Planning and urban climate: the example of the metropolitan area of Barcelona

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ABSTRACT

Cities have a special role in Climate Change (CC). According to the Center for Human Settlements (UN-HABITAT) cities stand for 75% of global energy consumption, as well as 80% of greenhouse gas emissions (GHG). The contribution of urbanisation to climate change has two sides. On the one hand, the urban generation of GHG, which contributes in a decisive way to the global warming; and on the other hand, the radiation generated by the surface of the urbanised land, which determines a certain sensible and latent heat flow due to the type of urban roofs, as well as their degree of humidity. Although the climate of cities depends mainly on factors of regional character, the local and micro-scale factors, such as the different characteristics of the urban structure, the topography and surface of the ground cover, vegetation, as well as the anthropogenic heat generated by urban metabolism, among other factors, can modify the regional climate and generate urban microclimates. There are significant differences in the climate of urban areas compared to rural areas: the urban heat island (UHI) describes the influence of urban surfaces on the temperature patterns in contrast to the surrounding areas.

Despite there is a high consensus that urban planning has a fundamental role to study, coordinate and implement measures to improve the urban climate for facing the climate change effect, the professionals still does not seem have internalized it. The Metropolitan Plan of Barcelona is now in process. The new plan for the metropolitan area should direct the urban development of 36 municipalities, bringing together about 3.5 million inhabitants. For the first time, the aim is to include climate assessment in urban planning in Barcelona in order to mitigate the effects of the UHI. The present paper shows the results of the research project developed at the Technical University of Catalonia (Urban CLIM-PLAN) directed to build a set of physical and urban models of UHI in order to integrate them into a platform for multiscale simulation of the climate system of the Metropolitan Area of Barcelona. The paper shows the methodology used to define "local climate zones", or "climatopes", and their insertion in metropolitan urban planning. The urban climate zones are areas with similar microclimatic characteristics. They differ especially in the daily temperature curve, the vertical roughness (wind field disturbances), the topographic position and exposure and above all in the type of current land use. Another criterion to identify "climatopes" is the quantity of emissions produced. As microclimatic characteristics in built-up areas are primarily determined by the type of land use and especially by the type of development, “urban climate zones” are named after the dominant type of land use. Its inclusion in metropolitan planning in Barcelona can be a decisive step to reduce the city's climate impacts, increasing its resilience to climate change.

Keywords: Metropolitan Planning; Urban Heat Island; Climatopes; Local Climate Zones.

1. INTRODUCTION

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen." (IPCC 2014[1], page 30). "Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was very likely the warmest 30-year period of the last 800 years in the Northern Hemisphere, where such assessment is possible (high confidence) and likely the warmest 30-year period of the last 1400 years (medium confidence)" (IPCC 2014[1], page 40) (Fig. 1). This temperature increase is distributed throughout the planet and is more pronounced in the higher northern latitudes. The terrestrial regions have warmed faster than the oceans. The variation of greenhouse gas (GHG) concentrations in the atmosphere and variations in land cover and solar radiation, alter the energy balance of the climate system. In this sense, the anthropogenic origin of the observed changes[2] seems today an equally incontrovertible fact. The global emissions of GHG due to the effects of human activities have increased, since the pre-industrial era, by 70% between 1970 and 2004. The result of the different models of the evolution of the temperatures of the earth's surface, show the prominence of anthropogenic forcing origin, with respect to those of a natural nature.

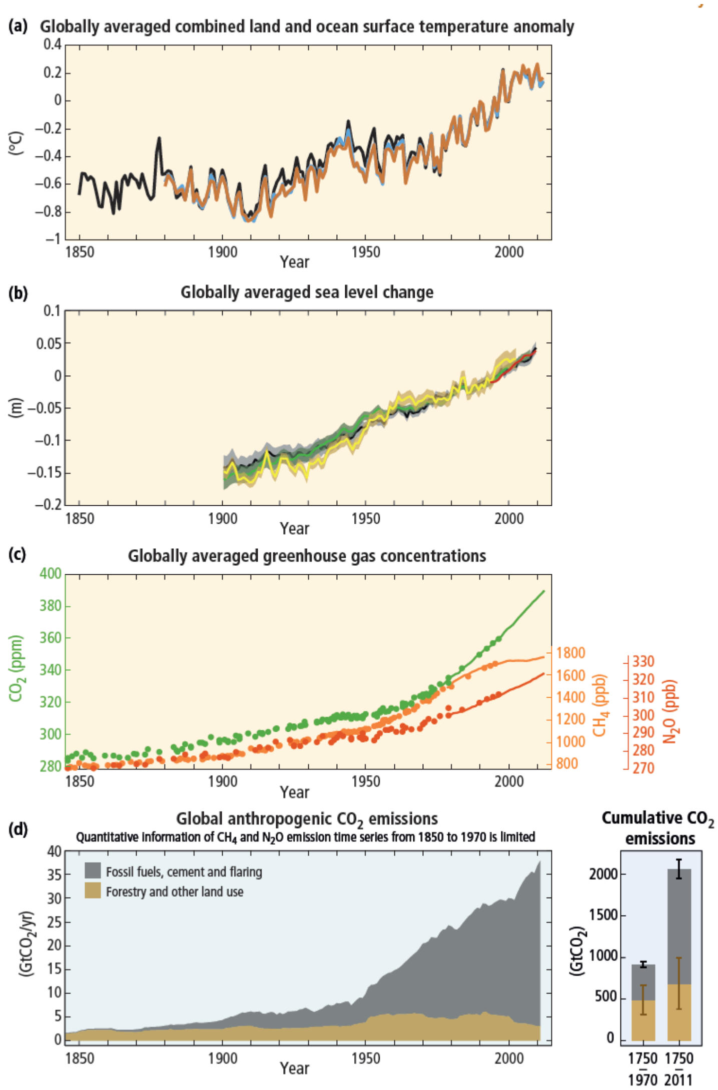

Figure n. 1: Evolution of temperatures, sea level, GHG concentrations and anthropogenic CO_2 emissions. Source: IPCC 2014[1]

In the case of Spain and Catalonia, the studies carried out[3,4] have obtained results similar to those observed on a global scale, with increments of the order of 0.5ºC by decade, especially in spring and summer, denoting changes that also affect the rainfall regime, as well as in general to extreme events of climatic origin.

These trends will continue to occur, even accelerating, throughout the 21st century. Climate simulation models show a high level of agreement that, with current policies to mitigate the effects of climate change, global GHG emissions will continue to increase in the coming decades. "Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise" ([1] page 10, figure 2).

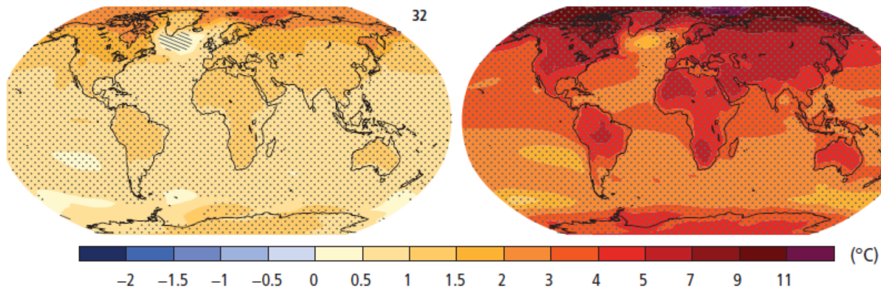

Figure 2. Change in average surface temperature (1986−2005 to 2081−2100)[1]. RCP2.6 (left) RCP8.5 (right)

There is a consensus on the fact that cities have a special role in the climate change. According to the Center for Human Settlements (UN–HABITAT, http://www.un.org/press/en/2007/gaef3190.doc.htm), cities are responsible for 75% of global energy consumption, as of 80% of GHG emissions. The contribution of the urbanization to the climatic change is of double nature: on the one hand, by the urban generation of GHG, a factor that contributes in a decisive way to the global warming of the planet; on the other, by the radiation generated by the surface of the urbanized land, which determines a marked flow of sensible and latent heat according to the type of urban covers, as well as their degree of humidity.

Although the urban climate depends essentially on global and regional factors, local and micro-scale factors, such as the different characteristics of the urban structure, topography and surface of land covers, vegetation, anthropogenic heat generated by urban metabolism, among other factors, can modify the local climate on the urban scale.

There are significant differences between the climate of urban and rural areas: *the urban heat island* (UHI) describes the influence of urban surfaces on the patterns of temperature in urban areas as opposed to the surrounding areas. The sealed land and artificial materials (especially asphalt and concrete) used usually in urban areas are one of the main causes.

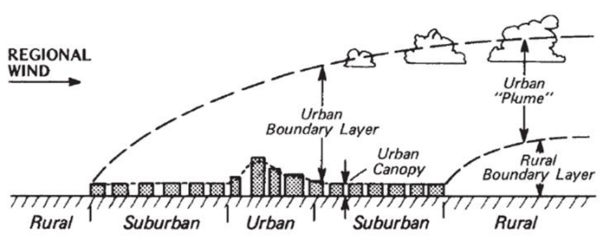

Figure 3. Urban Canopy & Urban Boundary Layers. Source: Oke (1987)[5]

The effects of the UHI manifest in different scales. Two types of UHI can be distinguished: the "canopy layer heat island" and the "boundary level heat island" (Fig. 3). The first depends on the roughness of the soil generated by the buildings and the canopy of the trees, with an upper limit located just above the level of the roofs of the buildings. In this layer, air flow and energy exchanges are governed by microscale processes that depend on the specific characteristics of the surface. The second is situated above the first, with a lower limit subject to the influence of the urban surface. In the urban boundary layer, which is the part of the atmospheric boundary layer above the level of the buildings whose characteristics are affected by the presence of the city, the UHI operates in a different way, in the case of a mesoscale local scale phenomenon, controlled by processes that operate on a larger spatial and temporal scale.

Heat accumulation in cities not only affects urban environments, but also has local and even global effects: the urban heat island (UHI) is closely linked to general climate change[6,7]. Changing the wet and permeable uses characteristic of the rural space, by the dry and waterproofed ones of paving and edification of the urban areas, the energy balance and the temperature of the soil are strongly affected as well as many other properties such as evapotranspiration, infiltration of water on the surface, the drainage system, among other factors that affect the climate as well as the set of ecosystems.

There is a wide consensus that *Land Surface Temperature* (LST) plays a key role in the generation of the Urban Heat Island, representing a determining factor in terms of surface radiation and the interchange of the energy[8], in addition to controlling the distribution of heat between the surface and the atmosphere[9]. The composition of land covers are one of the main factors that influence the LST. Specialized literature has emphasized that built up area and the pervious surface (occupied areas provided with vegetation) and impervious surface (paved and built areas) have a significant impact on the generation of a UHI[10]. In this sense, the reduction of vegetation affects not only in an increase of the LST, but also the reduction of precipitation and evapotranspiration[11,12]. The relationship between the LST and the Normalized Difference Vegetation Index (NDVI) is especially well-documented.

Other research has shown the positive correlation between the LST with different building intensity indicators, such as the NDBI (Normalized Difference Built-up Index), which represents that the island of urban heat is higher in the areas built with respect to those not built; several authors have indicated that NDBI it is more stable than NDVI, as it does not depend heavily on the season of the year, as well as for having a more linear relationship with the LST than the vegetation index. The specialized literature has also shown how the LST is related not only to the type of vegetation but also to soil moisture and population density. Applying remote sensing techniques, Weng [13] analyzed the urban expansion and its impacts in the LST, obtaining that the urban expansion caused the growth of the LST in 13.01 K.

Remote sensing provides spatially continuous information that allows obtaining the LST at scales from tens of meters to kilometers. The satellites provide data on characteristics and land uses that make it possible to quantify the UHI using various indicators[14]. Remote sensing has made possible the generalized study of the LST and, consequently, of the UHI at local and regional scales. At present, there are several operational sensors that allow to measure the LST: MODIS, Advanced Spaceborne Thermal Emission and Reflection (ASTER), Landsat-7 ETM +, Landsat-8 TIRS, Geostationary Operational Environmental Satellite (GOES), NOAA Advanced Very High Resolution Radiometer. AVHRR), Indian National Satellite System (INSAT), Geostationary Meteorological Satellite (GMS) as well as the Meteorology Satellite (Meteosat), among others[15].

Although the LST can be easily measured by remote sensing, the UHI has been commonly studied through the air temperature in the atmospheric surface layer, usually at a height of 2 m above the ground (land air surface temperature, LSAT). The air temperature, measured in the weather stations, is one of the observations most frequently recorded, with great precision and temporal resolution[16].

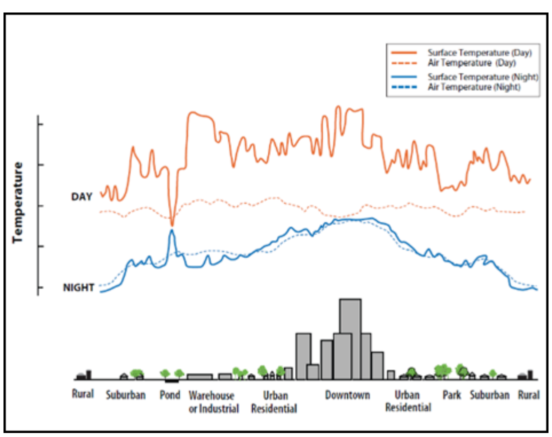

Figure n. 3: LST & LSAT, Day & Night time. Source: Environmental Protection Agency (2008)[17]

The air temperature, despite its lower climatic relevance in relation to the LST, has an essential role at the scale of human comfort. It is the temperature that people perceive, and in relation to which the exchange of energy works with the environment. However, there are usually few meteorological stations, which in general terms means that the data obtained from the stations do not efficiently represent the spatial variation of the air temperature at the intra-municipal or neighbourhood level. For example, at the RMB (Metropolitan Region of Barcelona) there are only 33 weather stations.

Urban planning has a fundamental transcendence to inform, coordinate and implement measures to improve the climate quality of cities in the face of global climate change[18]. There have been some initiatives to introduce methodologies, in the spatial planning, aimed at mitigating climate change. Especially on the "small scale", there is an extensive experience of urban bioclimatic design. In turn, at the building level there has been a significant effort in recent years to increase energy efficiency, with the aim of reducing the generation of GHG (Directives 2002/91 / EC and 2010/31 / EU of the European Parliament and the Council concerning the energy performance of buildings). On the "large scale", however, that of urban and territorial planning, there does not seem to be a parallel awareness, with few initiatives to adapt it in order to increase urban resilience to climate change.

The development of the so-called *climatopes* has become one of the most effective mechanisms for the introduction of climate in territorial and urban planning to the "large scale" (meso-scale, in climatic terms). The beginnings of this technique are found in the pioneering works developed by German researchers at the end of the 70's[19], which developed the new technique of the climatopes in the seminal researches of Baumuller et al. (1998)[20] and Scherer et al. (1999)[21].

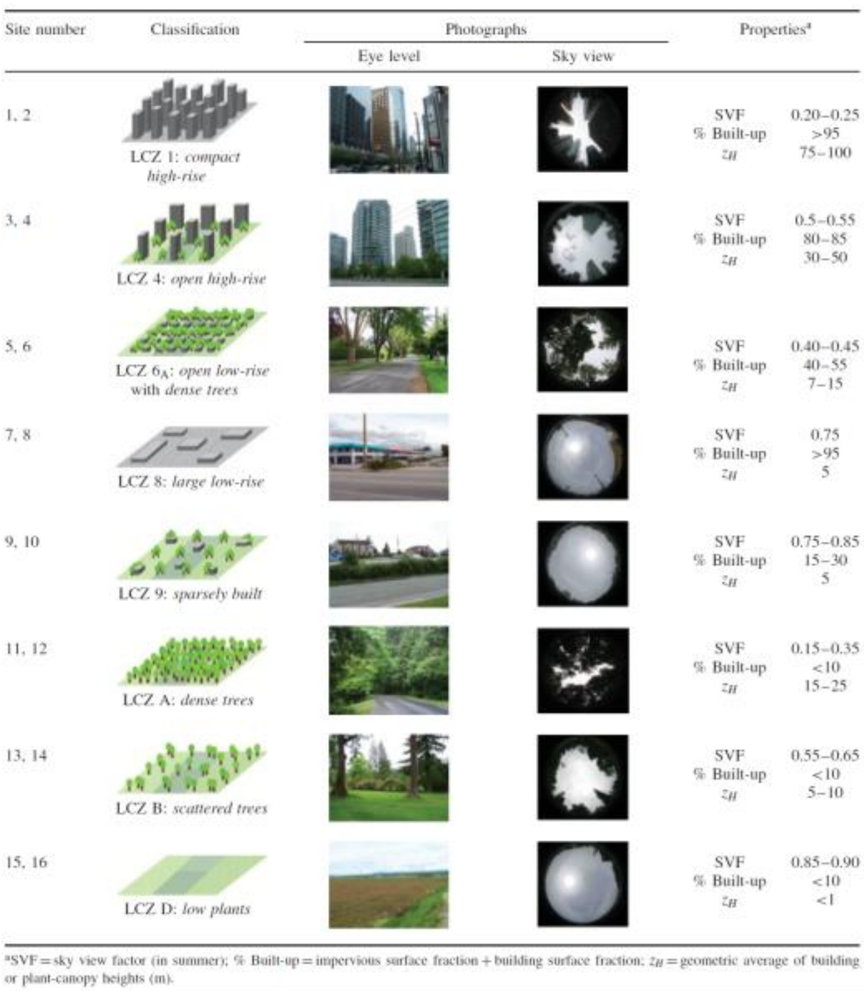

Figure 4. Local Climate Zones[25]

Chao et al. (2010) have carried out a systematic review of the specialized research on urban climate analysis, called in the English-language literature, urban climatic maps (UCM), or more specifically *local climate zones* (LCZ). Highlights include work done for Tokyo[22], Berlin[23], Freiburg, Hong Kong[24], Lisbon or Vancouver[25]. These works have highlighted the importance of integrating climate assessment into territorial and urban planning. The traditional approach that differentiated exclusively the "urban" from the "rural" has been definitively overcome. The "small scale" has come to have a fundamental role in the analysis of the urban climate. In this sense, the incorporation of "climatopes" (typical of Central European culture) in the official (Anglo-Saxon) discourse of urban climatology has been especially relevant. The LCZ[26] have served as a link between both approaches, previously separated from each other.

The introduction of climate assessment in urban and territorial planning can serve to mitigate the effects of the UHI. The practice of planning must include measures such as the limitation of urban expansion, the increase of green areas (including the roofs and facades of buildings) as well as the percentage of pervious land. It is also important to include the modification of the albedo of the built areas (increasing the degree of reflection of incoming solar radiation), the integration of artificial water bodies, the promotion of urban ventilation, the architectural composition of the building and, in general, the composition of urban morphology in a way that facilitates air circulation, generates urban canyons and softens temperatures. All these are measures that must be included in the daily practices of urban and territorial planning.

In this sense, many questions remain. Can the urban climate be modeled with enough detail to assess the effects on the UHI of different urban policies? Which is more efficient, from the point of view of the UHI, the compact city or the dispersed city? Does the urban structure (mono / polycentric) affect the generation of the UHI? Can planning introduce measures that increase the efficiency of the compact and polycentric city from a climate point of view? How does urban design affect the climate of the city? These are, among others, questions that research in the field of climatology and urban planning hopes to be able to provide answers.

2. OBJECTIVE OF THE RESEARCH

The general objective of the research is to study, using remote sensing techniques, *how urban design affects the generation of the Urban Heat Island in the Metropolitan Area of Barcelona (MAB)*, as well as the determination of LCZ specifically adapted to the case of Barcelona. The case of study is the *Metropolitan Area of Barcelona* (figure 5), which includes more than 30 municipalities, bringing together about 3.5 million inhabitants. The Metropolitan Area is the economic and political heart of the Metropolitan Region of Barcelona (MRB), which includes 164 municipalities with a population of 4.7 million people and an extension of 3,200 square kilometers. At this *metropolitan scale*, the spatial configuration of the UHI will be studied.

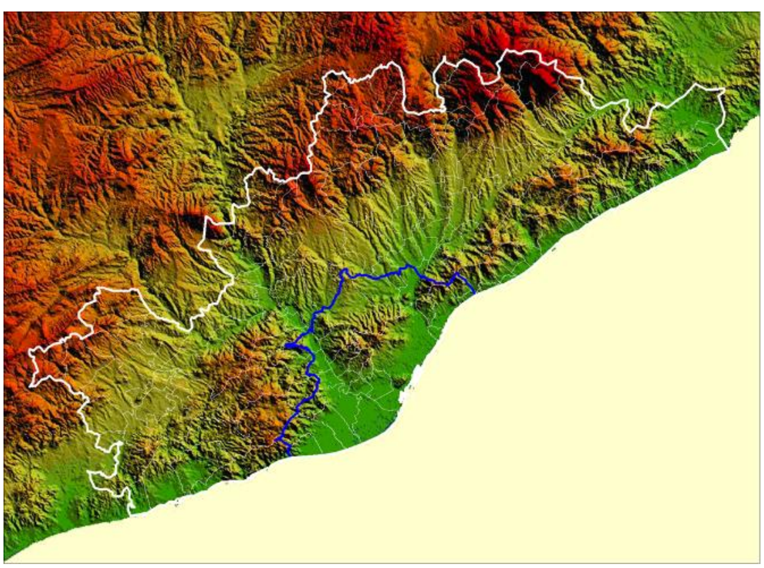

Figure 5. MR (white) and MA (blue) of Barcelona

At present, the "Plan Director Urbanistico" (PDU) of the MAB is being developed. Said urban planning will replace the current "Plan General Metropolitano" (PGM) of Barcelona (figure 6), established in 1976.

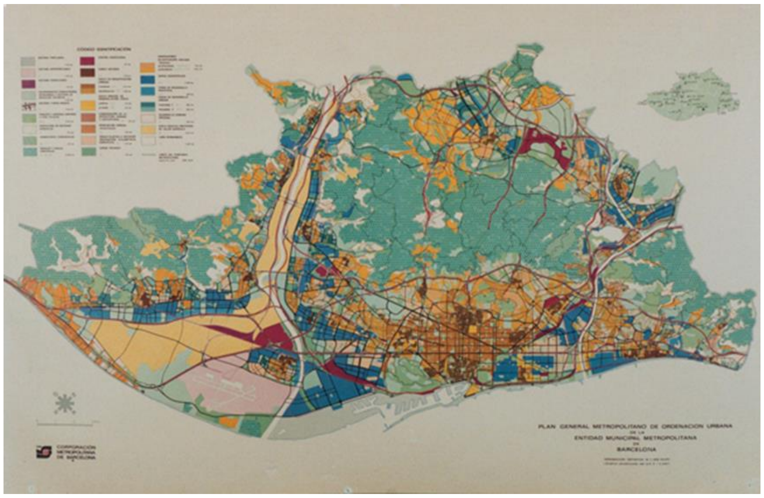

Figure 6. PGM of Barcelona (1976)

The objective of our study is to integrate the evaluation of the urban climate in the metropolitan planning of Barcelona. It is necessary to overcome the traditional vision of urban zoning, from a strictly morphological vision, from regulation of land uses, to a more integral perspective, which incorporates the environmental assessment (and particularly the generation of GHG) and climate of the urban territory.

3. METHODOLOGY

The methodology used in this paper combines the use of remote sensing technologies, of high and medium resolution (1000-10 meters / pixel), with the analysis of the attributes that characterize the different areas of urban planning. The combination of both approaches, remote and local data allow the construction of the different LCZ or "climatopes", as well as incorporate climate analysis in urban planning.

Specifically, the research methodology[27] is developed in the following steps:

I. *Remote sensing analysis*:

a. The daytime LST will be obtained from LANDSAT 8, at resolution scale of 30x30 meters / pixel.

b. Next, an OLS model is developed to resize the previous LST at 10 m / pixel. This transformation is carried out according to the information provided in the visible and infrared bands of the Sentinel 2 satellite. This transformation allows to significantly improve the visualization of the LST, and consequently of the metropolitan UHI of Barcelona.

c. The nighttime LST will be obtained from MODIS, at 1 km^2 / pixel. Due to the low resolution of MODIS, the results of the night LST do not allow a detailed analysis at the local level. However, the nighttime LST obtained through MODIS allows us to know the configuration of the nocturnal UHI at the metropolitan scale.

d. The information obtained through the satellites allows knowing, together with the LST, some indices that affect the UHI, such as the NDVI, NDBI, Urban Index and others indicators. Particularly the NDVI helps to know the effect of the tree canopy and the quality of the vegetation in the UHI of the MAB. These indices have been calculated for the resolution of 30 meters / pixel of LANDSAT8, as well as for 10 m / pixel of Sentinel 2.

e. Daytime and nighttime temperatures, obtained by remote sensing in the previous sections, allow to make a detailed approximation of the UHI of the MAB and MRB. Given the limited spatial resolution of Modis, an OLS model is developed to estimate the nocturnal LST at a higher resolution, comparable with that obtained in the day.

II. *Local Analysis*. The objective of this second stage of the research is to integrate the different indicators obtained through remote sensing in the analysis of the built environment. The aim is to develop a methodology of urban-climatic zoning, which integrates the main components of urban climate in the traditional urban zoning. Among others, the following indicators will be used at the local level:

a. Albedo.

b. Sky View Factor.

c. Aspect ratio.

d. Pervious/impervious surface.

e. LST (in warm season).

f. LSAT (in warm season).

g. Three canopy and quality of vegetation.

h. NDBI and other indices of building intensity.

i. Floor area ratio.

The integration of the previous indicators with the data obtained through remote sensing allow the construction of the metropolitan climate or LCZ of Barcelona.

4. OBTAINING LST

4.1. Daytime LST.

The method used to obtain the LST using information from LANDSAT consists of converting the numerical coding (Digital Number-DN) of the thermal band (infrared heat) facilitated by the satellite in physical units, i.e. in Celsius degrees. As such:

- The *DN* is transformed into *spectral radiance*.
- *At-sensor brightness temperature* is calculated. This temperature does not take into account the type of material or land that emits the energy captured, it would therefore be equivalent to the temperature emitted by a black body.
- The final step for obtaining the LST is to correct the numerical value obtained in the previous steps, by introducing the *emissivity* of the soil materials. In this case, the emissivity has been obtained from the NDVI (normalized difference vegetation index). The use of the NDVI with respect to other alternatives, such as land use classification has two main advantages: 1. both, temperature and vegetation index come from the same moment in time, and 2. the immediacy involved in the calculation of this index.

The used image (LC81970312015176LGN00) was in the summer of 2015 (an extremely hot year). Specifically from June 25. LANDSAT 8 image with the following bands: 1 = Coastal; 2 = Blue (30 m); 3 = Green (30 m); 4 = Red (30 m); 5 = Close-up infra-red (30 m); 6 = SWIR 1 (30 m); 7 = SWIR 2 (30 m); 8 = Pan (15 m); 9 = Cirrus; 10 = TIR 1 (100 m); 11 = TIR 2 (100 m).

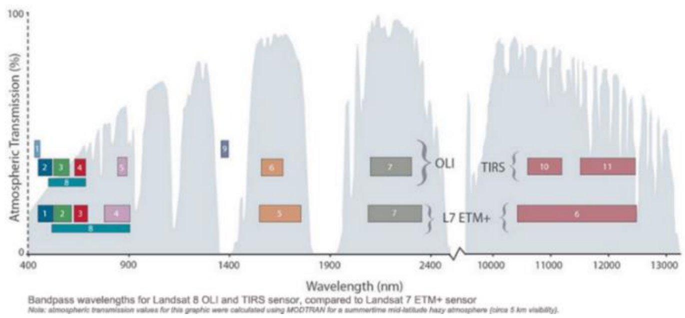

Figure 7. Landsat bands

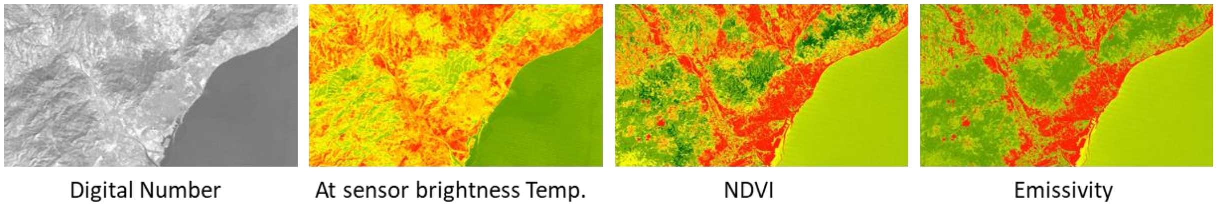

Figure n. 8: LST process

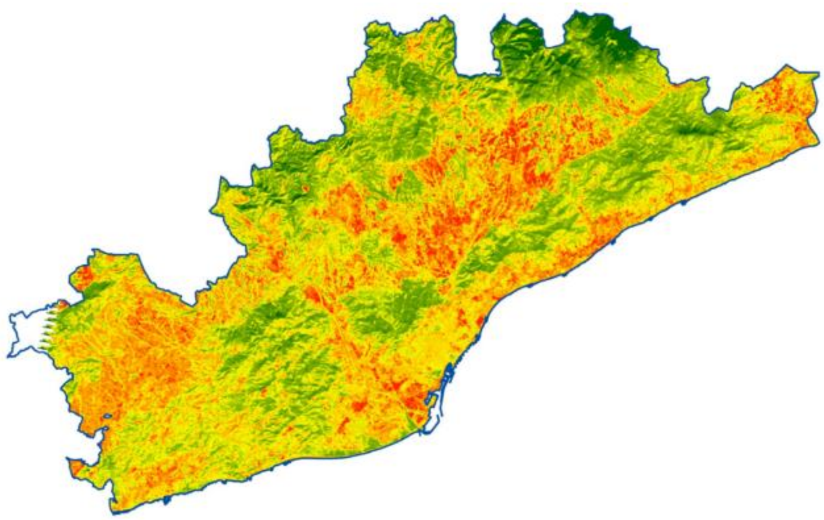

Figure 9. LST

4.2. Improving the spatial resolution of the LST

The resolution of Landsat (30 meters pixel in the visible and infrared bands, 100 m / pixel in the thermal band) does not allow a detailed knowledge of the LST (figure 10). Sentinel 2 (10 m / pixel) offers the possibility of resizing the thermal image to a higher level of spatial resolution. To change the resolution from 30 to 10 meters / pixel, two differentiated OLS models are developed:

- On the one hand, a strictly *geographical model* is tested. Such model incorporates, as independent variables, the altitude (DTM), orientation, slope and distance to the sea. The model explains 38.5% of the variation of the LST.

- In a similar way, an "urban model" can be constructed to explain the daytime LST (Landsat) .The best model of the tested ones explains 55% of the variation of the LST, with the NDVI (-), NDBI and UI (+) , and the average LST of the urban planning areas (which appears as the most significant variable).

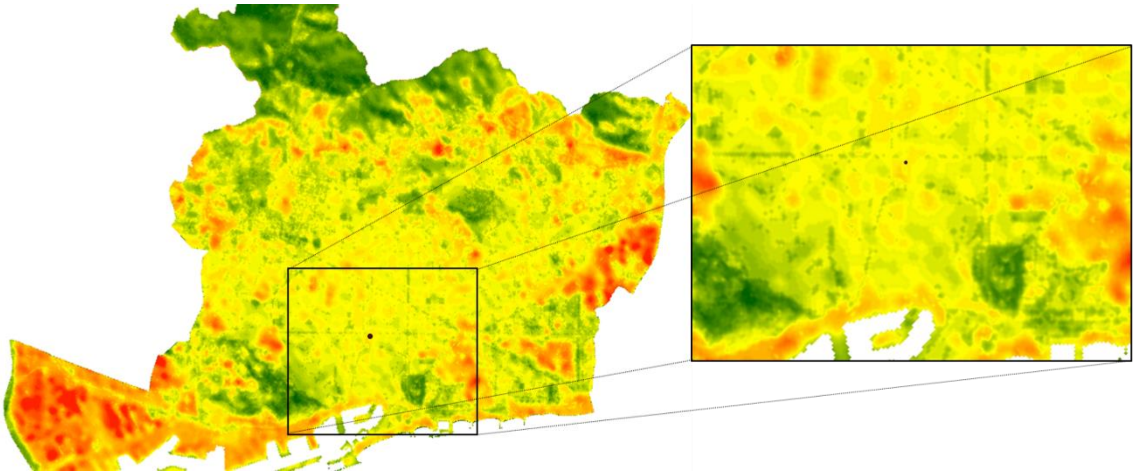

Figure 10. LST by Landsat 8

- The integration of the two previous models, allows to improve the R2 up to 0.572. The change of scale from 30 (Landsat 8) to 10 meters (Sentinel2) allows to substantially improve the visibility of the UHI.

- Finally, a "hybrid" model at 10 meters / pixel is tested (figure 11 and table 1). This model explains 64% of the spatial variation of the LST, improving in a sensible way the visualization of the UHI of Barcelona. The model is constructed with the NDVI (-), NDBI (+), orientation (-), slope (+), UI (+), altitude (-), distance to the coast (-), emissivity (-), distance to the centre of the city (+), albedo (-) and the average LST of the different zones of metropolitan planning (+).All the variables are significant (except for the Urban Index, due to its high collinearity with the NDBI) and appear with the expected sign. It is noteworthy that, at the scale of the municipality of Barcelona, the distance to the center appears with a positive sign, due to the existence of (hot) industrial zones in the periphery of the city.

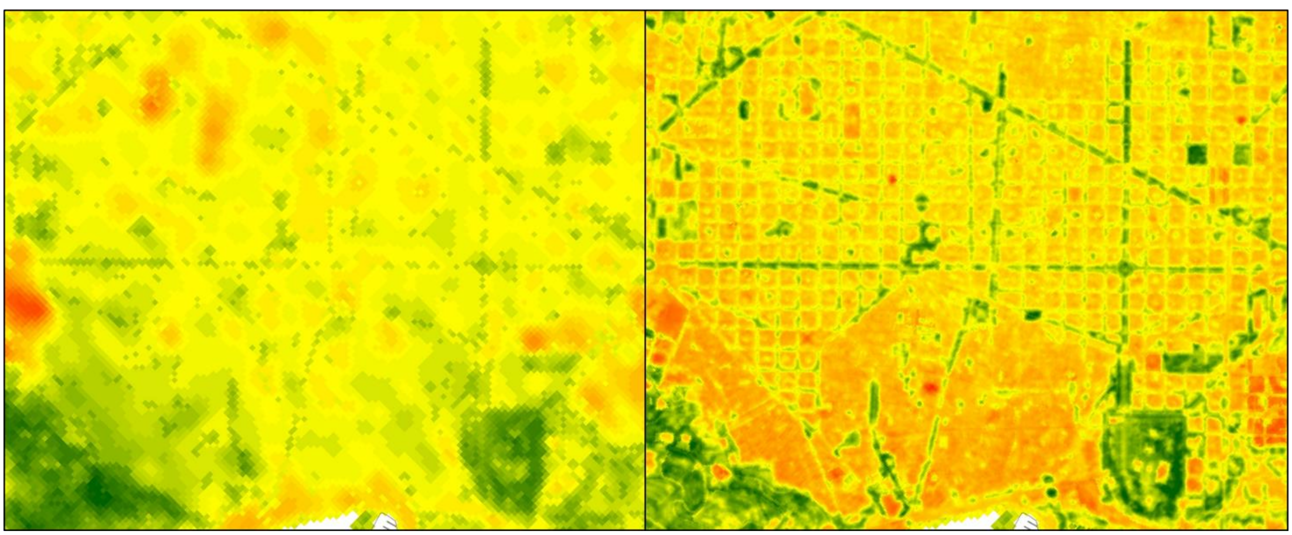

Figure 11. LST (Landsat 8) vs “hybrid” model

Resumen del modelo[b]

Modelo	R	R cuadrado	R cuadrado ajustado	Error estándar de la estimación
1	,800[a]	,640	,640	1,375257857

a. Predictores: (Constante), lst2_BCN_10_PGM, Dist_Cat, Orient, albedo_bcn, NDBI_Sen2_, pendent_gr, emiss_BCN, Dist_Coast, ndvi, DTM_BCN_pr, UI_Sen2_07

b. Variable dependiente: lst2_BCN

Coeficientes[a]

Modelo		Coeficientes no estandarizados		Coeficientes estandarizados	t	Sig.
		B	Error estándar	Beta		
1	(Constante)	24,07151665	,064		379,005	,000
	ndvi	-1,60314462	,014	-,154	-114,518	,000
	NDBI_Sen2_	4,581614842	,063	,263	72,725	,000
	Orient	-,002640599	,000	-,093	-146,191	,000
	pendent_gr	,0310215485	,000	,119	105,243	,000
	UI_Sen2_07	,0355701525	,049	,003	,720	,472
	DTM_BCN_pr	-,000852859	,000	-,042	-27,301	,000
	Dist_Coast	-,000156073	,000	-,182	-134,097	,000
	emiss_BCN	-7,19689641	,041	-,186	-173,944	,000
	Dist_Cat	,0002307857	,000	,216	243,607	,000
	albedo_bcn	-3,33769201	,073	-,042	-45,692	,000
	lst2_BCN_10_PGM	,4314942479	,002	,293	280,874	,000

a. Variable dependiente: lst2_BCN

Table 1. "Hybrid" Model

4.3. Nighttime LST

As indicated, the LST, obtained through Landsat / Sentinel, shows a kind of "donut" around the metropolitan center, due to the peripheral position of the industrial estates, which generates the illusion that the UHI does not follow the conventional pattern of major temperatures in the CBD. To solve this paradox it is necessary to analyze the LST at night, by means of the information provided by the Terra sensor of Modis.

Once the LST was obtained at daytime by means of Landsat (30 m/pixel) and Sentinel (10 m/pixel), *the LST at nighttime was obtained through MODIS* (1 km / pixel). Figure n. 12 compares the LST of day (Landsat) with the LST at night. Figure 13 shows the nighttime UHI of MRB (MODIS resolution).

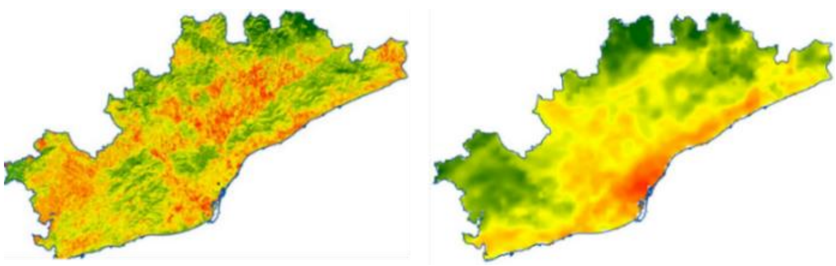

Figure 12. LST (daytime Landsat vs. nighttime Modis)

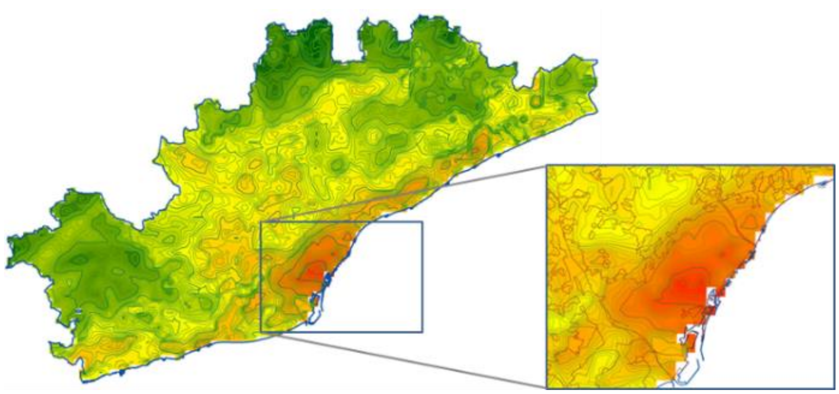

Figure 13. UHI of Metropolitan Region of Barcelona (nighttime)

As can be seen in figure 12 and 13, *the morphology of UHI during daytime differs sharply from nighttime UHI*. *During the day*, the metropolitan center (the city of Barcelona) does not show the highest metropolitan LST. They are the industrial areas of the first metropolitan ring (that surrounds the city except for the North side, where Collcerola Park closes the ring) that reveal the highest surface temperatures. The extreme LST are also located in the industrial areas and in the compact centers located in the Pre-coastal Depression, which runs parallel to the sea, beyond the Coastal Mountains (Garraf, Collserola and so on). The agricultural areas of the Pre-coastal Depression, especially the vineyards, also observe elevated LST. On the opposite side, the forested areas show the lowest temperatures at metropolitan scale: the spaces characterized by a high quantity and quality of the vegetation observe the most moderate LST in the MRB, as evidenced by the high negative correlation between the NDVI and the daytime LST (table 3).

During the night, the spatial distribution of the LST varies in a meaningful way. The compact urban centers, and especially the city of Barcelona, denote the highest LST. On the other hand, in rural areas, the reduction of night temperatures is pronounced. The agrarian zones, and especially the vineyards, observe a much more pronounced cooling than the urban spaces. And the highest LSTs move from the Pre-coastal Depression to the Coastline. The industrial areas, on the other hand, also show a marked reduction of the LST: they cool much more sharply than the compact residential fabrics. And the wooded areas, except for those located at very high altitudes (> 1,000 meters), also observe, like the urban centers, a greater thermal inertia. Forests preserve surface temperature much more than open spaces (table. 4).

The problem is that MODIS has an approximate resolution of 1 km, too poor to establish with precision the metropolitan UHI of Barcelona. Therefore it is necessary to proceed to model the nighttime LST, in order to better understand the spatial pattern of MRB and MAB UHI. Specifically, the "night cooling" will be modeled, based on the difference between the day and night temperatures obtained by Modis. Later this model will be applied to the daytime LST of 30 m / pixel (obtained by Landsat), in order to estimate the nocturnal LST with a higher level of spatial resolution.

The results of the model are presented in Table 2 and figure 14. The OLS model explains 81.5% of the nightly cooling of the MRB. The model is built with the altitude (DTM), the orientation, the slope, the NDVI, the NDBI, the LST of day, the distances to the sea and the metropolitan center, as well as the main covers of Corine Land Cover (CLC).

Especially noteworthy is the positive sign of both the distance to the sea and the metropolitan center. Night cooling is less pronounced on the coast line, as well as in the metropolitan CBD. In turn, the negative sign of the NDVI shows the lowest cooling of the areas characterized by a high vegetation, due to its greater thermal inertia. In relation to the different land covers, the compact built areas observe a lesser cooling nighttime effect than the urban sprawl areas. At the same time, industrial and agricultural land undergoes an important night cooling.

Resumen del modelo[b]

Modelo	R	R cuadrado	R cuadrado ajustado	Error estándar de la estimación
1	,903[a]	,815	,814	1,06122

a. Predictores: (Constante), NDBI, Altres Rurals, Dist_costa, Orientació, Altres Urbans, Dist_Centre, Dispers, Industrial, Compacte, Pendent, MLST_dia1, Agrícola, DTM, ndvi_30, Forestal

b. Variable dependiente: Dif_mlst_dia1_nit1

Coeficientes[a]

Modelo		Coeficientes no estandarizados		Coeficientes estandarizados		
		B	Error estándar	Beta	t	Sig.
1	(Constante)	-22,893	,643		-35,595	,000
	DTM	,004	,000	,362	26,362	,000
	Orientació	,001	,000	,029	4,068	,000
	Pendent	-,013	,001	-,104	-11,240	,000
	ndvi_30	1,627	,219	,107	7,428	,000
	MLST_dia1	1,130	,015	1,021	76,973	,000
	Compacte	-,471	,481	-,046	-,978	,328
	Dispers	,385	,478	,046	,805	,421
	Industrial	,411	,484	,034	,849	,396
	Altres Urbans	,176	,489	,011	,359	,719
	Agrícola	1,250	,477	,227	2,620	,009
	Forestal	,842	,477	,163	1,765	,078
	Altres Rurals	,710	,478	,102	1,485	,138
	Dist_costa	4,284E-5	,000	,172	17,212	,000
	Dist_Centre	1,681E-5	,000	,087	11,624	,000
	NDBI	1,538	,211	,098	7,290	,000

a. Variable dependiente: Dif_mlst_dia1_nit1

Table 2. “Night cooling” model

The nocturnal LST, with a spatial resolution of 30 m/pixel, confirms the different geographical distribution of the metropolitan UHI in relation to the daytime LST. There is a clear relative warming (less cooling) of the coastal areas and the main urban centres of the pre-coastal depression. The metropolitan centre, the city of Barcelona, obtains the highest

LST. On the other hand, the industrial areas of the urban periphery as well as the agricultural ones are cooled down sharply, forming a marked UHI.

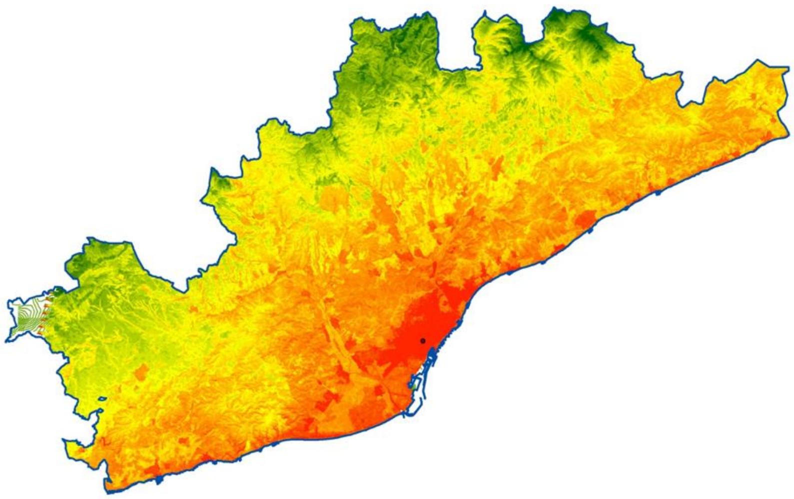

Figure 14. Nighttime LST (30 meters / pixel)

5. METROPOLITAN HEAT ISLAND OF BARCELONA

The LST (Landsat) has allowed to know the UHI (daytime) of Barcelona. Table 3 presents the average LST of the different planning zones of the MRB:

- The “economic activities & logistics” (34.40 ºC), “industrial” (33.29 ºC), “tertiary” and “services” (31.37 ºC) represent the hottest land uses at metropolitan scale.
- At the same time the “roads network” (31.34 ºC) as well as the “compact residential” (31.05 ºC), LST is clearly higher than the average of the MRB (28.58 ºC).
- These land uses contribute to the UHI in a clearly more pronounced way than the "traditional urban residential" (30.43 ºC), “historic center" (30.32 ºC), "residential in grouped houses" (30.30 ºC) or "single family homes"(28.62 ºC).
- The "non-developable land of special protection" (26.17 ºC), the "undeveloped land with protection" (28.16 ºC), the open spaces and greens areas"(28.23 ºC), as well as the "Hydrographic system" (28.61 ºC) are the best rated land uses from a climate perspective.
- On the other hand, the "non-developable rustic land", mainly agricultural land, shows an average LST of 29.08 ºC, higher than the “single family homes“.

In summary: *the artificialized areas observe an average LST that is 7.2% higher than the non-artificialized ones*.

During the night, as we said, the spatial distribution of the LST varies in a meaningful way: *the difference of the LST between the artificialized and non-artificialized zones drops to 1.67 celsius degrees*. This apparent decrease in the UHI occurs due to the cooling effect of the industrial areas (which go from 33-34º C to 16.6 ºC). The hottest land uses are the mixed areas (18.24 ºC), the aero-port system (18.04 ºC), the compact city (17.90 ºC) and the old city (17.65 ºC). While the coldest are the agricultural land (15.52 ºC) and the protected rural land (15.98 ºC). Detached houses represent the coldest urban use (16.47 ºC). On the other hand, semi-detached houses (16.80 ºC) retain, at night, more heat than the industrial, commercial and logistical land (16.60 ºC).

Hottest Uses	LST	Coolest Uses	LST
Logistics Activity	34,4	Rural (Spetial Protection`	26,17
Industry	33,29	Rural (Protection)	28,16
Dev. Land (economic ac	31,89	Green Areas	28,23
Tertiary	31,39	Hydrographic system	28,61
Roads and Streets	31,34	Detached Houses	28,62
Compact City	31,05	Agricultural Land	29,08
Mixed Area	31,04	Residential Blocks	29,6
Mixed Use Development	30,82	Dev. Land (residential)	29,71
Old City	30,32	Semi-Detached Houses	30,3

Table 3. LST by land use (daytime)

Table 4 presents the average LAST (day and night time) of the different Corine Land Covers of the MRB. The land uses that cool most during the night, are the agricultural (15.01 ºC) and industrial land (14.69 ºC). On the other hand, the lower nocturnal cooling occurs, due to its greater thermal inertia, in forest (11.7 ºC) and urban lands (12.72 ºC, the high and medium density lands and 12.63 ºC, the low density use).

CORINE LAND COVERS	LST (Daytime)	LST (Nighttime)	Difference
High and Medium Density	30,35	17,63	12,72
Urban Sprawl	28,8	16,17	12,63
Industrial and Commercial	31,21	16,52	14,69
Other Urban Land Uses	29,72	17,06	12,66
Agricultural Areas	30,07	15,06	15,01
Forest Areas	26,93	15,23	11,7
Other Rural Land Uses	28,35	15,32	13,03

Table 4. LST (day and night) by CLC

6. LOCAL CLIMATE ZONES OF THE METROPOLITAN AREAS OF BARCELONA

The data presented in the previous epigraph confirms the existence of a pronounced UHI in the metropolitan area of Barcelona. It is convenient, therefore, to propose (in urban planning) measures aimed at refreshing highly artificialized soils. For this, it is convenient the introduction of “climatopes” or “local climate zones” in urban planning.

The methodology used to delimit the LCZs of the MRB differentiates the following categories:

1. Urban fabrics.
    a. Residential:
        i. Old cities.
        ii. “Ensanches” (high and medium density compact urban fabrics).
        iii. Isolated Blocks.
        iv. Urban Sprawl.
    b. Industrial:
        i. In urban continuum.
        ii. Industrial parks.

2. Open spaces.

a. Agricultural lands.
b. Urban Parks.
c. Forest Areas.

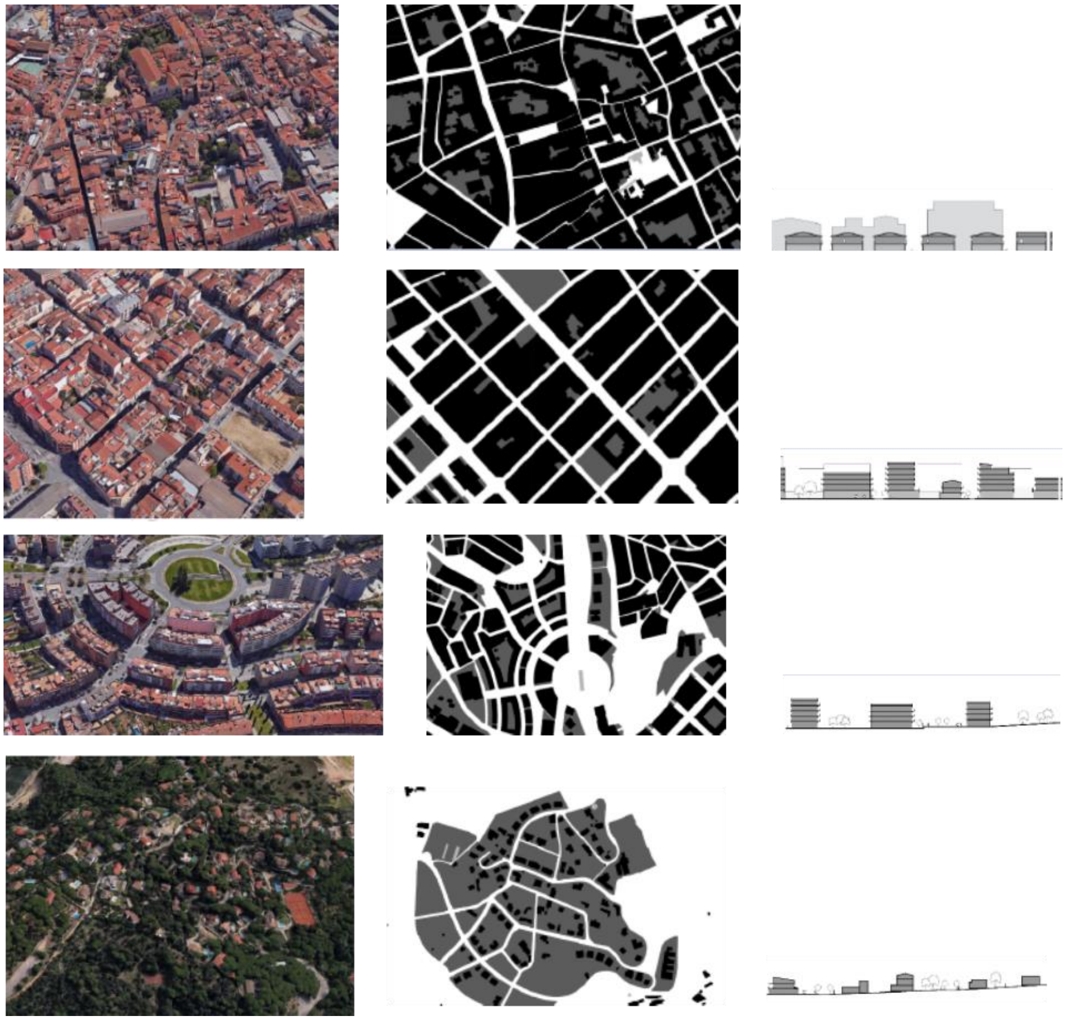

Figure 15. Urban fabrics (residential)

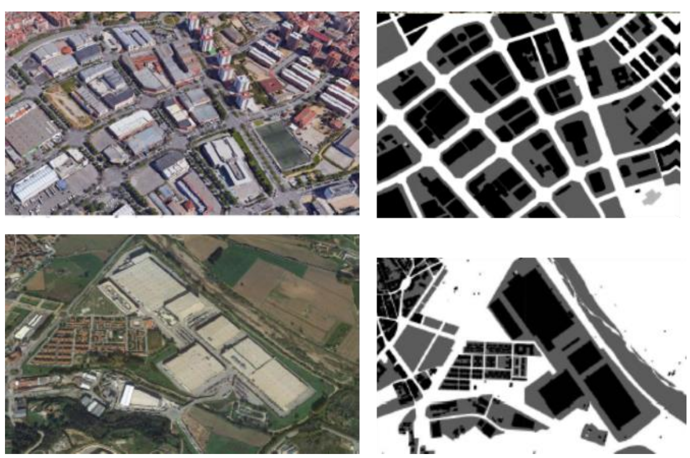

Figure 16. Urban fabrics (industrial)

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