Understanding Heat Extremes with Hot Days and Warm Nights Across India

Pritipadmaja[1], Rohit Sharma[1], Rahul Dev Garg[1]

[1]Department of Civil Engineering, Indian Institute of Technology Roorkee, India - 247667

Keywords: Land Surface Temperature, Climate Change, Big Data Analysis, Surface Heat Mapping.

Abstract

India is experiencing a significant intensification of heat extremes, with both hot days and warm nights becoming more frequent and severe in recent years. Studying these evolving patterns is crucial for understanding regional climate trends and addressing the growing vulnerabilities. This study focuses on the temporal trends in heat extremes by analysing the increase in the frequency of very hot days and very warm nights across Indian districts. By comparing data from a baseline period (2003–2012) to a recent period (2019–2023), the research aims to capture the evolving spatial patterns of heat extremes and assess their implications for vulnerable populations. The analysis was conducted using MODIS Aqua Land Surface Temperature (LST) daily products available on Google Earth Engine. The study derived thresholds for very hot days (90th percentile of daytime LST) and very warm nights (90th percentile of nighttime LST) based on the baseline period. These thresholds were applied to the recent period to quantify the increasing frequency of very hot days and warm nights across all districts. Temporal and spatial variations in the frequency of very hot days and warm nights were analysed to identify emerging hotspots and trends. The analysis reveals a significant increase in heat extremes across India, with both hot days and warm nights becoming more frequent and intense in recent years. These patterns highlight the complex thermal dynamics shaped by topography, urbanisation, and atmospheric processes, emphasising the need for targeted adaptation and mitigation measures. This study comprehensively assesses the temporal and spatial trends in heat extremes across India with a scientific foundation for targeted heat mitigation strategies and evidence-based policy-making for planning, agricultural strategies, and disaster management. Mapping heat extremes provides a robust foundation for designing policies.

1. Introduction

Global temperature has risen by ~ 1°C since the pre-industrial era (IPCC, 2014), primarily due to the increased anthropogenic emissions (Solomon et al., 2007). In a warming world, cities face higher temperatures than rural areas as they hold most of the world's population. Under future climate projections, weather and climate extremes, such as heat waves, droughts, floods, thunderstorms, and heavy rainfall events, are likely to become more frequent (IPCC, 2014). India will face more heat waves, heavy rainfall events, and other extreme weather patterns (IPCC, 2021). These escalating climate changes will disproportionately impact vulnerable populations, particularly in developing and tropical countries. India is increasingly experiencing frequent, intense and devastating heat waves, leading to the loss of many lives in recent years. Heat extremes are becoming increasingly severe across the country due to climate change and urbanisation, leading to significant socio-economic and environmental impacts.

India has recently become the most populous country in the world (in April 2023), surpassing China. The country has undergone rapid urban expansion in recent decades, a trend that is projected to continue in the coming years (Nayak et al., 2023). The country continues to urbanise rapidly, undergoing significant land-use transformation alongside the growing impacts of climate change. The interplay of natural and anthropogenic factors has intensified heat stress in various regions, posing severe challenges to public health, agriculture, and urban infrastructure. Studying these evolving patterns is crucial for understanding regional climate trends and addressing the growing vulnerabilities. A study of the frequency of hot days in 89 Indian cities showed a significant increase in hot days from 1951 to 2016 (Kumar & Mishra, 2019). This study focuses on the temporal trends in heat extremes by analysing the increase in the frequency of very hot days and very warm nights across Indian districts. By comparing data from a baseline period (2003–2012) to a recent period (2019–2023), the research aims to capture the evolving spatial patterns of heat extremes and assess their implications for vulnerable populations.

Spatial and temporal analysis of heat extremes across a country is critical to identifying regional hotspots, assessing trends, and supporting evidence-based policy-making. For this reason, large-scale datasets provide the opportunity for detailed spatiotemporal analysis of heat extremes over extended periods. Thus, leveraging big data techniques is essential to analyse heat extremes across a country, addressing the challenge of processing vast datasets over a large geographical area and extended time periods, contributing to understanding regional climate dynamics and informing targeted mitigation strategies.

To systematically analyse heat extremes, this study employs satellite-derived Land Surface Temperature (LST) data from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua. LST provides valuable information on the physical land dynamics process (Pandey et al., 2022). LST data offers medium-resolution, spatially continuous, and long-term temperature records, making it a crucial tool for monitoring heat stress across India's diverse climatic zones. Given the vast geographic extent and climatic variability of India, leveraging big data analytics and remote sensing techniques is essential for processing and analysing large-scale temperature datasets efficiently. This study integrates MODIS Aqua LST data with advanced spatial and temporal analysis methods to offer new insights into regional climate trends, emerging heat hotspots, and vulnerable areas. By providing a detailed assessment of heat extremes, the research aims to inform evidence-based policy decisions, support urban heat mitigation strategies, and enhance climate resilience planning at the national and regional levels.

Rapid urbanisation and climate vulnerability of India present a globally relevant case for managing extreme heat. With its diverse climatic conditions, socio-economic disparities, and high population density, the country faces unique challenges in addressing urban heat risks. While proactive measures such as

Heat Action Plans (HAPs), urban greening initiatives, and improved early warning systems have been implemented in several cities, significant gaps remain in understanding localised patterns of heat exposure. The limited integration of good-resolution satellite data and big data analytics in heat risk assessments hinders the development of targeted mitigation and adaptation strategies. By leveraging advanced remote sensing and geospatial analysis, this study aims to bridge these knowledge gaps, providing a scientific basis for urban planning, climate adaptation, and public health interventions to reduce heat-related risks in India's rapidly transforming landscape.

2. Data and Methods

The study assessing heat extremes involves a comprehensive analysis of LST (both day and night) data using MODIS LST daily products with a spatial resolution of 1 km assessed through the Google Earth Engine (GEE) catalog. The analysis was conducted on GEE, a cloud-based platform that enables efficient processing of large-scale geospatial datasets (Gorelick et al., 2017). The MODIS onboard the Terra and Aqua satellites has high temporal resolution with four daily observations, making it suitable for diverse applications, including detailed analysis of LST variations (Phan & Kappas, 2018; Pritipadmaja et al., 2024). For this study, MODIS Aqua LST is preferred for heat stress analysis due to its observations around 13:30 local time, which is closer to the daily maximum LST (Sharifnezhadazizi et al., 2019), as its reduced data contamination and improved accuracy in detecting maximum daytime and retained nighttime heat (Wan, 2014).

The study examines two distinct time periods to capture changes in heat extremes: a baseline period (2003–2012) used for reference temperature thresholds and a recent period (2019–2023) to assess deviations from historical norms. First, the LST pixel values are rescaled using the 0.02 constant and converted to Celsius. The LST data is further selected for the study area and study period. The LST data was then spatially aggregated to the district level by averaging pixel values within district boundaries, allowing for regional-scale comparisons.

To quantify heat extremes, percentile-based thresholds were established for both daytime and nighttime LST. A very hot day was defined as any day where daytime LST exceeded the 90th percentile of the baseline period. In contrast, a very warm night was defined as any night where nighttime LST exceeded the 90th percentile of the baseline. These thresholds were applied to the recent period to measure the frequency of extreme heat events across all Indian districts. Temporal and spatial variations in the frequency of very hot days and warm nights were analysed to identify emerging hotspots and trends. This study offers a comprehensive assessment of heat stress evolution in India, providing critical insights for climate resilience planning, agricultural adaptation, and urban heat mitigation strategies.

3. Results

The results of the heat extreme analysis indicate a substantial intensification in the frequency and intensity of both hot days and warm nights across India in recent years, with significant regional variations. The spatial and temporal analysis of MODIS LST data reveals a clear trend of increasing heat extremes in recent years (2019–2023) compared to the baseline period (2003–2012). The result maps utilise a quantile-based classification approach, ensuring each category contains an equal number of districts. However, this method results in non-uniform class intervals, reflecting the changing distribution of LST values over time. In the baseline period, the temperature range for the highest quantile was relatively broad, suggesting that extreme heat events were more concentrated in specific regions. In contrast, the highest temperature category has a narrower range during the recent period, indicating that more districts are now experiencing similarly high temperatures. This shift suggests a spatial homogenisation of extreme heat, where high temperatures are no longer confined to historically hot regions but are becoming more widespread across the country

3.1 Daytime heat extremes

The spatial distribution of daytime heat extremes is evident in Figure 1, which presents the 90th percentile daytime LST during the baseline period, the mean daytime LST in recent years is shown in Figure 2, and the increase in the frequency of extremely hot days (Figure 3).

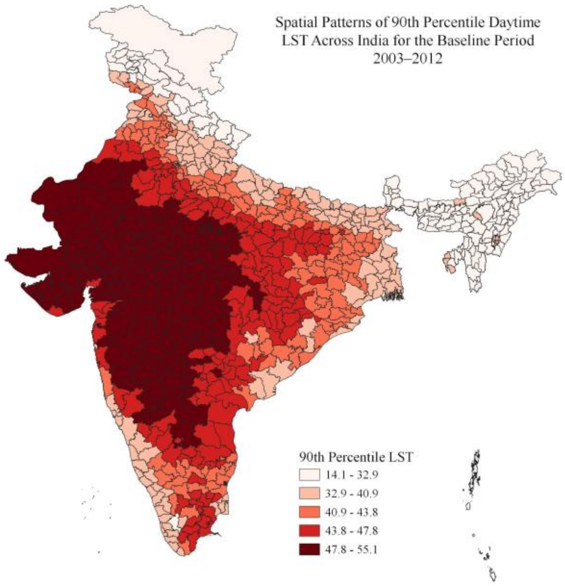

Figure 1: 90th Percentile Daytime LST of Baseline Period

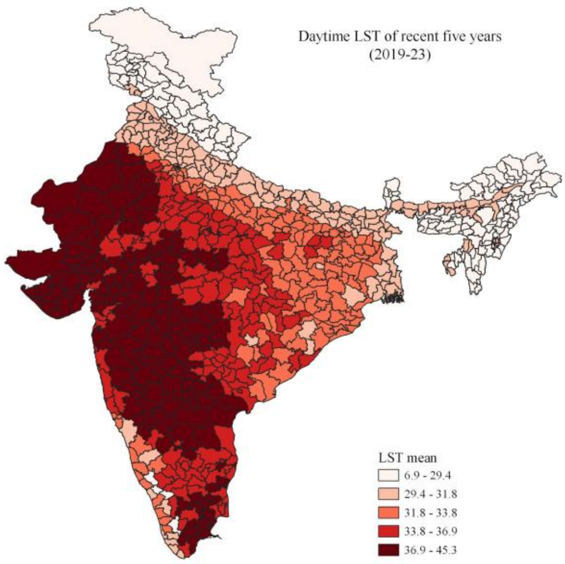

Figure 2 Mean Daytime LST recent period

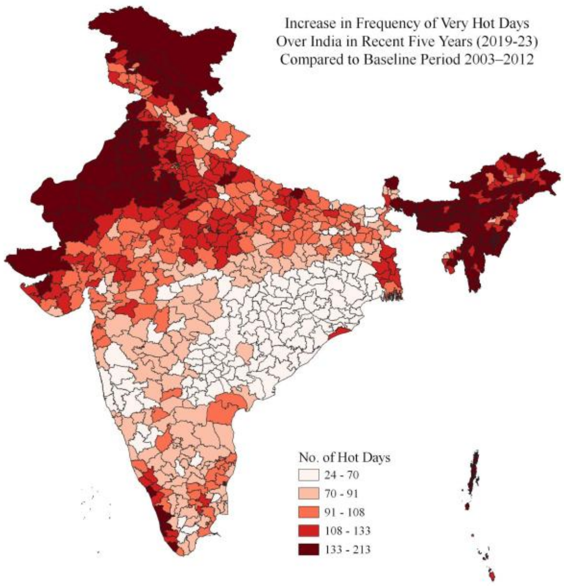

Figure 3 Number of increased hot days

During the baseline period (2003–2012) shown in 1, the highest daytime LST values were predominantly concentrated in northwestern and central India, with Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh exhibiting the most extreme temperatures. This region has historically been a persistent heat zone, influenced by its arid and semi-arid climate, limited vegetation cover, and high solar radiation exposure.

A comparison with the recent period (2019–2023) shown in 2 reveals a notable expansion of heat zones, particularly in southern and southeastern India. The emerging hotspots in Tamil Nadu, Andhra Pradesh, and Telangana indicate a shift in heat stress patterns driven by rapid urbanisation, deforestation, and land-use changes. The northern and northwestern regions, already high-temperature zones, continue to exhibit extreme LST values, further reinforcing their vulnerability.

The increase in the frequency of very hot days across India is shown in Figure 3 in the recent period compared to the baseline period. The analysis highlights a widespread rise in extremely hot days across multiple regions, with the most significant increases observed in northwestern, northern and northeastern. These patterns reflect changing climate trends and indicate that extreme heat events are becoming more frequent and intense in both historically hot regions and newly emerging heat-prone areas.

The northwestern and northern regions, including Punjab, Haryana, Rajasthan, Ladakh, Jammu and Kashmir, exhibit the most severe increases. This suggests continuing and intensifying extreme heat trends, likely driven by rising global temperatures, land surface changes, and increasing frequency of heatwave events. A notable shift is also observed with an emerging trend, as these regions have historically been less prone to prolonged extreme heat. The southwest coast of India also shows a substantial rise in extremely hot days. The increase in hot days along the southwestern coastal belt results from increased urbanisation.

Overall, Figure 3 provides strong evidence of increasing extreme heat across multiple climatic zones in India, with the highest rise occurring in northwestern, northern, and northeastern. These trends highlight the urgent need for climate adaptation measures, enhanced heat early-warning systems, and urban and planning strategies to mitigate the escalating impact of extreme heat on human health, agriculture, and infrastructure.

3.2 Nighttime heat extremes

The analysis of nighttime LST patterns provides critical insights into nocturnal heat retention and urban heat island (UHI) effects. Figures 4, 5, and 6 illustrate the 90th percentile nighttime LST during the baseline period, the mean nighttime LST in recent years, and the increase in the frequency of very warm nights, respectively.

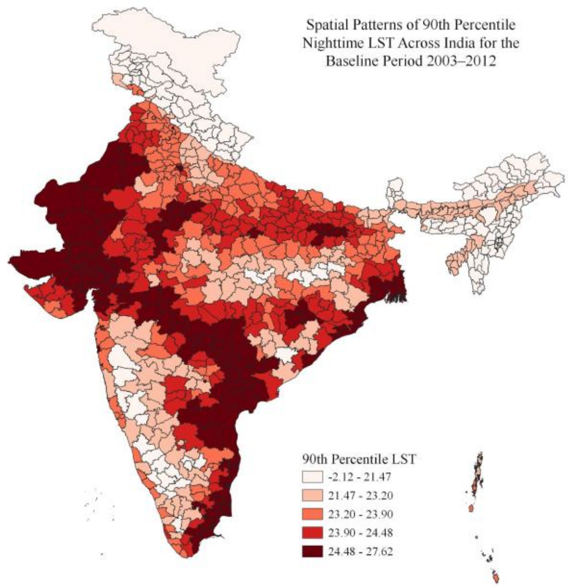

Figure 4 90th Percentile Nighttime LST of Baseline Period

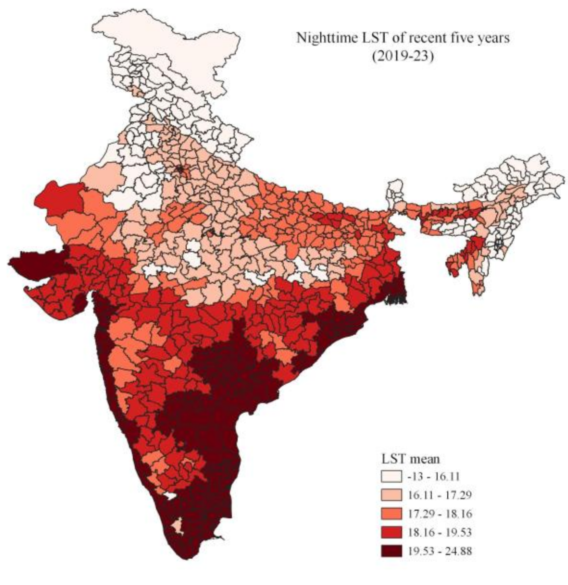

Figure 5 Mean Nighttime LST recent period

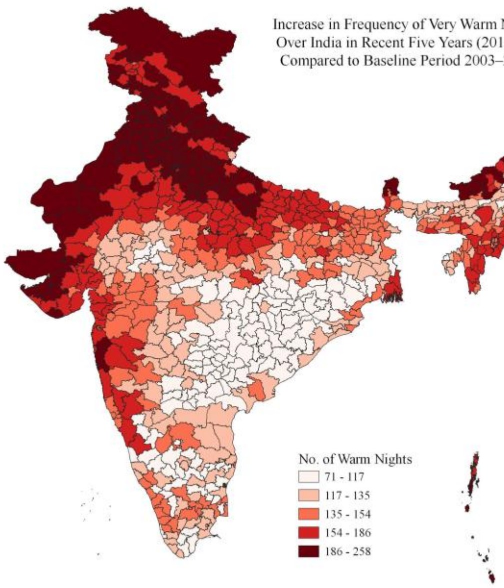

Figure 6 Number of increased warm nights

During the baseline period, northwestern, western, southeastern, east coast and central India exhibited the highest nighttime LST values shown in Figure 4, indicating persistent heat zones. The recent period shows a widespread increase in nighttime LST, as shown in Figure 5, with particularly significant rises in the west coast and south-central regions. Some regions have experienced some of the most pronounced increases in nighttime temperatures. These findings indicate that heat dissipation is becoming increasingly inefficient, leading to sustained nighttime heat stress. The baseline nighttime LST map shows that the highest 90th percentile values were primarily concentrated in western and southern India, with some pockets in central and eastern regions. The temperature range in the highest quantile is relatively wide, suggesting that extreme nighttime temperatures were confined to specific regions. In contrast, the recent nighttime LST map indicates a widespread increase in mean nighttime temperatures, with the highest temperature zones expanding further across the southern, western, and eastern parts of the country. More districts now fall within the upper-temperature categories, indicating that elevated nighttime temperatures have become more common across a larger spatial extent.

Figure 6 illustrates the increase in the frequency of very warm nights across India in the recent period compared to the baseline period. The analysis highlights a significant rise in nighttime temperatures across multiple regions, with the most substantial increases occurring in northwestern, northern and northeastern India. These patterns indicate that nocturnal heat retention is becoming more pronounced, likely due to climate change, increased urbanisation, and changes in atmospheric circulation patterns.

The increase in the frequency of very warm nights further highlights this trend, with a significant rise in the number of nights exceeding the historical 90th percentile threshold. In the baseline period, extreme nighttime temperatures were limited to specific hotspots. In contrast, in recent years, warm nights have increased across diverse climatic regions, including parts of northern and northeastern India that previously had lower nighttime temperatures. Some districts experience more than 186 warm nights annually, indicating prolonged exposure to elevated nighttime heat.

The persistence of high temperatures at night poses severe health risks, particularly for vulnerable populations such as older people, children, and outdoor workers, as it limits recovery time from extreme daytime heat. This underscores the urgent need for targeted mitigation strategies, such as expanding urban greenery, implementing cool roofing technologies, and strengthening early warning systems to protect vulnerable populations from nocturnal heat stress.

4. Discussion

The results of this study demonstrate clear evidence of climate change with significant intensification of heat extremes across India, with both hot days and warm nights becoming more frequent and widespread. This intensification is not uniform across the country, with different regions exhibiting distinct trends influenced by climate change, urbanisation, land-use changes, and regional atmospheric dynamics. The effects of extreme heat in recent periods, particularly in historically cooler areas than other regions, highlight the growing impact of human-induced environmental transformations. These findings align with broader global warming patterns, emphasising the urgent need for targeted mitigation and adaptation strategies to address the escalating risks of extreme heat on public health, agriculture, and infrastructure.

The comparison between the two periods reveals a significant increase in mean daytime LST, with the highest temperatures covering a larger geographic extent. The increase in very hot days further supports this trend, with previously moderate-temperature regions now experiencing a higher frequency of extreme heat events. The spatial distribution of this increase is particularly notable in northern and northeastern India, where the number of hot days has risen substantially compared to the baseline period. The persistence of extreme temperatures in western and central India and their expansion into new regions highlights the growing intensity and geographic spread of heat stress.

The analysis of daytime heat extremes highlights that northwestern, western and central India have consistently exhibited the highest daytime LST values, reaffirming their status as persistent heat zones. The Northwest region consistently exhibits high LST across baseline daytime, recent daytime, baseline nighttime, and mean max LST; however, in recent nighttime LST, it shows a relative decline compared to other areas. However, there is a notable shift is observed in the recent period, with heat zones expanding into southern and southeastern India. Both daytime and nighttime LST have shown a noticeable increase in South India in recent years. The newly emerging hotspots in districts there indicate a change in heat stress patterns, likely driven by rapid urbanisation, deforestation, and alterations in land use. The combination of high population density, increased built-up areas, and reduced green cover has intensified the UHI effect in these regions, making them more vulnerable to extreme heat events.

Northeastern India, which historically experienced more moderate temperatures due to its dense vegetation and monsoonal climate, is now witnessing a notable rise in extreme hot days. The southwestern coast has also shown a substantial rise in extremely hot days. This increase suggests a weakening of coastal cooling mechanisms, possibly due to the presence of many urban areas in Kerala.

The findings on nighttime heat retention provide critical insights into how heat stress evolves beyond daytime extremes. The analysis shows that warm nights are becoming increasingly prevalent across the country, with nighttime LSTs increasing in coastal areas. This indicates that heat dissipation is becoming increasingly inefficient, likely due to prolonged heatwave events, high urban density, and land surface modifications. The persistence of high temperatures at night is particularly concerning, as it limits human recovery from daytime heat stress, increases electricity demand for cooling, and exacerbates the UHI effect.

The spatial patterns of heat extremes across India highlight the complexity of thermal dynamics influenced by topography, land cover, and regional climate interactions. The northwestern, western and central regions have consistently exhibited high LST values, reinforcing their role as persistent heat zones. However, the frequency of both hot days and warm nights has intensified in recent years, with northern, northwestern, and northeastern parts of the country experiencing significant increases. The Himalayan region is now emerging as a new area of concern, with a rising frequency of both hot days and warm nights. Increasing temperatures in ecologically sensitive regions could accelerate glacial melt, disrupt local ecosystems, and threaten long-term water security. The trends in northeastern India are also significant, with exterior regions experiencing more warm nights while interior regions are affected by both extreme hot days and warm nights. This pattern may be linked to nocturnal airflow changes, reduced vegetation cover, and increasing surface heat storage. Meanwhile, coastal areas, particularly along the east coast and Western Ghats, face growing vulnerability to heat stress due to the increasing frequency of warm nights. The inability to cool down at night in these regions poses a severe challenge for populations, requiring urgent urban and regional planning and housing design interventions to enhance heat resilience.

Results suggest that nighttime warming is becoming widespread rather than being restricted to historically warm regions. The non-uniform class intervals in the quantile classification further emphasise that a larger number of districts are now experiencing similarly high nighttime temperatures, contributing to a narrowing of temperature ranges in the highest categories. The increase in nighttime temperatures is particularly concerning as it reduces the opportunity for cooling, exacerbating heat stress, particularly in urbanised and densely populated areas. These results underscore the growing need for adaptation measures, including heat-resilient urban planning and improved infrastructure to mitigate the impact of sustained nighttime heat.

Findings indicate that warming is not only intensifying but also affecting a larger number of districts uniformly. The rise in land surface temperature and the increasing frequency of hot days are consistent with patterns of urban expansion, land cover modifications, and broader climate change impacts. The quantile-based classification further emphasises that while some regions have historically experienced extreme heat, a growing number of districts now fall into higher temperature categories, reinforcing the need for region-specific heat mitigation strategies.

The comparison between the increase in the frequency of very hot days and very warm nights highlights distinct yet interconnected patterns of temperature rise across India. The rise in hot days is most pronounced in northwestern, central, and eastern regions, where some districts now experience more than 133 hot days annually. In contrast, the increase in warm nights is more widespread, affecting not only western and central India but also extending significantly into southern and northeastern regions. Some districts now record more than 186 warm nights annually, indicating prolonged heat exposure even after sunset. While extreme daytime temperatures have expanded in traditionally hot regions, nighttime warming appears to be occurring at a faster and more widespread rate, with cooler regions showing significant increases in warm nights. The persistent rise in nighttime temperatures aligns with the urban heat island effect, where built-up areas retain heat, preventing cooling during the night. This phenomenon disproportionately affects densely populated and urbanised areas, increasing thermal discomfort and raising the risk of heat-related illnesses.

The increasing frequency and severity of heat extremes have profound implications for multiple sectors, particularly public health, agriculture, and energy infrastructure. Prolonged exposure to extreme heat increases the risk of heat-related illnesses, including heatstroke, dehydration, and cardiovascular stress, particularly among vulnerable populations. The compounding effect of frequent warm nights exacerbates health risks, as sustained nighttime heat exposure prevents physiological cooling and recovery. The agricultural sector is also at risk, as high temperatures can reduce crop yields, accelerate soil moisture loss, and increase irrigation demands. The impact of rising nighttime temperatures is especially concerning, as elevated nocturnal heat affects plant respiration rates, leading to reduced agricultural productivity. Additionally, increasing heat extremes drive higher electricity consumption due to increased demand for cooling systems, which can strain power grids and contribute to further greenhouse gas emissions, creating a feedback loop that intensifies climate change.

5. Conclusion

This study provides clear and compelling evidence of the increasing severity and frequency of heat extremes across India. The analysis reveals significant spatial and temporal shifts in extreme heat patterns, with both hot days and warm nights becoming more prevalent.

The Northwest region of India consistently exhibits high LST across baseline daytime, recent daytime, baseline nighttime, and mean max LST; however, in recent nighttime LST, it shows a relative decline compared to other areas. The Himalayan and northeast regions, historically considered cooler climate zones, are now showing a rising frequency of both hot days and warm nights, which may accelerate glacial melt, disrupt local ecosystems, and threaten water security. Additionally, the sharp rise in nighttime LST in coastal regions suggests a weakening of natural cooling.

These findings have significant implications for public health, agriculture, urban planning, and energy demand. The increasing exposure to sustained heat stress can heighten the risk of heat-related illnesses, crop failures, water shortages, and rising energy consumption, particularly in regions experiencing prolonged hot days and warm nights. The continued expansion of urban infrastructure and impervious surfaces, coupled with declining vegetation cover, is intensifying heat stress in cities, necessitating urgent interventions to improve climate resilience.

Future research should integrate socio-economic data and high-resolution climate models to improve the understanding of localised heat risk patterns and their impacts on communities. The use of higher-resolution satellite data and long-term climate projections will further enhance the ability to predict, mitigate, and adapt to extreme heat events. By adopting a multi-disciplinary approach that combines climate science, urban planning, and public health policies, India can develop more effective heat resilience strategies that safeguard lives, livelihoods, and ecosystems.

This study underscores the urgent need for proactive climate adaptation and mitigation efforts to address the increasing threats posed by heat extremes across India. With the country's rapid urbanisation and ongoing climate change challenges, strategic policy interventions and sustainable urban planning will be critical in ensuring a more resilient and livable future for millions of people.

6. Acknowledgements

We sincerely thank IIT Roorkee for providing the necessary facilities and support to conduct this research. We also extend my gratitude to The ISPRS Foundation for awarding me the travel grant, enabling me to attend ISPRS GSW 2025 and present my work. Their support has been invaluable in facilitating the dissemination of this research.

7. References

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Intergovernmental Panel On Climate Change (Ipcc), 2023. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157896

Kumar, R., Mishra, V., 2019. Decline in surface urban heat island intensity in India during heatwaves. Environ. Res. Commun. 1, 031001. https://doi.org/10.1088/2515-7620/ab121d

Meyer, L., Brinkman, S., van Kesteren, L., Leprince-Ringuet, N., van Boxmeer, F., n.d. Technical Support Unit for the Synthesis Report.

Nayak, S., Vinod, A., Prasad, A.K., 2023. Spatial Characteristics and Temporal Trend of Urban Heat Island Effect over Major Cities in India Using Long-Term Space-Based MODIS Land Surface Temperature Observations (2000–2023). Appl. Sci. 13, 13323. https://doi.org/10.3390/app132413323

Pandey, P.C., Chauhan, A., Maurya, N.K., 2022. Evaluation of earth observation datasets for LST trends over India and its implication in global warming. Ecol. Inform. 72, 101843. https://doi.org/10.1016/j.ecoinf.2022.101843

Phan, T.N., Kappas, M., 2018. Application of MODIS land surface temperature data: a systematic literature review and analysis. J. Appl. Remote Sens. 12, 1. https://doi.org/10.1117/1.JRS.12.041501

Pritipadmaja, Sharma, R., Garg, R.D., Leuchner, M., 2024. A Spatial Analysis of Land Surface Temperature Anomalies Across India, in: IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium. Presented at the IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, IEEE, Athens, Greece, pp. 3881–3884. https://doi.org/10.1109/IGARSS53475.2024.10641021

Sharifnezhadazizi, Z., Norouzi, H., Prakash, S., Beale, C., Khanbilvardi, R., 2019. A Global Analysis of Land Surface Temperature Diurnal Cycle Using MODIS Observations. J. Appl. Meteorol. Climatol. 58, 1279–1291. https://doi.org/10.1175/JAMC-D-18-0256.1

Solomon, S., Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (Eds.), 2007. Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge ; New York.

Wan, Z., 2014. New refinements and validation of the collection-6 MODIS land-surface temperature/emissivity product. Remote Sens. Environ. 140, 36–45. https://doi.org/10.1016/j.rse.2013.08.027