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URBAN HEAT ISLAND AND GREEN SPACES IN THE CITY OF SKOPJE: AN ENVIRONMENTAL HEALTH APPROACH COMBINED WITH REMOTE SENSING DATA

The Surface Urban Heat Island (SUHI) is a well-documented urbanization-driven phenomenon, contributing to elevated city temperatures compared to surrounding rural areas. This study investigates the positive impact of green spaces in alleviating ambient temperatures during Skopje's summer. Conducted from July 22 to July 28, 2022, in Skopje, Republic of North Macedonia, our cross-sectional research involved thrice-daily temperature monitoring across various locations with and without tree coverage. Additionally, leveraging Landsat-8 data from July 22, 2022, we extracted and analyzed SUHI patterns.

Among the nine locations studied, four exhibited clear Urban Heat Island (UHI) effects. The most significant temperature disparity of 7.9°C was observed between a treeless one-way street and the City Park. On average, temperature differences between the hottest and coolest spots amounted to 6.8°C, consistently showcasing lower ambient temperatures in tree-covered areas.

Our findings underscore the pivotal role of green spaces, including parks and tree-lined gardens, in mitigating thermal stress and offsetting the adverse impacts of UHI on public health. This study emphasizes the critical importance of urban planning strategies that prioritize and integrate green infrastructure to address the challenges posed by UHI, urbanization, and climate change. Policies aimed at promoting and preserving green spaces are indispensable for fostering climate-resilient and sustainable cities that prioritize the well-being of their inhabitants.

Keywords: Urban Heat Island, Green Spaces, Landsat-8, LST, NDVI

INTRODUCTION

Urban environments are amidst an unprecedented era of transformation, driven by rapid urbanization and the omnipresent specter of climate change. In this context, understanding and addressing urban heat islands (UHIs) emerge as a pivotal concern for contemporary urban planners, policy-makers, and public health experts (Gabriel & Endlicher, 2011; Luber & McGeehin, 2008). This phenomenon, fueled by population growth and increasing industrialization, has resulted in the proliferation of cities and urban areas worldwide. However, this unprecedented urban sprawl has not come without consequences (Chatterjee & Majumdar, 2022). Surface Urban Heat Island (SUHI) is a phenomenon in which urban areas experience higher temperatures than their surrounding rural areas due to human activities such as industrialization, urbanization, and transportation (Almeida et al., 2021). This is caused by the modification of the land surface in urban areas, which leads to changes in the energy balance and creates a positive heat flux. The land surface modifications in urban areas, such as replacing vegetation with impervious surfaces like concrete and asphalt, result in changes to the surface properties that can trap and store heat (Ngie et al., 2014). Human activities such as energy consumption, transportation, and industrial activities can also generate heat that adds to the heat island effect. SUHI has a wide range of negative impacts, including increased energy consumption, higher cooling costs, reduced air quality, and negative impacts on human health. Mitigation strategies for SUHI include promoting green spaces and urban vegetation, green roofs, cool roofs, reflective pavements, and smart urban design incorporating natural ventilation and shading to reduce heat absorption. Insufficient soil volumes and soil compaction (Jim, 2019), increased air pollution (Chen et al., 2015) and high temperatures with their water stress effect (Meineke et al., 2016) undoubtedly may negatively affect growth of trees and their shading cooling effect. In addition, canopy size (Rahman et al, 2015), shape (McPherson et al., 2018), and structure (Smithers et al., 2018) are the other morphological characteristics that affect the tree shading. The vegetation absorbs solar energy and provides shade, which lowers the temperature of the ground and increases the latent heat exchange for evapotranspiration. The most important factor in UHI mitigation and adaptation is urban vegetation. Trees could lower daytime air temperatures by up to 2°C at 60 m above ground level and 4°C at the tree level (4 m above ground) (Wang & Akbari, 2016). It has been demonstrated that the effect of transpiration on air temperatures varies between 1° and 8°C (Rahman et al, 2017) or between 2°C to 8°C (Taha, 1997). In addition, according to Turner-Skoff, vegetation has a significant cooling effect in cities, lowering air temperatures by 0.5° to 9°C (Turner-Skoff & Cavender, 2019) and all of these are in line with our measured temperatures. Recent studies investigates the relationship between the land cover and thermal response (Fuladlu, 2022), LST and major air pollutants (Fuladlu and Altan, 2021), air quality and SUHI intensity (Alqasemi, Abduldaem S., et al, 2021).

While extant literature offers valuable insights into UHIs, our manuscript aspires to transcend the limitations of existing knowledge by offering novel perspectives on the intricate interplay between urban development, climate change, and the specific dynamics of UHI within the context of Skopje (Kaplan et al., 2019; Coutts et al., 2007). Departing from mere replication, our study embarks on uncharted paths by harnessing empirical data, in-situ measurements, and historical remote sensing analyses. This ambitious endeavor endeavors not only to unravel immediate UHI impacts but also to trace the historical trajectories that underpin these phenomena (Rahman et al., 2017; Wang & Akbari, 2016; Kocubovski et al., 2023).

Remote sensing techniques and urban climate models can also be used to monitor and understand the extent, causes of SUHI, and inform effective mitigation strategies (Despini et al., 2021). Land Surface Temperature (LST) refers to the temperature of the Earth's surface, as measured by remote sensing instruments or ground-based sensors. It is an important variable in climate studies and environmental monitoring, as it provides information on the energy exchange between the land surface and the atmosphere. LST can be estimated using thermal infrared (TIR) remote sensing data, which measures the thermal radiation emitted by the Earth's surface (Avdan & Jovanovska, 2016).

Remote sensing data unveils trends in Urban Heat Island (UHI) development within Skopje. Generally, higher Normalized Difference Vegetation Index (NDVI) values correspond to lower Land Surface Temperature (LST) due to vegetation's cooling effect through transpiration and photosynthesis (Chen et al., 2006). Conversely, lower NDVI areas like urban spaces tend to exhibit higher LST, reflecting increased heat absorption (Tao et al., 2020). Our study employs remote sensing techniques (Avdan & Jovanovska, 2016) alongside NDVI (Meili et al., 2021; Rahman et al., 2015) and urban climate models (Despini et al., 2021) to comprehend and address Surface Urban Heat Islands (SUHIs). Although the NDVI-LST relationship is context-dependent (Li et al., 2009), combining these data provides insights into land surface processes and UHI hotspots (Meili et al., 2021; Rahman et al., 2015). In-situ measurements corroborate the negative correlation between LST and NDVI, highlighting vegetation's pivotal role in mitigating UHI effects (McDonald et al., 2021; Steensen et al., 2022; Despini et al., 2021).Surface urban heat islands (SUHIs) differ from atmospheric UHI in that they are determined by the temperature of the entire 3-D surface envelope rather than just the air temperature differences between urban and rural areas. SUHIs are present both day and night but are strongest during the day when the sun is shining and heat is accumulating in cities. The loss of natural cooling effect due to the replacement of green areas with man-made structures causes built-up areas to release heat at night (Tomlinson et al., 2011). Factors, such as the type and density of buildings, surface materials, and meteorological conditions, can also influence UHI and LST.

This study represents an effort to transcend superficial observations, delving deeper into unraveling intricate patterns and changes in UHIs within Skopje. Employing a strategic blend of geospatial data and empirical evidence, our study seeks to deviate from conventional methodologies, exploring innovative approaches to comprehend and effectively manage UHIs. By providing actionable intelligence for sustainable urban development, our study endeavors to create a foundation for informed decision-making amidst an evolving climate landscape (McDonald et al., 2021; Meili et al., 2021). Through the integration of remote sensing satellite data and in-situ measurements, our study will facilitate the analysis of air temperature, derive NDVI and LST, and extract UHI areas from Landsat-8 data, enabling comprehensive comparative analysis.

The aim of the study is to combine in-situ (field-based) measurements with remote sensing data, providing a comprehensive analysis that bridges the gap between on-ground observations and broader spatial patterns of UHI in Skopje, and to reveal the differencies in ambient air temperatures between the streets with and without tree line during the heat waves in Skopje.

MATERIALS AND METHODS

STUDY AREA

The City of Skopje is situated in the central part of the Skopje valley 42°0′N 21°26′E, altitude 240 m and covering an area of 571,46 km^2. According to Census 2021 data, the population is 526,502 and urban density 1,400/km^2. The region's relief is complex, comprised of a valley and surrounding mountains on the northwest and on the south, and east. The main direction of the valley is from the northwest to the southeast, being shaped by the action of the river Vardar. Mostly the valley is under the influence of a Continental and Mediterranean type of climate, as well as under the influence of a mountain climate at higher elevations. Lower parts of the valley experience hot and dry summer periods and moderately cold and wet winters (Kaplan et al., 2018; Kendrovski, 2006). The valley's average annual air temperature is 12.9 °C, with an upward trend from 1978 to 2015. The last ten years have seen the most frequent short heat waves, which can last up to six days. The total annual precipitation is 484.8 mm on average. Long dry periods in the summer are a result of the irregular spatial and temporal distribution of precipitation (Donevska & Panov, 2019). The summers are long, hot and relatively dry with low humidity. Skopje's average July high is 31°C. On average Skopje has 88 days above 30°C each year, and 10.2 days above 35.0°C every year. The threshold temperature for heat wave in July in Skopje is 37.0°C according to three decades of air temperature measurements. The Heat-Health Action Plan to prevent consequences on the population's health in the Republic of Macedonia was adopted in 2011, and the threshold ambient air temperatures for Skopje have been used for the study we performed in July 2022. The Heat-Health Action Plan has been developed to implement adaptation measures and prevent health consequences of extreme heat caused by changing weather conditions as a result of the climate change (WHO, 2014).

IN-SITU MEASUREMENTS

During the 2022 heat wave in Skopje, Republic of North Macedonia, the cross-sectional study was conducted from July 22nd to July 28th, excluding July 28th when the heat wave had subsided. Six locations for temperature measurements across the day and an additional three locations were selected for midday measurements. To conduct these measurements, we opted for an eco-friendly mode of transport—bicycles. During the study our field measurements were compared with measured temperatures from both the Hydrometeorological Service of the Republic of North Macedonia and AccuWeather.

Measurements of the ambient air temperature were performed three times daily: in the morning (6 a.m. to 8 a.m.), midday (1:30 p.m. to 4:30 p.m.), and evening (9 p.m. to 11 p.m.). Specific boulevards and streets in Skopje have been selected - such as Saint Clement of Ohrid, Ilinden, Boris Trajkovski, Partizanski odredi, Nikola Trimpare, and Kosturski heroi—to compare temperatures with and without tree lines. Based on the Regulation for Urban Planning (Ministry of Transport and Communications, 2022), and it were noted differences in traffic lane widths, ranging from 3.25-3.75 meters.

Midday measurements included pedestrian refuge islands on main streets without tree cover (boulevard Ilinden and boulevard Saint Clement of Ohrid) and Skopje City Park, where tree lines are typically comprised of lime trees with medium or large canopies.

For the measurements, we used a calibrated thermometer that adhered to quality assurance guidelines accredited as per MKC EN ISO/IEC 17025:2018, calibrated on May 19th, 2022. The thermometer had a maximal registered measurement error of -0.3°C, with an allowed tolerance of ±0.6°C. The measurement uncertainty was calculated using EA-4/02 M:2022, with a coverage factor k=2, providing a 95% probability that the true value falls within the corresponding interval. The thermometer was placed at a height of 1.5 meters from the ground and it took 15 minutes to show the results. We sourced relative humidity data from AccuWeather (AccuWeather, 2022).

REMOTE SENSING DATA

In order to extract SUHI from satellite data, we used Landsat-8 data from 22 July, 2022. As the temporal resolution of Landsat-8 is 16 days, this date was the only available data within the in-situ measurement date. One of the key products of Landsat-8 is LST, which is derived from thermal infrared imagery acquired by the satellite's Thermal Infrared Sensor (TIRS).

LST is important in many Earth system science applications, including climate modeling, agriculture, hydrology, and urban planning. The TIRS instrument on Landsat-8 provides two thermal bands used to estimate LST. The algorithm used to calculate LST from TIRS data considers atmospheric effects, such as water vapor and aerosols, which can affect the accuracy of the LST estimates.

To calculate LST from Landsat-8, several LST algorithms have been developed over the years. In this study, we used the algorithm developed by (Avdan &Jovanovska, 2018). We added 100-m buffer around each air-temperature measuring point to better understand the in-situ points' surroundings.

From the LST data, SUHI was calculated from remote sensing data using the following equation:

$$SUHI = \mu + \frac{\sigma}{2}$$

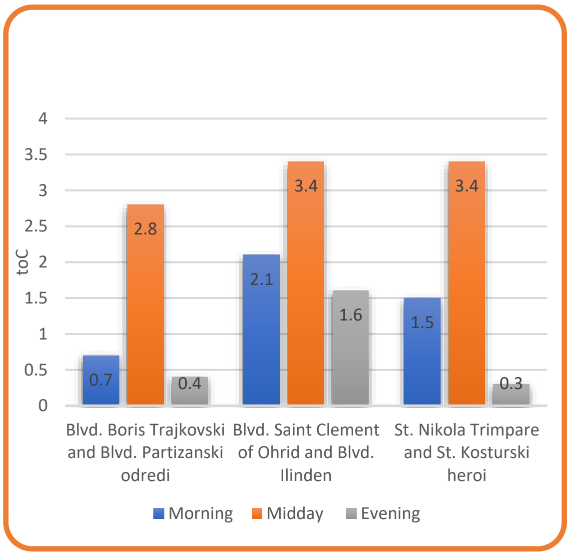
where μ is the mean LST value of the study area and σ is the standard deviation of the LST. Areas that have higher temperature values than the SUHI are considered areas highly affected by the UHI phenomenon.

To investigate the relation between SUHI, LST, air temperature and vegetation cover, we also calculated NDVI from the Landsat-8 data (Figure 2). NDVI is a widely used vegetation index that provides a quantitative measure of the amount of green vegetation in a particular area. It is based on the principle that healthy vegetation absorbs most of the visible light (i.e., blue, green, and red) and reflects much of the near-infrared (NIR) light. The NDVI is calculated by dividing the difference between the NIR and red bands' reflectance values by their sum. The resulting index ranges from -1 to 1, with values closer to 1 indicating a high vegetation density and values closer to -1 indicating a low vegetation density or non-vegetation areas. NDVI is commonly used in remote sensing applications to monitor vegetation density changes over time, detect and map land cover changes, and estimate biophysical parameters related to vegetation, such as leaf area index, biomass, and productivity.

ANALYSIS & RESULTS

The obtained measurements in our study showed the influence of the green spaces on the air temperature in the city of Skopje during the heat wave and one day later. In four tables we present the temperature difference in different periods of day i.e. on morning, midday and evening relative humidity.

Graph 1 illustrates the average ambient air temperature difference between the measuring



Graph 1. Temperature difference in the morning, at midday and in the evening on the investigated sites presenting the temperature differences between selected streets and boulevards

sites and the biggest difference was registered at midday and the lowest in the evening.

Table 1. Temperature difference in the morning, at midday and in the evening on the investigated sites

Date	Compared locations	Morning temperature difference (T°C)	Midday temperature difference (T°C)	Evening temperature difference (T°C)
22.07.2022	Blvd. Boris Trajkovski and Blvd. Partizanski odredi	1.4	1.1	0.4
23.07.2022		1.7	2.3	0.9
24.07.2022		0.7	2	0.7
25.07.2022		0.2	3.5	0
26.07.2022		0.2	1.8	0.2
27.07.2022		0.1	4.1	0.4
28.07.2022		0.8	4.8	0.3
Average T°C		**0.7**	**2.8**	**0.4**
Date				
22.07.2022	Blvd. Saint Clement of Ohrid and Blvd. Ilinden	1.8	3.1	3
23.07.2022		2.5	2	1.4
24.07.2022		2.1	4.1	2.1
25.07.2022		1,9	3,3	1,1
26.07.2022		2.3	4.3	2
27.07.2022		1.7	3.2	1.1
28.07.2022		2.6	4	0.2
Average T°C		**2.1**	**3.4**	**1.6**
Date				
22.07.2022	St. Nikola Trimpare and St. Kosturski heroi	1.7	2.6	0.5
23.07.2022		1.8	2.5	0
24.07.2022		1.7	3.8	0.2
25.07.2022		2.6	5.3	0.1
26.07.2022		1.7	5.2	0.4
27.07.2022		0.4	3	0.5
28.07.2022		0.6	1.5	0.7
Average T°C		**1.5**	**3.4**	**0.3**
Compared locations		Average morning temperature difference (T°C)	Average midday temperature difference (T°C)	Average evening temperature difference (T°C)
Blvd. Boris Trajkovski and Blvd. Partizanski odredi		0.7	2.8	0.4
Blvd. Saint Clement of Ohrid and Blvd. Ilinden		2.1	3.4	1.6
St. Nikola Trimpare and St. Kosturski heroi		1.5	3.4	0.3
Average T°C		**1.4**	**3.2**	**0.8**

From the obtained measurements of morning, midday and evening temperatures, it can be seen that the highest temperature range was registered on the measuring sites on Blvd. Saint Clement of Ohrid and Blvd. Ilinden in the morning and in the evening, compared to other locations.

Table 2. Morning, midday and evening temperature range

Date	Compared locations	Morning temperature range (T°C)	Midday temperature range (T°C)	Evening temperature range (T°C)
22.07.2022 – 28.07.2022	Blvd. Boris Trajkovski and Blvd. Partizanski odredi	0.1 - 1.7	1.1 - 4.8	0 - 0.9
	Blvd. Saint Clement of Ohrid and Blvd. Ilinden	1.7 - 2.6	2 - 4.3	0.2 – 3
	St. Nikola Trimpare and St. Kosturski heroi	0.4 - 2.6	1.5 - 5.3	0 - 0.7

The highest air temperature was registered on a pedestrian island on Blvd. Saint Clement of Ohrid. This was expected, as there are more trees on Boulevard Ilinden. The positive impact of the greenery is obvious.

Table 3. Air temperature on extra three locations for midday measurements

Date	Temperature on pedestrian refuge island on boulevard Ilinden (T°C)	Temperature on pedestrian refuge island on boulevard Saint Clement of Ohrid (T°C)	Skopje City Park (T°C)
22.07.2022	37.3	39.5	32.4
23.07.2022	38.1	38.9	33.4
24.07.2022	41.4	42	35.7
25.07.2022	38	39.4	32
26.07.2022	40.5	40.1	34.2
27.07.2022	38.1	36	33.3
28.07.2022	33.9	32.4	29.3
Average T°C	38.2	38.3	32.9

Skopje City Park was the coolest area among the measured places in 6 from 7 days (Table 4).

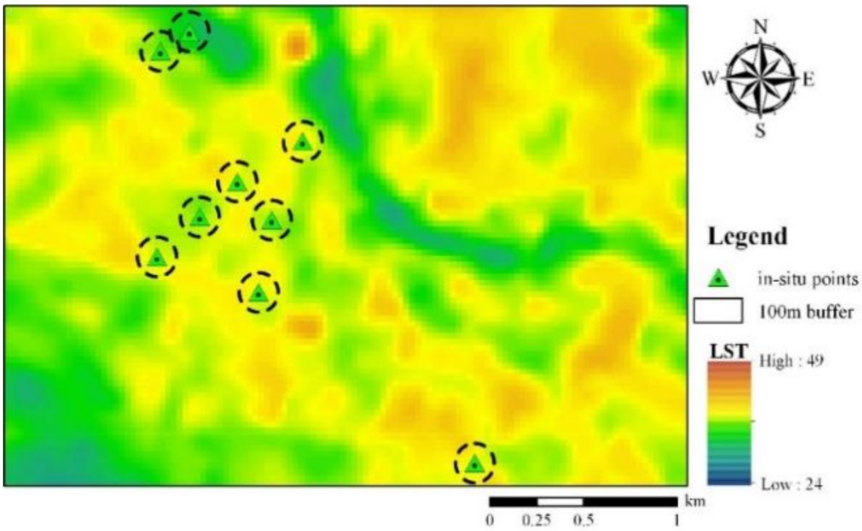


Figure 1. LST map in the study area

Table 4. The highest air temperature difference between the hottest and coolest measured areas at midday

Date	Areas with the highest temperature difference	T°C
22.07.2022	Pedestrian refuge island on boulevard Saint Clement of Ohrid and Skopje City Park	7.1
23.07.2022	St. Nikola Trimpare and Skopje City Park	6.2
24.07.2022	Pedestrian refuge island on Boulevard Saint Clement of Ohrid and Boulevard Partizanski odredi	7
25.07.2022	Pedestrian refuge island on boulevard Saint Clement of Ohrid and Skopje City Park	7.4
26.07.2022	St. Nikola Trimpare and Skopje City Park	7.9
27.07.2022	Pedestrian refuge island on boulevard Ilinden and Skopje City Park	5
28.07.2022	Blvd. Boris Trajkovski and Skopje City Park	7.2
Average T°C		**6.8**

RESULTS FROM THE REMOTE SENSING DATA

The recorded LST in the study area ranged from 24°C to 49°C, as depicted in Figure 1. On July 26th, 2022, the mean LST was 33.3°C, with a standard deviation of 2.9°C. Areas with temperatures surpassing 34.75°C were identified as being impacted by Surface Urban Heat Island (SUHI) effects. These findings guided our geospatial analysis to pinpoint UHI-affected zones, showcased in Figure 3.

To investigate the immediate surroundings, we conducted geospatial statistical analysis within 100-meter buffer zones, extracting NDVI values (Figure 2) and examining their impact on SUHI. Table 6 illustrates the NDVI values from this analysis, indicating whether specific locations

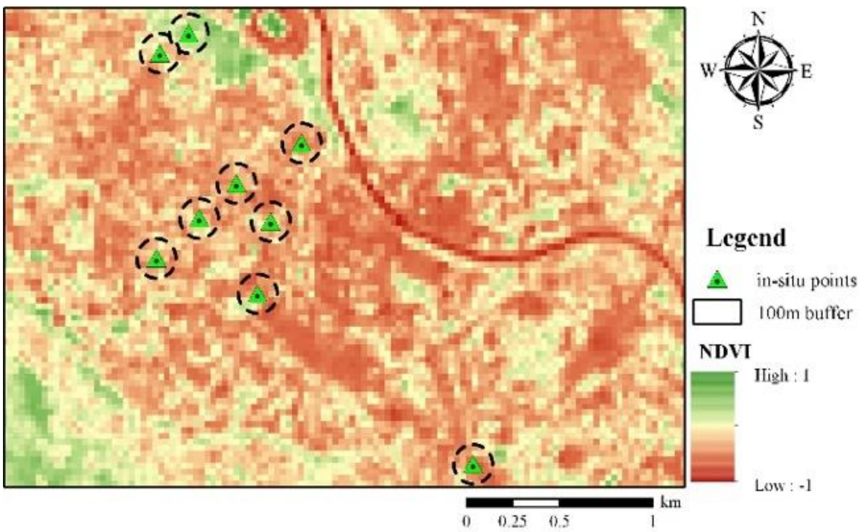


Figure 2. NDVI map in the study area

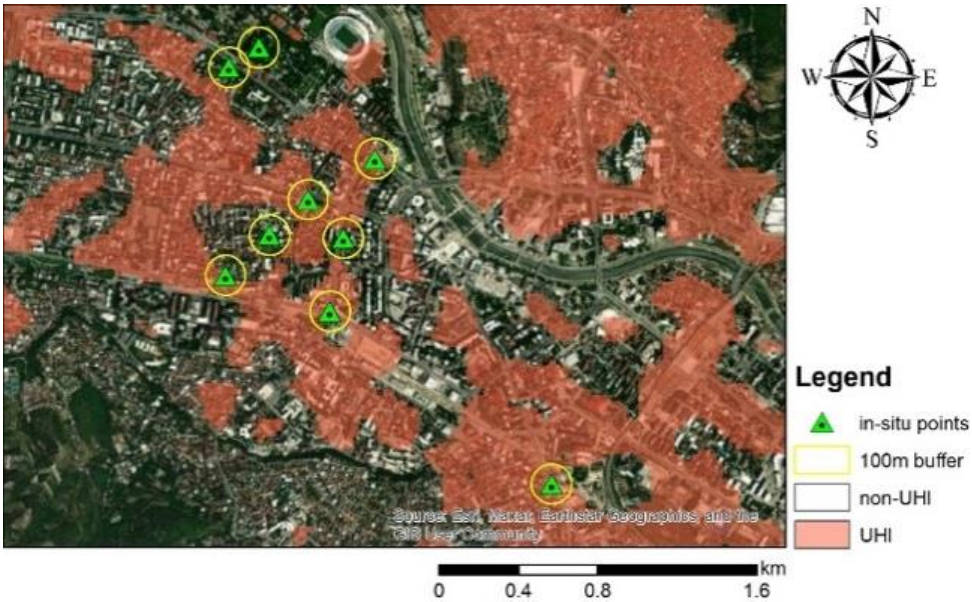


Figure 3. UHI-affected areas in the study area

Table 5 NDVI values in the in-situ locations and buffer zones

ID	1 Pedestrian refuge island on Blvd. Ilinden	2 Blv. Boris Trajkovski	3 Pedestrian refuge island on Blvd. Clement of Ohrid	4 St. Kosturski heroi	5 St. Nikola Trimpare	6 Blvd Partizanski odredi	7 Skopje City Park	8 Blvd Ilinden	9 Blvd Saint Clement of Ohrid
point	0.05	0.05	0.08	0.2	0.23	0.1	0.37	0.24	0.21
100 m min	0.05	0.03	0.02	0.07	0.08	0.07	0.19	0.09	0.06
100 m max	0.26	0.26	0.34	0.28	0.28	0.22	0.44	0.35	0.32
100 m mean	0.13	0.13	0.13	0.17	0.18	0.15	0.36	0.22	0.17
100 m sum	4.5	5	4.5	6	6.33	5.1	12	7.9	6
UHI	YES	YES	YES	NO	NO	YES	NO	NO	NO

Table 6 LST (land surface temperature) in Skopje on 26 July 2022

ID	1 Pedestrian refuge island on Blvd. Ilinden	2 Blv. Boris Trajkovski	3 Pedestrian refuge island on Blvd. Clement of Ohrid	4 St. Kosturski heroi	5 St. Nikola Trimpare	6 Blvd Partizanski odredi	7 Skopje City Park	8 Blvd Ilinden	9 Blvd Saint Clement of Ohrid
point	35.1	34.5	34.7	34.3	33.6	34.5	30.4	33.3	33.8
100 m min	33.7	34.03	34.1	33.7	33	34.16	29.8	31.7	33
100 m max	35.2	36.7	35.1	35.1	34.26	35.3	31.9	34.2	34.8
100 m mean	34.6	34.7	34.7	34.4	33.6	34.6	30.9	33.26	34
UHI	YES	YES	YES	NO	NO	YES	NO	NO	NO

were affected by SUHI according to Figure 3. Locations with NDVI values below 0.2 were identified as SUHI-affected areas. Furthermore, a total NDVI value below six indicated UHI impact, highlighting the vegetation cover's influence on UHI occurrence.

Table 7 showcases the results of the similar geospatial statistical analysis for LST data, correlating areas with temperatures exceeding 34.5°C to UHI-affected regions. It's evident that substantial portions of Skopje were impacted by UHI, with four out of nine in-situ locations experiencing these effects.

A strong negative correlation (R = -0.90) between LST and NDVI values (Figure 4) was observed. This correlation aligns with expectations, where higher NDVI values (indicating greater vegetation cover) correlated with lower LST values. Conversely, lower NDVI values (reflecting limited vegetation cover) corresponded to higher LST values. This relationship underscores the role of vegetation in mitigating heat by providing shade and transpiration, which reduces land surface temperatures. The observed correlation between LST and NDVI values serves as a valuable tool for monitoring land surface conditions and identifying areas prone to environmental stress. Areas with low vegetation cover exhibited higher temperatures, highlighting the significance of vegetation in moderating UHI effects. This understanding aids in tracking changes in land surface conditions and identifying areas susceptible to environmental impacts.

Urbanization has significantly influenced temperature shifts, evidenced by our comparative analysis of meteorological data between 2009 and 2019. Notably, we observed drastic increases in average temperatures from 20°C to 30°C, with maximum temperatures escalating from 27°C to 32°C during this period. These trends underscore a concerning association between urban expansion and escalating temperatures within our study area.

Remote sensing data unveiled a compelling correlation (R2 = 84) between the UHI and built-up areas, elucidating the dominant role of human activities in driving the UHI

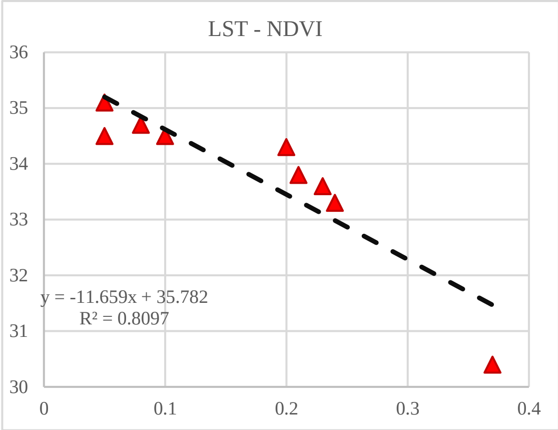


Figure 4. Correlation between NDVI and LST values from satellite data

phenomenon within our study locale. Moreover, an equally compelling correlation (R2 = 90) emerged between verdant spaces and areas unaffected by UHI, illuminating the substantial mitigation potential of green canopies in combatting UHI and SUHI effects, echoing previous findings (Kaplan, 2019). Vegetative

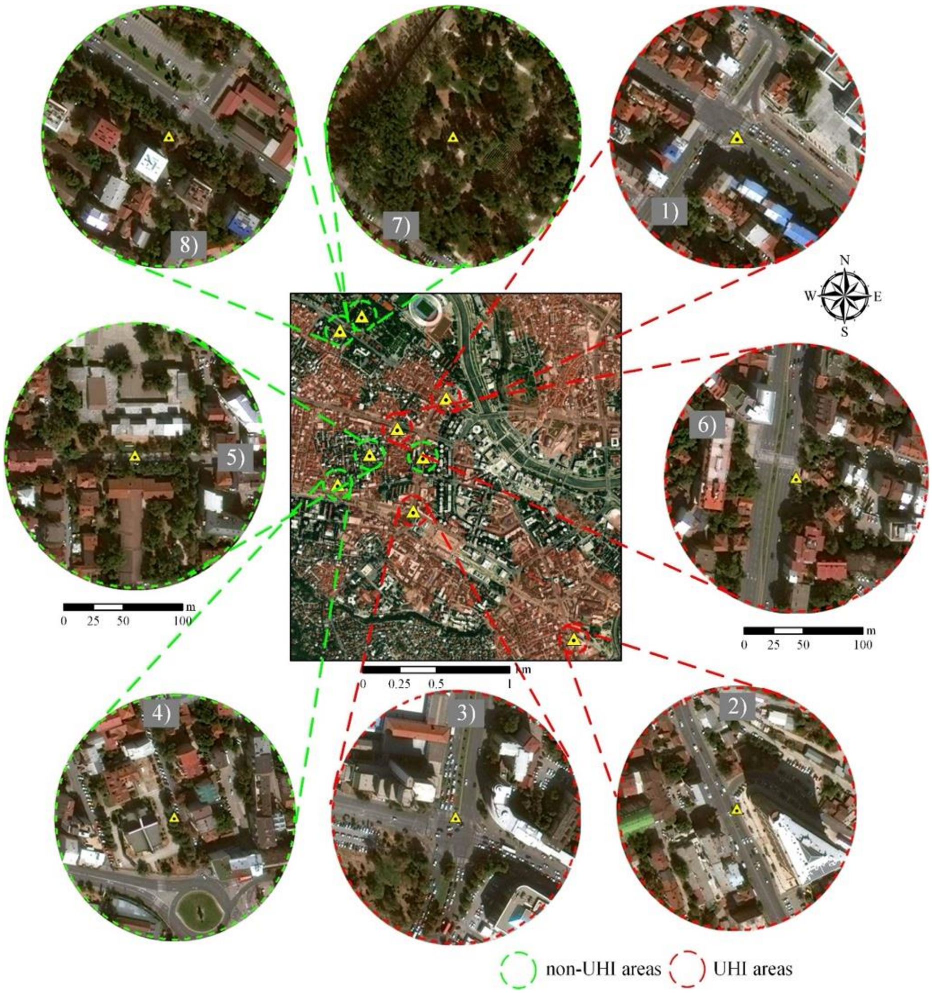


Figure 5. Detailed visualization of the 100-m buffers of the in-situ measurements; 1) Pedestrian refuge islands on Blvd. Ilinden; 2) Blvd. Boris Trajkovski; 3) Pedestrian refuge islands on Blvd. Saint Clement of Ohrid; 4) St. Kosturski heroi; 5) St. Niko

elements, including shrubs, trees, and urban forests, collectively known as biomass, exhibited a pronounced ability to ameliorate UHI effects. Their presence fosters critical processes like evapotranspiration and enhanced water absorption, thus nurturing a microclimate that curbs the adverse impacts of climate change, such as floods and localized atmospheric heating (Coutts et al., 2007).

Our findings align harmoniously with established literature, notably highlighting the substantial temperature differences observed during different times of the day. Morning-to-evening disparities of 0.6°C were detected between locations with and without trees, showcasing the cooling influence of vegetation. Most significantly, boulevards consistently exhibited the widest temperature differentials, irrespective of the time of measurement. Notably, the most extensive temperature range appeared between St. Nikola Trimpare and St. Kosturski heroi during morning and noon measurements, while evening measurements recorded the broadest range between boulevards. Intriguingly, pedestrian islands consistently exhibited equal or higher temperatures compared to the boulevards linking them, potentially influenced by slight delays at exit points, leading to heightened perceived temperatures.

The combined influences of evapotranspiration, shading, and the albedo effects of trees represent a triumvirate of factors shaping the urban climate (Schwaab et al., 2021). Characteristics such as tree height, canopy spread, and leaf density significantly contribute to the benefits trees offer. Notably, a mere 10% increase in tree cover demonstrated a substantial reduction in air temperatures by 3-4°C. This reduction not only curtails energy consumption but also yields consequential benefits such as decreased reliance on fossil fuels (Elmqvist et al., 2015). In our study, we recorded air temperature decreases of 3-4°C in streets and boulevards, both with and without tree lines, showcasing the substantial cooling potential of urban greenery. The average midday temperature difference notably stood at 3.2°C, affirming the cooling effect offered by vegetative cover during peak daytime temperatures.

Morphofunctional features of trees and the urban area circumstances have an impact on the level of transpiration and their cooling effect. The cooling effects via evapotranspiration are an undeniable fact confirmed by a series of scientific studies (Oke, 1988). There is a dilemma in climate projections about the impact of CO_2 concentrations (Sperry et al., 2019).

Temperature variations between the hottest and coolest areas of our study exhibited a substantial difference, with the largest reaching 7.9°C—from a treeless Nikola Trimpare street (42°C) to Skopje's City Park (34.1°C). Our findings echoed similar studies in various cities (Meili et al., 2021), showcasing that cooling effects are notably pronounced during summer afternoons.

Studies in different locations—Madison, Wisconsin (Ziter et al., 2019), Washington DC (Alonzo et al., 2021), and Beijing (Jiao et al., 2017)—highlighted morning cooling ranging from 1°C to 1.8°C, correlating with our observed morning temperature differences of 1.4°C within a range of 0.1-2.2°C. Streets with high tree cover showed a temperature variance of 5.4°C compared to 2.3°C for medium tree-covered streets (Ren et al., 2022). Variability in daytime temperatures within urban landscapes averaged 3.5°C (range, 1.1–5.7°C) (Ziter et al., 2019), aligning with our midday measurements of 3.2°C within a range of 1.1-5.3°C. Notable temperature drops between areas with and without trees were confirmed; streets with high tree canopy covers showed a potential afternoon air temperature reduction of up to 3.3°C (Huang et al., 2020). Nighttime temperatures also displayed a variance of 0.8°C in our study, akin to measurements in various cities like Phoenix, Singapore, Munich, Gothenburg and Melbourne (Meili et al., 2021).

UHI impact at night is evident due to absorbed solar radiation being slowly released, influencing subsequent day temperatures (Norton et al., 2015). Tree-lined streets showed significant summertime air temperature reductions of 0.5 to 2.0°C (McDonald et al., 2021). Additionally, street orientation and tree proximity to buildings affect air temperatures, aligning with our midday measurements ranging from 1.1°C to 5.3°C (Ibrahim, 2013).

Field measurements emphasized the thermal advantages of green spaces, particularly urban parks, with significant temperature differences observed, aligning with our findings regarding Skopje's City Park as the coolest area (Papangelis et al., 2012; Vidrich & Medved, 2013). This emphasizes the importance of trees in reducing daytime temperatures and extending cooling effects into the night, benefiting public health (Meili et al., 2021). Trees, either solitary or in clusters, have a considerable cooling impact by blocking solar

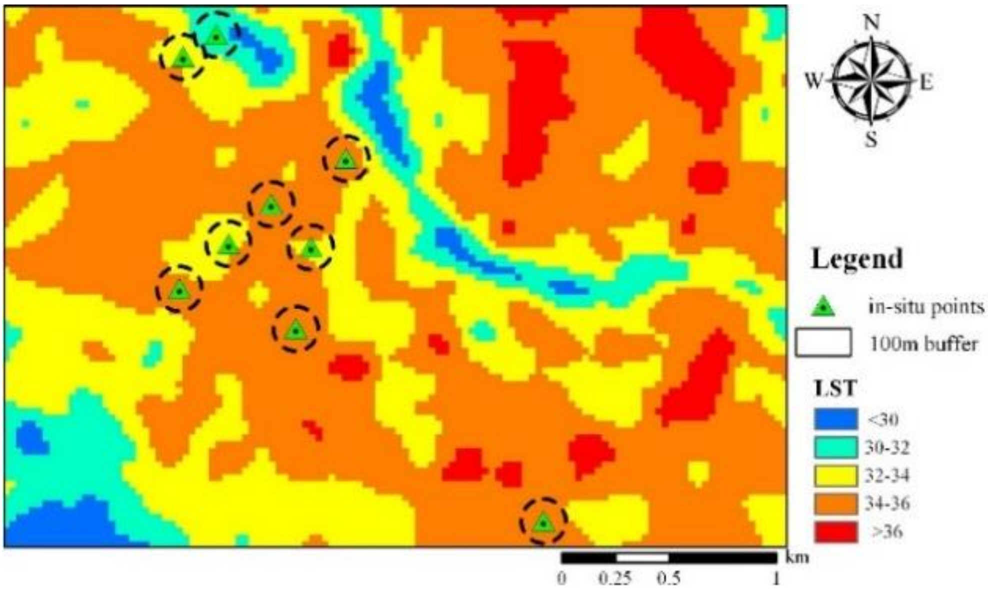


Figure 6: LST classification in 5 different classes

radiation and aiding evapotranspiration. Urban forests and tree-lined streets exhibit noticeable air temperature reductions, on average by 0.8°C under trees and up to 1.6°C within street canyons adjacent to parks (Vidrich & Medved, 2013).

It's essential to consider the interplay between vegetation and the albedo effect when analyzing their impact on urban temperature regulation. In urban areas like Sacramento, Houston, and Chicago, a rise in surface albedo was associated with a substantial decrease in daily air temperatures by 2.3°C (Jandaghian & Akbari, 2018). A study in Montreal demonstrated that enhancing albedo reduced daily air temperatures by 0.7°C, raised dew point temperatures by 0.4°C, and improved heat stress indices by 3%, collectively contributing to a nearly 4% reduction in heat-related mortality during two heat waves (Zahra & Umberto, 2019).

Earlier data suggested that modifying surface albedo alongside increasing vegetation could lower air temperatures by as much as 4°C (Taha, 199, Lopez-Cabeza et al., 2022). However, while high-albedo surfaces have the potential to decrease air temperatures, they might simultaneously heighten heat stress risk for pedestrians (Erell et al., 2014). It's crucial to advocate for active transport while ensuring conducive conditions.

In cities affected by UHI effects, extreme heat isn't evenly distributed, forming 'hot spots' due to intense urban development with limited vegetation and water, mirroring findings in Skopje similar to the Norton study. The city's General Urban Plan (2012) allocated 6% of its total area to green spaces, crucial in mitigating heat (Study on greening in the area of the City of Skopje, 2012). Research from Melbourne suggested a 10% rise in vegetation could reduce daytime urban temperatures by about 1°C (Coutts & Harris, 2013). Land cover analysis in Skopje (2013-2017) showed a slight decrease in vegetated areas alongside expanding urban zones, impacting local temperatures (Kaplan et al., 2018).

Unfortunately, in many Southern and South-Eastern European cities, including ours, the cooling effectiveness of urban trees diminishes during extreme heat periods (Schwaab et al., 2021). Anticipated dry summers in Europe will further reduce vegetation benefits (Christidis & Stott, 2021), necessitating immediate action. Green spaces play a vital role in stabilizing temperature variations caused by construction materials, contributing to 'cool islands' within cities (Andoni & Wonorahardjo, 2018). With urban expansion, more land covered by heat-retaining surfaces limits green spaces, exacerbating the UHI effect and causing outdoor thermal discomfort (Mirzaei, 2015).

In heat-wave conditions, even a 1°C rise above the heat cut-off point (30.8°C) increases mortality by 4.8% (Luber & McGeehin, 2008). Extreme heat remains a significant cause of preventable deaths globally, especially during intense heat waves, affecting various vulnerable groups, including children, older adults, and socioeconomically marginalized populations (Mayrhuber et al., 2018).

Urbanization, coupled with UHI effects and global warming, escalates thermal stress in cities, posing a growing concern for public health (Gabriel & Endlicher, 2011). Estimates suggest that the costs of heat-related health damage in Skopje reach MKD 170 million per year, far outweighing the MKD 12 million spent annually on heat-health adaptation measures (Kendrovski et al., 2014). Projections indicate a stark increase in heat-related deaths in Skopje in the coming decades compared to the baseline period of 1986-2005.

Addressing these challenges requires consistent and comprehensive health action plans tailored to regional conditions (Lancet, 2021 & Kocubovski et al., 2023). Despite recent advocacy by the World Health Organization to include health authorities in climate change mitigation efforts, healthcare facilities' preparedness remains inconsistent, posing potential challenges in treating patients during extreme heat events.

The investigation into UHIs benefits significantly from a dual approach integrating in-situ measurements and remote sensing analysis. While in-situ measurements offer precision, they are limited to specific locations and can be time-consuming. In contrast, remote sensing provides a more practical solution by capturing data across expansive regions, allowing for a comprehensive analysis of UHI patterns on a larger scale. Additionally, remote sensing provides a wealth of data beyond temperature, including estimations of crucial factors such as vegetation cover, which plays a pivotal role in mitigating UHI effects.

The synergy between these methods is evident in their distinct advantages. In-situ measurements yield precise data for specific points, while remote sensing ensures efficiency and a broader scope for analysis. Moreover, remote sensing allows researchers to delve into historical data, enabling the identification of UHI development trends over time. This historical perspective is invaluable for devising effective urban planning and management strategies.

One illustrative example is the classification depicted in Figure 6, showcasing the segmentation of the study area into five temperature classes. This visual representation not only highlights the spatial distribution of temperature variations, from cold to warm areas, but also facilitates a clearer understanding of UHI effects in different zones.

The integration of in-situ measurements and remote sensing analysis offers a comprehensive insight into the multifaceted nature of UHIs. While in-situ measurements offer precise localized data, remote sensing extends the analysis horizon, providing a comprehensive view of diverse factors influencing UHI, including historical trends and the impact of vegetation cover. This combined approach constitutes a robust toolset for both understanding and managing UHIs in urban settings.

The convergence of in-situ measurements and remote sensing analysis not only enhances our comprehension of UHIs but also offers actionable insights crucial for effective urban planning and sustainable development. By amalgamating precise local data from in-situ measurements with the broader perspective afforded by remote sensing, decision-makers can formulate targeted strategies to mitigate UHI effects.

This comprehensive approach empowers city planners and policymakers with a nuanced understanding of the complex interplay between urban landscapes and temperature variations. The insights derived aid in identifying high-risk zones prone to UHI effects, prioritizing areas for green infrastructure development, and implementing heat reduction measures where they are most impactful. Furthermore, it assists in optimizing resource allocation by directing efforts toward areas most in need of intervention.

In essence, the synergy between in-situ measurements and remote sensing not only deepens our understanding of UHIs but also equips stakeholders with the knowledge necessary to implement informed and strategic interventions for creating more resilient and sustainable urban environments.

CONCLUSION

In summary, our study highlights the significant impact of trees on the diurnal pattern of urban air temperature modification. We've observed that evapotranspiration from trees offers substantial cooling effects during both day and night, yet there's a delicate balance to strike between maximizing daytime cooling and preserving radiative cooling at night, especially concerning street trees and their geometry.

The vulnerability of urban residents to medical and economic challenges due to extreme temperatures is evident. Access to green spaces, particularly those with trees like parks and gardens, emerges as a potential solution to mitigate thermal stress caused by the urban heat island effect during the day, safeguarding public health.

Our findings underline the urgency for strategic tree planting near streets and boulevards to combat UHI and reduce health risks for pedestrians and cyclists facing soaring midday temperatures. Further investigations are essential, encompassing additional parameters like canopy height and volume measurement, assessing the impact on human health, and considering relative humidity variations across micro-locations and times of the day. It's crucial to acknowledge the need for ongoing research to validate and extend these findings to diverse urban settings, especially amid potential urban expansion and changing climates. Our study, leveraging both in-situ and remote sensing data, contributes to the broader understanding of UHI dynamics and holds implications for sustainable urban development and environmental management.

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