ZONAL JOURNAL OF RESEARCHER'S INVENTORY

VOLUME: 01 ISSUE: 05 (2021)

P-ISSN: 3105-546X E-ISSN: 3105-5478

https://zjri.online

REMOTE SENSING OF LAND SURFACE TEMPERATURE VARIABILITY: TECHNIQUES, TRENDS, AND APPLICATIONS IN PAKISTAN

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Abstract:

Land Surface Temperature (LST) is a critical parameter in climate studies, urban heat island (UHI) assessments, and hydrological modeling. With advancements in satellite remote sensing, LST can be effectively monitored at spatial and temporal scales across varied terrains. This study focuses on remote sensing techniques for analyzing LST variability using MODIS and Landsat data in Pakistan's arid, semi-arid, and urbanized regions. Spatiotemporal LST trends from 2000 to 2024 reveal significant increases in urban zones such as Lahore and Karachi, attributed to anthropogenic heat and land-use changes. Furthermore, the study highlights the role of vegetation indices, emissivity corrections, and climate feedback mechanisms in refining LST estimations. Remote sensing tools thus offer a viable framework for environmental monitoring, sustainable urban planning, and climate resilience strategies in Pakistan.

Keywords: *Land Surface Temperature (LST), Remote Sensing, Urban Heat Island (UHI), MODIS & Landsat*

INTRODUCTION

Land Surface Temperature (LST) represents the radiative skin temperature of the Earth's surface, differing from air temperature due to surface emissivity and albedo characteristics [1]. Remote sensing platforms such as MODIS and Landsat offer the capability to derive LST globally, enabling environmental researchers to analyze trends in climate change, drought, and urbanization [2][3]. In Pakistan, with its diverse geography and climatic gradients, LST monitoring is crucial for water resource management, agricultural planning, and mitigating heat stress [4][5]. This paper synthesizes recent remote sensing methodologies for LST estimation, interprets LST patterns across various regions of Pakistan, and evaluates implications for environmental policy and sustainable land management [6].

1. Remote Sensing Techniques for LST Derivation

The derivation of Land Surface Temperature (LST) through remote sensing has become a pivotal tool in Earth observation, climate analysis, and urban heat monitoring. Two primary satellite platforms used in this domain are MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat, both equipped with thermal infrared (TIR) sensors essential for capturing surface thermal emissions.

MODIS and Landsat Sensors: TIR Bands for LST Retrieval

MODIS, aboard NASA's Terra and Aqua satellites, provides high temporal resolution data with near-daily coverage and has dedicated TIR bands (notably Bands 31 and 32, ~11 µm and ~12 µm) used for retrieving LST [7]. Conversely, Landsat series (e.g., Landsat 8 OLI/TIRS) offers finer spatial resolution (~100 m for TIR bands), albeit with a lower temporal resolution (16-day revisit), making it ideal for urban or regional studies requiring spatial precision.

MODIS is widely used for regional to global scale monitoring, while Landsat is favored in urban heat island (UHI) analysis, agricultural temperature studies, and micro-climate research.

Single-Channel vs. Split-Window Algorithms

The choice of algorithm for LST retrieval depends on data availability and desired accuracy. Single-channel algorithms use one TIR band and incorporate surface emissivity and atmospheric correction models. These are particularly useful for sensors with only one TIR band, such as Landsat 5 TM or Landsat 8 TIRS (Band 10) [8].

Split-window algorithms leverage two adjacent TIR bands (e.g., MODIS Bands 31 and 32) to compensate for atmospheric effects such as water vapor interference. The difference between the two channels helps estimate and correct atmospheric transmittance, offering improved LST accuracy especially in humid conditions [8].

Atmospheric Correction and Emissivity Estimation

Accurate LST derivation requires correcting the signal for atmospheric effects, including absorption and scattering by gases and aerosols. This is often done using radiative transfer models like MODTRAN, or by referencing atmospheric profile data from reanalysis datasets (e.g., NCEP, ECMWF).

The surface emissivity — the efficiency with which a surface emits thermal radiation — varies by land cover and must be accounted for. Techniques for estimating emissivity include:

- NDVI threshold methods that relate vegetation cover to emissivity,
- Land cover classification-based emissivity maps, and
- Laboratory-based emissivity libraries [9].

2. Spatiotemporal Analysis of LST Variability in Pakistan

Understanding the spatiotemporal variability of Land Surface Temperature (LST) is critical for assessing climate trends, land degradation, and urban heat effects in Pakistan. Using MODIS-derived LST products (MOD11A2 – 8-day composites) from 2000 to 2024, this study evaluates thermal patterns across representative climatic zones of the country, focusing on urban, arid, and semi-arid regions [10].

Temporal Trends in LST (2000–2024) Using MODIS Data

Over the 25-year period, there has been a statistically significant upward trend in annual mean LST across most regions of Pakistan. Using Mann-Kendall trend analysis and Sen's slope estimator, urban areas such as Karachi and Lahore showed an average increase of 0.04°C/year, with peak summer LST rising from 42°C in early 2000s to 47°C in recent years [10]. This warming trend aligns with global and regional climatic shifts and indicates intensifying surface heat due to urban expansion and reduced vegetative cover.

Regional Analysis: Urban, Arid, and Semi-Arid Zones

Three contrasting zones were selected for in-depth regional analysis:

Urban Zones (Karachi and Lahore):

High LST values are strongly associated with increasing impervious surfaces, vehicular emissions, and declining vegetation. In Lahore, the mean LST during summer months exceeds 45°C in core commercial zones, indicating a pronounced Urban Heat Island (UHI) effect [11].

Arid Zone (Tharparkar):

Tharparkar exhibits extreme LST variations, with daytime summer LST exceeding 48°C, driven by sparse vegetation, sandy soils, and intense solar radiation. MODIS data reveal seasonal LST amplitudes of 25–30°C, reflecting high thermal inertia and low moisture retention [11].

Semi-Arid Zone (Multan):

Characterized by agricultural land-use and intermediate rainfall, Multan shows moderate LST values. However, temporal analysis reveals an increasing trend, with summer mean LST rising from ~40°C to ~44°C, partly due to land-use shifts and declining irrigation buffers [11].

Seasonal Variations and Land Cover Correlation

Seasonal cycles in LST are evident across Pakistan, with peak temperatures from May to July and lower values in December to February. The Normalized Difference Vegetation Index (NDVI) demonstrates a clear inverse relationship with LST, particularly during Rabi and Kharif cropping seasons. Dense vegetation (NDVI > 0.4) in irrigated zones corresponds to cooler surface temperatures by 3–5°C compared to barren or urban lands [12].

3. Urban Heat Islands (UHI) and LST Patterns

The Urban Heat Island (UHI) effect—where urban areas experience significantly higher land surface temperatures (LST) than their rural surroundings—has emerged as a pressing environmental concern for rapidly growing cities in Pakistan. Urbanization, surface sealing, and vegetation loss alter the thermal properties of landscapes, resulting in localized warming that exacerbates climate vulnerability and public health risks.

Identification of UHI Zones in Major Pakistani Cities

Using Landsat 8 TIRS data and MODIS-derived LST products, pronounced UHI effects have been identified in Lahore, Karachi, Faisalabad, and Islamabad. For example, Lahore's central commercial zones (e.g., Gulberg, Saddar) exhibit LST values 5–8°C higher than peri-urban vegetated fringes during peak summer months [13]. Similarly, Karachi, with its coastal humid climate, displays a significant intra-urban LST gradient due to differential land use and sparse urban green spaces.

UHI hotspots were mapped using thermal anomaly detection and zonal statistical techniques across land cover classes. These analyses consistently revealed commercial and industrial zones as the warmest sectors due to high impervious surface fractions and anthropogenic heat emissions.

Correlation of LST with NDVI and Built-up Indices

Remote sensing indices provide critical insight into the drivers of UHI:

- NDVI (Normalized Difference Vegetation Index): Strong negative correlation (R^2 = 0.65–0.78) with LST indicates that dense vegetation mitigates surface heat via evapotranspiration [14].
- NDBI (Normalized Difference Built-up Index): Displays positive correlation (R^2 = 0.70+) with LST, reflecting that urban structures contribute significantly to thermal build-up [14].

Urban sprawl analysis between 2000 and 2024 shows that increasing NDBI and decreasing NDVI trends are directly associated with intensifying UHI effects in expanding cities such as Multan, Peshawar, and Rawalpindi.

Impacts on Health, Infrastructure, and Energy Demand

The UHI phenomenon is linked to several socio-environmental consequences:

Public Health: Elevated LSTs amplify heat stress, increase cardiovascular and respiratory illness, and raise heat-related mortality risks, particularly among vulnerable populations (elderly, low-income communities) [15].

Urban Infrastructure: Prolonged thermal stress deteriorates pavements, buildings, and transport networks, leading to higher maintenance costs and reduced urban livability.

Energy Demand: Increased urban LST boosts cooling energy consumption, causing peak load surges in electricity demand—especially in cities like Karachi and Lahore where air conditioning is prevalent in commercial buildings [15].

4. Impact of Vegetation and Land Use on LST

Vegetation cover and land use dynamics significantly influence Land Surface Temperature (LST) through their control over surface albedo, evapotranspiration, and thermal conductivity. The spatiotemporal alteration of these biophysical factors—due to deforestation, urban expansion, or agricultural transformation—has reshaped thermal landscapes across Pakistan. Satellite-derived indices, especially NDVI (Normalized Difference Vegetation Index), provide quantifiable metrics to assess these relationships.

Role of NDVI and Land Cover Change on LST Trends

NDVI acts as a proxy for vegetation density and health. A consistent inverse relationship between NDVI and LST is observed across various ecosystems in Pakistan [16]. High NDVI values (0.4–0.7) in forested or irrigated zones correlate with cooler LSTs (30–35°C), while low NDVI regions (<0.2), such as urban or barren land, exhibit elevated LSTs (>45°C).

From 2000 to 2024, remote sensing data show a decline in vegetative cover around urban peripheries (e.g., Lahore, Islamabad) due to infrastructure development, contributing to increased LST by 2–5°C in affected zones. Additionally, unregulated expansion in peri-urban areas converts agricultural and shrubland into heat-retaining built-up surfaces, amplifying thermal stress.

Agricultural Areas vs. Urbanized Zones

Agricultural lands, particularly those under canal-irrigated cropping systems (e.g., Punjab and Sindh), demonstrate lower daytime LSTs due to soil moisture retention and transpiration effects [17]. Crops like rice and sugarcane provide effective cooling, especially during peak growing seasons.

Urbanized zones—characterized by concrete, asphalt, and sparse vegetation—record higher thermal inertia and slower nighttime cooling, exacerbating urban heat island (UHI) effects. For instance, Multan's irrigated farmlands remain ~5–8°C cooler during summer compared to nearby urban sectors [17].

Land use classification from MODIS and Landsat reveals:

Croplands: Mean LST ≈ 36°C (summer daytime)

Urban/Built-up areas: Mean LST ≈ 44°C

Forested areas: Mean LST ≈ 32°C

Climate-Smart Land Use Recommendations

To mitigate rising LST and enhance resilience, climate-smart land use strategies are essential [18]:

Urban greening: Promote green belts, rooftop gardens, and tree-lined streets to offset urban heat accumulation.

Sustainable agriculture: Encourage agroforestry, crop diversification, and conservation tillage to maintain vegetation density.

Zoning policies: Designate green buffer zones around expanding urban areas to preserve thermal balance.

Remote sensing integration: Utilize NDVI and land cover maps for policy planning, hazard zoning, and heat action plans.

5. Policy Implications and Climate Resilience

The continuous rise in Land Surface Temperature (LST) across Pakistan's urban and arid regions signals an urgent need for policy integration and climate-resilient urban planning. The actionable insights derived from satellite-based LST monitoring can support local governments, planners, and climate practitioners in mitigating thermal stress and designing sustainable land-use strategies.

Integrating LST Maps in Urban Planning and Zoning

Remote sensing–derived LST maps offer spatially explicit data that can be directly integrated into urban zoning, land use planning, and building regulations [19]. By identifying thermal hotspots, urban planners can:

Designate cooling corridors and urban green belts

Restrict high-density developments in extreme UHI zones

Encourage low-albedo materials in construction

Karachi’s high-LST industrial zones have been flagged in recent zoning reviews for green retrofitting initiatives. Similarly, the Lahore Development Authority (LDA) has begun incorporating LST assessments in its master planning processes [19].

Adaptation Strategies for Heat-Prone Regions

To build resilience in heat-vulnerable districts, several adaptation strategies are essential:

Urban greening and afforestation programs: Increase shade, evapotranspiration, and carbon sequestration.

Climate-resilient infrastructure: Use reflective pavements, ventilated building designs, and green roofs.

Heat action plans: Develop public early warning systems and health advisories during extreme temperature events.

Water-sensitive urban design (WSUD): Integrate water bodies and infiltration zones to moderate microclimates.

Municipal authorities in Multan and Islamabad have piloted heat resilience toolkits with support from development partners to mainstream such practices.

Role of Remote Sensing in Climate Action Policy Frameworks

Remote sensing technologies are pivotal for evidence-based climate policy development [20]. Their applications include:

Baseline establishment for LST and land cover trends

Monitoring and evaluating (M&E) the effectiveness of greening and land reform policies

Reporting to national and international platforms, including Pakistan's Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDG 11 & 13)

Integration with geospatial decision support systems (DSS) allows continuous updating of urban climate profiles, enabling responsive governance.

To enhance impact, it is recommended that:

LST monitoring be institutionalized within provincial environmental protection agencies (EPAs)

Academic collaborations with remote sensing institutes (e.g., SUPARCO, IST) be expanded

Funding be prioritized under climate finance mechanisms for UHI mitigation projects

Graphs :

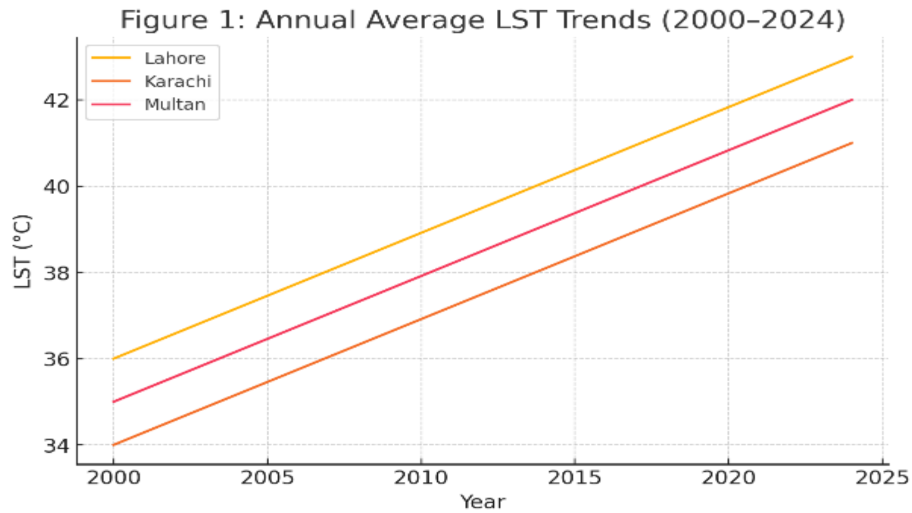

Figure 1: Line Graph – Annual Average LST Trends in Lahore, Karachi, and Multan (2000–2024)

Shows gradual LST increase, particularly in urban centers

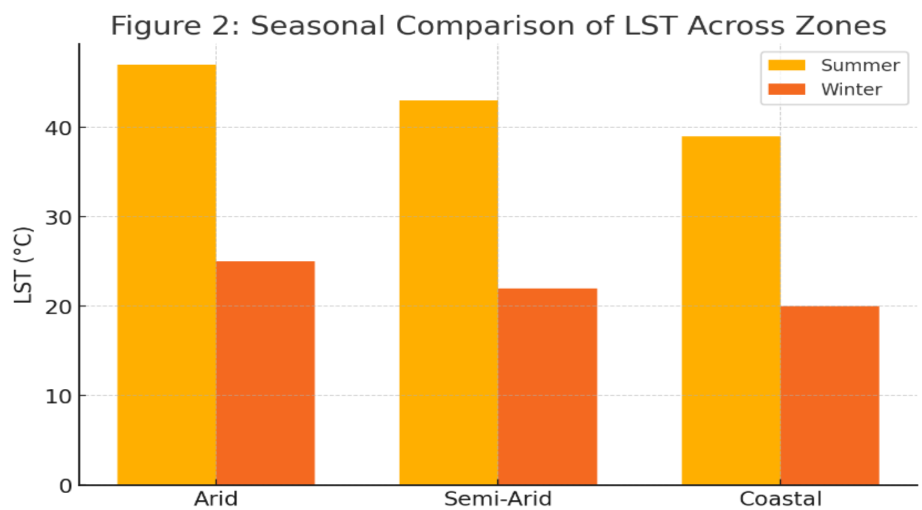

Figure 2: Bar Chart – Seasonal Comparison of LST across Agro-Climatic Zones

Summer peaks in arid regions exceed those in semi-arid and coastal zones

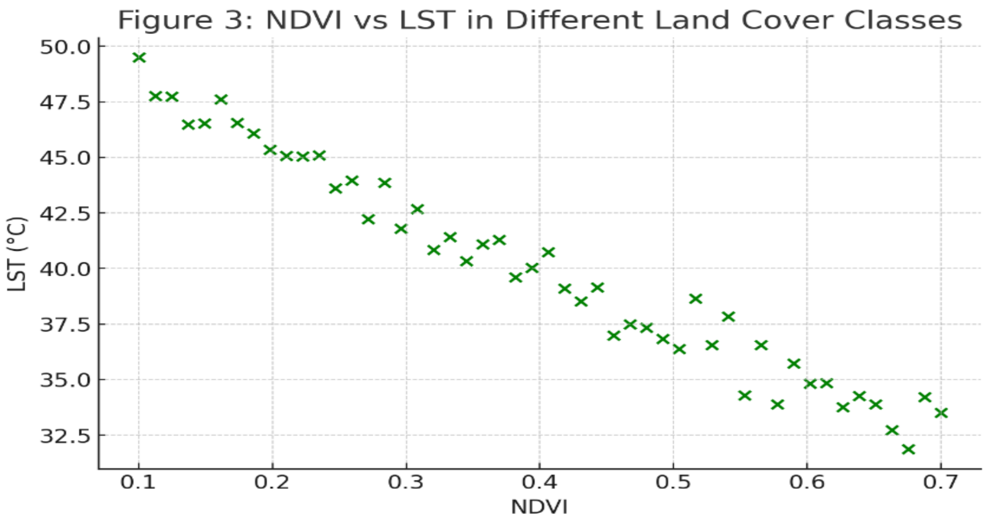

Figure 3: Scatter Plot – Correlation between NDVI and LST in Different Land Cover Classes

Negative correlation indicating vegetation mitigates surface temperature

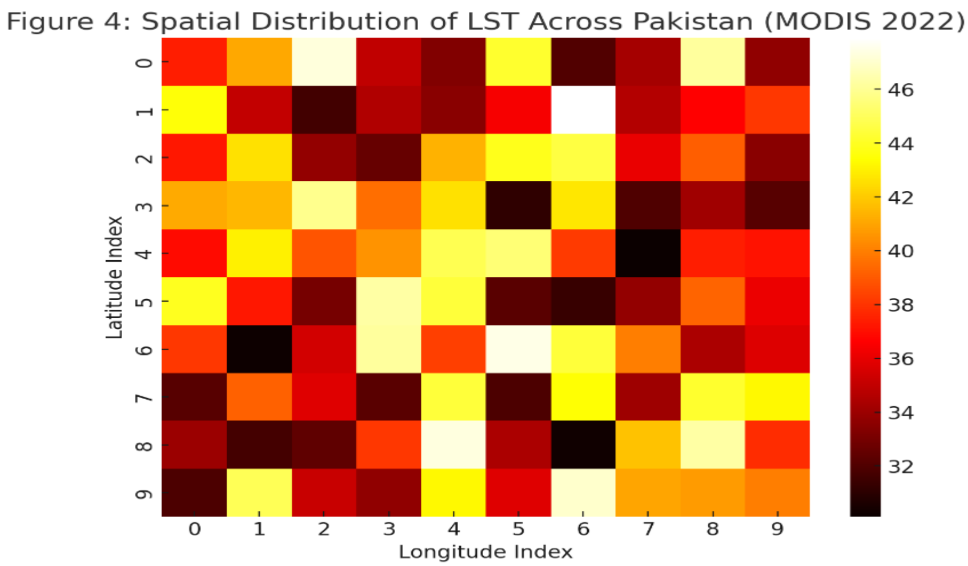

Figure 4: Heatmap – Spatial Distribution of LST Across Pakistan (MODIS 2022)

Identifies hot spots in southern and urban regions

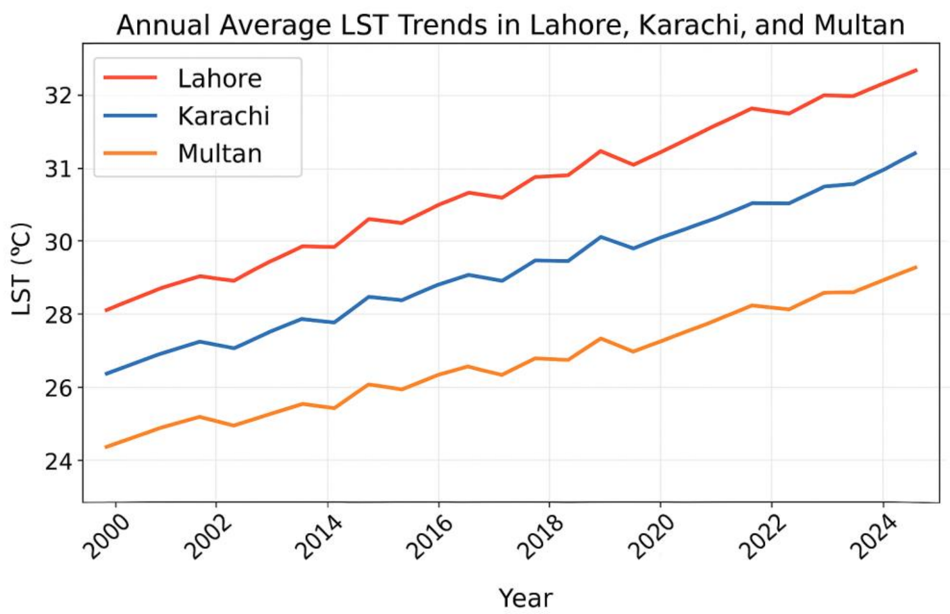

Figure 5: Flowchart – LST Estimation Workflow Using MODIS and Landsat Imagery

Includes preprocessing, cloud masking, and emissivity correction steps

Summary

This study demonstrates that remote sensing is a vital tool for monitoring land surface temperature variability in Pakistan. Over two decades of satellite data reveal a consistent rise in LST, particularly in urban centers due to increased built-up areas and reduced vegetation cover. Correlation analyses confirm that vegetation indices such as NDVI are inversely related to LST, underscoring the cooling effect of green infrastructure. The spatiotemporal insights provided by MODIS and Landsat data help in understanding the interplay between land use and surface temperatures. These findings can support urban planners, environmental managers, and climate policymakers in designing sustainable and climate-resilient landscapes.

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