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A Comparative Analysis of Land Surface Temperature (LST) Data from Landsat-8 and ENVI-met Monitoring Softwares: A Case Study of an Urban Park in Budapest

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Abstract: *Urban Heat Islands (UHI) present a significant environmental challenge in urban centres worldwide, exacerbated by global warming and intense urbanisation. This study explores methods for monitoring Land Surface Temperature (LST) within urban environments, focusing on the comparative analysis of satellite imagery and ENVI-met simulations. An urban park from Budapest was selected to analyse the surface temperature during three summer days using satellite imagery and ENVI-met. Statistical analyses reveal a strong correlation between LST derived from satellite imagery and ENVI-met simulations with a (R2) value of 0.97 ($p < 0.001$) on day 1, 0.95 ($p < 0.01$) on day 2, and 0.98 ($p < 0.01$) on day 3, suggesting potential for calibrating ENVI-met models using satellite data depending on a method proposed by authors. However, distinct variations can be noticed when specific spots are compared, especially under tree canopies and hard surfaces, which needs further investigation. The study underscores the complementary nature of satellite observation and numerical simulation approaches, highlighting the need for integrated methodologies to understand and mitigate UHI effects.*

Keywords: *ENVI-met, Land Surface Temperature (LST), Urban parks, Urban Heat Island, Microclimate.*

1. RESEARCH BACKGROUND

Numerous urban centres struggle with thermal stress due to the phenomenon known as the Urban Heat Island (UHI) effect, stemming from a confluence of global warming and intense urbanisation. This situation presents a substantial environmental challenge deserving of scientific exploration [1]. The UHI effect substantially elevates summertime temperatures within densely populated metropolises, resulting in elevated temperature conditions and extreme thermal stress occurrences [2]. The cumulative thermal load of the UHI effect carries multiple consequences, including a decrease in thermal comfort [3], a surge in heat-related illness and death rates [4], deterioration of air quality [5], increased demand for cooling energy, and auxiliary economic and sociological costs [6]. While the term "UHI" predominates in urban research, "surface urban heat island" (SUHI) is frequently adopted when comparing temperature variations between urban and rural locales. Addressing urban overheating necessitates the application of climate-sensitive urban design. This method involves strategically consolidating innovative choices encircling urban structural configurations, morphological adaptations, and reintegrating green and blue infrastructures (GBI), such as vegetation, water bodies, and green roofs [7, 8]. Urban greenery is a highly effective countermeasure primarily due to its ability to provide shade, manipulate airflow patterns, intercept precipitation, and promote evapotranspiration [9].

One of the methods of detecting SUHI is satellite observation and remote sensing, observing land surface temperature (LST), which is one of the most critical parameters in the field of land surface processes at all scales. With their extensive coverage and regular review over time, satellite observations represent the exclusive means for globally measuring land surface temperature (LST) at a pixel scale that provides spatial averaging. However, there were significant factors in developing methods for satellite-based LST measurement [10]. For this purpose, thermal infrared (TIR) instruments operating in the atmospheric window wavelength region of (8-14 µm) have been carried by several satellites since the 1960s, including the National Oceanic and Atmospheric Administration (NOAA) series, Landsat series, Earth Observing System Terra and Aqua satellites, Metaset Second Generation (MSG) series, and Chinese Fengyun (FY) series [11]. Later, many ways to measure LST have been created based on TIR remote sensing data [12]. These include products from global to local scale and with various spatial resolutions such as (MODIS), Landsat Collection 2, ASTER, and Copernicus LST production [13].

There are many factors affecting LST: the interaction effect of seasons [14], the percentage of urban green space [15, 16], the landscape pattern and green space typology [17], the conversion of wetlands and marshlands into agricultural land and the transition of vegetated regions into urban developments are significant factors contributing to the rise in Land Surface Temperature (LST) [18]. Global warming is strongly related to additional contributing elements accountable for the increase in urbanisation [19].

ENVI-met is another method to simulate SUHI on the microclimate scale, which is a comprehensive three-dimensional computational fluid dynamics (CFD) model initially developed by Michael Bruse in 1998 [20]. The software has gained extensive application in over 50% of thermal effects simulations related to vegetation [21]. Operating on the tenets of fluid dynamics, thermodynamics, and atmospheric physics, ENVI-met facilitates the modelling of interactions between the urban surface, plant life, and the atmospheric medium. A distinctive characteristic of ENVI-met pertains to its involved vegetation model [22, 23], wherein plant life is not merely conceptualised as a passive recipient of solar radiation and wind flow but actively engages with the surrounding environment via evapotranspiration mechanisms [24]. With this distinct specification and fine-grained spatial resolution, the software simulates the microclimate, including air temperature and surface temperature, with a high accuracy that makes it scientifically valid in many scholarly research [8]. This technique aligns with the scientific approach, allowing for a systematic exploration of urban climate dynamics and thermal mitigation strategies. It should also be mentioned that apart from ENVI-met, many other CFD simulation software can be used on the scale of microclimate modelling, which has been mentioned in [23].

With a wide range of capabilities of ENVI-met for simulating microclimate parameters, few studies have used it to evaluate LST. ENVI-met has been used to study surface temperature, wind speed and solar radiation in less than 10% of the scholarly work related to the software [25]. Researchers in [26] used Landsat images and Envi-met modelling for the simulation microclimate at a scale of 30m resolution based on the Local Climate Zone (LCZ) with statistical analysis to determine SUHI in a city in Turkey. They noticed that LCZ classes such as the compact high-rise, compact mid-rise, lightweight low-rise, and sparsely built did not show significant differences in mean LST between Landsat 8 and ENVI-Met. However, scholarly research predominantly uses satellite images and remote sensing for measuring LST, taking advantage of mesoscale analytic opportunities; yet, it is necessary to investigate the ability of the methods to detect the surface temperature under the canopy layer where satellite observation cannot detect, especially under the shaded areas such as trees; consequently, the variation in detecting the surface temperature over the canopy and under the canopy by both source of data has to be investigated. The primary aim of this research is to assess the performance of two distinct data sources, Landsat satellite imagery and the ENVI-met software simulation, in capturing spatiotemporal variations in land surface temperature (LST) within an urban park scale. The research attempts to detect the validity of both data results and investigate the possibility of calibration of ENVI-met models by land surface temperature parameters. Another objective is to develop a method to calibrate ENVI-met models using LST results from satellite imagery.

2. RESEARCH METHODS

The central objective of this study is to determine the efficacy of Landsat satellite imagery and ENVI-met software in monitoring LST within an urban park. The authors aimed to assess their performance concerning temperature change detection and applicability to urban planning and sustainability assessments. An urban park in Budapest city, Hungary, was chosen to undergo the investigation in this study named "János Pál Pá tér" (coordinates: 47°30'14 "N 19°03'03" E), surrounded by buildings with an average height of 15m ranging from (5-50m) with different types of softscapes and hardscapes (Figure 1). The choice of this location is motivated by its representation of urban microclimate variations and its relevance to local urban planning and environmental management.

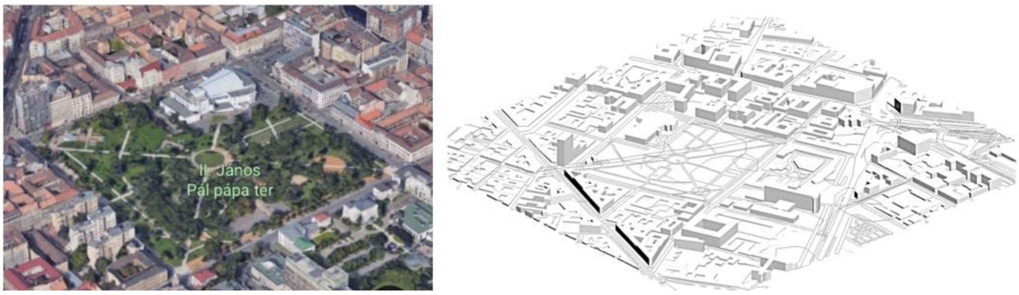


Figure 1: view of the study area. Right, cadmapper.com, Left, earth.google.com

2.1. *Research framework and data collection*

A comparative analysis is conducted to evaluate the performance of the two data sources. The authors assessed their abilities to capture spatiotemporal variations in LST within the urban parks. Three primary data sources are employed for this study: Remote Sensing Data from Landsat-8 covering the Janos Pal Papap park was collected to process the LTS analysis. The collected data were for a two-week interval for two months (August 1st -September 30th, 2023). Field data for the urban parks, such as urban geometry, surface materials and specifications, green area and plant size and types, were determined from different sources like field observation, the Google Earth engine and the Cadmapper website (www.cadmapper.com). Field data are necessary for processing the model geometry in ENVI-met software. Further, meteorological data were collected from the nearest weather stations to the park for the same study period, including air temperature, relative humidity, wind speed, and direction. These data are also necessary to work as boundary condition data input for software simulation. (Figure 2) shows the main research framework for the research conduction.

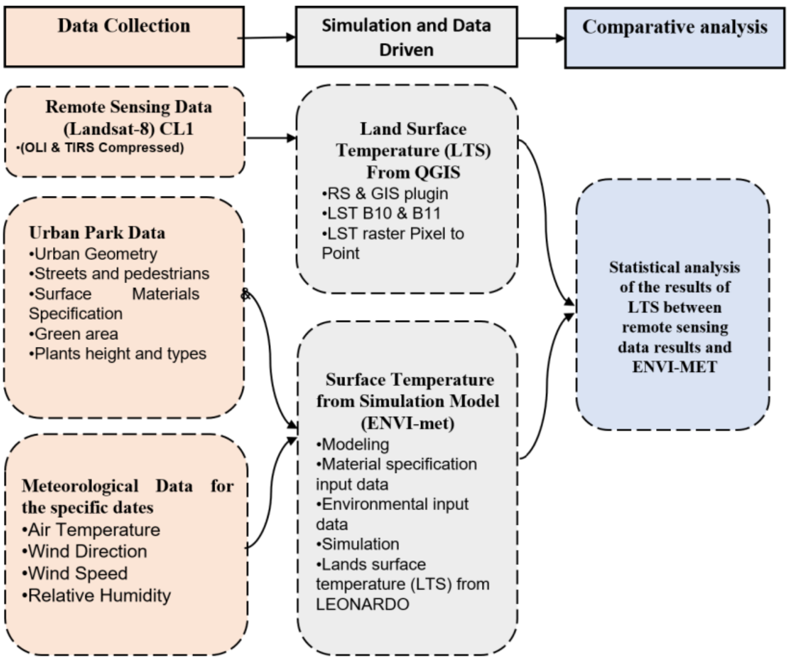


Figure 2 Research Framework

2.2. *LST image processing from satellite*

NASA deployed the Landsat-8 satellite into Earth's orbit in 2013, marking the successful establishment of two pivotal instruments. These instruments comprise the Operational Land Imager (OLI), characterised by a spatial resolution of 30 meters, encompassing nine spectral bands spanning the visible (VIS), near-infrared (NIR), and short-wave infrared (SWIR) domains alongside the Thermal Infrared Sensor (TIRS), housing two spectral bands within the long-wave infrared (LWIR) spectrum. The latter instrument facilitates revisiting the same geographical area at intervals of 16 days [27].

This research aims to determine Land Surface Temperature (LST) during the hot days of the summer period. Consequently, acquiring Landsat imagery requires the slightest existence of cloud cover, preferably less than 3% in the observational domain and nil within the target area. Access to relevant data is facilitated through the United States Geological Survey (USGS) Earth Explorer website. Precisely, data retrieval was executed from the Landsat-8 Collection 2 Level 1 archive, passing above the area on three distinct acquisition dates: August 12, September 13 and 29 of the year 2023. Each acquisition instance corresponds to a satellite pass at 09:27 AM Greenwich Mean Time (GMT), at 11:27 AM local summertime in Budapest.

Quantification of LST is achieved by utilising Quantum Geographic Information System (QGIS 3.36.0), which features plugins conducive to temperature estimation. Among these, the Spatial Climate Plugin (SCP), as explained by [12], and the Remote Sensing and Geographic Information System (RS&GIS) plugin, as mentioned by [28], are notable. In this inquiry, the RS&GIS_V17.0 plugin is employed owing to its compatibility with various satellite datasets, including Landsat 8 OLI/TIRS sensor Level 1 data. The processed data, representing Land Surface Temperature (LST) derived from Band 10 and Band 11 of the Landsat-8 sensor, are expressed in Celsius units. Band 10, predominantly utilised for LST derivation, is considered primary throughout the analysis.

2.3. *ENVI-met model simulation*

For the simulation part of the research, the ENVI-met 5 version was employed. As previously mentioned, this tool simulates dynamic microscale climate conditions within a simple 3D dimensional grid cell model area. The dynamic, numerical computational models rely on the core principles of thermodynamics, fluid dynamics, and broader atmospheric physics. To achieve a comprehensive simulation, the software necessitates the implementation of a 2.5D modelling approach for the designated site encompassing a geometric representation of buildings with their envelope materials and characterisation of the site materials, including soils, hardscapes, soft-scapes, and various plant typologies along with their abstract geometries [26].

Additionally, the software mandates the incorporation of the meteorological data of the site comprising parameters such as minimum and maximum temperature of a specific date, humidity, wind speed and direction. These meteorological data serve as site boundary conditions and are configured through the ENVI-guide section of the software. Subsequently, the results of the simulations are extrapolated to simple 2D and 3D graphs utilising the Leonardo section. These graphical representations provide comprehensive insights into variables such as wind patterns, temperature distributions, humidity levels, and surface temperatures across various temporal intervals during the simulation [25].

The selected area size measured (450×400) square meters and was represented in the model by grid cells of 93x80x35, providing a spatial resolution of (5×5) m in the X and Y direction and 3 m in the Z direction. The modelled size of the site ensures comprehensive coverage of the park area and the surrounding buildings and includes most surface types of a typical park. The buildings' dimensions and the site's configuration were derived from CAD-Mapper and Google Earth tools engine, allowing for precise extrapolation. Moreover, details regarding building envelop materials, site properties encompassing hardscape and soft-scapes, tree height and geometry were configured based on thorough site observations (Figure 3).

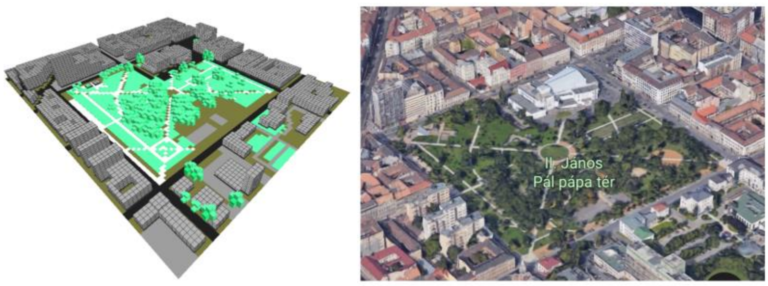


Figure 3 Right, Google Earth view of the study area, Left, ENVI-met model of the study area (Source, Authors)

The simulation was set under simple forcing depending on the weather data from the nearest weather station close to the site, located 4.5 km from “Budapest-Lágymányos: 44505”, were collected for the boundary condition data. The selected date for the simulation was the same as the selected data of the Landsat. The simulation ran for 24 hours for the three selected days, and the target simulation was to pick the results of the same hours of the satellite images for comparison; however, it was at 11:27 AM local summer time, corresponding to the 9:27 GMT satellite image. According to the ENVI-met user guide, starting simulations at 5:00 AM local time is a standard practice, as the model typically requires approximately 3 hours to achieve equilibrium conditions. This approach ensures that the simulation results reflect a realistic representation of urban microclimatic conditions at the target time. The ENVI-met boundary conditions for the simulation of the three selected days are shown in Table 1.

	Day 1	Day 2	Day 3
Simulation Date	2023-08-12	2023-09-13	2023-09-29
Start time	5:00 AM	5:00 AM	5:00 AM
Simulation hours	24 hours	24 hours	24 hours
Max temp	28 C°	30.9 C°	25.9 C°
Min Temp	17 C°	18.4 C°	15 C°
Humidity	75%	56%	60 %
Wind Speed	1.3 m/s	1.9 m/s	1.6 m/s
Wind Direction	18°	225 °	18°

Table 1 ENVI-met boundary condition data for the simulation of the three selected days

2.4. *Results' processing*

The target factors for results processing in ENVI-met were Surface Temperature at the Leonardo section of the software. The picked times were the same as the satellite images of the three selected days. However, as the satellite imaging follows the Greenwich Mean Time GMT zones, the selection of the simulation time was chosen to be 2 hours ahead of the GMT following the central European time zone during summer to ensure the exact local time when the satellite image was captured.

Following preprocessing, statistical analysis techniques were employed to derive insightful patterns and trends from the processed data. Descriptive statistics such as mean, standard deviation, and correlation coefficients were calculated to summarise the central tendencies and relationships within the dataset. An egression diagnostic model was used to explain the linear regression between the LST captured by Landsat as independent variables (LST sat [°C]) and simulated by ENVI-met as dependence variables (STsim [°C]). Pearson's correlation coefficient (R) is calculated to measure the rate of the linear relationship between the two variables. The root mean square error (RMSE) is also calculated to determine the original data's standard deviation. The regression model is calculated based on the following basic model:

$$STsim\ [°C]). = (ß_0 + ß_1\ LST\ sat\ [°C]) + \varepsilon$$

Where:

STsim [°C] – is the Dependent Variable (Surface temperature simulated by ENVI-met);
$ß_0$ – is the intercept of the regression model;
$ß_1$ – is the slope of the regression model;
LST sat [°C] – is the Independent Variables (Surface temperature captured by Landsat);
ε – is the residual term, error.

To further contextualise and understand the efficacy of both methods in determining the LST, the researchers chose eight spots of a size of (30×30) m from the studied area that are varied by their surface materials and covering. Areas covered by lawn, dense trees, stone finishing, asphalt or sand were chosen. Figure 4 shows the eight different points with described surface material variables. Notably, the discrepancy in spatial resolutions between Landsat imagery of 30 m and ENVI-met model output of 5m posed a methodological challenge. Mitigating this disproportion necessitated a process of spatial overlay facilitated by image manipulation software such as Photoshop. Using this method, a novel grid system mirroring the spatial resolution of Landsat imagery was overlaid onto ENVI-met outputs, enabling recalibration of LST readings for the designated locales. Subsequent comparative analysis between dataset outputs facilitated nuanced insights into the similarities and disparities inherent to both modalities.

3. RESULTS AND DISCUSSION

3.1. *Statistical comparison of LST from Landsat and ENV-met results*

A box plot whisker analysis was conducted to explain the descriptive relationship between three simulated dates and the LST data derived from Landsat imagery. The findings reveal a considerable range in simulated surface temperatures across the three dates, rating from 20°C to 47°C, 21°C to 46°C, and 18°C to 43°C, respectively, as depicted in Figure 5. In contrast, analysis of the satellite imagery reveals comparatively less variability, with temperature ranges of 27°C to 33°C, 25°C to 30°C, and 23°C to 27°C across the corresponding dates.

The observed variances in the surface temperature by the ENVI-met could result from several factors. Firstly, differences in spatial resolution between the two datasets may contribute to deviation in temperature estimations, with Landsat potentially tending to generalise surface temperature across larger areas, or deviations may appear from limitations in the Landsat's capacity to accurately detect microclimatic temperature variations, particularly relating to localised meteorological conditions. On the other hand, regarding ENVI-met, some meteorological conditions occurring before the specified simulation date may affect surface temperatures but remain unaccounted for within the ENVI-met framework.

Figure 4 Specific spots from the study area, showing the top view, photos and surface specification of the studied area

However, as an overall view of the variances, it can be noticed that the median surface temperature extrapolated from both datasets remains very close to each other on the three observed days. The observed median surface temperature on day 1 was 34°C in ENVI-met and 31°C in Landsat; on day 2, it was 32°C in ENVI-met and 27.5°C in Landsat; and on day 3, the values were even closer, with 27.5°C in ENVI-met and 25.5°C in Landsat. This indicates that the results are still relevant and can be further compared and analysed.

A regression diagnostic test was conducted to determine the relationship between ENVI-met simulations and LST data from Landsat. The results indicate significant validation, with a (R2) value of 0.97 ($p < 0.001$) on day 1, 0.95 ($p < 0.01$) on day 2, and 0.98 ($p < 0.01$) on day 3. These high R2 values suggest a strong correlation between the simulated and observed data across all three days, as shown in Figure (6).

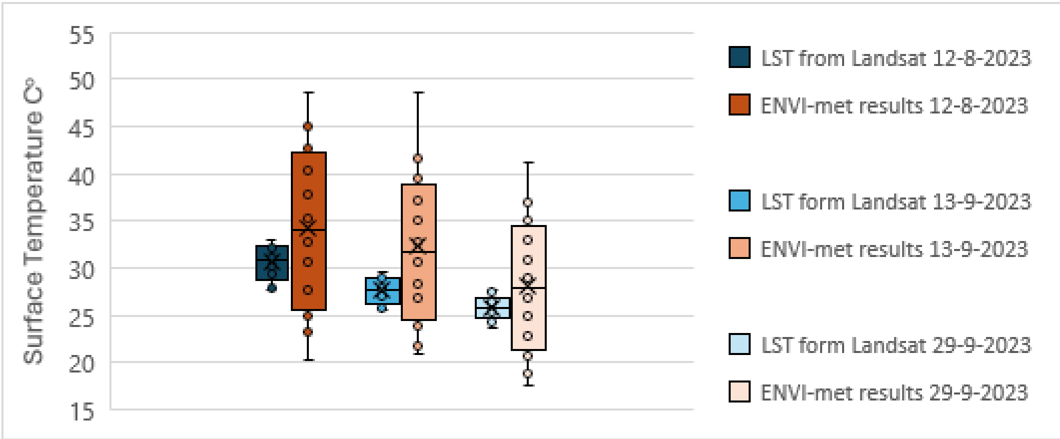


Figure 5 Box plot whiskers showing the surface temperature range between ENVI-met results and LST from Satellite

Furthermore, the Root Mean Square Error (RMSE) values provide insights into the accuracy of the simulations. On day 1, the RMSE is 3.5°C, indicating a relatively small deviation between the simulated and observed LST. Day 2 shows a slightly higher RMSE of 4.6°C, suggesting a more considerable discrepancy between the simulation and observation than on day 1. However, on day 3, the RMSE drops to its lowest value of 2.4°C, indicating the closest agreement between the simulated and observed LST.

The decreasing trend in RMSE from day 1 to day 3 is due to the complexity of the microclimatic variables surrounding the urban areas, such as the cloud percentage, which is usually fixed by default ranges inside the software. However, the overall regression diagnostic test indicates strong agreement between ENVI-met simulations and Landsat-derived LST data, with the simulations demonstrating high accuracy and reliability across multiple days. These results suggest that LST from satellite imaging could be another methodology for calibrating ENVI-met models, as it has not been indicated in scholarly works before, to the author's knowledge.

3.2. *Comparison of LST results between spots of different surface materials*

As mentioned before, eight spots were selected, each featuring varying surface materials, to observe their behaviour regarding the surface temperature in both satellite imagery and simulation of ENVI-met. To overcome the disproportion of the resolution between the LST image from the satellite with 30 m resolution and 5 m resolution of ENVI-met outputs, a new grid system was added to the ENVI-met result’s image equal to the size of the resolution of the satellite image. Recalculation of the ENVI-met surface temperature for the spots of 30×30 was carried out, and the average temperature was extrapolated and compared with the exact spot of the satellite images, as shown in Figure 7.

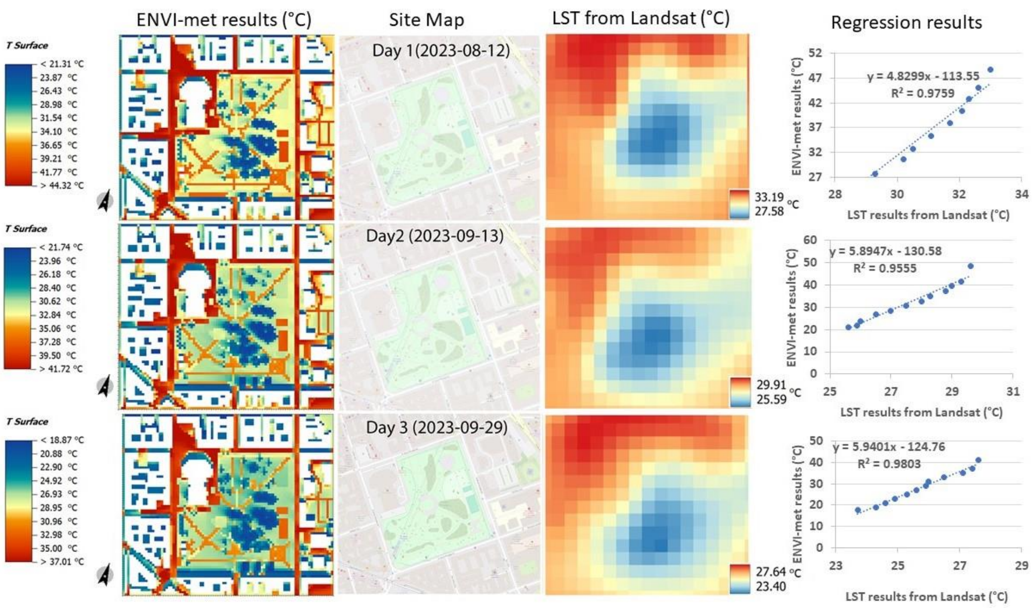


Figure 6 Surface temperature and regression diagnostic results between LST from satellite and ENVI-met simulations

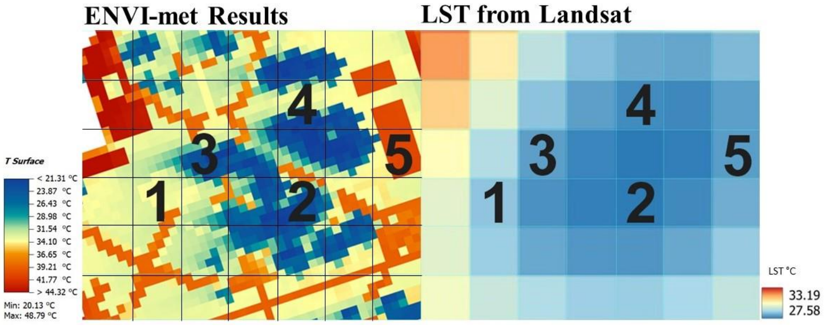
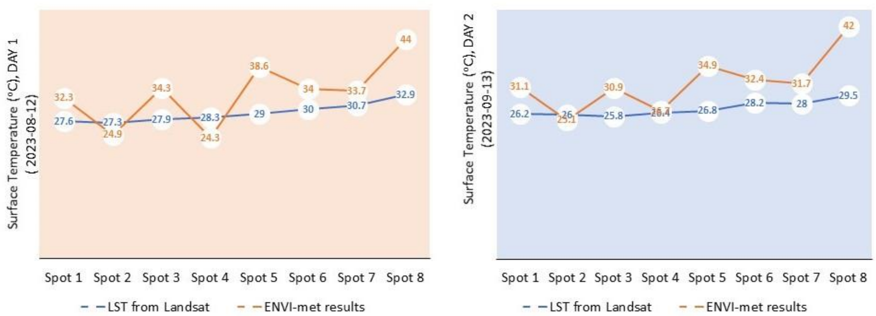


Figure 7 Re-scaling of the ENVI-met image results based on the satellite image resolution.

The results of the methods show that the ENVI-met outputs of the surface temperature for hard surfaces such as concrete or asphaltic surfaces were considerably higher than the outputs of the satellite images. For instance, spot 5 represents the concrete surface, surface temperature change between satellite images and ENVI-met results ranged between (5-9)ºC during the three observed days (Figure 8). Moreover, at spot 8, representing an asphaltic parking lot, the surface temperature change between both data sets was even more, at least 10ºC. However, in spot zones with dense trees with either lawn surface or sand surfaces, such as spots 2 and 4, the surface temperature simulated by ENV-met was lower than the remote sensing images. Probably, that is because of the difference in the methodology of capturing the surface temperature in both data sets, as the remote sensing imagery takes the picture above the trees and ENVI-met takes the simulation below the tree's areas. Common sense is that the temperature will be lower under the shaded area than in the area exposed to solar radiation. These findings have not been mentioned or observed in previous scholarly works.

The surface temperature difference was between 1-3ºC lower in the ENVI-met results during the three observed days. Moreover, at spots without shades and with different surface types, such as lawny areas surrounded by trees (spot 1), lawny areas surrounded by stone pathways (spot 2), sandy areas (spot 6), and concrete pedestrian rout surrounded by trees and asphaltic road (spot 7), the surface temperature difference was slightly higher in ENVI-met than satellite imagery depending on the typology of the surface. The observed average surface temperature difference is 4ºC in Spot 1,4.3ºC in Spot 2, 3ºC in Spot 6, and 2.6ºC in Spot 8. The more complex the surface is, with more thermal mass and lower albedo property, the higher the surface temperature read by ENVI-met than by remote sensing.



	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot 6	Spot 7	Spot 8
LST from Landsat	27.6	27.3	27.9	28.3	29	30	30.7	32.9
ENVI-met Results	32.3	24.9	34.3	24.3	38.6	34	33.7	44
LST from Landsat	26.2	26	25.8	26.4	26.8	28.2	28	29.5
ENVI-met Results	31.1	25.1	30.9	26.7	34.9	32.4	31.7	42
LST from Landsat	24.3	23.8	28.9	24.8	24.5	26	26.6	27.6
ENVI-met Results	24.7	21.6	26.2	23.2	29.2	26.7	27.9	37.2

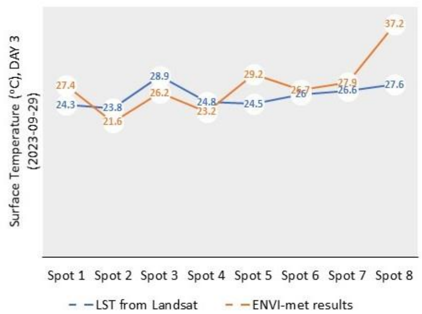


Figure 8 compressions of the surface temperature between the results of the ENVI-met and Satellite Image of the eight selected spots from the study area

4. CONCLUSION

Exploring urban heat islands (UHI) and methods for monitoring land surface temperature (LST) within urban environments offers critical insights into the complex interplay between urbanisation, climate change, and environmental health. The research delves into the challenges UHI effects pose and the necessity for effective mitigation strategies.

Satellite observation and remote sensing are indispensable tools for monitoring LST at various scales, offering extensive coverage and temporal resolution. However, challenges persist in accurately capturing microclimatic variations, especially within densely urbanised areas. The ENVI-met model provides a complementary approach, simulating microscale climate conditions with high spatial resolution and incorporating dynamic interactions between urban surfaces, vegetation, and the atmosphere.

The comparative analysis conducted in this study reveals both the strengths and limitations of satellite imagery and ENVI-met simulations in capturing spatiotemporal variations in LST. While satellite imagery offers broader coverage and consistent revisits over time, ENVI-met simulations provide finer-grained insights into localised microclimatic conditions. The observed discrepancies between the two methods underscore the importance of considering methodological differences and environmental factors influencing temperature dynamics.

Statistical analyses, including regression diagnostics and RMSE calculations, demonstrate a strong correlation between LST derived from satellite imagery and ENVI-met simulations, suggesting the potential for calibrating ENVI-met models using satellite-derived data. However, variations in surface materials and canopy coverage introduce complexities, with ENVI-met often overestimating surface temperatures on hard surfaces and underestimating temperatures in shaded areas. The methodology suggested in this paper has not been mentioned or observed in previous scholarly works, which offers further investigation in the future.

Overall, the study emphasises the complementary nature of satellite observation and numerical simulation approaches in understanding and mitigating urban heat island effects. By integrating these methodologies and considering local environmental conditions, policymakers and urban planners can develop more effective strategies for climate-sensitive urban design and sustainability assessments.

5. STUDY LIMITATION AND DIRECTION OF FUTURE STUDIES

This study has several limitations that warrant consideration and provide opportunities for future research. First, the temporal scope of the analysis was constrained to three sample days, two of which were in September. While this timeframe enabled a meaningful comparison of Land Surface Temperature (LST) data between ENVI-met simulations and Landsat imagery, it may not fully capture the peak summer Urban Heat Island (UHI) effects. Future studies should consider incorporating additional sample days during the height of summer to provide a more comprehensive assessment of UHI dynamics and seasonal variations.

Second, although this study demonstrates a strong correlation between simulated and observed LST data, localized discrepancies were observed in certain areas, with temperature differences exceeding 10^{o}C in some areas. These deviations highlight the need for further refinement of simulation models and data preprocessing techniques. Future research should investigate the underlying causes of these discrepancies, such as variations in surface material properties, urban morphology, or microclimatic influences, to enhance the accuracy of UHI modelling.

Addressing these limitations will not only strengthen the reliability of ENVI-met and Landsat-derived analyses but also contribute to advancing the understanding of urban thermal environments in diverse climatic and geographic contexts.

6. REFERENCES

[1] **Oke, T**., The energetic basis of the urban heat island. *Quarterly journal of the royal meteorological society, 1982. 108(455): p. 1-24.*

[2] **Brysse, K., et al**., Climate change prediction: Erring on the side of least drama? *Global environmental change, 2013. 23(1): p. 327-337.*

[3] **Hartz, D.A., A.J. Brazel, and G.M. Heisler,** A case study in resort climatology of Phoenix, Arizona, USA. *International Journal of biometeorology, 2006. 51: p. 73-83.*

[4] **Harlan, S.L., et al**., Neighborhood microclimates and vulnerability to heat stress. *Social science medicine, 2006. 63(11): p. 2847-2863.*

[5] **Stone Jr, B.**, Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American planning association, 2005. 71(1): p. 13-25.*

[6] **Akbari, H., M. Pomerantz, and H. Taha**, Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar energy, 2001. 70(3): p. 295-310.*

[7] **Salih, K., Z.O. Saeed, and A. Almukhtar**, Lessons from New York high line green roof: conserving biodiversity and reconnecting with nature. *Urban Science, 2021. 6(1): p. 2.*

[8] S**antamouris, M., et al.**, Progress in urban greenery mitigation science–assessment methodologies advanced technologies and impact on cities. *Journal of Civil Engineering and Management2018. 24(8): p. 638-671.*

[9] **Liu, Z., et al.**, An in-depth analysis of the effect of trees on human energy fluxes. Urban Forestry Urban Greening, 2020. 50: p. 126646.

[10] **Li, Z.L., et al.**, Satellite remote sensing of global land surface temperature: *Definition, methods, products, and applications. Reviews of Geophysics, 2023. 61(1): p. e2022RG000777.*

[11] **Duan, S.-B., et al.** Temporal normalization of Terra-MODIS land surface temperature product. in 2013 IEEE *International Geoscience and Remote Sensing Symposium-IGARSS. 2013. IEEE.*
[12] **Jombach, S., et al**., Green Space Intensity, Land Surface Temperature and Green Canopy Top Mapping: A Case Study in the Suburban Settlement of Törökbálint, Hungary. *Journal of Digital Landscape Architecture, 2023: p. 417-425.*
[13] **Zhu, W., A. Lű, and S. Jia,** Estimation of daily maximum and minimum air temperature using MODIS land surface temperature products. *Remote Sensing of Environment, 2013. 130: p. 62-73.*
[14] **Wu, W., L. Li, and C. Li,** Seasonal variation in the effects of urban environmental factors on land surface temperature in a winter city. *Journal of Cleaner Production, 2021. 299: p. 126897.*
[15] **Yao, L., et al.**, How the landscape features of urban green space impact seasonal land surface temperatures at a city-block-scale: An urban heat island study in Beijing, China. *Urban Forestry & Urban Greening, 2020. 52: p. 126704.*
[16] **Hassan, Y.N., et al.,** A Comparative Assessment of UGS Changes and Accessibility Using Per Capita Metrics: A Case Study of Budapest and Vienna. *Journal of Digital Landscape Architecture, 2024: p. 723-734.*
[17] **Shukla, A. and K. Jain**, Analyzing the impact of changing landscape pattern and dynamics on land surface temperature in Lucknow city, India. *Urban forestry & urban greening, 2021. 58: p. 126877.*
[18] **Mallick, J., Y. Kant, and B. Bharath,** Estimation of land surface temperature over Delhi using Landsat-7 ETM+. *J. Ind. Geophys. Union, 2008. 12(3): p. 131-140.*
[19] **John, J., et al.,** Land use/land cover and land surface temperature analysis in Wayanad district, India, using satellite imagery. *Annals of GIS, 2020. 26(4): p. 343-360.*
[20] **Toparlar, Y., et al.,** A review on the CFD analysis of urban microclimate. *Renewable Sustainable Energy Reviews, 2017. 80: p. 1613-1640.*
[21] **Yang, Y., et al.**, The "plant evaluation model" for the assessment of the impact of vegetation on outdoor microclimate in the urban environment. *Building environment, 2019. 159: p. 106151.*
[22] **Simon, H.**, Modeling urban microclimate: development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met. 2016, Mainz, Univ., Diss., 2016.
[23] **Salih, K. and I.R. Báthoryné Nagy**, Review of the Role of Urban Green Infrastructure on Climate Resiliency: A Focus on Heat Mitigation Modelling Scenario on the Microclimate and Building Scale. *Urban Science, 2024. 8(4): p. 220.*
[24] **Morakinyo, T.E., et al**., A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. Building Environment, 2017. 115: p. 1-17.
[25] **Liu, Z., et al.**, Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment, 2021. 200: p. 107939.*
[26] **Kotharkar, R. and P. Dongarsane**, Investigating outdoor thermal comfort variations across Local Climate Zones in Nagpur, India, using ENVI-met. *Building and Environment, 2024. 249: p. 111122.*
[27] NASA. LANDSAT 8. 2013 5/11/2024]; Available from: https://landsat.gsfc.nasa.gov/satellites/landsat-8/.
[28] **Herlawati, H., et al**. Evaluating the Effects of Mobility Restrictions during COVID-19 on Land Surface Temperature with GIS and Satellite Data. in 2023 Eighth International Conference on Informatics and Computing (ICIC). 2023. IEEE.