Analyzing the Land Surface Temperature Dynamics in Kolkata City, India

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Abstract

The increasing global urbanization trend has raised concerns over the amplified warming of urban landscapes. This urbanization process is closely linked to the rise in Land Surface Temperature (LST). As urban areas expand and develop, they often experience what is known as the Urban Heat Island (UHI) effect, wherein temperatures within the urban environment become significantly warmer compared to surrounding rural areas. This phenomenon is primarily attributed to changes in land cover, increased heat retention from human activities and infrastructure, reduced vegetation, and altered surface properties. The increasing LST is one of the budding anthropogenic issues causing problems for livelihood in urban areas. This study aims to present a temporal analysis of LST diurnally and seasonally for the megacity of Kolkata for 2002-2022 over 20 years. The spatiotemporal changes in LST during the day and the night times are analysed for both summer and winter seasons. Trend analysis is conducted for both the seasons during day and night LST. The observations indicate that the significant increasing trend of LST values is more prominent in night as compared to the day, due to the high amount of radiation by the impervious surfaces during the night. This study contributes to the body of knowledge surrounding the urban climate dynamics for Kolkata, India, offering valuable insight to policymakers, urban planners, and environmental scientists.

Keywords: Land Surface Temperature, Urbanization, Megacity, MODIS, Trend analysis.

Introduction

The transformation of the built environment from rural areas to urban settlements is a complex socio-economic process called urbanization (*United Nations*, 2010). There has been a dominant change in the occupational structures, culture, and lifestyle preferences which has also altered the demographic structure of the rural as well as the urban areas. About 56% of the population of the world contemporarily works in the cities and it is estimated that this trend will double by the year 2050 (United Nations, 2009). There are several consequences seen for this urban expansion (Nichol & Wong, 2005). Diminishing green spaces and expansion in impervious land are the most significant challenges cities face. It affects the surface and air temperature which in turn deteriorates environmental health and eventually human health (Singh & Jain, 2022). The most prominent effect is the conversion of vegetated areas into concrete jungles. The high built-up area is supposed to have a higher

Land Surface Temperature (LST) than the surrounding areas with less built-up intensity. These areas thus have lower surface reflectance resulting in higher heat capacity making the city regions warmer and warmer.

Global warming plays a significant role, especially in the less developed and developing areas. Climate change has increased global warming which is prominently seen in both the rural and urban areas however the effect of the rising temperature is felt more in the urban areas (Halder et al., 2023). Extreme heat is the leading cause of weather-related mortality and causes various physical and psychological illnesses. The LST is presumed to have increased due to the conversion of green spaces into built-up areas (Ramaiah et al., 2020). Through the usage of remote sensing data and Geographic Information System (GIS) techniques, urbanization and its adverse effects on the LST can be studied (Feyisa et al., 2016). A study carried out in Lucknow, India highlights that the impervious surfaces have a higher LST of about 4-6˚ C than the greener surfaces (Shukla & Jain, 2021). The incoming solar radiation from the sun interacts with the ground surface which heats up and the LST measurements basically detect these thermal radiations. Thus, LST has serves as a strong indicator to measure the microclimatic changes caused due to urbanization globally and is seen more prominently in developing countries. One of the reasons for this might be the unplanned development and unbound utilization of resources (Kanai et al., 2018).

The current study aims to analyze the variation of LST of Kolkata megacity from 2002 and 2022, which is in relation to the urban expansion from the core of the city towards the periphery where the green spaces decrease. The trend of LST is studied for day and night times for summer and winter seasons throughout the period of two decades. The study provides a knowledge base to formulate a more sustainable eco-system around urban environment so that rapid urban expansion does not disrupt the green spaces of the urban area.

Materials and Method

Study Area: The megacity of Kolkata situated at the banks of River Hooghly has a geographical extension of 22˚ 24’ 39” N to 22˚ 46’37” N latitude and 88˚ 11’19” E to 88˚ 34’ 25” E longitude (Ramachandra et al., 2014). It is an important city in eastern India which is a fast-growing-million-population-level city. It ranks as India's third most densely populated metropolis and stands as the thirteenth most populous urban agglomeration globally. It boasts the distinction of being the eighth largest city of its kind in the world, with an approximate population of 14.11 million according to the latest census data (Census of India 2011, n.d.). According to the census of India, the annual growth rate of Kolkata Urban Agglomeration (KUA) is 1.8%, and the population density of the region has increased by about 90.24% from the year 1901 to the year 2011. And currently the KUA area has expanded to about 1886.67 km^2 (Mithun et al., 2021).

There are four Municipal Corporations administering the KUA, namely the Municipal Corporation of Kolkata, Howrah, Bidhan Nagar and Chandannagar. This urban agglomeration has a population growth rate of 0.84% making it the seventh-largest populated city in India (Paul & Sen, 2018). It is situated in a tropical climate with very hot summers where the temperature ranges between 24 to 38˚C and warm winters too with 12 to 27˚C temperatures (Bera et al., 2022). This massive rate of expansion of the city has given rise to several environmental problems along with an estimated rising trend of LST, especially in the highly urbanized areas. The expansion of these built-up spaces is at the expense of the city's Green Spaces and open spaces (Sikarwar, 2020). A shifting centre has been noticed from the south to the northern side of the Urban Agglomeration, particularly on the eastern side of the river Hoogly (Chatterjee et al., 2019).

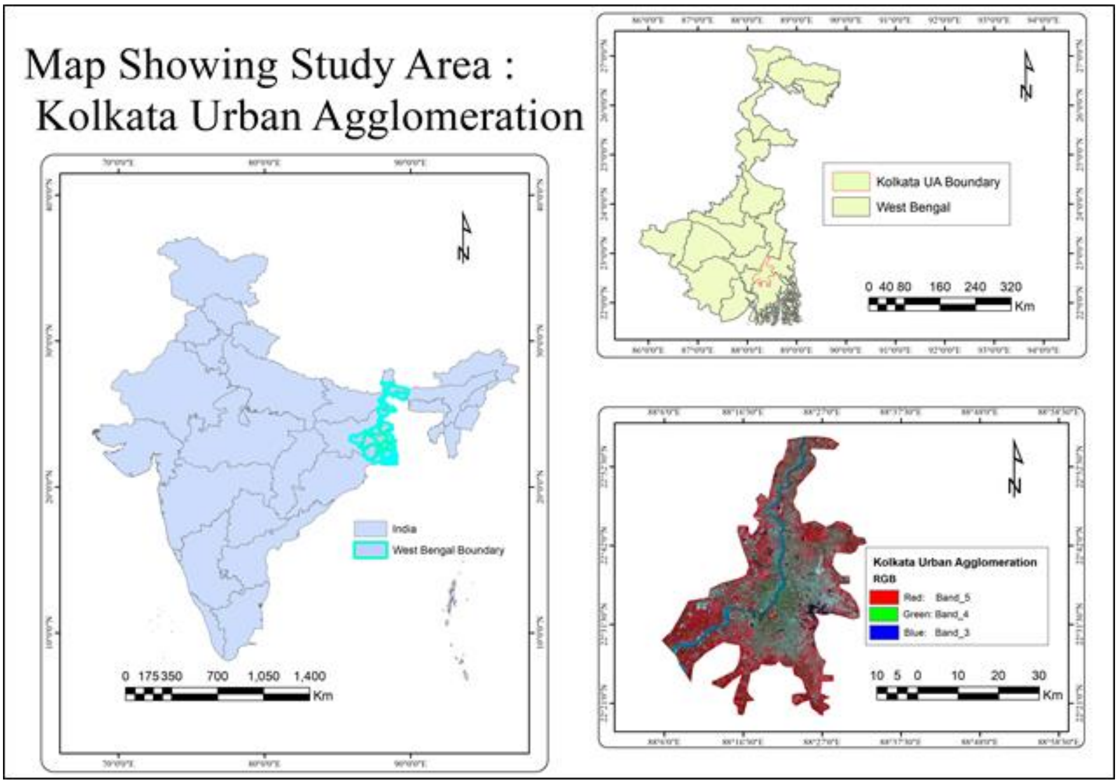

Fig. 1 The picture shows (a) Map of India, (b) Map of West Bengal, and (c) Map of Kolkata Urban Agglomeration which is the study area for this research.

Data Sources: In this study, the LST data is quantified using MODIS (Moderate resolution Imaging Spectroradioter) 8-day emissivity data (MOD11A2) from TERRA satellite, having a resolution of 1 km × 1 km. The LST Day and LST night data is used for both summer and winter seasons. The mean temperature per pixel is calculated for the months of April and May as summer LST, and for months November, December, and January as winter LST.

VIIRS (Visible Infrared Imaging Radiometer Suite) Stray Light Corrected Day/Night Band Composites Version 1, nighttime lights data for the year 2022 was taken. The boundary of the Urban Agglomeration was delineated by using the Night Light Intensity data of the year 2022 using Google Earth Engine (GEE) and drawing the boundary.

GEE is a cloud-based computing platform for "petabyte-scale scientific analysis and visualization of geospatial datasets" it makes possible to extract and process huge amount data over single platform. Here, the GEE was used as the primary platform for retrieving the required LST data, preprocessing it, and retrieving LST data pixel-wise for two decades and for two extreme seasons.

Methodology

Quantification of LST: LST is said to be the "skin temperature" of the ground surface and is determined by the radiating temperature of the earth. The daytime LST was retrieved by using the 'LST_Day_1 Km' band of MOD11A2 data, and the 'LST_Night_1 Km' band was used for night-time LST in GEE platform. The average LST values per pixel were acquired after getting the mean of the chosen months for both summer and winter seasons. This procedure is conducted for each year from 2002 to 2022. The temperature was converted from Kelvin to Celsius for convenience and feasibility of interpretation. The trend in LST is studied for both the seasons for day and night. This enables us to comprehend the LST variation during day and night for both the seasons and percentage of area showing variations.

Mann-Kendall Trend Test and Sens's Slope Analysis: Mann-Kendall trend test is a non-parametric trend analysis technique that is monotonic and works good with both linear and non-linear data. Hence, it has found a wide application in time-series analysis (Mohammad & Goswami, 2021). This test does not confine to any distribution of datasets and is not sensitive to abrupt breaks. This trend also does not assume normality and indicates the direction of the significant trend. The method hypothesize a null hypothesis H_0 which states that there exist no monotonic trend in the time series, x_i, $i = 1, 2, 3, .., n$, and the alternative hypothesis H_1 states that a monotonic trend exists in the data (Wang et al., 2020). The Trend Test statistic S is derived as given below (Henry, 1945; Kumar Sen, 1968):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(LST_j - LST_i)$$

where LST_i and LST_j are the observed LST of the year i and j, respectively and sgn is given by,

$$sgn(LST_j - LST_i) = \begin{cases} +1, & LST_j - LST_i > 0 \\ 0, & LST_j - LST_i = 0 \\ -1, & LST_j - LST_i < 0 \end{cases}$$

it is seen that the values of the sgn function varies between -1, 0, and 1 based on the value of $(\boldsymbol{LST_j - LST_i})$. The variance can be calculated as shown below.

$$Var(S) = \frac{n(n-1)(2n+5)}{18}$$

The standard orthogonal statistical distribution, Z, of the Mann-Kendall trend test can be calculated as under.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases}$$

Here, Z follows a standard normal distribution. The trend of Z that is positive indicates a rising trend and the negative value of Z indicates a falling trend. Sen's slope gives an estimate of the changing trend over a time series which also takes care of the missing values and outliers (Gocic & Trajkovic, 2012). It is given by the equation below.

$$slope = median\left(\frac{LST_j - LST_i}{j - i}\right), \qquad \forall j > i$$

Here, the median is the median function, LST_j and LST_i are the observed values of j and i time in time series.

Result and Discussion

Quantification of LST: The LST values form 2002 to 2022 were quantified. The significant variation in summer and winter season is observed both during the day and the night throughout the study period of two decades. An increase in the lowest and the highest value of LST in both the seasons can be seen through Figure 2 and Figure 3.

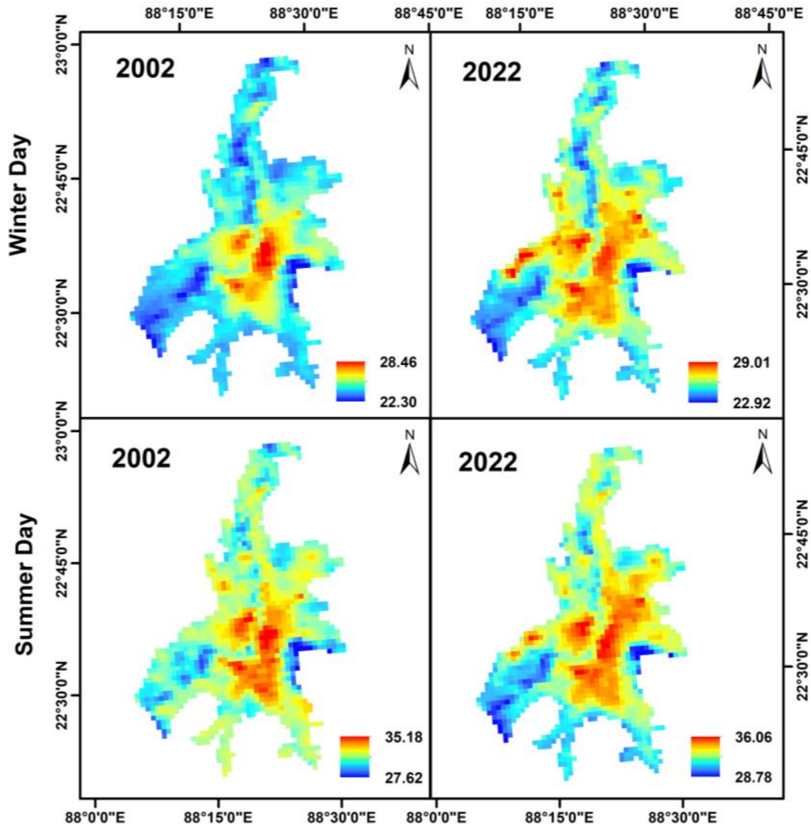

Fig. 2 LST of Winter and Summer Day for the years 2002 and 2022.

Day-time LST variations in summer and Winter: The winter-day map of 2002 in Figure 2 shows that the temperature is highest in the urban core in the central and west central parts of the study area. The central region consists of areas like Baranagar, Hastings, Bow Barracs, Maidan, Hastings etc., and a patch at the west central part of the study area has Howrah station situated. The maximum LST for winter day for the year 2002 is 28.46˚C which increases to 29.01˚C in 2022. The extent of the heat core increases in all directions in two decades. The west-central edges of the study area, from Dankuni to Dhulagori under Howrah Municipality, highest LST is noticed along with other areas where high LST already persisted in 2002 also.

In case of summer-day, the highest LST in 2002 was seen to be 35.18˚C which increases to 36.06˚C in the year 2022. Prominent heat core is seen in the central part of the study area in 2002 and it increases in all the directions in the year 2022. The northern edge of the study area also shows significantly high LST which increases in the year 2022. A trend of increase in

LST is observed in the north-eastern part of the study area, which comprises of areas like Panihati, Hridaypur, Malikpur.

Night-time LST variations in summer and Winter: The winter-night LST maps given in Figure 3 show significant changes over time. In 2002 the maximum temperature was 19.23˚C whereas in the year 2022, the maximum temperature drastically increased to 20.01˚C. The high LST was seen throughout the central part of the study area which intensified and spread over time.

In summer-night, the patches of LST in central part of the study area also intensifies during the study period. There is also an increase in the LST towards the northern part of the study area in 2022. The areas in the north like Baidyapara, Bhatpara, Chandannagar, Chinsura, Naihati, etc., show an increase in LST in 2022. As compared to summer-night, it is observed that the increase in LST is noticed more prominently during the winter nights.

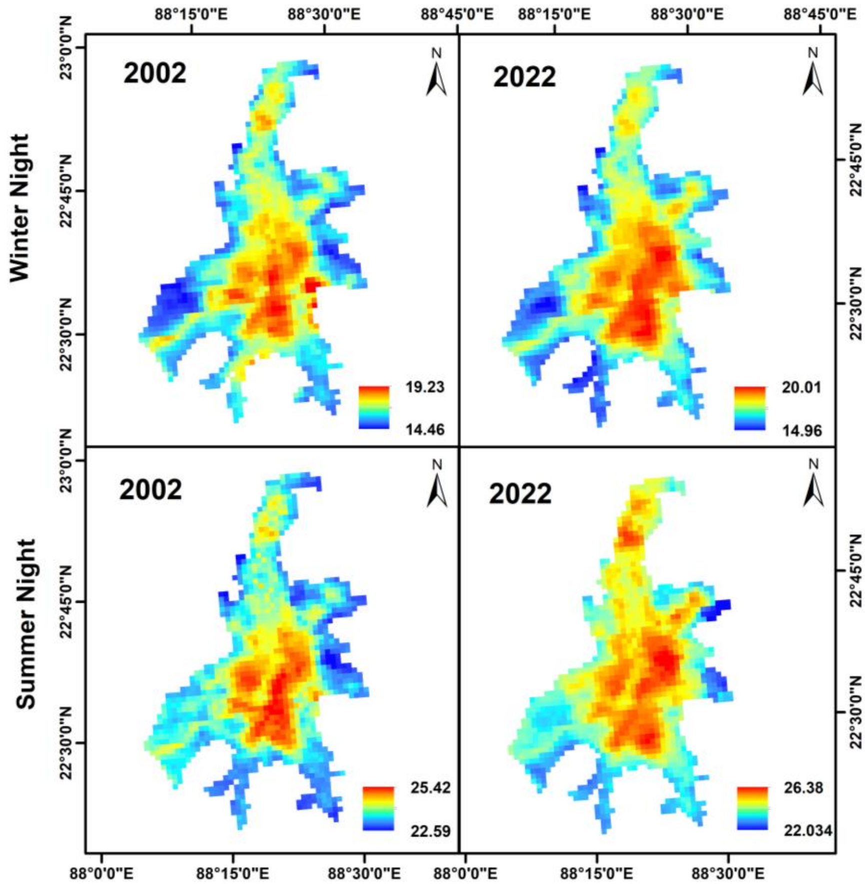

Fig. 3 LST of Winter and Summer Night for the years 2002 and 2022.

LST Trend Analysis

Mann- Kendall Trend Test: Mann-Kendall trend analysis was carried out on the per-pixel LST data of 20 years (2002-2022). It was conducted for summer-day, summer-night, winter-day, and winter-night. Some areas showed no trend. While there was no decreasing trend observed in LST during the study period, a significant increasing trend was noticed in all the four scenarios studied.

Table 1 Number and percentage of pixels exhibiting increasing and no trends in all scenarios.

		Summer Day	Summer Night	Winter Day	Winter Night
Increasing trend	**No. of pixels**	692	783	607	698
	Percentage	54%	61%	47%	52%

Table 1 shows the number and percentage of pixels exhibiting trends (increasing) and no trend. The total number of pixels covered in the study area is 1291. Winter-night results show that about 52%, and summer-nights show 61% of the total study area exhibit an increasing trend. Winter-day and summer-day results show that 47% and 54% of the study area exhibit an increasing LST trend. The urban area of Kolkata is rapidly expanding and capturing the surrounding green areas, by transforming them into urban. The winter-nights have clear skies and less atmospheric disturbances, due to which the phenomenon of increase of LST becomes more prominently visible.

Sen's Slope:

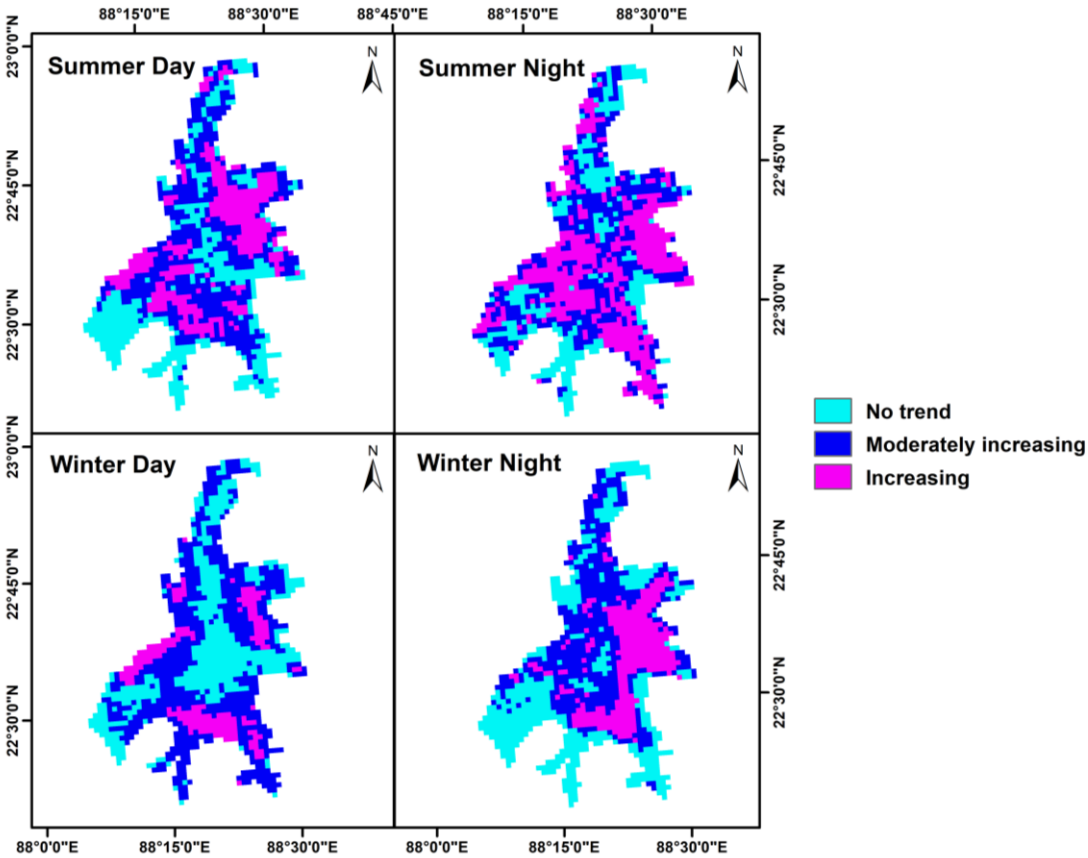

Fig. 4 Sen's Slope for LST of Kolkata from 2002-2022.

The sen's slope map is shown in Figure 4, for the four cases. Sen's slope represents the magnitude of the increase or decrease of trend. From the analysis it is observed that during the summer season, both day and night LST values show an increasing trend in majority of the area. In summer day, the mean increase in LST is 0.07˚C/year and in summer-night, it is 0.035˚C/year. In case of winter-night, the mean increase in LST is 0.044˚C/year, and that for winter-day, it is 0.0324˚C/year. The highest rate of growth is observed in summer day LST.

The observations indicate that the sens's slope values of high magnitude is more prominent in night LST images. This is due to the high amount of radiation by the impervious surfaces during the night. Throughout the day, impervious land keeps on absorbing a large amount of heat, which is then radiated in the night hours during its cooling process.

Discussion

A significant increase in the LST trend is seen over the two decades. The study found that with the expansion of unplanned urbanization, impervious spaces rapidly increase which results in elevating the LST of the city. Whereas, the increase in high LST zones were observed in the core urban region. The findings from the study is in line with the previous studies (Rahaman et al., 2019; Rukhsana & Hasnine, 2021; Sahana et al., 2019; Sharma et al., 2015). It is also revealed that summer-night, have the increasing trend of LST which contributes more warmer nights in summer. Human activities, including the utilization of fossil fuels, the release of industrial pollutants, and the emission of greenhouse gases, exacerbate the urban heat island effect created by urban development (Shukla and Jain, 2021).

The Mann-Kendall test and Sen's slope analysis also confirm that there is an overall increase in the trend of the LST as a significant number of pixels show an increasing trend. The increase in LST in night of winter depicts the impact of these activities are contributing to climate change. Therefore, it is crucial to monitor these patterns to facilitate the potential implementation of sustainable urban management initiatives. Consequently, the analysis of LST on a city-wide scale remains relevant, and this analysis should be conducted periodically to stay informed about evolving conditions and the potential impact of any urban heat island mitigation measures. Moreover, such investigations should ideally encompass not only the central urban area but also the surrounding peri-urban and rural zones, as urban development is expected to expand into these areas in the future, leading to alterations in land use and changes in LST therein. Thus, in future we would like to expand the study on peri-urban conditions of the city.

Conclusions

The study shows that LST in the KUA increased significantly between 2002 and 2022. This upward trend, particularly pronounced during summer nights, is driven by urbanization, leading to the expansion of the heat from the city centre to its periphery. This finding underscores the urgent need for sustainable urban planning, policies, and interventions to mitigate the adverse effects of rising temperatures. To ensure Kolkata's live-ability and resilience in the face of urban growth and climate change, cooling strategies, green infrastructure, and community engagement are essential. Our research provides a valuable foundation for informed decision-making, offering insights to create a more climate-responsive and environmentally sustainable KUA in the future.

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Chowdhury, A., Anand, T., Singh, S., Shukla, A. (2024). Analysing the Land Surface Temperature Dynamics in Kolkata City, India. In: Dandabathula, G., Bera, A.K., Rao, S.S., Srivastav, S.K. (Eds.), Proceedings of the 43rd INCA International Conference, Jodhpur, 06–08 November 2023, pp. 418–427, ISBN 978-93-341-2277-0.