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Research Article

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Posted Date: May 21st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-442136/v1>

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Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on November 24th, 2021. See the published version at <https://doi.org/10.1007/s00704-021-03872-x>.

Changes in Urbanization and Urban Heat Island Effect in Dhaka City

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Abstract

Urbanization changes the local environment, resulting in urban heat island (UHI) effect and deteriorating human life quality. Knowledge of urban environments and temperature changes is important to outline the urban planning process for mitigation of UHI effect. 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 the Dhaka city area has grown by 19.12% 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 temperatures at Dhaka city's warmest location were nearly 7 and 5°C, respectively, more than the coolest point outside the city. The city's annual average day- and nighttime temperature was increasing at a rate of 0.03° and 0.023°C/year over the period 2001-2017. 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.

Keywords: City clustering algorithm., Dhaka city, MODIS, urban heat island, trend analysis.

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; Elsayed 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. 2020; Shahid et al. 2012; Khan et al. 2019d). Extensive removal of natural surfaces and use of higher heat retention materials used for urban development reduces heat evaporative and transformative rates, modify the local climate, airflow and atmosphere and thus, cause 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 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 risk of these problems (Khan et al. 2019c; Khan et al. 2019a). Apart from the adverse health outcomes, UHIs cause a high electricity consumption by increasing demand for indoor cooling demand, which causes a feedback effect resulting in an increased 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.

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 area (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.

Monitoring 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 record, mobile thermometers (Wong and Yu 2005), and both 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 condition 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. Through 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).

A variety of satellite-based sensors, such as HCMM, Landsat TM/ETM+, AVHRR, MODIS, ASTER, and TIMS have been developed to retrieve LST and emissivity and estimation of 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) image 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.

Several studies have been conducted to evaluate the expansion of urbanization and UHIs 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 increased 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 three years 1990, 2000 and 2011. They reported transformation of vegetation to built-up area could increase LST of Dhaka city by 2°C.

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. The majority 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 spatiotemporal changes UHI 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 close to sea level (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 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).

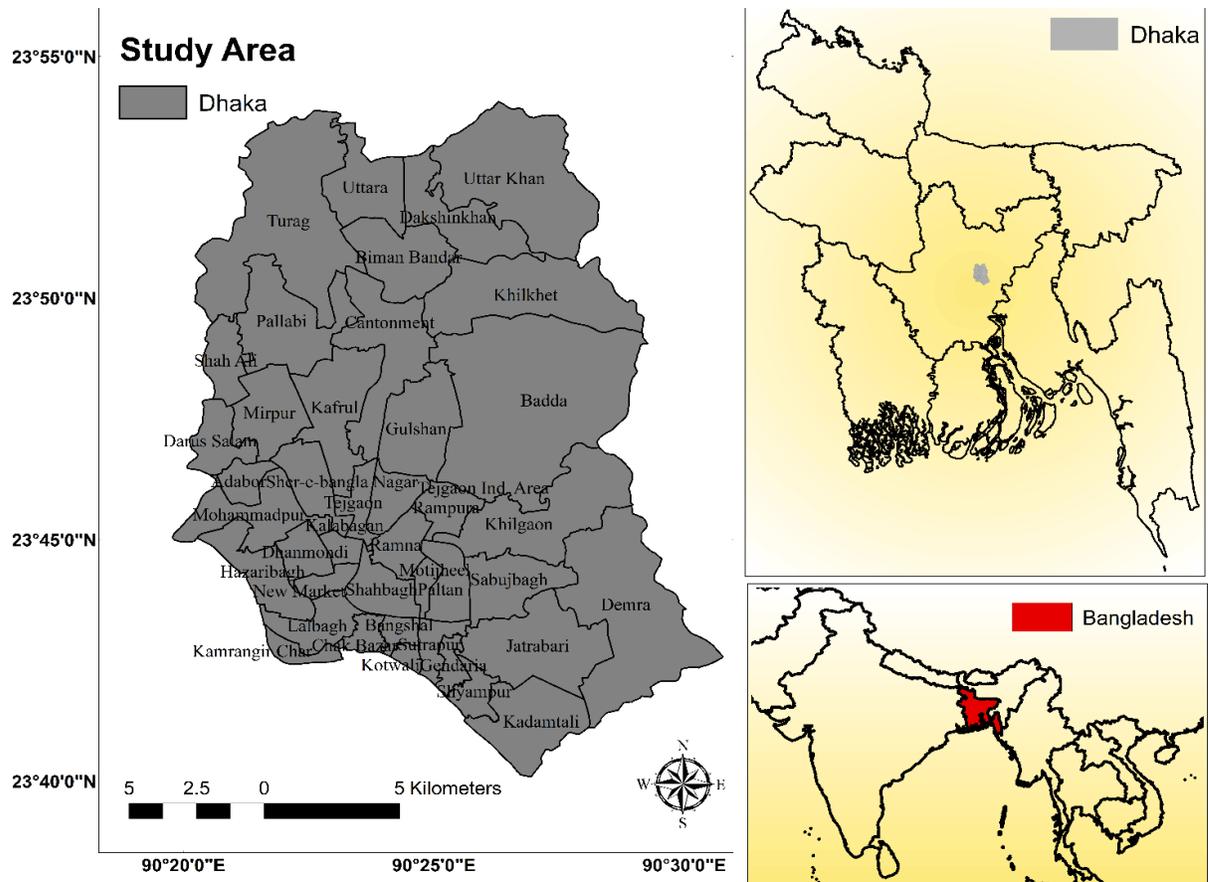


Fig. 1. Location map of Dhaka city with corresponding latitude and longitude

2.1 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 and 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 both MODIS Terra and Aqua image (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 of less than 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 the 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 (CCA)

The CCA, proposed by Peng et al. (2011), was utilized to identify the extent of the 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, and add the neighbourhood pixels obtained from the MODIS LC data

set and examine the pixels' queue, 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,

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

3.2 Sen's Slope Estimator

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

$$M = \frac{A(t') - A(t)}{t' - t} \quad (2)$$

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 ,

$$T = \sum_{j=1}^{n-1} (\sum_{k=j+1}^n (\sin x_j - 1)) \quad (3)$$

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

The T is utilized to get the significance level Z ,

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

where $\sigma(T)$ is the variance of temperature (T).

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 km² in 2001 to 1458.6 km² in 2017, with a rate of 330 km²/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 19.12% 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 increased population faster than the expansion of urban areas caused an increase in population density of the city. The city's population density increased from 9481.6 people/km² to 12950.8 people/km², or the increase in population density was by 76.59%. 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.

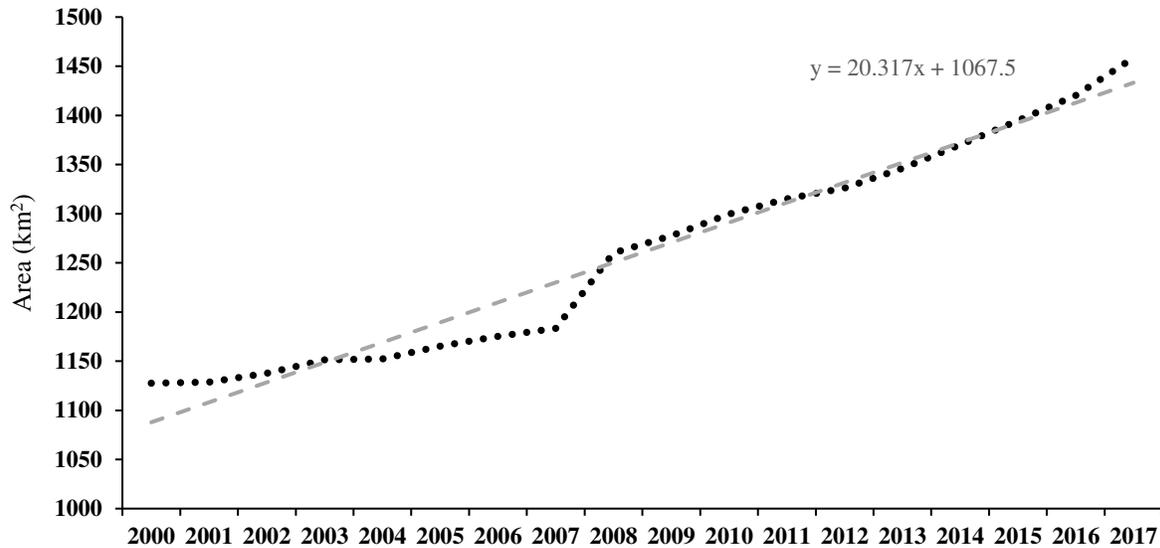
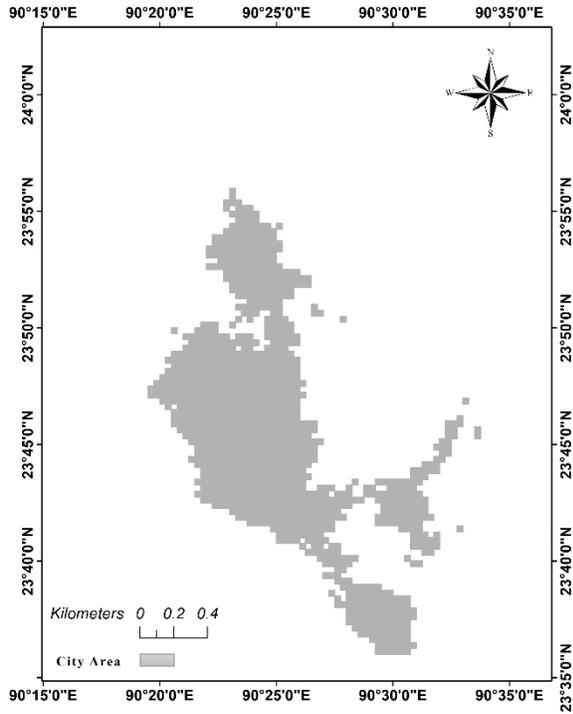


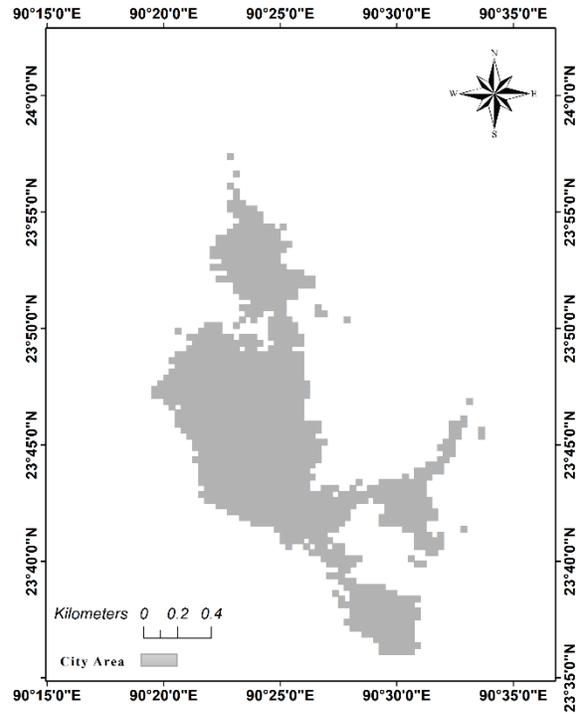
Fig 2. Time series of city area shows the expansion of Dhaka city during 2001 to 2017

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

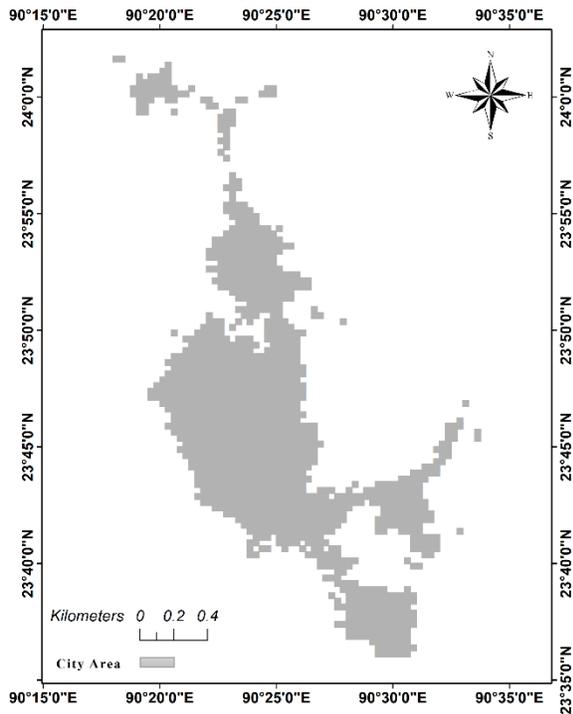
Year	City Area	City Area Change (%)	Population (million)	Change in population (%)	Population Density
2001	1128.50	-	10.70	-	9481.6
2002	1137.65	0.81	11.08	3.62	9739.4
2003	1151.38	1.19	11.48	3.62	9970.6
2004	1152.29	0.08	11.90	3.63	10327.3
2005	1165.11	1.10	12.33	3.61	10582.7
2006	1175.18	0.86	12.78	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		19.12		76.65	



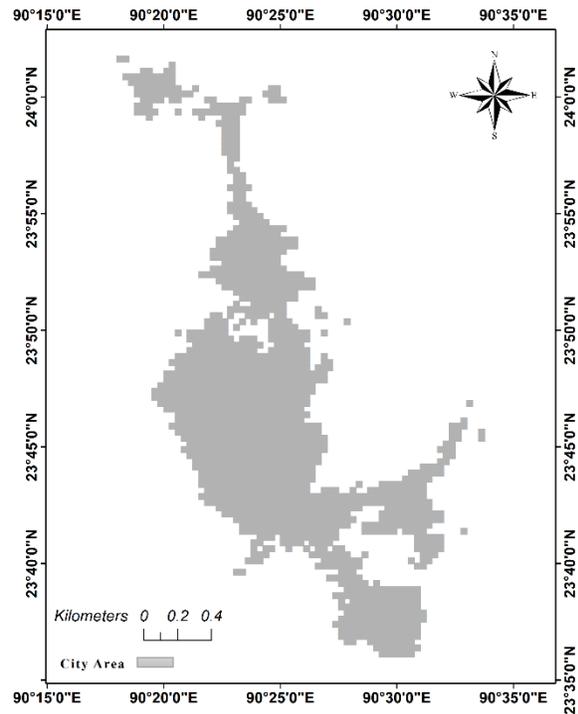
(a) Year 2001



(b) Year 2005



(c) Year 2010



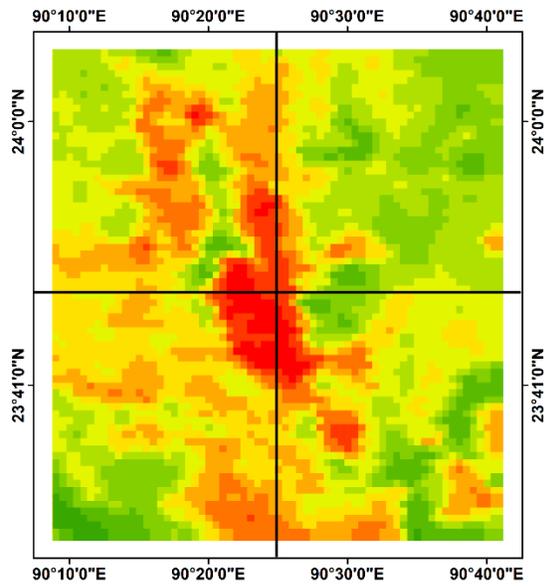
(d) Year 2017

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.

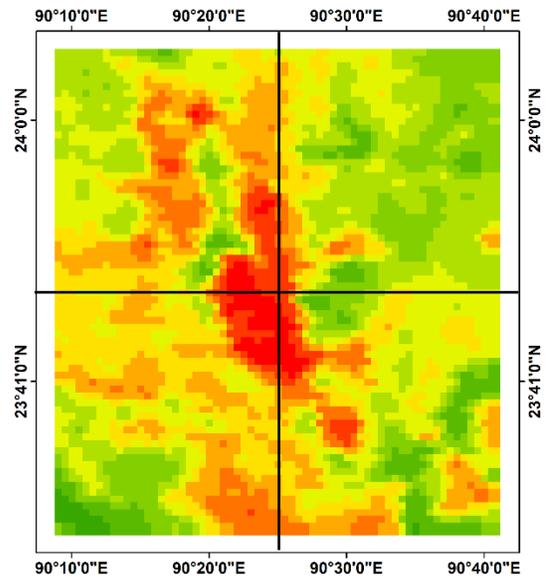
4.2 Estimation of urban heat in Dhaka city

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 surrounding rural and suburban areas. The colour bar represents the temperature of the 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 of Dhaka city areas is more than 7°C compared to its surrounding non-urban areas. The increase in UHI was more in the northern and eastern regions of Dhaka city, which have experienced rapid development in recent years (Figure 3).

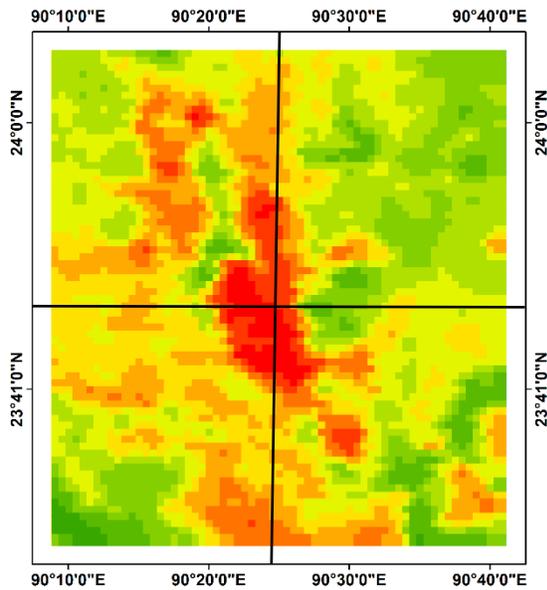
The nighttime temperature showed a lower difference in temperature (5°C) between Dhaka city and the nearby region, as presented in Figure 5. The temperature ramp shows a temperature variation between 17 and 22°C. The highest nighttime temperature was in the more developed urban region and in the areas comprised of 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 in the daytime and release heat during night time (Xiong et al. 2012). This caused higher nighttime temperature in the city area compared to its surroundings.



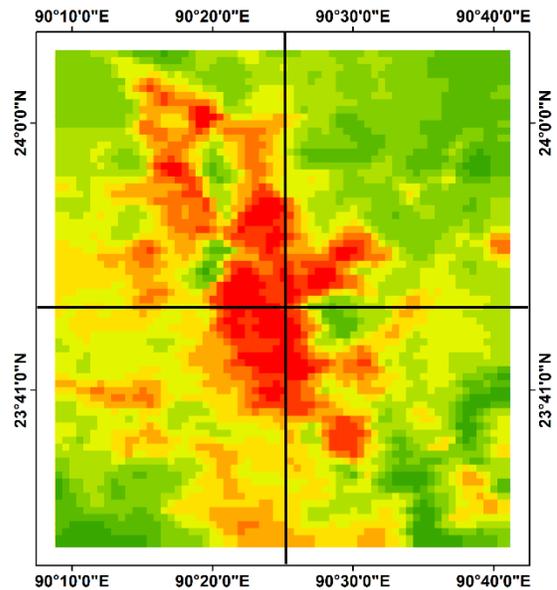
(a) Year 2001



(b) Year 2005



(c) Year 2010



(d) Year 2017

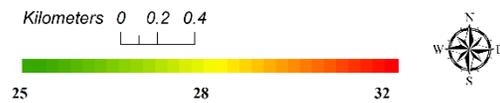
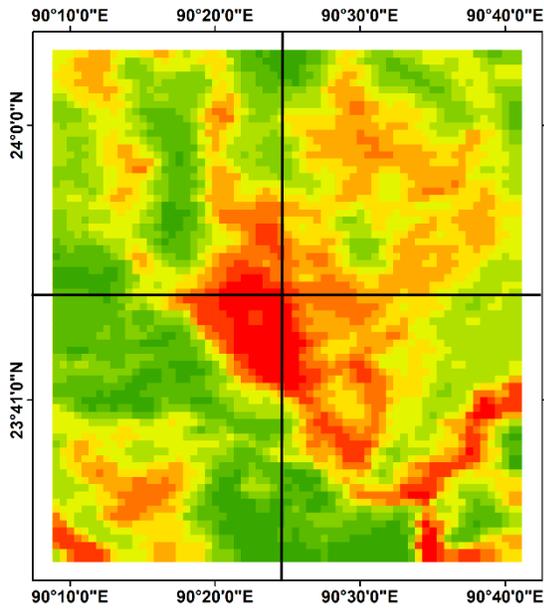
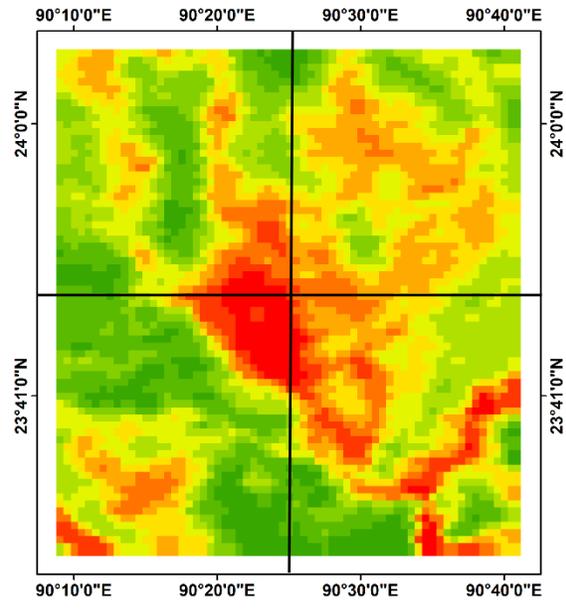


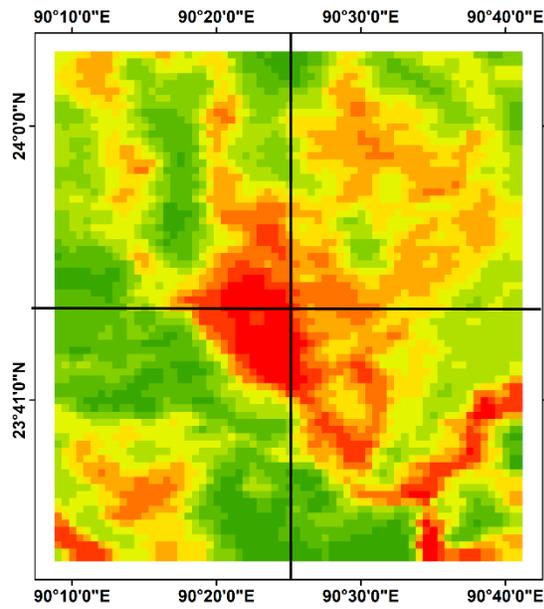
Fig. 4. Spatial distribution of daytime land surface temperature of Dhaka city and surrounding area for years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017



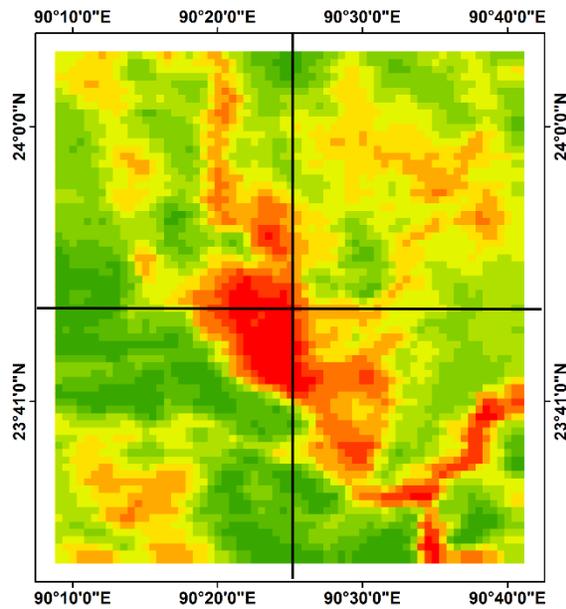
(a)Year 2001



(b)Year 2005



(c)Year2010



(d)Year2017

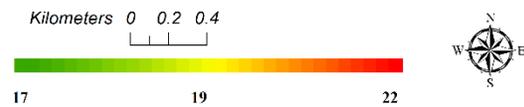


Fig. 5 Spatial distribution of nighttime land surface temperature of Dhaka city and surrounding area for years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017

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 $90^{\circ}20'00''$ to $90^{\circ}25'00''$ and longitude $23^{\circ}49'00''$ to $23^{\circ}42'00''$, which coincides with the defined city region using CCA. The temperature reaches its maximum when it crosses through the central region of the city.

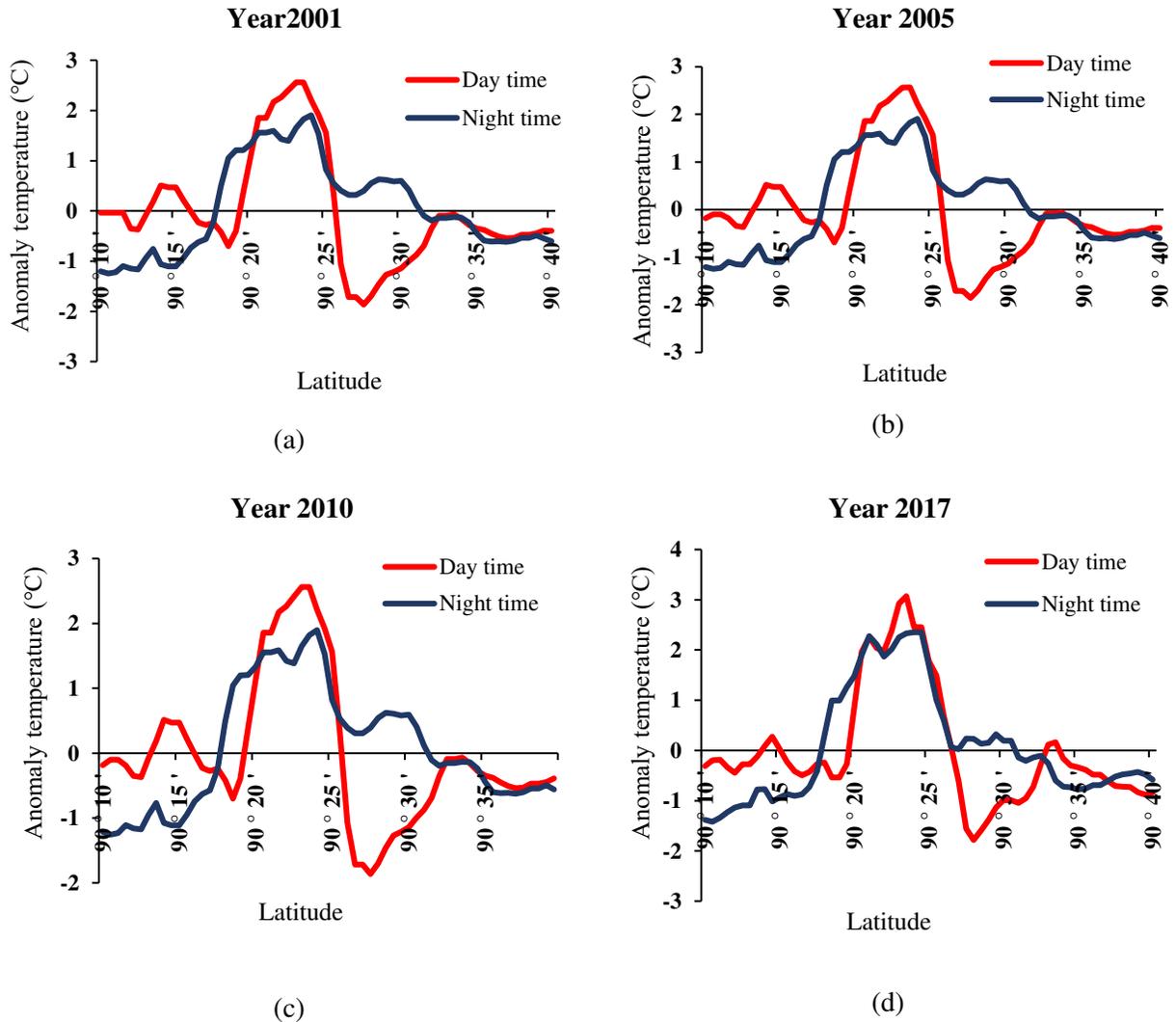


Fig. 6 Changes in the day and nighttime temperature along the latitudinal line shown in Figures 4 and 5, respectively for the years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017

The variation of the temperature 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 compared to that

observed at the city boundary. This clearly indicates the effect of urbanization on temperature or the urban heat island effect.

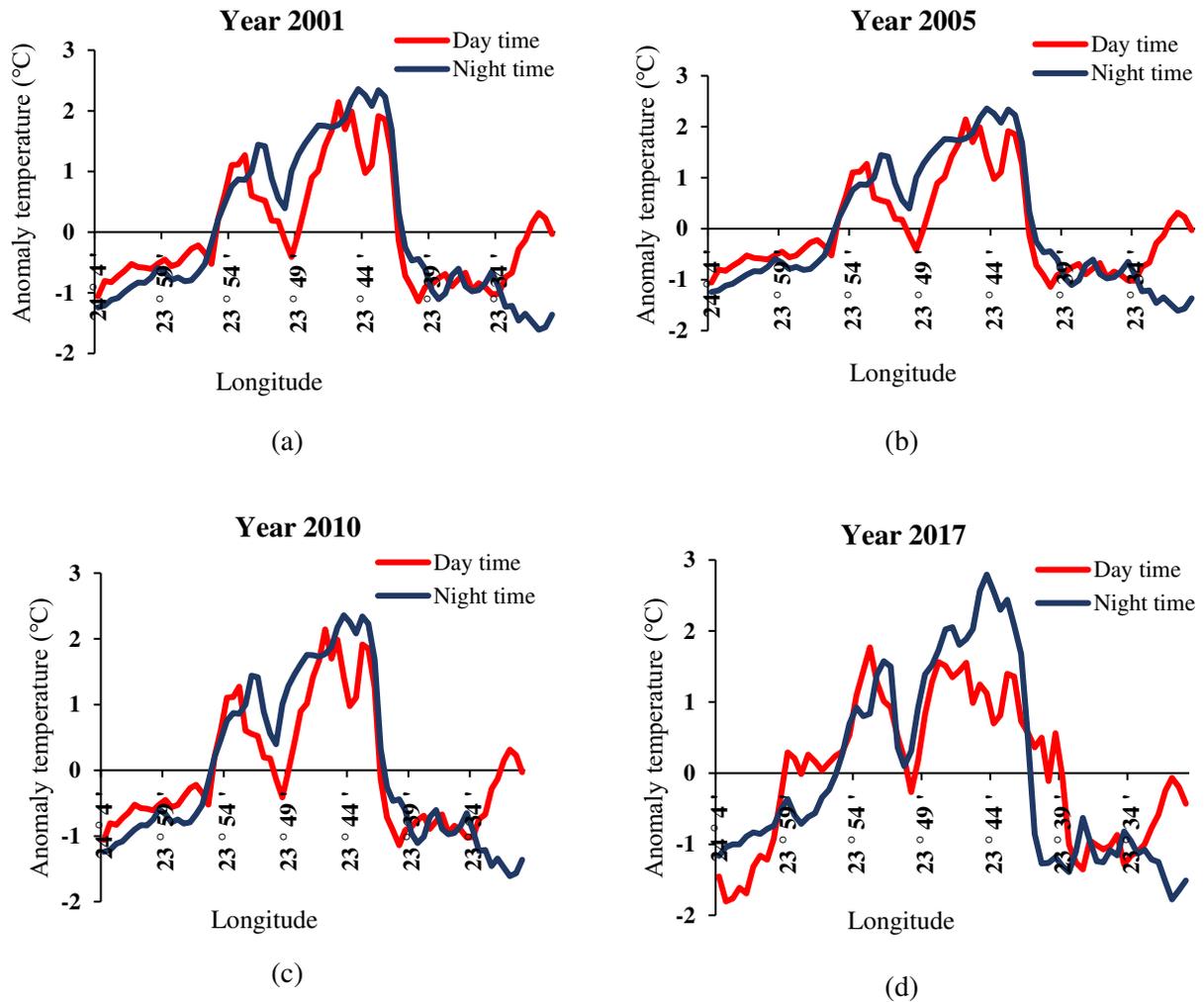


Fig.7 Changes in the day and nighttime temperature along the longitudinal line shown in Figures 4 and 5, respectively for the years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017

4.2 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 $0.023^{\circ}\text{C}/\text{year}$ 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 temperature 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 $0.04^{\circ}\text{C}/\text{year}$, respectively. The increase in winter day- and nighttime temperatures were 0.047 and $0.01^{\circ}\text{C}/\text{year}$, 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.

4.3 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 temperature. Significant association with winter day- and nighttime UHI temperature was also noticed. However, the correlations of the urban area and population density with summer UHI day- and nighttime temperature were not significant. This is expected as the UHI affects minimum temperature more compared to maximum temperature.

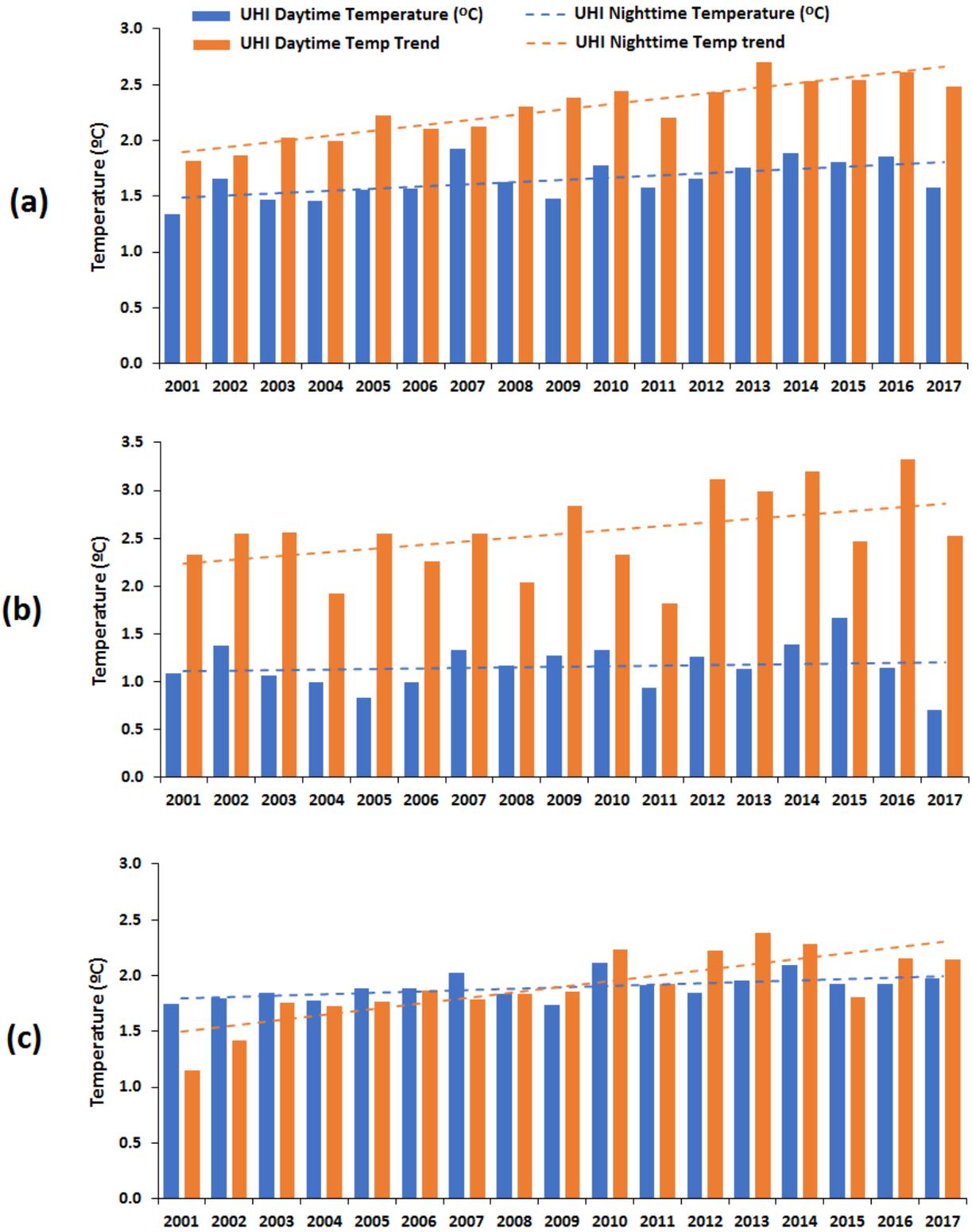


Fig. 8 Trends in the areal average of (a) annual (b) summer, and (c) winter day- and nighttime urban heat island temperature of Dhaka city over the period 2001-2017

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

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. The day- and nighttime temperature of Bangladesh 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.

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 depended. 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 get 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 United Kingdom (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 19.12% during 2001-2017. The population of the city has increased by 76.65% during this period. Higher population increase compared to urban expansion increases in urban settlement density to accommodate a large population, leading to an increase in 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 temperature 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 alteration 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.

Acknowledgement

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

Funding

Not Applicable

Conflict of interest

The authors declare no conflict of interest.

Availability of data:

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

Availability of code

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

Authors' 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.

Consent for publication

All the authors consented to publish the paper

Ethics approval

Not Applicable

Consent to participate

Not Applicable

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Figures

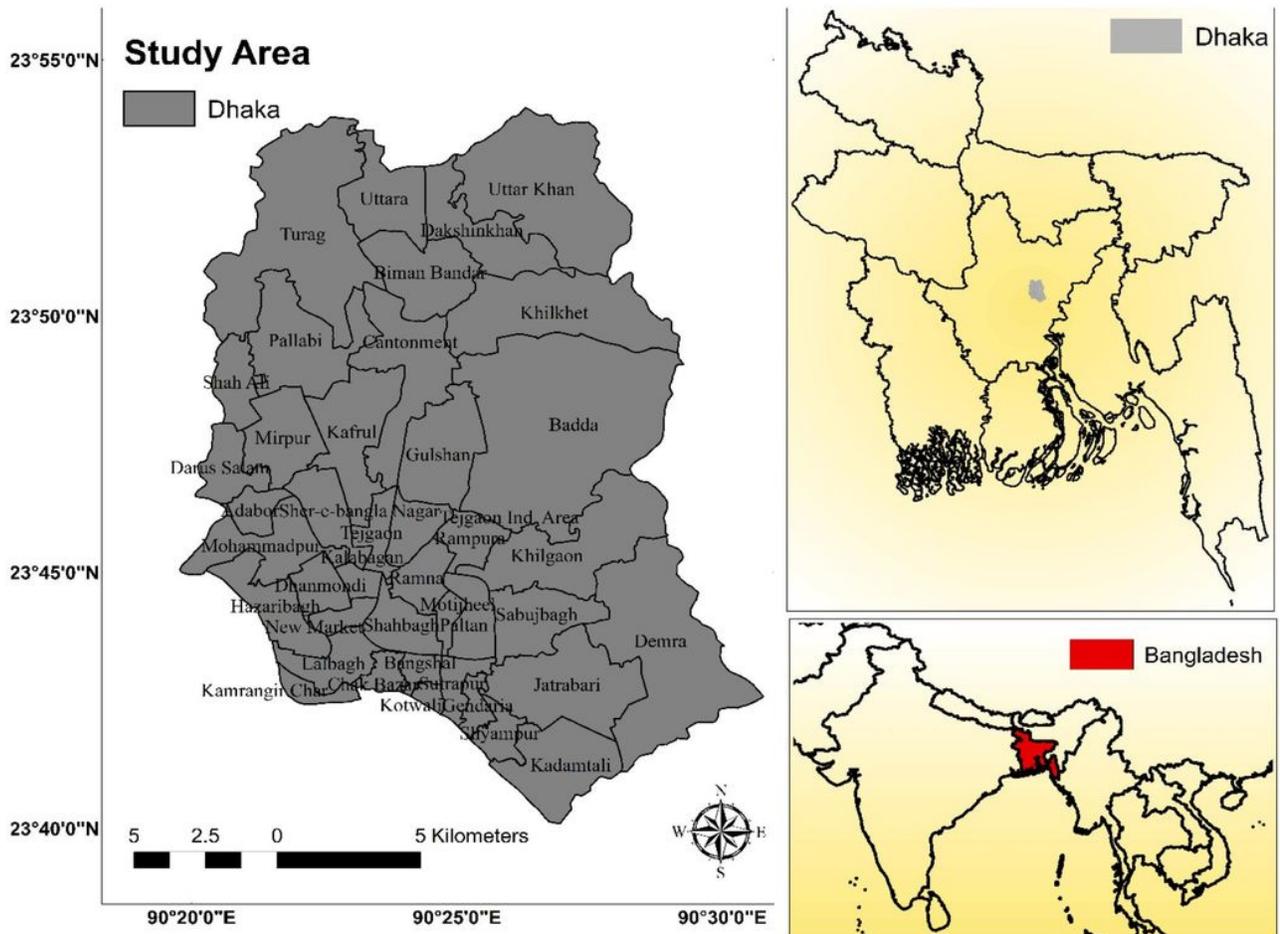


Figure 1

Location map of Dhaka city with corresponding latitude and longitude Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

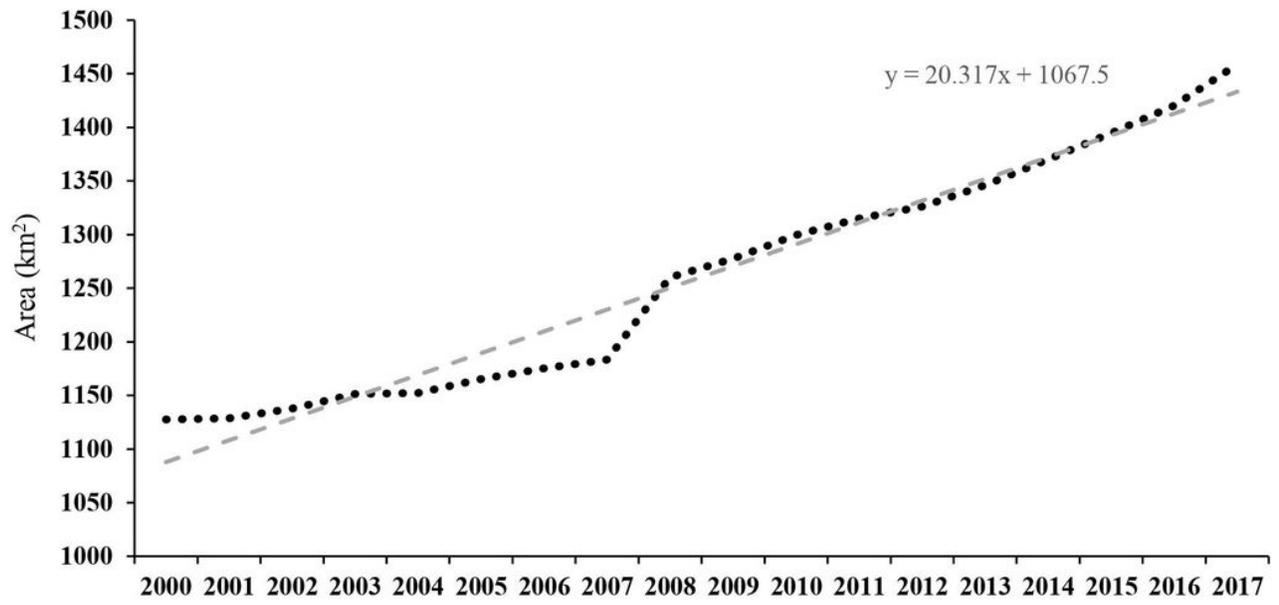


Figure 2

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

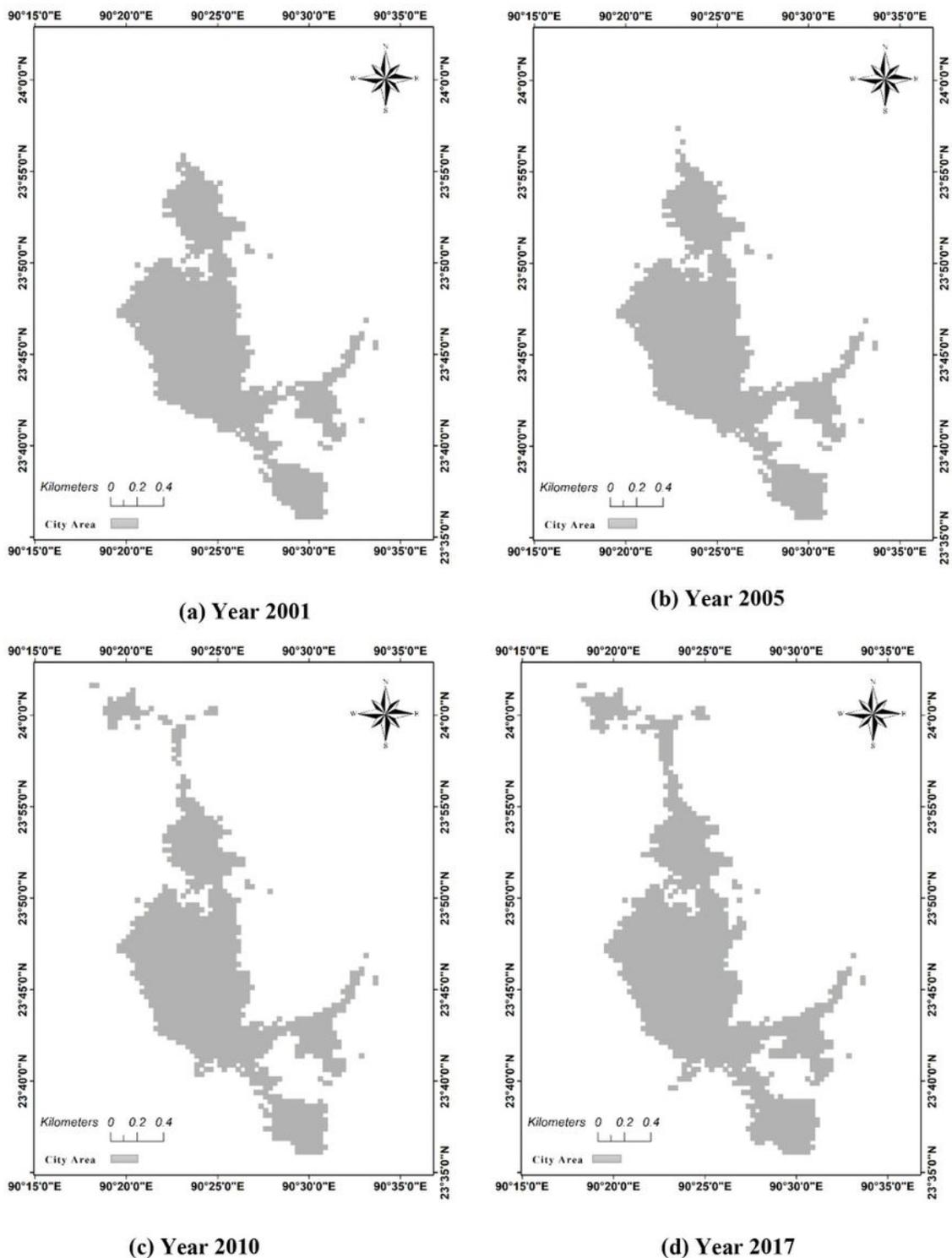


Figure 3

The spatial extend of Dhaka city in the year: (a) 2001, (b) 2005, (c) 2010 and (d) 2017, estimated using city clustering algorithm. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

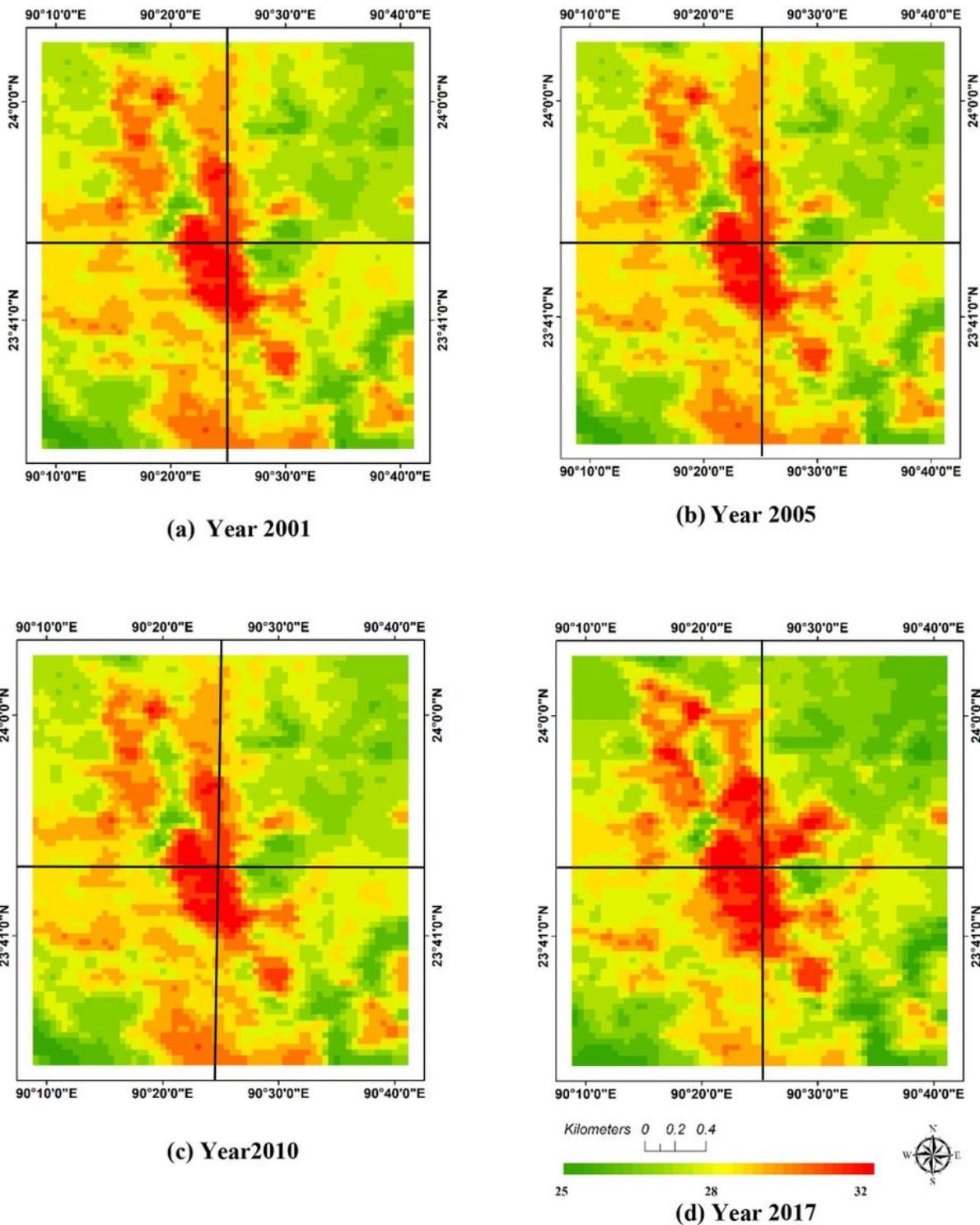


Figure 4

Spatial distribution of daytime land surface temperature of Dhaka city and surrounding area for years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

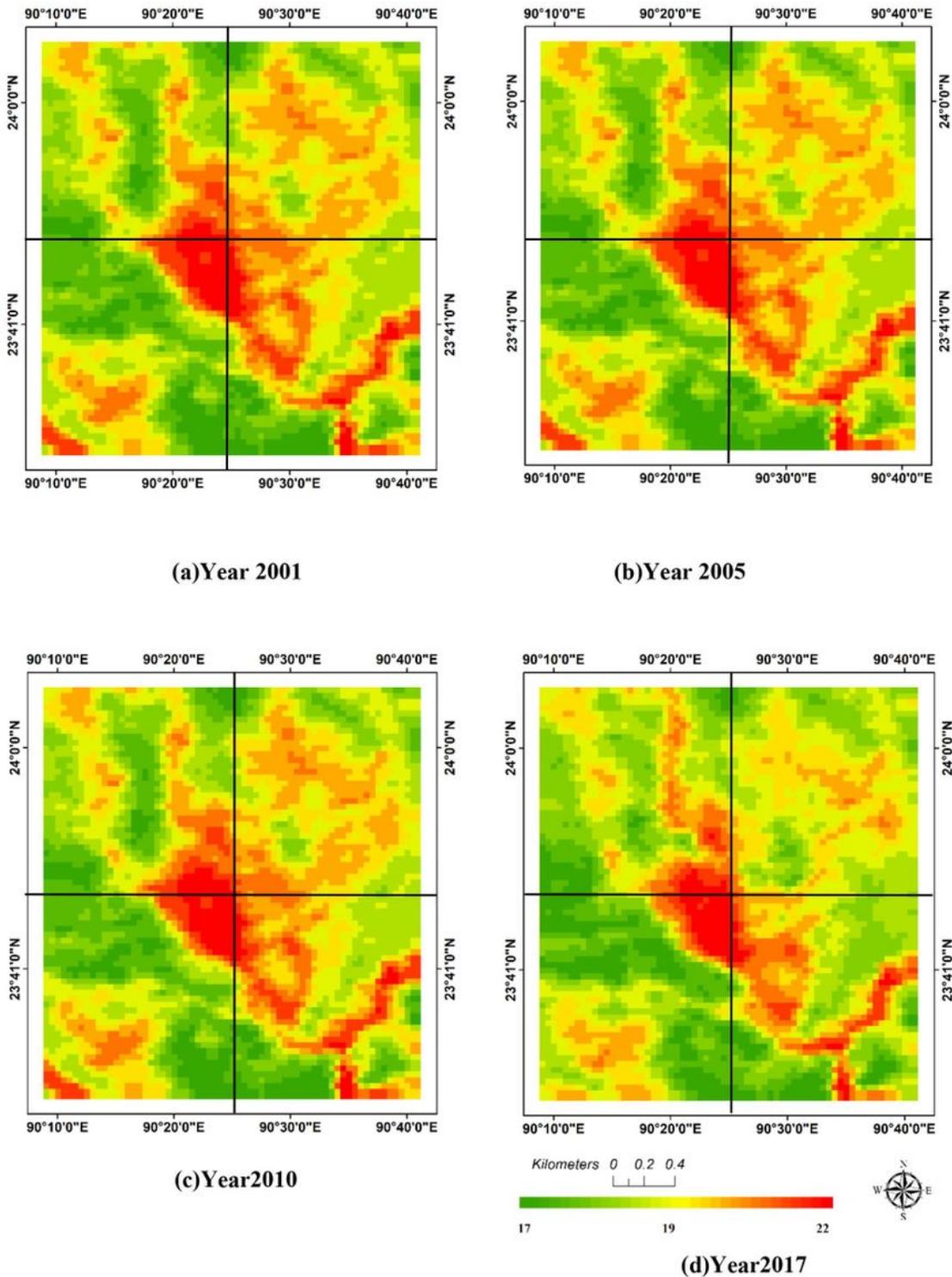


Figure 5

Spatial distribution of nighttime land surface temperature of Dhaka city and surrounding area for years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

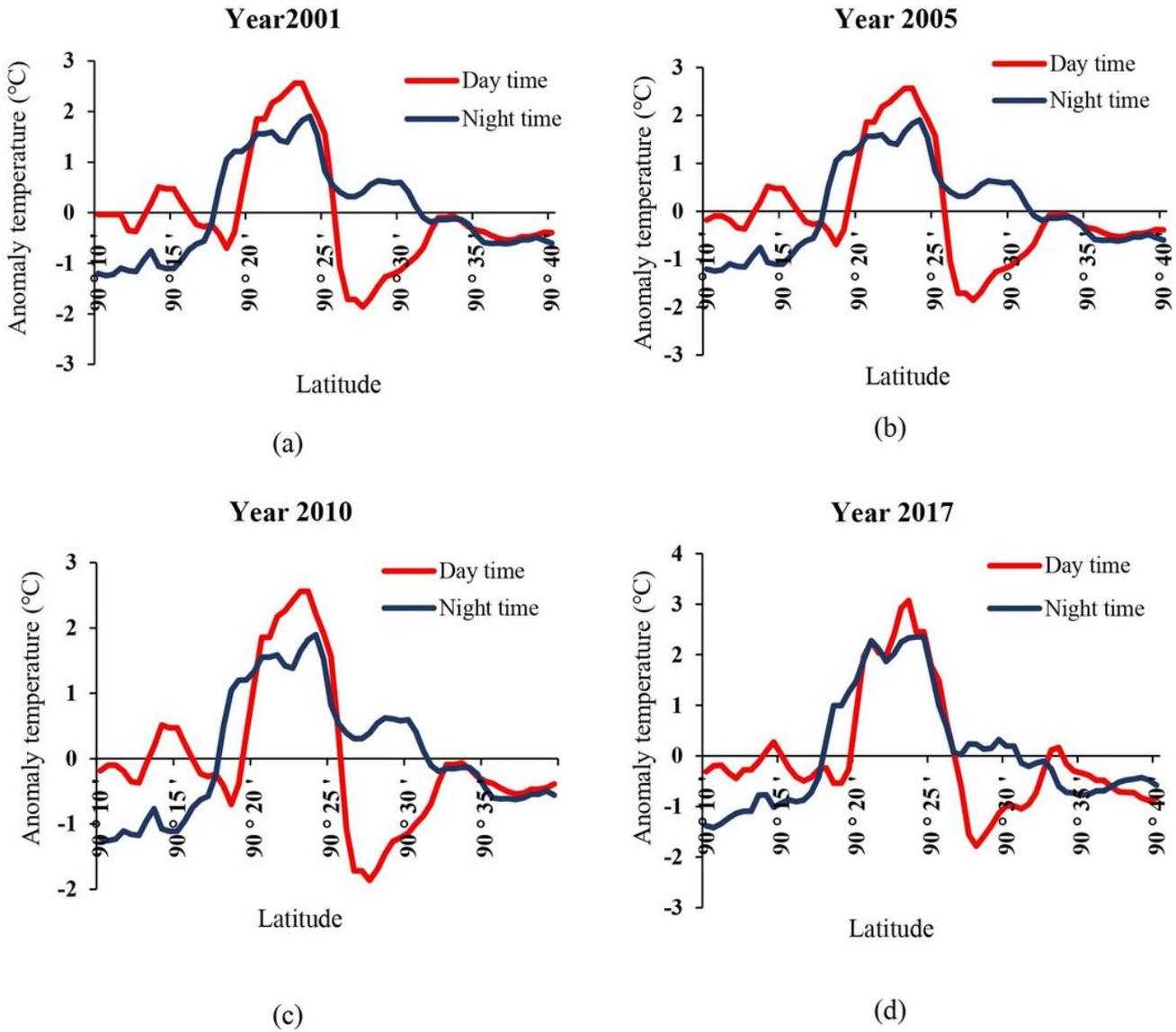
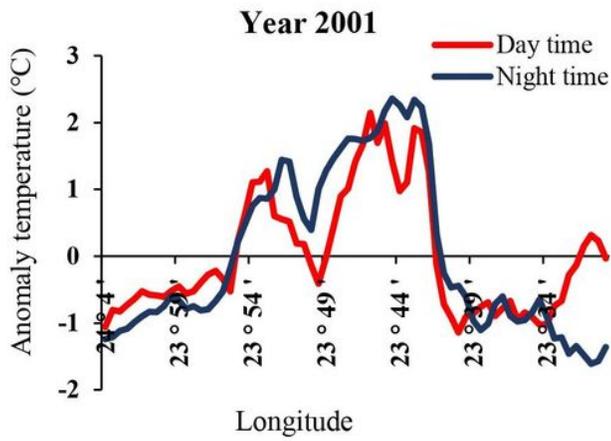
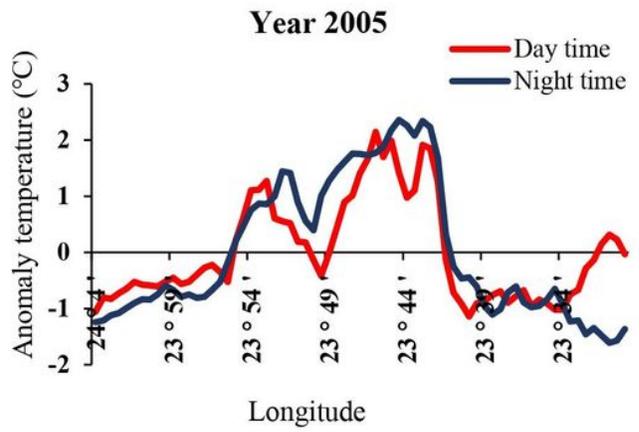


Figure 6

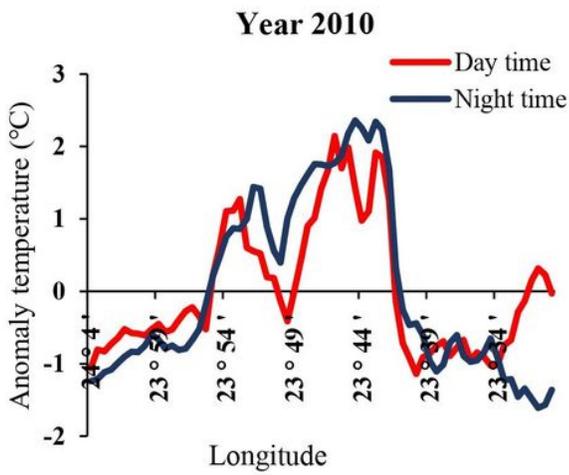
Changes in the day and nighttime temperature along the latitudinal line shown in Figures 4 and 5, respectively for the years: (a) 2001, (b) 2005, (c) 2010 and (d) 2017



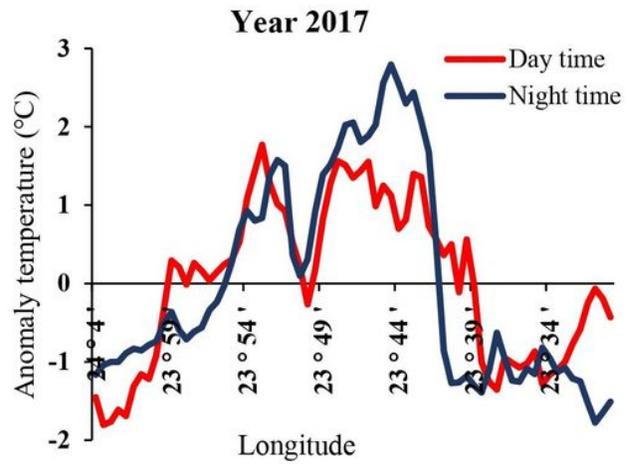
(a)



(b)



(c)



(d)

Figure 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

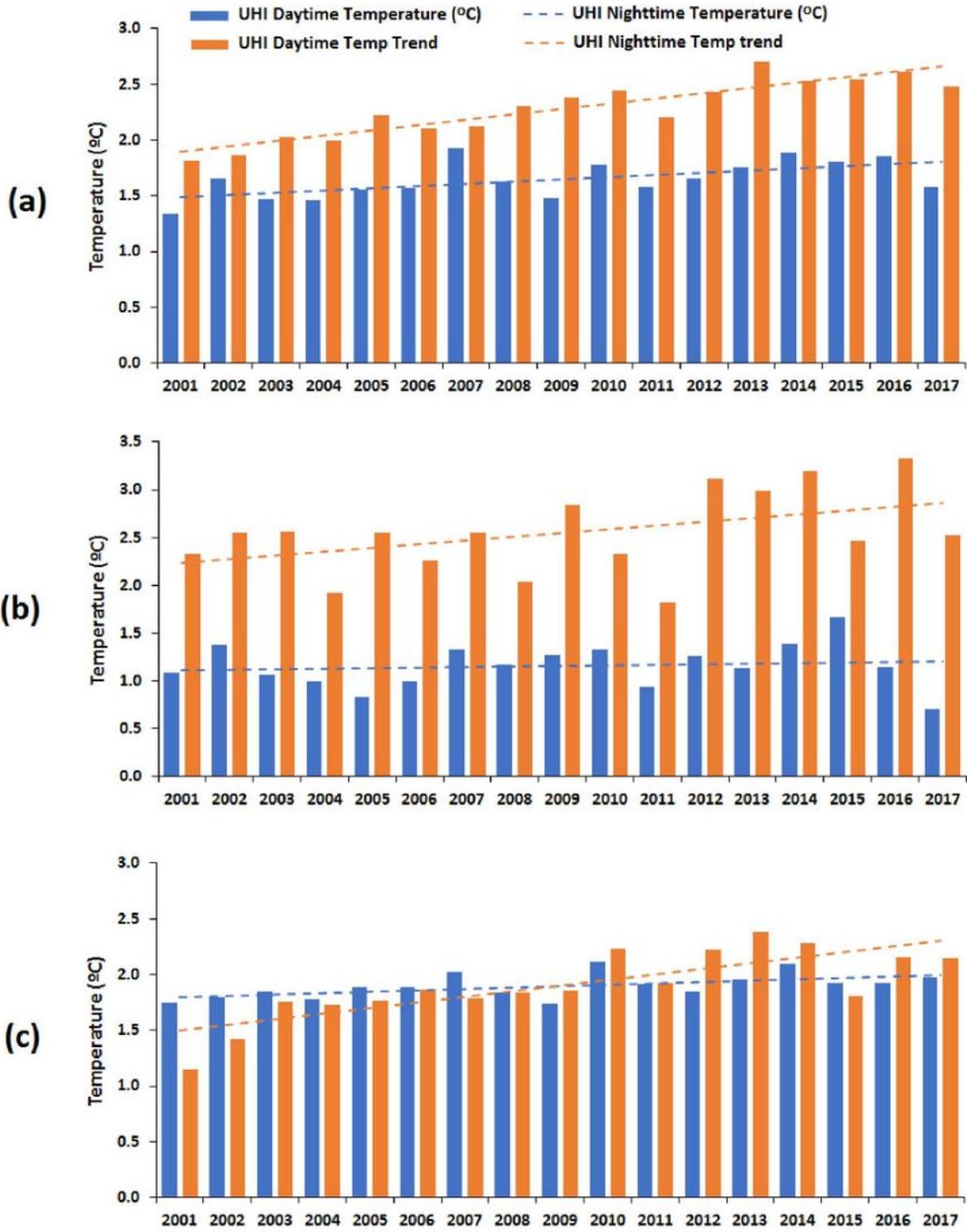


Figure 8

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