Diurnal Surface Urban Heat Island Effect in Catalonia: Land Surface Temperature Analysis from Landsat Data

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Abstract: This study analyzes the Diurnal Surface Urban Heat Island (DSUHI) across four Catalan cities (Barcelona, Girona, Tarragona, and Lleida) from 2020 to 2024. A workflow combining QGIS and R is used to process Landsat 8/9 imagery, calculating Land Surface Temperature (LST) to estimate urban-rural thermal differentials. The main contribution is a reproducible methodology for DSUHI analysis, which also compares LST results derived from Landsat Level-1 and Level-2 data. Findings highlight key differences in DSUHI characteristics among the cities and the implications of using different data processing levels.
Keywords: UHI, DSUHI, Landsat, Remote Sensing, LST, Climate Change
SDGs: 11 (Sustainable Cities and Communities), 13 (Climate Action)

I. INTRODUCTION

In recent decades, climate change has intensified various environmental and social risks, notably increasing the frequency and intensity of heatwaves, with a disproportionate impact on urban areas [1]. This phenomenon is especially relevant in Mediterranean regions, where climatic conditions, urban density and scarce vegetation aggravate its effects. A direct manifestation is the Urban Heat Island (UHI), defined as the temperature difference between urban areas and their rural surroundings. This thermal difference arises from heat storage in constructed surfaces during the day and its release at night, combined with scarce evapotranspiration and urban geometry that limits ventilation [2].

The study of UHI requires temperature data with adequate spatial resolution, achievable through advances in satellite remote sensing. The United States Geological Survey (USGS), in collaboration with NASA, manages the Landsat program, the longest-running terrestrial observation mission, active since 1972 [3]. Landsat 8 and 9 satellites, equipped with multispectral (OLI) and thermal (TIRS) sensors, provide images with a 30 m resolution and revisit each point on Earth combined every 8 days. In Catalonia, images are captured around 10:10 local solar time, allowing for the analysis of coherent diurnal thermal patterns.

Although UHI or SUHI (Surface Urban Heat Island) studies often focus on the nocturnal period when the urban-rural thermal contrast is maximal [4], morning images also allow observation of consistent thermal patterns, especially on clear days, avoiding interferences from cloudiness and facilitating analysis standardization. For satellite-based diurnal thermal imagery, the term Diurnal Urban Heat Island (DUHI) or Diurnal Surface Urban Heat Island (DSUHI) is preferred, reflecting the superficial thermal contrast captured during the day.

This work analyzes the evolution and distribution of the DSUHI effect in four Catalan cities (Barcelona, Girona, Tarragona, and Lleida) during the period 2020-2024. A methodological approach based on processing Landsat 8 and 9 images using GIS tools (QGIS) and automated analysis in R is employed. Land Surface Temperature (LST) is calculated from thermal and spectral data, and the urban-rural thermal differentials are estimated. The primary contribution is methodological, proposing a reproducible workflow applicable to other urban contexts or for extended temporal analysis.

A. Theoretical Framework

The UHI concept was formally introduced by Luke Howard in the 19th century but has gained increasing importance in the current context of accelerated urbanization and climate change [5]. UHI influences not only thermal comfort and public health but also energy consumption and urban air quality.

Physically, UHI is explained by the energy balance of urban surfaces, where absorption of solar radiation predominates, and heat loss by convection or evaporation is limited. Urban materials like asphalt and concrete have high thermal capacity and low reflectivity, favoring heat accumulation. Urban geometry (e.g., tall buildings, narrow streets) forms "urban canyons" limiting thermal dissipation and contributing to overheating [2]. The replacement of green areas with impermeable surfaces drastically reduces evapotranspiration, a key process in heat dissipation, diminishing the environment's thermal self-regulation capacity [6]. Anthropogenic activity (e.g., vehicles, air conditioning, heating, lighting) generates additional direct thermal input, known as anthropogenic heat, further increasing air temperature in dense urban zones [7]. The effect is typically more intense at night when constructed surfaces release accumulated heat, while rural areas cool more rapidly.

Methodologically, UHI can be studied via in-situ air temperature measurements or by analyzing LST obtained from satellites. The latter, while not directly measuring air temperature, allows for extensive and repetitive spatial coverage, ideal for comparative SUHI studies, and avoids logistical limitations of terrestrial sampling [8]. Landsat 8 and 9, with their TIRS sensors, enable LST calculation by transforming digital numbers (DN) to radiance, then to brightness temperature, and finally to corrected LST. The free availability of their images and relatively high resolution have made Landsat a widely used tool for SUHI studies at urban and regional levels [9].

B. Case Study Selection

The analysis of UHI requires a territorial approach considering the climatic, morphological, and urban conditions of the analyzed environment. This study selected four Catalan capital cities: Barcelona, Girona, Tarragona, and Lleida, covering a diversity of urban and geographic profiles. The selection was based on technical and scientific criteria:

- Representative geographical distribution (coastal, pre-littoral, and inland areas).
- Climatic diversity (Mediterranean, continental, and maritime influence).
- Presence of a clearly delimited urban area with sufficient Landsat coverage [9].
- Medium-high demographic size, sufficient to generate a detectable UHI effect.
- Accessibility of data, both satellite and socio-urban.

Table I: Basic demographic and geographic data of the case study cities.

City	Population	Area (km^2)	Density (hab/km^2)
Barcelona	1,686,208	101.4	16,638
Girona	106,476	39.1	2,722
Lleida	144,878	212.3	682
Tarragona	141,018	57.9	2,436

The selected cities represent distinct geographical, climatic and urban typologies: Barcelona (coastal and densely populated), Girona (medium-sized city with abundant vegetation), Lleida (continental, surrounded by agricultural land) and Tarragona (industrial and coastal). These cities differ in population, surface area and urban structure, as summarized in Table I [10]. For each city, a vector mask delimiting the consolidated urban extent was used for clipping Landsat images and for extracting and comparing thermal values. Future studies could complement this with a Local Climate Zones (LCZ) classification for more precise differentiation between urban, suburban, and rural typologies [11], [12].

II. METHODOLOGY

The methodology used involves five main steps: image selection and download, preprocessing, LST calculation from Level-1 and Level-2 images, and DSUHI estimation.

A. Image Selection and Download

Landsat 8 and 9 images from 2020 to 2024 (inclusive) were used. For each city, one image per month was manually selected, prioritizing cloud-free conditions, and downloaded from the USGS EarthExplorer platform. The products included:

- Level-1: Spectral bands B4 (Red), B5 (NIR), B10 (Thermal), and the MTL.txt metadata file for radiometric calibration.
- Level-2: Bands B4, B5, B10, already atmospherically corrected.

B. Image Preprocessing

All downloaded images (Level-1 and Level-2) were clipped to exclusively cover the study area of each city. This clipping used a vector mask of urban limits, previously ensuring its coordinate reference system matched the original raster's projection (UTM zone 31N).

C. LST Calculation from Landsat Level-1 Images

Level-1 Landsat images provide digital numbers (DN) not yet atmospherically corrected. A series of physical and mathematical steps are necessary to obtain LST.

1. Conversion of DN to Spectral Radiance (L_λ): Thermal band DNs are converted to at-sensor spectral radiance (L_λ) (also called TOA - Top of the Atmosphere), measured in $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$, using calibration factors from the MTL.txt file:

$$L_\lambda = M_L \cdot Q_{cal} + A_L, \quad (1)$$

where M_L is the band-specific multiplicative rescaling factor, Q_{cal} is the DN value of the pixel, and A_L is the band-specific additive rescaling factor. This step calibrates the sensor's thermal signal into real physical terms.

2. Conversion of Radiance to Brightness Temperature (BT): Brightness temperature (T_b) is the temperature of an ideal blackbody that would emit the same radiance at a specific wavelength. It is calculated using the inverse of Planck's law:

$$T_b = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}, \quad (2)$$

where L_λ is the spectral radiance, and K_1 and K_2 are band-specific thermal conversion constants from the MTL file.

3. Calculation of NDVI: The Normalized Difference Vegetation Index (NDVI) estimates vegetation cover, crucial for determining thermal emissivity. It is calculated from Near-Infrared (B5) and Red (B4) bands:

$$NDVI = \frac{B5 - B4}{B5 + B4} \tag{3}$$

NDVI values range from -1 to 1; values close to 1 indicate dense vegetation, while values near 0 or negative correspond to bare soil or water.

4. Proportion of Vegetation (PV): NDVI is transformed into an estimation of the fraction of vegetation cover (PV):

$$PV = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2 \tag{4}$$

This allows local adjustment of emissivity based on vegetation presence.

5. Calculation of Land Surface Emissivity (LSE): Emissivity (ϵ) represents the efficiency with which a surface emits thermal radiation compared to a blackbody. It is calculated empirically:

$$\epsilon = 0.004 \cdot PV + 0.986 \tag{5}$$

This value adjusts the conversion from brightness temperature to real surface temperature, especially in environments with heterogeneous vegetation.

6. Final LST Calculation (Level-1): The true Land Surface Temperature (LST in °C) is obtained by correcting the brightness temperature with emissivity, using a transformation derived from Planck's law:

$$LST = \frac{T_b}{1 + \left(\frac{\lambda \cdot T_b}{\rho}\right) \cdot \ln(\epsilon)} - 273.15, \tag{6}$$

where T_b is brightness temperature in Kelvin, $\lambda = 10.8\mu m$ (effective wavelength of Landsat TIRS Band 10), $\rho = 14380 \mu m \cdot K$ (a constant derived from $h \cdot c/k_B$, where h is Planck's constant, c is the speed of light, and k_B is Boltzmann's constant). The final LST is exported as a GeoTIFF raster image. Figure 1 illustrates the intermediate products for LST calculation.

D. LST Calculation from Landsat Level-2 Images

Landsat Level-2 images are already atmospherically corrected by the USGS using radiometric and atmospheric algorithms, allowing direct work with calibrated data. Followed steps to obtain LST are shown below:

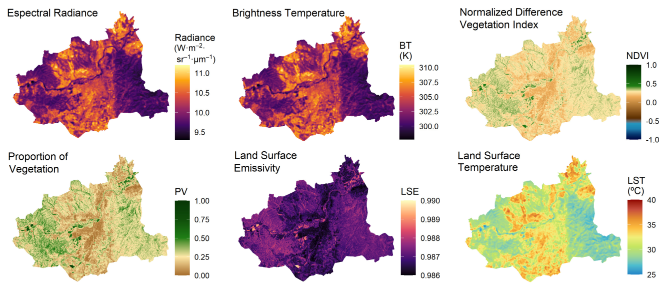

Figure 1: Example of intermediate images for LST calculation in Girona from Landsat 9 Level-1 (August 10, 2023), showing TOA, BT, NDVI, PV, LSE and LST.

1. Conversion of B10 to Brightness Temperature: Level-2 Band 10 is provided as scaled integers representing temperature in Kelvin. The conversion is:

$$T_b = DN \cdot 0.00341802 + 149 \tag{7}$$

This formula applies a scale factor and offset to adjust DNs to physical values directly.

2. Estimation of NDVI, PV and LSE: Similar to Level-1, bands B4 and B5 are used to obtain NDVI, PV, and then emissivity (ϵ) using the equations 3, 4 and 5), respectively.

3. Final LST Calculation (Level-2): The final LST calculation is analogous to Level-1, albeit with slightly adjusted constants:

$$LST = \frac{T_b}{1 + \left(\frac{10.8 \cdot T_b}{14388}\right) \cdot \ln(\epsilon)} - 273.15 \tag{8}$$

Here, $\rho = 14388\ \mu m \cdot K$. This temperature represents the corrected land surface temperature, considering atmospheric conditions and emissivity. Results are exported as GeoTIFF and used for comparison with Level-1 derived values.

E. Estimation of DSUHI

The DSUHI is estimated from Level-1 LST images as follows:

1. Selection of a Rural Reference Zone: For each city, an adjacent rural zone is subjectively selected based on:

- Consistently low LST values, indicative of non-urbanized areas.
- Coverage by natural vegetation or dense crops, verified visually using high-resolution orthophotography in QGIS.
- Location outside the urban core.

This selection is made through visual inspection of previously generated thermal maps and superimposed orthophotos. A polygonal vector mask is then created to precisely delimit the pixels forming the rural reference environment.

2. Calculation of Mean Rural Temperature: The mean LST (T_{mean_rural}) is calculated within the delimited rural zone using the generated mask. This mean temperature serves as the baseline for estimating the urban thermal differential.

3. Calculation of Urban Thermal Differential: Finally, a subtraction operation is applied to the complete LST image of each city:

$$\Delta T_{DSUHI}(x, y) = LST(x, y) - T_{mean\_rural} \tag{9}$$

Where $LST(x, y)$ is the LST of each urban pixel, and ΔT_{DSUHI} is the DSUHI intensity. This operation generates a new raster map representing the spatial distribution of DSUHI, where positive values indicate urban overheating relative to the rural environment. This methodological approach allows for the visualization and quantification of the DSUHI effect, consistent with methodologies applied in similar studies [13], and adapted to the climatic and urban characteristics of Catalonia. It is also applicable to nocturnal images for UHI assessment.

III. RESULTS AND DISCUSSION

A total of 840 Level-1 and 534 Level-2 Landsat files were downloaded for this study. LST was derived for 388 different dates, from which 210 Level-1 scenes were ultimately selected for the Diurnal Surface Urban Heat Island analysis.

A. Comparison between Level-1 and Level-2 LST.

Although not shown here, the results show systematic differences between LST derived from Landsat Level-1 and Level-2 images. Barcelona and Girona exhibit positive and relatively stable differences between both processing levels throughout the year. In contrast, Lleida and Tarragona show larger and more variable differences, with Tarragona's being less extreme than Lleida's.

These discrepancies can be explained by the atmospheric preprocessing incorporated in Level-2 images. Previous studies have indicated that this type of correction might underestimate the actual temperature in arid or low relative humidity zones, where local atmospheric conditions are not well represented by standard applied models [8], [14]. In dense cities like Barcelona, atmospheric correction tends to smooth out extreme thermal values captured in Level-1, leading to a flattening of the urban thermal profile. This effect has also been observed in prior research highlighting how automatic corrections can reduce sensor sensitivity to urban microclimates [15].

Despite these differences, the comparison between both levels does not significantly alter the spatial patterns or the relative order of thermal intensity among cities. In summary, this comparison demonstrates that the choice of satellite product type can influence LST values, especially in inland regions with low humidity.

B. DSUHI Analysis

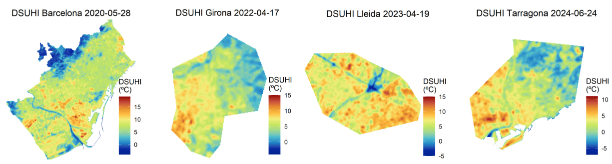

Figure 2: Raster images representing the spatial distribution of DSUHI in Barcelona (2020/05/28), Girona (2022/04/17), Lleida (2023/04/19), and Tarragona (2024/06/24).

The spatial distribution of the DSUHI (Figures 2 and A.1) varies significantly according to each city's urban morphology. In Barcelona, the effect is highly concentrated in the Raval and Eixample districts. Conversely, Lleida exhibits a more dispersed pattern but reaches the highest intensity of all four cities (up to 10 ºC). Girona and Tarragona show DSUHI hotspots linked to their historic centers and, in Tarragona's case, industrial zones.

The monthly evolution of DSUHI between 2020 and 2024 (Figure 3) reveals significant heterogeneity among the cities, with no common pattern observed in either seasonality or interannual variability.

In Barcelona and Tarragona, DSUHI values remain relatively constant throughout the year; no season with significantly higher thermal values is identified. This stability is likely explained by the thermoregulatory effect of the sea, which moderates thermal differences between the urban and rural environment. Conversely, Girona and Lleida show a clear seasonal evolution. DSUHI tends to increase from winter, peak between spring and summer, and decrease in the second half of the year. This unimodal behavior is more pronounced in Lleida, where the remoteness from the sea, the agricultural surroundings, and dry conditions favor this heat accumulation.

Although complete five-year series are not available for some months, no clear interannual trend is detected. For example, in May in Barcelona, there seems to be a slight decrease in DSUHI between 2020 and 2023, but this evolution is not consistently repeated in other months or in other cities.

IV. CONCLUSIONS

This study develops a methodology that is subsequently applied to analyze the DSUHI in four Catalan cities, yielding a reproducible workflow and several key findings:

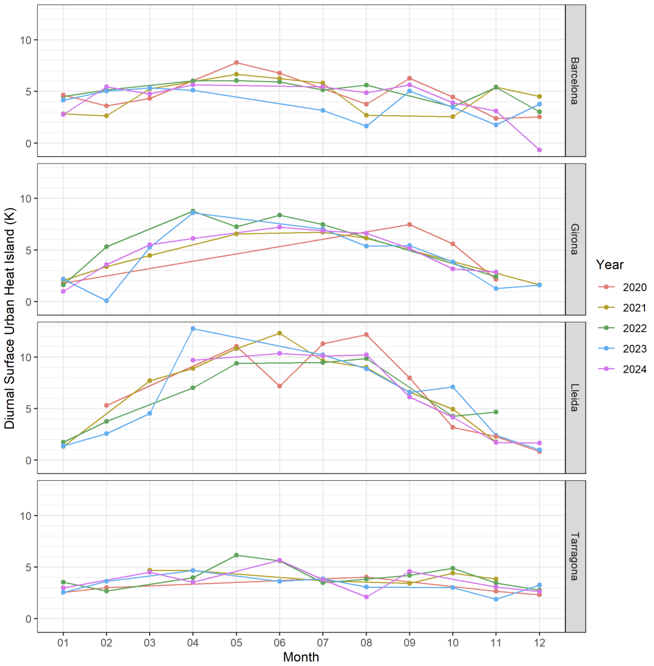

Figure 3: Representation of the DSUHI effect in the four cities monthly over 5 years (2020-2024).

- The Diurnal Surface Urban Heat Island (DSUHI) variable is defined based on LST estimated using Landsat 8 and 9 sensors.
- The spatial LST patterns derived from Level-1 and Level-2 products are consistent, although Level-2 data tend to smooth thermal extremes.
- The DSUHI exhibits distinct behaviors across the studied cities. Coastal cities (Barcelona, Tarragona) show relatively stable DSUHI year-round, influenced by the sea's moderating effect. Inland cities (Girona, Lleida) display a more pronounced seasonal DSUHI cycle, peaking in summer, with Lleida showing the highest intensities, likely due to its continental climate and surrounding agricultural land.
- No uniform interannual DSUHI trend was identified for the 2020-2024 period. The effect of climate change on the DSUHI itself remains unclear, as it impacts both urban and rural temperatures. A longer time series would be necessary to identify any significant long-term trends amid the observed local variations.

The proposed methodology is a robust tool for urban planning. Future work could involve expanding the temporal analysis, incorporating more detailed urban morphology data (e.g., LCZs), and comparing diurnal DSUHI with nocturnal UHI patterns.

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L'Illa de Calor Urbana Diürna en Superfície (DSUHI) a Catalunya: Anàlisi de la Temperatura de la Superfície Terrestre amb dades Landsat

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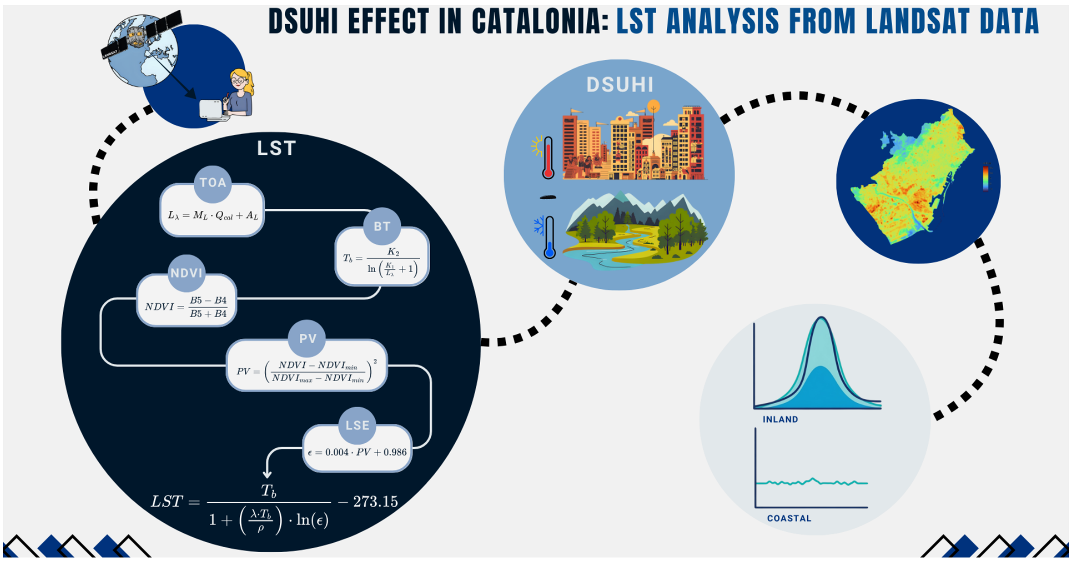
Resum: Aquest estudi analitza l'Illa de Calor Urbana Diürna en Superfície (DSUHI) a quatre ciutats catalanes (Barcelona, Girona, Tarragona i Lleida) durant el període 2020-2024. Mitjançant un flux de treball que combina QGIS i R, es processen imatges dels satèl·lits Landsat 8 i 9 per a calcular la Temperatura de la Superfície Terrestre (LST) i s'estimen els diferencials tèrmics entre zones urbanes i rurals. La principal contribució del treball és una metodologia reproduïble per a l'anàlisi de la DSUHI, que a més compara els resultats de LST obtinguts a partir de dades Landsat de Nivell-1 i Nivell-2. Els resultats posen de manifest diferències clau en les característiques de la DSUHI entre les ciutats i les implicacions d'utilitzar diferents nivells de processament de dades.
Paraules clau: UHI, DSUHI, Landsat, Teledetecció, LST, Canvi Climàtic.
ODSs: 11 (Ciutats i comunitats sostenibles), 13 (Acció climàtica)

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	X
3. Salut i benestar		12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climàtica	X
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures			

El contingut d'aquest TFG es relaciona amb l'ODS 11 (Ciutats i comunitats sostenibles), particularment amb les fites 11.6 (reduir l'impacte ambiental negatiu per càpita de les ciutats) i 11.b (augmentar l'adopció de polítiques integrades per a la mitigació i adaptació al canvi climàtic i la resiliència als desastres), ja que l'estudi de les illes de calor urbanes és crucial per entendre i mitigar els impactes ambientals i de salut a les ciutats. També es vincula amb l'ODS 13 (Acció climàtica), especialment les fites 13.1 (enfortir la resiliència i la capacitat d'adaptació als perills relacionats amb el clima) i 13.3 (millorar l'educació i la sensibilització sobre la mitigació del canvi climàtic), atès que la comprensió de fenòmens com la DSUHI és fonamental per a l'adaptació urbana al canvi climàtic i la sensibilització sobre els seus efectes.

GRAPHICAL ABSTRACT



Appendix A: SUPPLEMENTARY MATERIAL

This appendix includes selected supplementary raster images representing the spatial distribution of the Diurnal Surface Urban Heat Island (DSUHI) effect in the four analyzed cities: Barcelona, Girona, Lleida, and Tarragona. These visuals complement the analysis presented in the Results section and provide further insight into the spatial variability of urban heating patterns during selected dates. The images have been processed following the methodology described in Section II and are intended to illustrate specific examples of DSUHI intensity across different urban morphologies.

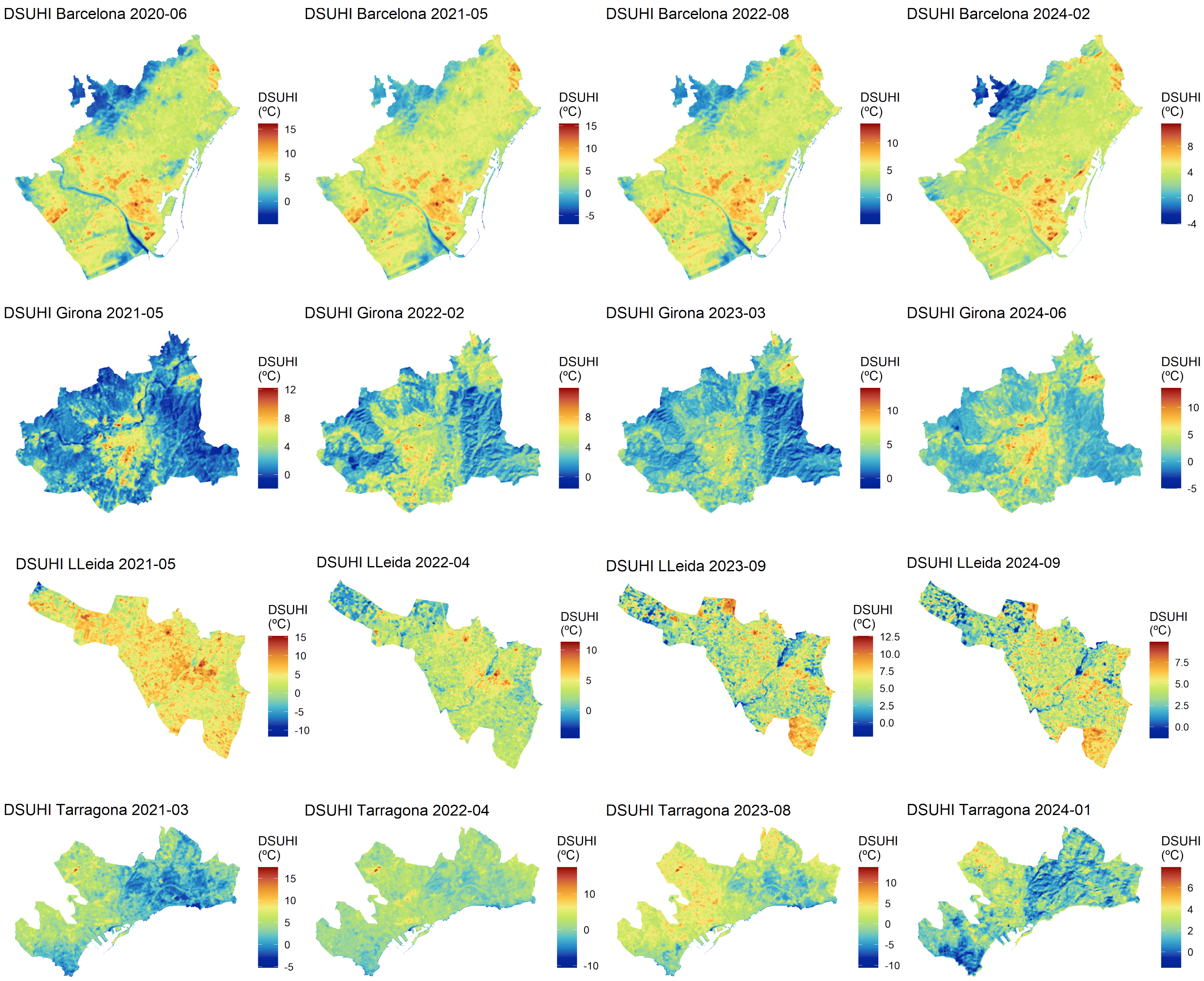


Figure A.1: Selected raster images representing the spatial distribution of DSUHI in Barcelona, Girona, Lleida, and Tarragona.