Study of Air and Surface Temperatures in the City of Rouen (France) in Order to Evaluate the Characteristics of the Urban Heat Islands

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ABSTRACT: Due to its concave topography, the climate in the Rouen region is affected by the impact of urbanization. The urbanized area occupies the bottom of the Seine Valley and extends onto slopes and plateaus. These topographic conditions contribute to the formation of well-differentiated local climates. To better understand the urban heat island, an expeditionary measurement campaign was carried out from 25 June to 11 August 2020. This campaign is based on the knowledge of the spatial distribution of temperatures in the city. These measurements were carried out according to different profiles and a specific programme. During this period, the region was affected by three heatwaves.. In this study, we present the results regarding the air temperatures obtained on 25 June 2020. The study also relies on the analysis of "Landsat 8" channel 11 satellite images, with a spatial resolution of 30 m to define surface temperatures. The results obtained during the measurement campaign show the importance of the differences between vegetated and built spaces. They also highlight hotspots (at traffic intersections and on main transport corridors – boulevards).
The results obtained from the processing of satellite images show significant temperature differences between the industrial area and the rest of the city. There is an important thermal contrast between green spaces and asphalt squares in the city centre. There is a thermal lag between the "west" plateau, Cailly Valley, and the rest of the city.

KEY WORDS: urban climate, spatial distribution of temperatures, urban heat island.

1. Introduction

In large cities, the expansion of urban areas and the intensity of air pollution lead to more or less significant changes in the local energy balance. Primarily at night, differences in land use patterns between the urban area and rural peripheral areas generate a heat "bubble" (known as urban heat island, UHI) above the city (Figure 1). This thermal peculiarity is mainly explained by the gradual release in the form of sensible heat of solar energy stored during the day by the volumes and materials that make up the city (buildings, roads, etc.), whereas cooling in rural areas is much faster (Oke, 1982). The emergence of the UHI is the most concrete climatic manifestation of urban activities (Zhou, Rybski and Kropp, 2017). The extent and distribution of the UHI may be estimated both by the air temperature recorded at weather stations and by the land surface temperature evaluated from satellite images (such as those taken from the Landsat satellite) (Aniello C et al. 1995). These two approaches can be combined, as is the case, for example, in the study of the city of Leipzig (Schwarz, Schlink, Franck, & Grossmann, 2012).

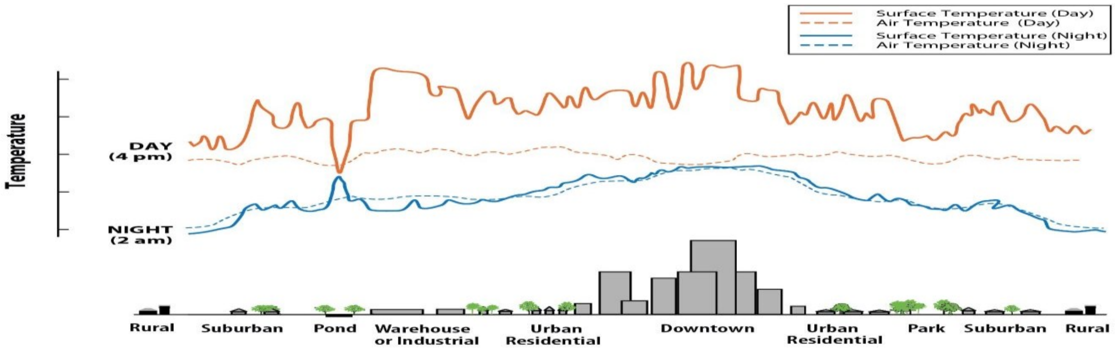

Figure 1 Urban heat island (Source: https://www.usgs.gov/media/images/urban-heat-islands).

The city of Rouen (located in the northwest of the Paris Basin in the Seine-Maritime department) is part of the Rouen-Normandie Metropolis. It is an intercommunal group of 71 municipalities, which has been in existence since 1 January 2015, with a population of 498,822 and a population density of approximately 751 inhabitants per km² (metropole-rouen-normandie.fr). The total area of the metropolis is about 664 km². This area is divided into three types of equally distributed developments: agricultural areas (193 km²), natural and forested areas (250 km²), and urbanized areas (200 km²) (metropole-rouen-normandie.fr). Due to its concave topography and the concentration of inhabitants and industries, this city's climate is directly affected by urbanization. It has only one station that continuously records all meteorological variables, but this station is not directly representative of the urban environment because it is located on the northern plateau (Boos Airport). The current measurement network thus does not allow for a comprehensive study of urban topoclimates and microclimates (a necessary step to highlight the urban heat island). The Jardin des Plantes station is the only intracity station, but its temperature measurements at daily intervals (minimum and maximum) do not allow us to understand the reality of the urban heat island in all its diversity and mechanisms (air refreshing effect). "Atmo-Normandie", the air quality monitoring network, has several weather stations located in the industrial area, but only one of them records temperatures 9 metres above the ground, therefore under conditions that do not allow for comparison with standardized meteorological measurements.

In the context of Climate Change, urban effects on climate are likely to intensify, especially during the summer, which is why numerous studies are currently being carried out to adapt the city by significantly reducing discomfort and excess mortality related to heatwave episodes. City adaptation to climate change requires UHI control. However, the implementation of mitigation measures calls for a detailed understanding of a phenomenon whose intensity, duration and spatial extent vary from one city to another (the role of geographic location in local climatology). Thus, in recent years, regulations have required cities to consider this phenomenon in their development plans, leading to initiatives and methods for observing the UHI that vary from one community to another. For example, in Paris, studies on this topic reveal an estimated heat island of +2.3°C (Apur, Paris Urban Planning Workshop, 2014, and the Paris Council, 2023). In the Lyon metropolitan area, (Bocher et al. 2018) and (Garde et al. 2020) have evaluated the heat islands of several large French cities through simulation. These simulations reveal a very strong heat island of +4.56 in the fifth arrondissement of Lyon. In the centre of Le Havre, the UHI is also considered strong, as its value is estimated at +3.37. In the centre of Rouen, estimates from these studies give a value that is considered significant, +2.41.

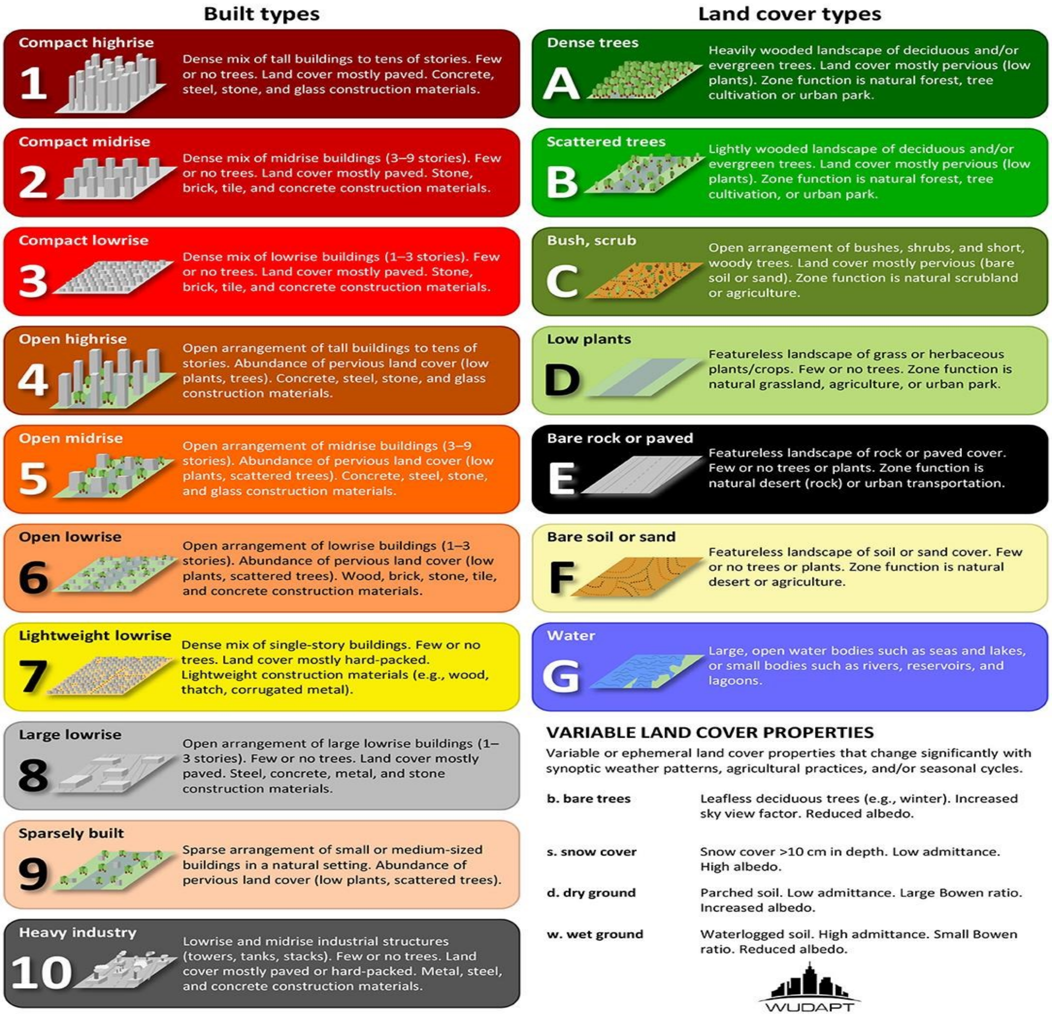

Figure 2 Urban (1–10) and natural (A–G) Local Climate Zone definitions (Stewart and Oke, 2012; Demuzere et al., 2021).

The UHI intensity is generally proportional to the density of buildings and the distance from the centre of the urban area. In medium-sized urban areas (with hundreds of thousands of residents), the UHI exists, but its effects are more limited because there is generally no intra-urban station to analyse it (such is the case in the Rouen metropolitan area). The first step in this approach is to conduct a detailed analysis of spatial planning in this highly urbanized environment. Each urban area has its own morphology and "thermal identity", which vary over time and space. Its characteristics reflect the multitude of possible combinations between regional climatic conditions, seasonal context, specific features of each city (physical layout and the density of buildings, nature of construction materials, industrial activities etc.), and the occurrence of "favourable weather types" that express local factors in the lower layers of the atmosphere. In 2011, Douglas Stewart, a researcher in urban climatology, grouped these characteristics into different classes: "Local Climate Zones" (LCZ). Based on experimental measurements in three cities and numerical simulations, Stewart and Oke (2012) were able to determine 17 LCZ classes, making it possible to characterize territories: 10 "built" LCZ classes and 7 "natural" LCZ classes, each with homogeneous temperature and characteristics (figure 2).

2. The urban morphology of the city of Rouen

Although the differences in altitude are relatively modest (<200 m), the Rouen region still exhibits very contrasting landscapes (valleys and plateaus). The urban area mainly occupies the bottom of the Seine Valley. Building density on the plateaus is medium to low. The block diagram (Figure 3) shows the relief over which the urban area extends and the various land use patterns around the Rouen metropolitan area. We should remark the influence of the Seine loop on this site. We should also note the proximity of forests to the west. These elements bring new climatic nuances (due to the response in terms of humidity and temperature in these spaces compared to urban areas). Air mass movements (thermal breeze) thus reinforce thermal inversions and the diversity of local climatic environments. These phenomena generate marked contrasts among plateaus, valley bottoms, the Seine corridor, and are of concern as they favour the concentration of pollutants in the lower layers of the atmosphere.

These classic plateau/valley variations are accompanied by urban effects: generally warmer and drier air, weaker winds, which this study aims to highlight. With climate change, the temperature differences between cities and rural areas are likely to increase in the coming decades. The UHI is expected to consolidate, because, on the one hand, urban development will increase and, on the other hand, climate models predict a greater number of heatwaves and canicules in Western Europe (according to the latest IPCC report https://www.ipcc.ch/report/ar5/syr/).

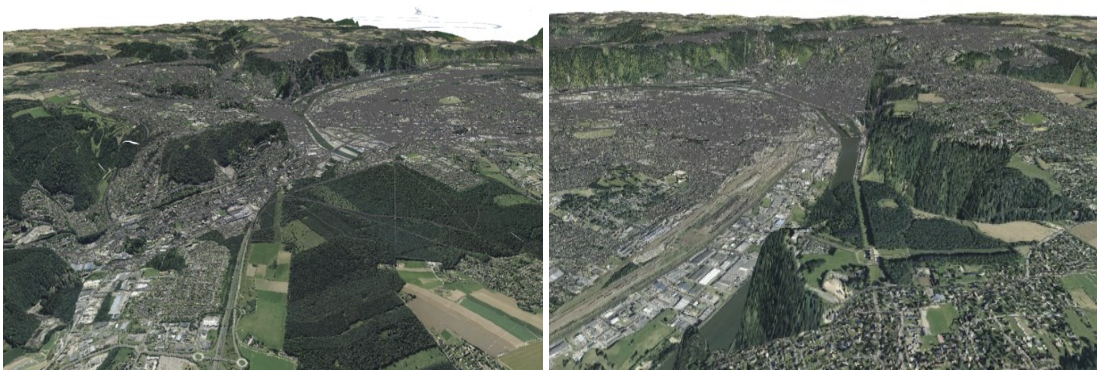

Figure 3 Three-dimensional block diagram of the Rouen region (Source: extract from the topographical database of the Seine-Maritime department.

In order to classify the local climate zones in the metropolitan area of Rouen, research work has been conducted as part of the preparation for a master's degree in Geography at the University of Rouen (France) - Leal, 2023. This work is part of the "ArchiAdapt" project, which aims to assess the adaptation of buildings and territories to climate change. The methodology used for the classification of urban areas is based on several morphological criteria such as residential density, average building height, average footprint coefficient and average plot size. These data were extracted from the Local Urban Development Plan (PLU) of the Rouen Metropolis (https://www.metropole-rouen-normandie.fr/les-donnees-gegraphiques-de-la-metropole). The result (Figure 4) shows that only 10 out of the 17 LCZs are present in the urban area of Rouen. Industrial areas and commercial and tertiary activities (LCZ 8) are distributed along the Seine following the river loop and along the Austreberth valley. The historical social separation between the left bank and the right bank is clearly visible. This contrasts the so-called "working" residential areas (LCZ 3) with villas and individual housing complexes (LCZ 6). Large complexes built after the destruction caused by the Second World War are grouped in the LCZ 6 class.

The agglomerate area develops in the meadow of the Seine Valley and extends onto the slightly inclined slopes and plateaus. To the south, and especially to the west of Rouen, there are compact forest areas that extend into the valley corridor. These elements contribute to the juxtaposition of differentiated local climates due to the specific thermal behaviour of cultivated lands, forests and wetlands compared to urban areas, and the possible channelling of air masses by the relief (thermal and gravity breeze) as well as by the Seine corridor.

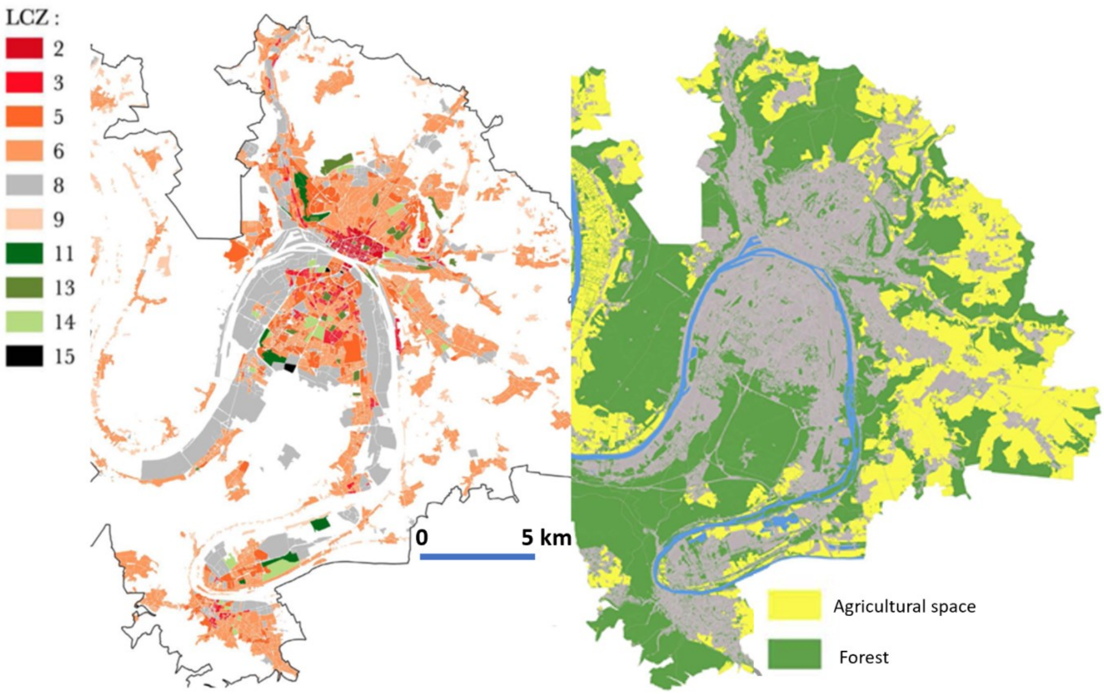

Figure 4 Local climatic zone of Rouen city (Leal, 2023 - modified and simplified). Legend :

2 – Historical centre of Rouen and collective buildings - 3 - Housing for workers (suburbs). There is little or no vegetation and the surface is mostly paved 5 - Collective buildings (open blocks) - Low plants and scattered trees create a permeable landcover. 6 – City centres (residences, villas and groups of individual habitats), Low plants and scattered trees create a permeable landcover 8 - Areas (commercial, industrial and tertiary activities) - There is little or no vegetation and the surface is mostly paved. 9 - Agricultural activities and dispersed housing - Low plants and scattered trees create a permeable landcover. 11 – Forested area. 13 – Heterogeneous vegetated space. 14 – Low vegetation. 15 – Waterproof surfaces - Areas occupied by facilities (industrial zones, sports complexes, shopping centres, parks, hospitals etc.) - Location, city centre and peri-urban suburbs.

3. Research issues and methodology

3.1. Issues

To mitigate the impact of heat islands in cities, it is necessary to create development programmes that should promote more ecological forms of construction and integrate more green spaces. These mitigation measures require a detailed understanding of a phenomenon whose intensity, duration and spatial extent vary from city to city, depending on the frequency of meteorological situations that are most conducive to its occurrence, favoured by the topographic characteristics of each site. All studies demonstrate that UHI mapping is the first approach to identify and implement mitigation measures. Therefore, understanding the UHI in Rouen involves strengthening the existing meteorological measurement network and installing new sensor-recorders in strategic sectors of the urban area. In fact, Rouen has only one station that continuously records all meteorological variables but is not directly representative of the urban area because it is located on the northern plateau (Boos airport). The current measurement network, therefore, does not allow for a comprehensive study of the urban climate and microclimate maps in the Seine Valley (a necessary step to highlight the urban heat island).

- The goal of this measurement campaign is, therefore, to establish a knowledge base regarding the urban climate of the Rouen metropolis.

- The analysis of thermal surfaces (performed using “Landsat” satellite imagery) is the second step that will allow for better identification of urban heat and cool islands.

3.2. Methodology and Research ToolsIssues

3.2.1. Measurement campaign

This method aims at characterizing the real spatial diversity of temperatures and humidity on a finer scale. Several profiles, such as north-south, east-west, the Seine Valley, plateau-plain-valley, could be conducted at different times of the day. These were carried out between 09:00 and 18:00 by a single person equipped with an electric bicycle. This approach did not take into account the administrative measures imposed by the university management - the administrative closure of the university starting on 14 July.

The advantage of this method is to provide a better understanding of UHI at the neighbourhood level and of the experienced temperature. The limitations were imposed by the complex organization of data collection (human resources, materials, methods, and for example, for security reasons, night and weekend measurements could not be carried out for this project).

These surveys targeted heatwaves and temperature peaks observed between 25 June and 15 August 2020. The calendar below (Table 1) details all the days affected by these measurement surveys.

Table 1 Calendar of measurement campaigns carried out in the summer of 2020.

Month	Campaign 1	Campaign 2	Campaign 3	Campaign 4
June	25 - 26			
July	2 - 3	13 - 17	20 - 22	27 - 31
August	5 - 7	10 - 11		

In this research paper, we aim to present only the results obtained (between 12:00 and 18:00) during the temperature measurement campaign on 25 June. For thermography, we present the photographs taken on 31 July 2020 between 14:00 and 14:30.

The measuring devices (Photo 1) were placed inside a "Davis" weather shelter in a ventilated basket in front of an electric bicycle. These instruments were programmed to perform continuous measurements, within a time interval that can vary from 30 seconds to 5 minutes. The speed of the cyclist, which varies depending on the weather and topographic conditions, determines the number of measurements taken.

Photo 1 Weather shelter and measuring devices (Skywatch BL and RHT 35) (https://www.jdc.ch/skywatch-bl/?lang=fr; https://www.sdec-france.com/centrales-acquisitions-donnees-meteo-extech)

3.2.2. Surface temperature assessment through satellite image analysis

Landsat satellite images

The "Landsat 8" satellite makes a complete orbit of the Earth every 16 days. The images obtained in 16-bit format have a ground spatial resolution of 30 m and cover an area of 185 km x 185 km. This satellite has two main instruments. A multispectral sensor (9 bands) called "Operational Land Imager" (OLI) and a thermal sensor called "Thermal Infrared Sensor" (TIRS) with two bands (10 and 11). The first multispectral sensor is a push-broom sensor (a fixed network of detectors that allows data acquisition across the full width of the imaging field). This satellite collects data in the visible, near-infrared, short-wave infrared and panchromatic bands. The TIRS sensors are in the thermal infrared range (these sensors measure the radiative energy emitted by the Earth's surface).

Table 2 shows the different spectral bands of the Landsat-8's OLI and TIRS sensors. Bands 2, 3 and 4 are visible bands that allow for natural colour imagery. Band 2 is in the blue range, band 3 represents the green range and band 4 represents the red range. The wavelengths of these bands range from 0.452 to 0.673. Band 5 refers to the near-infrared (NIR) range (wavelengths from 0.851 to 0.79 µm). Bands 4 and 5 enable the calculation of the Normalized Difference Vegetation Index (NDVI), which allows for the estimation of plant chlorophyll function. Bands 10 and 11 are part of the thermal infrared bands.

Table 2 Landsat 8 spectral bands.

Landsat-7 ETM+ Bands (µm)			Landsat-8 OLI and *TIRS* Bands (µm)		
			30 m Coastal/Aerosol	0.435 - 0.451	Band 1
Band 1	30 m Blue	0.441 - 0.514	30 m Blue	0.452 - 0.512	Band 2
Band 2	30 m Green	0.519 - 0.601	30 m Green	0.533 - 0.590	Band 3
Band 3	30 m Red	0.631 - 0.692	30 m Red	0.636 - 0.673	Band 4
Band 4	30 m NIR	0.772 - 0.898	30 m NIR	0.851 - 0.879	Band 5
Band 5	30 m SWIR-1	1.547 - 1.749	30 m SWIR-1	1.566 - 1.651	Band 6
Band 6	60 m TIR	10.31 - 12.36	*100 m TIR-1*	*10.60 – 11.19*	Band 10
			100 m TIR-2	*11.50 – 12.51*	Band 11
Band 7	30 m SWIR-2	2.064 - 2.345	30 m SWIR-2	2.107 - 2.294	Band 7
Band 8	15 m Pan	0.515 - 0.896	15 m Pan	0.503 - 0.676	Band 8
			30 m Cirrus	1.363 - 1.384	Band 9

Surface temperature assessment using a GIS application, "ArcMap"

To characterize surface temperatures using "Landsat 8 - bands 4, 5, 10 and 11" satellite images, it is highly useful to utilize GIS (Twumasi et. al., 2021) and (Kasniza Jumari N.A.S.et.al.2023). The image processing using "ArcMap" is inspired by the studies of Foissard X et al. (2013), Alonso (2017), and Avdan et al. (2016). This method recommends performing multiple treatments. All these manipulations were carried out under "ArcMap" using specific determinations for each stage of the analysis:

Calculation of the spectral radiance of thermal bands 11 and 12 using the raster calculator

$$L\lambda = MLQcal + AL$$

Lλ = Spectral radiance (in Watts/m²/steradian/nanometre),

Qcal, ML and AL are the values of specific multiplicative and additive bands available in the satellite image metadata (which can be downloaded from the USGS, United States Geological Survey) table 3:Lλ = Spectral radiance (in Watt/m²/steradian/nanometre).

Table 3 ML and AL values of bands 10 and 11.

	M_L	A_L
Band 10	3.3420E-04	0.1
Band 11	3.3420E-04	0.1

Conversion of spectral radiance to brightness temperature for bands 10 and 11

The data from the TIRS band must be converted from spectral radiance to brightness temperature (TB) using the thermal constants provided in the metadata file and the following equation:

$$Tb = \frac{K_2}{\ln\ln\left(\frac{K_1}{L_\lambda}+1\right)} - 273.5$$

Lλ = Spectral radiance

T = Satellite brightness temperature in degrees Celsius

The values K1 and K2 (Table 4) are available in the metadata and represent calibration constants 1 and 2.

Table 4 K1 and K2 values of bands 10 and 11.

	K_1	K_2
Bande 10	774.8853	1321.0789
Band 11	480.8883	1201.1442

Image processing is continued with the raster computer to determine the emissivity (E) value. Emissivity corresponds to the ability of bodies or surfaces to absorb and emit radiated energy. However, in order to obtain it, it is necessary to first calculate the NDVI (Normalized Difference Vegetation Index) with the raster images of the infrared bands 4 and 5. Positive values of NDVI represent vegetated surfaces, therefore, the higher the values are, the closer this index will be to 1, indicating a greater vegetation cover. Values close to zero represent bare soils and values between 0 and -1 represent non-vegetated surfaces, such as snow, anthropic infrastructure or even clouds (Tucker, 1979).

- Calculation of the NDVI index with the infrared bands 4 and 5

$$NDVI = \frac{band\ 5 - band\ 4}{band\ 5 + band\ 4}$$

Next, we need to deduce Pv (proportion of vegetation).

- Calculation of Pv (proportion of vegetation).

$$Pv = \left(\frac{NDVI - NDVI_s}{NDVI_v - NDVI_s}\right)^2$$

NDVIs represents all NDVI values below 0.2, and NDVIv represents all values above 0.5. For NDVI values between 0 and 0.2, the land is considered as covered soil. NDVI values from 0.2 to 0.5 represent mixtures of soil and vegetation cover. However, when NDVI is equal to 0.5, the land is considered to be covered with vegetation (Wang et al., 2015).

- Calculation of emissivity

$$E=0.004\times Pv+0.986$$

- Surface temperature of bands 10 and 11

From the emissivity and brightness temperatures, we can obtain the surface temperature for bands 10 and 11.

$$TS\,10 = \frac{T_{b10}}{1 + \frac{10.8 \times T_{b10}}{14388 \times ln\, ln\, E}} \qquad TS11 = \frac{T_{b11}}{1 + \frac{10.8 \times T_{b10}}{14388 \times ln\, ln\, E}}$$

The surface temperature is obtained by averaging the two values.

$$Ts = \frac{TS10+TS11}{2}$$

The advantage of this method is the identification of hotspots and cooler areas (islands of freshness). The coarse resolution only at Metropolis scale (estimated at 1:50,000) is a limitation.

Thermography

This scientific approach consists in evaluating the response of the environment (green spaces or buildings) to excess heat during heatwaves. It also makes it possible to visualize energy accumulation based on coverings and remarkable contrasts between materials. The use of the infrared thermal camera IR-8 (988OSI) (Photo 2) has made it possible to reveal all these subtleties.

Thermal camera Infrared (IR-8) Reference 9880SI
Thermal camera with IR resolution 80x80 p (high resolution visible 320 x 240 pixels – video format 1280 x 960 pixels) for temperatures of 20˚ to 350˚C)

Photo 2 Thermal camera used for thermography (https://www.instruments-mesure.com/camera-thermique/694-camera-thermique-infrarouge-ir-8.html)

4. Results and discussion

4.1. Weather during the summer of 2020

In the summer of 2020, throughout France, anticyclonic conditions truly settled in only between 22 and 24 June 2020. A heat peak affected the country from the 23rd to the 26th (observed in Rouen). In July, rainfall was weak across the entire country. The first heatwave of the summer was observed on 23-26 July. The month of August was also marked by a heatwave observed between 6 and 13 August. The curve of maximum daily temperatures recorded in Rouen (Figure 5) highlights these exceptional periods. We thus note the peak of 33.1°C recorded on 25 June, the increase in temperatures on 31 July (37.9°C) (excluding the nationwide heatwave). Finally, temperatures above 35°C were observed on 7, 9 and 11 August during the heatwave episode which affected the entire France. A temperature above 38.4°C was recorded on Sunday, 9 August (this is a new record), with the previous one dating back to 2003.

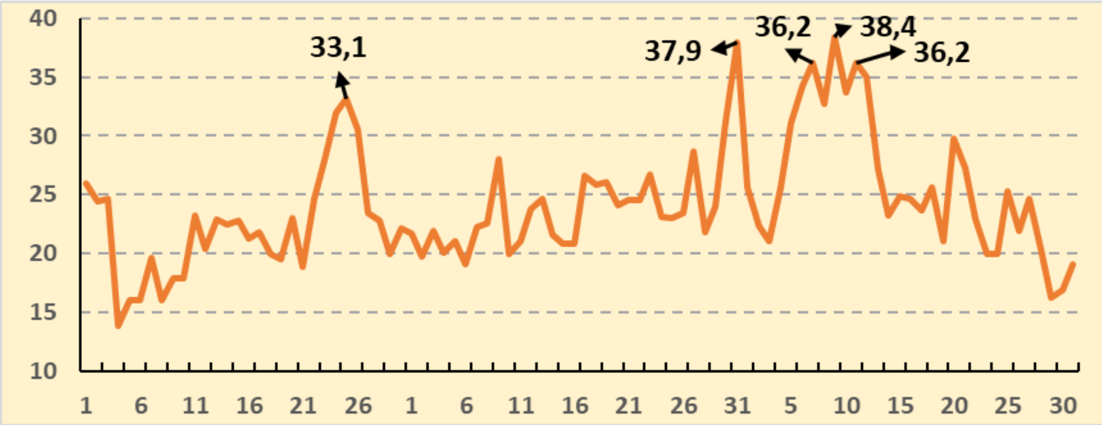

Figure 5 Maximum daily temperatures in °C, recorded at Rouen, in summer 2020 (June, July and August) (the numbers indicate the heat peaks observed on 25 June, 31 July, 7, 9 and 11 August). Data source, Météo ciel (https://www.meteociel.fr)

4.2. Measurement campaign on 25 June 2020

The measurements carried out on 25 June 2020 reveal an organization of temperatures that respects two main criteria in the thermal response of the urban area of Rouen: the influence of major transport routes and the role of substrate diversity (vegetated or built spaces) and the land use percentage of these two criteria. The map in Figure 6 clearly shows these differences. Thus, we may observe the large crown of boulevards (Boulevard de l'Yser in the top left (C), Boulevards de la Marne (B), de Verdun (D) (in the top part of the map), and finally, Boulevard Gambetta on the right (E). These major axes display values close to 33.3°C. These temperatures slightly increase at major traffic intersections (for example, at the intersection of Boulevard Gambetta and Rue d'Amiens, a temperature of 33.9°C is to be noted). The same applies further down on the map at the intersection of this boulevard with the quays of Paris (F) (33.9°C). Also on the quays of Paris (F), despite the proximity to the River Seine, a hotspot is observed (34.3°C), corresponding to the built area of the Rouen Opera House (4) (this is a combined double effect of the anthropized space and the nearby traffic axis). On the left bank of the Seine, after the Boieldieu Bridge (I), a temperature of 34.2°C (5) is also noted on Rue Saint-Sever (probably a channelling effect of air mass, as the same values are observed all along the street up to the Church of Saint-Sever (3). In the square of this place of worship, the vegetal space is reduced.

The vegetation plays a significant role in mitigating high temperatures in urban environments (through plant and tree evapotranspiration). The 25th of June was particularly hot, being one of the three days (24, 25 and 26 June) of intense heat observed in Rouen Boos (weather station - France, Boos located at 151 metres on the southeast plateau). This threshold for thermal classification is adopted by Météo France based on the maximum temperature value "Tmax" recorded, which must be ≥ 30°C. Thermal contrasts are clearly identified on the air temperature map. The city hall gardens (1) reveal these thermal differences. We note a temperature of 33.6°C in the street behind the green space, while the thermal value at the level of gardens shows 31.3°C, and in the city hall square, the thermometer displays 31.9°C. The differences are well highlighted around Notre-Dame Cathedral (1). Very close to the gardens, the temperature displayed is 30°C, but it rises to 33.8°C in the streets bordering this cathedral. The role of green spaces is further demonstrated at Fontaine Sainte Marie and the proximity of Place André Maurois (intersection of rue Louis Ricard and rue Sainte-Marie) (7). In this location, the displayed temperature is 33°C, increasing slightly to 33.1°C at the end of the first street and reaching 34°C in Place Beauvoise (6). Zooming in square (6) shows the clear differences between the point near the vegetated area of the square (33.1°C) and the point on the adjacent opposite sidewalk (34°C).

The map in Figure 6 also shows hot spots and cold spots directly related to the type of land use and existing urban development. Photo 4 shows the Rouen Opera House and its completely anthropized main square, with temperatures above 34°C. Photo 8 shows rue Daliphard (a narrow alley but densely lined with trees and with numerous vegetated spaces) with a value of 31.1°C.

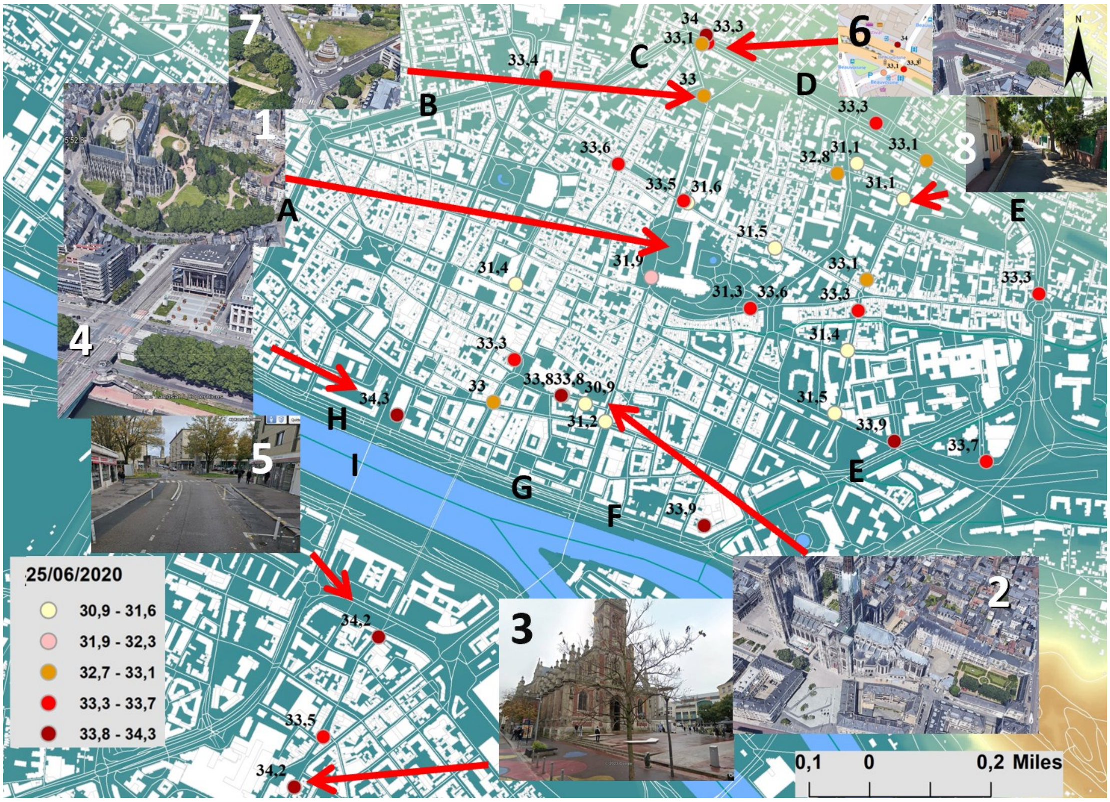

Figure 6 Temperatures in °C, observed at Rouen on 25 June 2020. A, Boulevard des Belges – B, Boulevard de la Marne – C, Boulevard de l'Yser – D, Boulevard de Verdun – E, Boulevard de Gambetta – F , Quai de Paris – G, Quai Pierre Corneille – H, Quai du Havre – I, Pont Boieldieu.

4.3. Processing of satellite image on 13 July 2020

The satellite image from 13 July 2020 shows the spatial distribution of surface temperatures (Figure 7). We note that the highest values (above 30°C) are observed in industrial areas (west and 'east' banks of the Seine loop) and commercial areas (zones 1 and 7) (Figure 4).

The lowest temperatures are found in vegetated surfaces and water bodies (2, 3, 4 and 5). The old quarter of the square (6) stands out for its high temperatures (above 33°C) recorded in the urban central area. The difference between paved urban areas and vegetated quarters (park, garden or shaded roads) is estimated at +4°C, increasing when vegetation density is high and can reach 10°C (e.g., the peri-urban agricultural area, 6). On Verdun Boulevard, the trees along this traffic axis provide a low thermal response (between 2 and 27°C) captured by satellite (zone 4). It is also the case of the botanical garden (2) which represents an island of freshness surrounded by very dense urbanization.

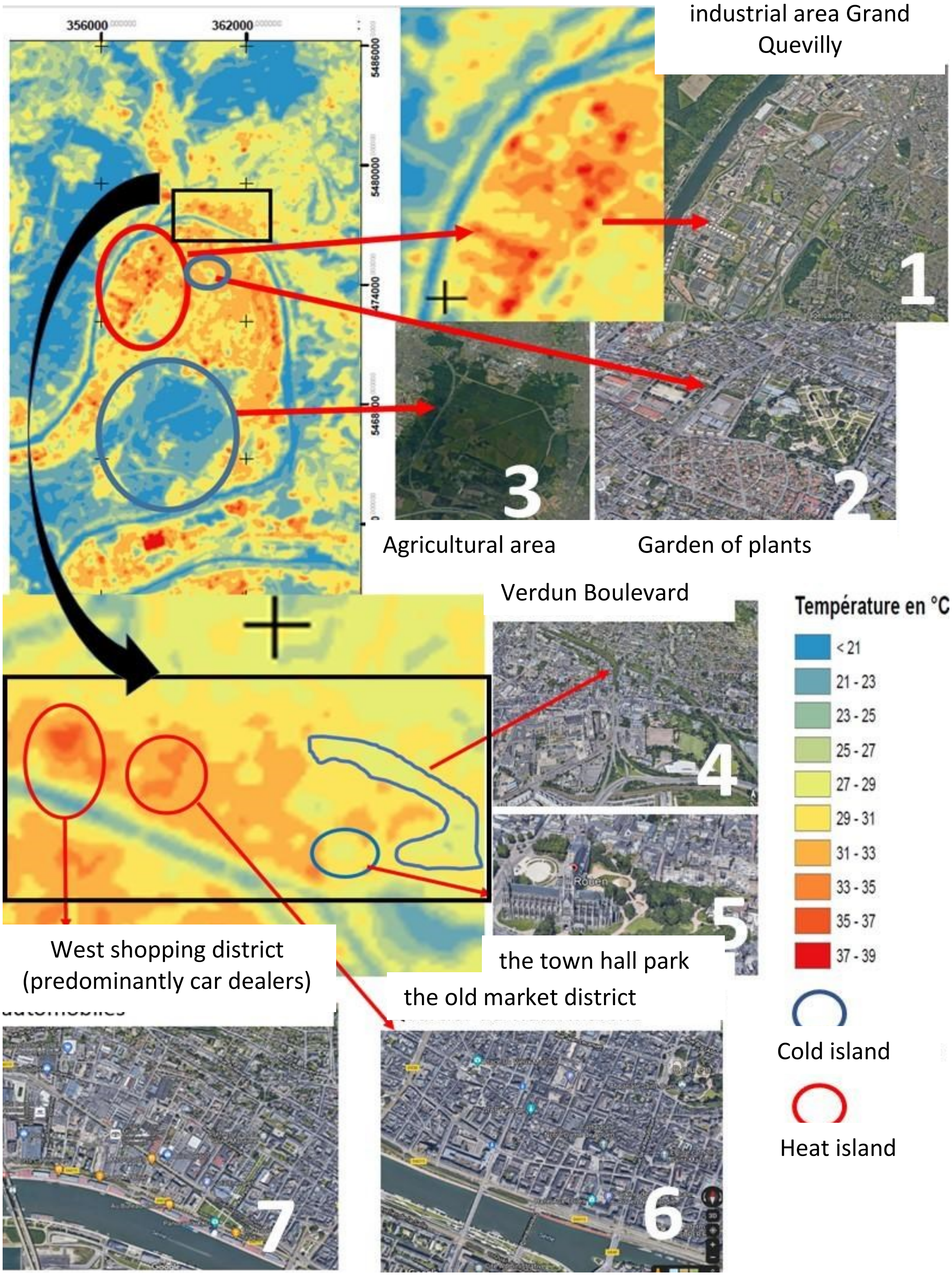

Figure 7 Surface temperatures on 13 July 2020 (obtained by processing the Landsat image, a photo taken at 10:45 a.m. - UT).

4.4. Thermography results

The thermography conducted on 31 July 2020, at the hottest time of the day between 14:00 and 15:30 p.m. (the thermometer reached 37.3°C around 14:00 on this extremely hot day), shows very significant thermal contrasts generated by the construction materials used in districts, especially for traditional Norman houses with timber (Figure 8 A). This temperature difference is also observed between vegetated and paved spaces. For example, in Place Verdrel (in the centre of Rouen), we can see that the asphalt spaces are marked in red, while the shaded green spaces and aquatic areas are blue (Figure 8 B and C).

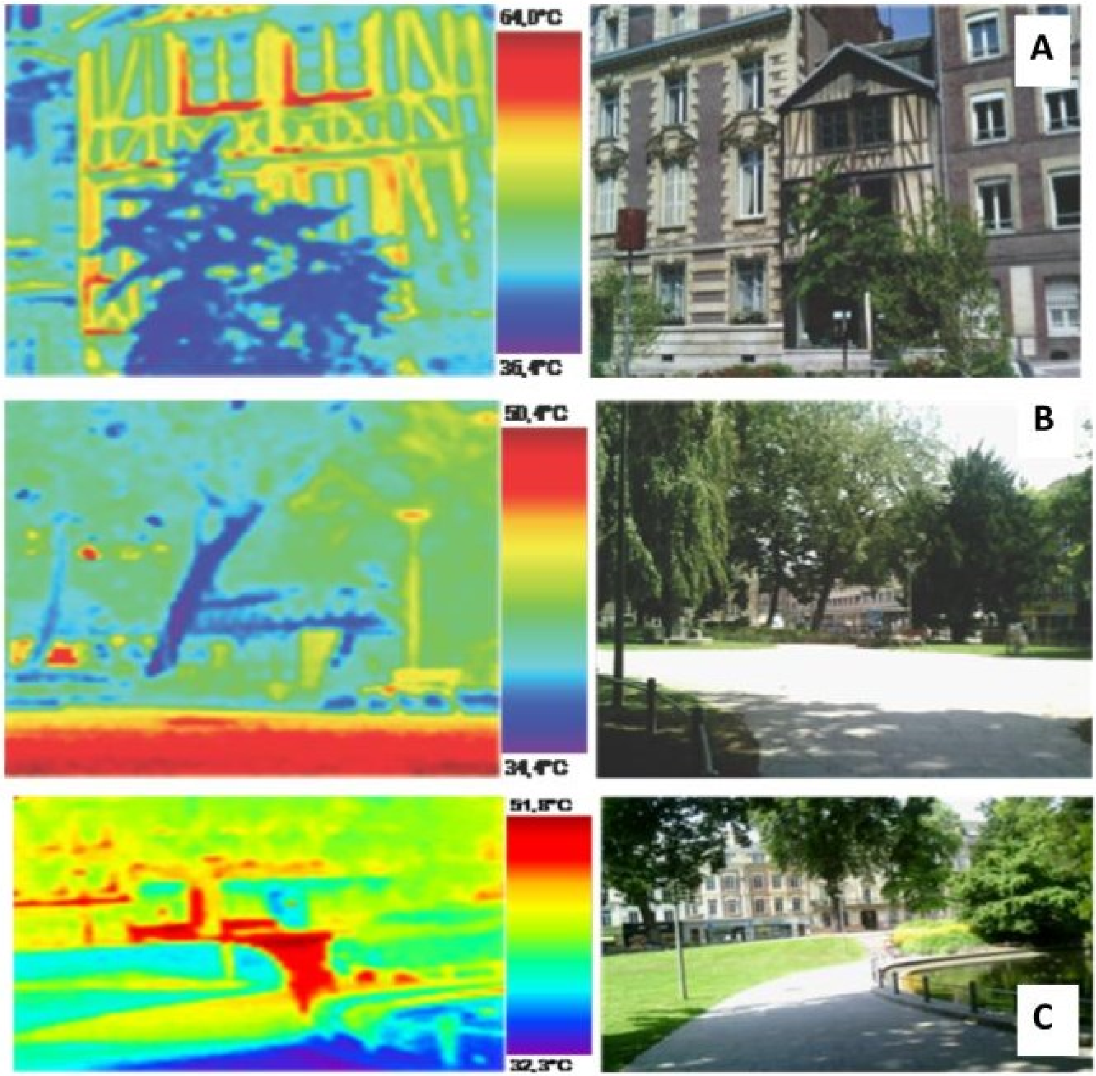

Figure 8 Thermography carried out on 31 July 2020 in Place Verdrel.

5. Conclusion

Cities are currently at the heart of climate change. Temperatures in the Rouen metropolitan area have increased by 4% since 1973 and heatwave episodes are becoming more numerous and more intense. As part of this climate change, heatwaves and temperatures are likely to intensify, which is why many studies are currently being implemented to adapt cities with a view to reducing discomfort and mortality related to heatwave episodes, such as the one in the summer of 2003. Therefore, in recent years, local authorities have been financing research on Urban Heat Island (UHI) and its mitigation actions (the integration of this issue in SCOT - Schema of Territorial Coherence and PLU - Local Urban Development Plan). This study on UHI (funded by the Rouen metropolitan area) proves interest in using various methods such as remote sensing and expeditionary measurements to analyse this phenomenon. The study on the climatic influence of urban forms has shown that both density and urban activity play a very important role on the heat in the city. However, even within the same urban climate class, surface temperatures vary.

The processing of “Landsat 8” satellite images from 20 July 2020 made it possible to obtain surface temperature maps that revealed a significant thermal contrast between industrial areas and urban areas. This contrast was also found to be substantial between vegetated and built areas. However, this thermal response sometimes remains quite imprecise, as the satellite captures surface radiation. Thus, in the satellite image (Figure 6), Verdun Boulevard appears as an island of freshness (an effect of the trees bordering this road axis and covering the asphalt with their crowns). This surface thermal response is completely different from the one provided by the air temperatures recorded in this sector during the measurement campaign on 25 June (the observed values were the highest in this geographic sector) (Figure 5). Therefore, field measurements made it possible to correctly determine the effect of urban density and surface waterproofing on urban temperatures (a maximum difference of +3.4°C was observed between vegetated spaces and built open spaces on 25 June 2020) (Figure 6). Field measurements also revealed the importance of the hotspot in Place Verdrel (Figure 7). It is a recently developed square, but it will undergo significant expansion through the planting of trees along Lecanuet Street, allée Eugène Boudin and rue Jeanne d’Arc to mitigate the impact of heatwaves and canicule.

Although the satellite imagery approach allows for a clear localization of hotspots and cooler spaces (islands of freshness), this method remains quite imprecise due to the low spatial resolution of the image (30 m), i.e., a scale of 1/150,000. The field analysis approach is more precise and detailed, allowing for the detection of contrasts at a very small spatial scale. Thus, it is possible to highlight the various shades of the urban microclimate. Nonetheless, this method is still subject to limitations related to the influence of altitude on temperatures and the hourly variability of solar radiation.

Finally, thermography is another analysis method that allows for the accumulation of energy based on the visualized surfaces. It is used at a very fine scale and has made it possible, for example, to highlight the thermal characteristics of traditional Norman construction materials - wooden houses (timber).

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