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Thailand Land Surface Temperature Variation and Forecasting

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ABSTRACT

Climate change has emerged as a global challenge, influenced by human activities, industrial operations and energy systems that depend on non-renewable energy such as carbon, gas, and petroleum. These activities have contributed to long-term shifts in temperature and broader climatic conditions. Land Surface Temperature (LST) has become an important standard for informing weather-related strategies at regional scales. This study aims to examine the seasonal pattern and variation of LST, including forecasting. Thailand is organized into six super-regions, each comprising nine sub-regions, for a total of 54 units. The sub-regions were delineated according to cardinal and intercardinal directions, with the central sub-region following the island's shape. The separation between sub-regions is defined by a 150-pixel grid in latitude and longitude, approximately 95 km, covering the entire country. This study utilizes Moderate Resolution Imaging Spectroradiometer (MODIS) data from NASA's Terra Satellite, spanning the years 2000-2025. Cubic spline models incorporating eight, four, and three knots were applied to examine seasonal cycles, long-term variability, and LST projections for 2021-2031. The estimated mean increase in LST is 0.117^{o}C per decade (1.17^{o}C per century), statistically significant at the 5% level, [0.082, 0.272]^{o}C of the confidence interval. The mean projected LST change designates a further significant increase of 0.219^{o}C per decade. No statistically significant acceleration in LST is detected across Thailand's super-regions, as the estimated acceleration of 0.103^{o}C per decade^{2} does not meet the 0.05 significance threshold, and the associated p-value is 0.177.

HIGHLIGHTS

- Climate change has emerged as a major global challenge.
- LST has become an important indicator for climate monitoring.
- LST variation was effectively characterized with a combination of linear and cubic spline functions.
- The mean of LST exhibited a statistically significant increase of 0.117^{o}C per decade.
- The projected mean LST variation exhibited a statistically significant increase of 0.219^{o}C per decade.

1. INTRODUCTION

Climate change has become a global challenge primarily driven by human activities, particularly industrial processes that rely on non-renewable energy such as carbon, gas, and petroleum for transportation and power use (Swagatika Priyadarshini et al., 2025). These activities have contributed to persistent change in temperature and climate patterns. As a result, the greenhouse effect has intensified, leading to greater heat retention in the atmosphere and increased variability in temperature and precipitation. Such changes exceed the Earth system's natural adaptive capacity and alter atmospheric composition at both local and regional scales (Karl and Trenberth, 2003; Mikhaylov et al., 2020).

From the late nineteenth century onward (1850-1900 baseline), the Earth's mean surface temperature has shown a consistent upward trend, increasing by roughly 1^{o}C per decade. Warming has occurred more rapidly over land than over the oceans, and the Arctic

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has experienced particularly accelerated temperature increase relative to most other regions between 1901 and 2023 (Lindsey and Dahlman, 2020). Empirical evidence indicates that rising temperatures have negatively influenced the human system, plant communities, and animal populations, leading to ecosystem degradation and declines in biodiversity (Mall et al., 2021). Furthermore, ongoing climate change presents significant challenges to global economic development and heightens the risk of extinction for vulnerable species.

The impacts of climate-related events differ substantially between developed and developing regions. Climatic conditions play a crucial role in shaping strategic policy decisions made by governmental institutions at both regional and national levels, particularly in relation to economic planning (Chinowsky et al., 2011; Tol, 2018). In low-income countries, the agricultural sector is particularly vulnerable to the economic impact of climate due to of its scale and high sensitivity to environmental variability (Mendelsohn, 2009). Furthermore, rising Land Surface Temperature (LST) has emerged as an important climate indicator that informs the formulation and selection of climate adaptation and mitigation policies (Fox et al., 2019).

As a Southeast Asian nation, Thailand faces growing challenges related to rising LST, driven in part by the expansion of economic activities (Iamtrakul et al., 2024). The country's economy is largely supported by the service sector, particularly tourism, alongside industrial and agricultural activities (Sangnak, 2025). Variations in LST can influence Thailand's economic performance, potentially slowing the implementation of national development agendas. Projections indicate that by 2100, an increase in average temperature of up to 4ºC could result in heat-related mortality exceeding the number of cold-related deaths avoided during warmer and wetter periods. Without the adoption of effective preventive measures, the net increase in projected mortality across the region is estimated to range between 5% and 13% (Tawatsupa et al., 2014).

LST influence Sea Surface Temperature (SST), which can contribute to severe flooding events (Yulihastin et al., 2021). Toward the end of November 2025, warmer ocean conditions enhance evaporation, leading to the formation of moisture-rich clouds that produce intense rainfall when transported toward mountainous areas. In Southeast Asia, rising temperatures in Thailand may affect SST and LST in adjacent marine regions, including the Andaman Sea and parts of the South China Sea, with potential implications for neighbouring countries (Narenpitak et al., 2025).

Thailand has physical topography such as mountains in the north, urban areas in the central and southern regions, and the longest coastline. Phumkokrux (2020) found that Thailand was classified within the equatorial climate category with two dominant subtypes: the tropical savanna climate with a dry winter, and the tropical monsoon climate controlled by the seasonal influence of the southwest and northeast monsoon systems. Over the past four decades, Thailand has experienced a substantial increase in average temperatures nationwide. During this period, notable changes have also been observed in the frequency and intensity of extreme cold and hot events, as reflected in the distribution of daily minimum and maximum temperatures (Limjirakan and Limsakul, 2012).

The temperature data should span 30 years to provide sufficient data for the next analysis and to capture the comprehensive result in climate science. The data were downloaded from the NASA MODIS (Moderate Resolution Imaging Spectroradiometer) website from 2020 to 2025, with forecasting up to 2031. In contrast to earlier works, which focused on identifying LST cycles and variance by applying spline functions with seven and eight knots in Borneo Island and the Malaysian Peninsula, the present study adopts a broader analytical framework. After removing annual and seasonal components using a cubic spline approach, long-term LST trends were extracted from the residual series. Furthermore, regional LST mapping was conducted by integrating information on temperature fluctuation, acceleration, and projected future conditions (Munawar et al., 2024; Munawar et al., 2022; Prasetya et al., 2020).

The principal contributions of this study are to develop cubic spline models with appropriate knots using satellite data to examine the seasonal patterns, variations and forecasts to have sufficient data of LST in Thailand, and provide recommendations for further studies to improve the accuracy and comprehensiveness of climate modelling.

This manuscript is structured into five main sections. The first section presents the study background, research rationale, objectives, and identified research gap. The second section outlines the materials and methods framework, including the study area, data sources, and statistical techniques

employed in the analysis. The third section presents findings related to LST variability and projected trends. The fourth section discusses the findings and compares them to previous research. The final section summarizes the principal conclusion regarding LST variation and forecasting in Thailand.

2. METHODOLOGY

2.1 Study area

Thailand, as a country in Southeast Asia, lies between latitudes 5.5° and 20.5°N, and longitudes 97.5° and 105.5° E, marked with cyan dots (Figure 1). The nation has maritime boundaries with Vietnam to the southeast and with Indonesia and India to the southwest. Its land borders include Laos and Cambodia to the east, Malaysia to the south along the Gulf of Thailand, the Andaman Sea to the west, and Myanmar and Laos to the north (Khedari et al., 2002).

For analytical purposes, the country was divided into six major regions, each further subdivided into nine smaller units. Grid centers defined these sub-regions spaced approximately 150 pixels (about 95 km) apart in both latitude and longitude, ensuring full spatial coverage of the study area. Each of the 54 sub-regions comprised 49 pixels arranged in a 7×7 grid. At the time of data acquisition, the sub-regions were delineated according to the eight cardinal and intercardinal directions, along with the central region, resulting in a nine-directional classification that also accounted for each island's geographical shape.

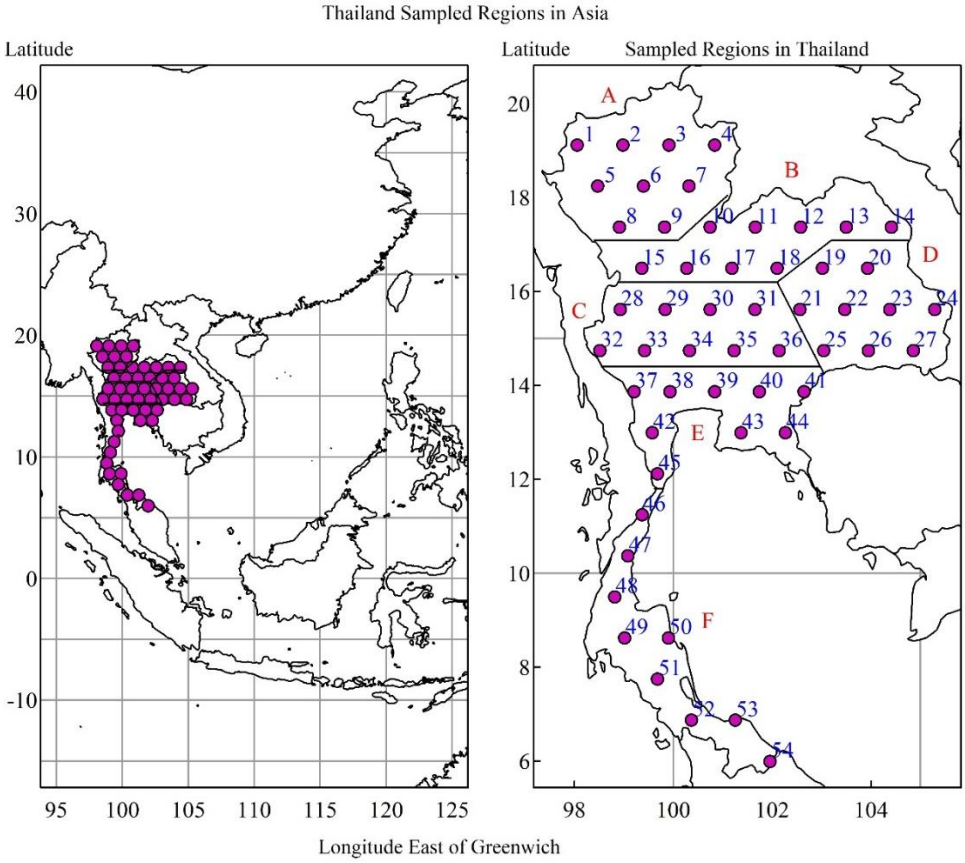


Figure 1. Study area of Thailand

Figure 1 illustrates Thailand's spatial division into super-regions and sub-regions on the right side of the figure. Super-region A represents the northern area centered on Chiang Mai, while super-region B corresponds to the north-central region around Khon Kaen. Super-region C covers the western region near Nakhon Sawan, and Super-region D represents the southeastern area centered on Maha Sarakham. Super-region E denotes the central region, whereas Super-region F encompasses the southern part of the country. Together, these super-regions provide complete coverage of Thailand.

2.2 Data

This study used LST data from the NASA MODIS online database, which offers global daytime and nighttime temperature observations. The dataset consists of mean LST values recorded at eight-day

intervals with a spatial resolution of approximately 0.859 km^2, under clear-sky conditions (Wan, 2008; Phan et al., 2018; Distributed Active Archive Center (Daac), 2018). A sine-wave processing approach was applied to MODIS sets measuring 10×10 magnitudes in latitude and longitude, each subdivided into 1,200×1,200 pixels to ensure consistent spatial representation across the study domain.

To minimize data loss, LST values were extracted from the centers of predefined sub-regions, and incomplete records were excluded from the analysis. Extreme natural events, land use/land cover (LU/LC), and land elevation (LE) that could introduce abrupt and irregular variations were not considered. Aliabad et al. (2024) reported that, in an arid environment, the contrast in LST NASA MODIS between mountainous and lowland areas reaches its greatest magnitude during the hottest part of the day, while smaller differences are observed at other daytime and nighttime hours. In addition, all remaining outliers were retained to maintain the integrity and representativeness of the temperature dataset. Prior to data exploration, LST values, initially expressed in Kelvin, were converted to degrees Celsius.

2.3 Methods

Temperature data typically exhibit a non-linear pattern; this study employed a combination of linear regression and cubic spline functions, using appropriately selected knot locations. A cubic spline model alone may overfit, whereas a simple linear model may underfit, failing to capture the underlying data structure. The conventional linear and cubic spline formulations adopted are based on the methodology proposed by Ahlberg et al. (2016):

$$y = a + bx + \sum_{k=1}^{p-3} c_k S_k(x) \quad (1)$$

Where; a, b, c_1, c_2, …, c_{p-3} denote the coefficients of the linear component. The cubic spline formulation can be expressed in extended form as follows (Wongsai et al., 2017):

$$S_k(x) = (x - x_k)_+^3 - \frac{(x_p - x_k)(x_{p-1} - x_k)}{d_3 d_2}(x - x_{p-2})_+^3 + \frac{(x_p - x_k)(x_{p-2} - x_k)}{d_1 d_2}(x - x_{p-1})_+^3 - \frac{(x_{p-2} - x_k)(x_{p-1} - x_k)}{d_3 d_1}(x - x_p)_+^3 \quad (2)$$

Three constrain conditions were define, including $x_+ = \max(x,0)$, where $d_1 = x_p - x_{p-1}$, $d_2 = x_{p-1} - x_{p-2}$ and $d_3 = x_p - x_{p-2}$.

In addition, the cyclical-adjusted LST series was modeled using an AR(2) process, a second-order autoregressive process. The general form of this model follows the framework described by Venables and Ripley (2013):

$$Y_{at} = \alpha_1 Y_{at-1} + \alpha_2 Y_{at-2} + \varepsilon_t \quad (3)$$

The parameters α_1 and α_2 were estimated, while the error distribution ε_t was assumed to have constant variance and zero mean, where t=1, …, 365 denotes daily observations. The variable $Y_{\alpha t-1}$ represents the LST value at time t-1, whereas $Y_{\alpha t}$ denotes the seasonally adjusted LST at time t. The statistical study and graphical output were conducted using the R software environment (R Core Team, 2023).

3. RESULTS AND DISCUSSION

Figure 2 illustrates the seasonal pattern of LST for super-region A in Thailand. Comparable plots were employed to examine seasonal variations across the remaining super-regions.

The same figures as in Figure 2 have been produced for the remaining of the super-regions to observe the seasonal pattern. The patterns are almost the same as in Thailand, considered a tropical area with 2 seasons: dry and wet. Figure 2 presents the daily mean temperature averages of all LST values from 2000 to 2025 for each sub-region of super-region A, corresponding to calendar days, resulting in 46 data layers (966 observations, excluding missing values). Figure 2 also shows the fitted natural spline models with eight knots (solid red lines), while blue crosses indicate the observed values. For super-region A, the curves reveal a moderate seasonal cycle, characterized by a peak in April and lower LST values around November. Temperatures generally increase from January, reach their maximum during the mid-year period, and then gradually decline toward December. Among the sub-regions, sub-region six has the highest mean daily LST, at 33.181°C.

Figure 3 presents Thailand's super-region A seasonal-adjusted LST time series. Comparable figures were used to assess cyclical patterns in the remaining super-regions.

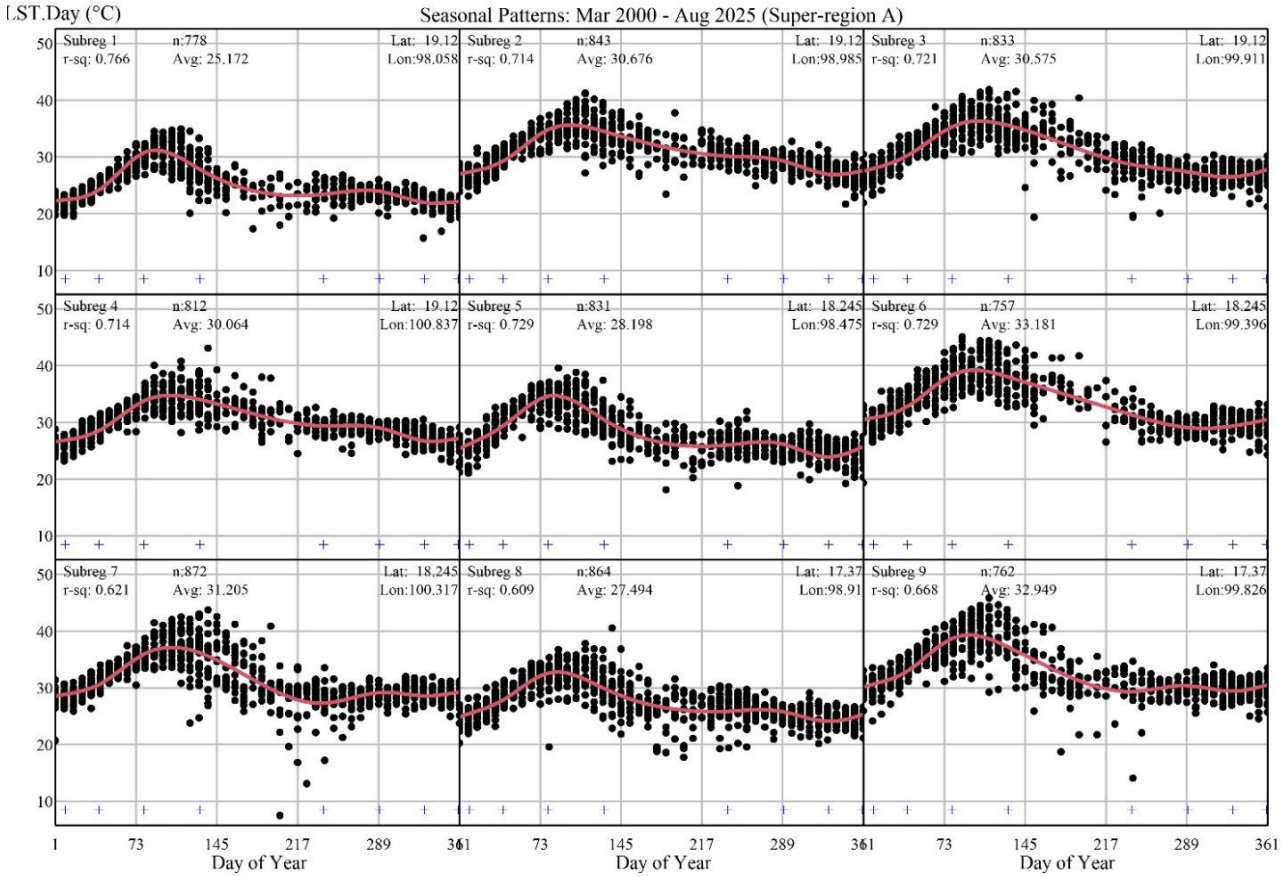


Figure 2. Seasonal LST pattern in Thailand's super-region A

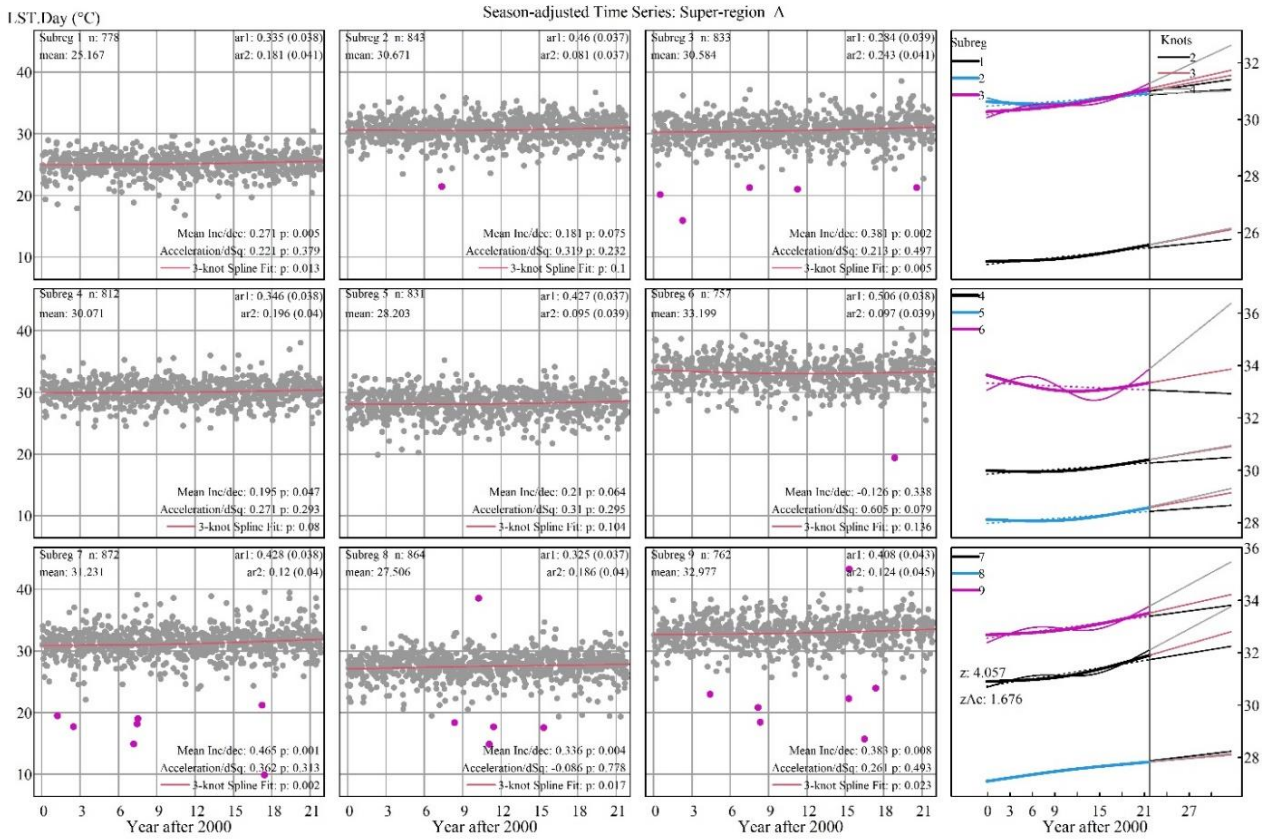


Figure 3. Seasonally Adjusted Analysis and Forecasting of LST in Thailand's Super-Region A

The fitted seasonal components were removed from the mean-adjusted series to obtain seasonally refined temperature values, as illustrated in the panels of Figure 3. The first-order autoregressive AR(1) models have tolerable coefficient estimation, which means the daily LST residual exhibited data independence. In comparison, the stationary second-order autoregressive model AR(2) produced smaller coefficient values than those observed for AR(1).

In Figure 3, the left-hand panels depict 26 years of LST variation across all sub-regions using solid black curves. In contrast, the right-hand instrument panels display a dotted strip on different scales. Including two parameters, the estimated linear (zero-knot) equations indicate statistically significant increases in LST for most sub-regions, except for sub-regions 2, 5, and 6, as the p-value exceeds the significance level α=0.05.

The cubic spline model with four knots yielded no statistically significant p-values across all sub-regions, indicating no detectable acceleration or deceleration in LST. In contrast, the cubic spline with three knots identified sub-regions 1, 3, 7, 8, and 9 as having statistically significant LST projections. The corresponding p-values confirm the presence of meaningful temperature trends in these sub-regions. Figure 3 also illustrates the fitted cubic splines as solid curves in the right-hand panels, using four knots for the historical period (2000-2021) and three knots for the projections period (2021-2030), for each sub-region with significant results. The bottom-right panel of Figure 3 reports a z-value with a statistically significant value of 4.057, the increase in daily LST mean, and 1.676 toward the acceleration term. Based on a 95% confidence level ($|z| \geq 1.96$), the decadal increase in LST is statistically significant, whereas the acceleration component is not.

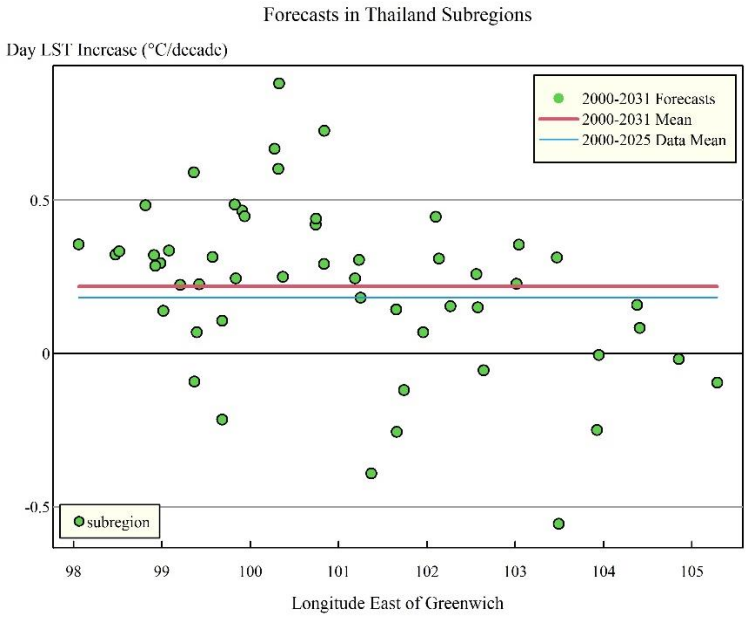


Figure 4. Forecast LST trends in Thailand (°C per decade) by location

Figure 4 shows the forecast of the increase in LST in Thailand for each sub-region with the location of longitude east of Greenwich. Most sub-regions are expected to experience rising LST, while a smaller number are expected to show declining trends. The red line denotes the overall mean LST increase forecast for the coming decade, estimated at 0.219°C per decade. This value exceeds the historical average increase derived from 2000-2025 data and shown by the blue line, which is 0.183°C per decade.

Figure 5 presents the projected LST variability for 2031 (marked by red dots) alongside the mean LST changes observed during 2000-2025 for each super-region in Thailand (marked by black dots), including 95% confidence intervals. The national mean forecast for LST in 2031 indicates an increase of 0.219°C, corresponding to a warming rate of 0.177°C per decade (or 1.77°C per century). This increase is statistically significant, with a z-value of 3.653 and a 95% confidence interval of [0.082, 0.272]°C. For most super-regions, the decadal mean LST increases are significant at the 95% confidence level, except for super-regions C and E, which contain zero values and are considered insignificant. For example, super-

region A shows a projected mean LST of 0.357ºC in 2031 and a mean increase of 0.255ºC, with the interval [0.142-0.368]ºC.

The LST projections and observed variations indicate a consistent increase in LST across Thailand on a decadal scale; however, no meaningful acceleration in LST is detected over time. None of the super-regions shows statistically significant acceleration when expressed per decade² or per century. This is supported by a low z-value of 0.809 and an overall mean acceleration estimate per decade² of 0.103°C, with the interval of -0.147 to 0.352°C in Figure 6.

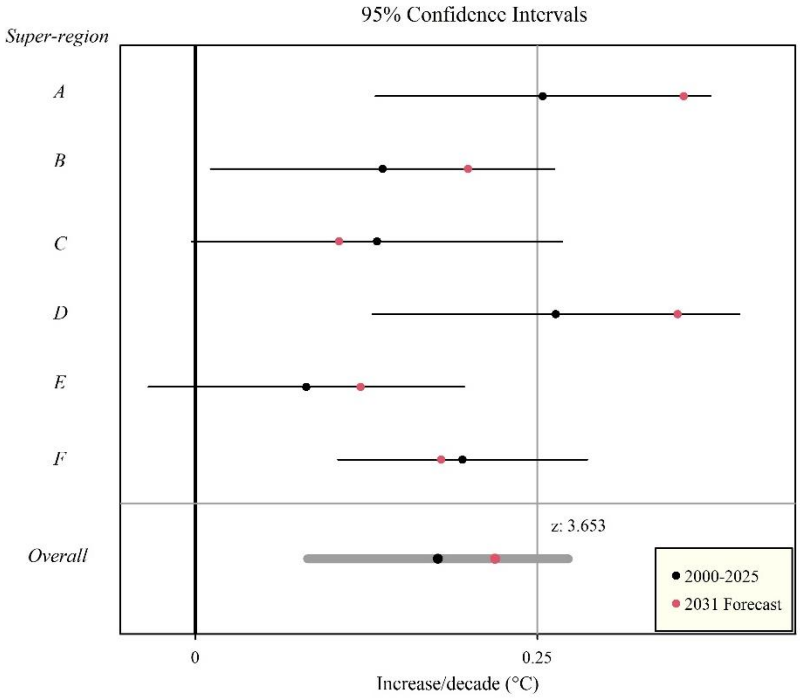


Figure 5. LST variations in Thailand with 95% confidence intervals

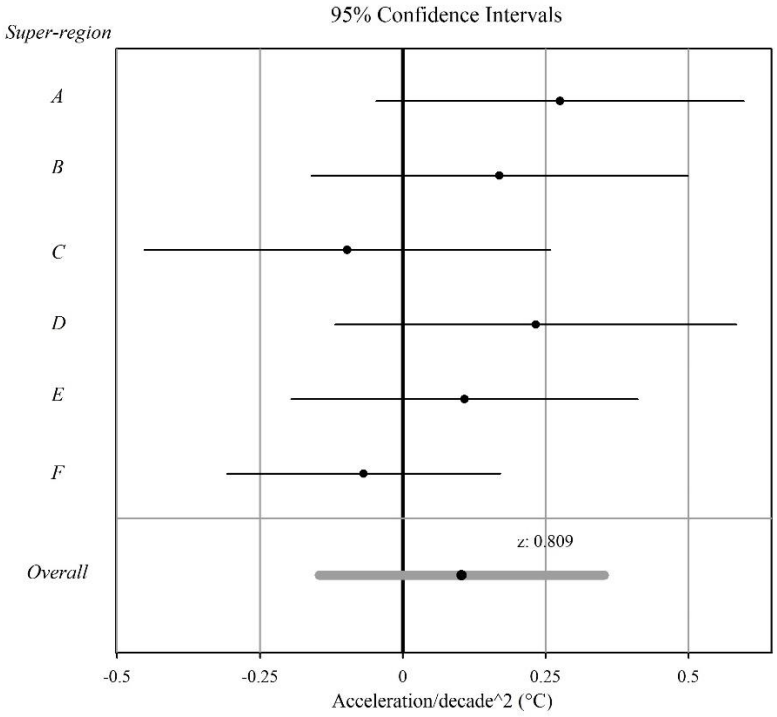


Figure 6. Thailand LST acceleration rates with 95% confidence intervals

Figure 7 illustrates the estimated LST acceleration, expressed per decade², for Thailand's sub-regions over the period 2000-2025. At the 0.05 significance threshold, no statistically significant acceleration in LST on a centennial scale is detected, as indicated by a p-value of 0.117.

4. DISCUSSION

The seasonal behaviour of LST in super-region A shows relatively weak variability, with consistently low values throughout the year and a single warm-season maximum occurring in March. In contrast, Khorchani et al. (2018) and Singh et al. (2014) conducted studies in an area with four well-defined seasons, reporting summer peak summertime LST in the middle of the year and in September. Seasonal patterns and long-term changes in LST across Thailand's super-regions were investigated using cubic splines. This analysis reveals models with statistically significant variations in daily LST over the span 2000-2025. Moreover, projections for 2031 suggest that the LST level will exceed the average conditions observed during 2000-2021. Regional differences are evident across Thailand; the southern and central parts of the country show concurrent rises in temperature and precipitation, accompanied by strong upward trends in annual rainfall, while the eastern and northeastern regions exhibit more complex climatic responses, with a simultaneous increase in both precipitation and temperature (Waqas et al., 2024).

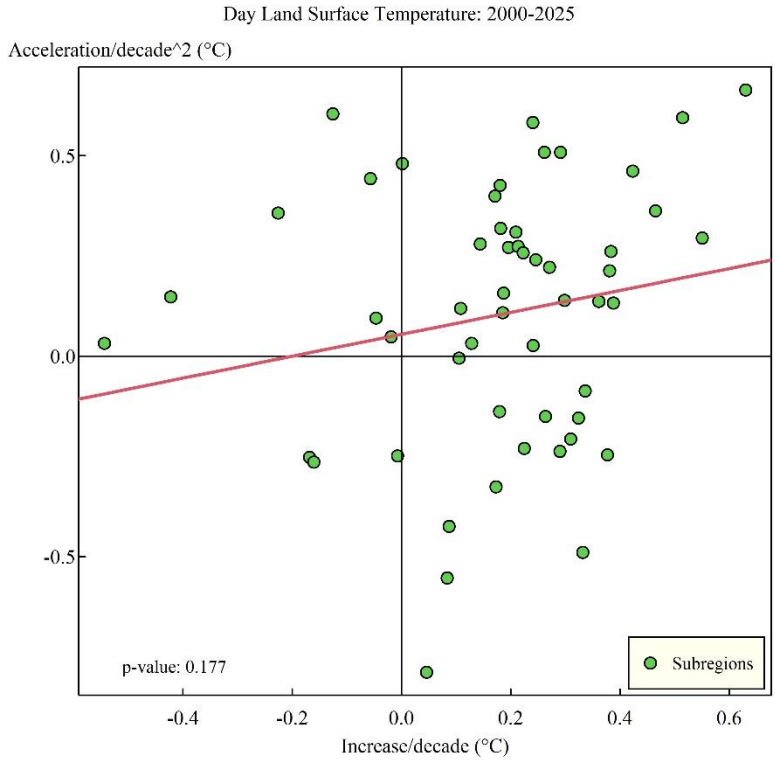


Figure 7. LST acceleration in Thailand during 2000-2025

The results indicate that Thailand's LST has risen by approximately 0.177ºC per decade, equivalent to about 1.77ºC per century. Variations in LST across the country are influenced by seasonal conditions, vegetation cover as represented by NDVI (Normalized Difference Vegetation Index), and geographic location. Reported seasonal contrasts include differences of 1.24°C between winter and summer, -1.54°C between winter and the rainy season, and -2.78°C between summer and the rainy season (Kliengchuay et al., 2025). Previous studies have shown that the western area of Bangkok may experience future warming of around 1-2°C due to the reduction of green spaces associated with urban expansion (Khamchiangta and Dhakal, 2021). In addition, increases in LST variability have been linked to LU/LC change and deforestation (Wolff et al., 2018). In this study, cubic spline models with eight knots were used to represent seasonal behavior, while four knots were applied to project decadal LST changes. Although the estimated mean acceleration of LST is 0.103°C per decade² and is not statistically significant, overall LST levels in Thailand are expected to continue rising over the coming decade.

Differences in LST are strongly influenced by LU/LC characteristics, particularly vegetation density (Buyadi et al., 2014). Ghaderpour et al. (2025) found that the correlation between LU/LC and wildfires in Italian regions since 2001 affects LST in the area. Rahimi et al. (2025) showed that the negative correlation between the global NDVI and LST has temporal and spatial patterns from 2000 to 2024. Areas with abundant vegetation tend to moderate surface heating by absorbing and dissipating energy, thereby limiting temperature increases. Babalola and Akinsanola (2016) note that green vegetation captures incoming solar radiation and utilizes it in photosynthetic processes rather than converting it to heat. Consistent with this, Ferreira and Duarte (2019) reported a clear negative association between NDVI and LST, indicating that higher vegetation cover is generally associated with lower surface temperature.

Research has shown that local temperature conditions are strongly shaped by LU/LC variation, including changes driven by reforestation or deforestation (Prevedello et al., 2019). Majumder et al. (2020), Odindi et al. (2015), and Rasul et al. (2017) have further linked alterations in LU/LC patterns to changes in LST. Parmesan and Hanley (2015) noted that reductions in vegetated LC are generally associated with increasing temperatures. Wilkinson et al. (2018) found evidence from Malaysia that rising temperatures are correlated with substantial declines in functional richness and freshwater fish diversity. Moreover, Yaung et al. (2021) reported that converting forested areas into settlement areas produces a stronger warming effect than converting forests to cropland.

5. CONCLUSION

LST patterns in Thailand from 2000 to 2025 were analyzed and extended to a 2031 projection using a cubic-spline framework. An appropriate number and placement of knots were selected to ensure smooth and stable model behaviour. Seasonal variability was effectively represented using eight knots, while four knots were applied to assess long-term LST changes, and three knots were used to generate decadal projections. The analysis shows a statistically significant increase in mean daily LST across Thailand's super-regions. Furthermore, LST variability is expected to continue rising between 2021 and 2031, with no clear evidence of a deceleration in the warming trend.

This study provides regional evidence of warming in Thailand, reflected by rising LST. Nevertheless, further investigation is necessary to strengthen and validate these findings. Future analyses could be improved by expanding the study domain to include larger landmasses located farther from the equator, such as regions in Russia and India, to enhance the robustness of temperature estimates. Because large land areas often encompass complex topography and diverse LU patterns, incorporating additional variables, such as LE, LC type, and the NDVI, would likely improve the accuracy and explanatory power of future assessments.

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AUTHOR CONTRIBUTIONS

Conceptualization, Resources, Munawar Munawar; Methodology, Investigation, Writing-Original Draft Preparation, Writing-Review and Editing, Rhysa McNeil; Software, Data Curation, Formal Analysis, Rohana Jani; Visualization, Validation, Sarawuth Chesoh and Nitinun Pongsiri.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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