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Linking Land Surface Temperature and Tourist Thermal Comfort: Implications for Sustainable Tourism Development in Bali, Indonesia

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***Abstract**. Tourism is widely recognized as one of the most climate-sensitive economic sectors, with destinations in tropical regions increasingly exposed to the impacts of global warming and rapid urbanization. Rising temperatures and the intensification of urban heat island effects have become critical challenges for tourist thermal comfort, destination competitiveness, and the sustainability of tourism development worldwide. As a globally renowned tourism destination, Bali faces growing environmental pressures associated with land-use change and expanding built-up areas; however, empirical studies linking surface temperature dynamics with tourism comfort remain limited. This study aims to analyze the spatiotemporal dynamics of Land Surface Temperature (LST) in Bali Province and assess their implications for tourist thermal comfort and sustainable tourism planning. A remote sensing-based analysis was conducted using satellite imagery from 2014 and 2024 to identify LST changes and evaluate thermal conditions in major tourism hotspots. Thermal comfort benchmarks were established based on internationally recognized thermal comfort indices and tourism climate literature to determine whether current temperature conditions remain within acceptable comfort thresholds. Land cover change analysis was also performed to examine the relationship between land-use transformation and surface temperature variations. The results indicate a significant increase in LST across key tourism areas, particularly in densely urbanized environments, with several popular destinations exceeding optimal thermal comfort ranges. These findings suggest potential risks to visitor experience and long-term destination attractiveness. The study emphasizes the importance of integrating LST and thermal comfort considerations into tourism and spatial planning and provides a replicable methodological framework.*

***Keywords**. Land surface temperature, tourist thermal comfort, spatio-temporal analysis, sustainable tourism.*

Introduction

Tourism has emerged as one of the largest and fastest-growing sectors in the global economy, yet it is also among the industries most vulnerable to environmental and climatic change (Chikodzi et al., 2022; Khan et al., 2023). Unlike many other economic activities, tourism is highly dependent on favorable natural and climatic conditions, particularly in destinations that rely on outdoor attractions and experiences (Dong & Qu, 2023). In tropical regions, where high temperatures and humidity are already inherent characteristics, even small shifts in climate patterns can have a substantial impact on visitor comfort and satisfaction (Lam-González et al., 2022). The growing intensity of global warming, combined with rapid urban expansion and environmental degradation, has begun to alter the thermal characteristics of many tourism destinations around the world (Marlon et al., 2021; Rahaman et al., 2022). These changes raise

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fundamental questions about the long-term sustainability of tourism development under increasingly warmer climatic conditions (Dong & Qu, 2023).

The concept of thermal comfort has gained growing attention in recent years as an important dimension of tourism quality and destination competitiveness (Y. Liu et al., 2023; Lopes et al., 2021). For many travelers, especially those visiting tropical destinations, the ability to enjoy outdoor environments comfortably is a key factor influencing travel decisions and overall experience (Lopes et al., 2021). Excessive heat can reduce the willingness of tourists to engage in outdoor activities, shorten the duration of visits, and negatively affect perceptions of a destination (Dong & Qu, 2023). In extreme cases, uncomfortable thermal conditions may even pose health risks to visitors (Li et al., 2023). Despite its importance, thermal comfort considerations are still rarely integrated into tourism planning and destination management frameworks (Wang & Li, 2023). Tourism development strategies often prioritize economic growth, infrastructure expansion, and marketing, while the climatic suitability of destinations receives relatively limited attention.

At the same time, rapid urbanization in tourism areas has contributed to significant environmental transformations that influence local temperature conditions (Zhou et al., 2023). The conversion of natural landscapes into built-up environments, the reduction of green spaces, and the expansion of transportation infrastructure have all been associated with the intensification of urban heat (Xu et al., 2022). These processes not only affect local residents but also shape the environmental experience of tourists. In many popular destinations, the very development that supports tourism growth may simultaneously reduce environmental quality and comfort (Wang & Li, 2023). Understanding how physical development interacts with local climate is therefore essential for ensuring that tourism remains sustainable and attractive in the long term.

Advances in remote sensing technology have opened new possibilities for analyzing environmental change and its implications for tourism. Land Surface Temperature (LST), derived from satellite imagery, has become a widely used indicator for monitoring spatial and temporal variations in heat conditions (Kiavarz et al., 2022). LST analysis enables researchers to observe how temperature patterns evolve over time and how they differ across urban, rural, and natural landscapes (Niclòs et al., 2023). While this approach has been extensively applied in urban planning and environmental studies, its integration into tourism research remains relatively limited (Z. Liu et al., 2023). Most tourism-climate studies still rely primarily on meteorological data, which often lack the spatial detail needed to understand conditions in specific tourism hotspots. The potential of satellite-based thermal analysis to support tourism planning and management has not yet been fully explored (Kiavarz et al., 2022).

Bali provides a particularly important and timely case study for examining the relationship between temperature dynamics and tourism sustainability. As one of the most iconic tropical destinations in the world, Bali has long been a major hub of international tourism (Rosalina et al., 2023). Prior to the COVID-19 pandemic, Bali consistently attracted more than six million international visitors each year, in addition to around ten million domestic tourists, placing it among the most visited destinations in Asia (Hendrawan et al., 2023). Tourism contributes more than half of Bali's regional economy and supports a large proportion of local employment and business activities. The island's global reputation for culture, nature, and hospitality continues to make it a leading destination for travelers from Europe, Australia, East Asia, and other parts of the world (Suryawan et al., 2024).

However, the success of Bali as a global tourism destination has also brought significant environmental pressures (Hendrawan et al., 2023). Over the past decade, the island has experienced rapid growth in hotels, resorts, transportation networks, and urban infrastructure to accommodate increasing visitor numbers. Large areas of agricultural land and natural vegetation have been converted into tourism facilities, residential developments, and commercial zones (Suryawan et al., 2024). These land use changes have the potential to alter local microclimates and contribute to rising surface temperatures, particularly in highly developed tourism centers such as Kuta, Seminyak, Nusa Dua, and Ubud (Rosalina et al., 2023). As tourism development continues to intensify, concerns have emerged regarding whether the environmental conditions that originally attracted visitors to Bali can be maintained in the future.

Despite Bali's global importance, there remains limited empirical research examining how temperature dynamics on the island have changed over time and how these changes affect tourist comfort (Niclòs et al., 2023). Most existing tourism studies in Bali focus on economic impacts, cultural issues, or environmental management, while the thermal dimension of tourism experience is rarely addressed (Suryawan et al., 2024). There is also a lack of integrated studies that connect satellite-based temperature analysis with assessments of thermal comfort specifically from a tourism perspective (Hendrawan et al., 2023). This represents a critical research gap, particularly for destinations like Bali where outdoor experiences are central to the tourism product (Li et al., 2023). Addressing this gap is essential for developing more climate-sensitive and evidence-based tourism policies.

This study seeks to contribute to that need by analyzing the dynamics of Land Surface Temperature in Bali Province over a ten-year period and assessing their implications for tourist thermal comfort. The research combines spatio-temporal LST analysis, thermal comfort benchmarking for international and domestic tourists, and land cover change assessment to provide a comprehensive understanding of how environmental change interacts with tourism conditions (Kiavarz et al., 2022; Xu et al., 2022; Zhou et al., 2023). By examining both the physical and human dimensions of temperature change, the study aims to offer practical insights for more sustainable tourism planning and management. Ultimately, this research seeks to support the development of climate-resilient tourism strategies that can help Bali and other tropical destinations remain attractive and competitive in a warming world.

Literature Review

Land Surface Temperature (LST) has become an increasingly important parameter in environmental and spatial planning studies, particularly in understanding the thermal characteristics of urban and regional landscapes (Haldar et al., 2023; Santhosh & Shilpa, 2023; Ullah et al., 2023). LST represents the radiative temperature emitted from the Earth's surface and can be effectively measured through satellite-based remote sensing platforms such as Landsat and MODIS (Santhosh & Shilpa, 2023) The availability of long-term satellite data has enabled researchers to monitor spatial and temporal variations in surface temperature, making LST a valuable indicator for assessing environmental change, urban heat island effects, and land use transformation (Haldar et al., 2023). Numerous studies have demonstrated that LST is highly sensitive to alterations in land cover, especially the expansion of built-up areas and the reduction of vegetation cover (Santhosh & Shilpa, 2023). These changes modify surface energy balance and lead to localized warming, which has important implications for environmental quality and human well-being.

In parallel with the growing concern over climate change, sustainable tourism development has emerged as a key global agenda (Zhou et al., 2023). Sustainable tourism emphasizes the need to balance economic benefits with environmental protection and social equity in order to ensure the long-term viability of tourism destinations (Arismayanti, 2019; Naila, 2023). Climate and environmental conditions play a crucial role in shaping tourism experiences, particularly in destinations that rely heavily on outdoor attractions (Y. Liu et al., 2023). Tourists tend to prefer locations with favorable and comfortable climatic conditions, while excessive heat and poor environmental quality can negatively influence visitor satisfaction and destination attractiveness (Lopes et al., 2021). Consequently, understanding the relationship between climate-related factors and tourism development has become increasingly important in tourism planning and management.

Despite the recognition that climate conditions affect tourism, most tourism climate studies have traditionally relied on general meteorological data such as air temperature and precipitation (Sandoval et al., 2023). The use of spatially explicit indicators such as Land Surface Temperature in tourism research remains relatively limited. However, LST offers significant advantages because it reflects the actual thermal conditions of the physical environment experienced by tourists at specific locations (Santhosh & Shilpa, 2023). Areas with high surface temperatures, often associated with dense urban development and limited green spaces, can reduce outdoor thermal comfort and affect the overall quality of tourist experiences (Y. Liu et al., 2023). Recent studies in urban climatology suggest that integrating LST analysis into tourism studies can provide deeper insights into how environmental heat patterns influence the usability and attractiveness of tourism spaces (Ciuha & Mekjavic, 2016; Sumaryana et al., 2024).

Another important aspect closely related to LST dynamics is land cover change. The conversion of natural landscapes into impervious surfaces such as buildings, roads, and other tourism infrastructure has been widely identified as a major driver of increasing surface temperatures (Pradeep Kumar et al., 2023; Sumaryana et al., 2024) Vegetated areas and water bodies generally contribute to cooling effects through evapotranspiration and shading, whereas built-up surfaces absorb and retain more heat. In major tourism destinations undergoing rapid development, land cover transformation is often inevitable due to the growing demand for accommodation, transportation, and recreational facilities (Z. Liu et al., 2023). These processes, while economically beneficial, may unintentionally create thermal environments that are less comfortable and less sustainable in the long term (Rahaman et al., 2022). Therefore, analyzing land cover change in conjunction with LST provides an essential basis for understanding the environmental consequences of tourism growth.

Although extensive research has been conducted on LST in the fields of urban studies and environmental science, its application within the context of tourism planning and sustainable tourism development remains underexplored (Higgins-Desbiolles, 2018). Existing tourism research tends to focus more on economic performance, visitor behavior, and service quality, with relatively little attention given to spatial thermal conditions as a determinant of sustainability (Asmelash & Kumar, 2019). Furthermore, only a limited number of studies have attempted to link spatio-temporal LST dynamics with tourism development strategies, particularly in tropical destinations where heat stress is a critical issue (Pradeep Kumar et al., 2023). This represents a significant research gap, as rising surface temperatures driven by climate change and urbanization may directly affect the future competitiveness and livability of tourism destinations.

Bali, as one of the world's most popular tropical tourism destinations, provides a highly relevant context for examining this issue (Geria et al., 2023; Kardi et al., 2021). The rapid growth of tourism in Bali over recent decades has been accompanied by substantial land use changes, urban expansion, and infrastructure development (Hendrawan et al., 2023; Tunjungsari, 2018). While these developments have contributed significantly to economic growth, they have also altered the island's environmental conditions, including its thermal landscape (Rosalina et al., 2023). However, empirical studies that analyze how changes in Land Surface Temperature relate to sustainable tourism development in Bali are still very limited (Pradeep Kumar et al., 2023). Most existing studies focus on tourism demand, economic impacts, or general environmental issues, rather than on spatial temperature dynamics and their implications for tourism sustainability.

Given these gaps, there is a need for integrated research that connects remote sensing-based LST analysis with sustainable tourism planning (Pradeep Kumar et al., 2023). Understanding how surface temperature patterns evolve over time and how they are influenced by land cover change can provide valuable insights for developing more climate-responsive tourism strategies (Haldar et al., 2023). This study seeks to contribute to the existing body of knowledge by examining the spatio-temporal dynamics of Land Surface Temperature in Bali and evaluating their implications for sustainable tourism development. By positioning LST as a practical and measurable indicator within tourism planning, the research offers a new perspective on how environmental data can support more resilient and sustainable destination management in the face of climate change (Geria et al., 2023).

Research method

Study Area

This study was conducted in Bali Province, Indonesia, one of the most prominent international tourism destinations in the world. Geographically, Bali is located between 8°03′–8°50′ South Latitude and 114°25′–115°42′ East Longitude, with a total area of approximately 5,780 km² (Hendrawan et al., 2023). Administratively, Bali consists of nine regencies and municipalities, including Denpasar City, Badung, Gianyar, Tabanan, Buleleng, Karangasem, Klungkung, Bangli, and Jembrana. The province is characterized by diverse landscapes ranging from coastal tourism areas, urban centers, agricultural zones, to mountainous regions.

Bali has experienced rapid tourism-driven development over the past decades, leading to significant land use transformation, particularly in major tourism hotspots such as Kuta, Seminyak, Sanur, Ubud, and Nusa Dua (Rosalina et al., 2023). These areas attract millions of domestic and international tourists annually and have become centers of intensive infrastructure development. Such rapid urbanization and tourism expansion have raised concerns regarding environmental sustainability, including increasing surface temperatures and the reduction of green open spaces.

Climatically, Bali is situated in a tropical region with relatively high temperatures throughout the year (Geria et al., 2023). This climatic characteristic makes Bali highly relevant for examining the relationship between Land Surface Temperature (LST) dynamics and sustainable tourism development. Understanding spatial temperature patterns in relation to tourism concentration areas is essential for developing climate-responsive tourism planning strategies. The administrative map of Bali Province and the distribution of major tourism destinations are presented at the end of this section to provide spatial context for the analysis (Boakes et al., 2022).

Data & Analysis Method

This study employed remote sensing and spatial analysis techniques to examine the dynamics of Land Surface Temperature (LST) and its implications for sustainable tourism development in Bali. The primary data used in this research consisted of multi-temporal satellite imagery obtained from the United States Geological Survey (USGS). Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) imagery for the year 2014 and Landsat 9 OLI/TIRS imagery for the year 2024 were selected as the main datasets for LST extraction and land cover analysis. These datasets were chosen due to their adequate spatial resolution, consistent temporal coverage, and suitability for environmental monitoring applications. Only images with minimal cloud cover were utilized to ensure data reliability and comparability between the two observation periods.

The analysis began with preprocessing procedures, including radiometric correction, atmospheric correction, and image calibration, to improve the accuracy of the satellite data. Land Surface Temperature was derived from the thermal infrared bands of Landsat imagery through a series of standard remote sensing steps, including the conversion of digital numbers to spectral radiance, transformation into brightness temperature, and emissivity correction to obtain actual surface temperature values (Kumar et al., 2022). The LST extraction process was conducted separately for the years 2014 and 2024 to enable a spatio-temporal comparison of surface temperature conditions across Bali Province.

To understand the factors influencing LST dynamics, land cover classification was performed using supervised classification techniques (Santhosh & Shilpa, 2023; Ullah et al., 2023). Land cover maps for both years were generated to identify major categories such as built-up areas, vegetation, water bodies, agricultural land, and open spaces. Change detection analysis was subsequently carried out to quantify the extent and pattern of land cover transformation over the ten-year period. The relationship between land cover change and variations in LST was initially examined through spatial overlay and correlation analysis, allowing for the identification of areas where land conversion has contributed to increasing surface temperatures (Haldar et al., 2023).

In addition to spatial correlation analysis, this study employed logistic regression analysis to quantitatively assess the influence of land cover characteristics on Land Surface Temperature (Haldar et al., 2023). For this purpose, LST values were classified into two categories (e.g., high LST and low LST) based on statistically determined thresholds. Land cover types and land cover change variables were used as independent predictors in the logistic regression model. This approach enabled the estimation of the probability of high surface temperature occurrence associated with specific land cover classes and conversion patterns, thereby providing a more robust assessment of the effect of land cover on thermal conditions. The results of the logistic regression were interpreted using odds ratios to identify which land cover types significantly increase or reduce the likelihood of higher LST.

A focused spatial analysis was also conducted on major tourism hotspots in Bali, including areas with high concentrations of tourist activities such as Kuta, Seminyak, Sanur, Ubud, and Nusa Dua. Average LST values for these locations were calculated and compared between 2014 and 2024 to assess thermal changes in key tourism destinations. This approach enabled the evaluation of whether tourism-intensive areas have experienced significant temperature increases that may affect their environmental quality and long-term sustainability. All spatial processing and analysis were performed using Geographic Information System (GIS) and remote sensing software. GIS was utilized for mapping, spatial visualization, and overlay analysis, while remote sensing tools were applied for image processing and LST derivation. Logistic regression and descriptive statistical analyses were employed to summarize temperature variations and to model the relationship between land cover and LST across different spatial units. The overall analytical framework of the study integrated LST extraction, land cover change detection, regression-based modeling, and hotspot-based tourism analysis to generate a comprehensive understanding of thermal dynamics in Bali.

The outputs of this methodological process include spatial maps of LST distribution for 2014 and 2024, land cover maps and change detection results, logistic regression model outputs, and detailed assessments of temperature trends in major tourism areas. These outputs provide an empirical basis for evaluating the implications of Land Surface Temperature dynamics for sustainable tourism development and for formulating climate-responsive tourism planning strategies in Bali. To ensure a structured and replicable research process, the types of data, sources, and analytical techniques applied in this study are outlined in Table 1.

Table 1. Data and Analysis Methods

Component	Data Type	Data Source	Year	Analysis Technique	Output
Land Surface Temperature (LST)	Landsat 8 OLI/TIRS satellite imagery	USGS Earth Explorer	2014	Conversion of DN → spectral radiance → brightness temperature → emissivity correction	LST map of Bali 2014
Land Surface Temperature (LST)	Landsat 9 OLI/TIRS satellite imagery	USGS Earth Explorer	2024	Standard thermal band processing for LST extraction	LST map of Bali 2024
Temperature Change Analysis	LST datasets 2014 & 2024	Processed LST results	2014–2024	Spatio-temporal comparison and descriptive statistical analysis	Map of LST dynamics
Land Cover Data	Multispectral Landsat imagery	USGS Earth Explorer	2014 & 2024	Supervised classification	Land cover maps
Land Cover Change	Classified land cover maps	Image processing results	2014–2024	Change detection analysis	Land cover change matrix
LST–Land Cover Relationship	LST maps and land cover maps	Processed spatial data	2014–2024	Spatial overlay and correlation analysis	Spatial relationship between LST and land cover
Thermal Comfort Assessment	LST values and comfort benchmarks	International thermal comfort literature	–	Comparison between LST values and thermal comfort thresholds	Evaluation of tourist thermal comfort
Spatial Analysis	Integrated thematic datasets	GIS processing	–	Mapping and spatial interpretation	Spatial implications for sustainable tourism planning

Results & Discussion

Spatio-Temporal Dynamics of Land Surface Temperature in Bali

To analyze the evolution of thermal conditions across Bali Province, Land Surface Temperature (LST) was classified into five temperature ranges (<22°C, 22.1–28.0°C, 28.1–33.0°C, 33.1–39.0°C, and >39.1°C) for two observation years, 2014 and 2024. This classification provides a consistent framework for comparing spatial temperature patterns across regencies and cities and for identifying long-term warming trends associated with land use change and tourism-driven development.

Table 2 presents the spatial distribution of LST classes across Bali Province in 2014 and serves as a baseline representation of thermal conditions at the beginning of the observation period. The results indicate that Bali in 2014 was predominantly characterized by the 28.1–33.0°C temperature class, which covered approximately 1,264,439 ha of the total observed area. The 33.1–39.0°C class was the second most extensive, occupying 835,827 ha, suggesting that large portions of the island were already experiencing relatively high surface temperatures. Cooler temperature classes were spatially limited; areas below 22°C accounted for only 12,647 ha and were largely concentrated in highland regions such as Bangli, Karangasem, and parts of Buleleng, where elevation and vegetation exert a moderating influence on surface temperature. In contrast, areas exceeding 39.1°C covered 166,977 ha, primarily in lowland coastal areas with dense built-up land and intensive tourism activity, including Badung, Gianyar, and Denpasar City.

Table 2. Spatial Distribution of Land Surface Temperature Classes in Bali Province, 2014

Regency/City	***Land Surface Temperature* 2014 (Ha)**						
	<22°C	**>39.1°C**	**22.1-28.°C**	**28.1-33.0°C**	**33.1-39°C**	**Cloud Cover**	**Grand Total**
Badung	989	24.036	57.660	156.226	87.100	446	326.457
Bangli	513	17.457	60.134	163.010	126.056	8	367.177
Buleleng	4.111	37.351	74.981	158.543	38.461	14.290	327.738
Gianyar	0	23.132	58.620	155.862	84.266		321.879
Jembrana	140	7.552	17.667	158.872	116.965	21.354	322.551
Karangasem	2.755	20.343	59.608	158.199	126.094	147	367.146
Klungkung	65	11.423	179	155.875	89.326	121	256.990
Denpasar City		20.125		751	83.507	1	104.385
Tabanan	4.072	5.558	59.807	157.101	84.051	10.060	320.650
Grand Total	**12.647**	**166.977**	**388.655**	**1.264.439**	**835.827**	**46.427**	**2.714.972**

Source: Analysis Result, 2024

A decade later, the spatial structure of Land Surface Temperature in Bali shows a clear intensification of thermal conditions. Table 3 presents the distribution of LST classes in 2024, reflecting the cumulative impacts of urban expansion, tourism infrastructure development, and broader climatic warming. Compared to 2014, the most notable change is the substantial expansion of higher temperature classes. The 33.1–39.0°C range increased to 1,010,327 ha, representing the largest absolute growth among all categories, while the 28.1–33.0°C class also expanded to 1,315,578 ha, indicating a widespread upward shift in surface temperature across the island. In contrast, the spatial extent of extreme temperatures above 39.1°C decreased to 73,513 ha, suggesting that the most extreme heat became more spatially concentrated while a much larger proportion of Bali transitioned into persistently high, but slightly less extreme, thermal conditions.

Table 3. Spatial Distribution of Land Surface Temperature Classes in Bali Province, 2024

Regency/City	***Land Surface Temperature* 2024 (Ha)**						
	<22°C	**>39.1°C**	**22.1-28.°C**	**28.1-33.0°C**	**33.1-39°C**	**Cloud Cover**	**Grand Total**
Badung	1.600	7.736	69.754	162.752	114.805	472	357.118
Bangli	2.505	12.234	72.411	165.076	111.153	671	364.050
Buleleng	6.632	27.059	92.393	165.165	109.329	15.261	415.838
Gianyar	232	3.319	70.511	160.840	107.869	50	342.820
Jembrana	270	551	23.057	165.813	124.553	24.101	338.345
Karangasem	3.916	14.295	72.568	161.441	108.768	363	361.351
Klungkung	2	1.308	944	167.890	117.135	0	287.279
Denpasar City		6.542	0	1.410	106.135	1	114.089
Tabanan	6.346	469	72.900	165.192	110.579	10.252	365.738
Grand Total	**21.502**	**73.513**	**474.538**	**1.315.578**	**1.010.327**	**51.171**	**2.946.629**

Source: Analysis Result, 2024

At the regency and city level, the spatio-temporal comparison reveals consistent warming trends across nearly all administrative units. Southern Bali, which hosts the island's most intensively developed tourism destinations, exhibits the most pronounced thermal intensification. Badung Regency experienced a notable increase in the 33.1–39.0°C class, from 87,100 ha in 2014 to 114,805 ha in 2024, accompanied by an expansion of the 28.1–33.0°C range. Similar patterns are evident in Gianyar and Denpasar City, reinforcing their status as primary thermal hotspots linked to high densities of tourism facilities, transportation infrastructure, and urban land cover.

Warming trends are not limited to southern Bali. Buleleng, Karangasem, and Tabanan also show substantial increases in mid-to-high temperature classes, indicating that thermal intensification has expanded into northern and eastern regions traditionally characterized by lower development intensity. For example, the area within the 33.1–39.0°C class in Buleleng increased dramatically over the decade, signaling a growing exposure to heat stress beyond core tourism centers. Highland regions such as Bangli continue to retain relatively larger extents of cooler temperature classes, including areas below 22°C and within the 22.1–28.0°C range; however, even these areas experienced an expansion of warmer classes, suggesting that the warming signal is increasingly pervasive across Bali's diverse topography.

Overall, the comparison between 2014 and 2024 reveals a clear spatio-temporal transition toward higher surface temperature regimes across Bali Province. Rather than a simple increase in extreme heat zones, the findings indicate a broad redistribution of land from moderate temperature classes into sustained warm and hot categories. This pattern is particularly critical from a tourism perspective, as many of the areas experiencing increased LST correspond to major tourism destinations where outdoor activities and thermal comfort are central to visitor experience. These results provide a strong empirical foundation for the subsequent analysis of tourist thermal comfort and underscore the urgency of integrating temperature-sensitive considerations into tourism planning and destination management in Bali.

To complement the tabular analysis and provide a clearer spatial interpretation of the observed temperature patterns, the distribution of Land Surface Temperature in Bali for 2014 and 2024 is further illustrated through thematic maps. These maps visualize the spatial configuration of LST classes across the island and highlight the geographic concentration of warming trends identified in the numerical results. By presenting the spatial context of temperature change, the maps enable a more intuitive understanding of how thermal conditions have evolved over time, particularly in relation to major tourism destinations and areas of intensive land development.

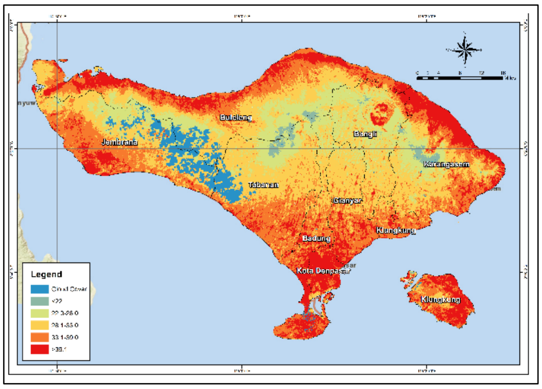

Figure.3 Land Surface Temperature Analysis of Bali Province in 2014

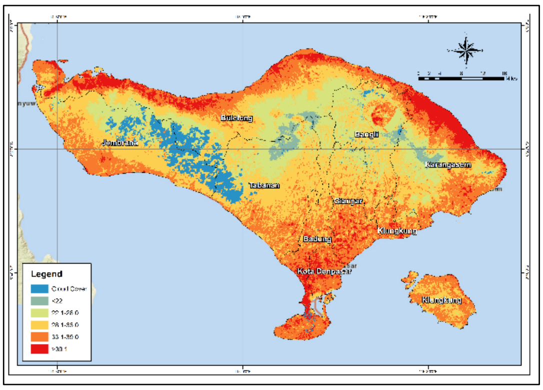

Figure.4 Land Surface Temperature Analysis of Bali Province in 2024

Implications of LST Increase for Tourist Thermal Comfort

The increasing Land Surface Temperature (LST) observed across Bali Province has direct implications for tourist thermal comfort, particularly when assessed using established benchmarks of human thermal tolerance. Numerous studies in biometeorology and tourism climatology indicate that the optimal thermal comfort range for outdoor human activities generally lies between 21–26°C, within which most individuals can maintain physical comfort without experiencing heat stress (Lopes et al., 2021). Temperatures exceeding this range have been associated with physiological discomfort, reduced outdoor activity participation, and declining tourist satisfaction, especially among visitors from temperate regions who are less acclimatized to tropical climatic conditions (Ciuha & Mekjavic, 2016). Using this comfort threshold as a reference, the LST results from 2014 and 2024 suggest that large portions of Bali already exceed thermally comfortable conditions for tourists under normal daytime exposure.

A comparison between the LST distributions and the 21–26°C comfort benchmark indicates that even in 2014, thermally comfortable areas were spatially limited, with most of the island dominated by temperature classes above 28°C. By 2024, this condition intensified considerably, as extensive areas transitioned into the 28.1–33.0°C and 33.1–39.0°C classes, far exceeding the upper limit of human thermal comfort. This shift implies a growing prevalence of thermal environments that are likely to be perceived as uncomfortable or stressful for tourists engaging in outdoor activities such as sightseeing, walking, and beach recreation. Similar patterns of widespread thermal discomfort associated with rising surface temperatures have been documented in other tropical and subtropical tourism destinations experiencing rapid land use change and urbanization (Kumar et al., 2022).

Spatially, the most thermally uncomfortable conditions for tourists are concentrated in southern Bali, which coincides with the island's most intensively developed tourism regions. Badung Regency, encompassing major tourism hubs such as Kuta, Seminyak, and Nusa Dua, is almost entirely characterized by LST values exceeding 28°C, with large areas surpassing 33°C by 2024. Comparable thermal profiles are observed in Kota Denpasar and Gianyar Regency, where dense urban land cover and tourism infrastructure contribute to elevated surface temperatures. These findings are consistent with research demonstrating strong linkages between built-up land expansion, urban heat intensification, and reduced outdoor thermal comfort in tourism destinations (Haldar et al., 2023).

Importantly, the analysis also reveals that thermal discomfort is no longer confined to highly urbanized tourism centers. Buleleng, Karangasem, Tabanan, and Jembrana exhibit substantial increases in high-temperature LST classes between 2014 and 2024, indicating that tourists visiting northern and eastern Bali for nature-based or rural tourism are increasingly exposed to thermally stressful conditions. Although localized areas with relatively lower temperatures persist, particularly in vegetated and upland zones, the dominant thermal environment in these regions increasingly exceeds the 26°C comfort threshold. This spatial expansion of thermal discomfort reflects broader regional warming trends and mirrors findings from comparable island destinations in Southeast Asia and the Pacific (Kiavarz et al., 2022; Kumar et al., 2022).

Highland areas, most notably Bangli Regency, remain relatively closer to thermally comfortable conditions due to the moderating effects of elevation and vegetation cover. However, even in these areas, the expansion of temperature classes above 28°C suggests a gradual erosion of thermal comfort over time. This trend raises concerns regarding the long-term viability of upland regions as climate refuges for tourism, particularly as development pressure expands into previously less-disturbed areas (Kiavarz et al., 2022). From a tourism perspective, sustained exposure to thermally uncomfortable environments can influence tourist behavior in several ways, including reduced participation in outdoor activities, shifts toward early morning or evening visitation, and increased reliance on air-conditioned indoor spaces. Over time, these adaptations may affect visitor satisfaction, length of stay, and destination competitiveness, particularly for destinations that rely heavily on outdoor and nature-based tourism (Asmelash & Kumar, 2019; Higgins-Desbiolles, 2018). Overall, the findings indicate that a significant proportion of Bali has transitioned into thermally uncomfortable conditions for tourists when evaluated against the 21–26°C human comfort benchmark, underscoring the urgency of integrating thermal comfort considerations into tourism planning and climate-resilient destination management strategies.

Land Cover Change Analysis in Bali

Land cover change is a critical indicator of environmental transformation in tourism destinations, as it reflects the cumulative impacts of urban expansion, infrastructure development, and shifts in land management practices. In Bali Province, land cover dynamics over the past decade have been closely linked to the rapid growth of tourism activities and supporting urban functions, particularly in coastal and lowland areas. Analyzing land cover change alongside thermal conditions provides an integrated understanding of how physical landscape modification contributes to environmental stress in tourism regions (Haldar et al., 2023; Santhosh & Shilpa, 2023).

Table 4 presents the spatial distribution of land cover classes in Bali Province in 2014, serving as the baseline condition prior to the most recent phase of accelerated tourism and urban development. At that time, dense vegetation dominated the island's landscape, accounting for the largest proportion of land cover across almost all regencies, particularly in Buleleng, Bangli, Karangasem, and Tabanan. These regions, characterized by mountainous terrain and extensive forest or agricultural vegetation, functioned as important ecological buffers that moderated local microclimates. In contrast, built-up areas were relatively limited in extent, with higher concentrations primarily observed in Badung Regency, Gianyar, and Denpasar City, corresponding to established tourism cores and urban centers in southern Bali.

Table 4. Land Cover Classes in Bali Province, 2014

Regency/City	Land Cover 2014 (Ha)						
	Cloud Cover	**Badan air**	**Cloud Cover**	**Lahan terbuka**	**Cloud Cover**	**Vegetasi lebat**	**Cloud Cover**
Badung		24	3.431	3.889	16.162	16.121	39.626
Bangli		1.595	1.477	1.473	6.357	41.921	52.822
Buleleng		680	1.457	2.901	21.721	105.105	131.866
Gianyar		14	2.986	948	15.140	17.345	36.433
Jembrana		152	1.036	1.532	11.023	71.266	85.009
Karangasem		7	1.463	3.286	21.209	57.864	83.830
Klungkung	107,8511	15	1.424	3.990	13.948	11.773	31.258
Denpasar City		39	3.119	4.004	3.456	1.844	12.463
Tabanan		399	2.352	535	21.837	59.742	84.864
Grand Total	**107,8511**	**2.926**	**18.747**	**22.558**	**130.852**	**382.981**	**558.171**

Source: Analysis Result, 2024

By 2024, notable changes in land cover composition are evident across Bali Province, as shown in Table 5. The most significant transformation is the substantial expansion of built-up areas, particularly in Badung Regency and Denpasar City, where urban land cover increased markedly compared to 2014. This expansion reflects continued development of tourism infrastructure, accommodation facilities, transportation networks, and supporting services. At the same time, increases in built-up land are accompanied by reductions or spatial fragmentation of vegetated land, especially sparse vegetation and open land, indicating ongoing conversion of natural and semi-natural landscapes into urbanized forms.

Table 5. Land Cover Classes in Bali Province, 2024

Regency/City	Land Cover 2024 (Ha)						
	Cloud Cover	**Water Bodies**	**Built up Areas**	**Open/Bare Land**	**Sparse Vegetation**	**Dense Vegetation**	**Grand Total**
Badung	9	35	7.534	1.591	10.559	19.918	39.645
Bangli	606	1.597	2.444	918	5.535	41.723	52.822
Buleleng	456	742	5.363	2.027	15.527	107.681	131.795
Gianyar	49	30	4.770	375	9.357	21.846	36.428
Jembrana	2.932	152	1.636	337	7.699	72.300	85.056
Karangasem	169	35	2.432	2.050	18.585	60.549	83.820
Klungkung	0	29	1.679	512	8.798	20.216	31.233
Denpasar City		48	7.622	531	1.970	2.298	12.469
Tabanan	150	406	3.572	261	14.434	66.053	84.876
Grand Total	**4.372**	**3.075**	**37.051**	**8.600**	**92.462**	**412.583**	**558.144**

Source: Analysis Result, 2024

Spatially, the land cover changes between 2014 and 2024 reveal a clear north–south contrast in development intensity. Southern Bali, encompassing Badung, Gianyar, and Denpasar City, experienced the most pronounced urban expansion, while central and northern regencies such as Bangli and Buleleng retained relatively high proportions of dense vegetation, despite localized increases in built-up and open land. Nevertheless, even in these less urbanized regions, gradual encroachment of development into vegetated landscapes suggests an emerging diffusion of land use pressure beyond traditional tourism hubs. This pattern aligns with broader trends observed in island tourism destinations, where development initially concentrates in coastal zones before progressively expanding inland (Purwanto et al., 2023).

To enhance spatial interpretation, the land cover conditions for both observation years are further illustrated through thematic maps. Figure X and Figure Y depict the spatial configuration of land cover in Bali in 2014 and 2024, respectively, enabling direct visual comparison of landscape transformation over time. The maps clearly show the consolidation of built-up areas in southern Bali and the increasing fragmentation of vegetated land, particularly along major development corridors and coastal zones.

Overall, the land cover change analysis demonstrates a clear trajectory toward increased urbanization and reduced dominance of vegetated landscapes across Bali Province over the study period. These changes are particularly significant in tourism-intensive areas and have important implications for environmental quality, ecosystem services, and thermal conditions. When viewed in conjunction with the observed increase in Land Surface Temperature, the findings highlight land cover change as a key driver of thermal intensification, underscoring the need for integrated land use planning and climate-sensitive tourism development to ensure long-term destination sustainability (Boavida-Portugal, 2022; Chen et al., 2022).

To further clarify the spatial patterns and magnitude of land cover change, the tabular analysis is complemented by a set of thematic land cover maps. These maps provide a visual representation of the spatial distribution of major land cover classes across Bali Province for the years 2014 and 2024. By illustrating the geographic concentration of built-up expansion, vegetation persistence, and areas of land conversion, the maps allow for a more intuitive interpretation of landscape transformation that cannot be fully captured through numerical data alone. Spatial visualization is particularly important in the context of tourism destinations, where the location and clustering of development relative to natural landscapes strongly influence environmental quality and thermal conditions experienced by visitors (Higgins-Desbiolles, 2018).

Figures 5 and 6 present the land cover maps for Bali Province in 2014 and 2024, respectively. A comparative examination of these maps highlights the intensification and spatial consolidation of urban and tourism-related development in southern Bali, especially in Badung Regency and Denpasar City, as well as the gradual expansion of built-up and open land into surrounding areas. At the same time, the maps reveal the continued dominance of dense vegetation in central and northern regions, albeit with increasing fragmentation along major development corridors. This spatial perspective reinforces the tabular findings and provides essential context for understanding how land cover change contributes to observed variations in Land Surface Temperature and tourist thermal comfort across the island.

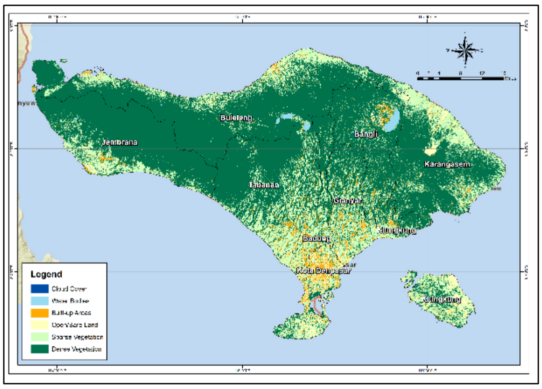

Figure.5 Land Cover Analysis of Bali Province in 2014

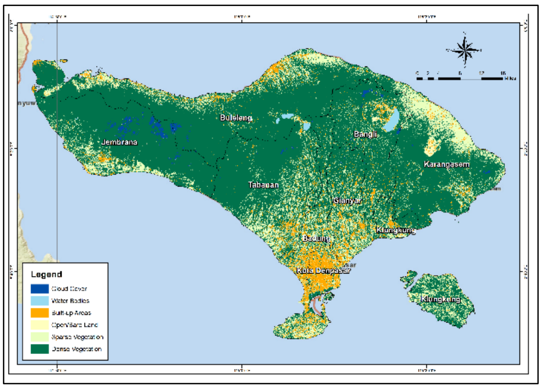

Figure.6 Land Cover Analysis of Bali Province in 2024

Land Cover Change and Its Influence on Temperature Patterns

To quantitatively assess how land cover composition influences surface temperature conditions, this study employed logistic regression analysis, using thermally comfortable land surface temperature (21–26°C) as a binary dependent variable. The model estimates the probability of experiencing thermally comfortable conditions based on the proportional coverage of different land cover classes within each 750 m × 750 m grid cell. Table 6 summarizes the regression coefficients, odds ratios, and significance levels for both 2014 and 2024, enabling a direct comparison of land cover effects over time.

Table 6. Influence of Land Cover Types on the Probability of Thermally Comfortable Surface Temperature in Bali (2014 and 2024)

Variable	**Coefficient (β) 2014**	**Odds Ratio 2014**	**p-value 2014**	**Coefficient (β) 2024**	**Odds Ratio 2024**	**p-value 2024**	**Interpretation**
Water Bodies	15.39	4.84×10^6	< 0.001	06.43	620.06.00	< 0.001	Strong positive cooling effect
Dense Vegetation	0,587	8.49×10^5	< 0.001	07.46	1,738.9	< 0.001	Most consistent and effective cooling element
Open/Bare Land	0,526	1.58×10^5	< 0.001	06.29	540.06.00	< 0.001	Moderate positive cooling contribution
Sparse Vegetation	05.26	193.03.00	0,071528	−0.80	00.45	0,391	Not statistically significant
Constant	−14.93	—	< 0.001	−8.62	—	< 0.001	Built-up dominant condition is thermally unfavorable

Source: Analysis Result, 2024

In 2024, the same land cover classes remain statistically significant, but their coefficients and odds ratios have decreased noticeably. This decline suggests that the influence of land cover structure on thermal comfort has weakened over time. While dense vegetation continues to be the most reliable cooling element, its effectiveness has lessened compared to 2014. A similar reduction is seen for water bodies and open land, indicating that rising background temperatures and accumulated urban heat are increasingly limiting the cooling potential of these land-based mitigation features.

Sparse vegetation does not have a statistically significant effect in either year, and its impact turns negative in 2024, though this change is not significant. This finding highlights that the mere presence of vegetation is not enough to ensure thermal comfort; rather, factors such as vegetation density, canopy continuity, and overall quality are crucial. The consistently negative and significant model constants further confirm that areas dominated by built-up land are the most thermally unfavorable environments in both periods. Overall, the regression results indicate that while land cover change remains a key driver of surface temperature patterns in Bali, its explanatory power has declined over the past decade. The reduced cooling effect of certain land cover types supports the conclusion that tourism-driven urban expansion, combined with broader climatic warming, is reshaping thermal environments—posing important challenges for tourist comfort and the long-term sustainability of the destination.

Conclusion

This study examined the dynamics of Land Surface Temperature (LST) and their implications for tourist thermal comfort in Bali Province by integrating spatio-temporal LST analysis, land cover change assessment, and logistic regression modeling over the period 2014–2024. The findings reveal that thermal conditions in Bali have changed significantly over the past decade, reflecting the combined impacts of tourism-driven urban development and broader climate warming. By connecting physical environmental changes with human thermal comfort thresholds, this research offers a comprehensive perspective on the sustainability challenges confronting tropical tourism destinations.

The spatio-temporal analysis of land surface temperature (LST) reveals a clear warming trend across the island, characterized by a significant increase in areas experiencing surface temperatures above the human comfort range of 21–26°C. This trend is especially evident in southern Bali, particularly in Badung Regency and Denpasar City, where tourism infrastructure and urban development are densely concentrated. Consequently, thermally comfortable zones have become increasingly limited and fragmented, indicating a reduced availability of suitable outdoor environments for tourism activities. These changes suggest that thermal comfort is becoming a crucial factor influencing destination quality and visitor experience.

Land cover change analysis reveals significant landscape transformation between 2014 and 2024, marked by the expansion of built-up areas and increased fragmentation of vegetated land, particularly in tourism-intensive regions. While dense vegetation still dominates central and northern Bali, ongoing development pressures have diminished the island's natural ability to regulate surface temperatures. Logistic regression results confirm that land cover composition plays a crucial role in determining the likelihood of thermally comfortable conditions. Dense vegetation and water bodies consistently offer the strongest cooling effects, whereas built-up areas are the most thermally unfavorable environments.

The decreasing explanatory power of land cover variables over time indicates a reduced sensitivity of thermal comfort to land cover structure. This suggests that rising background temperatures and accumulated urban heat are increasingly diminishing the localized cooling effects provided by vegetation and water bodies. As a result, traditional land-based mitigation strategies alone may no longer suffice to maintain comfortable thermal conditions in rapidly developing tropical destinations. Overall, this study highlights the growing challenge of sustaining tourist thermal comfort in a warming climate and emphasizes the need to incorporate thermal considerations into tourism and spatial planning frameworks. Climate-sensitive development strategies that prioritize the quality and spatial arrangement of vegetation, the integration of water features, and broader climate adaptation measures will be essential to enhance the long-term resilience and competitiveness of Bali and similar tropical tourism destinations.

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