International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 10 No. 4, 2024
https://theaspd.com/index.php

Spatiotemporal Variations of Land Surface Temperatures in Eastern South Asia

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ABSTRACT
Understanding the fluctuations in land surface temperature (LST) is essential for precisely forecasting climatic patterns and implementing effective measures. This study aimed to investigate the spatiotemporal patterns and trends of LST in Eastern South Asia from 2000 to 2024 using MODIS data. Cubic spline was used to assess seasonal patterns and auto-regressive model was used to assess the trend of LST. The average increase of LST was determined by the multivariate regression model. Daytime LST showed a general decreasing trend across most regions, while nighttime LST exhibited a consistent warming trend, with notable regional variations. The Lower North region experienced the most pronounced nighttime warming, while the Far East and Lower Central West regions showed higher increases in nighttime LST. The forecasting model indicated persistence of these trends, with daytime LST expected to continue cooling and nighttime LST forecast to steadily increase. The difference has significant implications for ecology, agriculture, human health, and urban development. In order to mitigate climate change and support evidence-based policymaking in South Asia, this study highlights the necessity for developing policies along with conducting further studies on LST trends.
KEYWORDS: *Land Surface Temperature, Climate Change, Trend, Cubic Spline, Remote Sensing, Eastern South Asia, Spatiotemporal variation*

1. INTRODUCTION

Understanding the variations in land surface temperature (LST) is crucial for accurately predicting climate trends and formulating effective adaptation strategies. Changes in LST significantly affect ecosystem function and biodiversity, altering habitats, migration patterns, and reproduction rates of various species (Albright et al., 2011; Ogutu et al., 2024). Evaluating environmental and climatic changes requires extensive LST analysis for environmental monitoring and management, especially in places with high climate variability and different ecosystems (Good et al., 2022; Hegglin et al., 2022; Sismanidis et al., 2022; Mansourmoghaddam et al., 2024).

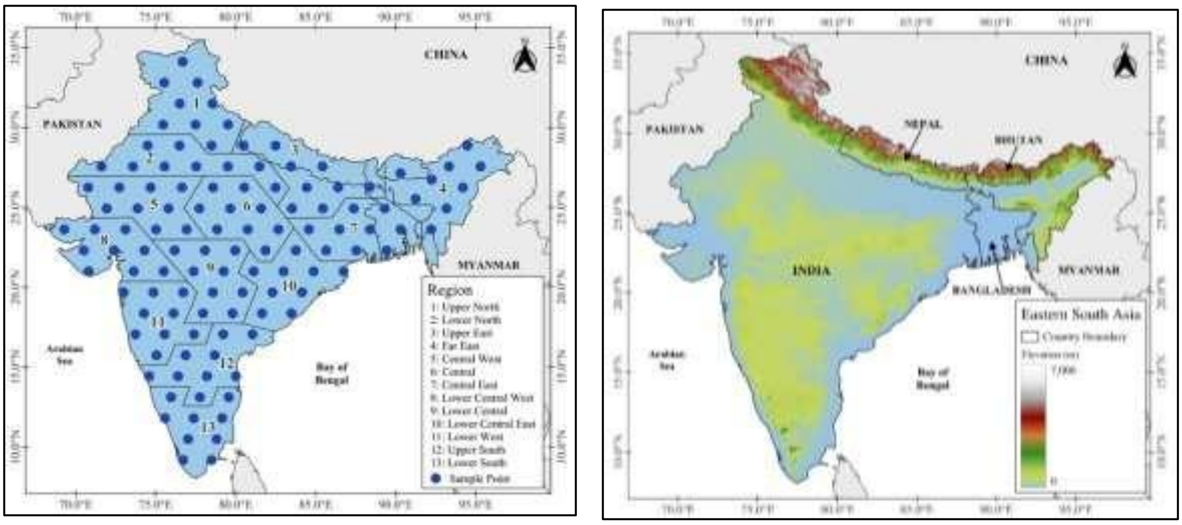
Eastern South Asian countries (including India, Bangladesh, Bhutan, and Nepal) are characterized by their varied ecosystems and climates. In India, rapid urbanization has been widely documented as a key driver of increasing land surface temperature (LST) (Pandey et al., 2022). Empirical evidence from city- and regional-scale studies indicates that urban expansion and land use change significantly intensify surface thermal conditions. For example, Khandelwal et al. (2018) reported a pronounced rise in LST in Jaipur associated with the growth of built-up areas. Using long-term Moderate Resolution Imaging Spectroradiometer (MODIS) LST data, Nayak et al. (2023) further demonstrated that major Indian cities consistently exhibit higher LSTs than their surrounding rural areas, highlighting the presence of a strong urban heat island effect. At a more localized scale, Neog (2022) analyzed seasonal variations in LST in Agartala and identified an inverse relationship between LST and vegetation cover. Similarly, Panwar et al. (2018) examined land use and land cover changes in the Uttarakhand region and found elevated LSTs in areas characterized by increased impervious surfaces, while comparatively lower temperatures were observed in regions with greater forest coverage. In Eastern South Asia, a growing body of evidence highlights the strong influence of urbanization and environmental change on land surface temperature (LST). In Nepal, Kandel et al. (2022) analyzed urban heat island (UHI) effects in major cities and identified a significant association between increasing LST and vegetation loss, as measured by the Normalized Difference Vegetation Index (NDVI). Consistent with these findings, Regmi et al. (2021) reported that rapid urbanization and deforestation in the Phewa watershed have contributed to elevated LST, thereby increasing local climate vulnerability. Extending this perspective to Bhutan, Chhetri et al. (2024) examined interactions between urban dynamics and environmental factors and demonstrated that urban expansion has markedly intensified LST, particularly in low-lying areas. Similarly, in Bangladesh, Abdullah et al. (2022) projected future LST trends in Chittagong, indicating that continued urban growth is likely to further elevate LST and exacerbate UHI effects. Collectively, these studies underscore the urgent need for sustainable urban planning and effective environmental management strategies to mitigate the adverse thermal impacts associated with ongoing urban expansion across Eastern South Asia Daytime and nighttime temperature trends offer complementary insights into the changing climate dynamics. Daytime temperatures typically reflect direct solar radiation impacts and urban heat island effects, while nighttime temperatures are influenced by the earth's radiative cooling and thermal properties of the surface. Therefore, analyzing daytime and nighttime LST provides a comprehensive understanding of temperature variations and their underlying causes (Murari et al., 2015). The differentiation in daytime and nighttime temperature trends is crucial due to its diverse climatic regions and the varying impacts of urbanization, deforestation, and agricultural practices across these regions (Bhutiyani et al., 2007; Kothawale et al., 2010). Previous studies have documented pronounced spatiotemporal variations in land surface temperature (LST) across diverse environmental settings. In India, analyses based on Moderate Resolution Imaging Spectroradiometer (MODIS) data revealed a decline in winter LST alongside an increase in nighttime summer LST, with the highest temperatures observed in desert, urban, and semi-arid regions (Pandey et al., 2022). At a finer spatial scale, a multi-temporal Landsat-based study in Pune City demonstrated that urbanization has significantly contributed to increasing LST, with built-up areas consistently exhibiting higher surface temperatures than vegetated and green spaces (Di Leo et al. 2016). Together, these findings highlight the combined influence of seasonal dynamics and land use characteristics on LST variability, emphasizing the role of urban expansion in intensifying surface thermal conditions.

Previous research frequently concentrated on restricted geographical areas or shorter temporal periods, thereby failing to encompass the complete scope of LST variations throughout Eastern South Asia, especially the difference in daytime and nighttime LST. To address this gap, the present study employs 24 years of data (2000–2024) from MODIS LST data to examine the seasonal and temporal variations in both daytime and nighttime LST throughout the entire region of Eastern South Asia. Adopting a long-term and thorough strategy ensures that the results are accurate and provide a comprehensive picture of LST trends, which in turn supports the implementation of effective methods for climate adaptation and mitigation. Two primary research questions are addressed in this study 1) how did the Spatiotemporal patterns of daytime and nighttime LST in Eastern South Asia evolve over the 24-year study period (2000–2024), and what are the quantifiable disparities in these trends across various regions and sub-regions? 2) based on these empirical observations, what are the projected LST variations for the next decade? By addressing these questions, this study aimed to gain a comprehensive understanding of LST dynamics across this climatically diverse region. The results of this study will contribute to the growing body of knowledge on climate change impacts in Eastern South Asia and provide valuable insights for formulating evidence-based strategies for climate resilience and sustainable development.

2. MATERIALS AND METHODS

2.1 Study Area

This study analyzed LST across Eastern South Asia to ensure comprehensive data coverage. Eastern South Asia, located north of the equator, is between 8°4' north to 37°6' north latitude and 68°7' east to 97°25' east longitude. India, covering an area of approximately 3.287 million square kilometers, is the world's seventh-largest country (Wolpert et al., 2024). Its diverse range of climatic and ecological zones provides a rich context for environmental research. Nepal, with its varied topography that includes some of the world's highest peaks, covers about 147,516 square kilometers and significantly influences regional climate dynamics (Sapkota and Rijal, 2016; Dawadi, 2017; Rose et al., 2024). Bangladesh, known for its lush landscapes and high population density, occupies approximately 148,460 square kilometers. It plays a crucial role in shaping the climate pattern of the region (Masum, 2019; Tinker and Husain, 2024). Bhutan, with its mountainous terrain and significant elevation changes, spans around 38,394 square kilometers and profoundly affects the regional climate dynamics (Nagai et al., 2014; Lehner and Formayer, 2023; Norbu and Karan, 2024). The combined area of Eastern South Asia, totaling around 3.62 million square kilometers, offers a unique opportunity to study climatic and environmental patterns in one of the most climatically diverse regions globally. The elevation map, illustrating the topographical characteristics of the study area, is presented in Figure 1.



(a) (b)

Figure 1 (a) Study area in Eastern South Asia (India, Nepal, Bangladesh, and Bhutan) and (b) Elevation Map of the study area

2.2 LST Data

Daytime and nighttime LST data were downloaded from the MODIS LST/E 8-Day product MYD11A2 (ORNL DAAC, 2018). This dataset provides an 8-day averaged LST per pixel, with 46 orbits per annual, at a spatial resolution of 1 kilometer (km) within a 1,200 × 1,200 km grid. This study divided Eastern South Asia into 13 regions, each comprising nine sub-regions, resulting in a total of 117 sub-regions. These sub-regions were selected through random sampling based on equal latitudinal and longitudinal spacing. Each sub-region comprises 1,104 LST records, corresponding to 46 satellite orbits per year across the 24-year study period. The study delineated thirteen regions using a distance-based spatial classification, assuming that geographically proximate points experience similar climatic conditions. Each sub-region's LST data extends 3 km from the centre in all four directions, resulting in a sub-regional area of 7 km × 7 km composed of 49 grids (Wan et al., 2021). Before performing data analysis, we converted the Kelvin temperature data points to the Celsius scale. There were 13.1% of daytime and 15.9% of nighttime LST data missing. The missing LST data from each 8-day orbit from 49 grids, which could be attributed to clouds in each sub-region, were averaged. The assessment of quality and data consistency was conducted and found to be satisfactory. Outliers and errors were investigated and eliminated before developing the model for estimating the LST trend.

2.3 Statistical Modeling Techniques

Statistical modeling was employed to examine the daytime and nighttime patterns and trends of LST data throughout the study area. To find the trend of time series data, commonly used methods are multiple regression models, autoregressive models, and moving average models. Some of the latest researches suggest using cubic spline models due to their piece-wise linear interpolation feature, and they can be used for statistical inference (Wongsai et al., 2017; Munawar et al., 2023; Abdulmana et al., 2023; Abdulmana et al., 2024).

The natural cubic-spline modeling was employed to capture the seasonal patterns in the daytime and nighttime LST data. This method applies a continuous and smooth curve to the data, guaranteeing continuity and smoothness at the spots where polynomial segments intersect, referred to as knots. The natural cubic spline function $\hat{S}(t)$ is defined as

$$\hat{S}(t) = a + bt + \sum_{k=1}^{p} c_k (t - t_k)_+^3 \quad (1)$$

where t is the time in day, k is the number of knots, and $(t - t_k)_+$ is defined $(t - t_k)$ if $t \geq t_k$ and 0 otherwise. The parameters a, b and c_k are coefficients estimated from the data. Eight knots were strategically placed at the beginning and end of each year, reflecting the seasonal characteristics. The selection of cubic spline modeling was predicated on its capacity to capture non-linear trends and seasonal patterns in LST data with high fidelity. After capturing the seasonal patterns, using cubic spline deseasonalization process was applied. The seasonally adjusted time series was calculated as:

$$y_{SA} = y - \hat{S}(t) + \bar{y} \quad (2)$$

where y_{SA} is the seasonally adjusted daytime and nighttime LST, $\hat{S}(t)$ is the fitted value from the cubic spline model, y represents the observed LST, and $\bar{y}$ is the mean of the observed LST.

After seasonal adjustment, we used Autoregressive (AR) models to analyze the autocorrelation between the LST with its lags. Hence, we used a second-order AR model to analyze the autocorrelation. If a series has strong autocorrelation at lag two, then we can add more lags by increasing the order to observe the pattern of autocorrelation with its lags. The AR(2) model is as:

$$Y_t = \alpha_1 Y_{t-1} + \alpha_2 Y_{t-2} + \epsilon_t \quad (3)$$

where Y_t is the daytime and nighttime LST at the time t, Y_{t-1} and Y_{t-2} are the LST lags, which were the 8- and 16-day lags as LST data was taken in 8-day. ϵ_t is the random error term.

After adjusting the seasonal trend and autocorrelation, we used the natural cubic spline model for a comprehensive analysis of how LST varies across different sub-regions and over time, providing insights into the spatial-temporal dynamics of temperature changes. Moreover, the important feature of the three-knot natural cubic spline model is that it considers slope and its derivative, which is the slope of the slope and is considered as the estimate of acceleration of LST. This acceleration provides a true picture of the future trends in LST. In addition to the increasing or decreasing trends, we can also understand the accelerating/decelerating behavior. For example, if temperature is increasing in the regions, will that increasing trend accelerate, decelerate, or remain the same over time? Thus, to measure the overall acceleration, we took the average of the 24 years of LST. For measuring the region-wise and overall increase/decrease in the daytime and nighttime LST, we used a 95% confidence interval of the estimate using a three-knot cubic spline model. Finally, to understand the change in average LST and the role of acceleration force in future trends, we fit a straight-line model between the change in each region with its acceleration. All the analysis and graphical displays were performed using the R programming language (R Core Team, 2024). The flowchart of data processing and analysis is shown in Figure 2.

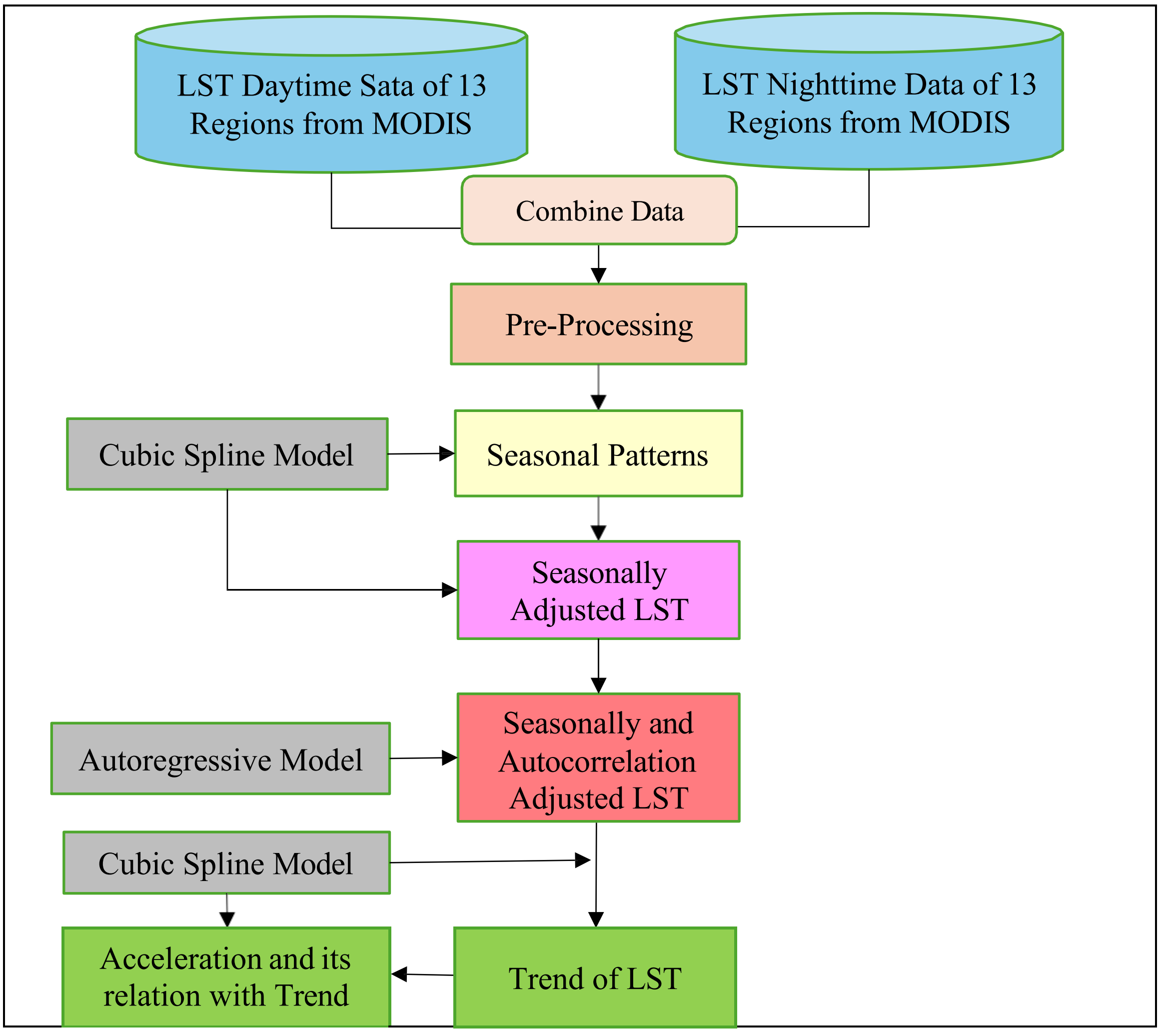


Figure 2 Flowchart of the study

3. RESULTS

3.1 Annual Seasonal Trend

The optimal cubic spline function, with eight knots selected for their highest R-squared value, was used to model the annual seasonal trends for all LST sub-regions. Figure 3 illustrates the seasonal patterns for the nine sub-regions within Region 1 in Eastern South Asia (Figure 3a). In Figure 3b and 3c, the vertical axis represents the LST for both daytime and nighttime, measured in degrees Celsius (°C), while the horizontal axis indicates the days of the year. The yearly seasonal patterns of both daytime and nighttime LST were fitted with natural cubic spline functions using eight knots, marked by blue plus signs. These plots depict the LST variations for the nine sub-regions in Region 1, located in the Upper North area of India. The dots represent the average surface temperature over 8-day periods recorded over 24 years, from February 2000 to February 2024, based on 46 annual orbits. The red curve represents the fitted cubic spline to the data points. The n denotes the total number of observations. By considering the space limitation, we have presented the result of only Region 1.

Seasonal fluctuations are evident in both daytime and nighttime LST, with daytime LST exhibiting more variability. Peak temperatures typically occur around July, mid-year, for most sub-regions. Each sub-region exhibits unique temperature ranges and slightly different seasonal patterns.

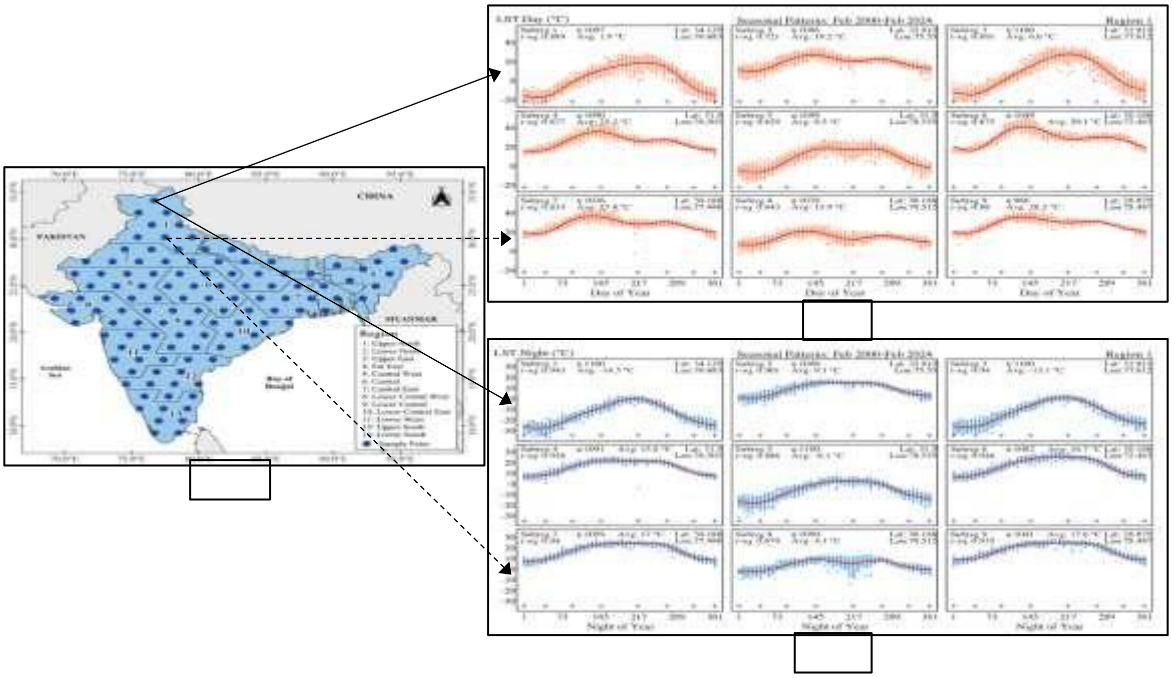
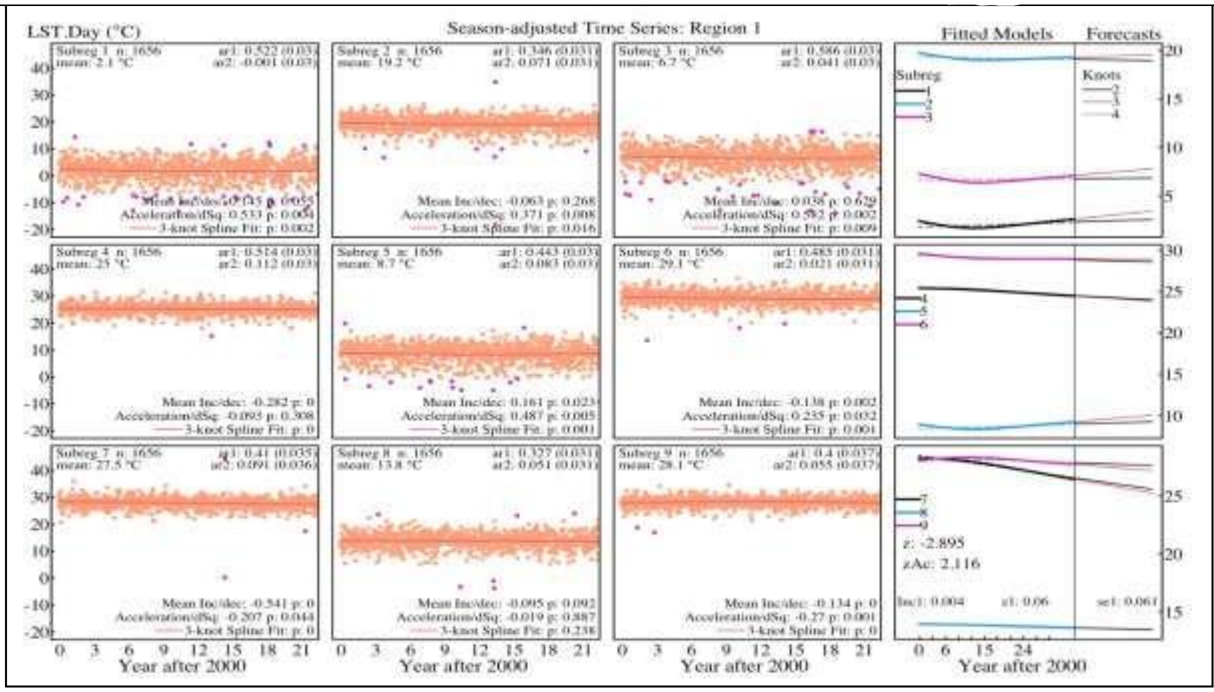


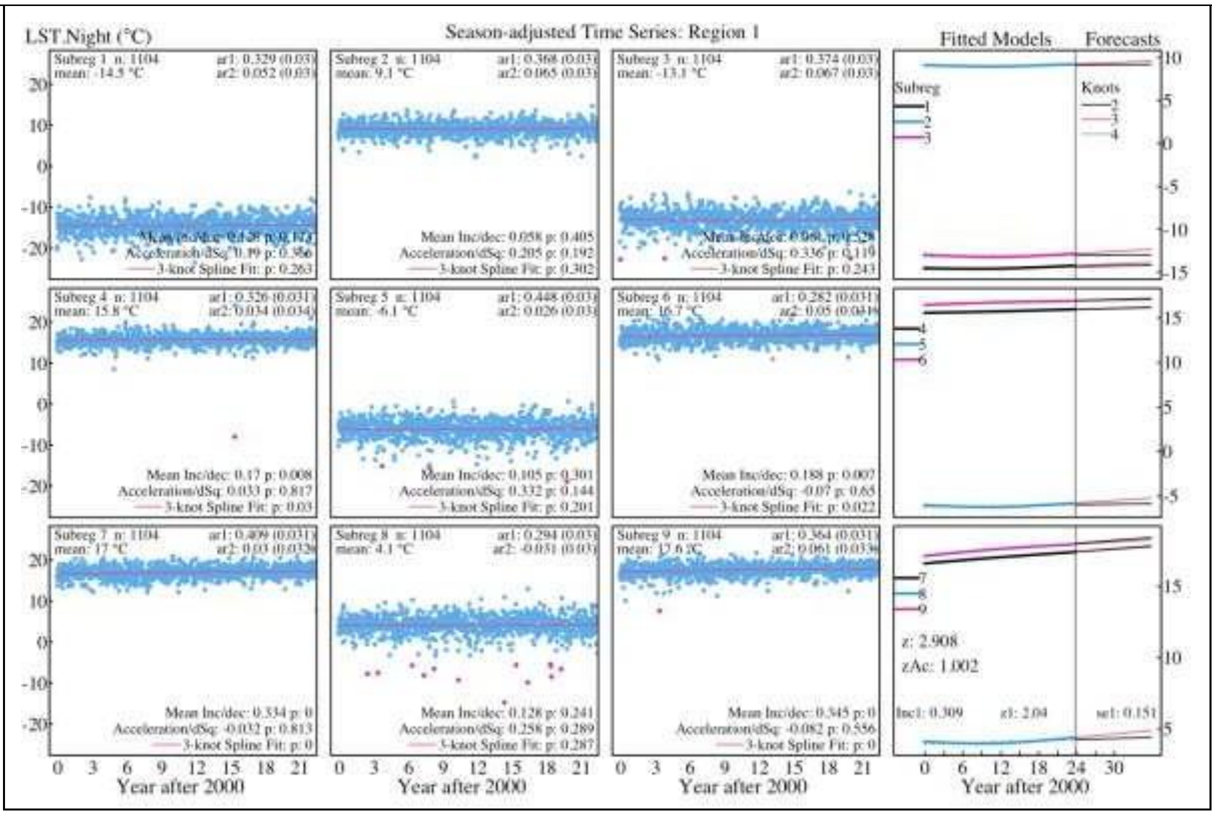
Figure 3 Seasonal pattern of (b) daytime and (c) nighttime LST in (a) Region 1 with 9 sub-regions

3.2 Seasonal Adjusted LST Trend and Forecast Trend

Figure 4 displays the spatiotemporal patterns of daytime (Figure 4a) and nighttime (Figure 4b) LST changes in the Upper North region (Region 1) of India from 2000 to 2024. The vertical axis represents the LST measured in degrees Celsius (°C), while the horizontal axis indicates the years since 2000. These season-adjusted time series graphs revealed LST's long-term trends and variability. Each plot includes the mean LST, coefficient of AR(1), and AR(2) extracted from the AR model. The pink dots represent significant deviations or outliers in the dataset. The curves in the rightmost column of graphs in Figure 4 show the fitted future trend for each sub-region using a cubic spline model with acceleration.



(a)



(b)

Figure 4 Predicted trend of seasonally adjusted LST (a) daytime and (b) nighttime LST, for Region 1 with 9 sub-regions.

The value of autocorrelation for all regions using the AR model is about 0.5, which shows that the LST has a moderate correlation with its first lag. While for the second lag, the autocorrelation is about 0.03. This showed very low autocorrelation and needed no filtering for autocorrelation in LST data. For most sub-regions, daytime temperatures showed an increasing trend, while nighttime temperatures varied, with some regions showing an increasing and others a decreasing trend. For daytime LST, there are clear seasonal patterns, with peak temperatures around mid-year. Sub-regions exhibit increasing trends over the years, as indicated by the fitted cubic splines. For nighttime LST, there is less variability compared to daytime temperatures. Trends varied across the regions and sub-regions. The fitted models provide insights into future temperature trends. The z is the value of z statistics for the significance of the overall model, whereas zAc is the z statistics for the significance of acceleration. The results of z values showed that the overall model is significant, while the acceleration is not significant in region 1.

3.3 LST Trend over Region

Figure 5 demonstrates the average increase in LST per decade in the daytime (Figure 4a) and nighttime (Figure 4b) LST across sub-regions and regions. Colour coding indicates sub-regions with significant increases (red, $z > 1.96$), likely increases (orange, $z > 1$), stable (green, $|z| <= 1$), likely decreases (deep sky blue, $z < -1$), and significant decreases of LST (blue, $z < -1.96$). The results show that most of the daytime LST by sub-regions decreased, except for sub-regions in the northern parts, where some areas exhibit stable or increasing trends. Conversely, nighttime LST indicates widespread warming across most regions, with significant increases observed particularly in northern and central areas.

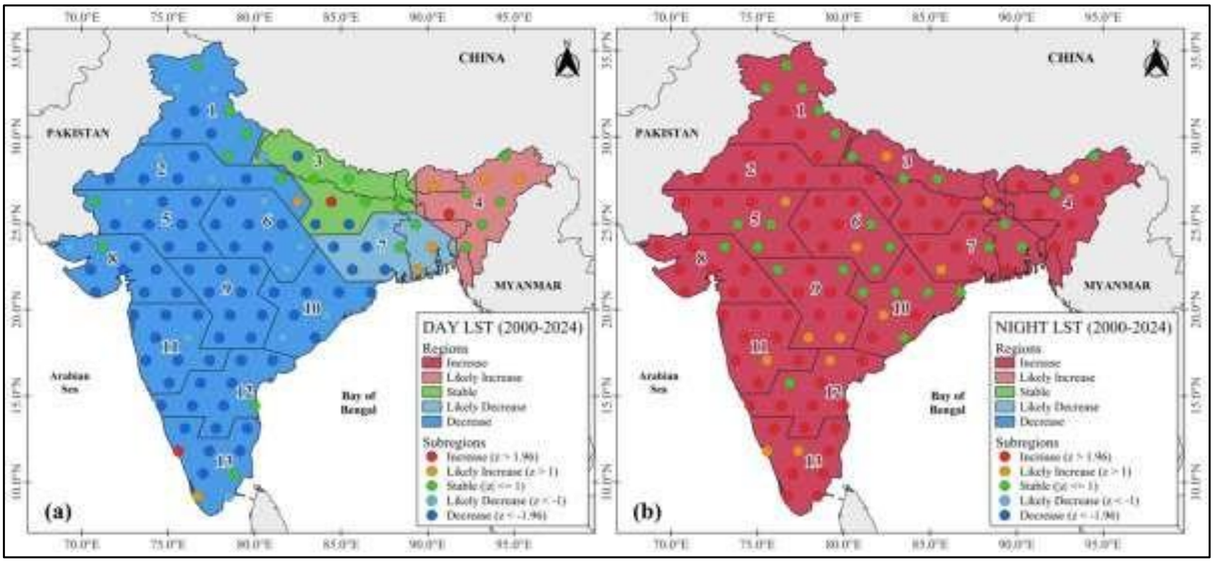


Figure 5 LST changes by sub-regions and regions in Eastern South Asia from February 2000-2024, (a) daytime LST change and (b) nighttime LST change.

3.5 Forecasted LST Trend

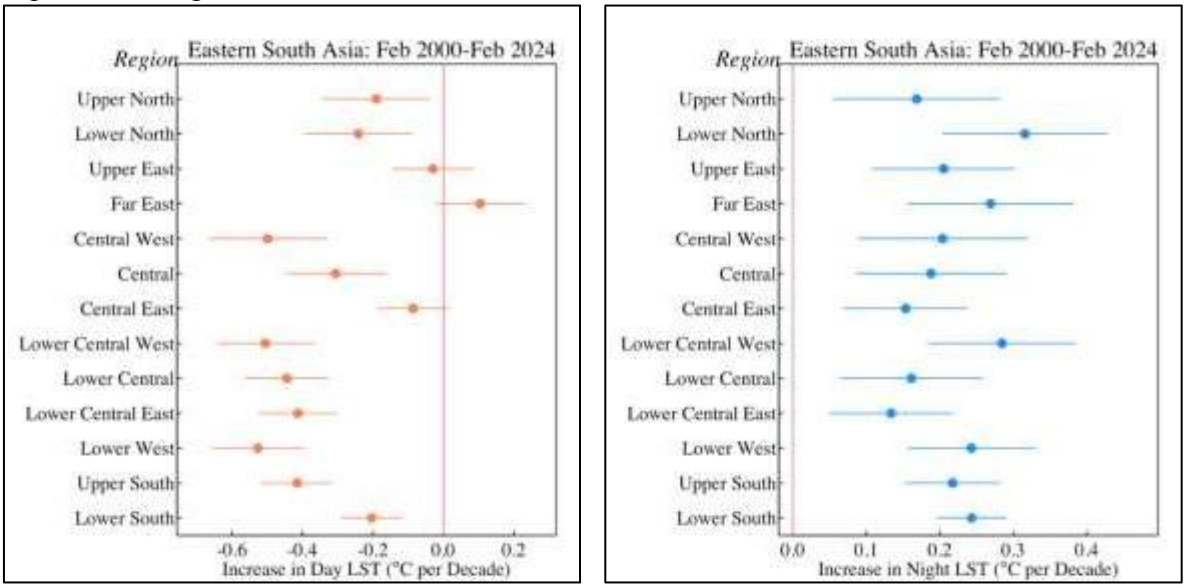
Figure 6 shows the 95% confidence intervals of the forest plots for daytime (Figure 6a) and nighttime (Figure 5b) LST increases per decade. The Y-axis represents the regions, which include: 1 Upper North, 2 Lower North, 3 Upper East, 4 Far East, 5 Central West, 6 Central, 7 Central East, 8 Lower Central West, 9 Lower Central, 10 Lower Central East, 11 Lower West, 12 Upper South, and 13 Lower South. The X-axis depicts the increase in daytime and nighttime LST per decade. The majority of regions experience a decreasing daytime temperature trend per decade, with Lower Central West, Central West, and Lower West having the highest significant decreasing trends. While the Upper East and Central East regions exhibited a non-significant trend, the Far East had a likely increasing daytime LST trend. The average decrease in daytime LST per decade was -0.29 °C. Conversely, the nighttime LST (Figure 6b) indicates an average increase of 0.21 °C in temperature per decade in all regions, with the highest increasing trend in the Lower North region. The increase and the associated p-values are given in Table 1.

Table 1 Day and night LST decadal increment in each region

Regions	Daytime LST		p-value	Nighttime LST		p-value
	Increase	SE		Increase	SE	
Upper North	-0.19	0.08	0.009	0.17	0.06	0.002
Lower North	-0.24	0.08	0.001	0.32	0.06	< 0.001
Upper East	-0.03	0.06	0.309	0.21	0.05	< 0.001
Far East	0.10	0.06	0.952	0.27	0.06	< 0.001
Central West	-0.50	0.08	< 0.001	0.20	0.06	< 0.001
Central	-0.31	0.07	< 0.001	0.19	0.05	< 0.001
Central East	-0.09	0.06	0.067	0.15	0.04	< 0.001
Lower Central West	-0.51	0.07	< 0.001	0.29	0.05	< 0.001
Lower Central	-0.45	0.06	< 0.001	0.16	0.05	0.001
Lower Central East	-0.41	0.06	< 0.001	0.13	0.04	0.001
Lower West	-0.53	0.07	< 0.001	0.24	0.04	< 0.001
Upper South	-0.42	0.05	< 0.001	0.22	0.03	< 0.001

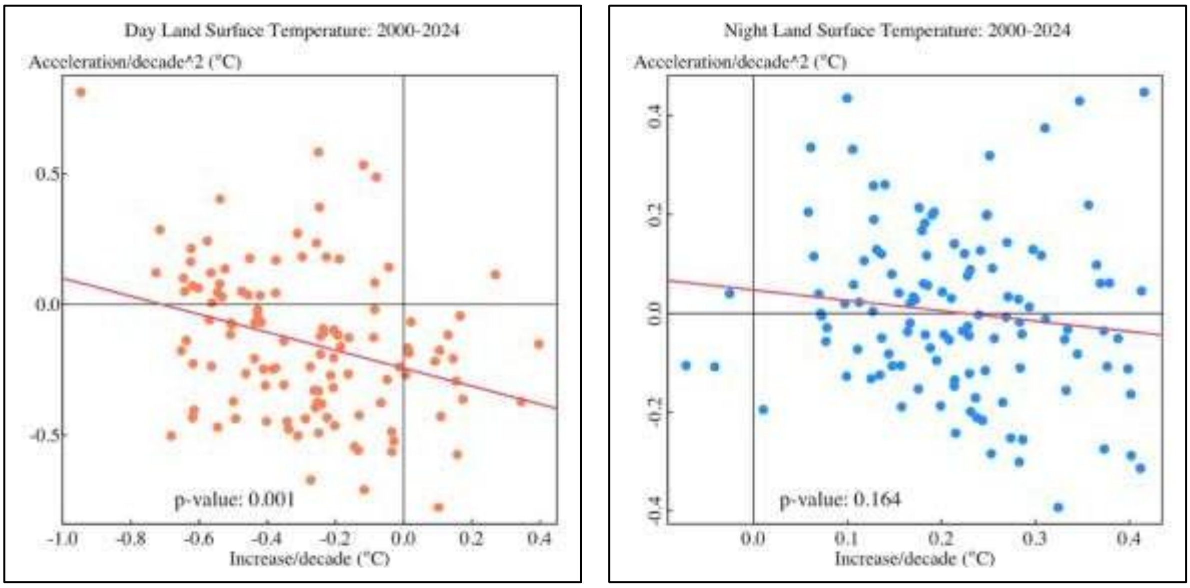
Lower South	-0.20	0.04	< 0.001	0.24	0.02	< 0.001

The relationship between daytime and nighttime estimated acceleration and LST change is illustrated in Figure 7. The X-axis represents the estimated temperature change, while the Y-axis represents temperature acceleration. There is a statistically significant negative correlation ($p < 0.05$) between the temperature increase and acceleration in daytime LST (Figure 7a). The rate of daytime LST warming was decelerating, particularly in regions where temperatures were increasing at a higher pace. Conversely, nighttime LST (Figure 7b) does not demonstrate a statistically significant trend ($p > 0.05$) between acceleration and temperature change.



(a) (b)

Figure 6 Forecasted trends and 95% confidence intervals for decadal (a) daytime LST change and (b) nighttime LST change in Eastern South Asia from February 2000-2024



(a) (b)

Figure 7 Relationship between estimated acceleration and change in the LST (a) daytime and (b) nighttime in Eastern South Asia from February 2000-2024.

4. DISCUSSION

This study analyzed the 8-day daytime and nighttime LST data from 2000 to 2024 from 13 regions of Eastern South Asia. Seasonal patterns and trends from the annual daytime and nighttime LST can be efficiently achieved by utilizing a cubic spline with eight knots. The findings indicated that there was a decrease in daytime LST per decade across almost all regions, with an average decrease of -0.29 °C per decade. The Lower Central West, Central West, and Lower West had the highest significant decreasing daytime LST trend. The Upper East and Central East regions exhibited a non-significant trend, whereas the Far East had a likely increasing daytime LST trend. In contrast, there was an increase in nighttime LST of 0.21 °C per decade, with the greatest increase observed in the Lower North region. The acceleration showed a negative relation with temperature in the daytime, which suggested that as daytime temperature increases, acceleration will slow down the rate of increment in the future. Whereas nighttime LST change had no relation to the acceleration.

In this study, a decrease in daytime LST per decade across most of the regions was found, while an increase in nighttime LST per decade of all regions was found. The results from our study are consistent with the findings from previous studies, which found that nighttime LST increased whereas daytime LST decreased (Bera et al., 2022; Shawky et al., 2023; Halder and Yaseen, 2024), and also consistent with the partial findings that nighttime LST increased and daytime LST decreased in specific months (Nayak et al., 2023; Ghaderpour et al., 2024). The possible explanations for this phenomenon are urbanization, anthropogenic activities, and the proportion of vegetation cover (Anees et al., 2025). The expansion of urban areas leads to an increase in LST, while an increase in vegetation causes a cooler LST (Anees et al., 2025). Urbanization has led to the emergence of tall buildings (Kumar, 2017). The expansion of tall buildings, particularly in urban areas, affects the intensity of sunlight by reducing the LST (Wang et al., 2023). The increasing concentration of absorbing aerosol also causes a decrease in daytime LST (Siddiqui et al., 2021; Bera et al., 2022). The increase in nighttime LST could be attributed to the urban heat island effect, which occurs when buildings, roads and concentrations of aerosol in the atmosphere absorb heat from the sun during the day and release it at night (Bera et al., 2022; Wang et al., 2023). Anthropogenic activities such as energy consumption, power generation systems, and transportation contribute to the urban heat island, which influences LST and contributes to increased LST, particularly at night (Mansour et al., 2022).

In our study, the Far East region had a slightly increasing daytime LST trend, but not significantly. Our finding is consistent with a recent study, which revealed an overall increase in LST in the Far East (Halder and Yaseen, 2024). This could be attributed to the influence of the extent of open bare land, built-up areas, and vegetation cover on the increase of LST (Pandey et al., 2022). A study of 30 years of land use and land cover changes in the Far East regions of India revealed that the decrease in vegetative cover and open forest has been transformed into agricultural land and a few built-up areas (Parapurath et al., 2022). These cause the increase in daytime and nighttime LST.

A negative correlation was found between the acceleration increase rate and the increasing rate of daytime LST, while the correlation between the increase rate and the acceleration increase rate of nighttime LST was not significant. The studies showed that daytime LST decreases with the deceleration rate. Thus, the change in LST gradually decreased, which may not have had an enormous effect on the environment or ecological system. The rise in nighttime land surface temperature did not exhibit a significant acceleration, suggesting that the pace of increase was minor and may not have an immediate effect on the ecosystem.

Uncertainties in the MODIS LST input data primarily arise from cloud contamination, atmospheric scattering, and sensor-related noise. Although the MODIS cloud-mask algorithm screens most cloudy pixels, residual undetected thin clouds or partial cloud cover can introduce cold biases in the retrieved LST. The anomaly that arose due to such a situation was not used in the modeling and was pointed out using a different colour in the graph. Moreover, Ahmed et al. (2023) suggested that using MODIS data for estimating the warming or cooling during daytime, nighttime is useful. Additionally, data fusion from other sources is more likely to improve the quality of the data.

There are a few limitations in this study. Firstly, land use/land cover and urbanization were not considered in this study. Secondly, this study used daytime and nighttime LST data and ignored the seasonal and month-wise variations to avoid a complex in-depth analysis, which can be opted in further studies.

5. CONCLUSION

Daytime LST showed a significantly decreasing trend across most regions except for the Upper East and Central East regions, with no significant decrease, whereas the Far East had a likely marginal increasing daytime LST trend. Nighttime LST had a significantly increasing trend for all regions. Daytime LST changed with a decreasing acceleration rate, whereas the nighttime LST changed with no significant acceleration rate. The findings from our study provided information on daytime and nighttime LST changes in the South Asia regions, which is useful for future planning and mitigation of climate change.

Ackowledgements

This study was funded by the Thesis Research Grant from the Graduate School at Prince of Songkla University, Thailand.

Authors' contributions

A.J., K.H., and L.A. planned and conceptualized the research and obtained the data. A.J., K.H., L.A., W.N., and M.D. formally analyzed the data. A.J., and U.A. wrote the initial draft. K.H., L.A., and W.N. revised the draft and finalized it. All the authors reviewed the final draft.

Data availability statement

The data that support the findings of this study are available in the MODIS LST/E 8-Day product MYD11A2 at https://ladsweb.modaps.eosdis.nasa.gov/. These data were derived from the following resources available in the public domain: - MODIS LST/E 8-Day, https://ladsweb.modaps.eosdis.nasa.gov/.

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