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# MAPPING AND DATA VISUALIZATION OF LAND COVER SURFACE HEAT DYNAMICS IN SOFIA, BULGARIA

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***Key words:*** *ECOSTRESS; urban heat; land surface temperature; heatwaves*

***Abstract***

*Heatwaves represent an increasingly critical challenge for European cities, particularly in regions with ageing populations and complex urban structures. This study examines the spatial variability of surface temperatures in Sofia, Bulgaria, using a combination of high-resolution ECOSTRESS thermal imagery and detailed land-cover data from Urban Atlas 2018. Two contrasting ECOSTRESS acquisitions were analysed: an evening scene from 14 July 2024, captured during an intense heatwave, and a morning scene from 2 July 2025, representing the baseline thermal state after nocturnal cooling. Zonal statistics were used to extract Land Surface Temperature (LST) metrics for each Urban Atlas polygon, allowing a detailed comparison of thermal behaviour across functional land-cover types. Results show strong diurnal contrasts, with evening mean LST exceeding morning values by approximately 9–10° C, and the highest thermal loads occurring in compact urban fabric, industrial zones, and transportation infrastructure. Natural and semi-natural areas, as well as mountainous terrain, consistently exhibited lower temperatures, confirming their cooling function within the urban environment.*

## Introduction

Under more frequent and longer heat waves, the urban environment responds in a particularly sensitive way. Different data sources consistently show that the spatial distribution of surface temperatures mirrors the structure, density, and functional characteristics of underlying land cover. Sofia is a city located in an intermontane basin with a highly heterogeneous urban fabric, in which different surface types accumulate, retain, and release heat in different ways, leading to significant intra-urban temperature contrasts. These processes are particularly pronounced on days with increased heat stress, when night cooling is incomplete, and the day begins on already heated urban surfaces.

Classical meteorological observations in-situ provide valuable information on air temperature, but do not capture the direct contact of humans with the urban surface and do not reveal the spatial logic of thermal anomalies across different urban zones. Satellite observations in the thermal infrared range, which allow for the measurement of Land Surface Temperature (LST) at high spatial resolution, are particularly useful for providing insights. In this context, the ECOSTRESS instrument located at the International Space Station provides daily imaging with a resolution of 70 m, which makes it possible to map urban heat and its distribution at the level of neighbourhoods and even individual functional areas.

Research on heatwaves and their consequences for the human population has emerged only in the past few decades. Today, the availability of freely accessible satellite products, such as MODIS, Landsat & Sentinel-3 LST products, or the International Space Station's ECOSTRESS data, has accelerated the growth of studies dedicated to this topic. Over the last five years, analyses based on these datasets have been conducted across diverse regions of the world [1–3]. There are also a variety of studies [4, 5] using satellite data in the country consistently demonstrating the substantial impact of extreme heat on urban environments. There is also a noticeable increase in publications focused on population structure, urban ecology, and extreme events in Bulgaria. A portion of these works is directly or indirectly linked to the challenges posed by climate change in urban settings [6–9].

According to the National Institute of Meteorology and Hydrology's monthly bulletins [10, 11] in the summer of 2025 during the periods of 30 June 2025 and 09 July 2025, and between 19 July 2025 and 29 July 2025, the country was experiencing a heat wave, which meets the criteria defined for the presence of more than 5 consecutive days with a maximum air temperature above 32°C. In 2024, an intense heatwave affected the country between 06 July 2024 and 24 July 2024. Monthly temperatures exceeded climatological norms by +1.4°C to +3.9°C, and July 2024 was nearly as warm as July 2012, which was the warmest July since 1930. The highest temperatures in urban areas, ranging from 32°C to 42°C were registered between 14 and 18 July.

Bulgaria is among the fastest-ageing countries in Europe, with a steadily increasing share of the population over the age of 65 and a significant decline in the working-age segment. This demographic structure elevates the country's vulnerability to extreme heat because older adults are physiologically more sensitive to extreme temperatures and often have limited adaptive capacity. In this context, studying heat exposure and thermal risks becomes particularly important, as it supports urban planning interventions and public health measures that aim to protect the most vulnerable segments of society.

This paper aims to examine the spatial variability of surface temperatures in Sofia by combining ECOSTRESS morning and evening thermal observations with Urban Atlas land cover data. Through a comparative analysis of morning and evening ECOSTRESS acquisitions during a heatwave, the study assesses the thermal load of different functional urban areas and identifies the land cover types that contribute most strongly to heat accumulation and retention during periods of elevated thermal stress.

## Methods and Data

### Data sources

ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station) is a multispectral thermal infrared (TIR) instrument mounted on the International Space Station (ISS) [12]. It was designed to measure the temperature of the Earth's surface with high spatial and temporal detail. ECOSTRESS provides one of the most precise satellite-based Land Surface Temperature (LST) datasets currently available for environmental and urban studies. Because ECOSTRESS is hosted on the ISS, it does not follow a sun-synchronous orbit like other satellites used for urban studies & Earth observation. As a result, its overpass times are variable, allowing acquisition of surface temperature data at different moments of the diurnal cycle, for example, early in the morning, mid-day, or nighttime scenes. This characteristic of the data is highly advantageous for studying surface heat dynamics as it captures temperature states that are often missed by conventional sensors.

The research is based on two ECOSTRESS Land Surface Temperature (LST) scenes acquired over Sofia City Province during periods of elevated summer heat (Fig. 1). The first dataset represents an evening observation captured on 14 July 2024 at 20:53 local time, and the second corresponds to a morning observation taken on 2 July 2025 at 07:13 local time. Both scenes were selected as the only cloud-free or minimally impacted acquisitions available for the region during the respective summer seasons and captured during officially recognised heatwave periods by the National Institute of Meteorology and Hydrology's meteo bulletins.

Each ECOSTRESS scene provides surface temperature at a spatial resolution of 70 m. Prior to the analysis, both datasets were inspected for cloud-related pixels. In the 2024 scene, pixels affected by clouds were excluded entirely to ensure the reliability of the temperature statistics. They were located outside the city centre, which allowed further analysis without extracting important parts of the studied territory. The 2025 morning scene did not contain cloud-contaminated areas within the study extent.

To characterise the functional structure of Sofia's urban landscape, the study uses the dataset of Copernicus Land's product Urban Atlas 2018 V1 [13], a Copernicus dataset offering harmonised, high-resolution land-cover and land-use information for European cities. Urban Atlas polygons provide detailed classification of artificial surfaces, green urban areas, industrial zones, transportation infrastructure, agricultural land, forests, and water bodies. This spatial framework allows for a fine-grained assessment of thermal patterns across functionally distinct urban zones and is widely used in many studies and urban planning activities.

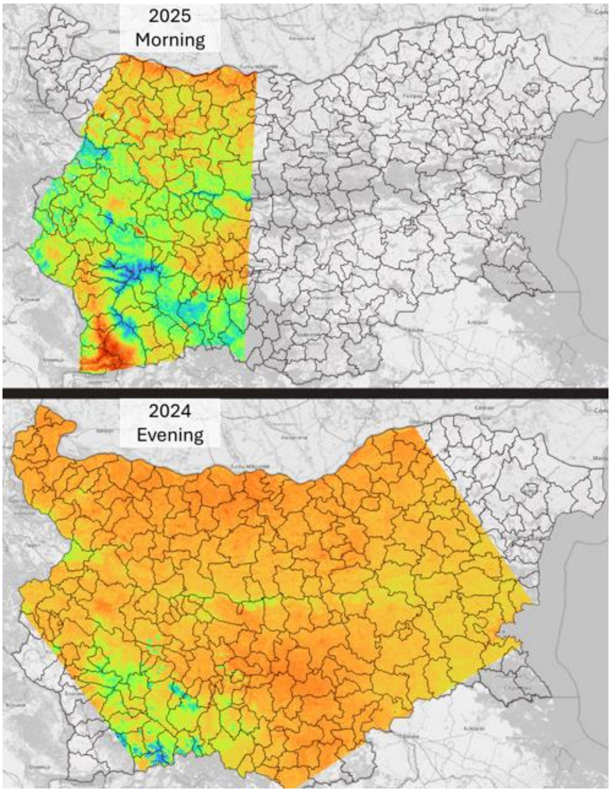


*Fig. 1. ECOSTRESS data captured during heatwave periods used in the study*

The combination of ECOSTRESS LST data with Urban Atlas polygons allows for a robust assessment of thermal load across different urban surfaces and supports a more nuanced interpretation of observed temperature patterns, particularly in complex and heterogeneous cities such as Sofia.

**Zonal Statistics and Data Harmonisation**

The surface temperature statistics of the rasters were converted from Kelvin to Celsius and then were derived using the Zonal Statistics tool in QGIS. For every Urban Atlas polygon, key descriptive indicators of the LST distribution were computed – minimum, maximum, mean, and median temperature values. These statistics were calculated separately for the 2024 evening and 2025 morning scenes. All statistics were harmonised to a unified naming scheme to enable consistent comparison between the two datasets. Polygons with zero pixel coverage were removed. To support comparative analyses, an additional "broad land cover group" attribute was created based on the hierarchical structure of Urban Atlas codes, grouping polygons into categories such as Artificial surfaces, Agricultural areas, Natural and semi-natural areas, Wetlands, and Water bodies.

The harmonised datasets were merged into a single analytical table, preserving for each polygon its land-cover classification, area, and population (sourced from the layer Urban Atlas 2018), and LST statistics for both time periods. The comparison focuses on the overall temperature distributions in morning vs evening conditions, the differences in thermal load across broad Urban Atlas groups, detailed contrasts between specific land-cover classes, and the magnitude of evening–morning temperature differences for each class (Fig. 2).

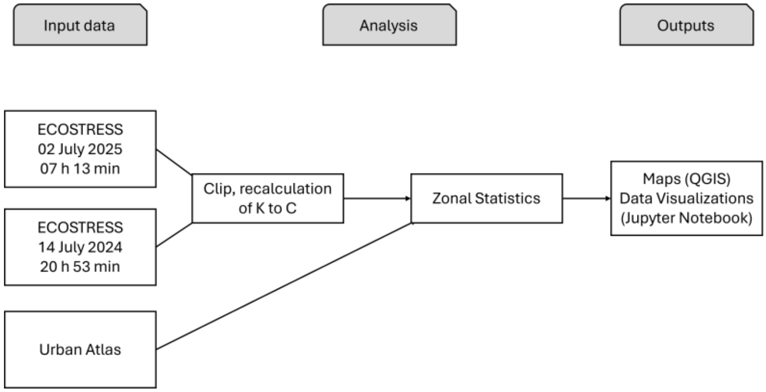


*Fig. 2. Data processing steps & outputs of the study*

Data exploration, descriptive statistics, and visualisations were performed in a dedicated Jupyter Notebook using Python libraries like pandas, matplotlib, and seaborn. The notebook and data analysis are publicly available on GitHub.

## Results

### Comparative Surface Temperature Patterns – Morning 2025 vs Evening 2024

The two ECOSTRESS acquisitions shown in Fig. 3 reveal distinct thermal patterns that reflect the different stages of the diurnal heating cycle during periods of elevated summer temperatures. The evening scene from 14 July 2024 on the right shows a persistent retention of daytime heat across Sofia's built-up areas. Median LST values remain elevated, with artificial surfaces displaying the highest thermal load and forming a pronounced warm core within the urbanised territory. Natural and semi-natural areas appear noticeably cooler, though the thermal gradient between land cover types is still moderate, indicating that the urban fabric has not yet undergone significant nocturnal cooling.

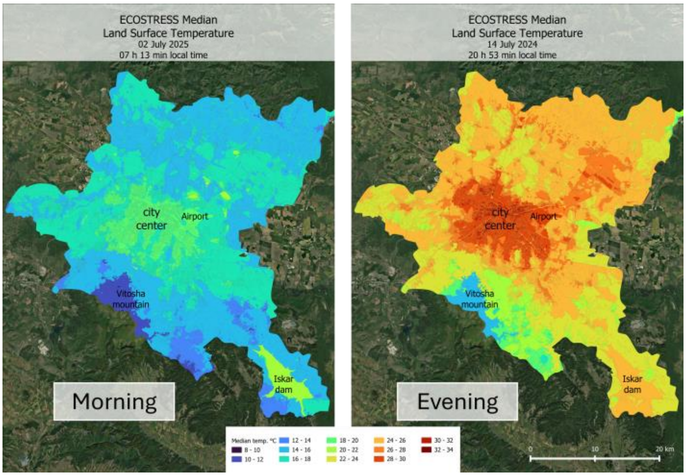


*Fig. 3. Median LST of Urban Atlas polygons for the morning and evening ECOSTRESS data*

The morning scene from 2 July 2025, acquired at 07:13 local time, depicts the city at the start of a new heating cycle. Surface temperatures are substantially lower across all land cover groups, and the overall distribution is narrower and shifted toward cooler values. Vegetated and mountainous areas exhibit the lowest LST, while artificial surfaces remain comparatively warmer, but with a considerably reduced thermal contrast relative to the evening dataset. This suggests that built-up areas retain higher residual heat overnight, yet early-morning conditions still allow clearer differentiation between surface types before solar heating intensifies.

In both scenes, the city centre forms the warmest and most spatially extensive hot spot, with the highest median surface temperatures in the evening and still clearly elevated values in the morning compared to the rest of the municipality. The area around Sofia Airport shows intermediate conditions that are warmer than the vegetated western and southern parts of the city, yet generally cooler than the compact central districts, reflecting a mixture of paved surfaces, runways, and open grassland.

Iskar Dam appears noticeably warmer than the surrounding mountainous terrain in the morning scene, forming a local warm patch within an otherwise cool landscape. In the evening scene, however, the dam becomes hotter, but not as much as in the morning, relative to its surroundings.

A Jupyter Notebook & Python libraries such as matplotlib, seaborn, and numpy were used for further statistical analysis of the data. Fig. 4 shows the density distributions of mean LST for the two ECOSTRESS acquisitions. It reveals a pronounced thermal contrast between morning and evening conditions. The morning scene (2 July 2025) is characterised by a compact, unimodal distribution centred around 14–18°C, reflecting the cooler state of the urban surface at the start of the day after partial nocturnal cooling.

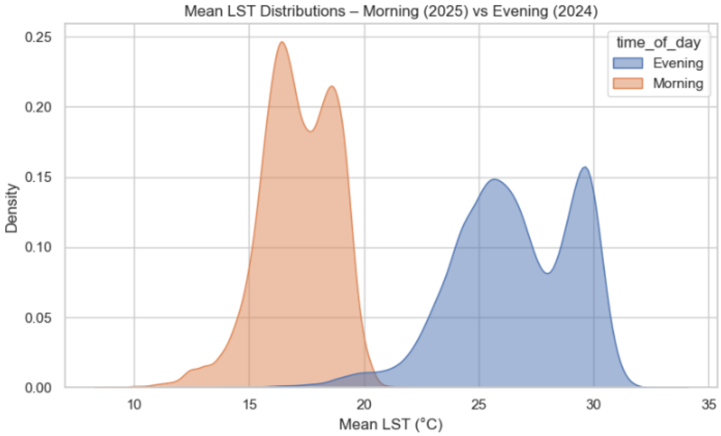


*Fig. 4. Mean LST distributions in the evening and morning data capture*

The evening scene (14 July 2024) exhibits a distinctly warmer and broader distribution, with values concentrated between 24°C and 30°C, indicating substantial heat storage throughout the day during a period of intense heat. The evening curve shows a slight bimodality, likely reflecting different thermal behaviours of dense built-up areas versus more vegetated or open surfaces. The two distributions show no overlap, illustrating that even the coolest evening surfaces remain significantly warmer than the warmest morning surfaces. This strong separation confirms the magnitude of diurnal temperature variability in Sofia during summer heat events and highlights the persistent thermal load in the city's built-up areas.

Fig. 5 is a data visualisation of a boxplot comparison of mean LST across broad Urban Atlas land-cover groups. It highlights consistent thermal differences between morning and evening conditions, as well as clear contrasts among surface types. In all categories, evening temperatures are significantly higher and exhibit wider variability, reflecting the accumulated daytime heat during the July 2024 heatwave. Artificial surfaces show the highest evening medians, surpassing 28–30°C, and display the broadest spread, indicating strong intra-group heterogeneity typical of dense urban fabric. Agricultural areas and natural & semi-natural surfaces form intermediate evening ranges, while wetlands and water bodies remain relatively cooler but still elevated compared to morning values.

The morning scene from July 2025 presents a more compressed temperature range across all land-cover groups, with medians clustering around 14–18°C. Although absolute temperatures are lower, the relative ranking of land-cover types remains similar, with artificial surfaces consistently warmer than vegetated categories, indicating persistent residual heat in built-up zones even after nocturnal cooling. Water bodies show a distinct pattern: cooler than surrounding areas in the evening but comparatively warmer in the morning, reflecting their slower diurnal response compared to land surfaces.

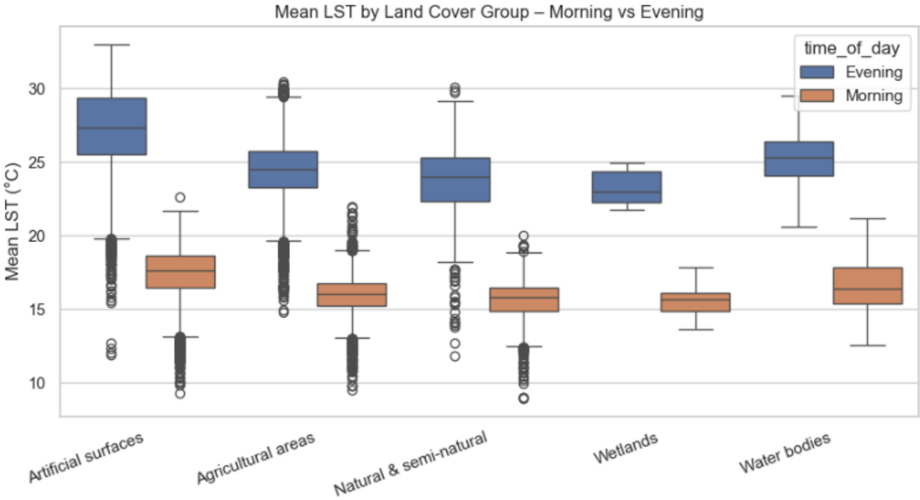


*Fig. 5. Mean LST by land cover groups – a comparison between evening and morning data capture*

The ranking of Urban Atlas classes by evening–morning LST difference reveals the land-use categories that retain the most heat during the day and release it the slowest overnight (Fig. 6). Continuous urban fabric (S.L. > 80%) exhibits the highest thermal contrast, with evening temperatures exceeding morning values by nearly 10°C, highlighting the strong heat storage capacity of dense, highly impervious surfaces.

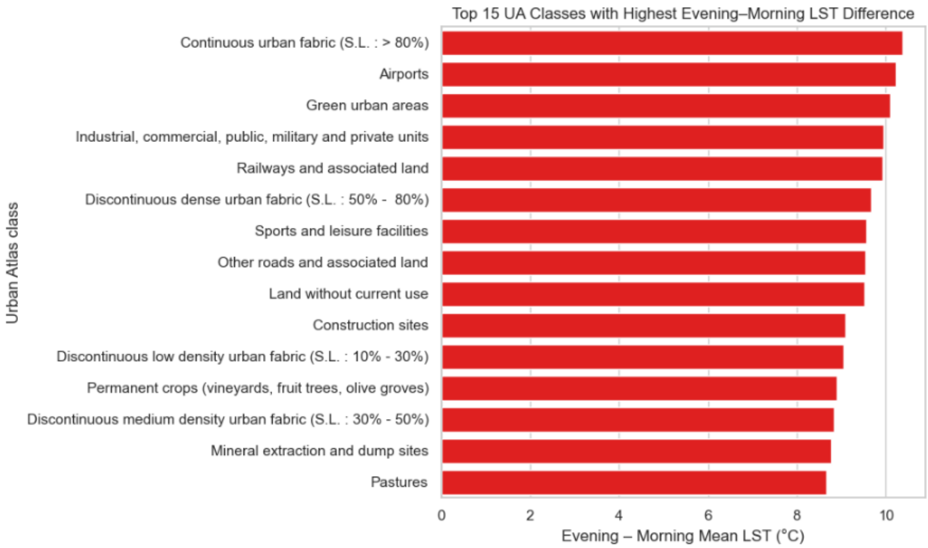


*Fig. 6. Top 15 Urban Atlas Classes that have the highest evening-morning LST differences*

Airports and green urban areas also demonstrate substantial differences, reflecting extensive paved infrastructure in the former and complex vegetation–soil interactions in the latter. Industrial and commercial units, along with transportation-related categories such as railways and associated land and other roads, show similarly large evening-morning temperature gaps, indicative of large asphalted and concrete surfaces with high thermal inertia. Among residential categories, discontinuous dense urban fabric (50–80% sealing) stands out with a substantial thermal range, suggesting that areas combining built-up patches with limited vegetation also accumulate considerable heat.

Lower-density settlement types, construction sites, and permanent crops (e.g., vineyards and fruit trees) appear in the lower portion of the top 15 but still exhibit differences of 7–8°C, reflecting moderate but significant heat retention. Even natural and semi-natural categories such as pastures appear in the list, although these show the smallest contrast among the top-ranked classes.

The summary statistics in Table 1 highlight the substantial diurnal contrast in surface temperatures captured by the two ECOSTRESS acquisitions. The evening scene registers a mean LST of 26.51°C, with maximum values approaching 33°C, reflecting the strong heat accumulation characteristic of late-afternoon and early-evening conditions during a summer heat event. The morning scene shows lower temperatures, with a mean of 17.09°C and a maximum of 22.59°C, indicating that overnight cooling significantly reduces surface heat, although residual warmth remains in certain areas.

*Table 1. Summary table for pixel statistics in °C*

| Time of day | Mean LST | Median LST | Min LST | Max LST |
|---|---|---|---|---|
| Evening | 26.51 | 26.453 | 11.827 | 32.977 |
| Morning | 17.09 | 17.090 | 8.938 | 22.588 |

Minimum temperatures also differ notably, with the evening recording 11.83°C compared to 8.94°C in the morning.

The magnitude of evening-morning differences varies substantially across land use types, with the highest thermal amplitudes occurring in compact residential fabric, transportation infrastructure, and industrial zones. Natural and semi-natural surfaces exhibit more moderate fluctuations. These findings confirm that during summer heat events, Sofia's urban core functions as a persistent heat reservoir, whereas peripheral vegetated areas and higher altitudes show significantly lower thermal loads. The combined use of ECOSTRESS and Urban Atlas thus provides a detailed and coherent view of the spatial structure of urban heat, forming a solid basis for interpreting the drivers of these patterns.

## Discussion

The results of this study demonstrate the clear potential of combining ECOSTRESS thermal data with detailed urban land cover classifications to gain meaningful insights into the spatial structure of urban heat in Sofia. Despite the contrasting acquisition times and seasonal conditions, both datasets consistently capture the strong influence of land cover on surface temperature, revealing coherent and interpretable thermal patterns across the city. The observed alignment between Urban Atlas classes and LST behaviour, such as the systematically higher temperatures in compact built-up areas and the pronounced cooling signature of natural and higher-elevation zones, shows that even a single high-quality morning or evening scene can provide valuable information about the functioning of the urban thermal environment. These findings confirm that open satellite data, when integrated with harmonised urban classifications, offer a robust and accessible foundation for understanding heat dynamics in complex metropolitan settings.

A key limitation of the present analysis arises from the spatial resolution of the ECOSTRESS data. Although the nominal pixel size of approximately 70 m is well suited for regional assessments of surface temperature, it restricts the level of detail achievable in dense urban environments. Fine-scale features such as individual streets, narrow green corridors, small parks, or internal temperature variability within residential blocks cannot be fully resolved. As a result, thermal contrasts may be smoothed, and the heterogeneity of urban microclimates, especially in compact and mixed-use areas, can be partially obscured. Despite this, the integration with Urban Atlas polygons helps mitigate some of these limitations by aggregating pixel values within meaningful urban units, allowing broader functional patterns to emerge even when fine-grained details remain beyond the sensor's capability.

The study also underscores the essential role of open geospatial data in advancing urban heat research. Both ECOSTRESS surface temperature datasets and the Urban Atlas land-cover layers are freely accessible, enabling high-quality, reproducible analyses without financial or institutional barriers. The ability to combine remote sensing products with harmonised European land-use classifications significantly enhances the interpretability of thermal patterns and supports robust cross-city comparisons across the EU. Open data availability thus not only democratizes access to advanced analytical tools but also strengthens policy-oriented research, allowing municipalities, planners, and researchers to collaboratively evaluate the thermal behaviour of cities in a consistent and comparable manner.

The findings further highlight the urgent need to deepen the understanding and communication of heatwave impacts on public health, especially in rapidly warming urban environments. Bulgaria's ageing population, combined with increasing frequency and intensity of heat extremes, positions heat-related risks as a growing public health concern. The observed strong thermal load in densely built-up areas suggests that large segments of the urban population may be exposed to sustained heat stress, particularly during evenings when cooling is limited. Strengthening early-warning systems, improving public outreach, and conducting interdisciplinary research that links surface temperature patterns with demographic vulnerability, morbidity, and mortality data will be essential for developing effective adaptation strategies. In this context, remote sensing products such as ECOSTRESS can play an important role in informing targeted interventions and communicating risk in an accessible and spatially explicit manner.

**Funding & Data Sharing**

The repository is located at https://github.com/eugeniasarafova/mapping-dataviz-ecostress-sofia/tree/main, and the Jupyter Notebook at https://github.com/eugeniasarafova/mapping-dataviz-ecostress-sofia/blob/main/Paper.ipynb

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## КАРТОГРАФИРАНЕ И ВИЗУАЛИЗАЦИЯ НА ДАННИ ЗА ДИНАМИКАТА НА ПОВЪРХНОСТНАТА ТОПЛИНА НА ЗЕМНОТО ПОКРИТИЕ В СОФИЯ, БЪЛГАРИЯ

***Е. Сарафова, К. Найденов***

**Резюме**

В настоящата статия пространственото разпределение на повърхностните температури в София е анализирано чрез комбиниране на данни от сензора ECOSTRESS и класификацията на градските функционални зони Urban Atlas 2018. За целите на изследването са използвани две термални сцени от различни етапи на денонощието – вечерно заснемане от 14 юли 2024 г. и сутрешно заснемане от 2 юли 2025 г. На базата на тези данни за всеки полигон от Urban Atlas са изчислени статистически показатели (минимум, максимум, медиана и средна стойност) посредством инструмента Zonal Statistics в QGIS. За да бъде осъществена сравнима оценка, данните са хармонизирани в единна структура и анализирани и вузуализирани в Jupyter Notebook с помощта на езика Python. Резултатите показват ясно изразени разлики между сутрешното и вечерното термично състояние на градската среда, както и отчетлива зависимост на температурните стойности от вида на земното покритие. Най-високи термични натоварвания се установяват в зоните с плътна урбанизация, индустриални територии и транспортна инфраструктура, докато естествените и полуприродните площи запазват значително по-ниски температури. Представените резултати демонстрират потенциала на отворените сателитни данни за оценка на топлинните процеси в градска среда и подчертават необходимостта от по-задълбочени изследвания върху влиянието на горещите вълни върху общественото здраве.