



Heatwave Hotspots: SUHI and Intra-Urban Surface Temperature Mapping in Three Argentine Cities

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Abstract

This study analyzes the Surface Urban Heat Island (SUHI) effect and the spatial distribution of Land Surface Temperature (LST) during heatwaves in three climatically and geographically distinct Argentine cities: Posadas, Buenos Aires, and Neuquén. Leveraging high-resolution satellite imagery (MODIS, Landsat 8, Sentinel-2) and the Local Climate Zone (LCZ) classification, the research quantifies SUHI intensity and identifies fine-scale thermal patterns across urban, peri-urban, and rural areas. Results show that all three cities experience significant SUHI effects, particularly at night, with urban areas consistently exhibiting higher LSTs than their surroundings. However, daytime patterns vary considerably. In Neuquén's semi-arid plateau, a negative SUHI was observed, with rural areas reaching higher temperatures than urban centers. Densely built environments—especially compact zones—demonstrate elevated heat retention, exacerbating heat-wave impacts. Conversely, areas with substantial vegetation, such as parks and river corridors, consistently show lower surface temperatures, underscoring their role in urban cooling. By integrating multi-source remote sensing data with the LCZ framework, this study provides a robust and transferable methodology for analyzing intra-urban thermal variability. The findings offer valuable insights for climate adaptation and urban planning, particularly in rapidly expanding cities facing increasing exposure to extreme heat.

Graphical Abstract

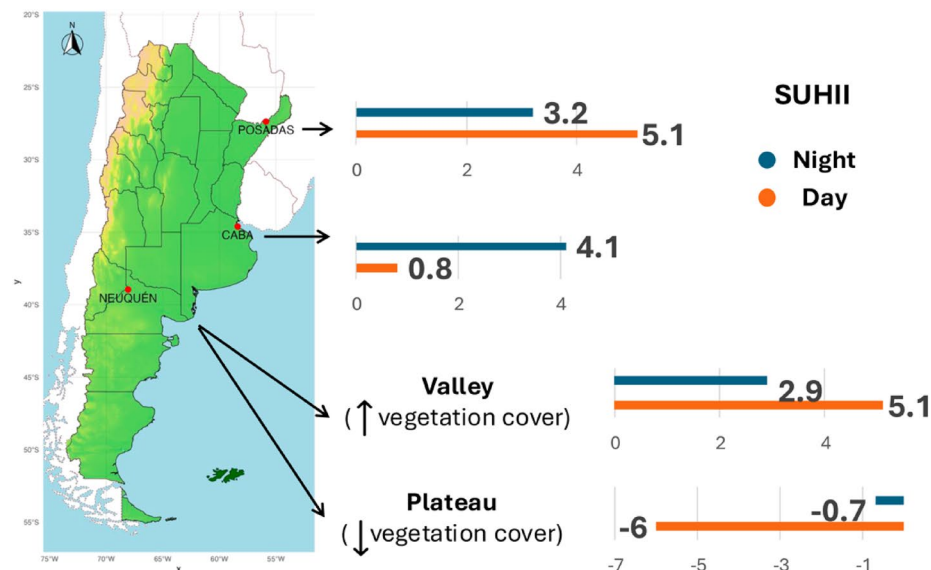
This study examines the effects of extreme heat in urban environments by analyzing the Surface Urban Heat Island (SUHI) phenomenon and the spatial distribution of Land Surface Temperature (LST) across three climatically diverse Argentine cities: Posadas, Buenos Aires (CABA), and Neuquén. The research integrates high-resolution satellite imagery (MODIS, Landsat, Sentinel) and Local Climate Zone (LCZ) classification to capture fine-scale thermal dynamics during heatwaves. The two main goals were: (1) to assess SUHI intensity in different urban contexts, and (2) to explore how surface temperature varies within cities based on land cover and built environment characteristics. The results show that densely built zones, particularly compact LCZs, experience higher LSTs both during the day and at night. Vegetated and peri-urban areas consistently exhibit lower surface temperatures, confirming the cooling role of green infrastructure. In Posadas and CABA, the SUHI effect is strongest at night, while Neuquén presents a unique case of daytime negative SUHI, especially in semi-arid rural plateaus with low vegetation and soil moisture. The findings highlight how local geography, urban morphology, and vegetation interact to shape heat exposure, emphasizing the need for spatially targeted heat mitigation strategies. These insights are particularly valuable for guiding urban planning and climate adaptation efforts in rapidly expanding cities facing growing risks from extreme heat events.

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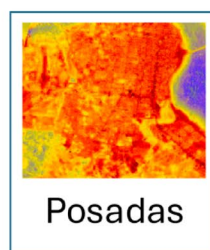
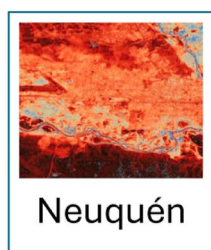
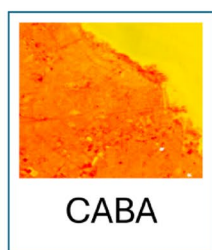
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Surface temperature distribution



The temperatures shown are hypothetical examples based on real data measured in this study, presented for illustrative purposes.

Keywords Climate adaptation · Land surface temperature · Remote sensing · Urban heat Island · Urban planning

1 Introduction

Cities are open systems that exchange energy and mass with their surroundings. This characteristic, combined with the

growing risks of climate change, intensifies urban challenges (Oke et al. 2017). Urban populations have increased by more than 397 million people, with over 90% of this growth occurring in less developed regions. These numbers

are projected to reach 5 billion by 2050 (Dodman et al. 2022; OECD/European Commission 2020). Such rapid expansion heightens vulnerabilities to climate change impacts, including extreme heat, flooding, and pollution, requiring effective adaptation and mitigation strategies.

Urban climate studies must adapt a comprehensive approach that includes urban, rural, and peri-urban zones due to their interconnected nature. Urban areas are characterized by high population density and extensive infrastructure, while rural areas tend to have lower population density and are dominated by agricultural land use (Hutchings et al. 2022a). Peri-urban zones located at the urban-rural interface, experience rapid population growth and mixed land use, including agriculture, industry, and residential development. These regions often suffer from fragmented governance and uneven infrastructure development, which disproportionately affects vulnerable populations (Hutchings et al. 2022a).

Extreme heat poses a major threat to urban residents, particularly in expanding cities. Variables such as radiation, air temperature, humidity, and wind speed are essential to monitor, as they contribute to thermal stress on the human body. Under extreme heat, the body's regulatory systems can struggle to maintain a stable internal temperature, potentially leading to hyperthermia (Oke et al. 2017). This condition is associated with cardiovascular complications (Cheng and Su 2010; Silveira et al. 2019), respiratory problems (Linares et al. 2015), and elevated mortality rates in urban areas.

The Urban Heat Island (UHI) effect refers to the temperature increase in urban areas compared to surrounding rural or suburban regions (Oke 1982; Voogt J.A. and Oke T.R. 2003). This phenomenon is most intense during calm, clear nights when radiative cooling differences are amplified (Voogt J.A. and Oke T.R. 2003). The UHI effect worsens the impacts of global warming, particularly during heatwaves, posing serious health risks for city dwellers (Heaviside et al. 2017). The Surface Urban Heat Island (SUHI), measured via satellite imagery, quantifies the land surface temperature (LST) difference between urban and rural areas (Zhou et al. 2019). Surface urban heat island intensity (SUHI) is a crucial metric for assessing the magnitude of the urban heat island effect and its spatial and temporal variations (Liu and Zhang 2024; Peng et al. 2024).

Although typically more pronounced at night due to the thermal inertia of urban construction materials (Oke 1982; Santamouris et al. 2007; Tzavali et al. 2015), the UHI effect can also occur during the daytime, depending on the surrounding environment. Peng et al. (2012) found a strong negative correlation between urban vegetation cover and daytime UHI intensity across 419 cities worldwide. Only a few cities, mainly in desert regions like Jeddah (Saudi

Arabia) and Mosul (Iraq), showed negative daytime SUHI. Oke et al. (2017) also observed that UHI behavior varies with climate; cities in tropical, Mediterranean, and temperate zones often show year-round positive UHI effects, whereas desert cities experience seasonal variations.

Understanding the influence of local urban context is vital for evaluating UHI intensity and planning appropriate responses. Effective UHI research must consider variables such as elevation, climate, urban morphology, vegetation cover, and urban form (Tzavali et al. 2015; Oke et al. 2017). Urban density is especially important. Compact cities, while more energy-efficient in terms of transport and land use, may experience reduced ventilation, limited solar access, and elevated UHI effects due to lower green space availability. Martilli (2014) found that while compact cities are more energy-efficient in building consumption, intermediate densities tend to provide better outcomes for outdoor comfort and health. Despite these efficiencies, high urban density can have drawbacks, such as limited access to solar energy, restricted ventilation, reduced green spaces, and an intensified UHI effect (Oke et al. 2017). UHI exposure is closely tied to a city's development patterns and the spatial distribution of its residents (Chakraborty et al. 2019).

Urban form also reflects a region's socioeconomic development. Cities in low-income countries typically have population densities four times higher than those in high-income countries (OECD/European Commission 2020). A major concern in the Global South is the rise of informal settlements, which often emerge in areas highly vulnerable to climate extremes (Revi et al. 2014). Informal settlements arise outside formal legal systems meant to regulate land ownership, planning, and safety standards, often lacking proper infrastructure and services (Satterthwaite et al. 2020). As urbanization accelerates in low- and middle-income countries, the growth of these settlements has become a major factor in the concentration of climate risks in urban areas.

Urban management can play a key role in reducing the UHI effect. For example, maintaining and expanding urban green areas can lower surface temperatures, while nearby rural areas may act as 'thermal sinks' that absorb and dissipate urban heat (Yang et al. 2024). However, the cooling effect of vegetation varies by zone, influenced by factors such as shape, size, and connectivity of urban green spaces (Ke et al. 2021; Al-Saadi et al. 2020). Green areas are commonly identified using satellite-derived indices such as Normalized Difference Vegetation Index (NDVI), a widely recognized indicator of vegetation health and growth (Huang et al. 2021). NDVI typically shows a negative correlation with surface temperature, although the strength of this relationship can vary depending on vegetation type and geographic location (Singh et al. 2024).

Urban vegetation plays a central role in shaping the thermal behavior of cities, particularly under extreme heat conditions. Building on the established correlation between NDVI and lower surface temperatures, vegetation acts as a natural regulator by providing shading, enhancing evapotranspiration, and reducing both surface and ambient temperatures. This capacity to lower urban heat is especially important in compact, impervious areas, where cooling through natural means is otherwise limited. Interventions such as tree planting, green roofs, and vegetated surfaces have been shown to significantly reduce heat exposure and improve outdoor thermal comfort (Bowler et al. 2010; Wong et al. 2021), offering both climatic and health co-benefits.

The effectiveness of urban vegetation, however, is not uniform and depends strongly on its type, structure, and spatial arrangement. As Gunawardena et al. (2017) emphasize, vegetation operates at multiple scales. At the microscale, individual trees can provide immediate shading and local cooling, while at the neighborhood or mesoscale, larger parks and vegetated corridors produce extended cooling effects through the formation of air temperature gradients—known as “park-breeze” effects. These cooling zones may extend several hundred meters from the source, especially under low-wind, high-heat conditions. The three-dimensional characteristics of trees, such as crown size and canopy density, are critical in determining their capacity to intercept solar radiation and generate convective and evaporative cooling. Furthermore, increased vegetation roughness can enhance mechanical turbulence, which is particularly relevant in humid environments where evapotranspiration alone may be less effective.

However, access to these benefits is not equally distributed. Socioeconomic disparities within cities often translate into unequal access to green spaces, resulting in disproportionate exposure to urban heat. Chakraborty et al. (2019) have shown that UHI intensity is frequently higher in marginalized communities with limited tree cover and poorly planned open space, exacerbating environmental injustice. This underscores the need for climate adaptation strategies that prioritize equity in the spatial distribution of vegetation and its associated benefits.

From a planning perspective, integrating green infrastructure into urban development offers a multidimensional solution that addresses both thermal regulation and social vulnerability. As Norton et al. (2015) argue, green infrastructure not only mitigates heat stress but also enhances biodiversity, improves air quality, and contributes to urban livability. To maximize its impact, vegetation must be embedded into the urban fabric in a strategic and connected manner, moving beyond isolated patches toward integrated networks that reflect climatic conditions, community needs, and urban growth patterns.

Satellite imagery has become essential for analyzing surface temperature patterns and vegetation cover across extensive regions. These remotely sensed images offer critical insights not only into UHI phenomena but also into broader surface temperature variations, enabling researchers to monitor environmental changes effectively. Satellite sensors are capable of detecting electromagnetic radiation that is both emitted and reflected by the Earth’s surface, providing key datasets for environmental studies (Šalkovič and Paudišová 2023). Satellite constellations can generally be classified into four major categories: global monitoring (GM-), environmental monitoring (EM-), nanosatellites, and civilian satellites. GM-satellites, such as MODIS Terra, operate in high orbits or geostationary positions and are characterized by their ability to deliver frequent temporal data—ranging from daily to infra-hourly—albeit at coarse spatial resolutions exceeding 100 m. In contrast, EM-satellites like Landsat and Sentinel-2 offer a more balanced approach by providing moderate spatial resolution (10–100 m), intermediate temporal resolution (every few days), and spectral resolution encompassing around ten bands. This combination makes EM-satellites particularly well-suited for detailed environmental monitoring applications. Furthermore, integrating data from multiple satellite platforms can significantly enhance the robustness and effectiveness of environmental analyses, facilitating more precise and comprehensive achievement of research objectives (Alvarez-Vanhard et al. 2021).

Understanding urban ecosystems and their distinct climatic behaviors requires a clear differentiation between various types of land cover and urban morphology. To address this, Stewart and Oke (2012) introduced the LCZ classification system, which provides a standardized framework for categorizing both urban and rural areas at the neighborhood scale. This system is based on a combination of key physical and anthropogenic variables, including surface cover, urban structure, building materials, and human activity patterns (Oke et al. 2017). The LCZ framework has become a valuable tool for urban climate research, particularly in the study of surface urban heat islands (SUHI), as it facilitates meaningful comparisons among areas with similar surface and exposure characteristics. This standardization contributes to a more coherent interpretation of SUHI intensity and spatial distribution (Stewart and Oke 2012). Numerous studies have successfully applied the LCZ classification to investigate SUHI effects in diverse urban contexts around the world, thereby demonstrating its versatility and scientific utility (Zhao et al. 2020; Yang et al. 2020; Anjos et al. 2020; Xia et al. 2022; Zheng et al. 2023; Milošević et al. 2058). Figure 1 illustrates the LCZ categories as defined by (Stewart and Oke 2012) highlighting the diverse types of built

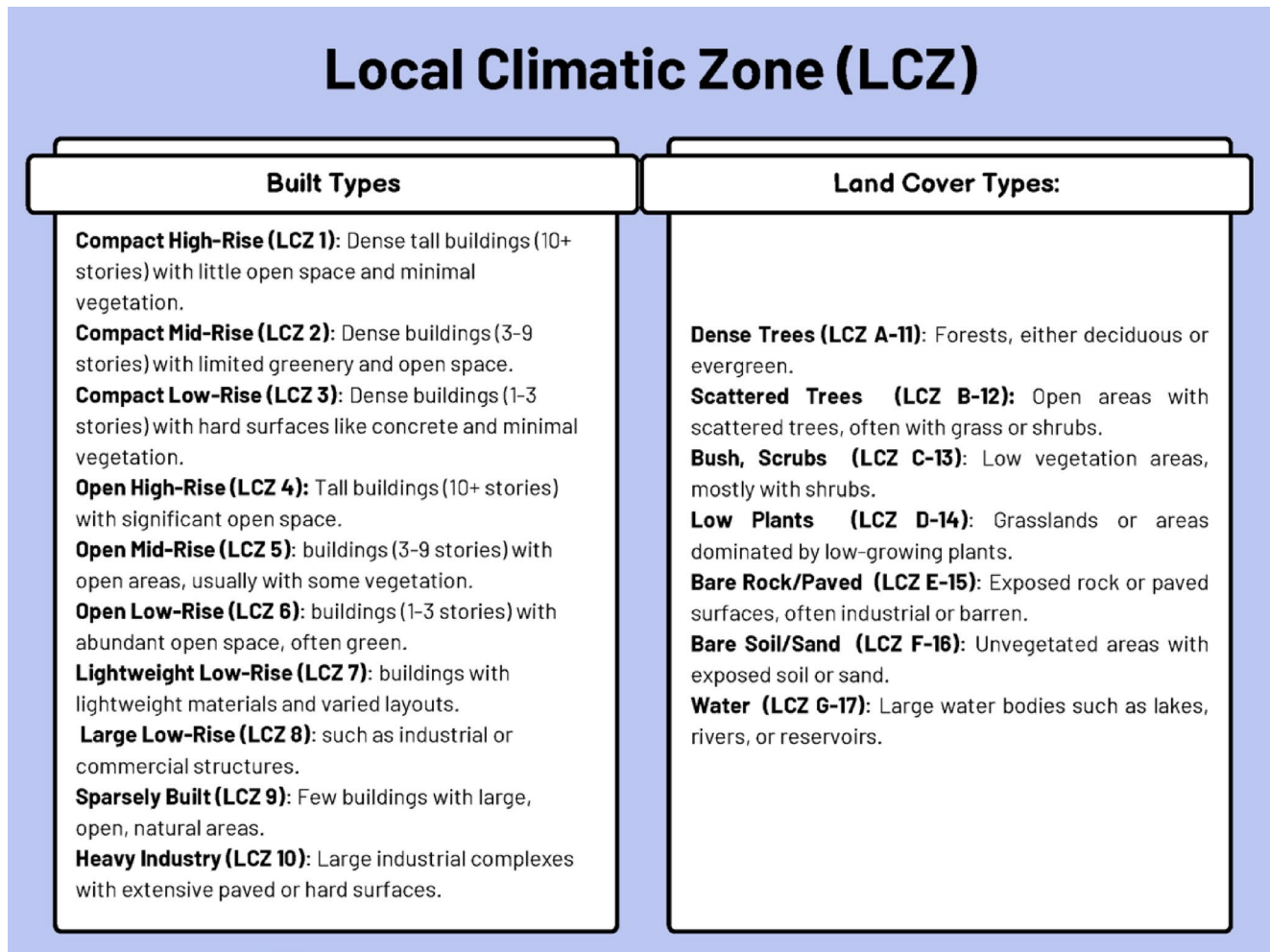


Fig. 1 Classification of the various Local Climate Zone (LCZ) categories. Made from Stewart and Oke (2012)

environments and land cover classes that are distinguished by their specific structural and material characteristics.

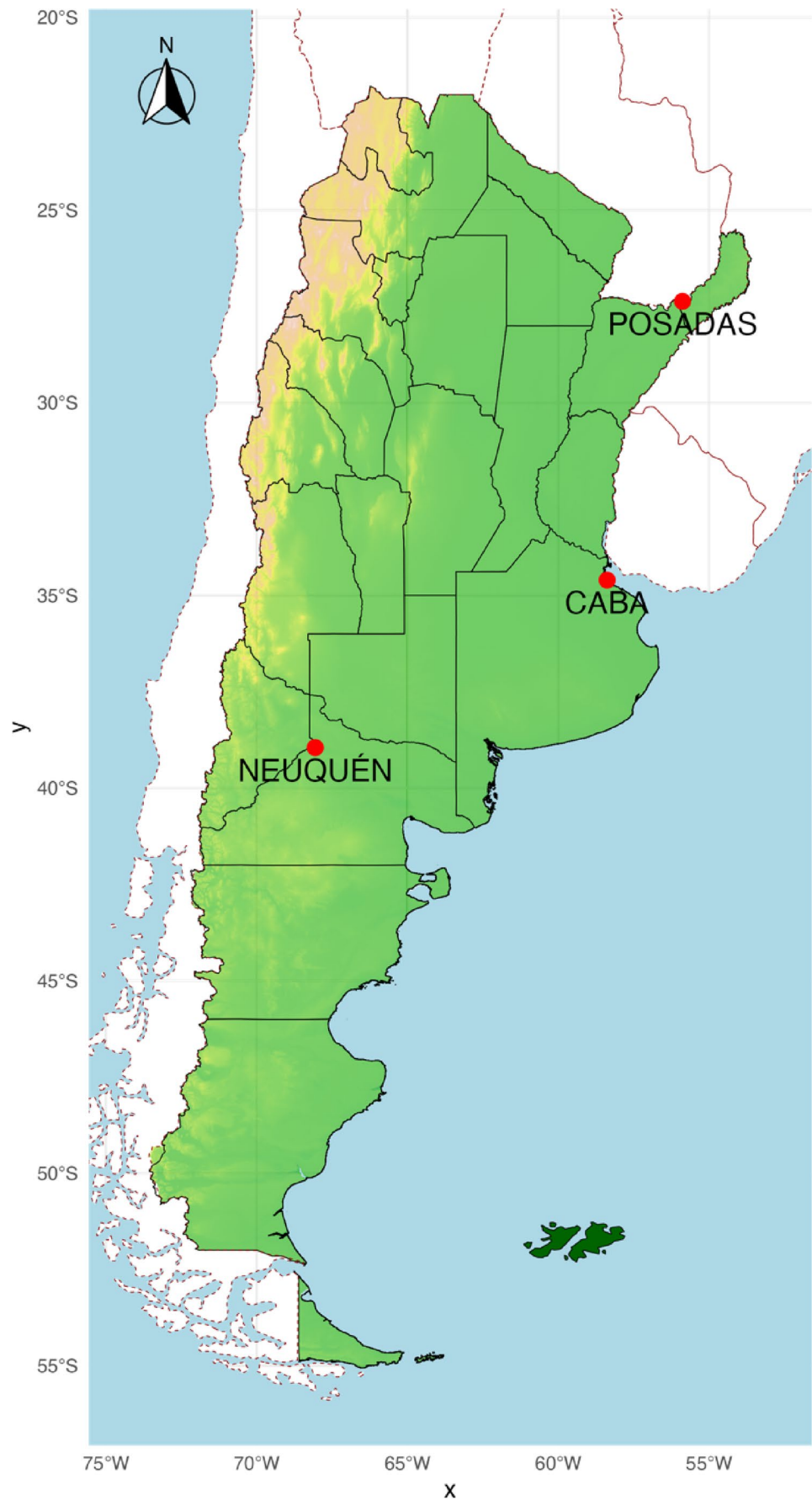
In Argentina, heatwaves have exhibited heterogeneous upward trends across the country, affecting both maximum and minimum temperatures (Cimolai and Aguilar 2024). However, cities do not experience these climatic extremes uniformly; their exposure and vulnerability vary according to geographical, climatic, and urban characteristics (Oke et al. 2017). To capture this diversity, the present study focuses on three major urban centers located in distinct regions of the country (Fig. 1): Posadas in the northeast, Buenos Aires (CABA) in the central region, and Neuquén in northern Patagonia. This selection provides a representative cross-section of Argentina's urban diversity, offering a unique opportunity to analyze how different environmental and socio-economic contexts shape urban thermal behavior.

Each city brings distinct geographical, economic, and climatic attributes to the analysis. Posadas functions as a key commercial node within the Mercosur region, given its strategic proximity to Brazil and Paraguay. As a major tourist

destination, home to iconic sites like the Iguazú Falls, and a hub for agro-industrial activities such as yerba mate, tea, and tobacco production, the city combines high natural resource value with growing urban pressure. Buenos Aires, the capital and the largest urban agglomeration in the country, constitutes the political, financial, and industrial epicenter of Argentina. Its coastal location, dense population, and expansive metropolitan area create a complex urban fabric that is highly susceptible to urban heat island (UHI) effects. In contrast, Neuquén stands out for its semi-arid climate and pivotal role in the national energy matrix, particularly through the exploitation of the Vaca Muerta shale formation. As the principal city in northern Patagonia, it is also experiencing rapid urban growth, making it an essential case study for exploring how emerging cities in dry regions respond to climate extremes.

The selected cities fall into two distinct Köppen-Geiger climate classifications—Temperate Hot Humid (Posadas and CABA) and Cold Desert (Neuquén)—which further broadens the analytical scope for comparing the thermal

Fig. 2 Geographical location of Posadas (Misiones Province), Buenos Aires City, and Neuquén City (Neuquén Province) within Argentina. The map was created using base layers from Natural Earth (2023) and administrative boundaries from GADM (2023)



impact of heatwaves across varying climatic zones (Beck et al. 2018). Additionally, their urban typologies range from a massive metropolis to medium-sized regional centers, allowing for a comprehensive exploration of how urban scale, density, and morphology affect heat distribution. This diversity of contexts enriches the analysis by enabling a nuanced investigation into how climatic stressors interact with urban form across the national territory.

This study aims to analyze the spatial distribution of surface temperatures during heatwave events in these three urban regions and their surrounding environments. Two main objectives are addressed: first, the identification and quantification of surface urban heat islands (SUHIs) using high-temporal-resolution satellite data, which captures both daytime and nighttime temperature variations across urban, peri-urban, and rural zones; second, the application of high-spatial-resolution imagery to assess land surface temperature (LST) distribution at a finer scale. To deepen this analysis, the study incorporates the Local Climate Zones (LCZ) classification system to evaluate how differences in land use, vegetation cover, and built environment influence LST during heatwave conditions.

By integrating multi-source remote sensing techniques—both high temporal and high spatial resolution—with LCZ-based urban morphology analysis, this research offers a comprehensive framework for assessing urban thermal dynamics. Unlike studies that rely solely on coarse-resolution or single-timeframe satellite data, this approach allows for a multi-scale, multi-temporal examination of heatwave effects that is sensitive to both diurnal variation and intra-urban heterogeneity. The methodological novelty lies in the simultaneous use of complementary remote sensing datasets, enhancing the accuracy and applicability of the results for urban planning.

Beyond academic contribution, the findings have direct implications for urban policy and climate adaptation. This study provides critical insights for urban planners,

environmental managers, and policymakers, especially in the context of climate resilience and sustainable development. By identifying spatial patterns of heat accumulation and their correlation with urban form, the results inform targeted interventions such as green infrastructure deployment, zoning strategies, and urban design adjustments. Ultimately, this work supports the creation of healthier, more adaptive cities by offering actionable knowledge on mitigating heat-related risks in diverse urban settings.

To meet these objectives, the structure of this paper is as follows: Sect. 2 outlines the data sources and methodological framework used to calculate and interpret land surface temperatures in relation to LCZ categories. Section 3 presents the main findings from the thermal analyses. Sections 4 and 5 offer a discussion of the results, conclusions, and directions for future research aimed at enhancing urban resilience to extreme heat events.

2 Methodology

This study represents a significant methodological innovation and, to the best of our knowledge, is among the first to combine multiple high-resolution satellite data sources, advanced downscaling techniques, and a tailored adaptation of Local Climate Zones (LCZ) for analyzing urban temperatures during heatwaves. This methodology uniquely integrates data from MODIS, Landsat 8, and Sentinel-2 to provide a comprehensive and multidimensional analysis of urban thermal variations. All images used in this study were carefully selected from periods of heatwaves occurring within the last decade. It is important to note that these heatwave periods were previously identified by Cimolai and Aguilar (2024).

Importantly, this methodology is not limited to the case studies presented here—it is broadly applicable to any urban or peri-urban setting. Its modular structure and reliance on globally accessible remote sensing data make it a transferable tool for assessing SUHI effects and LST variability across diverse climatic, morphological, and socioeconomic contexts. As such, it offers valuable potential for replication in cities with limited ground-based climate data, particularly in rapidly urbanizing regions.

2.1 Data

To develop the study, different kind of data were used. Table 1 lists the satellites and datasets used in this study, accessed via the Google Earth Engine (n.d).

The MODIS datasets (MOD21A1N and MOD21A1D) provide daily global LST at a 1 km resolution, including 3-band emissivity data. MOD21A1N focuses on nighttime

Table 1 Satellites and datasets used in this study. Compiled from Google Earth engine (n.d.), U.S. Geological survey (2019), European space agency

Derived variable	Dataset	Temporal resolution	Spatial resolution
Surface temperature - night	MODIS - MOD21A1N	Daily	1 km
Surface temperature- day	MODIS - MOD21A1N	Daily	1 km
Surface temperature- day	LANDSAT - LANDSAT/LC08/C02/T1_L2	16 days	30 m
NDVI	SENTINEL - COPENICUS/S2_SR	5 days	10 m

observations, averaging LST for each grid cell using cloud-free data with good accuracy, weighted by observation coverage. Similarly, MOD21A1D provides daytime observations. On the other hand, Landsat 8 offers a temporal resolution of 16 days, equipped with the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). OLI has a spatial resolution of 15–30 m, while TIRS is resampled to match OLI bands at 30 m. We used Landsat 8 Collection 2 Level-2 images, which include surface temperature measurements from April 2013 onwards. Note that no nighttime surface temperature products are available for this dataset. Landsat Level-2 products are derived from Level-1 inputs and take about 14–16 days to process. Finally, the SENTINEL COPERNICUS/S2_SR dataset was used. Sentinel-2 provides multispectral imagery with a 10-meter resolution and a 5-day revisit frequency, offering higher spatial resolution than Landsat but lacking thermal infrared data.

2.2 Classification of urban areas and LCZ

The study involved visually identifying pilot zones belonging to each LCZ for each of the cities examined. These pilot zones were used as training areas used to define the LCZ categories with the LCZ Generator tool developed by Demuzere et al. (2021). Given the social, economic, geographical, and structural differences between the cities, there may be variations in the characterizations of LCZ categories among them. Therefore, it is pertinent to highlight some of the characteristics for Posadas, Buenos Aires (CABA), and Neuquén. It's important to note that not all categories were determined in every city.

In Posadas the LCZ 2 category was characterized by a mix of tall buildings (more than five stories) and low-rise structures without presenting homogeneous zones. This same characteristic was observed for this category in Neuquén. The Open Low-rise (LCZ 6) zone was defined by neighborhoods consisting of low houses with gardens, which are typically covered with vegetation. In the case of Open Mid-rise (LCZ 5), areas were identified with buildings up to nine stories high that did not have adjacent constructions, allowing for visible space between the buildings. In CABA, the Compact High-rise (LCZ 1) category was marked by a predominance of buildings exceeding nine stories, although lower structures and trees may also be found within the blocks. For LCZ 2, there was a prevalence of buildings ranging from two to eight stories, with some taller buildings present in certain blocks. The Open categories (LCZ 4, LCZ 5, and LCZ 6) included various heights of buildings that featured spaces between them and a greater presence of unconstructed surfaces, with or without additional green areas. The Lightweight Low-rise category (LCZ 7) encompassed areas characterized by very dense urbanization that

was poorly planned or unplanned, with minimal vegetation. Finally, LCZ 10 referred to zones where the built surface was almost entirely constructed, lacking vegetation and predominantly featuring construction materials such as concrete and sheet metal.

In Neuquén, the Open Mid-rise and Open Low-rise (LCZ 5, LCZ 6) categories were characterized similarly to those in CABA, where space between buildings and a greater presence of unconstructed surfaces were evident. In the case of Lightweight Low-rise (LCZ 7), these areas also exhibited poor or no planning; however, urbanization was more dispersed and typically featured a significant amount of unconstructed surface area in semi-arid regions. The Large Low-rise category (LCZ 8) was characterized by non-urbanized areas with low density and warehouse-type industrial buildings. Lastly, Sparsely Built areas (LCZ 9) also represented zones with little or no planning but were distinguished by their dispersed urbanization and significant unconstructed surfaces in irrigated zones, often accompanied by associated vegetation. Overall, it can be observed that this area is predominantly inhabited by a segment of society with greater purchasing power compared to LCZ 7. This disparity is especially evident in the size of the residences and the quality of construction materials used.

2.3 Surface temperature analysis

Once the data were obtained and the LCZ classification was completed, the methodology necessary for analyzing surface temperatures was applied. This approach enables the analysis of various urban areas and involves multiple steps using Google Earth Engine (n.d.) and RStudio (Fig. 3). The process begins by describing how daytime and nighttime temperature differences were detected among urban, peri-urban, and rural areas in the studied cities. Next, the analysis of daytime temperature distributions was conducted using LCZ classifications. Surface temperatures were derived from Landsat 8 images, with downscaling methods applied to improve spatial resolution.

To identify differences in surface temperatures during the day and night, we used MODIS products for previously identified heatwaves. Images from over 25 periods were analyzed for each city (26 for Posadas, 30 for CABA, 30 for Neuquén). The study areas were classified into urban, peri-urban, and rural zones based on land use, using sources like IDERA, municipal maps, and Google Earth (n.d.). The urban region included built-up city areas, peri-urban zones were adjacent areas with lower density, and rural zones consisted mostly of natural or cultivated vegetation with minimal built-up spaces. For Neuquén, there were subdivided peri-urban and rural zones into valley and plateau (locally known as “barda”) due to differences in soil and moisture

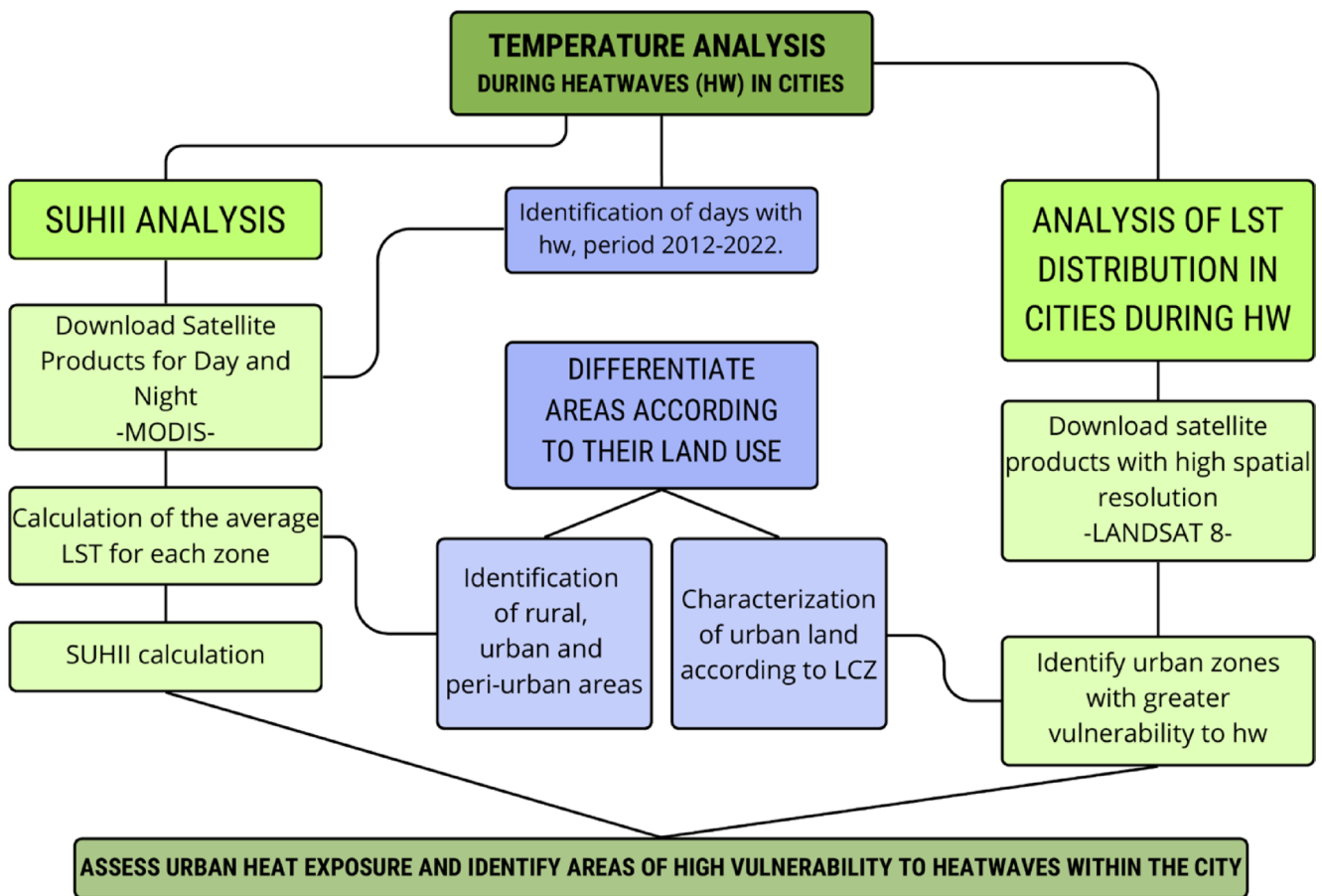


Fig. 3 Methodological framework used for the analysis of urban temperature patterns

that impact land surface temperature (LST). Non-parametric statistical methods were used to ensure robust analysis. The Kruskal-Wallis test identified significant temperature differences among urban, peri-urban, and rural zones, with Dunn's post-hoc test specifying which zones differed significantly, particularly during heatwaves.

For urban analysis, areas were classified by LCZ following Stewart and Oke (2012), adapting categories to each city's specific characteristics. These classifications (Fig. 1) helped identify areas most affected by heatwaves. The LCZ maps were generated using the LCZ Generator tool (Demuzere et al. 2021), ensuring consistent classification. It is important to note that the internal homogeneity depicted by each LCZ is unlikely to be found in real-world settings. Therefore, the categories were adapted for each city, with the specific characteristics of each zone detailed in the "LCZ characterization" section.

We downloaded Landsat LST products for specific heatwave periods, however, the image availability determines the number of images analyzed (e.g., 10 for Posadas, 8 for CABA, 16 for Neuquén). LCZ maps were overlaid with LST data, and mean temperatures were calculated for each LCZ, with results presented in boxplots. Non-parametric

statistical methods, such as the Kruskal-Wallis test and Dunn's post-hoc test, are selected because surface temperatures do not follow a normal distribution.

To address the high variability of LST in urban areas, images are statistically downsampled. Downscaling is based on both Landsat 8 and Sentinel-2 data (COPERNICUS/S2_SR), which offers high-resolution, multispectral imagery with a revisit frequency of 5 days. The downsampled LST maps, covering 4 to 5 heatwave periods for each city, offer detailed insights into spatial variability during extreme heat events. This approach enables the creation of high-resolution maps that highlight temperature distribution across cities during heatwaves, even though these downsampled images are not used for statistical calculations due to data availability constraints. The resulting downsampled LST maps offer valuable insights into the spatial variability of heat events, contributing to a more comprehensive understanding of urban heat islands. Finally, we adapted a methodology by Onačillová et al. (2022), using multiple linear regression models based on spectral indices such as NDVI, NDBI, and NDWI to estimate LST. This approach was applied to Sentinel-2 data, generating high-resolution (10 m) maps. These maps revealed fine-scale thermal variations, allowing for

better identification of heat islands and the impact of urban features on temperature distribution.

The methodology provides a comprehensive analysis of temperature variability across urban environments, incorporating advanced spatial and statistical techniques. By combining high-resolution satellite data, innovative down-scaling methods, and spectral index-based modeling, we have developed a robust approach to better understand the thermal surface characteristics of cities during heatwaves. The adaptability of this methodology is demonstrated through its successful application to three Argentine cities with distinct geographical and climatic characteristics. This versatile methodology not only enhances the capacity to identify and visualize fine-scale surface thermal variations but also shows promise for adaptation to various urban settings worldwide, contributing to the study of urban heat dynamics.

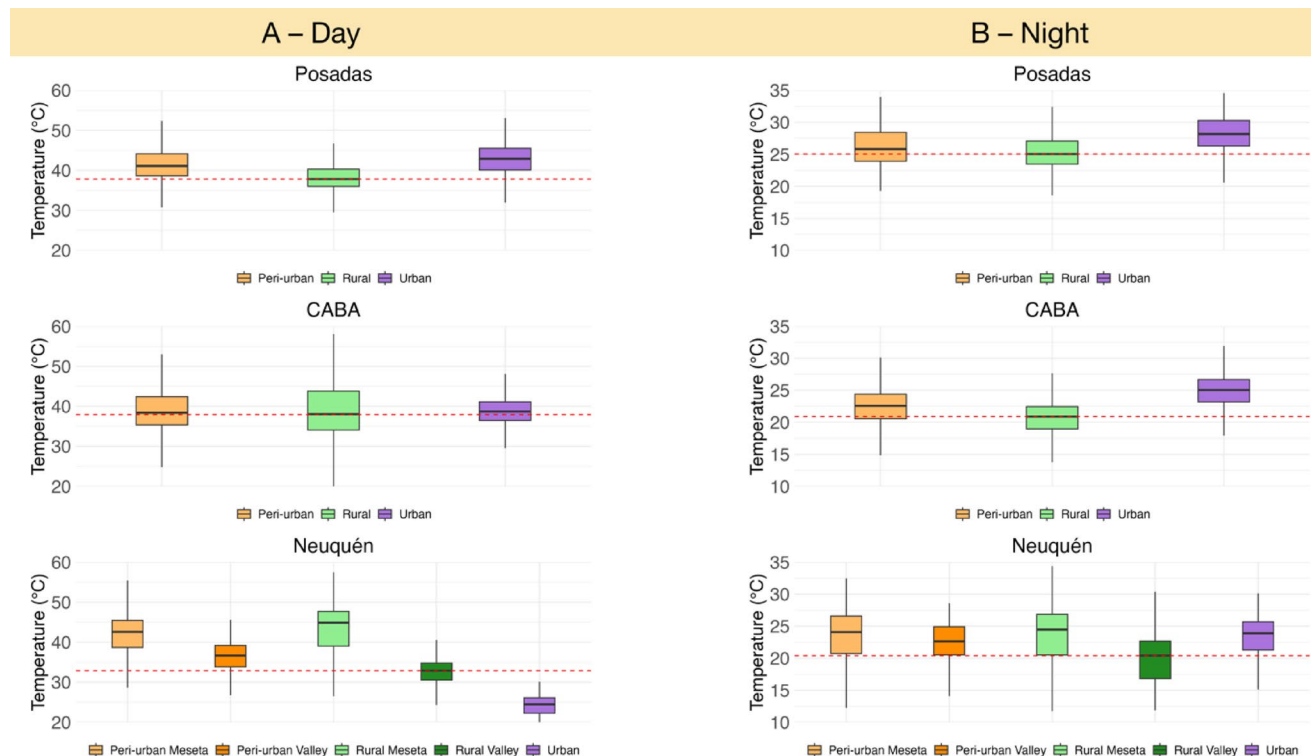
3 Results

To analyze the temperature differences between the studied cities and their surrounding areas during both day and night, this study uses MODIS data with a spatial resolution of 1 km, providing imagery for both diurnal and nocturnal periods. The study areas are divided into three zones: urban,

peri-urban, and rural. For each zone, aggregated mean temperatures are calculated by averaging all the pixels within each category during heatwave periods. These averages are then used to generate boxplots to visualize temperature distributions across the zones and times of day (Fig. 4).

In Posadas, urban areas consistently exhibit higher surface temperatures compared to peri-urban and rural zones, both during the day and at night. The median daytime temperature (Fig. 4A) in the city is 42.9 °C, compared to 37.8 °C in rural areas (SUHII=5.1°C). At night (Fig. 4B), the city remains warmer with a median of 28.2 °C, while rural areas cool down to a median of 25.0 °C (SUHII=4.1°C). Statistical analysis using the Kruskal-Wallis test shows significant temperature differences between the areas during both day ($p=6.392e-08$) and night ($p=0.0001641$). The SUHII is calculated at 5.1 °C during the day and 3.1 °C at night. Further analysis with Dunn's test indicates that most zones have significantly different median temperatures, except for the rural and peri-urban areas at night, where no significant differences are found.

In CABA, the urban heat island effect is more pronounced at night (Fig. 4B). The city's median nighttime temperature is 25.0 °C, compared to 20.9 °C in rural areas, resulting in a SUHII of 4.1 °C. However, during the day (Fig. 4A), temperatures are relatively similar across urban, peri-urban, and rural zones, with medians of 38.7 °C, 38.4 °C, and 37.9 °C,



Figs. 4 Boxplots of daytime (A) and nighttime (B) land surface temperature (LST) for urban, peri-urban, and rural areas in Posadas, Buenos Aires City (CABA), and Neuquén. Mean LST values were

computed for each zone by averaging pixel values during heatwave periods. The red dashed line indicates the mean LST of rural areas, shown as a reference baseline.

respectively. As a result, the Kruskal-Wallis test does not show significant differences in daytime temperatures, but there is a marked difference at night ($p=1.84\text{e-}09$). Dunn's test confirms that nighttime temperatures in all zones are significantly different, emphasizing the pronounced SUHI effect after dark.

In Neuquén, the categorized areas—urban, peri-urban, and rural zones—are further subdivided into valley (irrigated) and plateau (semi-arid) categories. Daytime temperatures (Fig. 4A) show significant variability, with the rural-plateau area reaching the highest median temperature of 43.4 °C, while the rural-valley zone is much cooler at 32.3 °C, and the city has a median of 37.4 °C. At night (Fig. 4B), the city is warmer than the rural-valley area (23.2 °C vs. 20.3 °C), but cooler than the rural-plateau area (23.9 °C). Kruskal-Wallis tests confirm significant differences across all areas for both daytime ($p=2.2\text{e-}16$) and nighttime ($p=4.222\text{e-}05$) temperatures. Dunn's test reveals no significant differences between rural-plateau and peri-urban-plateau areas during the day, nor between these plateau areas and the city at night. Interestingly, during the day, the peri-urban-valley area shows temperatures similar to the city, but at night, it cools down more. The SUHI, comparing the city to the rural-valley areas, is 5.04 °C during the day and 2.1 °C at night. However, when comparing the city to the rural-plateau zone, the SUHI is negative, indicating that the rural plateau is cooler, with values of −6.0 °C during the day and −0.7 °C at night.

When comparing the UHI effects across the three cities, notable differences emerge. Posadas consistently shows the highest temperatures, with daytime urban medians reaching 41.8 °C, followed by Neuquén (38.3 °C) and CABA (38.0 °C), which have relatively similar daytime temperatures. At night, Posadas maintains an urban median of 28.2 °C, while CABA and Neuquén record medians of 25.0 °C and 23.9 °C, respectively. SUHI also varies significantly across cities and between day and night. During the day, Neuquén experiences the strongest UHI effect when compared to its rural valley, with a difference of 5.0 °C, followed closely by Posadas at 5.1 °C. CABA shows negligible SUHI during the day. Neuquén's situation is more complex due to its diverse landscape. When compared to its rural plateau, the city exhibits a negative SUHI of −6 °C during the day, indicating that the semi-arid rural plateau is cooler than the urban area. At night, all cities exhibit positive UHI intensities, with urban areas retaining more heat than their rural counterparts. The most pronounced nighttime UHI effect is observed in CABA, further highlighting the variability of UHI effects between day and night cycles. This comparison underscores the complexity of UHIs and the influence of surrounding geography, particularly in regions with diverse land cover and topography.

Figure 5, 6 and 7 present a comprehensive analysis of the urban heat landscape for each city. These figures are composed of three key elements:

- A boxplot illustrating the Land Surface Temperature (LST) distribution in degrees Celsius (°C) for each LCZ.
- A map displaying the identified Local Climate Zones (LCZs).
- A map showing the spatial distribution of downscaled LSTs across the entire city.

In the boxplot (A), it's important to note that the blue dots represent the average temperatures for each heatwave period used in the analysis. These averages provide insight into the temperature variations across different heatwave events within each LCZ. This multi-faceted visualization allows for a detailed examination of the relationship between urban structure (as represented by LCZs) and temperature patterns during heatwave periods, offering a comprehensive view of each city's thermal characteristics.

The city of Posadas (Fig. 5), with its humid and vegetated climate, presents an interesting pattern: natural categories such as Dense Trees (LCZ 11) with a median temperature of 34.6 °C, Scattered Trees (LCZ 12) with 37.3 °C, and Water (LCZ 17) with 29.8 °C have noticeably lower temperatures compared to urban categories. Despite these lower temperatures, significant differences were found between the means of Water (LCZ 17) and the urban zones Compact Mid-Rise (LCZ 2) at 44.1 °C, Compact Low-Rise (LCZ 3) at 43.5 °C, Open Mid-Rise (LCZ 5) at 43.0 °C, and Open Low-Rise (LCZ 6) at 41.8 °C. Additionally, Dense Trees (LCZ 11) showed significant differences when compared to Compact Mid-Rise (LCZ 2) and Open Mid-Rise (LCZ 5).

Figure 5 shows coherence across all its subfigures, illustrating distinct temperature patterns across the city of Posadas and their relationship with LCZ. Figure 5C, labeled "LST Downscaled", depicts clear contrasts in land surface temperature (LST) during heatwaves. Cooler zones, represented in shades of blue, align with natural areas such as dense and scattered trees (e.g., LCZ 11– Dense Trees and LCZ 12– Scattered Trees), which correspond to lower surface temperatures during extreme heat. The adjacent map (Fig. 5B), showing the LCZ Categories, further emphasizes this, as these vegetated zones are mainly colored green, indicating lower temperatures. In contrast, the red and orange areas seen in both maps, especially within LCZ 2 (Compact Mid-Rise) and LCZ 3 (Compact Low-Rise), show higher temperatures, confirming the findings from the boxplot (Fig. 7A) where these urbanized zones demonstrate median temperatures exceeding 43.0 °C. These visualizations together highlight the temperature disparity between

Fig. 5 Urban heat characteristics and spatial temperature patterns across Posadas (Misiones, Argentina). **(A)** Map showing the geographical distribution of Local Climate Zones (LCZs). **(B)** High-resolution (10 m) land surface temperature (LST) map during heatwave events. **(C)** Box-plot of LST values ($^{\circ}\text{C}$) for each LCZ category. Together, these panels illustrate the relationship between urban morphology and surface temperature under extreme heat conditions

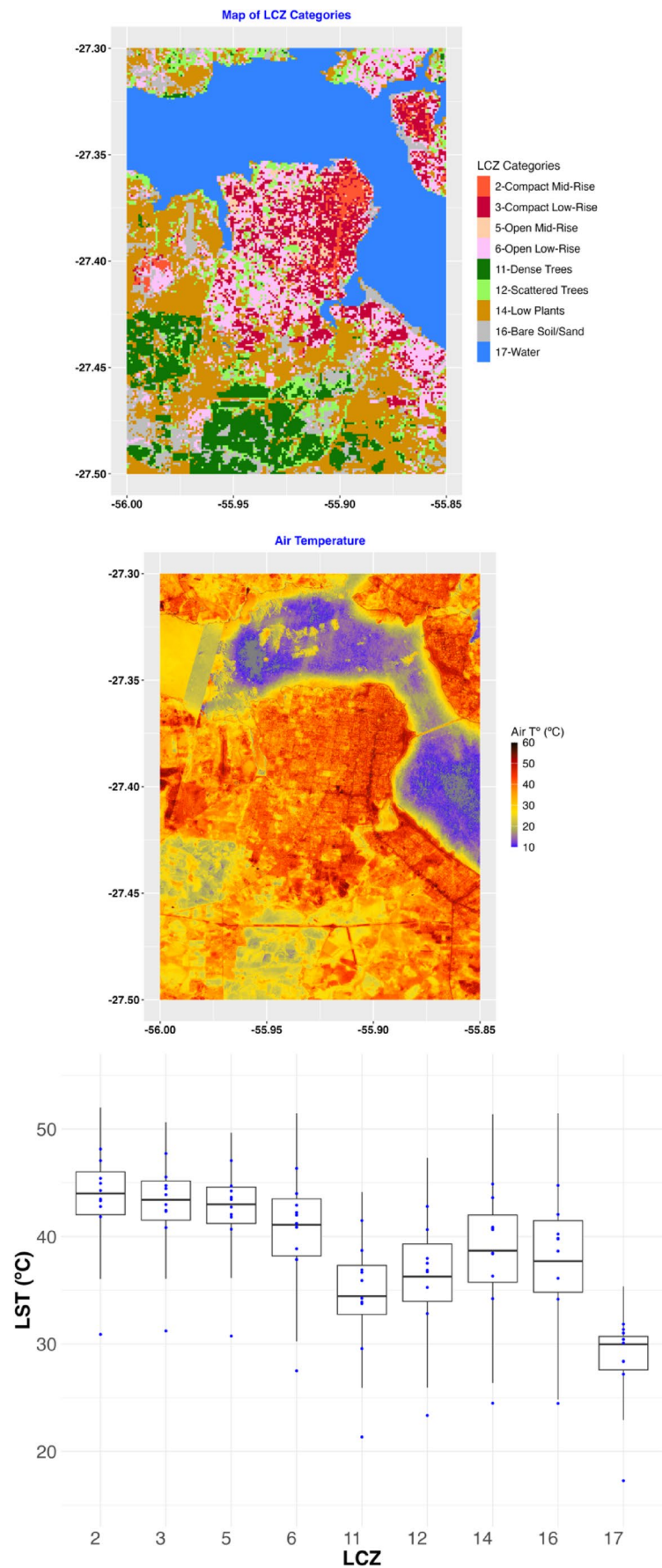


Fig. 6 Urban heat characteristics and spatial temperature patterns across Buenos Aires City: **(A)** Map showing the geographical distribution of Local Climate Zones (LCZs). **(B)** High-resolution (10 m) land surface temperature (LST) map during heatwave events. **(C)** Boxplot of LST values (°C) for each LCZ category. Together, these panels illustrate the relationship between urban morphology and surface temperature under extreme heat conditions

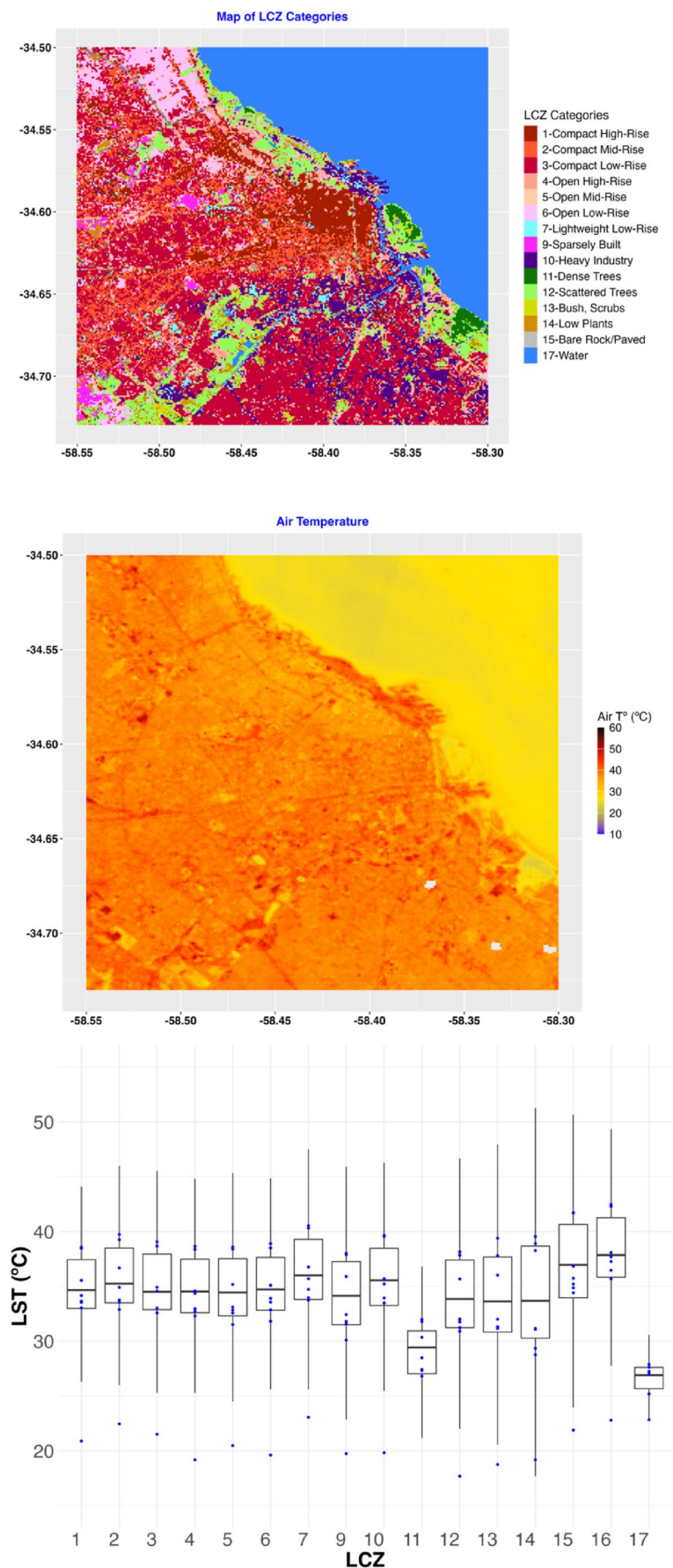
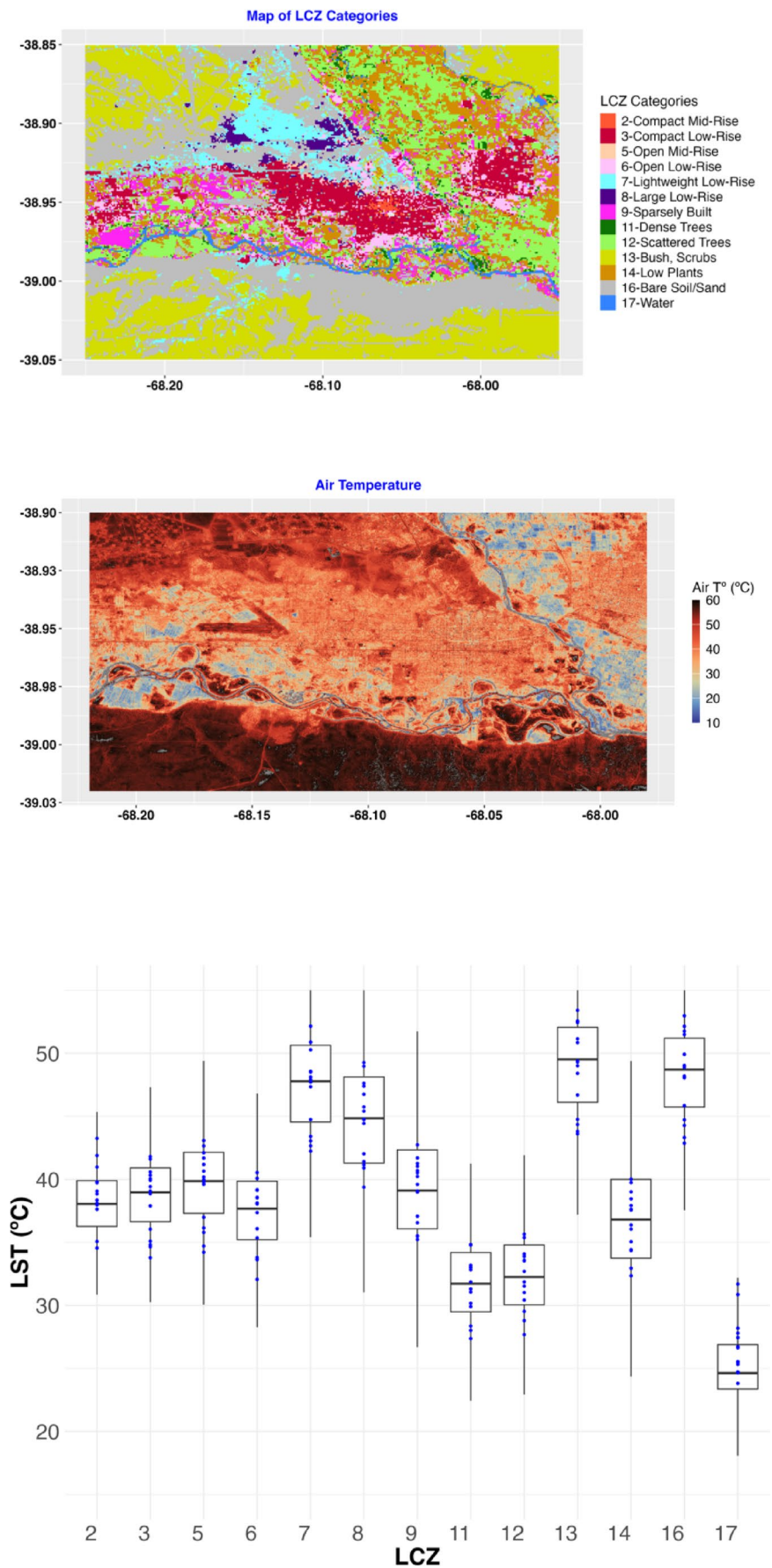


Fig. 7 Urban heat characteristics and spatial temperature patterns across Neuquén (Neuquén, Argentina): **(A)** Map showing the geographical distribution of Local Climate Zones (LCZs). **(B)** High-resolution (10 m) land surface temperature (LST) map during heatwave events. **(C)** Boxplot of LST values ($^{\circ}\text{C}$) for each LCZ category. Together, these panels illustrate the relationship between urban morphology and surface temperature under extreme heat conditions



densely vegetated and heavily urbanized areas in the city of Posadas during heatwave events. It is also worth mentioning the areas with little vegetation cover, such as Bare Soil/Sand (LCZ 16), which exhibit high temperatures, as can be observed in Fig. 5B and C, even though no significant differences were found compared to other categories.

In CABA (Buenos Aires), analyzing the information of Fig. 6, the LCZs corresponding to denser urban areas exhibit the highest temperatures, with median values around 35.9 °C in Lightweight Low-Rise (LCZ 7), 34.4 °C in Compact High-Rise (LCZ 1), 35.2 °C in Compact Mid-Rise (LCZ 2), and 34.6 °C in Open High-Rise (LCZ 4). Elevated temperatures are also observed in Bare Soil/Sand (LCZ 16) with a median of 37.25 °C. In natural areas like Dense Trees (LCZ 11) with 29.2 °C and more open vegetated areas like LCZ 12 with 34.5 °C, there is a significant reduction in temperature, suggesting surface thermal moderation due to vegetation. The Water (LCZ 17) category shows the lowest temperature at 27.3 °C, as expected, since water bodies tend to be cooler. However, in CABA, significant differences were only found between Water (LCZ 17) and LCZ 16, as well as Bare Rock/Paved (LCZ 15) with 36.5 °C, and between LCZ 11 and LCZ 16.

The hottest zones are predominantly located in the southern and western parts of Buenos Aires (Fig. 6C). These areas exhibit temperatures ranging from 38 °C to over 40 °C, appearing in dark red and purple on the map. Specifically, the Southern Industrial Zone, likely corresponding to industrial areas and less vegetated regions, shows the highest temperatures. Western Residential Areas also display large patches of high temperatures, likely due to densely built residential zones with limited green spaces. In contrast, cooler areas are mainly observed in the northern neighborhoods, which generally display lower temperatures, with some areas showing readings below 34 °C. Along the eastern coastline by the Río de la Plata, a narrow strip of cooler temperatures is evident, likely due to the moderating effect of the water body. Scattered cooler spots throughout the city, particularly in the north and center, correspond to parks and other vegetated areas. A clear temperature gradient is visible from east to west and from north to south: temperatures generally increase as one move from the eastern coastline towards the western inland areas. A similar trend is observed from north to south, with the southern regions experiencing significantly higher temperatures than the northern parts of the city.

The city of Neuquén shows greater variability in temperatures across urban categories, but once again, densely urbanized zones (Compact High-Rise and Compact Mid-Rise) have the highest temperatures (Fig. 7). For instance, Compact Mid-Rise (LCZ 2) has a median temperature of 37.8 °C and Compact Low-Rise (LCZ 3) reaches 38.7 °C.

Vegetated areas such as Dense Trees (LCZ 11) display significantly lower temperatures, with a median of 31.8 °C, while semi-arid or sparsely built areas like Bare Rock/Paved (LCZ 15) and Bare Soil/Sand (LCZ 16) exhibit elevated temperatures, with values of 49.7 °C and 47.9 °C, respectively. Significant differences were found between LCZ 17 (Water, 30.9 °C) and various other zones like LCZ 6 (37.8 °C), LCZ 8 (43.8 °C), LCZ 5 (39.8 °C), LCZ 9 (39.3 °C), LCZ 2 (37.8 °C), and LCZ 3 (38.8 °C), highlighting the thermal impact of water areas compared to urbanized zones. Significant differences were also observed between LCZ 11 (dense vegetation, 31.9 °C) and more arid or urban zones like LCZ 13 (49.8 °C), LCZ 16 (47.8 °C), LCZ 7 (46.1 °C), LCZ 8 (43.8 °C), LCZ 5 (39.8 °C), and LCZ 9 (39.3 °C), as well as between LCZ 12 (scattered vegetation, 32.4 °C) and more urban or desert-like zones like LCZ 13, LCZ 16, LCZ 7, and LCZ 8. Other comparisons include contrasts between arid and vegetated areas, such as LCZ 13–14 (36.9 °C), LCZ 14–16, and LCZ 13–9, and differences between various urban and semi-urban zones like LCZ 3–7, LCZ 16–3, and LCZ 2–7, highlighting the thermal variations between natural and built environments.

The map (Fig. 7C) reveals a distinct temperature pattern across the city of Neuquén. In the central urban area, moderately high temperatures are observed, generally ranging from 36 °C to 40.0 °C. These values align with the data reported for Compact Mid-Rise (LCZ 2) and Compact Low-Rise (LCZ 3) zones. The hottest temperatures, exceeding 44 °C, are found in the western and northwestern outskirts of the city. These areas likely correspond to Bare Rock/Paved (LCZ 15, 49.8 °C) and Bare Soil/Sand (LCZ 16) zones, where limited vegetation and arid conditions contribute to the intense heat. Conversely, the coolest areas, with temperatures below 34.0 °C, are located along the rivers in the northern and eastern parts of the city. This matches the Water (LCZ 17) category, which exhibits a median temperature of 30.9 °C, demonstrating the cooling effect of water bodies. The spatial distribution of temperatures also highlights the presence of cooler patches in vegetated areas. Dense Trees (LCZ 11, 31.9 °C) and scattered vegetation (LCZ 12, 32.4 °C) contribute to lower temperatures within the urban fabric, creating distinct thermal contrasts. The urban core, though generally warmer, shows a mix of moderate to high temperatures depending on land use and building density. Meanwhile, the extreme temperature differences between vegetated areas and barren or paved surfaces are clearly visible, emphasizing the cooling influence of vegetation and the heat-retaining properties of bare areas.

4 Discussion

This study explores SUHI effects and LST patterns across multiple Argentine cities and their surrounding environments. Although the primary focus lies on temperature dynamics at the urban scale, it is essential to situate these patterns within the broader climatic context that shapes regional thermal behavior. Large-scale atmospheric phenomena, particularly the El Niño–Southern Oscillation (ENSO), play a significant role in modulating temperature extremes and, by extension, the manifestation of SUHI and LST variations across Argentina. ENSO-related external forcings exert differentiated impacts depending on region and phase, influencing the occurrence and intensity of heatwaves. For instance, El Niño episodes are typically associated with elevated temperatures and intensified heatwaves across central and northern Argentina, characterized by warmer nights and reduced frost events (Rusticucci et al. 2016). Conversely, La Niña events often trigger prolonged droughts and exacerbate heatwave conditions in Patagonia while simultaneously increasing the likelihood of persistent cold spells in other parts of the country (Poveda et al. 2020). Recent findings indicate that El Niño intensifies heatwaves across most of the country except Patagonia, where La Niña has a more pronounced effect (Cimolai and Aguilar 2024). These findings underscore the complex interplay between ENSO phases and Argentina's regional climate, emphasizing the necessity of incorporating broader climatic drivers when interpreting urban thermal patterns.

Beyond natural climate variability, anthropogenic factors—most notably greenhouse gas emissions—substantially contribute to the long-term rise in urban temperatures (Dogar and Sato 2018; Dogar 2019). Among these gases, carbon dioxide (CO₂) is particularly critical, as it drives global warming and elevates the baseline thermal conditions in urban environments. Elevated atmospheric CO₂ levels promote persistent heat retention in densely developed areas, making UHIs especially sensitive to these anthropogenic drivers (Dogar 2019). While episodic phenomena such as volcanic eruptions can also alter atmospheric temperatures through short-term feedbacks (Dogar et al. 2017, 2023, 2024; Dogar and Sato 2019), the persistent effects of human-induced emissions remain a dominant force (Dogar 2019). Moreover, cities serve as concentrated sources of anthropogenic heat, intensifying the UHI effect through a combination of heat-retaining materials, limited vegetation, and high energy consumption. This localized warming becomes particularly acute during heatwaves, compounding health risks and increasing the demand for cooling infrastructure, especially among vulnerable urban populations (Dogar and Sato 2019; Yuan et al. 2022).

Capturing these complex interactions between climate, urban form, and human activity requires a multifaceted approach that leverages diverse remote sensing tools. In this context, the integration of multiple satellite datasets significantly enhances the precision and depth of SUHI and LST analysis (Alvarez-Vanhard et al. 2021). This study applies a combination of high-temporal-resolution MODIS imagery and high-spatial-resolution Landsat 8 data to monitor and quantify heatwave intensity across Posadas, Buenos Aires (CABA), and Neuquén. MODIS data were instrumental in identifying temporal fluctuations in surface temperature during heatwave events, offering near-daily observations of thermal dynamics. Meanwhile, Landsat 8 imagery enabled the estimation of average LST values for each Local Climate Zone (LCZ) within the study areas, allowing for a finer-grained spatial assessment of thermal variability across distinct urban morphologies. To further enhance resolution, Sentinel imagery was employed to downscale Landsat data, producing highly detailed LST distribution maps that capture the intra-urban heterogeneity often missed by coarser datasets. By combining these complementary data sources, the methodology addresses limitations inherent in using a single satellite platform and facilitates a more nuanced and reliable understanding of urban thermal behavior.

Building upon this methodological foundation, a key contribution of the present study lies in its integrated, multi-scale approach—merging the high-temporal frequency of MODIS imagery with the high spatial resolution of Landsat and Sentinel data, all contextualized through the Local Climate Zone (LCZ) framework. This combination not only bridges the temporal-spatial trade-off inherent in remote sensing, but also allows for a nuanced reading of thermal variability across diverse urban morphologies. By capturing both inter-city and intra-city contrasts, the approach moves beyond traditional global-scale SUHI analyses to deliver site-specific, typology-driven insights that are crucial for effective urban climate adaptation.

The analysis of urban heat patterns in Posadas, CABA (Buenos Aires), and Neuquén reveals complex and varied UHI effects, highlighting different levels of risk, hazard, vulnerability, and exposure across these Argentine cities during heatwave events. This variability aligns with the findings of (Kong et al. 2021), who emphasized that heatwaves amplify the intensity and consequences of UHI phenomena. In all three cities, densely built urban areas display a marked accumulation of heat both during the day and at night, a process exacerbated by the low thermal emissivity and poor cooling capacity of urban materials. These effects are particularly visible in areas with limited vegetation and high surface imperviousness, which prevent natural cooling mechanisms from functioning effectively. As noted by Tan et al. (2010), urbanization intensifies SUHI effects globally,

with urban areas facing more frequent and prolonged hot days compared to adjacent rural regions. Urban morphology, including building density and street orientation, plays a key role, shaping the absorption, reflection, and release of solar radiation within the urban canopy layer and thereby determining the extent of UHI formation.

Among the three cities, Posadas displays the most pronounced spatial thermal gradients during heatwaves, with the urban core consistently recording the highest temperatures both day and night. The calculated SUHI intensity (SUHI) reaches 4.33 °C during the day and 2.67 °C at night, reflecting a stark contrast with the surrounding rural and peri-urban zones. This pattern is driven in part by the dense vegetation and high soil moisture content found outside the city, typical of the region's humid subtropical climate. These findings support Peng et al.'s (2012), who demonstrated a strong negative correlation between SUHI intensity and vegetation cover, confirming that green areas exert a crucial cooling influence. Buenos Aires, by contrast, exhibits a unique profile characterized by a strong nocturnal SUHI effect (4.4 °C), with limited daytime temperature differences between urban and surrounding areas. This thermal uniformity during the day is likely a consequence of reduced vegetation and sealed surfaces in peri-urban regions, which undermines the typical rural cooling advantage. The persistence of high night-time temperatures in Buenos Aires, consistent with the thermal inertia described by Oke (1982) and Santamouris et al. (2007), presents critical health implications, particularly during extended heatwave events when nighttime recovery becomes vital.

Neuquén presents the most complex and spatially variable UHI dynamics due to its unique topography and land use patterns. During the day, the urban center is cooler than the adjacent rural plateau, resulting in a negative SUHI of −7.2 °C, but warmer than the valley areas, producing a positive SUHI of 5.3 °C. At night, this relationship reverses slightly, with SUHI values of −0.1 °C for the plateau and 3.3 °C for the valley. This dual pattern reveals that Neuquén's exposure to heat hazards varies considerably based on topographic context, creating a mosaic of thermal conditions within and around the city. The negative SUHI relative to the plateau is likely driven by the semi-arid, vegetation-sparse nature of the surrounding highlands, whereas the positive SUHI compared to the cooler, vegetated valleys underscore the importance of microclimates in modulating urban temperature profiles. These contrasting dynamics highlight both the opportunities and challenges for climate-sensitive urban planning in Neuquén. Enhancing green infrastructure, promoting ventilation corridors, and adapting design strategies to local topography are key to mitigating heat stress in this spatially heterogeneous setting.

The strong temperature contrasts observed across LCZs in all three cities further highlight the critical role of vegetation and natural land cover in mitigating urban heat. In Posadas, for instance, areas classified as Dense Trees (LCZ 11) and Water (LCZ 17) consistently exhibited significantly lower surface temperatures compared to built-up zones such as Compact Mid-Rise (LCZ 2) and Compact Low-Rise (LCZ 3). These patterns are consistent with findings from Gunawardena et al. (2017), who emphasize that vegetated surfaces reduce heat through both shading and evapotranspiration, and that the effectiveness of this cooling varies by vegetation structure and spatial scale. Larger vegetated zones not only cool their immediate surroundings but can also extend their influence into nearby urban areas through park-breeze effects—an observation particularly relevant to the cooler pockets found in the north of Buenos Aires and along the riverbanks in Neuquén. The results from Neuquén, where LCZ 11 (Dense Trees) and LCZ 12 (Scattered Trees) were up to 17 °C cooler than LCZs dominated by bare soil or paved surfaces, underscore the dramatic impact that land cover type has on surface temperature.

These thermal differences also reflect broader issues of spatial inequality and access to cooling resources within cities. In Buenos Aires, the hottest zones identified during heatwaves often correspond to the southern and western sectors of the city, which are characterized by high building density, limited vegetation, and, in many cases, informal urban development. This spatial pattern supports findings by Chakraborty et al. (2019) who demonstrated that exposure to urban heat tends to be higher in lower-income neighborhoods with less access to green infrastructure. As noted by Norton et al. (2015) green spaces not only offer cooling benefits but also improve environmental justice by reducing thermal vulnerability in disadvantaged areas. Ensuring equitable distribution of vegetated areas should therefore be a key priority in urban heat mitigation strategies. Moreover, empirical evidence supports the effectiveness of green infrastructure—such as green roofs and urban vegetation—in significantly reducing surface temperatures, as demonstrated in previous studies (Bowler et al. 2010; Wong et al. 2021), and reflected in the temperature differentials across LCZs observed in this study.

The distinct UHI patterns observed in the studied cities also reflect broader geographic and climatic interactions that extend beyond urban form alone. As noted by Oke et al. (2017), rural–urban temperature contrasts are strongly shaped by regional land cover and soil conditions. This is particularly evident in Neuquén, where the thermal inversion between the cooler rural valley and the hotter rural plateau illustrates the influence of topography, vegetation, and soil moisture on surface temperature dynamics. In semi-arid regions like northern Patagonia, eroded and sparsely

vegetated plateau soils exhibit limited cooling capacity, while irrigated valleys with dense vegetation retain cooler temperatures, creating localized thermal gradients. These findings align with the global trends reported by Li and Chen (2023), who observed that daytime SUHI tends to decrease during heatwaves in arid and equatorial regions, while nighttime SUHI increases across most climate zones due to reduced radiative cooling. Additionally, the SUHI intensities recorded in Posadas (4.33 °C during the day and 2.67 °C at night) and Buenos Aires (4.4 °C at night) exceed the global average SUHI of $1.3 \text{ °C} \pm 0.8 \text{ °C}$ reported by Peng et al. (2012) for 419 cities. This discrepancy may be explained by the focus on heatwave conditions in this study, as well as the use of high-resolution thermal imagery and LCZ classification, which allow for a more precise identification of intra-urban thermal differences. These results underscore the importance of context-sensitive approaches in UHI research and the need to account for local climatic and geographic factors when interpreting urban thermal patterns.

In this context, urban structure and air pollution emerge as key variables influencing LST variability and intensifying UHI effects. Dense, compact urban forms, such as those classified as LCZ 2 (Compact Mid-Rise) and LCZ 3 (Compact Low-Rise), exhibit heightened thermal retention, especially during prolonged heatwave events (Oke et al. 2017). In contrast, vegetated zones such as LCZs 11–14 and water-dominated zones like LCZ 17 show markedly lower temperatures due to their capacity for evaporative cooling and shading. These patterns align with Peng et al. (2012), reinforcing the inverse relationship between vegetation presence and SUHI intensity. Achieving a balance between built density and natural green space is critical, particularly in fast-growing peri-urban zones, where unregulated expansion can exacerbate thermal vulnerability (Tahir et al. 2025).

The interaction between urban geometry, pollution, and heat further complicates mitigation efforts. While compact cities are generally more energy-efficient in building performance, intermediate densities combined with optimized geometrical layouts offer superior outcomes in terms of outdoor thermal comfort and public health (Martilli 2014). According to, Liang et al. (2021), non-optimal urban configurations can increase nighttime SUHI by up to 1.23 °C, with 23% of this increase attributable to elevated air pollution. Air pollutants not only trap heat but also enhance longwave radiation absorption, contributing to additional surface warming of up to $0.70 \pm 0.26 \text{ °C}$ at night (Cao et al. 2016). These effects are particularly intense in urban areas where pollutant concentrations are high, and atmospheric conditions favor longwave radiation entrapment—surpassing even the warming effects of water vapor and other greenhouse gases (Cao et al. 2016; Jacobson et al. 2019).

Urban morphology plays a critical role in shaping these dynamics. Liang et al. (2021) advocate for proper elongation and decentralization of urban forms while avoiding disorderly sprawl to mitigate these effects. In contrast, disordered urban sprawl or overly continuous construction can trap heat and pollutants, intensifying thermal discomfort. Informal settlements—such as those classified as LCZ 7 (Light-weight Low-Rise) in Buenos Aires or rapidly expanding peri-urban areas in Neuquén—face a dual burden: elevated temperatures due to low-quality construction materials and limited adaptation capacity due to socio-economic vulnerabilities (Hutchings et al. 2022b). These areas are especially at risk during extreme heat events, where lack of access to cooling infrastructure, green space, and emergency services heightens exposure and limits resilience.

Green infrastructure offers a powerful solution to counteract both UHI effects and air pollution. Wong et al. (2021) demonstrate that green roofs, walls, and ground-level greenery can reduce peak surface temperatures by up to 17 °C through shading and evapotranspiration. Vegetation further facilitates evapotranspiration, converting solar energy into water vapor and replacing sensible heat with latent heat, thereby lowering surface temperatures and reducing long-wave emissions (Takebayashi and Moriyama 2007). Large contiguous green spaces are particularly effective in mitigating urban overheating by creating significant microclimatic cooling effects that extend beyond their boundaries.

These findings reaffirm that mitigating extreme urban heat requires strategies tailored to the physical, climatic, and social characteristics of each city. Within this framework, the methodological approach adopted in this study stands out as one of its main strengths: the integration of multi-scale satellite data (MODIS, Landsat 8, and Sentinel) with the LCZ classification enabled a high-resolution assessment of intra-urban thermal variability during extreme heat events. This combination not only enhances the spatial and temporal accuracy of SUHI analysis but also provides a replicable framework applicable to other urban environments, including those with limited technical or institutional resources. Its implementation is particularly valuable in intermediate and peripheral cities across the Global South, where conventional meteorological data are often scarce, and the impacts of climate change are unevenly distributed. Moreover, the use of the LCZ framework allows for standardized comparisons between cities with distinct urban morphologies, facilitating the identification of typologies that are more vulnerable to overheating. In this sense, studies like this not only deepen the understanding of SUHI phenomena but also offer an operational tool for climate-informed urban planning. Strengthening this line of research can play a critical role in shaping public policies aimed at

thermal resilience and environmental justice across diverse urban contexts.

5 Conclusion

This study enhances the understanding of LST variations in urban and peri-urban areas by integrating spatial analysis tools to identify regions most vulnerable to heatwaves. The findings underscore the significance of urban planning strategies that incorporate green infrastructure, optimize land use, and balance urban density with natural spaces to mitigate the UHI effect. Notably, densely built environments exhibit persistent heat retention, intensifying both daytime and nighttime temperatures, whereas areas with substantial vegetation cover demonstrate lower LST due to the cooling effects of shading and evapotranspiration. The integration of LCZs into the analysis allowed for fine-grained insights into how specific urban forms and land covers influence thermal behavior, reinforcing the importance of typology-based approaches to heat mitigation.

A critical concern identified is the heightened vulnerability of rapidly expanding peri-urban zones, where unplanned urbanization, limited vegetation, and inadequate infrastructure exacerbate exposure to extreme heat. These conditions amplify health risks, particularly for socioeconomically disadvantaged populations residing in informal settlements. This study reaffirms that the unequal spatial distribution of green infrastructure contributes to disproportionate heat exposure, a pattern previously observed in other urban contexts and confirmed here through the clear temperature disparities between vegetated and built-up LCZs. Addressing this imbalance is essential for promoting climate justice and reducing urban vulnerability to heatwaves.

Furthermore, the study highlights the diverse spatial manifestations of the surface UHI effect across cities with distinct climatic and geographic conditions, demonstrating the need for tailored, location-specific mitigation strategies. The role of vegetated areas—ranging from isolated trees to large contiguous parks—emerges as fundamental in modulating local temperatures at multiple scales. As previous research has shown, well-distributed green infrastructure not only reduces surface heat but also produces broader microclimatic effects such as the “park-breeze,” extending thermal benefits beyond vegetated areas themselves.

Beyond its empirical findings, this study also contributes methodologically by demonstrating the potential of combining multi-source satellite imagery (MODIS, Landsat 8, Sentinel-2) with the LCZ classification system to analyze urban thermal dynamics at high spatial and temporal resolution. This integrated approach offers a scalable and transferable framework that can support similar analyses in a wide range

of urban and peri-urban contexts. Its adaptability is particularly relevant for cities in data-scarce regions, where access to ground-based climate monitoring is limited. In such settings, the methodology provides a practical and replicable tool for assessing SUHI intensity and informing context-specific urban climate adaptation strategies.

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Declarations

Competing Interests The authors declare that they have no financial interests that could have influenced the work reported in this study. The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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References

- Al-Saadi LM, Jaber SH, Al-Jiboori MH (2020) Variation of urban vegetation cover and its impact on minimum and maximum heat islands. *Urban Clim* 34:100707
- Alvarez-Vanhard E, Corpetti T, Houet T (2021) UAV & satellite synergies for optical remote sensing applications: A literature review. *Sci Remote Sens* 3:100019. <https://doi.org/10.1016/J.SRS.2021.100019>
- Anjos M, Targino AC, Krecl P et al (2020) Analysis of the urban heat Island under different synoptic patterns using local climate zones. *Build Environ* 185. <https://doi.org/10.1016/j.buildenv.2020.107268>

- Beck HE, Zimmermann NE, McVicar TR et al (2018) Present and future köppen-geiger climate classification maps at 1-km resolution. <https://doi.org/10.1038/sdata.2018.214>. *Sci Data* 5:
- Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plan* 97:147–155
- Cao C, Lee X, Liu S et al (2016) Urban heat Islands in China enhanced by haze pollution. *Nat Commun* 7. <https://doi.org/10.1038/ncomms12509>
- Chakraborty T, Hsu A, Manya D, Sheriff G (2019) Disproportionately higher exposure to urban heat in lower-income neighborhoods: A multi-city perspective. *Environ Res Lett* 14(10):105003
- Cheng X, Su H (2010) Effects of Climatic temperature stress on cardiovascular diseases. *Eur J Intern Med* 21:164–167
- Cimolai C, Aguilar E (2024) Assessing argentina's heatwave dynamics (1950–2022): a comprehensive analysis of Temporal and Spatial variability using ERA5-LAND. *Theor Appl Climatol* 155:4925–4940. <https://doi.org/10.1007/s00704-024-04915-9>
- Demuzere M, Kittner J, Bechtel B (2021) LCZ generator: A web application to create local climate zone maps. *Front Environ Sci* 9. <https://doi.org/10.3389/fenvs.2021.637455>
- Dodman D, Hayward B, Pelling M, Castan Broto V, Chow W, Chu E, Dawson R, Khirfan L, McPhearson T, Prakash A, Zheng Y, Ziervogel G (2022) Cities, Settlements and Key Infrastructure. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 907–1040. <https://doi.org/10.1017/9781009325844.008>
- Dogar MM (2019) The sensitivity of DTR to the increased CO₂ over Mid-latitude Semi-dry regions item type Article JOJ horticulture the sensitivity of DTR to the increased CO₂ over Mid-latitude Semi-dry regions
- Dogar MM, Stenchikov G, Osipov S et al (2017) Sensitivity of the regional climate in the middle East and North Africa to volcanic perturbations. *J Geophys Res* 122:7922–7948. <https://doi.org/10.1002/2017JD026783>
- Dogar MM, Hermanson L, Scaife AA et al (2023) A review of El Niño Southern Oscillation linkage to strong volcanic eruptions and Post-Volcanic winter warming. *Earth Syst Environ* 7:15–42
- Dogar MM, Fujiwara M, Zhao M et al (2024) ENSO and NAO linkage to strong volcanism and associated Post-Volcanic High-Latitude winter warming. *Geophys Res Lett* 51. <https://doi.org/10.1029/2023GL106114>
- Dogar MM, Sato T (2019) Regional climate response of middle eastern, african, and South Asian monsoon regions to explosive volcanism and ENSO forcing. *J Geophys Research: Atmos* 124:7580–7598. <https://doi.org/10.1029/2019JD030358>
- Dogar MM, Sato T (2018) Analysis of climate trends and leading modes of climate variability for MENA region. *J Geophys Research: Atmos* 123:13,074–13,091. <https://doi.org/10.1029/2018JD029003>
- European Space Agency Sentinel-2 Copernicus Data Space Ecosystem. <https://dataspace.copernicus.eu/explore-data/data-collection/sentinel-data/sentinel-2>. Accessed 4 Nov 2024
- GADM (2023) Database of Global Administrative Areas (Version 4.1)
- Gunawardena KR, Wells MJ, Kershaw T (2017) Utilising green and Bluespace to mitigate urban heat Island intensity. *Sci Total Environ* 584–585:1040–1055. <https://doi.org/10.1016/j.scitotenv.2017.01.158>
- Google Earth Engine Catalog <https://developers.google.com/earth-engine/datasets/catalog>
- Google Earth <https://earth.google.com/web/>. Accessed 4 Nov 2024b
- Linares C, Diaz J, Tobías A et al (2015) Impact of heat and cold waves on circulatory-cause and respiratory-cause mortality in Spain: 1975–2008. *Stoch Env Res Risk Assess* 29:2037–2046. <https://doi.org/10.1007/s00477-014-0976-2>
- Liang Z, Huang J, Wang Y et al (2021) The mediating effect of air pollution in the impacts of urban form on nighttime urban heat Island intensity. *Sustain Cities Soc* 74. <https://doi.org/10.1016/j.scs.2021.102985>
- Huang S, Tang L, Hupy JP et al (2021) A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *J Forest Res* 32(1):1–6
- Heaviside C, Macintyre H, Vardoulakis S (2017) The urban heat island: implications for health in a changing environment. *Curr Environ Health Rep* 4:296–305
- Hutchings P, Willcock S, Lynch K et al (2022a) Understanding rural–urban transitions in the global South through peri-urban turbulence. *Nat Sustain* 5:924–930. <https://doi.org/10.1038/s41893-022-00920-w>
- Hutchings P, Willcock S, Lynch K et al (2022b) Understanding rural–urban transitions in the global South through peri-urban turbulence. *Nat Sustain* 5:924–930. <https://doi.org/10.1038/s41893-022-00920-w>
- Jacobson MZ, Nghiem SV, Sorichetta A (2019) Short-Term impacts of the megaurbanizations of new Delhi and Los Angeles between 2000 and 2009. *J Geophys Research: Atmos* 124:35–56. <https://doi.org/10.1029/2018JD029310>
- Ke X, Men H, Zhou T et al (2021) Variance of the impact of urban green space on the urban heat Island effect among different urban functional zones: A case study in Wuhan. *Urban For Urban Green*
- Kong J, Zhao Y, Carmeliet J, Lei C (2021) Urban heat Island and its interaction with heatwaves: A review of studies on mesoscale. *Sustain (Switzerland)* 13. <https://doi.org/10.3390/su131910923>
- Li K, Chen Y (2023) Characterizing the indicator-based, day-and-night, and climate-based variations in response of surface urban heat Island during heat wave across global 561 cities. *Sustain Cities Soc* 99. <https://doi.org/10.1016/j.scs.2023.104877>
- Liu L, Zhang W (2024) Contrary to expectation: the surface urban heat Island intensity is increasing in population shrinking region while decreasing in population growing region-A comparative analysis from China. *PLoS ONE* 19. <https://doi.org/10.1371/journal.pone.0300635>
- Martilli A (2014) An idealized study of City structure, urban climate, energy consumption, and air quality. *Urban Clim* 10:430–446. <https://doi.org/10.1016/j.uclim.2014.03.003>
- Milošević D, Savić S, Kresoja M et al (2058) Analysis of air temperature dynamics in the local climate zones of Novi sad (Serbia) based on long-term database from an urban meteorological network. <https://doi.org/10.1007/s00484-020-02058-w> Published Natural Earth. (n.d.). Natural Earth: Free vector and raster map data at 1:10m, 1:50m, and 1:110m scales. Retrieved June 27, 2025. <https://www.naturalearthdata.com/>
- Norton BA, Coutts AM, Livesley SJ et al (2015) Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc Urban Plan* 134:127–138. <https://doi.org/10.1016/j.landurbplan.2014.10.018>
- OECD/European Commission (2020), *Cities in the World: A New Perspective on Urbanisation*, OECD Urban Studies, OECD Publishing, Paris. <https://doi.org/10.1787/d0efc6baen>
- Onačillová K, Gallay M, Paluba D et al (2022) Combining landsat 8 and Sentinel-2 data in Google Earth engine to derive higher resolution land surface temperature maps in urban environment. *Remote Sens (Basel)* 14. <https://doi.org/10.3390/rs14164076>
- Oke TR, Mills G, Christen A, Voogt JA (2017) *Urban climates*. Cambridge University Press
- Oke TR (1982) *The energetic basis of the urban heat island*

- Peng J, Qiao R, Wang Q et al (2024) Diversified evolutionary patterns of surface urban heat Island in new expansion areas of 31 Chinese cities. <https://doi.org/10.1038/s42949-024-00152-1>. npj Urban Sustainability 4:
- Peng S, Piao S, Ciais P et al (2012) Surface urban heat Island across 419 global big cities. *Environ Sci Technol* 46:696–703. <https://doi.org/10.1021/es2030438>
- Poveda G, Espinoza JC, Zuluaga MD, Solman SA, Garreaud R, Van Oevelen PJ (2020) High impact weather events in the Andes. *Front Earth Sci* 8:162
- Revi A, Satterthwaite D, Aragón-Durand F, Corfee-Morlot J, Kiunsi RBR, Pelling M, Roberts D, Solecki W, Gajjar SP, Sverdlík A (2014) Towards transformative adaptation incities: the IPCC's Fifth Assessment. *Environ Urban* 26(1):11–28. <https://doi.org/10.1177/0956247814523539> (Original work published 2014)
- Rusticucci M, Kysely J, Almeida G, Lhotka O (2016) Long-term variability of heatwaves in Argentina and recurrence probability of the severe 2008 heat wave in Buenos Aires. *Theor Appl Clim* 124:679–689
- Satterthwaite D, Archer D, Colenbrander S, Dodman D, Hardoy J, Mitlin D, Patel S (2020) Building resilience to climate change in informal settlements. *One Earth* 2(2):143–156
- Takebayashi H, Moriyama M (2007) Surface heat budget on green roof and high reflection roof for mitigation of urban heat Island. *Build Environ* 42:2971–2979. <https://doi.org/10.1016/j.buildenv.2006.06.017>
- Tahir Z, Haseeb M, Mahmood SA et al (2025) From green to grey: assessing the impact of urbanization on land surface temperature and thermal comfort in Multan City. *Earth Syst Environ*. <https://doi.org/10.1007/s41748-025-00598-y>
- Tan J, Zheng Y, Tang X et al (2010) The urban heat Island and its impact on heat waves and human health in Shanghai. *Int J Biometeorol* 54:75–84. <https://doi.org/10.1007/s00484-009-0256-x>
- Tzavali A, Paravantis JP, Mihalakakou G et al (2015) Heat Island phenomenon and cool roofs mitigation strategies in a small City of elevated temperatures. *Fresenius Environ Bull* 8:55–62
- Šalkovič M, Paudítšová E (2023) Use of satellite images to determine the temperature of urban surfaces for landscape management purposes, case study Bratislava (Slovak Republic). *Land (Basel)* 12. <https://doi.org/10.3390/land12020384>
- Santamouris M, Pavlou K, Synnefa A et al (2007) Recent progress on passive cooling techniques: advanced technological developments to improve survivability levels in low-income households. *Energy Build* 39:859–866. <https://doi.org/10.1016/J.ENBUILD.2007.02.008>
- Singh P, Verma P, Chaudhuri AS et al (2024) Evaluating the relationship between urban heat Island and Temporal change in land use, NDVI and NDBI: a case study of Bhopal city, India. *Int J Environ Sci Technol* 21:3061–3072. <https://doi.org/10.1007/s13762-023-05141-y>
- Silveira IH, Oliveira BFA, Cortes TR, Junger WL (2019) The effect of ambient temperature on cardiovascular mortality in 27 Brazilian cities. *Sci Total Environ* 691:996–1004. <https://doi.org/10.1016/j.scitotenv.2019.06.493>
- Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. *Bull Am Meteorol Soc* 93:1879–1900. <https://doi.org/10.1175/BAMS-D-11-00019.1>
- U.S. Geological Survey (2019) Landsat 8 (L8) Data Users Handbook. Version 5.0
- Voogt JA, Oke TR (2003) Thermal remote sensing of urban climates. *Remote Sens Environ*. [https://doi.org/10.1016/S0034-4257\(03\)0079-8](https://doi.org/10.1016/S0034-4257(03)0079-8)
- Wong NH, Tan CL, Kolokotsa DD, Takebayashi H (2021) Greenery as a mitigation and adaptation strategy to urban heat. *Nat Rev Earth Environ* 2:166–181
- Xia H, Chen Y, Song C et al (2022) Analysis of surface urban heat Islands based on local climate zones via Spatiotemporally enhanced land surface temperature. *Remote Sens Environ* 273. <https://doi.org/10.1016/j.rse.2022.112972>
- Yang M, Ren C, Wang H et al (2024) Mitigating urban heat Island through neighboring rural land cover. *Nat Cities* 1:522–532. <https://doi.org/10.1038/s44284-024-00091-z>
- Yang Z, Witharana C, Hurd J et al (2020) Using Landsat 8 data to compare percent impervious surface area and normalized difference vegetation index as indicators of urban heat Island effects in connecticut, USA. *Environ Earth Sci* 79. <https://doi.org/10.1007/s12665-020-09159-0>
- Yuan Y, Li C, Geng X et al (2022) Natural-anthropogenic environment interactively causes the surface urban heat Island intensity variations in global climate zones. *Environ Int* 170:107574. <https://doi.org/10.1016/J.ENVINT.2022.107574>
- Zhao C, Jensen JLR, Weng Q et al (2020) Use of local climate zones to investigate surface urban heat Islands in Texas. *GISci Remote Sens* 57:1083–1101. <https://doi.org/10.1080/15481603.2020.1843869>
- Zheng Y, Ren C, Shi Y et al (2023) Mapping the Spatial distribution of nocturnal urban heat Island based on local climate zone framework. *Build Environ* 234. <https://doi.org/10.1016/j.buildenv.2023.110197>
- Zhou D, Xiao J, Bonafoni S et al (2019) Satellite remote sensing of surface urban heat islands: progress, challenges, and perspectives. *Remote Sens* 11(1):48

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