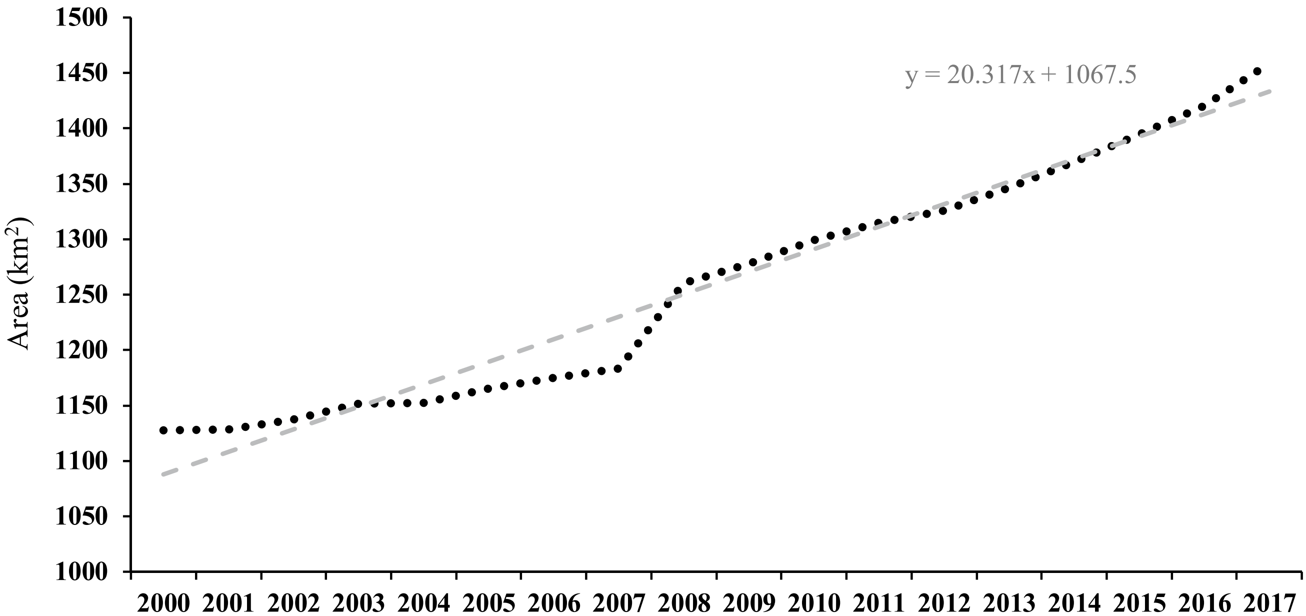


Figure 2 Time series of city area shows the expansion of Dhaka city during 2001 to 2017

Table 1 Area of Dhaka city estimated using a city clustering algorithm, the population, and changes in the urban area in each year during 2001 to 2017

Year	City area	City area change (%)	Population (million)	Change in population (%)	Population density
2001	1128.50	-	10.70	-	9481.6
2002	1137.65	0.81	11.08	3.62	9739.4
2003	1151.38	1.19	11.48	3.62	9970.6
2004	1152.29	0.08	11.90	3.63	10327.3
2005	1165.11	1.10	12.33	3.61	10582.7
2006	1175.18	0.86	12.78	3.62	10874.9
2007	1183.41	0.70	13.24	3.62	11188.0
2008	1260.18	6.09	13.72	3.63	10887.3
2009	1277.57	1.36	14.22	3.62	11130.5
2010	1299.53	1.69	14.73	3.62	11334.9
2011	1315.08	1.18	15.26	3.62	11603.9
2012	1326.06	0.83	15.82	3.62	11930.1
2013	1346.19	1.50	16.39	3.62	12175.1
2014	1369.98	1.74	16.98	3.62	12394.3
2015	1394.68	1.77	17.60	3.62	12619.4
2016	1420.30	1.80	18.23	3.62	12835.3
2017	1458.60	2.63	18.89	3.62	12950.8
Total		**25.33**		**76.65**	

condition after political turmoil in 2006 caused a building boom of residential apartments in 2007–2008 in the periphery of Dhaka city (CRDP 2014; Alam 2018). This caused a large increase in the land area of Dhaka city during 2007–2008, as reflected in Figure 2.

4.2 Estimation of urban heat in Dhaka city

The day- and nighttime LST, averaged for Dhaka for 2001, 2005, 2010, and 2017, are shown in Figures 4 and 5, respectively. Each section of the figure represents Dhaka and

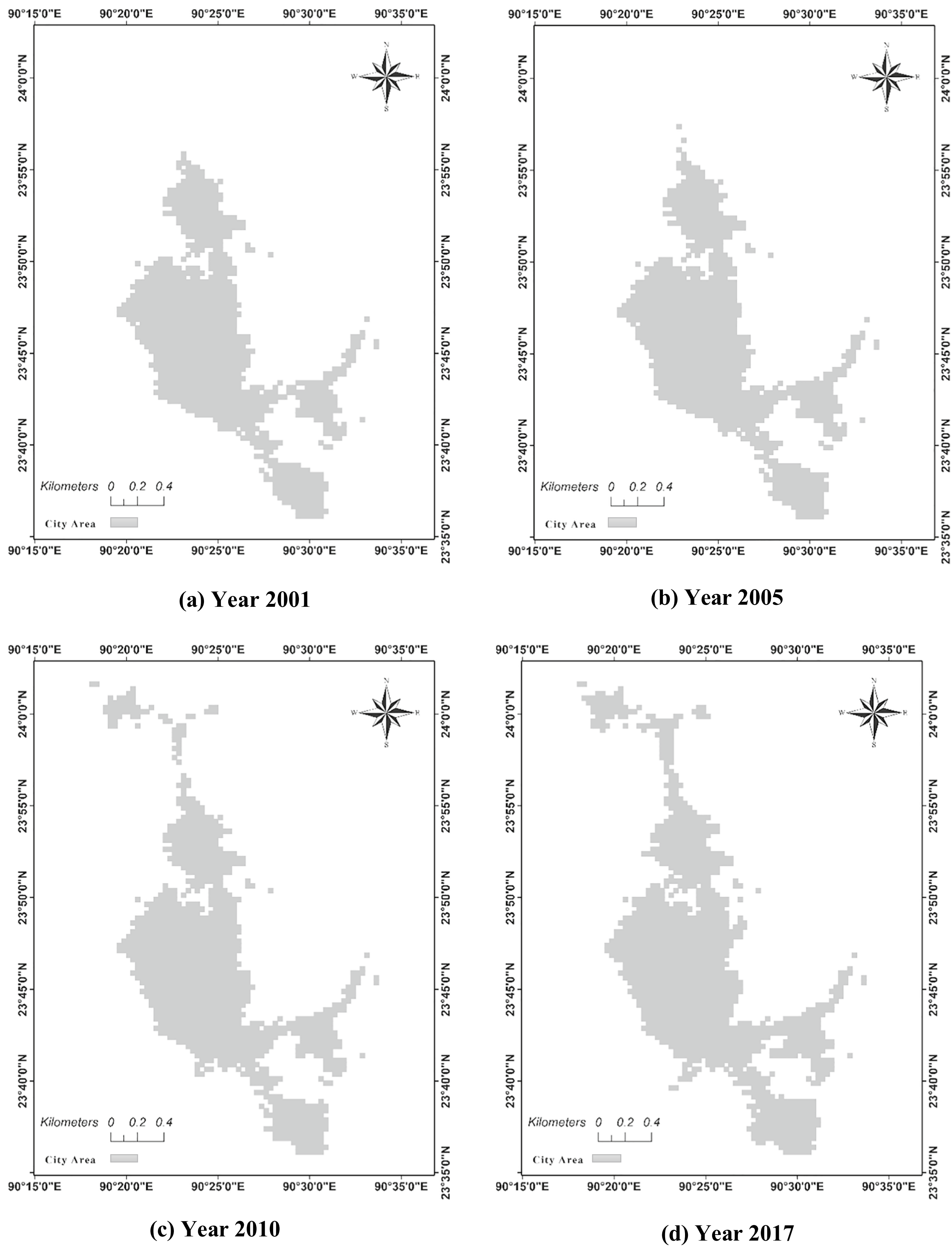


Fig. 3 The spatial extend of Dhaka city in the year (a) 2001, (b) 2005, (c) 2010, and (d) 2017, estimated using city clustering algorithm.

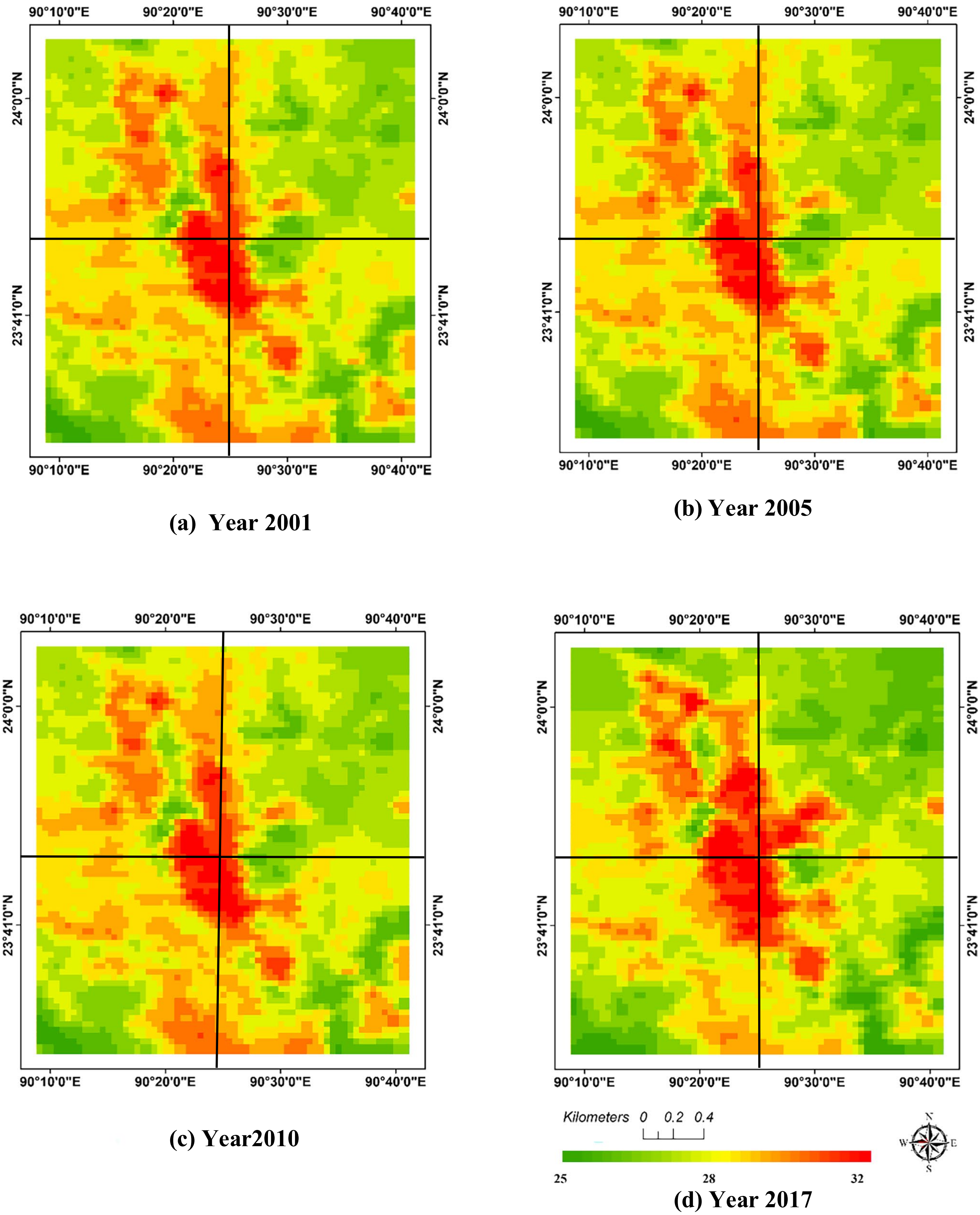
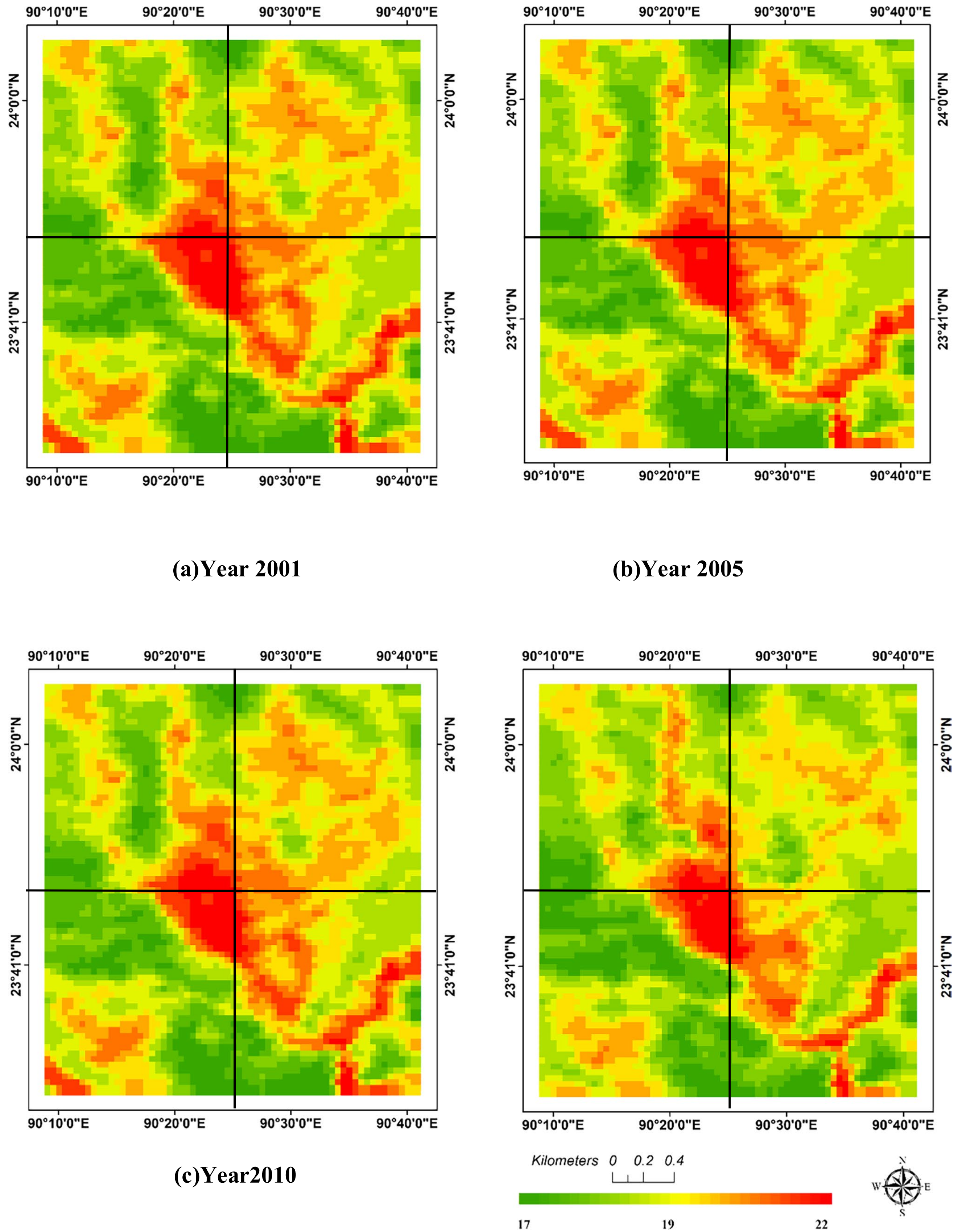


Fig. 4 Spatial distribution of daytime land surface temperature of Dhaka city and surrounding area for years (a) 2001, (b) 2005, (c) 2010, and (d) 2017



(a)Year 2001

(b)Year 2005

(c)Year2010

(d)Year2017

◂**Fig. 5** Spatial distribution of nighttime land surface temperature of Dhaka city and surrounding area for years (a) 2001, (b) 2005, (c) 2010, and (d) 2017

surrounding rural and suburban areas. The colour bar represents the temperature of Dhaka city, ranging from nearly 25°C to more than 32°C (daytime LST) and at a range of nearly 17°C to more than 22°C (nighttime LST). The highest temperature is indicated using red colour, while moderate and relatively lower temperatures are presented using yellow and green. A heat island can be seen over the city's densely populated region, with the temperature reaching more than 32°C compared to 25°C in the adjacent non-urban area. This indicates the temperature in some Dhaka city areas is more than 7°C compared to its surrounding non-urban areas. The increase in UHI was more in Dhaka city's northern and eastern regions, which have experienced rapid development in recent years (Figure 3).

The nighttime temperature showed a lower difference in temperature (5°C) between Dhaka city and the nearby region, as presented in Figure 5. The temperature ramp shows a temperature variation between 17 and 22°C. The highest nighttime temperature was observed in the more developed urban parts of Dhaka city and in the areas comprising water bodies due to the water bodies' higher convective nature (Khan et al. 2019b). The heat-absorbent materials in urban areas absorb a vast amount of heat during the daytime and release this absorbed heat during nighttime (Xiong et al. 2012). This causes a higher nighttime temperature in the urban area as compared to its nearby non-urban surroundings.

The variation of daytime LST over the latitudinal and longitudinal intersection line from Fig. 4 over Dhaka city is shown in Figures 6 and 7. The graph shows the difference in temperature at different points along the line than the mean temperature of the line. This can indicate how the temperature in the city is different from that at its boundary. The latitudinal and longitudinal variation of daytime LST shows changes in temperature from the adjacent undeveloped and rural regions compared to the city's built-up areas. Furthermore, the higher temperature was between latitude 90°20′00″ to 90°25′00″ and longitude 23°49′00″ to 23°42′00″, which coincides with the defined city region using CCA. The temperature reaches its maximum extent when it crosses through the central region of the city.

The temperature variation at latitudinal and longitudinal intersection showed 2.5°C more temperature in the city than that at its boundary in 2001. The difference in temperature between the city centre and city boundary was 3°C in 2017. The temperature difference between vegetated areas outside the city and the city's most heated area was nearly 3.5 (°C in 2001) while nearly 5°C in 2017. Nighttime temperature is less than the daytime temperature in the non-urban area than that observed at the city boundary. An opposite scenario was noticed in the city area, where the nighttime temperature was higher than the daytime temperature than that observed at the city boundary. This clearly indicates the effect of urbanization on temperature or the urban heat island effect.

4.3 Annual and seasonal changes in UHI temperature

The annual changes in temperature difference between Dhaka city and its surrounding during day and night are shown in Figure 8(a). The temperature difference was used to omit the impact of temperature rise due to global warming. Therefore, it indicates the UHI temperature of Dhaka city. The temperature differences at all the points over Dhaka city were averaged to estimate the annual UHI temperature series. Assessment of trends using Sen's slope and MK test revealed an increase in Dhaka city's day and night UHI temperature significantly. The increase was 0.03° and 0.023°C/year during daytime and nighttime, respectively. The MK test revealed that both the changes were significant at 0.01.

The changes in the day- and nighttime UHI temperatures during summer and winter for the period 2001–2017 are shown in Figure 8(b) and (c), respectively. The UHI temperature during these two seasons was also increasing. The day- and nighttime summer temperatures were noticed to increase by 0.012 and 0.04°C/year, respectively. The increase in winter day- and nighttime temperatures was 0.047 and 0.01°C/year, respectively. All the changes were found significant at 0.01. The highest increase was observed in winter daytime UHI temperature, followed by summer nighttime UHI temperature.

4.4 Correlation between urbanization and UHI temperatures

Dhaka city's urban area and population density were correlated with the city's annual and seasonal UHI temperature. Non-parametric Spearman rank correlation was used considering a small sample size (n=18). Obtained results are presented in Table 2. The bold number in the tables indicates a significant correlation at 0.01. The results show a significant association of urban area and population density with annual average UHI day- and nighttime temperatures. Significant association with winter day- and nighttime UHI temperatures was also noticed. However, the correlations of the urban area and population density with summer UHI day- and nighttime temperatures were not significant.

The UHI intensity is significantly related to cloud cover. Generally, the sky over Dhaka city is cloud-free during winter, allowing daytime receipt of higher solar radiation. The higher thermal retention property of urban materials causes a longer cooling period of urban land surface than

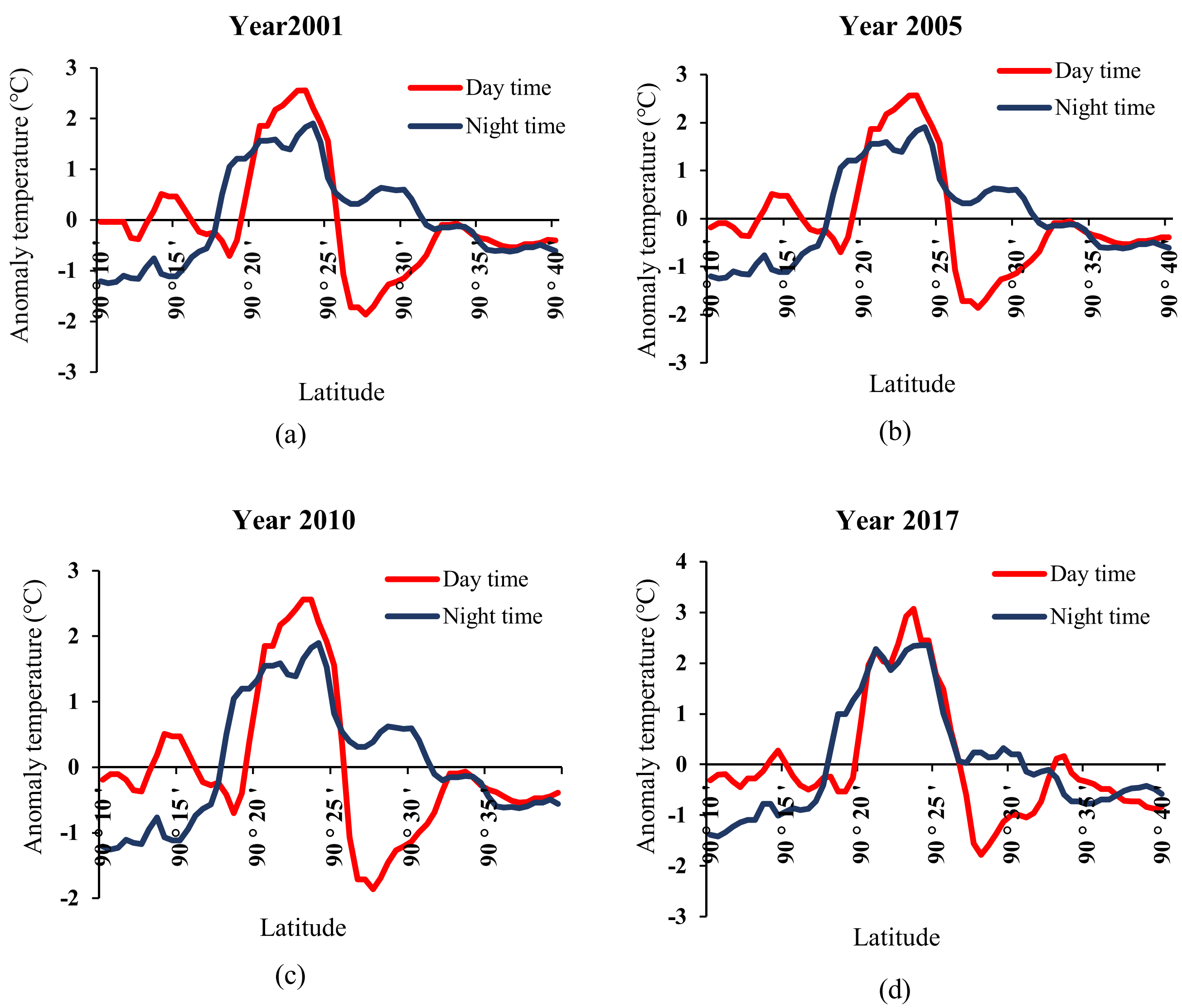


Fig. 6 Changes in the day- and nighttime temperatures along the latitudinal line shown in Figures 4 and 5, respectively, for the years (a) 2001, (b) 2005, (c) 2010, and (d) 2017

the vegetated non-urban areas. Therefore, a higher difference between urban and non-urban LST is also noticed during winter nights (Grimmond, 2007). It means the UHI effect is more noticeable in wintertime compared to summertime. Therefore, a higher and significant correlation between urbanization and winter UHI was noticed for Dhaka city.

4.5 Difference between land and air temperature

The in situ temperature record at a meteorological station of Dhaka (latitude: 90.38334 and longitude: 23.76668) was compared with the MODIS LST data averaged for few grid points in the vicinity of the in situ location. The air temperature depends not only on LST but also on several other meteorological factors, including wind speed, wind direction, and anthropogenic emission. Therefore, it is certainly different from LST. However, comparing air and land temperature for different months can show how UHI affects Dhaka city's air temperature in different seasons. Figure 9 shows the seasonal variability of daily maximum (daytime) and minimum (nighttime) air and land temperature at the meteorological station of Dhaka. The results showed that the daytime air and land temperatures are the same in winter, while the summer daytime maximum air temperature is more than land temperature. In contrast, the winter nighttime air temperature is much lower than land temperature, and it is a bit higher than the land temperature during summer.

The air cools quickly on winter nights while the paved surfaces retain the heat for a longer time. Therefore, winter nighttime air temperature is much less than LST. In

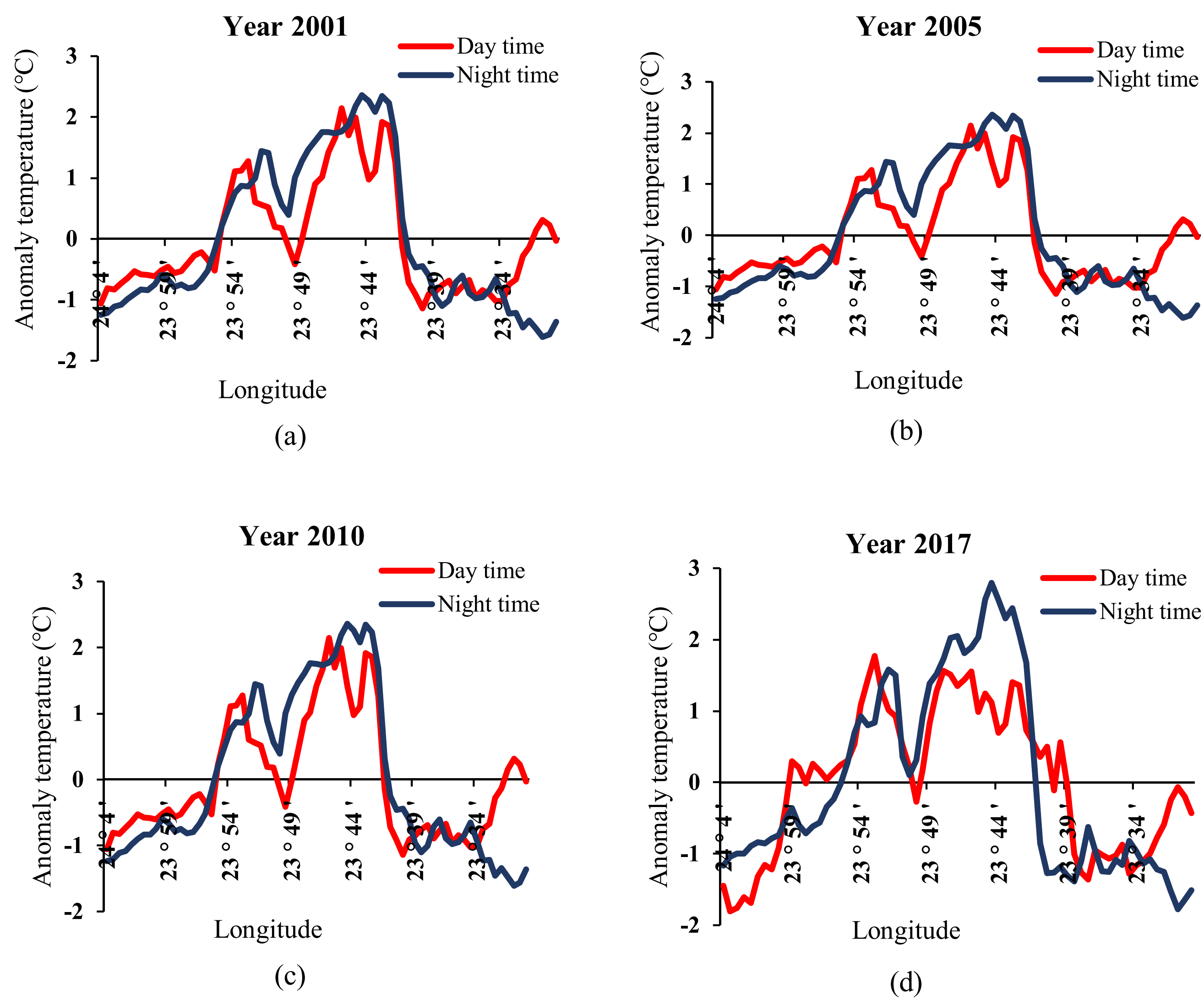


Fig. 7 Changes in the day- and nighttime temperature along the longitudinal line shown in Figures 4 and 5, respectively, for the years (a) 2001, (b) 2005, (c) 2010, and (d) 2017

summer, the air does not cool like in the winter. Besides, the heat released from the air-conditioned building makes the nighttime air temperature a bit higher than LST (de Munck et al. 2013). The air and land heat up at the same rate in the daytime. Therefore, the daytime maximum air and land temperatures are usually the same. However, the heat release from air-conditioned buildings makes the summer daytime air temperature higher than the LST. Higher use of air conditions in daytime compared to nighttime during the summer makes the summer air temperature higher in daytime compared to nighttime. Besides, transportation in the daytime causes a higher air temperature than LST (Haddad and Aouachria 2015). The present study revealed that Dhaka city's daytime maximum air temperature is 0.83 to 1.3 °C higher than the LST in summer, while the nighttime air temperature is 1.91 to 2.49 °C lower than the LST in winter.

5 Discussion

The study revealed an average 3°C higher temperature in Dhaka city compared to its surrounding. A significant and direct association of the area and the population density of Dhaka city with the temperature difference between the city and its surroundings indicate the rise in city temperature was due to the increasing urbanization. The annual UHI day- and nighttime temperatures were increasing by 0.03 and 0.023 °C/year at 0.01 significant level. A higher rate of increase was in winter nighttime temperature (0.047°C/year) than the other seasons. Urbanization generally affects minimum temperature more significantly compared to maximum temperature. The large increasing rate of winter nighttime temperature again indicates the UHI effect in Dhaka city. Bangladesh's day- and nighttime

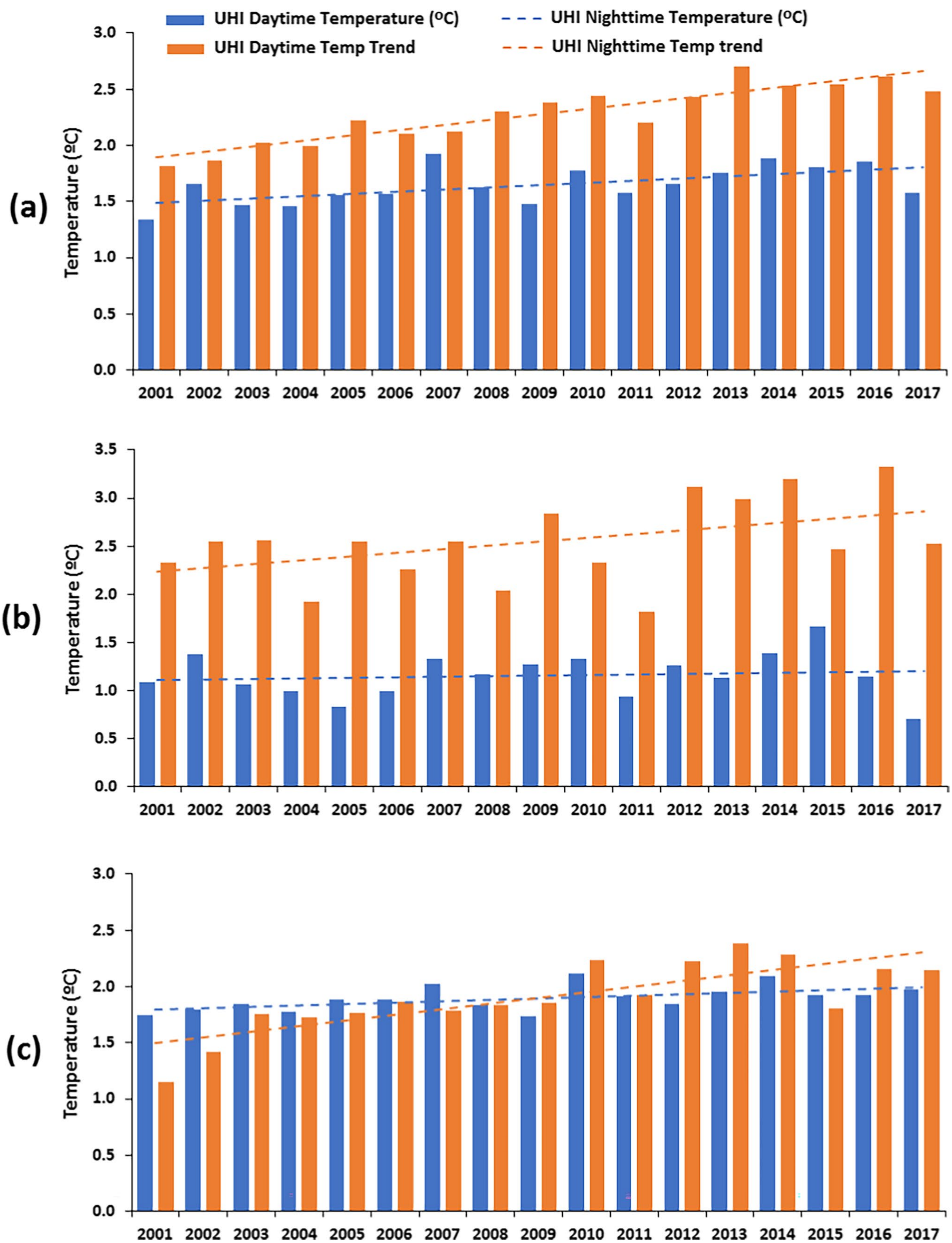


Fig. 8 Trends in the areal average of (a) annual (b) summer, and (c) winter day- and nighttime urban heat island temperatures of Dhaka city over the period 2001–2017

Table 2 Spearman rank correlation of urban area and population density with annual and seasonal urban heat island temperature of Dhaka city

	Annual night	Annual day	Summer night	Summer day	Winter night	Winter day
Urban area	**0.623**	**0.917**	0.147	0.350	**0.642**	**0.797**
Population density	**0.674**	**0.900**	0.157	0.365	**0.701**	**0.784**

The bold number indicates a significant correlation at 0.05

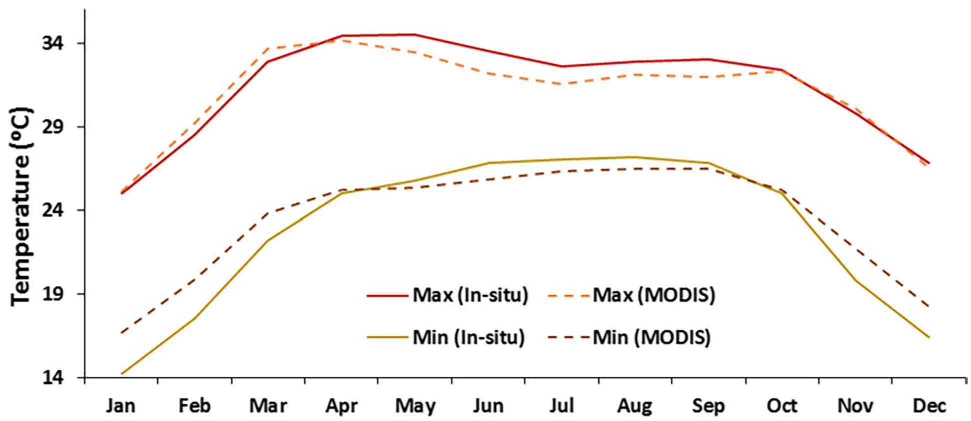


Fig. 9 Maximum and minimum MODIS land and in situ air temperature at Dhaka city at different months of a year

temperatures are rising by 0.0091 and 0.0097°C annually (Shahid 2010). The present study revealed that Dhaka city's day and night temperatures are rising at a much faster rate (0.03° and 0.023 °C/year) than global warming–induced increase temperature.

The MODIS LST data has significant bias. It was not possible to quantify the bias in MODIS LST for Dhaka city due to the unavailability of any in situ LST data. To ensure reliability, the MODIS LST data with an error range of ±2°C was employed in this study for analysis of UHI of Dhaka city. The positive and negative bias in MODIS LST is not consistent over time. Therefore, averaging MODIS LST over a year or a season cancels out most of the positive and negative biases and significantly reduces the average bias in LST. Tan et al. (2021) showed that the bias in MODIS daytime LST ranges between −2.91 and 4.50 °C. But it reduces to 1.32 °C when averaged for a year. In this study, LST data only within the error range of ±2 °C were used; therefore, it can be expected that the bias average LST values presented in this study are very less. Besides, the intensity of UHI (an average 3 °C higher temperature in Dhaka city) is sufficiently higher compared to the error range of LST data used in this study. Therefore, the major interpretation of the results presented in this study would not change if LST bias is considered.

Due to the UHI effect, the rise in urban temperature would be further aggravated by the temperature rise due to global climate change. A large increase in temperature may significantly affect different sectors, particularly the public health, water, and energy sectors. About 40% of Dhaka city's population lives in slums with extremely limited access to different urban services. Therefore, rises in UHI temperature can severely affect a vast urban inhabitant.

UHI can have the most significant implications in the community health of this densely populated city. Higher smog and pollution occurrences have been reported with the rises in atmospheric temperature (Shahid 2010). Besides, it has been evident that higher temperature increases the infectious diseases' conductivity and vector-borne diseases transmissivity in Dhaka city MoEF (2009). Shourav et al. (2018) estimated an increase in daily electricity consumption in the city by 6.5 to 12.0 million kWh for a unit rise in average temperature. Istiaque and Khan (2018) reported 75% power consumption of the city is temperature dependent. The UHI is a major cause rising electricity demand of the city. A large amount of electricity is used for cooling purposes. The large increase in the air-conditioned building also contributed to UHI. Besides, a higher temperature can affect the power transmission system and make the city's fragile power distribution system more vulnerable (Shahid 2012). Increased water demand and water scarcity during summer is a long-lasting problem for Dhaka city. Rises in temperature during summer are the major cause of higher water demand. Adhikary et al. found significant relation of water demand in the city with ambient temperature. Increasing water demand driven by the UHI effect has accelerated the summer water stress in the city.

Plenty of research has been conducted over the past few decades to reduce urban heat and give city dwellers a better life. Adaptation measures had been applied in various cities and obtained discernible results. Hence, some adaptation measures are applicable at the early stage of city planning, and others can be after city planning. The green and cool roof design in Italy revealed a significant reduction in temperature by 2-5 °C (Costanzo et al. 2016). The green roofs are the most efficient measures for lessening the UHI if enormous regions are covered. However, each green roof encompassing a small region might reduce local temperature and decrease indoor air temperature and energy demand of the specific place (Costanzo et al. 2016). According to Guan et al. (2011), novel innovative material reduces the urban temperature by 5.5 °C. The city planning with plenty of water bodies reduced the urban temperature by 0.7 °C in Hong Kong (Fung and Jim 2020) and at 3 °C in Japan (Syafii et al. 2017). However, such measures are often not realistic for a densely populated city like Dhaka. Most academics agree with urban green spaces and vegetation cover as a useful adaptive measure to reduce the UHI effect. A 1–6 °C temperature reduction using greening urban spaces compared to other adaptation measures has been noticed in the UK (Armson et al. 2012), China (Sun and Chen 2017), Germany (Sodoudi et al. 2018), Ethiopia (Feyisa et al. 2014), Egypt (Aboelata and Sodoudi 2020), and Copenhagen (Yang et al. 2020). Although several mitigation measures are well established, all are not applicable for Dhaka due to economic and city pattern constraints. The delineation of adaptation measures for a large and diverse city like Dhaka is challenging due to different anthropogenic heat sources and large variability of building height. However, a combination of green and cool roofs and plantation within a limited distance could be an effective solution (Doick et al. 2014; Qiu and Jia 2020; Skoulika et al. 2014). Finally, policymakers could play a pivotal role in establishing environment-friendly policies for the future build-up areas and preserving existing green areas and water bodies in Dhaka.

6 Conclusion

Urban area expansion and LST patterns have been accessed in this study. This is the first study for the assessment of spatial and temporal variability of UHI of Dhaka city. The study revealed that Dhaka city has expanded by 25.33% during 2001–2017. The population of the city has increased by 76.65% during this period. Higher population growth than urban expansion increases in urban settlement density to accommodate a large population, increasing urban temperature. The maximum and minimum temperature of Dhaka city has increased by 0.03 and 0.023 °C/year, respectively. The results show a steady rise in UHI temperature in the city, indicating a continuous increase in temperature in the future due to ongoing urbanization. This situation may become unbearable due to global warming–induced temperature rise, which is already noticed in the country like other parts of the globe. The climate of Dhaka city is humid due to its location in monsoon-dominated region. Higher temperatures combined with high humidity may cause a large increase in public health risk in this highly populated urban area. The city needs urgent attention to reduce the UHI effect to avoid catastrophic effects in the forthcoming years. Higher-resolution longer period temperature data, such as Landsat LST, can be used in the future for understanding the consequence of different urban LC alterations on the UHI of Dhaka city. The impact of global warming–induced climate change can be separated for a better evaluation of urbanization on UHI.

Acknowledgements The authors are grateful to Goddard Space Flight Center of The National Aeronautics and Space Administration (NSA) to provide MODIS data through web portals.

Author contribution All the authors contributed to conceptualize and design the study. Data were gathered by Shanawaz Uddin; the modelling was done by Najeebullah Khan and Shamsuddin Shahid; an initial draft of the paper was prepared by Shanawaz Uddin and Najeebullah Khan; the article was repeatedly revised to generate the final version by Towfiqul Islam and Mohammad Kamruzzaman.

Data availability All data used in the study are available in the public domain. Those are also available for sharing on request to the corresponding author.

Code availability The codes used for the processing of data can be provided on request to the corresponding author.

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication All the authors consented to publish the paper.

Conflict of interest The authors declare no competing interests.

References

Aboelata A, Sodoudi S (2020) Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. Build Environ 168:106490

Adhikary S, Das S, Islam M, Hossain Q Multivariate statistical approach for modelling domestic water demand of Dhaka city in Bangladesh.

Aguilar-Lome J, Espinoza-Villar R, Espinoza J-C, Rojas-Acuña J, Willems BL, Leyva-Molina W-M (2019) Elevation-dependent warming of land surface temperatures in the Andes assessed using MODIS LST time series (2000–2017). Int J Appl Earth Obs Geoinformation 77:119–128

Alam MJ (2018) Rapid urbanization and changing land values in mega cities: implications for housing development projects in Dhaka, Bangladesh. Bandung 5(1):1–19

Alamgir M, Khan N, Shahid S, Yaseen ZM, Dewan A, Hassan Q, Rasheed B (2020) Evaluating severity–area–frequency (SAF) of seasonal droughts in Bangladesh under climate change

scenarios. Stochast Environ Res Risk Assess 34(2):447–464. https://doi.org/10.1007/s00477-020-01768-2
Armson D, Stringer P, Ennos A (2012) The effect of tree shade and grass on surface and globe temperatures in an urban area. Urban For Urban Green 11(3):245–255
Arshad M, Khedher KM, Eid EM, Aina YA (2021) Evaluation of the urban heat island over Abha-Khamis Mushait tourist resort due to rapid urbanization in Asir, Saudi Arabia. Urban Clim 36:100772
Azad A, Kitada T (1998) Characteristics of the air pollution in the city of Dhaka, Bangladesh in winter. Atmos Environ 32(11):1991–2005
Bala R, Prasad R, Yadav VP (2021) Quantification of urban heat intensity with land use/land cover changes using Landsat satellite data over urban landscapes. Theor Appl Climatol 2021:1–12
Banerjee C, Kumar DN (2018) Assessment of surface water storage trends for increasing groundwater areas in India. J Hydrol 562:780–788
Belward AS (1999) The IGBP-DIS global 1-km land-cover data set DIS-Cover: a project overview. Photogramm Eng Remote Sens 65:1013–1020
Benali A, Carvalho A, Nunes J, Carvalhais N, Santos A (2012) Estimating air surface temperature in Portugal using MODIS LST data. Remote Sens Environ 124:108–121
Buo I, Sagris V, Burdun I, Uuemaa E (2020) Estimating the expansion of urban areas and urban heat islands (UHI) in Ghana: a case study. Nat Hazards 105(2):1299–1321
Cai S, Liu D, Sulla-Menashe D, Friedl MA (2014) Enhancing MODIS land cover product with a spatial–temporal modeling algorithm. Remote Sens Environ 147:243–255
Clinton N, Gong P (2013) MODIS detected surface urban heat islands and sinks: global locations and controls. Remote Sens Environ 134:294–304
Costanzo V, Evola G, Marletta L (2016) Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. Energy Build 114:247–255
CRDP (2014) City Region Development Planning Project (CRDP) draft report, preparation of revised structure plan for RAJUK under CRDP, Chapter 7, 14. Project Number: 39298-013
de Munck C, Pigeon G, Masson V, Meunier F, Bousquet P, Tréméac B, Marchadier C (2013) How much can air conditioning increase air temperatures for a city like Paris, France? Int J Climatol 33(1):210–227
Dewan AM, Corner R, Hashizume M, Ongee ET (2013) Typhoid fever and its association with environmental factors in the Dhaka metropolitan area of Bangladesh: a spatial and time-series approach. PLoS Negl Trop Dis 7(1):e1998
Dewan AM, Corner RJ (2014) Impact of land use and land cover changes on urban land surface temperature. In Dhaka Megacity (pp. 219–238). Springer, Dordrecht
Doick KJ, Peace A, Hutchings TR (2014) The role of one large greenspace in mitigating London's nocturnal urban heat island. Sci Total Environ 493:662–671
Duan S-B, Li Z-L, Wu H, Leng P, Gao M, Wang C (2018) Radiance-based validation of land surface temperature products derived from Collection 6 MODIS thermal infrared data. Int J Appl Earth Obs Geoinformation 70:84–92
Elsayed I The effects of population density on the intensity of the urban heat island: a case study on the city of Kuala Lumpur, Malaysia. In: Proceedings of the 13th Annual Sustainable Development Research Conference: Critical perspectives on health, climate change and corporate responsibility. Vasteras, Sweden, 2007
Elsayed IS (2012) Mitigation of the urban heat island of the city of Kuala Lumpur, Malaysia. Middle-East J Sci Res 11(11):1602–1613
Feyisa GL, Dons K, Meilby H (2014) Efficiency of parks in mitigating urban heat island effect: an example from Addis Ababa. Landsc Urban Plann 123:87–95
Fortuniak K, Kłysik K, Wibig J (2006) Urban–rural contrasts of meteorological parameters in Łódź. Theor Appl Climatol 84(1–3):91–101
Friedl MA, McIver DK, Hodges JC, Zhang XY, Muchoney D, Strahler AH, Woodcock CE, Gopal S, Schneider A, Cooper A (2002) Global land cover mapping from MODIS: algorithms and early results. Remote Sens Environ 83(1–2):287–302
Friedl MA, Sulla-Menashe D, Tan B, Schneider A, Ramankutty N, Sibley A, Huang X (2010) MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sens Environ 114(1):168–182
Fung CK, Jim CY (2020) Influence of blue infrastructure on lawn thermal microclimate in a subtropical green space. Sustain Cities Soc 52:101858
Grimmond SU (2007) Urbanization and global environmental change: local effects of urban warming. Geogr J 173(1):83–88
Guan B, Ma B, Qin F (2011) Application of asphalt pavement with phase change materials to mitigate urban heat island effect. In 2011 International Symposium on Water Resource and Environmental Protection (Vol. 3, pp. 2389–2392). IEEE
Haddad L, Aouachria Z (2015) Impact of the transport on the urban heat island. Int J Environ Ecol Eng 9(8):968–973
Hashizume M, Dewan AM, Sunahara T, Rahman MZ, Yamamoto T (2012) Hydroclimatological variability and dengue transmission in Dhaka, Bangladesh: a time-series study. BMC Infect Dis 12(1):98
Holec J, Feranec J, Šťastný P, Szatmári D, Kopecká M, Garaj M (2020) Evolution and assessment of urban heat island between the years 1998 and 2016: case study of the cities Bratislava and Trnava in western Slovakia. Theor Appl Climatol 141:979–997
Hossain S (2006) Rapid mass urbanization and its social consequences in Bangladesh: the case of the megacity of Dhaka. In: 16th Biennial Conferences of the Asian Studies Association of Australia in Wollongong, pp 26–29
Hsu A, Sheriff G, Chakraborty T, Manya D (2021) Disproportionate exposure to urban heat island intensity across major US cities. Nat Commun 12(1):1–11
Istiaque A, Khan SI (2018) Impact of ambient temperature on electricity demand of Dhaka city of Bangladesh. Energy Power Eng 10(07):319
Justice C, Townshend J, Vermote E, Masuoka E, Wolfe R, Saleous N, Roy D, Morisette J (2002) An overview of MODIS Land data processing and product status. Remote Sens Environ 83(1–2):3–15
Karakuş CB (2019) The Impact of Land Use/Land Cover (LULC) Changes on land surface temperature in Sivas city center and its surroundings and assessment of urban heat island. Asia-Pacific Journal of Atmospheric Sciences 55(4):669–684
Kaya S, Basar UG, Karaca M, Seker DZ (2012) Assessment of urban heat islands using remotely sensed data. Ekoloji 21(84):107–113
Kendall MG (1948) Rank correlation methods. Rank correlation methods. Griffin, Oxford, England
Kevern JT, Haselbach L, Schaefer VR (2012) Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems. Journal of Heat Island Institute International 7(2)
Khan N, Shahid S, Ismail T, Ahmed K, Nawaz N (2019) Trends in heat wave related indices in Pakistan. Stoch Environ Res Risk Assess 33(1):287–302. https://doi.org/10.1016/j.atmosres.2019.01.024
Khan N, Shahid S, Chung E-S, Kim S, Ali R (2019) Influence of surface water bodies on the land surface temperature of Bangladesh. Sustainability 11(23):6754
Kitsara G, Papaioannou G, Retalis A, Paronis D, Kerkides P (2018) Estimation of air temperature and reference evapotranspiration

using MODIS land surface temperature over Greece. Int J Remote Sens 39(3):924–948

Klein I, Gessner U, Dietz AJ, Kuenzer C (2017) Global WaterPack–a 250 m resolution dataset revealing the daily dynamics of global inland water bodies. Remote Sens Environ 198:345–362

Kovats S, Akhtar R (2008) Climate, climate change and human health in Asian cities. Environ Urban 20(1):165–175

Mann HB (1945) Nonparametric tests against trend. Econometrica 13(3):245–259. https://doi.org/10.2307/1907187

Mensah C, Atayi J, Kabo-bah AT, Švik M, Acheampong D (2018) Assessing the impacts of urbinization on the climate of Kumasi.

Patz JA, Olson SH (2006) Climate change and health: global to local influences on disease risk. Ann Trop Med Parasitol 100(5–6):535–549

Peng S, Piao S, Ciais P, Friedlingstein P, Ottle C, Fo-M Bréon, Nan H, Zhou L, Myneni RB (2011) Surface urban heat island across 419 global big cities. Environ Sci Technol 46(2):696–703

Pongrácz R, Bartholy J, Dezső Z (2010) Application of remotely sensed thermal information to urban climatology of Central European cities. Phys Chem Earth Parts A/B/C 35(1–2):95–99

Qiu K, Jia B (2020) The roles of landscape both inside the park and the surroundings in park cooling effect. Sustain Cities Soc 52:101864

Raja DR, Neema MN (2013) Impact of urban development and vegetation on land surface temperature of Dhaka city. In International Conference on Computational Science and Its Applications (pp. 351–367). Springer, Berlin, Heidelberg

Santamouris M, Cartalis C, Synnefa A, Kolokotsa D (2015) On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—a review. Energy Build 98:119–124

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389

Shahid S (2010) Probable impacts of climate change on public health in Bangladesh. Asia Pac J Public Health 22(3):310–319

Shahid S (2012) Vulnerability of the power sector of Bangladesh to climate change and extreme weather events. Reg Environ Change 12(3):595–606

Shahid S, Harun SB, Katimon A (2012) Changes in diurnal temperature range in Bangladesh during the time period 1961–2008. Atmos Res 118:260–270

Shastri H, Barik B, Ghosh S, Venkataraman C, Sadavarte P (2017) Flip flop of day-night and summer-winter surface urban heat island intensity in India. Sci Rep 7:40178

Sheng L, Tang X, You H, Gu Q, Hu H (2017) Comparison of the urban heat island intensity quantified by using air temperature and Landsat land surface temperature in Hangzhou, China. Ecol Indic 72:738–746

Shirani-Bidabadi N, Nasrabadi T, Faryadi S, Larijani A, Roodposhti MS (2019) Evaluating the spatial distribution and the intensity of urban heat island using remote sensing, case study of Isfahan city in Iran. Sustain Cities Soc 45:686–692

Shourav MSA, Shahid S, Singh B, Mohsenipour M, Chung E-S, Wang X-J (2018) Potential impact of climate change on residential energy consumption in Dhaka City. Environ Model Assess 23(2):131–140

Sidiqui P, Huete A, Devadas R (2016) Spatio-temporal mapping and monitoring of urban heat island patterns over Sydney, Australia using MODIS and Landsat-8. In: 2016 4th International Workshop on Earth Observation and Remote Sensing Applications (EORSA). IEEE, pp 217–221

Skoulika F, Santamouris M, Kolokotsa D, Boemi N (2014) On the thermal characteristics and the mitigation potential of a medium size urban park in Athens, Greece. Landsc Urban Plann 123:73–86

Sodoudi S, Zhang H, Chi X, Müller F, Li H (2018) The influence of spatial configuration of green areas on microclimate and thermal comfort. Urban For Urban Green 34:85–96

Sulla-Menashe D, Friedl MA (2018) User guide to collection 6 MODIS land cover (MCD12Q1 and MCD12C1) product. USGS, Reston, VA, USA:1-18

Sun R, Chen L (2017) Effects of green space dynamics on urban heat islands: mitigation and diversification. Ecosyst Serv 23:38–46

Syafii NI, Ichinose M, Kumakura E, Jusuf SK, Chigusa K, Wong NH (2017) Thermal environment assessment around bodies of water in urban canyons: a scale model study. Sustain Cities Soc 34:79–89

Tan J, Zheng Y, Tang X, Guo C, Li L, Song G, Zhen X, Yuan D, Kalkstein AJ, Li F (2010) The urban heat island and its impact on heat waves and human health in Shanghai. Int J Biometeorol 54(1):75–84

Tan J, Che T, Wang J, Liang J, Zhang Y, Ren Z (2021) Reconstruction of the daily MODIS land surface temperature product using the two-step improved similar pixels method. Remote Sens 13(9):1671

Tareq SM, Maruo M, Ohta K (2013) Characteristics and role of groundwater dissolved organic matter on arsenic mobilization and poisoning in Bangladesh. Phys Chem Earth Parts A/B/C 58:77–84

Trotter L, Dewan A, Robinson T (2017) Effects of rapid urbanization on the urban thermal environment between 1990 and 2011 in Dhaka Megacity, Bangladesh. AIMS Environ Sci 4(1):145–167

Ünal YS, Sonuç CY, Incecik S, Topcu HS, Diren-Üstün DH, Temizöz HP (2020) Investigating urban heat island intensity in Istanbul. Theor Appl Climatol 139(1):175–190

Vancutsem C, Ceccato P, Dinku T, Connor SJ (2010) Evaluation of MODIS land surface temperature data to estimate air temperature in different ecosystems over Africa. Remote Sens Environ 114(2):449–465

Vermote E, Kotchenova S, Ray J (2011) MODIS surface reflectance user's guide. MODIS Land Surface Reflectance Science Computing Facility, version 1

Viña A, Bearer S, Zhang H, Ouyang Z, Liu J (2008) Evaluating MODIS data for mapping wildlife habitat distribution. Remote Sens Environ 112(5):2160–2169

Voogt JA, Oke TR (2003) Thermal remote sensing of urban climates. Remote Sens Environ 86(3):370–384

Wan Z (2007) Collection-5 MODIS land surface temperature products users' guide. ICESS University of California, Santa Barbara

Wan Z, Zhang Y, Zhang Q, Li Z-L (2004) Quality assessment and validation of the MODIS global land surface temperature. Int J Remote Sens 25(1):261–274

Weng Q (2009) Thermal infrared remote sensing for urban climate and environmental studies: methods, applications, and trends. ISPRS J Photogramm Remote Sens 64(4):335–344

Wessels K, De Fries R, Dempewolf J, Anderson L, Hansen A, Powell S, Moran E (2004) Mapping regional land cover with MODIS data for biological conservation: examples from the Greater Yellowstone Ecosystem, USA and Pará State, Brazil. Remote Sens Environ 92(1):67–83

Wong NH, Chen Y (2008) Tropical urban heat islands: climate, buildings and greenery. Routledge

Wong NH, Tan CL, Nindyani ADS, Jusuf SK, Tan E (2012) Influence of water bodies on outdoor air temperature in hot and humid climate. In: ICSDC 2011: Integrating Sustainability Practices in the Construction Industry. pp 81-89

Wong NH, Yu C (2005) Study of green areas and urban heat island in a tropical city. Habitat Int 29(3):547–558

Xiong Y, Huang S, Chen F, Ye H, Wang C, Zhu C (2012) The impacts of rapid urbanization on the thermal environment: a remote sensing study of Guangzhou, South China. Remote Sens 4(7):2033–2056

Yang G, Yu Z, Jørgensen G, Vejre H (2020) How can urban blue-green space be planned for climate adaption in high-latitude cities? A seasonal perspective. Sustain Cities Soc 53:101932

Yang J, Wong MS, Menenti M, Nichol J (2015) Study of the geometry effect on land surface temperature retrieval in urban environment. ISPRS J Photogramm Remote Sens 109:77–87

Yow DM (2007) Urban heat islands: observations, impacts, and adaptation. Geogr Compass 1(6):1227–1251

Zhou W, Qian Y, Li X, Li W, Han L (2014) Relationships between land cover and the surface urban heat island: seasonal variability and effects of spatial and thematic resolution of land cover data on predicting land surface temperatures. Landsc Ecol 29(1):153–167. https://doi.org/10.1007/s10980-013-9950-5

Zhou X, Wang YC (2011) Dynamics of land surface temperature in response to land-use/cover change. Geogr Res 49(1):23–36