Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 37, 2025, Sofia

COMPARATIVE ANALYSIS OF URBAN HEAT ISLAND INTENSITY: A STUDY OF TEN GREEK CITIES

Paraskevi E. Gkatzioura, Konstantinos Perakis

Department of Planning and Regional Development, School of Engineering,
University of Thessaly
e-mail: pgkatzioura@uth.gr

Keywords: *Urban Heat Island; Google Earth Engine; Land Surface Temperature; Landsat; Sustainable Development Goals*

Abstract

This paper examines the Urban Heat Island (UHI) phenomenon across ten regions in Greece, leveraging Google Earth Engine (GEE) to process and analyze remotely sensed data. UHI intensity is assessed by calculating Land Surface Temperature (LST) and the Urban Thermal Field Variance Index (UTFVI), allowing for precise monitoring of thermal variations in urban and peri-urban environments. The selected study areas are characterized by varied population densities and geographic features, providing insights into how urbanization, land use, and climatic conditions influence UHI intensity.

Results indicate significant seasonal and spatial variability in UHI patterns, with inland regions experiencing greater thermal stress compared to coastal areas, partly due to the moderating effects of sea breezes. Notably, urban planning and green infrastructure are shown to play a critical role in reducing UHI impact, underscoring the need for sustainable urban planning practices. This research highlights the importance of UHI monitoring to inform mitigation strategies and assess the socio-economic costs associated with heat stress, particularly under conditions of rapid urban expansion and climate change.

1. Introduction

The increase in atmospheric temperature, combined with the Land Surface Temperature (LST), plays a decisive role in the climate crisis [1]. Since the second half of the 20th century, the rapid urbanization of cities, in combination with continuous changes in urban planning, technological advancement, human activities, structures, and the general increase in population, has been directly linked to the economic development and urban sustainability of cities [2].

The intensification of this phenomenon has become the most critical challenge of the 21st century globally, as dramatic changes in land cover were made to address issues related to urban economic growth and residents' needs [3].

The Urban Heat Island (UHI) phenomenon is inextricably linked to both human activity within cities and productive activities, and it has been extensively studied across a wide geographic range (Kim and Brown, 2021). The intensity of the UHI phenomenon is influenced and co-shaped by a set of factors (economic, social, topographical) [4], making its long-term study crucial for mitigating its impacts across various sectors and achieving environmental sustainability.

In order to create sustainable urban environments, systematic analyses of the dynamic phenomena affecting them, such as UHI effect, are essential. Remote sensing is a valuable tool for continuous observation, providing data to monitor and analyze thermal and environmental changes in urban areas [5].

Accordingly, the purpose of this study is to evaluate UHI intensity under various conditions across ten different regions in Greece. Specifically, the study aims to analyze the factors that influence UHI intensity, identify any unique typological characteristics of the phenomenon, and determine patterns and trends of the same intensity in coastal and inland regions.

The applied algorithm was launched within the Google Earth Platform Engine (GEE) platform. Google Earth Engine enables users to access and analyze time-series data from remote sensing data without requiring additional local storage capacity [6].

2. Materials and Methods

2.1. Study Areas

The selection of the ten Regions Of Interest (ROI) shown in Fig.1 was based on their population density and economic activity, measured by Gross Domestic Product (GDP) and population data distribution from the 2021 Census[1] regarding population distribution, as these regions commonly face similar challenges related to rapid urban development, environmental impacts, and socio-economic disparities.

[1]Hellenic Statistical Authority: https://elstat-outsourcers.statistics.gr/census_results_2022_en.pdf

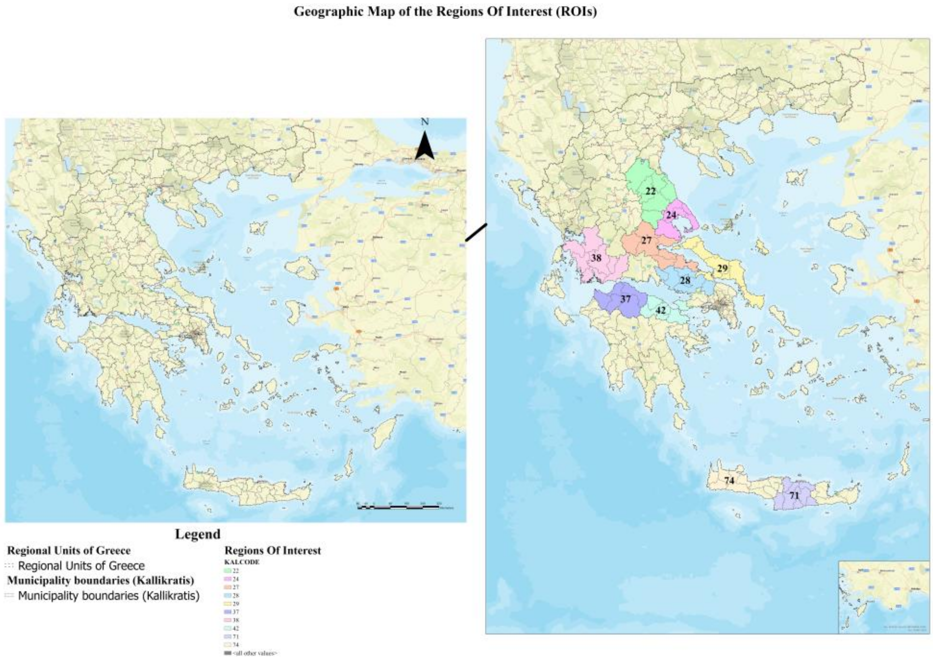

Fig. 1. Location map of the Regions of Interest

In determining these areas, spatial criteria such as the identity of the regions and their degree of polycentricity were also considered. The regions of Attica and Thessaloniki were excluded from the analysis, as their polycentric structure significantly influences the Urban Heat Island effect. Additionally, most island regions, except Crete and Euboea, were excluded due to their high population density [7].

The administrative boundaries of the study areas were obtained from the official website of the Greek National Open Data Catalogue[2]. This platform acts as a central hub for accessing and sharing spatial data across Greece, providing a comprehensive collection of geospatial datasets, including land cover, topography, transport networks, administrative boundaries, and more, all freely accessible to the public.

2.2. Input Data

Google Earth Engine (GEE), launched in 2010 by Google LLC, is a cloud-based geospatial data processing platform built on Google's computational infrastructure and open-access satellite data [6]. GEE has become the most widely

[2]Greek National Open Data Catalogue: https://geodata.gov.gr/dataset/

used platform for large-scale environmental and spatial analysis, supporting applications in vegetation monitoring [8], forest ecosystem assessment [9],[10], agricultural analysis, land cover change detection[11], and climate change impact studies through its "Climate Engine" [12].

Its functionality extends to urban environment analysis, hydrological cycles [13], coastal areas [14], and natural disaster response. A key advantage of GEE is its ability to perform data analysis entirely online without the need for data downloads, enabling efficient processing of large datasets.

In this study, we developed a GEE algorithm to determine Land Surface Temperature (LST) and analyze the Urban Heat Island effect at a 30 m resolution using Landsat 8 imagery with cloud cover less than 30%.

This analysis includes the Urban Thermal Field Variance Index (UTFVI) to evaluate thermal stress in urban areas. Utilizing GEE's cloud computing infrastructure allows for efficient processing of large-scale spatial and temporal data, eliminating the need for substantial local computing resources and enabling near real-time global analysis. GEE's scalability thus supports diverse applications across environmental monitoring, land use analysis, climate assessment, disaster management, and urban planning [16].

2.3. Computation of LST retrieval, SUHI & UTFVI Indices

The methodology section will outline the stages involved in image processing, extracting LST, estimating the magnitude of Surface Urban Heat Island (SUHI), and calculating the UTFVI Index, as well as exploring the correlation between SUHI and UTFVI. Specifically:

- The annual median LST was calculated using the GEE platform by analyzing data from the Landsat 8 Collection 2 Level 2 for the period 2019 to 2023. This approach enables accurate temporal assessment of thermal variations across the ROIs, utilizing GEE's computational capabilities to handle and analyze extensive datasets efficiently
- The annual average LST was computed for our study areas (ROI) to determine both the UHI intensity and UTFVI

UHI effect during the daytime was derived based on daily average temperatures. The UHI phenomenon occurs when the temperature in an urban center exceeds that of its surrounding areas. In order to compare UHI variations across different years, normalization was carried out using Eq. (1) as described by [17]:

(1)

$$SUHI = \frac{LST - LSTmean}{STD}$$

Where *LST is the land surface temperature*, *LSTmean is the mean land surface temperature*, and *STD is the standard deviation*.

Urban Thermal Field Variance Index (UTFVI) is applied in this study using Eq. (2) given by [18].

(2)

$$UTFVI = \frac{Ts - Tm}{Tm}$$

Where *Ts is the land surface temperature, Tm is the mean LST of the area.*

The Urban Thermal Field Variance Index is used to quantify the thermal homogeneity in urban areas, contributing to the assessment of prevailing environmental conditions. Depending on the intensity of the UHI phenomenon, it is classified into six levels for evaluating thermal differences and environmental stress [19].

Table 1. Threshold values of the Urban Thermal Field Variance Index (UTFVI) and ecological evaluation index

Urban Thermal Field Variation Index	Urban Heat Island Phenomenon	Ecological Evaluation Index
<0	None	Excellent
0-0,0005	Weak	Good
0,0005-0,010	Middle	Normal
0,010-0,015	Strong	Bad
0,015-0,020	Stronger	Worse
>0,020	Strongest	Worst

UTFVI values reflect different levels of environmental quality determined by thermal dispersion and temperature distribution within an area. These metrics provide critical insights into the region's thermal dynamics and potential ecological impacts, enabling the evaluation of environmental stress and sustainability challenges in urban ecosystems.

3. Results and Analysis

Following the theoretical analysis of the UHI phenomenon and examining the study areas, several conclusions emerge.

The Urban Heat Island phenomenon is, and will continue to be, a phenomenon manifesting with varying intensity and typology across modern urban centers, depending on environmental and climatic influences. Each ROI may be affected by one or more factors, which interact and shape the urban microclimate and prevailing conditions.

Table 2. Factors Influencing the Intensity of the Urban Heat Island (UHI) Phenomenon in the Greek Study Areas

Factors		Region Of Interest (ROI)	Cause
Location	Inland Areas	Larissa	
	Coastal Areas	Magnesia, Phiotis, Euboea, Corinthia, Aetolia-Acarnania	Sea Breeze
Urbanization & Lack of Urban Green Spaces		Larissa, Heraklion	Lack of regulatory framework and inability to adapt promptly to the climate crisis
Natural Disasters	Flood Events	Magnesia	Climate Change
	Heatwaves	Western Attica	
	Forest Fires	Euboea	
Climatic Factors		Heraklion, Chania	Climate Change
Urban Characteristics		Achaea	Urban Planning

Table 2 presents the categorization of the study areas according to the factors contributing to the UHI phenomenon.

Coastal regions such as Volos and Phthiotis benefit from the sea breeze, which helps reduce atmospheric temperatures and, consequently, the intensity of the UHI phenomenon, resulting in a milder thermal environment. Specifically, in the Region of Magnesia, a reduction in the UHI Index was recorded in 2023 due to the cooling effect caused by the destructive floods. Conversely, inland regions, such as the Region of Larissa, exhibit a higher intensity of the UHI phenomenon. The lack of proximity to the sea and limited air circulation contribute to higher temperatures and increased thermal stress in the urban environment.

Additionally, these regions have high population density and increased urbanization, where thermal stress is intensified due to the limited presence of green spaces and dense construction. The region of Heraklion has characteristics similar to those of Larissa.

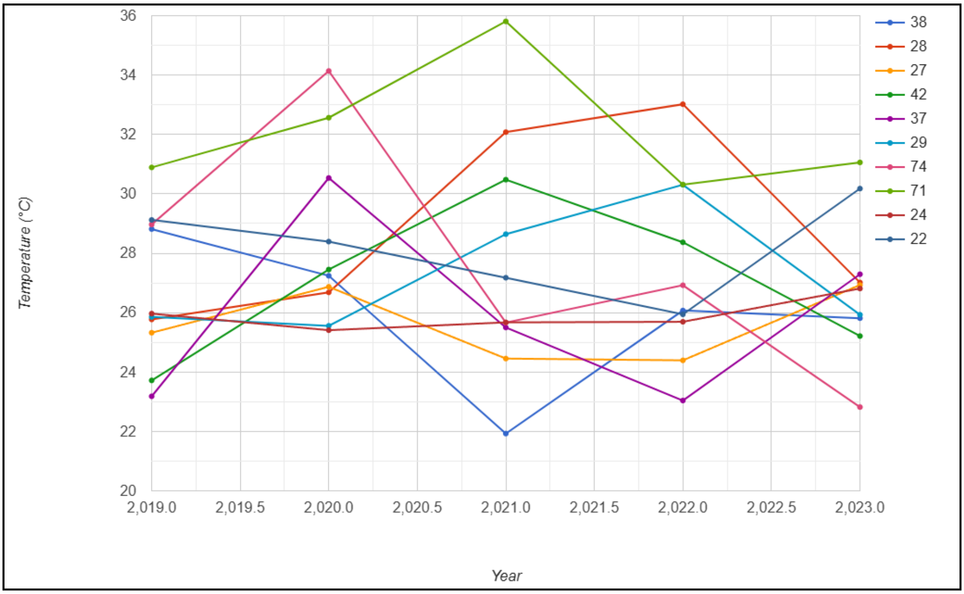

Fig. 2. Time Series Analysis of the Mean Temperature for all ROIs

The severe heatwave events observed across the country, such as during the summer of 2023, led to an increase in average temperatures and an intensification of the Urban Heat Island (UHI) phenomenon. This is particularly noticeable in central cities of the mainland, where thermal stress is higher, such as in the regions of Boeotia and Larissa.

On the other hand, the wildfires in the region of Euboea in 2021 resulted in the loss of extensive forest areas, which increased the absorption of solar radiation and created local heat islands. This negatively impacted the thermal balance of the area and raised the UHI Index.

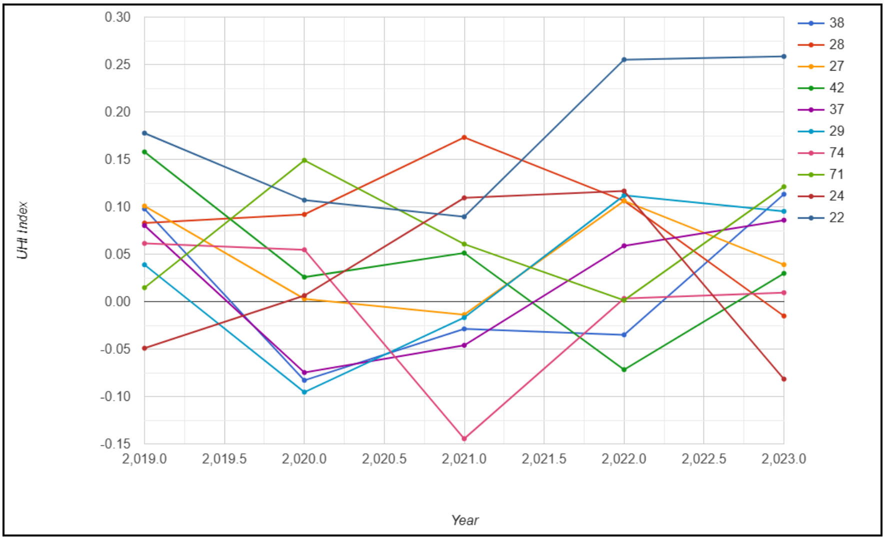

Fig. 3. Time Series Analysis of the UHI for all ROIs

A distinct case among the study areas is the region of Achaia, where specific urban planning characteristics result in a reduced UHI Index. This highlights the importance of urban planning in managing and mitigating the Urban Heat Island effect.

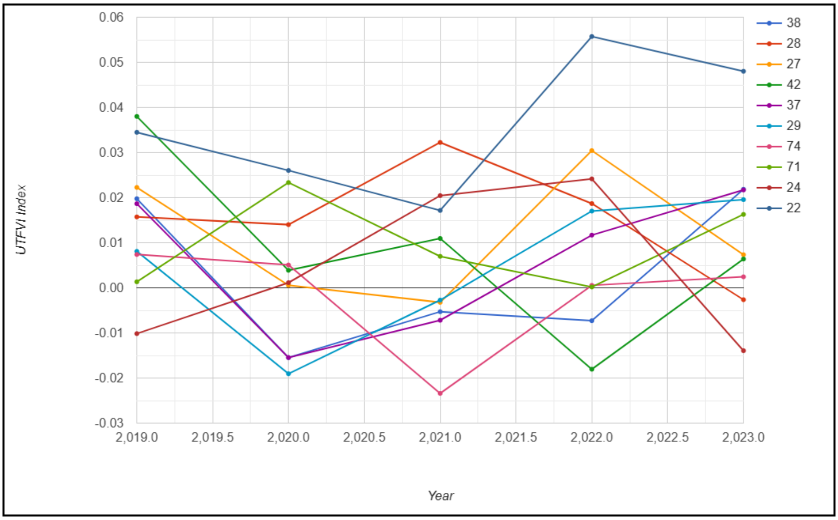

Fig. 4. Time Series Analysis of the UTFVI for all ROIs

Figure 5 illustrates the comparative analysis of mean temperature, UHI, and UTFVI across the studied regions, providing a clear comparison of thermal conditions and Urban Heat Island intensity.

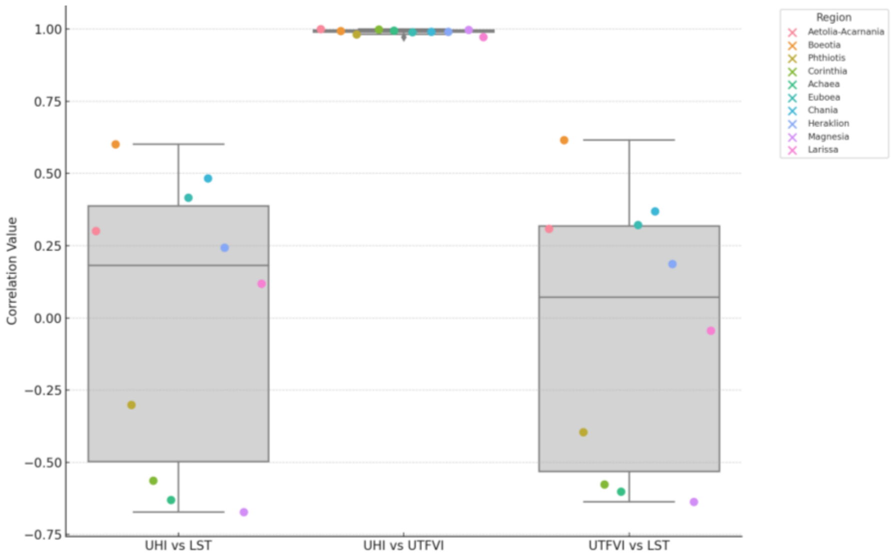

Fig. 5. Comparative analysis of UHI, LST, and UTFVI correlations across Regions

As we noticed, the correlations between the Urban Heat Island (UHI) Index and the Urban Thermal Field Variance Index (UTFVI) are particularly strong, with correlation coefficient values (r) ranging from 0.97 to 1 across all examined areas. This indicates that as temperatures rise due to the UHI effect, the UTFVI Index also increases correspondingly. This near-perfect positive correlation suggests that the rise in temperatures caused by the UHI effect has a direct impact on thermal variations, significantly affecting the thermal comfort of residents.

Regarding the correlation between Land Surface Temperature (LST) and the UHI Index, significant differences are observed depending on the area. According to the results in the Table 3, regions such as Aetolia-Acarnania, Chania, Heraklion, and Phthiotis exhibit a positive correlation between LST and UHI, indicating that the increase in average temperature is proportional to the intensity of the UHI phenomenon.

Conversely, in other regions, such as Phthiotis, Corinthia, Achaea, and Magnesia, a negative correlation is recorded, suggesting that an increase in UHI intensity is associated with a decrease in surface temperature. These variations may be due to differing degrees of UHI influence on local temperatures in each area, as well as the impact of other environmental factors.

Table 3. Correlation coefficients between UHI, LST, and UTFVI across regional units, showing temperature and thermal variance relationships

Regional Unit	OBJECT ID	UHI vs LST	UHI vs UTFVI	UTFVI vs LST
Aetolia-Acarnania	38	0.301	1.000	0.309
Boeotia	28	0.601	0.994	0.616
Phiotis	27	-0.301	0.982	-0.396
Corinthia	42	-0.564	0.999	-0.577
Achaia	37	-0.631	0.995	-0.601
Euboea	29	0.416	0.990	0.322
Chania	74	0.483	0.991	0.369
Heraklion	71	0.244	0.992	0.187
Magnesia	24	-0.673	0.998	-0.637
Larissa	22	0.119	0.973	-0.044

Notably, areas with a negative correlation between surface temperature and the UHI index share a common geographic feature: They are located near the coastline. The sea acts as a natural temperature regulator, reducing the thermal fluctuations caused by the UHI effect and highlighting the importance of geographic location in shaping strategies to mitigate the impact of this phenomenon.

Furthermore, the results of the correlation between UHI and UTFVI Indices vary according to the characteristics of each region. In areas such as Aetolia-Acarnania and Boeotia, a positive correlation is observed, indicating that the increase in UHI intensity is accompanied by a uniform distribution of thermal load, suggesting balanced thermal diffusion.

In contrast, areas such as Phthiotis and Corinthia show a negative correlation, indicating that an increase in atmospheric temperature is associated with thermal heterogeneity, or an uneven distribution of heat.

Conclusions

In this work, a methodology was developed to investigate the behavior of the UHI phenomenon, based on the large-scale analysis capabilities of GEE. GEE platform supports broad urban area coverage, enabling the methodology to be applied across multiple geographic locations and over various time periods.

According to the results, the ten ROIs were presented: they clearly show how urbanization influenced the UHI magnitude according to the LST changes. The findings reveal a strong correlation between increased urbanization and elevated UHI intensity, highlighting the role of land surface changes in amplifying heat stress in urban areas.

Analyzing UHI patterns and trends over time provides valuable insights into how different regions are affected. It serves as an essential tool for developing mitigation strategies and estimating the socio-economic costs associated with UHI effects. As UHI contributes to higher energy consumption, increased cooling costs, and deteriorating public health outcomes, understanding and addressing this phenomenon is crucial for minimizing long-term economic and societal impacts.

The study emphasizes that adopting green infrastructure, such as expanding green spaces and improving urban design, can significantly reduce the economic burden of managing heat-related stress in urban environments, thereby contributing to more sustainable and cost-effective urban development strategies. In the future, it would be valuable to study the impact of the urban heat island effect on residential energy costs across various environments with different characteristics.

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СРАВНИТЕЛЕН АНАЛИЗ НА ИНТЕНЗИТЕТ НА ТОПЛИННИЯ КУПОЛ НАД ГРАДСКИТЕ ЗОНИ: ИЗСЛЕДВАНЕ НА ДЕСЕТ ГРЪЦКИ ГРАДА

П. Грациура, К. Перакис

Резюме

Настоящото изследване анализира феномена на градски топлинен купол (UHI) в десет региона на Гърция, като използва Google Earth Engine (GEE) за обработка и анализ на дистанционно заснети данни. Интензитета на UHI се оценява чрез изчисляване на температурата на земната повърхност (LST) и индекса на вариация на градското топлинно поле (UTFVI), което позволява прецизно картографиране и мониторинг на топлинните вариации в градските и пери-урбанизираните територии. Избраните райони на изследване се характеризират с разнообразна гъстота на населението и географски особености, което дава възможност за задълбочен анализ на влиянието на

урбанизацията, земеползването и климатичните условия върху интензитета на UHI. Резултатите показват значителни сезонни и пространствени различия в UHI, като вътрешноконтиненталните региони са подложени на по-голям топлинен стрес в сравнение с крайбрежните зони, отчасти поради охлаждащия ефект на морските бризове. Освен това, градското планиране и зелената инфраструктура играят съществена роля в смекчаването на UHI ефекта, което подчертава необходимостта от прилагане на устойчиви урбанистични стратегии.

Настоящото изследване подчертава значението на мониторинга на UHI за разработването на ефективни мерки за неговото ограничаване, както и за оценка на социално-икономическите последици, свързани с топлинния стрес, особено в контекста на бързата урбанизация и климатичните промени.