

Original Research

COMBINED METEOROLOGICAL MEASUREMENTS OF URBAN AND RURAL THERMAL ENVIRONMENTS IN BELGRADE

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Abstract

Urbanization and climate change jointly intensify local thermal environments, leading to pronounced urban heat island (UHI) effects that impact environmental quality, human health, and energy demand. This study investigates urban microclimate variability through a comparative analysis of urban and rural temperature regimes using a combination of unmanned aerial vehicle (UAV)-based thermal imaging and ground-based meteorological measurement data. The research was conducted in and around Belgrade, where representative urban and rural sites were selected to capture contrasting land surface characteristics. UAV thermal surveys provided high-resolution spatial data on surface temperature distribution. The urban heat island intensity was quantified as the temperature difference between urban and rural environments. Preliminary results indicate a consistent positive temperature anomaly in urban areas, with the strongest UHI intensity observed during summer months and nighttime due to heat retention by built surfaces. Spatial analysis reveals significant heterogeneity within the urban environment, with green spaces exhibiting localized cooling effects. The findings highlight the importance of integrating remote sensing and in situ measurements to improve the understanding of urban climate dynamics under changing climatic conditions. This study contributes to ongoing research on urban climate adaptation by providing a scalable methodological framework and empirical evidence relevant for sustainable urban planning, environmental monitoring and aviation weather forecasting and operational safety.

Keywords: urban heat island (UHI), UAV thermal imaging, land surface temperature (LST), environmental monitoring, aviation safety.

INTRODUCTION

Rapid urbanization and global climate change are increasingly recognized as interacting drivers of environmental transformation, particularly at the local scale [1,2]. Urban areas alter the natural surface energy balance through modifications in land cover, surface albedo, and anthropogenic heat release, leading to the formation of the urban heat island (UHI) effect [3]. This phenomenon, characterized by higher temperatures in urban areas compared to their rural surroundings, has important implications for thermal comfort, air quality, and public health [4]. In recent decades, the interaction between climate change and urbanization has intensified, with rising background temperatures contributing to stronger and more persistent UHI effects [2,5], thereby increasing the frequency and severity of heat extremes in cities.

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Understanding urban microclimate variability is therefore essential for developing effective mitigation and adaptation strategies. However, conventional meteorological observations, typically based on sparse ground-based stations, often fail to capture the spatial complexity and fine-scale variability of urban thermal environments [6]. In response to these limitations, remote sensing approaches, particularly those based on unmanned aerial vehicles (UAVs), have emerged as powerful tools for high-resolution monitoring of surface temperature and land-atmosphere interactions [7]. UAV-based thermal imaging enables detailed mapping of spatial temperature patterns, providing valuable insights into intra-urban variability and complementing traditional in situ measurements.

Previous studies conducted in Belgrade have confirmed the presence of a significant urban heat island and highlighted its seasonal variability, as well as its impact on thermal comfort and urban living conditions [8,9]. These findings emphasize the importance of localized studies that integrate advanced measurement techniques with conventional observations. In this context, the present study aims to investigate urban microclimate variability under climate change conditions by integrating UAV-derived thermal data with ground-based meteorological observations. The specific objectives are: 1) to quantify temperature differences between urban and rural environments, 2) to analyze the temporal variability of UHI intensity, and 3) to assess the spatial distribution of thermal anomalies within urban areas.

By focusing on a representative case study in Belgrade, this research contributes to a better understanding of the local expression of global climate processes and demonstrates the applicability of combined measurement approaches in urban climate analysis.

MATERIALS AND METHODS

Study Area

The study was conducted along urban-rural transect in the vicinity of Belgrade, a metropolitan area characterized by pronounced urban heat island effects. The urban site was located in the New Belgrade municipality, representing a densely built environment with extensive impervious surfaces, high building density, and limited vegetation cover. Such characteristics contribute to increased heat storage and reduced nocturnal cooling. For comparison, the rural site was selected in the Surčin-Dobanovci agricultural zone, approximately 20 km west of the city center. This area is characterized by open land, natural vegetation, and minimal anthropogenic influence, providing a representative reference for background climatic conditions. The selected sites are situated within the same regional climate zone, ensuring comparable synoptic meteorological conditions while preserving distinct differences in land surface properties. This spatial configuration allows for reliable assessment of urban–rural thermal contrasts and urban heat island intensity.

Data Collection

UAV-Based Thermal Measurements

Thermal data were acquired using a UAV platform equipped with a calibrated infrared thermal camera and a high-precision air temperature sensor [10,11]. UAV platform was also equipped with RGB camera for surface classification. The system was configured with GNSS-based positioning (accuracy ~1–2 m) to ensure precise georeferencing of all

measurements, while onboard data logging and real-time telemetry enabled continuous monitoring and synchronization of spatial and thermal data. Flights were conducted under stable weather conditions at three key periods of the day: morning (06:00–09:00), midday (12:00–15:00), and nighttime (18:00–21:00), from 12 to 19 July 2024. Mission planning was performed using predefined autonomous flight paths to ensure repeatability across all observation periods. Flight altitude ranged between 50 and 120 m above ground level, with speed adjusted according to measurement objectives, allowing both stable hovering and controlled transect sampling. The UAV demonstrated stable flight performance with an average endurance of 25–35 minutes per mission. The sensor payload (~1–1.5 kg) was optimized for energy efficiency and measurement accuracy. Thermal images were processed using photogrammetric techniques to generate georeferenced orthomosaics representing spatial surface temperature distribution. These datasets enabled the identification of localized thermal hotspots and cooling zones, particularly distinguishing between impervious urban surfaces and vegetated areas. The integration of UAV system parameters ensured high spatial and temporal resolution, supporting detailed analysis of urban microclimate variability. The diurnal LST data have been collected in mid-July 2024 (12–19 July) on a clear days and mean land surface temperature values are calculated. UAV-derived Land Surface Temperature (LST) was compared with ground-based air temperature (T_a) observations from the Republic Hydrometeorological Service of Serbia (RHMZ) stations at Belgrade Observatory and Surčin Airport to evaluate urban–rural thermal variability, acknowledging the physical differences between surface and atmospheric temperature measurements (RHMZ, 2024) [12].

Ground-Based Measurements data

Ground-based meteorological measurements data are provided for both the urban and rural sites within the Belgrade transect in Belgrade, ensuring direct comparability under identical synoptic conditions [10,11]. Meteorological data used for the urban–rural temperature comparison were derived from high-resolution gridded climate datasets (e.g., MeteoSerbia1km and ERA5 reanalysis) [12–14]. Urban conditions were represented by grid cells corresponding to the central Belgrade metropolitan area, while rural conditions were defined using surrounding low-density and predominantly vegetated regions with minimal anthropogenic influence. Daily temperature values were aggregated to monthly means in order to reduce short-term variability and ensure climatic representativeness. The urban heat island (UHI) intensity was calculated as the difference between urban and rural mean temperatures (Equation 1):

$$\Delta T = T_{\text{urban}} - T_{\text{rural}} \quad (1)$$

This methodology ensures spatial consistency and enables comparison under homogeneous synoptic-scale atmospheric conditions. These measurement data were used to validate UAV-derived air temperature profiles and to quantify differences between surface and near-surface atmospheric conditions. Additionally, ground observations provided baseline conditions for assessing urban heat island intensity and for correcting potential radiative and environmental biases in UAV thermal data. The combined use of ground-based and UAV measurements data ensured robust cross-validation of datasets and improved the reliability of spatial temperature mapping across heterogeneous urban and rural environments.

Urban Heat Island Intensity Calculation

Urban Heat Island (UHI) is generally described as a higher average air temperature in cities compared to their less urbanized surrounding areas. Many factors influence the UHI intensity, including local and synoptic weather, season, time of the day, size of the city and its geographical location, urban morphology and anthropogenic heat release. It is well known that the UHI intensity is strong on clear and windless nights and exhibits diurnal and seasonal variations [15]. The examination of UHI can be very important in many fields of climatology and connected scientific disciplines.

Data Analysis

The collected data were analyzed using statistical and spatial methods: Monthly Mean air temperature values in urban and rural environments, independent sample t-tests to evaluate statistical significance between urban and rural temperatures, monthly variation of UHI intensity, diurnal variation of land surface temperature (LST) in urban and rural areas and their difference and UAV-derived thermal maps for visualization of temperature distribution. Temperature (LST) difference is calculated using Equation 2.

$$\Delta LST = LST_{\text{urban}} - LST_{\text{rural}} \quad (2)$$

RESULTS AND DISCUSSION

The observed urban heat island (UHI) pattern in Belgrade demonstrates a persistent and spatially coherent thermal anomaly characterized by higher temperatures in urban areas compared to surrounding rural environments [12–14]. The magnitude and seasonal variability of the UHI effect are consistent with established findings in urban climatology literature, where built-up environments exhibit enhanced heat storage and reduced nocturnal cooling due to surface material properties and anthropogenic heat emissions [3]. Monthly Mean Temperature in Urban and Rural environment as well as UHI values are presented in Figure 1.

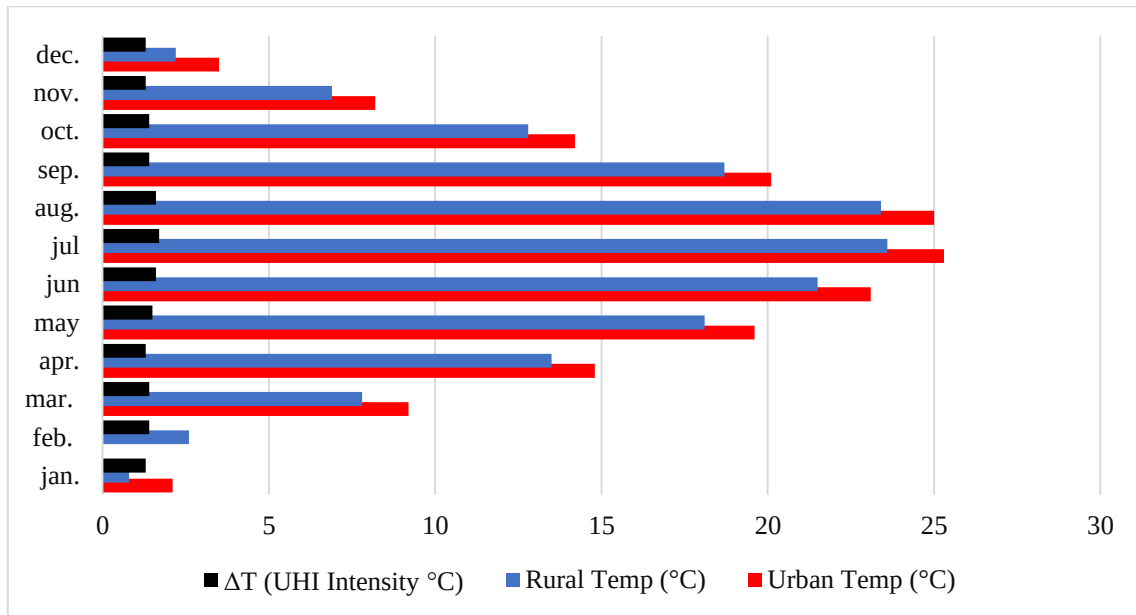


Figure 1 Monthly Mean Temperature (Urban vs Rural environment)

The strongest UHI intensity during summer months can be attributed to increased shortwave radiation absorption by impervious surfaces such as asphalt and concrete, combined with reduced vegetation cover and limited evapotranspiration in densely built areas. These factors contribute to higher sensible heat fluxes and reduced latent heat exchange, intensifying urban warming under clear-sky conditions [1]. Similar seasonal amplification of UHI intensity has been reported in other mid-latitude cities, where summer synoptic stability enhances radiative heating contrasts between urban and rural zones [16]. In contrast, the weaker UHI signal observed during winter months is likely the result of reduced incoming solar radiation, increased atmospheric mixing, and more homogeneous surface energy exchanges between urban and rural environments. Additionally, seasonal vegetation loss in rural areas reduces the thermal contrast between land-cover types, partially diminishing the urban–rural temperature gradient. The integration of high-resolution gridded climate data and spatial extraction methods provided a robust framework for quantifying urban–rural thermal differences. The use of datasets such as MeteoSerbia1km and ERA5 reanalysis ensured spatial consistency and allowed for reliable long-term comparison under uniform synoptic conditions [13,14]. However, while gridded datasets offer strong spatial coverage, they may smooth local-scale thermal extremes, particularly in highly heterogeneous urban environments. This limitation highlights the importance of complementing reanalysis data with in situ and UAV-based observations for improved microclimatic representation [7]. Overall, the results confirm that urbanization significantly modifies local thermal regimes in Belgrade, reinforcing the role of land surface transformation in regional climate modification. The findings are consistent with broader global evidence that urban areas are increasingly acting as localized heat amplifiers under contemporary climate change conditions [2]. This has important implications for urban planning, public health, and climate adaptation strategies, particularly in regions experiencing increasing frequency of heatwave events. The LST obtained results presented in Figure 2 clearly demonstrate a strong diurnal cycle in land surface temperature (LST) for both urban and rural environments.

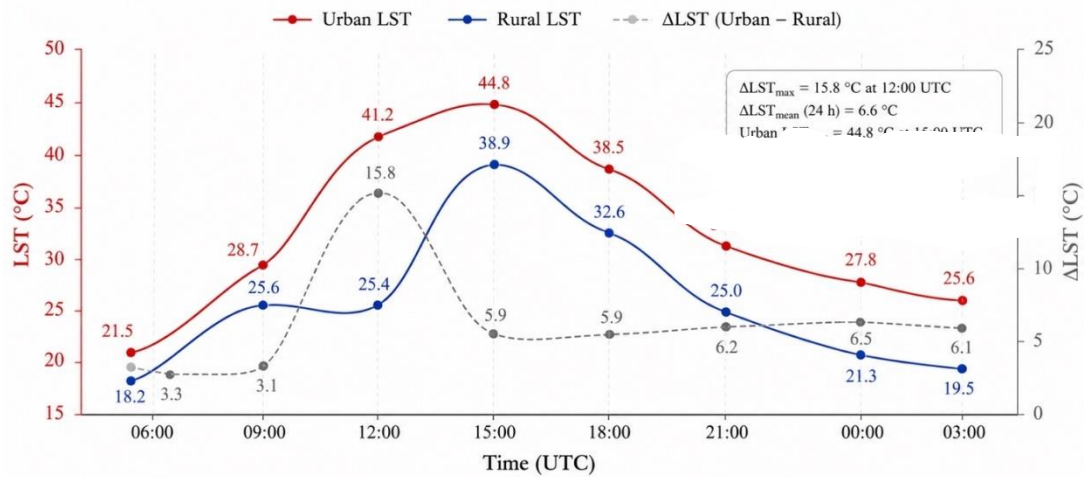


Figure 2 Diurnal variation of land surface temperature (LST) in urban and rural areas and their difference ($ALST = Urban - Rural$). Observations were derived from UAV-based thermal infrared imagery on a clear day through interpolation to represent continuous surface temperature variability under clear-sky conditions. All times are Coordinated Universal Time (UTC).

In both cases, temperatures increase steadily from early morning hours, reaching a pronounced peak in the early afternoon (15:00), followed by a gradual decline toward nighttime. This pattern reflects the expected response of land surfaces to incoming solar radiation and subsequent heat storage and release processes. A key finding is the consistently higher LST observed in the urban area compared to the rural site throughout the entire 24-hour period. The maximum urban LST reached 44.8°C, while the rural maximum was significantly lower at 38.9°C. This persistent temperature difference highlights the presence of a strong Surface Urban Heat Island (SUHI) effect in the study area. The intensity of the urban–rural thermal contrast (ΔLST) increases during the daytime, peaking around the period of maximum solar radiation. This behavior can be attributed to the higher heat capacity and thermal conductivity of urban materials such as asphalt and concrete, which absorb and store large amounts of heat. In contrast, rural surfaces, characterized by vegetation and soil moisture, exhibit greater evaporative cooling, which limits temperature rise. During nighttime and early morning hours, the temperature difference between urban and rural areas decreases but does not disappear entirely. This indicates that urban surfaces release stored heat more slowly than rural environments, contributing to sustained nocturnal warming. Such behavior is a well-documented feature of urban microclimates and is strongly linked to reduced longwave radiation loss and anthropogenic heat retention. Overall, the results confirm a typical urban thermal amplification pattern under clear-sky conditions. The observed diurnal dynamics are consistent with previous studies of SUHI formation, where maximum intensity occurs in the afternoon and is driven by both radiative forcing and surface material properties. These findings emphasize the importance of urban surface composition and land cover in controlling local microclimatic conditions. The results obtained by UAVs LSD temperature maps demonstrate consistently higher surface temperatures within urbanized areas compared to surrounding rural landscapes, particularly during nighttime observations, which is characteristic of urban heat island (UHI) development (Figure 3).

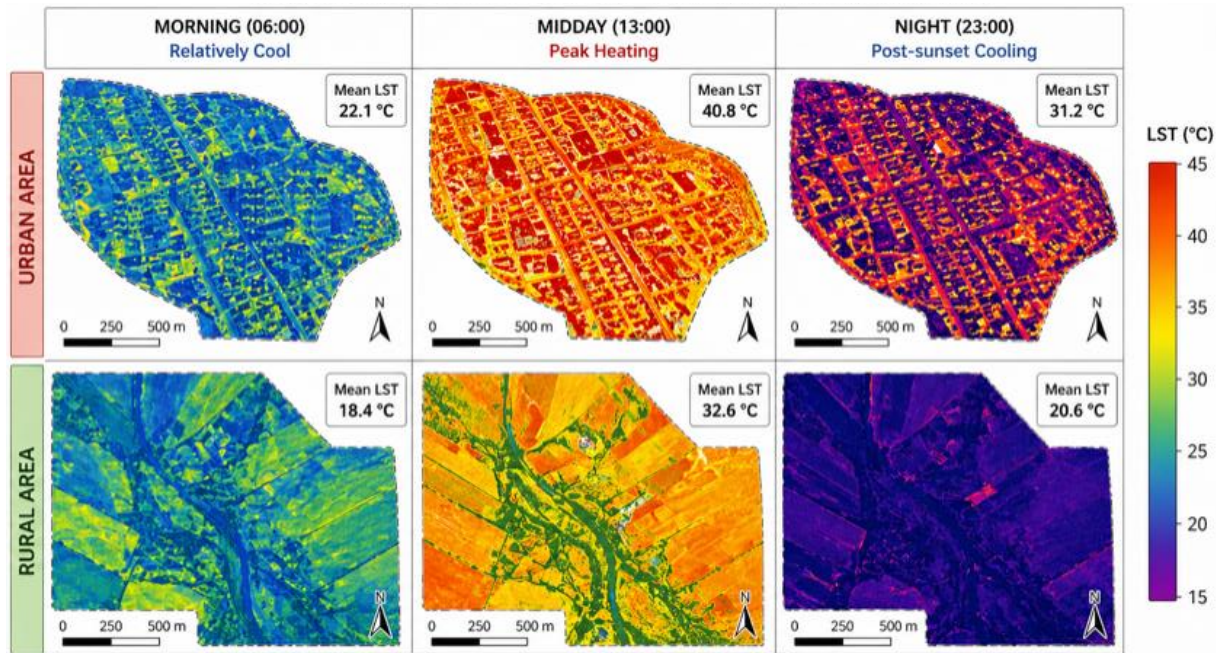


Figure 3 UAV- derived Land Surface Temperature maps (LST)

The observed thermal patterns are primarily driven by differences in surface properties and energy balance dynamics. Urban areas, dominated by impervious materials such as asphalt, concrete, and building facades, exhibit high thermal inertia, allowing them to store solar radiation during the day and release it slowly after sunset. This results in elevated nighttime LST values and reduced cooling rates. In contrast, rural areas characterized by vegetation and exposed soil show more efficient radiative cooling and evapotranspiration, leading to lower surface temperatures and stronger diurnal temperature gradients.

The UAV-based LST maps further highlight the influence of micro-scale land cover heterogeneity on local thermal behavior. Within the urban environment, distinct hotspots can be observed in densely built-up zones, transportation corridors, and industrial surfaces, while relatively cooler areas correspond to parks and vegetated patches. This fine-scale variability would not be detectable using coarser satellite imagery, demonstrating the added value of UAV platforms in urban climate studies.

Temporal analysis of UAV-derived thermal imagery indicates that the strongest urban–rural temperature contrasts occur during nighttime conditions. This supports the well-established concept that urban heat islands are primarily nocturnal phenomena, driven by delayed heat release from built surfaces and reduced atmospheric mixing in urban canyons. During daytime, although urban areas still exhibit higher surface temperatures, the contrast with rural zones is generally less pronounced due to the influence of solar heating across both environments.

Despite the strengths of UAV-based thermal mapping, several limitations should be acknowledged. Surface temperature retrieved from thermal imagery represents radiative land surface conditions rather than near-surface air temperature, and therefore direct comparison with meteorological station data should be interpreted cautiously. Additionally, atmospheric conditions, flight timing, and sensor calibration can introduce variability in absolute

temperature values. However, the relative spatial patterns observed in the UAV LST maps remain robust and provide valuable insight into urban thermal dynamics.

Overall, the UAV-derived LST analysis confirms that high-resolution thermal imaging is a powerful tool for detecting urban–rural thermal contrasts and understanding fine-scale heat distribution processes. These findings are consistent with established urban climatology theory and demonstrate the applicability of UAV systems for detailed environmental monitoring in heterogeneous landscapes.

CONCLUSION

This study demonstrates the effectiveness of UAV-derived land surface temperature (LST) mapping for analyzing fine-scale urban–rural thermal variability and its relationship to diurnal surface heating and cooling processes. The results show consistent spatial temperature contrasts between urban and rural environments, with stronger nighttime urban warming and more efficient nocturnal cooling in rural areas. These patterns reflect differences in surface materials, vegetation cover, and heat storage capacity, which govern local energy balance dynamics. When combined with official meteorological observations, UAV thermal imagery provides valuable contextual insight into atmospheric conditions near the surface. Although UAV-derived LST does not directly represent air temperature, the observed spatial and temporal patterns are consistent with established urban climatology and boundary-layer theory. From an aviation meteorology perspective, the findings are particularly relevant for understanding micro-scale thermal processes in the vicinity of airports. Surface temperature heterogeneity influences near-surface air temperature gradients, boundary layer stability, and local turbulence development, all of which are critical factors for flight operations during takeoff, landing, and low-altitude phases. In regions with mixed land cover, such as the urban–suburban–open terrain transition near Belgrade Nikola Tesla Airport, these thermal differences can contribute to localized atmospheric variability that is not fully captured by conventional point-based meteorological observations.

Therefore, UAV-based thermal mapping represents a valuable complementary tool for aviation meteorology by providing high-resolution spatial information on surface heating patterns that affect local atmospheric behavior. This enhances situational awareness of microclimatic conditions relevant to operational safety and supports improved interpretation of near-airport weather variability. Future integration of UAV observations with ground-based measurements and numerical weather prediction models could further strengthen short-range forecasting and risk assessment in aviation environments.

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