التباينات الحرارية الحضرية عبر المناطق: مقارنة درجة حرارة سطح الأرض في أربيل ولندن وباريس وساو باولو 2014-2024

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الكلمات المفتاحية: درجة حرارة سطح الأرض؛ التوسع الحضري؛ المناطق المناخية؛ السلاسل الزمنية.

كيفية اقتباس البحث

إسماعيل ، مصطفى صالح ، ئەڤین علی ڕەحمان اومر ، كاروان حمەسعيد حمەشريف ، التباينات الحرارية الحضرية عبر المناطق: مقارنة درجة حرارة سطح الأرض في أربيل ولندن وباريس وساو باولو 2014-2024،مجلة مركز بابل للدراسات الانسانية، تشرين الثاني 2025،المجلد: 15 ،العدد:6.

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Urban Thermal Contrasts Across Regions Comparing Land Surface Temperature in Erbil, London, Paris and São Paulo 2014–2024

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Keywords : Land Surface Temperature ; Urban Expansion ; Climate Zones; Time Series

How To Cite This Article
Ismael, Mustafa Salih, Aveen Ali Rahman, Karwan Hama Saeed, Urban Thermal Contrasts Across Regions Comparing Land Surface Temperature in Erbil, London, Paris and São Paulo 2014–2024, Journal Of Babylon Center For Humanities Studies, November 2025,Volume:15,Issue 6.

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ملخص

تُعدّ درجة حرارة سطح الأرض (LST) معيارًا أساسيًا لفهم التفاعلات بين المناخ والسطح والبيئات الحرارية الحضرية، إلا أن التحليلات المقارنة عبر مختلف المناطق المناخية لا تزال محدودة. في هذه الدراسة، استخدمنا البيانات الحرارية من قمري لاندسات 8 و 9 وخوارزمية النافذة الأحادية لتقييم التغيرات المكانية والزمانية في درجة حرارة سطح الأرض بين عامي 2013 و 2024 عبر أربع مناطق حضرية تُمثل مناخات متباينة: أربيل (شبه قاحلة)، ولندن (بحرية معتدلة)، وباريس (قارية)، وساو باولو (استوائية). تكشف النتائج عن اتجاه ثابت لارتفاع

درجة حرارة السطح في جميع المدن، مع تباين كبير في المقدار والتوزيع المكاني تبعًا للمنطقة المناخية. شهدت ساو باولو أكبر زيادة (0.197 درجة مئوية سنويًا)، تليها باريس (0.078 درجة مئوية سنويًا)، وأربيل (0.059 درجة مئوية سنويًا)، ولندن (0.015 درجة مئوية سنويًا). في حين أظهرت المدن الاستوائية والقارية ارتفاعًا واسعًا ومستمرًا في درجات الحرارة في مراكزها الحضرية، أظهرت مدينة أربيل شبه القاحلة نمطًا أكثر تباينًا مع زيادات مركزة في المركز الحضري، بينما أظهرت لندن المعتدلة تغيرات تدريجية وإن كانت محدودة مكانيًا. تتوافق هذه النتائج مع الأبحاث السابقة حول الجزر الحرارية الحضرية، وتقدم أدلة جديدة على دور السياق المناخي في تعديل ديناميكيات ارتفاع درجة حرارة الأرض. تؤكد الدراسة على أن استراتيجيات التخفيف والتكيف يجب أن تكون خاصة بكل منطقة مناخية، حيث يتجلى ارتفاع درجة حرارة المناطق الحضرية بشكل مختلف في البيئات الاستوائية والقارية والمعتدلة وشبه القاحلة.

Abstract

Land surface temperature (LST) is a key parameter for understanding climate–surface interactions and urban thermal environments, yet comparative analyses across different climatic zones remain limited. In this study, we used Landsat 8 and 9 thermal data and the Mono-Window Algorithm to evaluate spatio-temporal variations in LST between 2013 and 2024 across four metropolitan regions representing contrasting climates: Erbil (semi-arid), London (temperate maritime), Paris (continental), and São Paulo (tropical). The results reveal a consistent trend of surface warming across all cities, with substantial variation in magnitude and spatial distribution depending on climate zone. São Paulo exhibited the most pronounced increase (0.197 °C per year), followed by Paris (0.078 °C per year), Erbil (0.059 °C per year), and London (0.015 °C per year). While tropical and continental cities showed extensive and continuous warming across their urban cores, semi-arid Erbil displayed a more heterogeneous pattern with concentrated increases in the urban centre, and temperate London showed gradual but spatially limited changes. These findings align with previous research on urban heat islands while providing new evidence of the role of climate context in modulating LST dynamics. The study underscores that mitigation and adaptation strategies must be climate-zone specific, as urban warming manifests differently in tropical, continental, temperate, and semi-arid settings.

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1.Introduction

Land surface temperature (LST) refers to the temperature of the Earth's surface as measured at the interface between land and atmosphere (Abdullah, 2012). It is a fundamental parameter in the Earth system because it governs the exchange of energy and moisture between the surface and the atmosphere, thereby regulating hydrological, ecological, and climatological processes. Variations in LST influence soil moisture dynamics, vegetation growth, evapotranspiration rates, and atmospheric circulation, making it a key indicator in studies of climate change, agricultural management, and environmental sustainability (Makarieva et al., 2022). Understanding LST dynamics is therefore crucial for addressing challenges related to food security, human health, urbanisation, and adaptation to global warming.

With the advent of remote sensing (RS), LST has become one of the most widely monitored variables on regional to global scales. Satellite-based sensors such as MODIS, Landsat, ASTER, and Sentinel-3 provide multi-temporal, synoptic, and spatially continuous measurements of surface thermal conditions (Neinavaz et al.,2019). Unlike ground-based meteorological stations, which offer point-scale observations, RS data enable researchers to capture the spatial heterogeneity of LST across diverse land cover types, climate zones, and urban–rural gradients. Thermal infrared remote sensing, in particular, has been applied to quantify diurnal and seasonal changes in surface temperature, monitor vegetation stress, evaluate urban heat island intensity, and detect land degradation processes (Weng, 2009). These capabilities have positioned RS-derived LST as an indispensable variable in climate and environmental monitoring.

"Among the various sensors, MODIS (Moderate Resolution Imaging Spectroradiometer) has played a key role in advancing land surface temperature (LST) studies at both continental and global levels. Its ability to deliver daily and near-daily observations at moderate spatial resolution enables researchers to monitor changes in LST over time and examine long-term climate trends. The frequent data collection makes MODIS particularly valuable for analyzing seasonal patterns, tracking drought conditions, and exploring interactions between vegetation and temperature. Nonetheless, its relatively coarse spatial resolution limits its effectiveness in detecting detailed urban or landscape variations."

In contrast, Landsat 8, with its Thermal Infrared Sensor (TIRS), provides LST data at a much finer spatial resolution (30–100 m), making it well-suited for capturing localised thermal variations within cities and across heterogeneous land surfaces (Jimenez-Munoz et al., 2014). Landsat 8's

Journal of Babylon Center for Humanities Studies :2025 Volume: 15 Issue :6
(ISSN): 2227-2895 (Print) (E-ISSN):2313-0059 (Online)

higher spatial detail enables the detection of intra-urban thermal patterns, identification of urban heat islands, and assessment of land cover impacts on LST. Although its revisit period is longer compared to MODIS, Landsat 8 complements MODIS by offering high-resolution snapshots that enrich our understanding of LST at the city and regional levels. Together, the combined strengths of MODIS and Landsat 8 allow researchers to evaluate both large-scale temporal dynamics and fine-scale spatial variability, which is critical when studying LST across diverse climatic and geographic settings.

Previous studies have employed LST for a wide range of applications. For instance, numerous works have focused on assessing the urban heat island effect, revealing how impervious surfaces, vegetation cover, and anthropogenic activities alter surface thermal regimes (Wetherley et al., 2018; Yuan and Bauer, 2007; Peng et al., 2012). Others have integrated LST with vegetation indices such as NDVI to evaluate drought severity, crop water stress, and ecosystem productivity (Abdullah et al., 2020). Comparative analyses have also been carried out between rural and urban areas, demonstrating how land cover differences modulate LST patterns. In addition, temporal studies using long-term RS datasets have provided insights into seasonal variability and climate-induced trends in surface warming (Zhou et al.,2015). However, much of the existing literature has concentrated on single cities or limited geographic regions. Few studies have attempted to systematically compare LST across multiple cities that belong to distinct climatic zones.

The novelty of the present study lies in its cross-regional and comparative approach. To the best of our knowledge, this is the first investigation that systematically evaluates LST across different cities situated in contrasting climate regimes. By comparing urban areas located in semi-arid, temperate, continental, and Mediterranean climates, the study seeks to uncover how regional climatic factors shape the spatial and temporal variability of LST. The specific objectives are: (i) to compare and analyse RS-derived LST across cities exposed to different climatic conditions, and (ii) to identify the influence of regional climate context on urban surface temperature dynamics. The outcomes of this research are expected to contribute new insights into the interactions between climate and land surface processes, providing valuable implications for urban planning, climate adaptation strategies, and environmental management in diverse climatic settings.

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2. Methods

2.1 Study Areas and Buffer Delineation

We compared land surface temperature (LST) across four metropolitan areas representing distinct climatic contexts: Erbil (Iraq), London (UK), Paris (France), and São Paulo (Brazil) (Figure 1). These cities were selected because they are situated in markedly different geographic regions and climate zones, ranging from the semi-arid environment of Erbil to the temperate maritime setting of London, the continental climate of Paris, and the tropical climate of São Paulo. This diversity provides a robust framework for evaluating how regional climatic conditions shape urban thermal dynamics. In addition, all four cities have undergone rapid urban expansion and significant population growth over the past decades, intensifying challenges related to urban heat islands, land-use change, and environmental sustainability (Table 1). Including cities with such varied developmental trajectories allows for cross-comparison of LST responses under different climatic pressures and urbanisation patterns, thereby strengthening the generalizability of the findings.

For each city, a point representing the urban core was defined by latitude–longitude coordinates (Erbil: 36.1911°N, 44.0090°E; London: 51.5074°N, −0.1278°E; Paris: 48.8566°N, 2.3522°E; São Paulo: 23.5505°S, 46.6333°W). To capture the broader urban fabric and its peri-urban surroundings while limiting influence from distant rural pixels, we generated a circular buffer of 25 km radius around each point (area of interest, AOI). These AOIs were constructed natively in Google Earth Engine (GEE) by buffering a ee.Geometry.Point with a 25,000 m distance. The chosen radius balances (i) inclusion of the continuous built-up area and (ii) computational tractability and comparability across cities with different spatial extents.

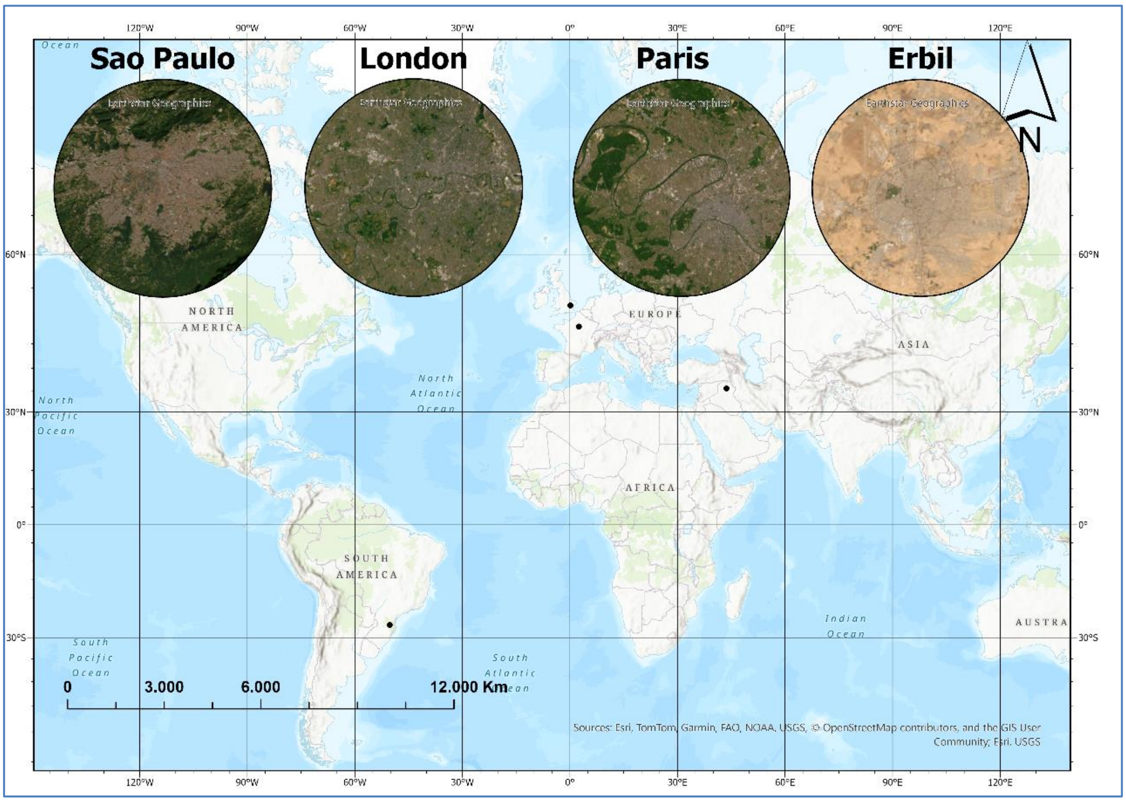

Figure 1. Location of the study area showing the selected cities used for analysis. The map highlights the spatial distribution of the cities within the region, which served as the basis for land surface temperature assessment.

Table 1. Population figures for selected metropolitan areas in 2014 and projected estimates for 2025, derived from Macrotrends and BRT data sources.

City	Population 2014	Population 2025	Source (metro area)
Erbil	777,000	941,000	Macrotrends – *Erbil, Iraq Metro Area Population (1950–2025)*. (Macrotrends)
London	8,537,000	9,841,000	Macrotrends – *London, UK Metro Area Population (1950–2025)*. (Macrotrends)
Paris	10,678,000	11,347,000	Macrotrends – *Paris, France Metro Area Population (1950–2025)*. (Macrotrends)
São Paulo	20,935,204	22,990,000	2014: BRTdata (*Population, metro area*). 2025: Macrotrends – *Sao Paulo, Brazil Metro Area Population (1950–2025)*. (BRTData, Macrotrends)

2.2 Satellite Data and Preprocessing

The analysis relied on Landsat Collection 2, Level-2 thermal products for Landsat 8 and Landsat 9, which provide atmospherically corrected surface reflectance and surface temperature data along with pixel-level quality assurance (QA) layers. To reduce data gaps in years with sparse acquisitions, Tier-1 and Tier-2 scenes were merged prior to processing. Each image was subjected to a standardised filtering procedure: pixels identified as fill, clouds, cirrus, cloud shadows, or snow were masked using the QA_PIXEL band, while thermal quality flags (ST_QA) greater than 2 were excluded to ensure reliable retrievals. Scenes were then clipped to the AOI and temporally filtered according to the compositing period (monthly or annual). These preprocessing steps were applied uniformly across all cities to ensure comparability and minimise spurious artefacts.

2.3 Calculating Land Surface Temperature (Mono-Window Algorithm)

The Land Surface Temperature (LST) was estimated using the Mono-Window Algorithm (MWA), which relies on the thermal infrared band of Landsat 8 (TIRS Band 10). This method corrects for atmospheric effects and surface emissivity to provide accurate LST retrievals (Qin et al.,2010).

First, the at-sensor brightness temperature (T_{10}) was derived from the spectral radiance using the inverse Planck function:

$$T_{10} = K_2 / \ln((K_1 / L\lambda) + 1)$$

where K_1 and K_2 are the calibration constants (K_1 = 774.8853 W/(m²·sr·μm), K_2 = 1321.0789 K for Landsat 8), and $L\lambda$ is the spectral radiance.

Next, the Mono-Window Algorithm estimates LST using the following formulation:

$$LST = [\, a(1 - C - D) + (b(1 - C - D) + C + D)T_{10} - DT_a \,] / C$$

where:

- T_a = mean atmospheric temperature (K)
- $C = \varepsilon \times \tau$
- $D = (1 - \tau)[1 + (1 - \varepsilon)\tau]$
- ε = land surface emissivity
- τ = atmospheric transmittance
- a, b = algorithm constants

Surface emissivity (ε) was estimated based on NDVI thresholds (Abdullah et al., 2019), while atmospheric transmittance (τ) was derived from standard atmospheric profiles. The mean atmospheric temperature (T_a) was obtained from reanalysis data. This approach ensures that surface temperature estimates account for both emissivity and atmospheric influences, thereby providing reliable LST retrievals.

2.4 Compositing, Aggregation, and Time Series

To characterise spatial patterns and temporal dynamics, we produced both annual and monthly LST composites. For each year between 2013 and 2024, valid scenes within each AOI were averaged on a per-pixel basis to generate mean annual LST, accompanied by an observation-count band (obsCount) to track the number of contributing acquisitions. Monthly mean composites were also generated for visualization of seasonal dynamics, and AOI-wide annual means were extracted using a mean reducer at 60 m scale. The results were compiled into a CSV table covering each city and year, supporting statistical analysis and visualisation of long-term trends.

2.5 Change Detection (2013 → 2024)

To evaluate decadal-scale thermal shifts, we constructed a change map by subtracting the 2013 annual mean from the 2024 annual mean:

$$\Delta LST\ (°C) = LST2024 - LST2013$$

Positive values indicate surface warming, negative values indicate cooling, and zeros denote no detectable change. Change rasters were clipped to each AOI, visualised with a diverging colour palette, and exported as GeoTIFFs for further interpretation.

2.6 Outputs and Visualisation

For each city, we exported three GeoTIFF products: Annual mean LST 2013 (°C), Annual mean LST 2024 (°C), and Decadal change (°C, 2024–2013). Visualisations in GEE used a continuous thermal palette for LST and a diverging palette for change, while city-wide annual means were exported as CSV tables. All products were stored in a dedicated Google Drive folder (GEE_LST) at 30 m resolution, enabling both map-based and statistical analyses.

3.Results

3.1 Spatio-Temporal Variation of Mean Annual Land Surface Temperature (2013–2024)

The mean annual land surface temperature (LST) maps for Erbil, London, Paris, and São Paulo between 2013 and 2024 reveal both spatial and temporal changes (Figure 2a–d).

In Erbil, Iraq (Figure 2a), LST values in 2013 range between approximately 27–57 °C, with cooler zones (blue to green, 27–37 °C) dominating the city centre and warmer values (45–57 °C) concentrated in the western and southern peripheries. By 2024, hotspots above 45 °C became more widespread, particularly across central and western areas, while cooler areas visibly contracted.

In London, England (Figure 2b), the 2013 map shows LST values ranging from about –5 °C in peripheral rural areas to nearly 39 °C in urban hotspots, with moderate zones (20–25 °C) dominating. In 2024, high-temperature zones (27–39 °C) expanded across the urbanised core and along the River Thames, while cooler areas (below 20 °C) decreased, reflecting intensified urban heat across the metropolitan region.

In Paris, France (Figure 2c), LST in 2013 ranges from around 3–49 °C, with cooler values (15–25 °C) prevalent in surrounding rural and vegetated zones, and warmer hotspots (above 27 °C) concentrated in the urban core. By 2024, these urban hotspots expanded and intensified, with the city centre showing more continuous coverage of temperatures above 29 °C, while surrounding cooler zones shrank.

In São Paulo, Brazil (Figure 2d), the 2013 map indicates LST values from roughly 9–49 °C, with cooler regions (15–25 °C) located in the forested southern and northeastern peripheries, and extensive hotspots (35–49 °C) in the urbanised core. In 2024, high-temperature zones further intensified and expanded, with values above 37 °C dominating large portions of the city, while cooler regions contracted considerably, leaving only limited patches in the outskirts. Overall, across all four cities, the spatial patterns demonstrate an expansion and intensification of urban heat zones over the 11-year period, with the highest increases observed in densely urbanized areas

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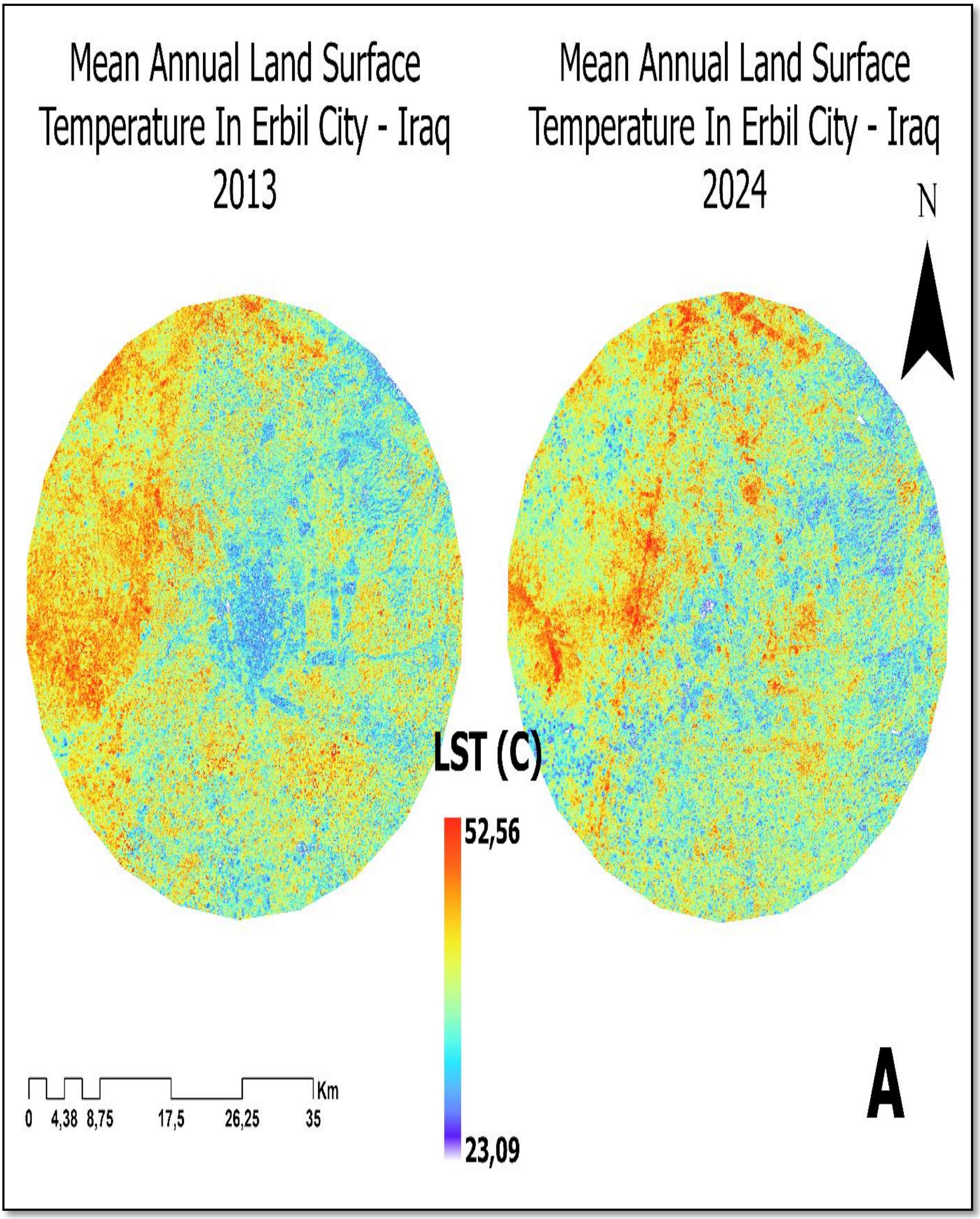
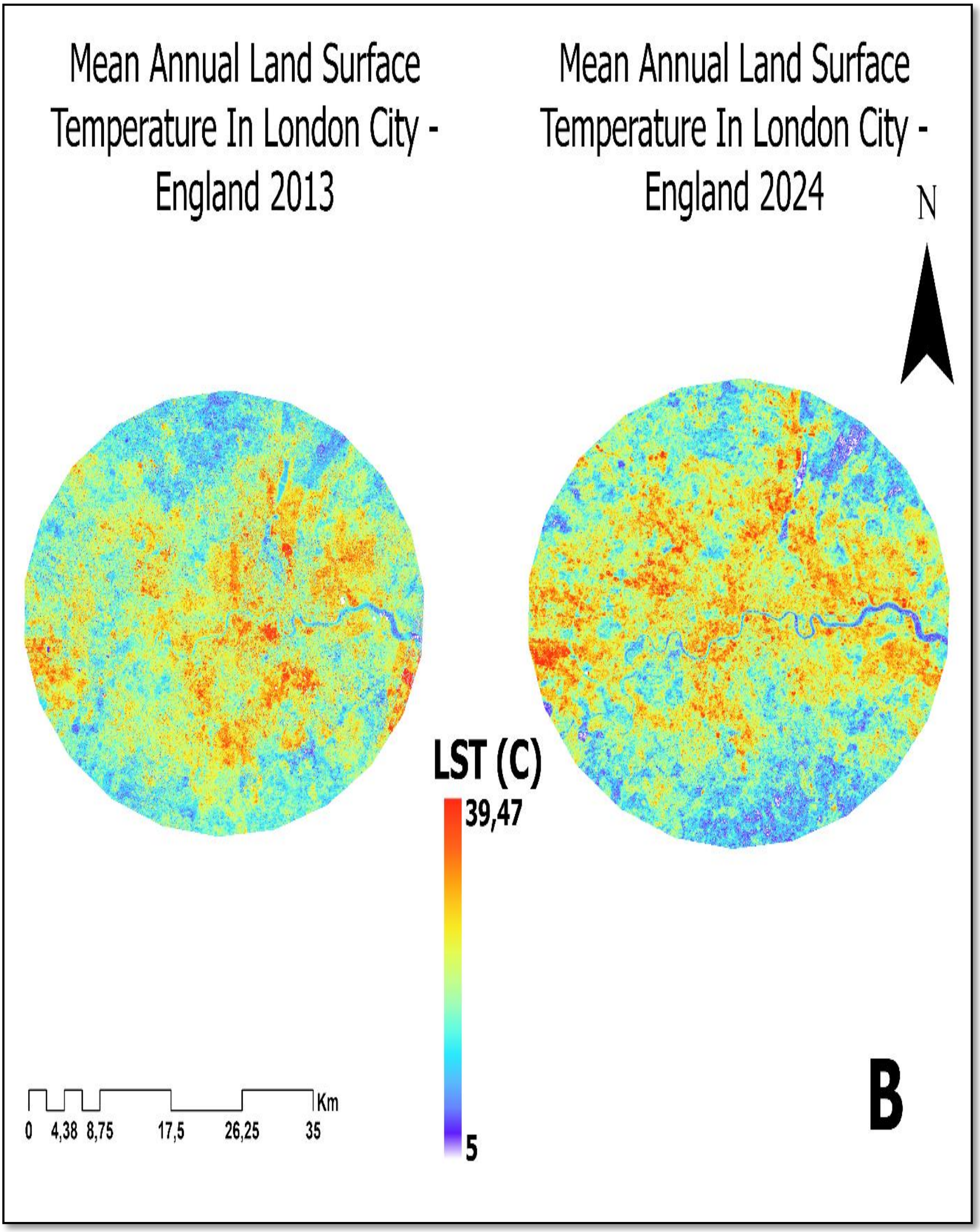
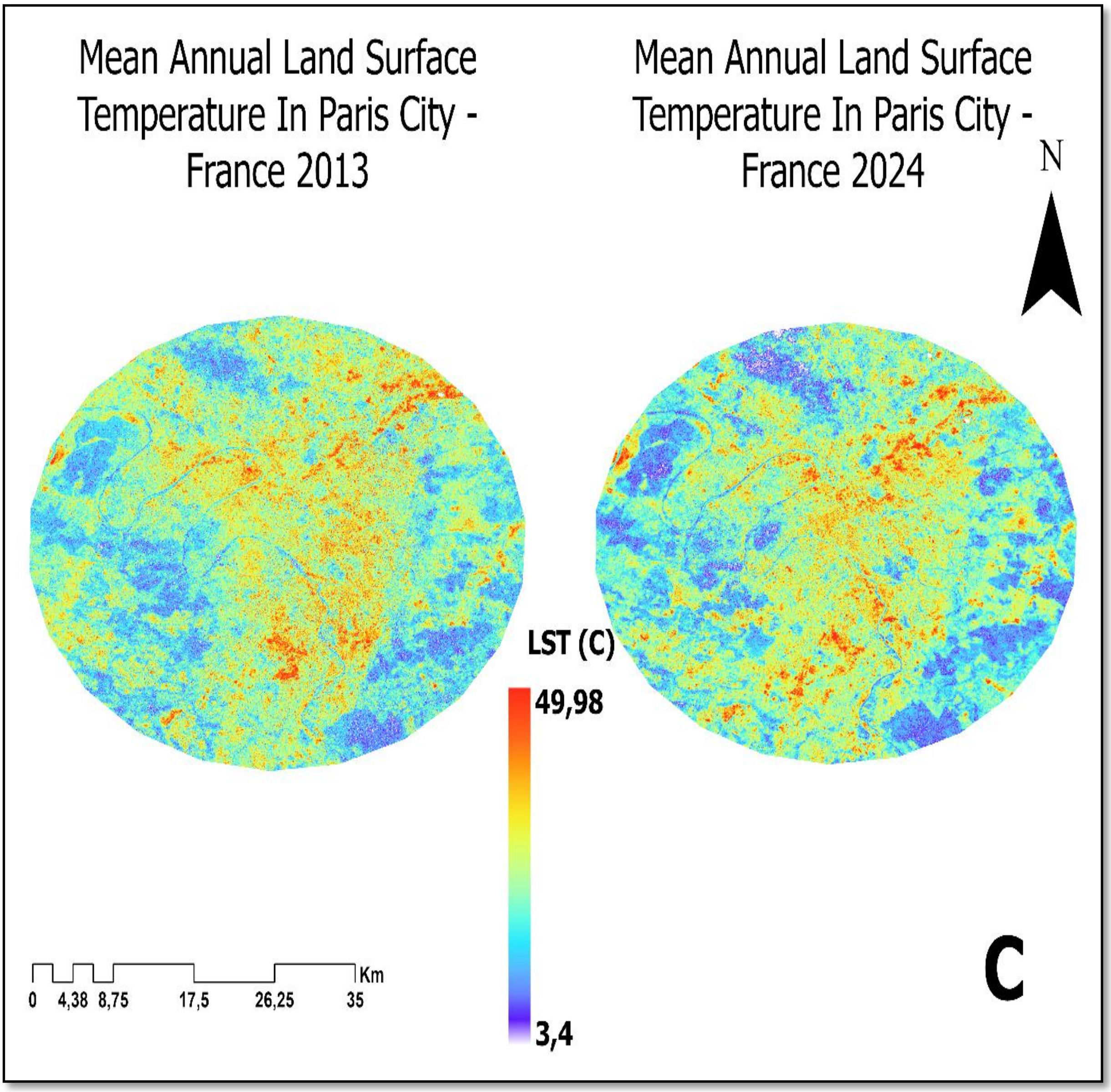
(ISSN): 2227-2895 (Print) (E-ISSN):2313-0059 (Online)


Mean Annual Land Surface Temperature In Erbil City - Iraq 2013
Mean Annual Land Surface Temperature In Erbil City - Iraq 2024
N
LST (C)
52,56
23,09
0 4,38 8,75 17,5 26,25 35 Km
A


Mean Annual Land Surface Temperature In London City - England 2013
Mean Annual Land Surface Temperature In London City - England 2024
N
LST (C)
39,47
5
0 4,38 8,75 17,5 26,25 35
Km
B


Mean Annual Land Surface Temperature In Paris City - France 2013
Mean Annual Land Surface Temperature In Paris City - France 2024
N
LST (C)
49,98
3,4
0 4,38 8,75 17,5 26,25 35 Km
C

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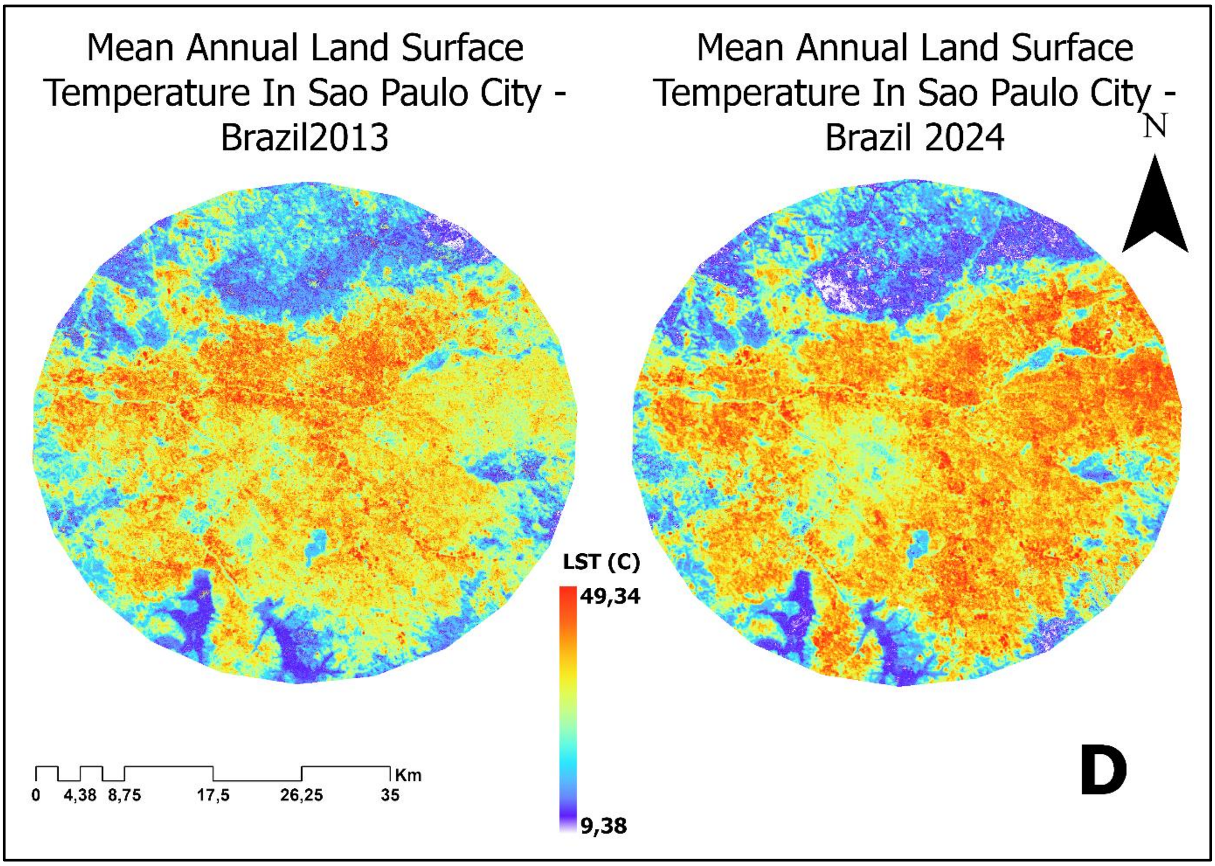

Figure 2. Mean annual land surface temperature (LST) in 2013 and 2024 for four major cities: (a) Erbil, Iraq; (b) London, England; (c) Paris, France; and (d) São Paulo, Brazil. Warmer colours (yellow to red) indicate higher LST, while cooler colours (blue to green) represent lower LST.

3.2 Spatial Distribution of Land Surface Temperature Change (2013–2024)

The spatial distribution of land surface temperature (LST) changes between 2013 and 2024 highlights zones of increase, decrease, and stability across Erbil, London, Paris, and São Paulo (Figure 3a–d).

In London, England (Figure 3a), large portions of the metropolitan area exhibit increased LST, particularly in central and northern zones. Cooler areas are patchy and concentrated along the southern and eastern edges. No-change zones occur in scattered clusters but cover a relatively small fraction compared to warming zones, confirming an overall trend of temperature increase across the city. While in Erbil, Iraq (Figure 3b), the spatial pattern shows a mixture of increased and decreased LST. Large parts of the urban centre and western sectors display higher LST (red), while decreased zones (blue) dominate the surrounding peripheries. Areas with no change (black) are scattered but limited, suggesting that warming trends are primarily concentrated in the city core.

In Paris, France (Figure 3c), the map is dominated by widespread increases in LST, with intensified warming across the urban core and extending into suburban areas. Decreased zones are limited to peripheral areas and appear fragmented, while no-change zones are minor, indicating that warming has become the prevailing trend throughout the metropolitan region. In São Paulo, Brazil (Figure 3d), the distribution is strikingly dominated by LST increases. Almost the entire metropolitan area is covered by red zones, with only minimal patches of decreased temperature and negligible no-change areas. This indicates a near-universal pattern of surface warming across the city.

Overall, the four cities reveal consistent warming trends between 2013 and 2024, though the magnitude and spatial distribution differ. São Paulo and Paris show the most extensive continuous increases, London displays mixed but warming-dominated patterns, and Erbil exhibits a balance of increases and decreases, with the strongest warming concentrated in the urbanized core.

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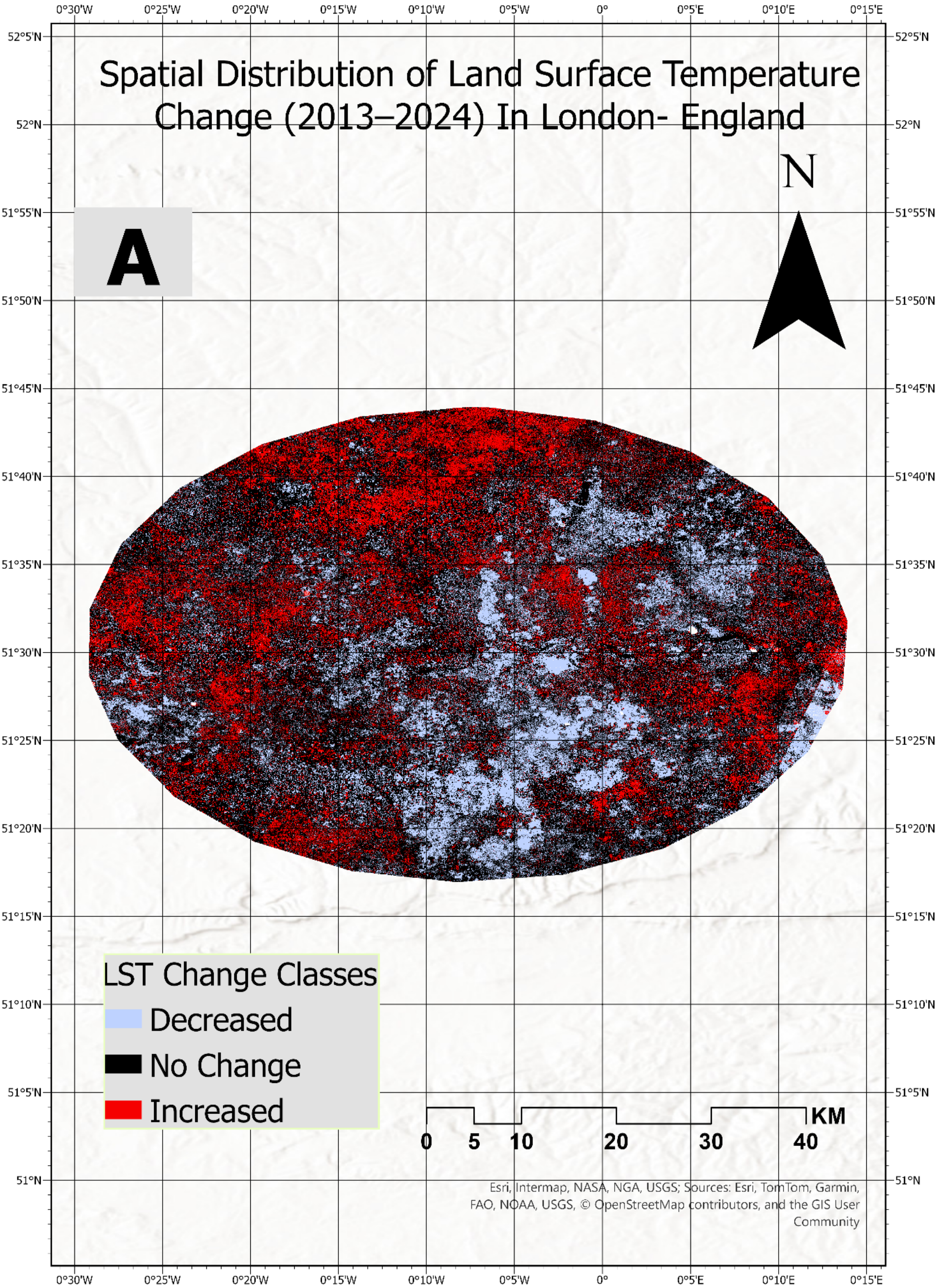
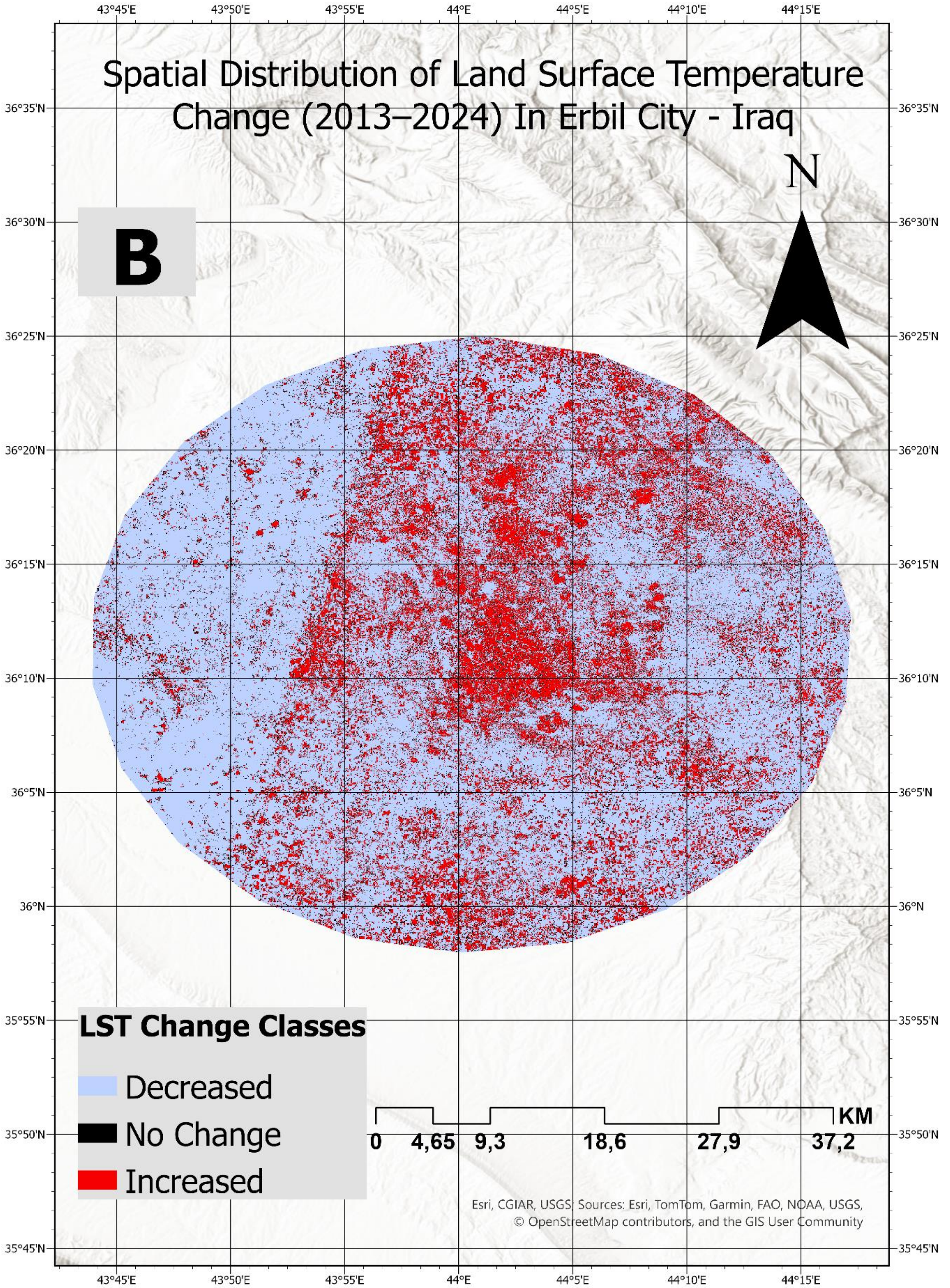

Spatial Distribution of Land Surface Temperature Change (2013–2024) In London- England
A
N
LST Change Classes
Decreased
No Change
Increased
0 5 10 20 30 40 KM
Esri, Intermap, NASA, NGA, USGS; Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community
0°30'W
0°25'W
0°20'W
0°15'W
0°10'W
0°5'W
0°
0°5'E
0°10'E
0°15'E
52°5'N
52°N
51°55'N
51°50'N
51°45'N
51°40'N
51°35'N
51°30'N
51°25'N
51°20'N
51°15'N
51°10'N
51°5'N
51°N



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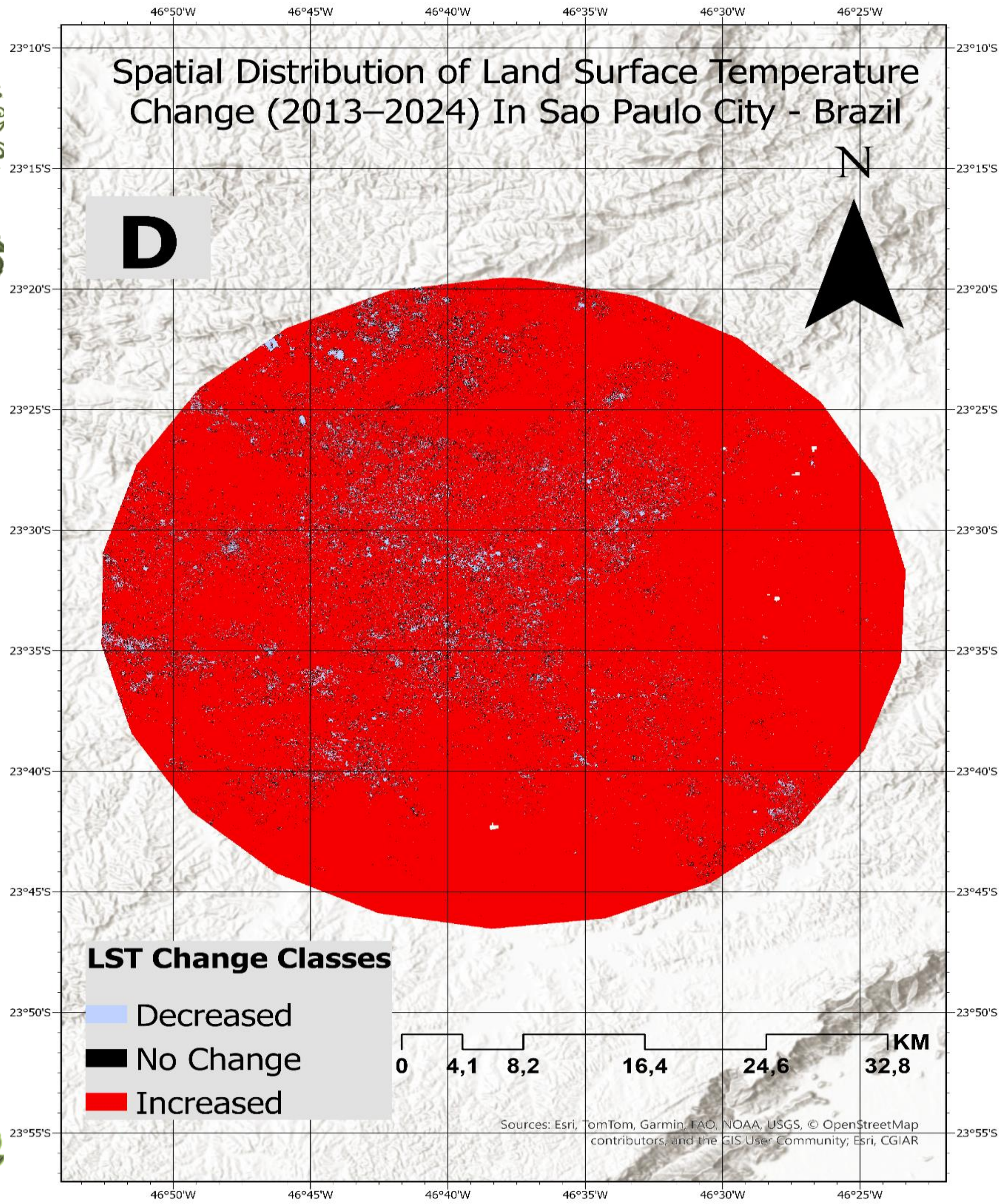

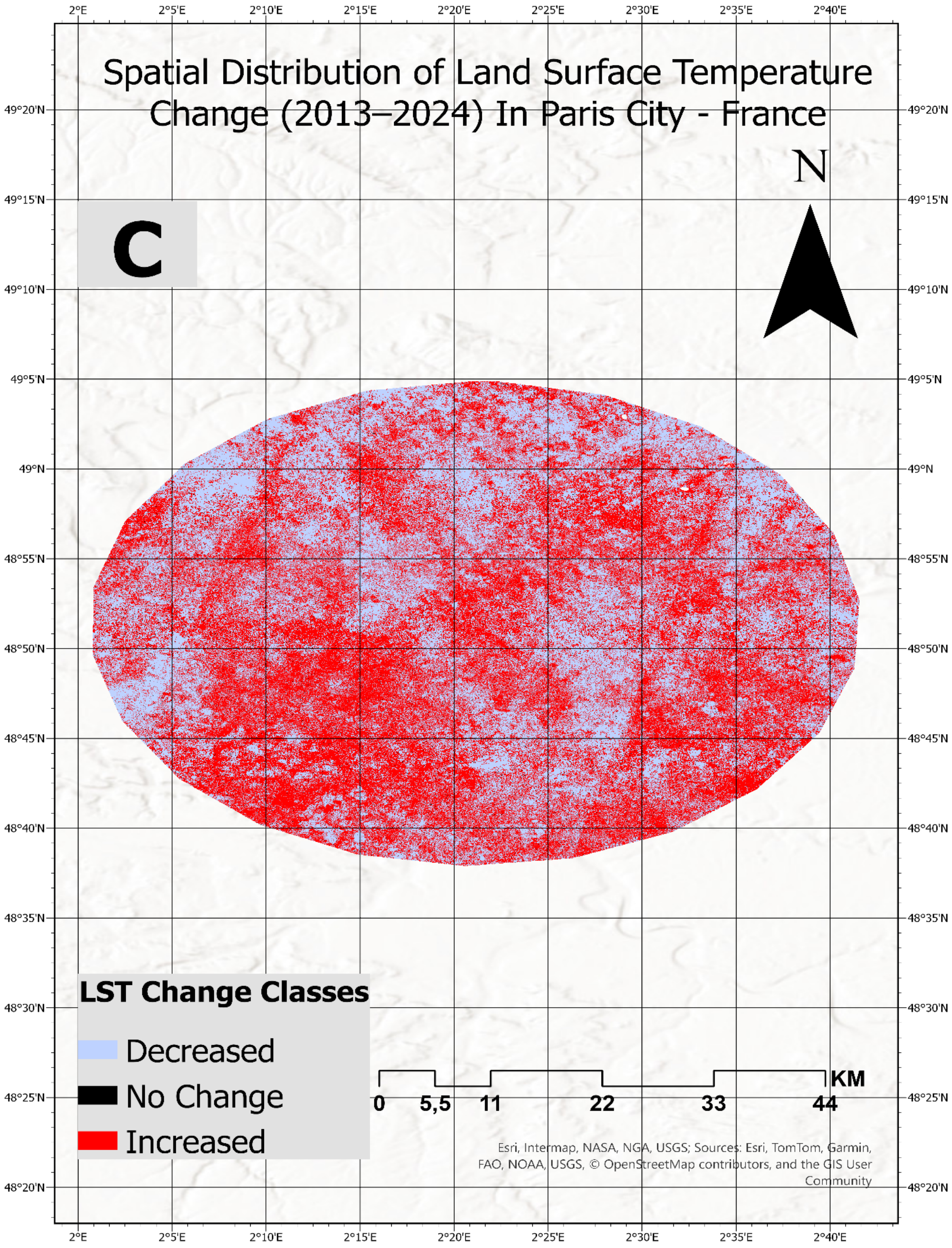

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Figure 3. Spatial distribution of land surface temperature (LST) change between 2013 and 2024 for (a) Erbil, Iraq; (b) London, England; (c) Paris, France; and (d) São Paulo, Brazil. Red areas indicate an increase in LST from 2013 to 2024, blue areas indicate a decrease, and black areas represent zones with no observable change.

3.3 Monthly Variability of Land Surface Temperature (2013–2024)

The temporal analysis of monthly mean Land Surface Temperature (LST) from 2013 to 2024 revealed clear seasonal dynamics and statistically significant warming trends across the examined cities. In Erbil City, Iraq, LST exhibited pronounced seasonal cycles, with summer maxima frequently exceeding 50 °C (Figure 4). The long-term linear trend indicated a warming rate of 0.059 °C per year, reflecting a progressive intensification of surface heat conditions. In London City, England, seasonal variability was evident, with LST ranging from near 0 °C in winter to approximately 35 °C during summer months. Although the magnitude of change was smaller relative to the other sites, the trend remained positive, with an annual increase of 0.015 °C per year, suggesting a consistent but gradual warming trajectory. Paris City, France, displayed similar seasonal fluctuations, with LST values oscillating between near-freezing in winter and above 35 °C in summer. The estimated warming trend was more pronounced than in London, reaching 0.078 °C per year, highlighting the greater sensitivity of urban surfaces in central Europe to recent climate variability and change. In contrast, São Paulo City, Brazil, showed less regular seasonality compared to the temperate cities, but the warming trend was the strongest among all sites. The analysis indicated an increase of 0.197 °C per year, suggesting rapid intensification of urban surface heat in tropical environments, potentially linked to both climatic and urbanisation processes. Overall, the results demonstrate that while all four cities experienced positive LST trends during the study period, the rate of warming varied substantially, with São Paulo showing the most pronounced increase, followed by Paris, Erbil, and London.

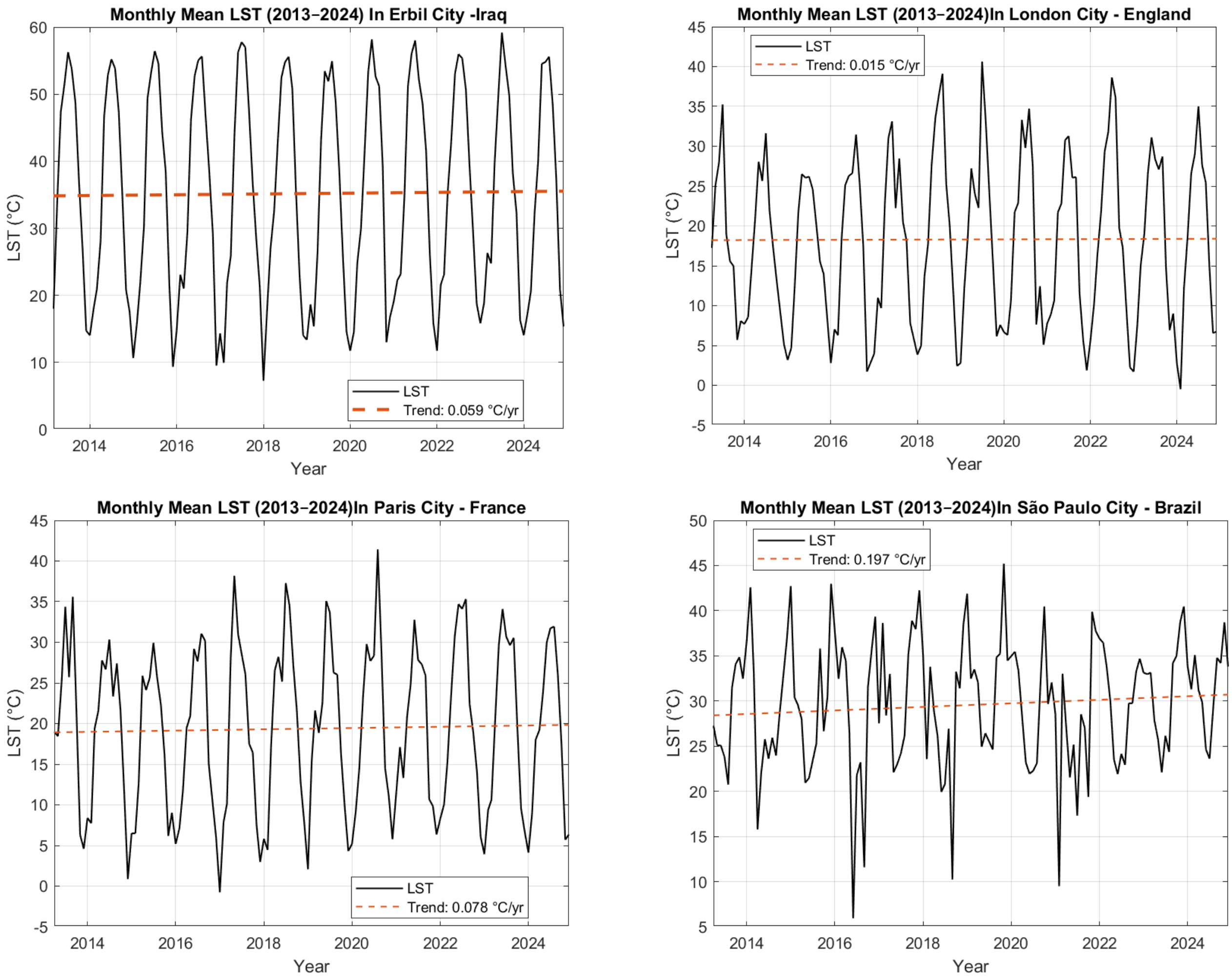

Figure 4. Monthly mean land surface temperature (LST) variation from 2013 to 2024 for (a) Erbil, Iraq; (b) London, England; (c) Paris, France; and (d) São Paulo, Brazil. Each panel highlights the seasonal dynamics specific to local climate regimes: pronounced summer–winter contrasts in Erbil, moderate variability in London, stronger continental influence in Paris, and consistently warm conditions with limited seasonality in São Paulo.

Discussion

This study provides new insights into the spatial and temporal dynamics of land surface temperature (LST) across four cities located in distinct climatic zones: Erbil (semi-arid), London (temperate maritime), Paris (continental), and São Paulo (tropical). By analysing Landsat-derived LST between 2013 and 2024, we demonstrate that although all cities experienced surface warming, the magnitude and seasonal dynamics of LST varied substantially depending on their climatic context. A key finding is the heterogeneity of warming rates, with São Paulo exhibiting the strongest increase (0.197 °C per year), followed by Paris (0.078 °C per year), Erbil (0.059 °C per year), and London (0.015 °C per year) (Figure 4). These differences highlight the crucial role of background climate in shaping urban thermal responses (Ge et al., 2024; Zhao et al., 2021; Estrada et al., 2021). For instance, the contrast between Paris and London, two geographically proximate European cities, illustrates how continental climates such as Paris are more sensitive to warming than maritime climates such as London, which benefit from higher atmospheric moisture and oceanic regulation.

The pronounced warming in São Paulo reflects the combined influence of rapid urban expansion, limited vegetative cover, and the amplification of tropical climate dynamics, leading to near-universal increases in surface temperature across the metropolitan area (Krizek et al., 2024). This is consistent with findings from other tropical megacities where urban heat islands (UHI) have intensified due to dense built-up surfaces and limited mitigation by green infrastructure (Monteiro et al., 2021; Aram et al., 2019). Paris also showed extensive warming, in line with previous studies that identified continental European cities as hotspots of UHI intensification due to reduced evaporative cooling and high thermal inertia of urban materials (de Munck et al., 2013). In contrast, Erbil presented a more heterogeneous pattern, with both warming and cooling zones, though the strongest increases were concentrated in the urban core. This aligns with regional studies of arid and semi-arid cities, where localised increases in impervious surfaces drive thermal intensification against a backdrop of already extreme summer temperatures (Hart et al., 2009; Buyantuyev and Wu, 2010). London, although showing a consistent positive trend, exhibited the slowest warming, a result that corroborates earlier work demonstrating the moderating influence of temperate maritime conditions and substantial vegetation cover (Tomlinson et al., 2011).

The broader context of these findings reinforces global evidence of urban warming but adds nuance by demonstrating how climate zones mediate both the rate and spatial distribution of LST change. Previous works based on MODIS and Landsat data have documented systematic increases in LST across cities worldwide (Peng et al., 2012), yet few have explicitly compared cities across contrasting climatic regimes. By doing so, our analysis shows that while warming is a universal trend, its expression differs significantly: tropical and continental cities are warming more rapidly and extensively, while temperate maritime and semi-arid cities show more moderated or spatially variable responses.

These differences carry important implications for urban climate adaptation. Tropical cities such as São Paulo may face the dual challenge of accelerating heat intensification and limited seasonal relief, with direct consequences for public health and energy consumption. Continental cities such as Paris risk exacerbated heatwave impacts as urban warming compounds regional climate trends. Semi-arid cities like Erbil, already at high baseline temperatures, may see further stress on water availability and human well-being. Even temperate cities such as London, though currently experiencing slower warming, remain vulnerable to projected future increases in urban heat.

Taken together, these results highlight that strategies for mitigating urban warming cannot be generalised across contexts but must be tailored to the climatic zone in which cities are located. Green infrastructure, reflective construction materials, and urban ventilation strategies may have different levels of effectiveness depending on whether a city lies in a tropical, continental, semi-arid, or temperate climate. By systematically comparing multiple cities across distinct climate regimes, this study emphasises that climate context is not simply a background condition but a key determinant of how urban heat manifests and intensifies.

Conclusion

This study provides a comparative assessment of land surface temperature (LST) dynamics across four metropolitan regions representing distinct climatic zones: Erbil (semi-arid), London (temperate maritime), Paris (continental), and São Paulo (tropical). Using Landsat-derived thermal data from 2013 to 2024 and the Mono-Window Algorithm, we demonstrated that all four cities experienced statistically significant surface warming, though the magnitude and spatial distribution of this change varied considerably by climate context.

São Paulo exhibited the strongest warming trend (0.197 °C per year), followed by Paris (0.078 °C per year), Erbil (0.059 °C per year), and London (0.015 °C per year). These differences highlight the critical role of background climate in modulating urban thermal responses, with tropical and continental environments showing more extensive and continuous warming than temperate and semi-arid settings. The results underscore that urban warming is not a uniform phenomenon but rather a climate-specific process shaped by interactions between urbanisation, vegetation cover, and regional atmospheric conditions.

From a practical perspective, our findings suggest that mitigation and adaptation strategies must be tailored to local climate regimes. For tropical megacities such as São Paulo, policies should prioritise green infrastructure and heat-resilient urban planning to offset rapid and widespread warming. Continental cities like Paris may require interventions focused on reducing heatwave risks and enhancing urban cooling capacity. Semi-arid cities such as Erbil will need to integrate water-sensitive urban design and vegetation management to alleviate thermal stress, while temperate cities like London should continue to safeguard and expand urban green spaces to maintain moderated thermal conditions.

In conclusion, by providing cross-regional evidence of how climate zones shape the intensity and spatial expression of urban surface warming, this study reinforces the importance of climate-sensitive planning. Future research should expand this comparative framework to additional cities and integrate socio-economic and health indicators to better understand the multi-dimensional impacts of urban warming on human and environmental well-being.

References

Abdullah, H. (2012). *The use of Landsat 5 TM imagery to detect urban expansion and its impact on land surface temperatures in the city of Erbil, Iraqi Kurdistan* (Master's thesis, University of Leicester).

Abdullah, H., Darvishzadeh, R., Skidmore, A. K., & Heurich, M. (2019). Sensitivity of Landsat-8 OLI and TIRS data to foliar properties of early stage bark beetle (*Ips typographus*, L.) infestation. *Remote Sensing, 11*(4), 398.

Abdullah, H., Polat, N., Bilgili, A. V., & Sharef, S. H. (2020). A comparison between day and night land surface temperatures using acquired satellite thermal infrared data in a winter wheat field. *Remote Sensing Applications: Society and Environment, 19*, 100368.

Aram, F., García, E. H., Solgi, E., & Mansournia, S. (2019). Urban green space cooling effect in cities. *Heliyon, 5*(4).

Buyantuyev, A., & Wu, J. (2010). Urban heat islands and landscape heterogeneity: Linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landscape Ecology, 25*(1), 17–33.

de Munck, C., Pigeon, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., ... & Marchadier, C. (2013). How much can air conditioning increase air temperatures for a city like Paris, France? *International Journal of Climatology, 33*(1), 210–227.

Estrada, F., & Perron, P. (2021). Disentangling the trend in the warming of urban areas into global and local factors. *Annals of the New York Academy of Sciences, 1504*(1), 230–246.

Ge, S., Zhan, W., Wang, S., Du, H., Liu, Z., Wang, C., ... & Dong, P. (2024). Spatiotemporal heterogeneity in global urban surface warming. *Remote Sensing of Environment*, *305*, 114081.

Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and Applied Climatology*, *95*(3), 397–406.

Jimenez-Munoz, J. C., Sobrino, J. A., Skoković, D., Mattar, C., & Cristobal, J. (2014). Land surface temperature retrieval methods from Landsat-8 thermal infrared sensor data. *IEEE Geoscience and Remote Sensing Letters*, *11*(10), 1840–1843.

Krizek, J. P. O., & Santos, L. C. M. (2024). Effects of landscape changes on urban climate change: A case study in the city of São Paulo. *Revista Brasileira de Geografia Física*, *17*(4), 2460–2581.

Makarieva, A. M., Nefiodov, A. V., Nobre, A. D., Sheil, D., Nobre, P., Pokorný, J., ... & Li, B. L. (2022). Vegetation impact on atmospheric moisture transport under increasing land-ocean temperature contrasts. *Heliyon*, *8*(10).

Monteiro, F. F., Gonçalves, W. A., Andrade, L. D. M. B., Villavicencio, L. M. M., & dos Santos Silva, C. M. (2021). Assessment of urban heat islands in Brazil based on MODIS remote sensing data. *Urban Climate*, *35*, 100726.

Neinavaz, E., Darvishzadeh, R., Skidmore, A. K., & Abdullah, H. (2019). Integration of Landsat-8 thermal and visible-short wave infrared data for improving prediction accuracy of forest leaf area index. *Remote Sensing*, *11*(4), 390.

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F. M., ... & Myneni, R. B. (2012). Surface urban heat island across 419 global big cities. *Environmental Science & Technology*, *46*(2), 696–703.

Qin, Z., Karnieli, A., & Berliner, P. (2001). A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. *International Journal of Remote Sensing*, *22*(18), 3719–3746.

Tomlinson, C. J., Chapman, L., Thornes, J. E., & Baker, C. J. (2011). Including the urban heat island in spatial heat health risk assessment strategies: A case study for Birmingham, UK. *International Journal of Health Geographics*, *10*(1), 42.

Weng, Q. (2009). Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *ISPRS Journal of Photogrammetry and Remote Sensing*, *64*(4), 335–344.

Wetherley, E. B., McFadden, J. P., & Roberts, D. A. (2018). Megacity-scale analysis of urban vegetation temperatures. *Remote Sensing of Environment*, *213*, 18–33.

Yuan, F., & Bauer, M. E. (2007). Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. *Remote Sensing of Environment*, *106*(3), 375–386.

Zhao, Z., Sharifi, A., Dong, X., Shen, L., & He, B. J. (2021). Spatial variability and temporal heterogeneity of surface urban heat island patterns and the suitability of local climate zones for land surface temperature characterization. *Remote Sensing*, *13*(21), 4338.

Zhou, D., Zhao, S., Zhang, L., Sun, G., & Liu, Y. (2015). The footprint of urban heat island effect in China. *Scientific Reports*, *5*(1), 11160.