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Spatiotemporal Variation of Land Surface Temperature and Urban Heat Islands in Dhaka City: A Geospatial Approach

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ABSTRACT: Rapid urban population growth and widespread urbanization are common occurrences in the modern world. They cause several negative repercussions among which Urban Heat Island (UHI) is the most widely recorded occurrence. The population of Dhaka city has increased by 12.64 million from 2011 to 2021 and the temperature by 0.57° C in the recent decade. Therefore, the city is facing increased public health-related problems associated with high temperatures, outbreaks of diseases, and scarcity of safe drinking water. Considering these matters, this study explores the spatiotemporal changes in Land Surface Temperature (LST) over the last twenty years and the present condition of heat islands. The city was found 3.9 °C warmer than the surrounding rural areas in 2022. The results also show recurring fluctuations in temperature together with a positive change in temperature during the study period. A year of high temperatures follows a gradual decrease in temperatures in the next two years, and a year of low temperatures follows several gradual increases in temperature. It is expected from the result that the upcoming two years (2023 and 2024) will be warmer than the last three years. The findings may provide insight into how LST and UHI fluctuate and aid in developing strategies to lessen their negative consequences.

Keywords: LST; UHI; Temperature; Microclimate; Correlation

INTRODUCTION

Widespread urban expansion with rapid urban population growth has been a comprehensive occurrence in the recent world. Urban areas expanded by 168% from 2001 to 2018 with the highest rate being observed in Asia and Africa (Huang et al., 2021). 66% of the world's population is expected to live in urban areas by 2050 (Hardin et al., 2018; UN DESA, 2014). Rapid urban growth causes several negative repercussions, among which Urban Heat Island (UHI) is the most widely recorded occurrence (Karimi et al., 2018). One of the consequences of unplanned urbanization is the creation of the UHI which is termed for the high temperatures in urban areas in proportion to surrounding rural areas due to human activity. Besides, anthropogenic emission of greenhouse gases triggers an increase in temperature (Filho et al., 2018).

UHI refers to the high temperatures found in urban areas compared to their surrounding rural areas due to factors such as increased heat-absorbing surfaces, human activities, and a lack of vegetation. It is a phenomenon in which urban areas experience higher temperatures than surrounding rural areas due to the absorption and retention of heat by built surfaces such as buildings, roads, and pavements (Oke, 1982). It is the positive temperature difference between an urban area and its hinterland and one of the most well-known consequences of urbanization on the local climate (Souch and Grimmond, 2006). The buildings and heat-absorbing surfaces emit the heat at night that they have absorbed during the day, bringing UHI to its peak. Night shows a larger difference in temperature than the day (Phelan et al., 2015). An effective definition of UHI has been given by the IPCC (2022). The organization defines UHI as the relative warmth of a city compared with surrounding rural areas.

Research in Bangladesh indicates that UHI-induced vulnerability has gradually increased during the past decades (Abrar et al., 2022). Dhaka city, the largest primate city (Islam, 2018) in Bangladesh, currently hosts about 10.29 million people in its two city corporations

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including Biman Bandar and Cantonment areas, compared to 6.97 million in 2011 (BBS, 2022). The population of Dhaka city is expected to increase by 53% by 2050 and it will be one of the 43 megacities of the world (IEP, 2022). The Ecological Threats Report 2022 assumes the city's climate will become wetter with unhealthy air quality (IEP, 2022). The wetter condition will occur only when the temperature increases. As the city is experiencing rapid urbanization and industrialization which will lead to an increase in the UHI effect. In April 2023, Dhaka experienced its warmest temperature in 60 years, reaching 40.6 °C (105.1 °F), and meteorologists have warned that severe heat waves (temperatures more than 40 °C) will get more frequent in the future (Mongabay Environmental News, 2023). Another study by Roy et al. (2019) found that the maximum temperature increased by 3.6 °C in 2014 compared to 1985.

Uddin et al. (2021) examined urban changes and the Urban Heat Island (UHI) effect in Dhaka city from 2001 to 2017 using MODIS land surface temperature data and found that urbanization led to temperature increases of nearly 3°C along with around 6°C difference in temperature between urban and rural areas. Besides, Hussain et al. (2023) try to correlate land use and land cover (LULC) with the surface temperature and generate a time series of temperature hotspots. The result exhibits that hot spots of UHI increased by 93.73%, and average temperatures rose by 3.26°C. Another attempt was made by Dewan et al. (2021) to examine time series diurnal MODIS land surface temperature (LST) data to generate baseline data for the years 2000–2019 about the intensity, drivers, and temporal trends of SUHI for five major cities of Bangladesh. The result exhibits greater intensity of SUHI for larger cities like Dhaka and Chittagong. Similar studies have been conducted to date. However, the pattern of LST and UHI fluctuations was not addressed but rather a comparison between two periods of time.

Therefore, the study has been conducted to investigate the spatiotemporal variation as well as the pattern of fluctuations of land surface temperature from 2001 to 2021 in Dhaka city and examine the resultant UHI condition. A comparison between the BMD's air temperature and LST has been done to synchronize the patter of temperature fluctuation. Besides, the impact of land use change on the variation of LST has been correlated in this study.

STUDY AREA

Dhaka, the Capital of Bangladesh, is one of the fastest-growing megacities in the world. The study area includes the areas of those thanas of Dhaka Metropolitan Area (DMP) situated in Dhaka North City Corporation (DNCC) and Dhaka South City Corporation (DSCC) including Biman Bandar and Cantonment area (Fig. 1). This is because they are located at the core area of DNCC. The study area occupies an area of 305.47 km^2 with a total population of 10.2 million (BBS, 2022). The average population density is 34914 per km^2 (BBS, 2022). The DSCC has a higher population density than the DNCC (Table 1).

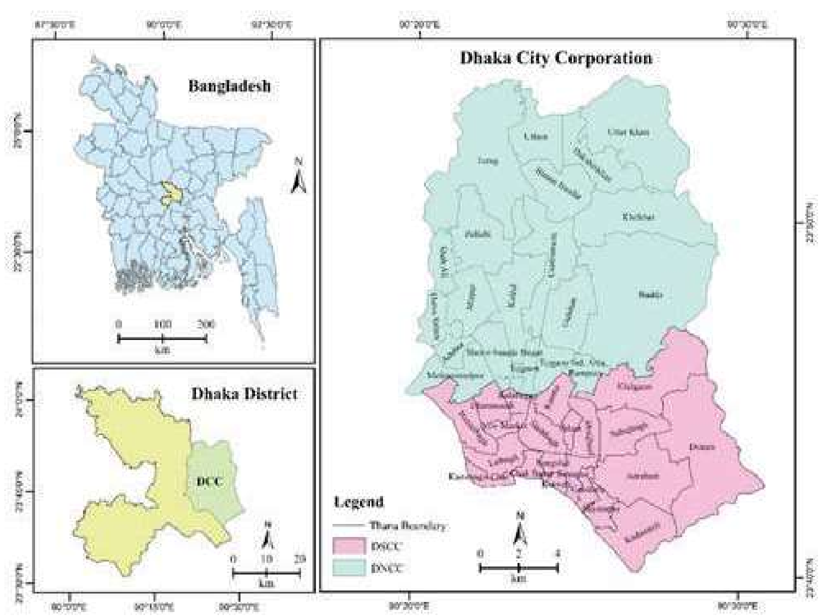

Figure 1: Study Area Location

Table 1: Locational Extent of the Study Area

	Latitude	Longitude	Thana	Area (km²)	Total Population	Population Density/km²
DNCC*	23°44´-23°54´	90°20´-90°28´	20	196.22	5,979,537	30,474
DSCC	23°40´-23°47´	90°21´-90°31´	21	109.25	4,299,345	39,353

*Including Cantonment and Biman Bandar Thanas. Source: BBS, 2022

METHODOLOGY

Data Sources and Analysis

The study includes spatiotemporal changes of LST and UHI using Landsat images from 2001 to 2022 and their comparison with the Bangladesh Meteorological Department's (BMD) air temperature data. NASA Goddard Space Flight Center and U.S. Geological Survey combinedly produce Landsat images and 30m resolution images are freely available at their website. They can also be used directly in the Google Earth Engine (GEE) platform. BMD's daily air temperature data is available on their website and usable after payment.

LST Calculation

Mean LST has been calculated using JavaScript in the GEE code editor for the five warm months (March-May to August-October) for twenty-one consecutive years from 2001 to 2022 (Appendix 2). BMD's analysis of 30 years (1981-2010) of temperature data shows that the maximum temperature of the Dhaka division was over 31°C from March to October (Khatun et al., 2016). Monsoon season is acute in June and July when maximum rainfall occurs in Bangladesh and keeps the temperature lower than the pre- (March-May) and post-monsoon (October-November) warmer months (Sutradhar et al., 2023). This time duration is not the same for all the years. Besides, heat waves seem to occur in the pre-and post-monsoon seasons (Rashid et al., 2024). Therefore, seven monsoon and winter seasons months (June to August and November to February) were excluded from calculating the mean. There are two exact causes for selecting this period. Firstly, many studies on time series analysis of BMD's temperature data have been conducted, showing the studied months remain warmer. Secondly, cloud-free images are rarely available during monsoon season. Landsat 5 images were used for calculating LST from 2001 to 2012 and Landsat 8 images from 2013 to 2022 (Appendix 1). Thematic Mapper (TM) sensor of Landsat 5 collects thermal data (B6). On the other hand, Landsat 8 has Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) sensors. Bands 10 and 11 of the satellite, also called TIRS 1 and TIRS 2 bands, provide more accurate surface temperature data and are collected at 100 meters resolution. The wavelengths of these bands are 10.6-11.19 micrometres and 11.50-12.51 micrometres respectively. We used band 10 for this study. Images that have more than 20% cloud cover were excluded for better results. The years 2017 and 2020 are excluded from this study due to the unavailability of cloud-free data for March to October. The cloud of the images could be removed but the cloud-erase images do not provide reliable results. However, the final estimation of LST went through a series of equations and finally found the result.

Instead of ground-truthing the LST data, this study compared the output with daily temperature data of BMD for the years 2001 to 2022 to justify the GEE-driven LST. The daily data, was then, calculated to the monthly average and to eight warmer months average for each of the years. Finally, a graph has been produced to investigate the trend of temperature change and compare it with the GEE-driven LST data.

UHI and UHII Calculation

Surface or atmospheric temperature measurements can be used to determine UHIs (US EPA, 2021). Air temperatures are significantly, but indirectly, influenced by surface temperatures. For instance, parks and other vegetated areas, which tend to have cooler surface temperatures, tend to cool the air. At the same time, densely populated areas usually tend to have warmer air temperatures. However, Due to air mixing within the atmosphere, the relationship between air and surface temperatures is not constant.

UHI is calculated from the mean LST. The mean temperature is subtracted from the surface temperatures and then divided by the result with a standard deviation (Chaudhary et al., 2021).

$$UHI = \frac{LST - LST_{mean}}{Standard \;\; Deviation} \qquad \text{(i)}$$

The UHI was classified into five categories namely very low intensity, low intensity, moderate intensity, high intensity, and very high intensity, using the Jenks natural breaks classification method, alternatively called the Jenks optimization method. It is a data clustering technique created to find the ideal classification of values. This method is generally used in thematic maps. It can distribute a "blanket of error" uniformly across the mapped surface (Jenks, 1967).

However, the UHI of the last nine years was calculated using the formula given above. The mean LST and standard deviation of the years are shown in Table 2:

Table 2: Mean LST and Standard Deviation of the Recent Years

Year	Mean LST (°C)	Standard Deviation
2022	35.94	2.31
2021	37.44	2.35
2019	39.00	2.72
2018	36.67	2.47
2016	34.41	2.04
2015	36.01	2.84
2014	38.06	3.10

Sources: Calculated from Landsat 8 Images

Several studies used the average temperature of urban and rural stations for the day or used the maximum and minimum temperature to calculate the UHI intensity (Hardin et al., 2018, Hawkins et al., 2004; Unger, 1996). UHII is calculated by subtracting the mean temperature of the rural areas from the mean temperature of the urban area (Kim and Brown, 2021). The formula for calculating UHII is as follows:

$$\Delta T_{u-r} = T_u - T_r \qquad \text{(ii)}$$

Two individual variables for urban and rural polygons were defined in the GEE code editor platform to calculate the maximum, minimum, and mean temperatures of the rural and urban areas. The polygons were created using the "draw a shape" tool in GEE.

Index Calculation

A Landsat image from December 2022 was used to calculate NDVI, NDBI, NDWI, and NDMI. The output was then clipped to the shape of Dhaka city. The zonal statistics tool of the spatial analysis toolbox in ArcMap was used to extract the Thana-wise indices value.

The normalized difference vegetation index (NDVI) assists in studying vegetation density and evaluating how effectively plants survive over time. NDVI is calculated as the ratio between the values of the red (R) and near-infrared (NIR) bands (Oke, 1973) (Table 2). NDVI value ranges from -1 to +1, indicating a high value for very dense vegetation (Fig. 2-A).

NDBI is calculated as the ratio between the values of the near-infrared (NIR) and short-wave infrared (SWIR) bands (Zhang and Tang, 2018) (Table 2). The value of NDBI lies between -1 to +1. High values exhibit built-up areas whereas negative values denote water bodies. NDBI value close to zero represents vegetation (Fig. 2-B).

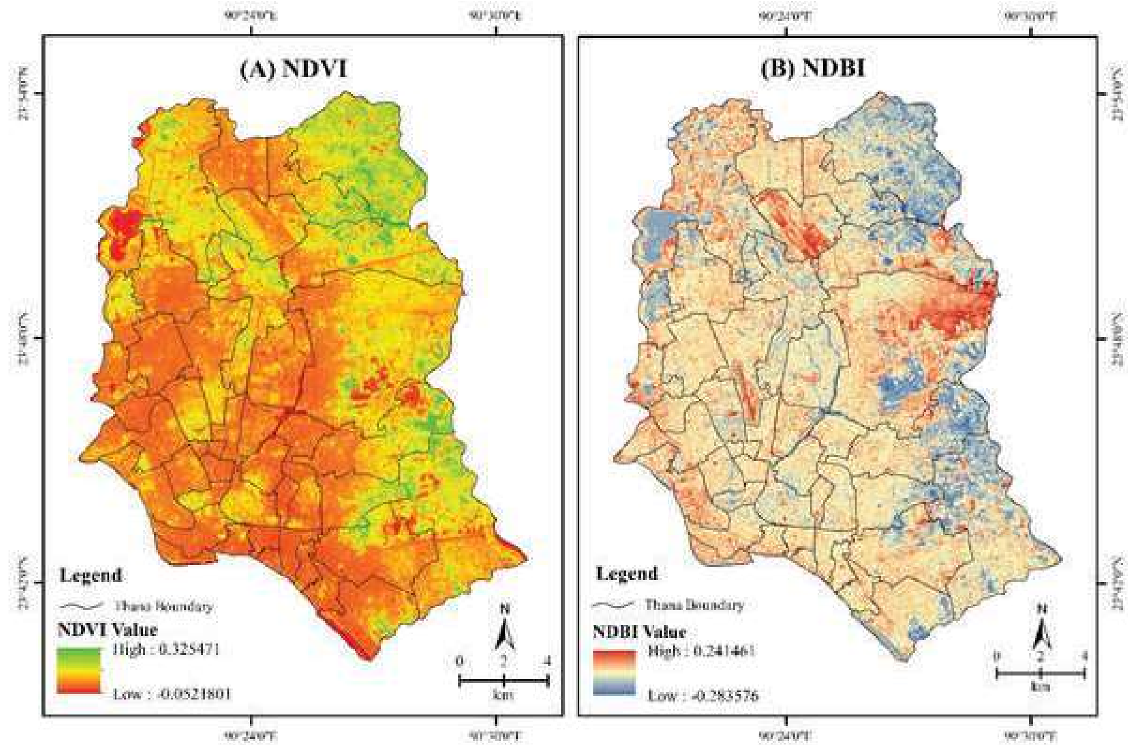

Figure 2: Processed NDVI and NDBI Maps

The ratio of green (G) and near-infrared (NIR) bands of remote sensing images is used to calculate NDWI (Sahu, 2014) (Table 3). This allows us to detect minor alterations in the water content of the water bodies. The values of NDWI range from -1 to +1. Generally, it is greater than 0.5 for water bodies, much smaller for vegetation, and 0 to positive 0.2 for built-up features (Fig. 3-A).

The NDMI uses near-infrared (NIR) and short-wave infrared (SWIR) to determine vegetation water content (Sahu, 2014) (Table 3). Like other indices discussed above, NDMI values also range from -1 to +1 (Fig. 3-B).

Table 3: NDVI, NDBI, NDWI, and NDMI Calculation Formula

Indices	Formula	Equation for Landsat 8 Image
NDVI	$NDVI = \frac{(NIR - R)}{(NIR + R)}$	$NDVI = \frac{(Band\ 5 - Band\ 4)}{(Band\ 5 + Band\ 4)}$
NDBI	$NDBI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$	$NDBI = \frac{(Band\ 6 - Band\ 5)}{(Band\ 6 + Band\ 5)}$
NDWI	$NDWI = \frac{(G - NIR)}{(G + NIR)}$	$NDWI = \frac{(Band\ 3 - Band\ 5)}{(Band\ 3 + Band\ 5)}$
NDMI	$NDMI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$	$NDMI = \frac{(Band\ 5 - Band\ 6)}{(Band\ 5 + Band\ 6)}$

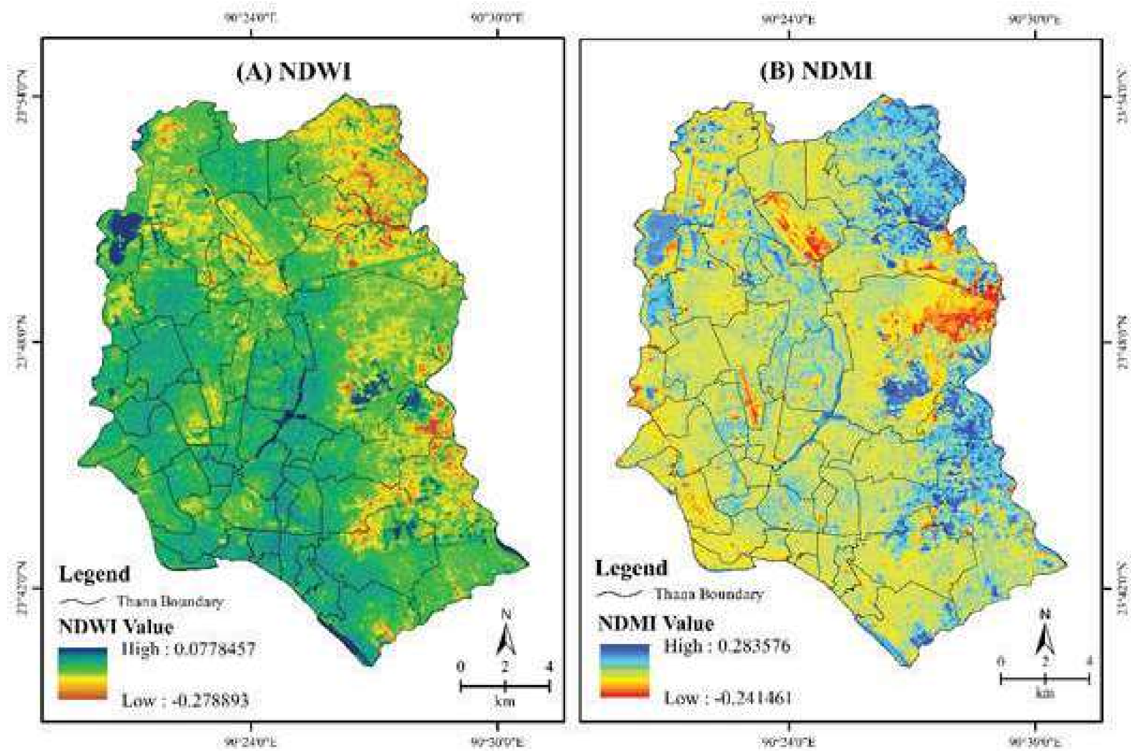

Figure 3: Processed NDWI and NDMI Maps

RESULTS

Temporal Changes of LST

Increased urbanization and decreased trends in vegetation and waterbodies increase the susceptibility to temperature rise. A climate change analysis of Bangladesh by BMD shows an increase in the number of hot days in the pre-monsoon, monsoon, and post-monsoon periods. Twenty years of analysis of the surface temperature of Dhaka city was done with five-year intervals from 2001 to 2021 (Fig. 4). Results show that the mean temperature was lowest in 2001 (33.98 °C) and reached 37.44 °C in 2021. The difference in temperature between 2001 and 2016 was minimal. A significant increase has been noticed in the last 20 years (3.46 °C) though the mean temperature in 2022 was lower than in 2021. A rising trend of LST with fluctuation has been found in them. It also shows a significant rise in temperature from 2016 to 2021. But this was less than the mean temperature of 2019. A sudden increase in temperature has been noticed from 34.41 °C in 2016 to 37.36 °C in 2018 and 39.85 °C in 2019. In the meantime, the years in the falling limb between 2011 and 2016 also experienced an increased temperature. For example, the mean temperature in 2014 was 38.89 °C. In the last twenty years, 2004 was the coldest year with a mean temperature of 31.6 °C and the hottest year was 2019 having a mean temperature of 39.79 °C.

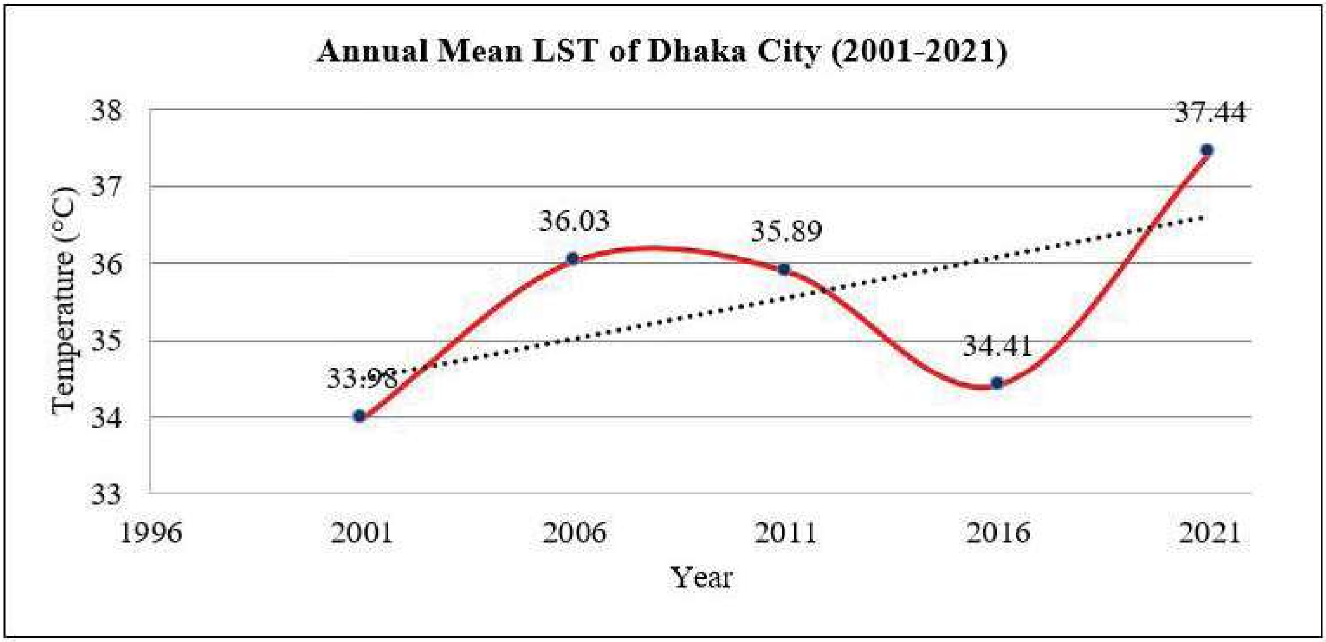

Figure 4: Annual Mean LST of Warmer Months from 2001-2021

Source: Calculated from Landsat images in GEE

Results show a clear picture of the fluctuation in temperature in the last twenty years. A year of high temperature was followed by a gradual decrease in temperature in the next two years. Again, a year of low temperatures was followed by several gradual increases in temperature. A positive change in mean temperature was noticed during this period. Together with temperature fluctuation, the upcoming years will be warmer if mitigation measures are not taken immediately.

The twenty-year analysis of BMD temperature data also shows an increasing trend (Fig. 5). There are differences between air and land surface temperatures. The temperature of the air surrounding the Earth, typically measured at a height of 1.5 to 2 meters above ground level, is referred to as air temperature, where LST represents the temperature of the Earth's surface, captured using thermal infrared sensors on satellites (Balas et al., 2023). Despite their differences, the rising trend of temperature and its fluctuation pattern exhibit a similar scenario.

Though fluctuations in temperature have been experienced which is likely to the result found in LST analysis driven from GEE, the yearly mean air temperature is much lower in BMD's data. For example, the mean temperature of 2021 driven from GEE was 37.44 °C but 29.50 °C observed in the ground station. There are 7 to 8 °C differences in mean temperature in each year of the study period. This difference is very much normal (Naserikia et al., 2023) for several reasons. Firstly, ground station data includes all the daily temperatures, where the Landsat provides 16 days of repeat cycle images and images having cloud cover of more than 20% were excluded in the calculation of mean LST. Secondly, BMD provides air temperature and Landsat provides land surface temperature. Thirdly, BMD provides temperature data of a point but the mean surface temperature is calculated by averaging all the pixel values in Dhaka city. Finally, temperature over 40 °C is found in several industrial areas of the city which have increased the overall yearly mean temperature. Though there are differences in the temperature of GEE-driven LST data and BMD's Dhaka station temperature data, the two matters are similar for both of them. The first one is temperature fluctuations over the years and the second one is the gradual increase in temperature over the study period.

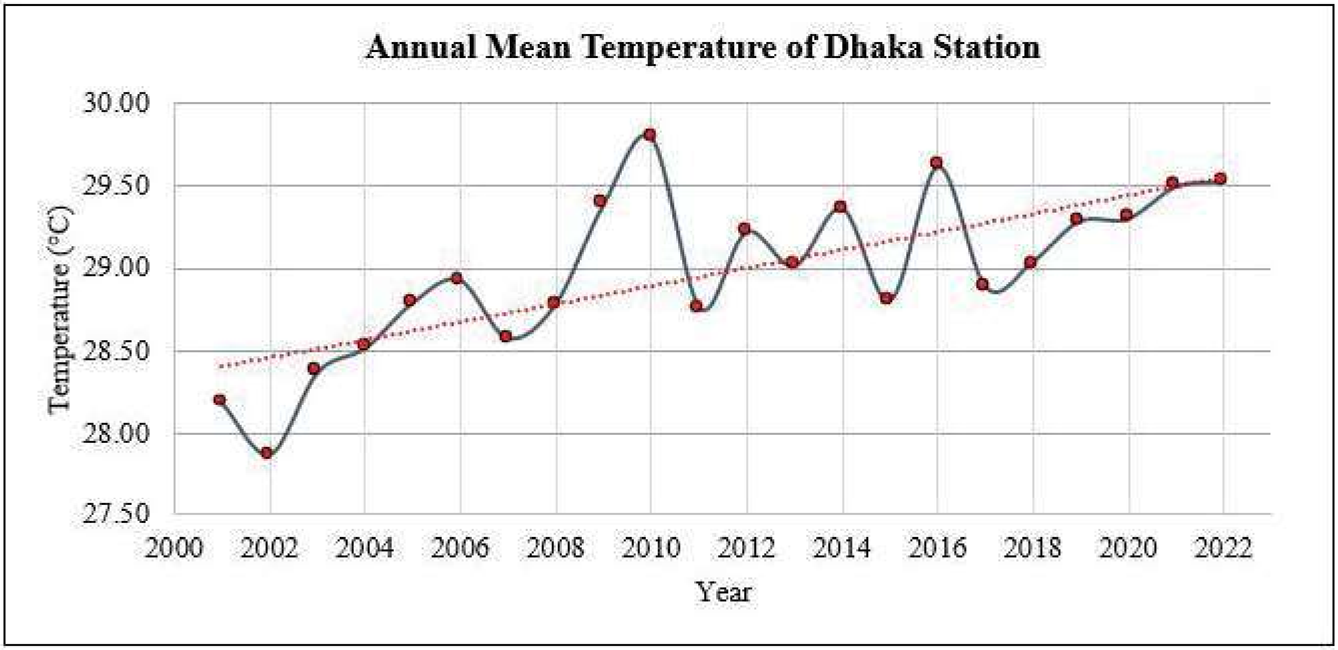

Figure 5: Annual Mean Temperature for the Warmer Months of Dhaka Weather Station

Source: BMD, 2023

Recent Trends of LST Change

The annual mean LST of Dhaka city ranges from 34.51 °C to 39.85 °C in the last nine years (2014 to 2022). This analysis excludes the years 2017 and 2021 due to the unavailability of cloud-free images in the warmer months. The mean temperature was lowest in 2016 (<35 °C). Except in 2016, the mean temperatures were above 35°C. The trend line shows a mild increase in mean temperature, though the average temperature in the last nine years has been above 37.5 °C and the maximum temperature sometimes exceeds 40 °C in some places (Figs. 7 and 8). A large portion of areas had a temperature ranging from 30 °C to 35 °C in the initial three years (2014-16). But in the last six years, greater areas have come under the range of 36 °C to 40 °C. The year 2019 was the warmest in the period. The mean temperature of the warmest months of the year was 39.85 °C. A continuous pattern of high and low temperatures is identified in time series analysis. If we thoroughly follow the pattern of the mean temperature of the last nine years, it can be assumed that the upcoming years (2023 and 2024) will be warmer than the last two years (2021 and 2022). The result has already been observed from April to June of 2023. Several heat waves having temperatures close to or above 40 °C were observed in Dhaka city.

The red portion of the graph represents the heat wave condition. The intensity of heat waves increases with the depth of colour. The heat waves observed in Dhaka city are mild (36-38 °C) to moderate (38-40 °C). A small portion of the city experiences severe (40-42 °C) to extreme (>42 °C) heatwaves. Such heat island effects were observed in 2019 and 2014. But this is not the real picture of the situation. A positive anomaly is found in urban areas. It means the observed temperature is higher than the baseline mean temperature. If a station in the plain land has a maximum temperature of more than or equal to 40 °C and 30 °C in the hilly region, it is considered a heat wave (Rathi et al., 2021; Ray et al., 2021).

As shown in (Fig. 6), sometimes the maximum temperature is as much as 8-10 °C higher than the mean temperature. A small portion of the city's water bodies and vegetated areas experience a temperature lower than 30 °C. The wetlands of the eastern part of the city, Hatirjheel, and National Zoo areas have experienced minimum temperatures in this period.

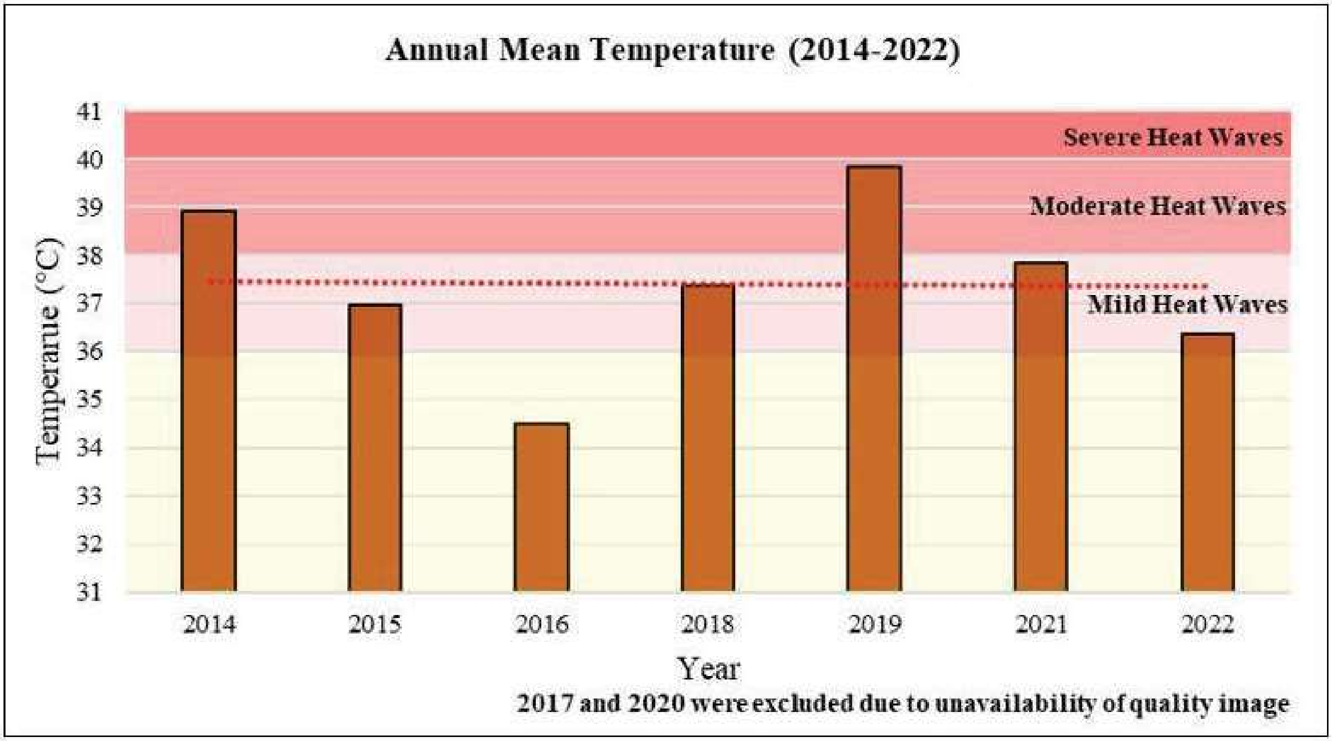

Figure 6: Annual Mean Temperature of Warmer Months in Dhaka City from 2014 to 2022

Source: Calculated from Landsat images in GEE

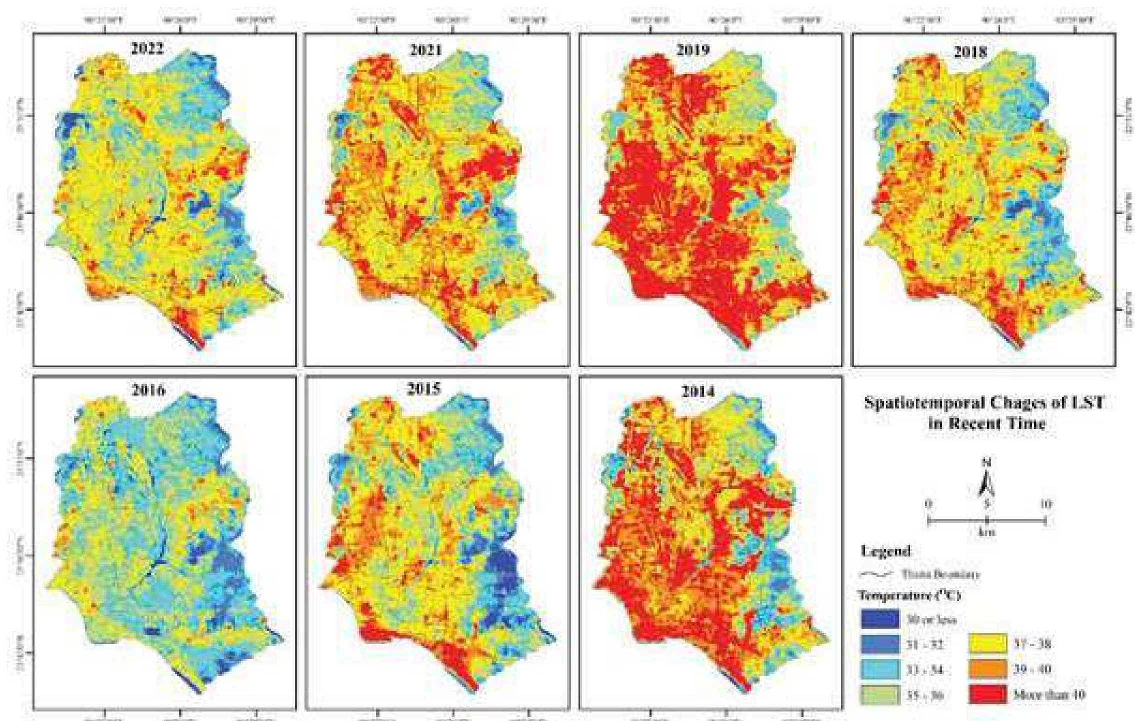

Figure 7: Spatiotemporal LST Changes in Dhaka City Over the Nine Years

Source: Calculated from Landsat images in GEE

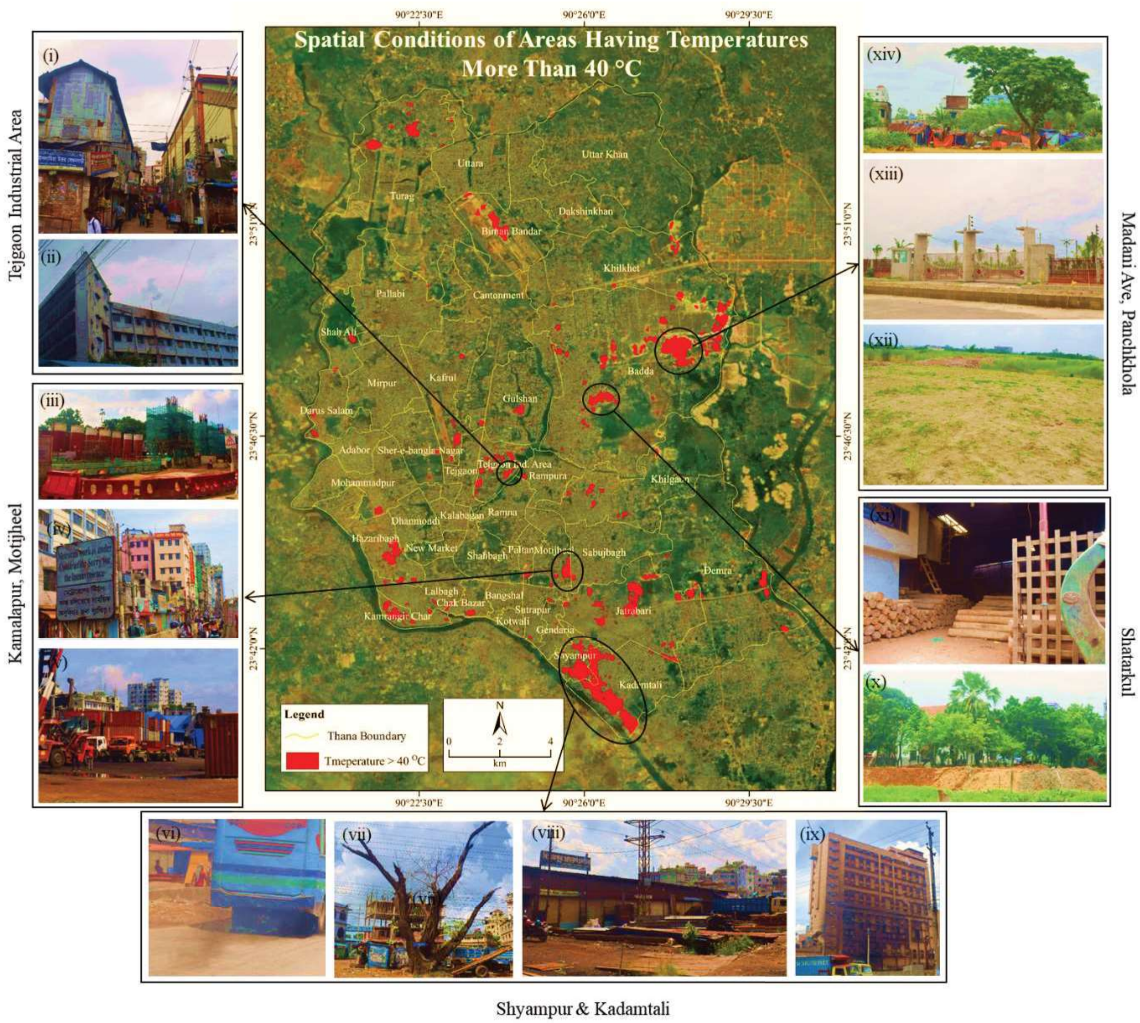

Figure 8: Location of the Areas Having a Mean Temperature of More than 40 °C in 2022

Source: Field study, 2023

(i) Congested housing and narrow roads, (ii) Warm and polluted air emitting from industries, (iii) Construction work, (iv) High-raised buildings, (v) Railway workshop and depo, (vi) Warm and polluted air from vehicles, (vii) Dead trees, (viii) Iron and steel mills, (ix) Warm and polluted air emitting from industries (x) Land filling in Shatarkul Khan (xi) Sawmill, (xii) Landfilling site, (xiii) New residential area under construction, (xiv) Informal settlement

Correlation Between LST and Various Indices

A correlation analysis based on the data of 2022 shows that LST has a positive correlation with population density, and NDBI (Table 4). The high-density population and greater built-up index raise the LST score. On the contrary, LST has a strong negative correlation with NDVI, NDWI, and NDMI. The relation between LST and NDVI is highly seasonal. Sun and Kafatos (2007) found a positive correlation between NDVI and LST in winter and a strong negative relation during the summer. On the contrary, NDWI's relation with LST is not time-specific but perpetually negative. Tiwari & Kanchan (2024) and Saha et al. (2024) found a positive correlation exists between NDBI and LST, indicating that increased built-up areas raise temperatures while NDVI and NDWI show an inverse relationship with LST, suggesting that healthy vegetation and water bodies help mitigate heat. Therefore, the temperature is low in the regions covered with vegetation and waterbodies. Moisture holds the heat and increases the temperature; also, moisture is derived from water bodies. Consequently, if greenery and water are there, the NDMI will also be high in those regions. Thus, these three have a negative correlation with HVI.

Table 4: Correlation Matrix of Different Indices, Population Density and LST

	LST	NDVI	NDWI	NDBI	NDMI	Pop. Density
LST	1					
NDVI	-0.74526	1				
NDWI	-0.690943	-0.99426	1			
NDBI	0.77622	-0.69314	0.620617	1		
NDMI	-0.77622	0.693137	-0.62062	-1	1	
Pop. Density	0.156105	-0.32158	0.326431	0.195039	-0.19504	1

Recent Condition of UHI

The mean temperature for urban polygons was found to be 37.01 °C, and it is 33.11 °C for rural polygons. The city is 3.9 °C warmer than the neighbouring rural area. Besides, several areas of Dhaka city, e.g., Badda, Jatrabari, Kadamtali, Kamrangir Char, Tejgaon Industrial Area, Biman Bandar, Motijheel, and many small parcels, created very high-intensity UHI. The UHI value is categorized into five classes i.e., very low intensity, low intensity, moderate intensity, high intensity and very high intensity (Table 5).

Table 5: UHI Categories and Their Value

UHI Category	UHI Value
Very Low Intensity	Less than -1.44
Low Intensity	-1.44 to -0.4
Moderate Intensity	-0.4 to 0.38
High Intensity	0.38 to 1.24
Very High Intensity	More than 1.24

The spatial pattern of UHIs has changed over time. The southern (Jatrabari, Kadamtali, Shaympur), south-western (Lalbagh, Hazaribagh, Kamrangir Char, Chalk Bazar), middle-eastern (Badda), northern (Biman Bandar, Turag), central (Tejgaon Industrial Area, Kafrul) and middle-western (Mirpur, Darus Salam) parts of the city experience the extreme UHI condition (Fig. 9). The intensity of UHI was very high in the recent past. The years 2016 and 2014 show a moderate intensity for the southern and southwestern parts but very high intensity in the middle eastern part of the city. The intensity of UHI in Darsu Salam, Adabor and the southern part of Shah Ali was very high in 2015 and 2016 but the intensity has decreased gradually in the last six years.

On the contrary, the southeastern (Demra), eastern (eastern part of Khilgaon, the southern part of Badda), northeastern (Uttar Khan, Dakshin Khan, Khilkhet), south-western part of Turag and northern part of Shah Ali were relatively cold in the study period. The area of very low-intensity UHI has decreased tremendously.

There were similarities between heatwave categories and UHI intensity in the city. There are mild to moderate type heat waves that create moderate to very high-intensity UHIs. There is an inconsiderable difference between heat waves and heat islands. Heat waves are continuous occurrences of extreme heat that may last for 3-10 days. Heat islands are short-term phenomena created due to the difference in temperature between a core area (relatively high temperature) and its surrounding rural areas (relatively low temperature).

The maximum areas of Dhaka city experience moderate to very high-intensity heat islands. The value of UHI for high and very high intensity is greater than 0.38. Areas with densely built-up areas have a high UHI value, which creates heat islands. A value of UHI less than -1.5 has the probability of being a water body. The value ranges from -1.5 to -0.5 in vegetation. Finally, built-up areas have a UHI value of more than -0.5. The places that are covered with waterbodies and vegetation, as found in land use classification, show a very low intensity of UHI. As there is a strong negative relationship between waterbodies, vegetation, and UHI, the temperature of vegetated areas and waterbodies can't exceed the tolerated level. The analysis of the previous section shows a gradual increase in LST in Dhaka city. Besides, the number of hot days is increasing. It can be foreseen that the future will be worse if immediate measures are not taken.

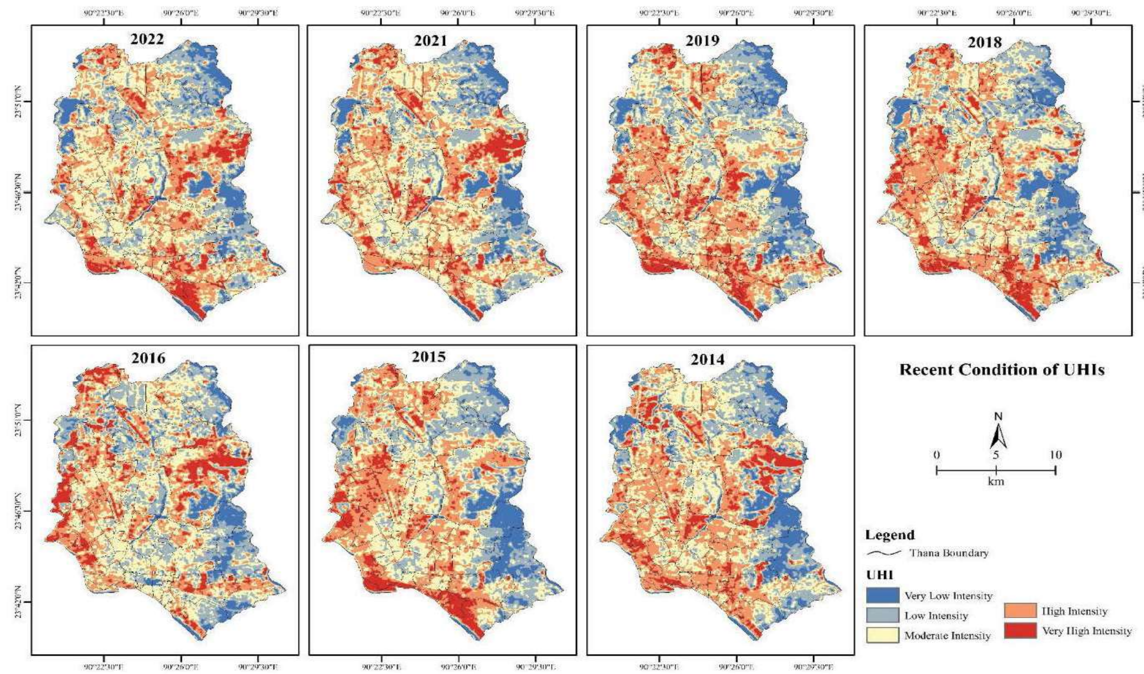

Figure 9: Incidence of UHIs in Dhaka City

DISCUSSIONS

The highest mean LST for the summer months was 39.86 °C and the lowest was 34.51 °C in the recent decade (2013-22). But the year 2004 was the coldest year found in the last two decades having a mean temperature of 31.6 °C. The rising trend of LST and air temperature found in this study is similar to previous studies which indicate that LST has increased at a rate of 1.26°C per decade from 1991 to 2014, with higher temperatures observed in densely built-up areas, particularly slums (Hossain et al., 2022).

The time series analysis of LST recorded a five-year recurring series of high and low temperatures. It is assumed that the next two years (2023 and 2024) are going to be warmer (mean summer LST will exceed 39 °C). The result has already been observed in the city. City dwellers have already experienced several heat waves between April to June 2023, with maximum temperatures above 40°C.

A strong relationship was found between land use and UHI. Densely built-up areas have high UHI values, and water bodies have the lowest. The average UHI intensity was 3.9°C in the summer months of 2022. It means the city was 3.9°C warmer than the surrounding rural areas. The actual temperature exceeds this limit at maximum time. There reported a positive correlation between NDBI and LST (Tiwari and Kanchan, 2024; Saha et al., 2024). Invariably, the densely built-up areas of old Dhaka, Tejgaon Industrial Area, and some newly formed built-up areas of Badda experience very high-intensity UHI. The UHI value of these areas is above 1.24.

The major constraints of this study are the unavailability of cloud-free data for the monsoon season, the use of LST for the eight months' images to calculate the mean annual summer time temperature, and the lack of information and data to validate the output of the GEE-driven LST. The initial constraints were checked excluding the images of monsoon seasons; only cloud-free images of pre- and post-monsoon were used to get the mean LST of warmer months. There is a lack of field-level LST data. Therefore, BMD's air temperature data was used to make a comparison of the LST output. Besides, the locations having LST more than 40°C were visited and verified the land use of the places.

However, the outcomes will assist in identifying areas most vulnerable to heat-related health risks, inform decisions about urban greening and infrastructure development, and evaluate the effectiveness of mitigation strategies. Additionally, understanding the relationship between LST and UHI can contribute to climate change adaptation planning and the development of resilient urban environments.

CONCLUSIONS

The time series analysis of land surface temperature has been performed using thermal bands of Landsat 5 (2001-2012) and Landsat 8 (2013-2022) imagery. The warmer months (March to October) have been considered in the calculation of annual mean temperature. Warmer months were selected based on the literature review. The output, was then, compared with BMD's ground station data of Dhaka. The LST has been analysed in two phases. One is long-term change detection with five-year intervals for the last twenty years and the other is changes in LST in recent decades. The UHI has been calculated from the annual mean LST for the last ten years and investigated the changes in the UHI pattern. Results indicate that the upcoming years are going to be warmer than the previous decades, and the densely built-up areas with little or no vegetation and waterbodies will increase the vulnerability of the people as well as environmental degradation. A positive change in mean temperature in the last twenty years with consecutive fluctuations of temperature is also found. A year of high temperature was followed by a gradual decrease in temperature in the next two years and several gradual increases followed a year of low temperatures in temperature. The study faced several constraints, including the unavailability of cloud-free data during the monsoon season, reliance on eight months' images for mean temperature calculations, and a lack of field-level data for validation. The study excluded monsoon season images, used BMD's air temperature data for comparison and conducted field visits to verify high LST locations to enhance the accuracy and reliability of the LST data. However, this study is crucial for understanding the city's microclimate and will assist in planning for mitigation of UHI risk.

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Appendix 1: Landsat Images Used for Calculating Mean Warmer-months LST

Year	Satellite	Date	Path	Row	Thermal Band Resolution
2001	Landsat 5	March 10, 2001	137	043	120m
		April 11, 2001	137	043	
		May 13, 2001	137	043	
		March 10, 2001	137	044	
		April 11, 2001	137	044	
		May 13, 2001	137	044	
		September 02, 2001	137	044	
2006	Landsat 5	March 08, 2006	137	043	120m
		April 25, 2006	137	043	
		October 02, 2006	137	043	
		March 08, 2006	137	044	
		April 25, 2006	137	044	
		October 02, 2006	137	044	
2011	Landsat 5	March 06, 2011	137	043	120m
		April 07, 2011	137	043	
		September 30, 2011	137	043	
		March 06, 2011	137	044	
		April 07, 2011	137	044	
		May 09, 2011	137	044	
2014	Landsat 8	March 14, 2014	137	043	100m
		March 30, 2014	137	043	
		October 08, 2014	137	043	
		March 14, 2014	137	044	
		March 30, 2014	137	044	
		May 01, 2014	137	044	
		May 17, 2014	137	044	
		October 08, 2014	137	044	
2015	Landsat 8	March 17, 2015	137	043	100m
		April 02, 2015	137	043	
		May 01, 2015	137	043	
		September 25, 2015	137	043	
		October 11, 2015	137	043	
		March 17, 2015	137	044	
		September 09, 2015	137	044	
		September 25, 2015	137	044	

2016	Landsat 8	March 03, 2016	137	043	100m
		September 27, 2016	137	043	
		October 13, 2016	137	043	
		March 03, 2016	137	044	
		April 20, 2016	137	044	
		May 06, 2016	137	044	
		September 27, 2016	137	044	
2018	Landsat 8	March 09, 2018	137	043	100m
		March 25, 2018	137	043	
		May 12, 2018	137	043	
		May 28, 2018	137	043	
		October 03, 2018	137	043	
		October 19, 2018	137	043	
		March 09, 2018	137	044	
		March 25, 2018	137	044	
		April 10, 2018	137	044	
		May 12, 2018	137	044	
		September 17, 2018	137	044	
		October 03, 2018	137	044	
2019	Landsat 8	March 28, 2019	137	043	100m
		April 13, 2019	137	043	
		May 15, 2019	137	043	
		September 20, 2019	137	043	
		March 28, 2019	137	044	
		April 13, 2019	137	044	
		May 15, 2019	137	044	
2021	Landsat 8	March 17, 2021	137	043	100m
		April 18, 2021	137	043	
		September 25, 2021	137	043	
		October 11, 2021	137	043	
		March 01, 2021	137	044	
		March 17, 2021	137	044	
		April 18, 2021	137	044	
		October 11, 2021	137	044	
2022	Landsat 8	March 04, 2022	137	043	100m
		March 20, 2022	137	043	
		May 07, 2022	137	043	
		September 28, 2022	137	043	
		March 04, 2022	137	044	
		March 20, 2022	137	044	
		May 23, 2022	137	044	

Appendix 2: LST Estimation and UHI Calculation Using JavaScript in GEE

(**Source:** NASA Applied Remote Sensing Training program)

```
var DATE_RANGE = ee.Filter.dayOfYear(59, 294);

var YEAR_RANGE = ee.Filter.calendarRange(2022, 2022,'year');

var STUDYBOUNDS = aoi;

var DISPLAY = true;

Map.setOptions('SATELLITE');

Map.setCenter (90.407608, 23.811056, 10);

var LC08_bands = ['ST_B10', 'QA_PIXEL'];

function cloudMask(image) {

  var qa = image.select('QA_PIXEL');

  var mask = qa.bitwiseAnd(1 << 3)

    .or(qa.bitwiseAnd(1 << 4));

  return image.updateMask(mask.not());

}

var L8 = ee.ImageCollection('LANDSAT/LC08/C02/T1_L2')

  .select('ST_B10', 'QA_PIXEL')

  .filterBounds(STUDYBOUNDS)

  .filter(DATE_RANGE)

  .filter(YEAR_RANGE)

  .map(cloudMask);

var filtered_L8 = L8.filter(ee.Filter.lt('CLOUD_COVER', 20));

print(filtered_L8, 'Landsat 8 ST');

function applyScaleFactors(image) {

    var thermalBands = image.select('ST_B10').multiply(0.00341802).add(149.0) // Scale factors for Kelvin

  .subtract(273.15); // Scale factor for degrees Celsius

  return image.addBands(thermalBands, null, true);

}

print(filtered_L8, 'Landsat ST (Celsius)');

var landsatST = filtered_L8.map(applyScaleFactors);

print("... Computing mean ST across image collection");
```

Calculate Mean Surface Temperature

```
var mean_LandsatST = landsatST.mean();

var clip_mean_ST = mean_LandsatST.clip(STUDYBOUNDS);

print(clip_mean_ST, 'Mean ST clipped to study area');

var values_ST = clip_mean_ST.select("ST_B10");

var histogram_ST_values = ui.Chart.image.histogram(values_ST, STUDYBOUNDS, 30);

print(histogram_ST_values);

Map.addLayer(clip_mean_ST, {

  bands: "ST_B10",

  min: 28, max: 47,

  palette: ['blue','white','red']}, "ST", DISPLAY);

print('... Mean/Min/Max ST for urban Dhaka');

var statsUrban = clip_mean_ST.reduceRegions({

  collection: Urban,

  reducer: ee.Reducer.mean().combine({

  reducer2: ee.Reducer.minMax(),

  sharedInputs: true

  }),

  scale: 30});

print (statsUrban);

print('... Mean/Min/Max ST for rural Dhaka');

var statsRural = clip_mean_ST.reduceRegions({
```

```
  collection: Rural,
  reducer: ee.Reducer.mean().combine({
  reducer2: ee.Reducer.minMax(),
  sharedInputs: true
  }),
  scale: 30});
print (statsRural);
Export.image.toDrive({
  image: values_ST,
  description: 'ST_2022MartoOctMean',
  scale: 30, // Set the spatial resolution to 30 meters
  maxPixels: 1e13, // Set the maximum number of pixels to export
  region: aoi // Set the export region to the study area
});
```

Calculate Surface Urban Heat Island

To calculate the surface urban heat island (SUHI) intensity for your aoi, find the Mean/Min/Max ST under the Console tab --> FeatureCollection --> features --> properties --> ST_B10_mean

Subtract the mean urban temperature from the mean rural temperature.

(ST_B10_mean [Urban]) - (ST_B10_mean [Rural]) = SUHI intensity