EFFECTS OF URBAN GREENERY ON HEALTH. A STUDY FROM REMOTE SENSING

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ABSTRACT:

Global warming is causing increasing Heat Waves that affect human health. High temperatures markedly increase morbidity and mortality. Urban Heat Islands increase the effects of Heat Waves and are a serious inconvenience to human health and comfort. Cities can substantially increase local temperatures and reduce temperature drop at night. During the night, the greater thermal inertia of the central areas reduces their cooling capacity. On the other hand, it is important to highlight that urban vegetation plays a key role in adapting cities to Global Warming and Urban Heat Island. Green areas have lower temperatures than the rest of land uses and generate a cooling effect that spreads to their surroundings creating a "cool island" effect. The main objective of this paper is to establish the nocturnal land surface temperature and land surface air temperature of Barcelona Metropolitan Area (35 municipalities, 636 km^2, 3.3 million inhabitants) in an episode of a nocturnal heatwave and to estimate its possible impact on health and mortality. Subsequently, nighttime temperatures are analysed in this extreme heat context to determine their spatial distribution and detect the urban landscapes that are most vulnerable to extreme night heat. Modelling of land surface temperature must reveal the elements that determine night Urban Heat Island and consequently identify actions that can be implemented at urban planning level to refresh the environment during the night and thus increase the resilience of the most vulnerable landscapes and improve residents' health. This paper studies the effect of urban greenery and green infrastructures on Nighttime Urban Heat Island and propose climate adaptation measures and design for urban green areas to decrease high temperature in a Heat Wave context, which contributes to reducing the serious negative impacts on people's health.

1. INTRODUCTION

Global warming (GW) is causing increasing heatwaves (HW) that affect human health (IPCC, 2012). Climate change (CC) increases the risk of extreme temperatures and weather events, such as heatwaves (HW). Summer heatwaves have increased in frequency and duration in most of Europe while extreme cold temperatures and cold waves are less frequent. Trends show that in the future with a warmer climate and increased mean temperatures, heatwaves will become more intense, longer lasting, and/or more frequent (Meehl and Tebaldi, 2004). As IPCC (2021) says: "It is virtually certain that the frequency and intensity of hot extremes and the intensity and duration of heatwaves have increased since 1950 and will further increase in the future even if global warming is stabilized at 1.5ºC.". Hence, it is highly likely that CC causes an increase in HWs, which negatively affect human health.

The effects of heatwaves on the population have been described by numerous authors who have established clear relationships between high temperatures and morbidity and mortality, especially in respiratory and cardiovascular diseases (Royé, 2017). The human organism and the atmosphere are in a constantly interacting physical and chemical equilibrium. All humans are forced to react to atmospheric elements to guarantee the correct, optimum functioning of their organs. The thermal environment plays a significant role in public health (Parsons, 2014). Sociodemographic and urban landscape characteristics are associated with mortality risk during heatwaves (Gasparrini et al, 2015). In much of the developed world, societies are aging and hence can be more vulnerable to climate extremes such as heatwaves. For example, Europe currently has an aging population, with a higher population density and lower birth rate (Eurostat, 2022). Climate change can therefore affect human health by changing the severity or frequency of health problems that are already affected by climate factors. It can create unprecedented or unanticipated health problems or health threats in places where they have not previously occurred.

Although the climate of cities depends fundamentally on mesoscale factors, local and microscale factors can modify regional climate at urban scale. These factors include the characteristics of the urban structure, the topography and surface of roofs, vegetation, and anthropogenic heat generated by urban metabolism. There are significant differences in the climate of urban areas compared to those of a rural nature. The urban heat island effect (UHI) describes the influence of urban surfaces on the temperature patterns of urban areas as opposed to surrounding areas (Oke, 1967). Cities accumulate heat in urban land covers and built infrastructures, representing true islands of heat in relation to the rural (less artificialized) environment. The densest urban spaces and industrial and commercial areas are characterized by accumulating more heat during the daytime. In this context, urban heat islands increase the effects of HW.

Urban heat islands increase the effects of heatwaves, representing a serious inconvenience to human health and comfort (Tan et al, 2010). Cities can substantially increase local temperatures and reduce temperature drop at night. During the night, the greater thermal inertia of the central areas reduces their cooling capacity, which represents a serious inconvenience in the case of "tropical" (> 20° Celsius) and "torrid" nights (> 25° Celsius). In cases of high nighttime temperatures, as a consequence of high daytime temperatures, heat stress persists and is impossible to rest and therefore sleep. The literature on urban climate has highlighted the importance of the nighttime UHI. It is during the night that the effects of UHI become more apparent, due to the low cooling capacity of urban construction materials and is during nighttime that temperatures can cause higher health risks. However, the study of nocturnal UHIs is still poorly developed, due to the

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structural problems regarding the availability of land surface temperature (LST) and land surface air temperature (LSAT) data for night time. Traditional methods for obtaining nocturnal UHI have been directed either to extrapolation of data from weather stations, or obtaining air temperatures through urban transects. In the first case, the lack of weather stations in urban landscapes makes it extremely difficult to obtain data to extrapolate and propose models at a detailed resolution scale. In the second case, there is a manifest difficulty in obtaining data simultaneously and significantly representative of urban and rural zones.

The use of satellite images has helped considerably to understand UHI, especially in analyses of daytime land surface temperature (LST). However, available nighttime sensors have a major limitation: their low spatial resolution does not allow detailed analysis of nighttime UHI. In general, few studies have focused on studying nocturnal UHI, due to the lack of information on LST. MODIS and Sentinel 3, for example, have a spatial resolution of 1000 meters/pixel, which is generally insufficient for the analysis of the spatial distribution of the UHI, which has led to the need to downscale said spatial resolution (Mahour et al, 2017; Guzinski et al, 2020). High resolution thermal images (Landsat, for example) are limited to daytime information. In general, few studies have focused on studying Nocturnal Urban Heat Island [NUHI], due to the lack of information on nighttime thermal imagery (Arellano & Roca, 2021). *The study of the nocturnal LST is of great importance in heat stress events derived from Night Heat Waves.*

Furthermore, the integration of LST (obtained from remote sensing imagery) with LSAT (obtained from weather stations) continues to be a pending challenge. The right estimation of the temperature of the air at ≈ 2-m height above ground (LSAT) from LST is possible but complex. The vertical lapse rate to be applied is function of the surface energy balance, which varies in function of the nature of the surface and of the instant of the day, as also of advection, adiabatic processes, turbulence and latent heat fluxes, all of them affected by cloud cover, water vapour content and vegetation (Benali, 2012). At night, however, there is a greater homogenization of advection and adiabatic processes, which represents less complexity in the modeling of air temperatures. The large differences between land surface and air temperatures during the day tend to moderate at night, with the LST and LSAT converging notably, especially in summer.

Air temperature estimated from satellite measurements would solve the weather stations scarcity in wider regions, where the geospatial interpolation methods cannot provide accurate estimations. In this way, LSAT estimation becomes of crucial importance to solve spatial gaps for a wide range of applications, in such a way that it is accepted that TIR produces better LSAT estimations than those obtained by interpolating ground-station temperatures (Mendelsohn et al, 2007). There is significant literature that has deepened on how to obtain the air temperature from MODIS LST. For example, the construction of multiple regression models with air temperature as the dependent variable and daytime and nighttime LSTs, along with other variables such as altitude, longitude, latitude, distance to the sea, NDVI or albedo, as independent variables (Serra et al, 2020). However, there are few studies that have managed to increase the resolution of the air temperature models, due to the low resolution of the data provided by MODIS or Sentinel 3 (Arellano et al, 2021).

This paper seeks to determine the nocturnal land surface and air temperature in a period of maximum nighttime heat (summer 2015). So, this research aims to develop a nighttime land surface air temperature (NLSAT) model by merging information from Landsat, MODIS and information from meteorological stations in order to study the contribution Night Urban Heat Island (NUHI) in episodes of heat wave. Given the practical identity that exists (at night) between air temperature (that is, that experienced by humans) and the temperature of the earth's surface (obtained by remote sensing), the study of the nocturnal LST is of great importance in thermal stress events derived from Night Heat Waves (NHW).

On the other hand, it is important to highlight that urban vegetation plays a key role in adapting cities to climate change. Greenery increases air humidity and due to the green canopy the shaded areas. Such characteristics break the UHI continuum, which is the rise in temperature that cities present, partly, because of high absorption of direct sun-heat in artificial surfaces. Thus, green areas have lower temperatures than the rest of land uses and generate a cooling effect that spreads to their surroundings creating a "cool island" effect (Bowler et al, 2010).

The cooling effect of parks is quantified by the extent limit, which is the maximum distance reached by the cooling spread outside boundaries of the park; and the intensity, which is the difference in temperature between the park and a certain urban space in its near surroundings (Spronken-Smith & Oke, 1998). There is a consensus on the calculation of the cooling intensity, but with slight differences on the spatial attribution of the temperature to the park and the one that represents the urban space. Previous investigations pointed that the cooling extent of parks between 3 and 200 ha size, is in the 50 to 300 meters (m) range, but larger parks go from 200 to 2000m. Whereas the cooling intensity registers values between 1 to 4°C during day and 2 to 5°C at night (Kuttler, 2012), with an average intensity between 0.94 and 1.15°C (Bowler et al, 2010).

From this perspective, *the research aims, through the use of remote sensing, to quantify the influence of the physical characteristics of urban parks and their surroundings to improve the criteria of climate-sensitive urban design and planning and reduce risks for the health of its inhabitants during extreme heat waves*. In this context, the paper studies the effect of urban greenery and green infrastructures on night-time UHI in Metropolitan Area of Barcelona (MAB, fig. 1), and propose climate adaptation measures and design for urban green areas to decrease high temperature in a Heat Wave context, which contributes to reducing the serious negative impacts on people's health.

Figure 1. Metropolitan Area of Barcelona (with municipalities)

2. METHODOLOGY

The methodology used can be summarized as follows:

1. First of all, the heat waves experienced in the city of Barcelona are studied, in order to determine the most appropriate period to carry out the analysis of the LST and the LSAT. There is no universal definition of a heatwave, but extreme events associated with particularly hot, sustained temperatures have been known to have a notable impact on human mortality, regional economies and ecosystems. In this paper, we use the concept of heatwave applied by the Spanish Meteorological Agency (AEMET). In this definition, a heatwave is considered an episode of at least three consecutive days in which at least 10% of the stations that are considered register maximums above the 95% percentile of the series of maximum daily temperatures for the months of July and August from the period 1971 to 2000. However, this definition has a major limitation: it refers only to maximum temperatures, not minimum ones. As indicated, it is the high minimum temperatures that make the most difference for health purposes. Maximum temperatures can have serious consequences, especially on heat stroke. However, the health effects are more pronounced in the case of night heat, where the inability to rest (especially in homes without air conditioning, as is generally the case in in Spain) can cause significant worsening of respiratory and cardiovascular diseases that produce a high proportion of premature deaths. For this reason, in this study we differentiate between heatwaves during the day (DHW) and at night (NHW), paying special attention to the latter.

2. The second step of the study consisted of determining the nighttime LST of Barcelona in a heatwave. August 2015 was chosen since it had temperatures that were higher than the average of the preceding years. There were various day and night heatwaves. This date was also selected due to the availability of night thermal images (bands 10 and 11) of Landsat 8, which allow the night LST of Barcelona Metropolitan Area to be obtained in detail. The day and night images of Landsat 8 from 3 and 28 August 2015 were used, complemented by the night image of 13 September 2015 (to achieve adequate exclusion of areas covered by clouds).

3. The estimation of LST from band 10 of Landsat 8 was carried out according to the abundant existing literature on the matter. However, the estimation of nighttime land surface temperature by Landsat thermal bands is not a trivial question. The most commonly used methodology to determine daytime LST is based on estimating the emissivity of the land from its degree of vegetation: the normalized difference vegetation index (NDVI) threshold (Sobrino et al, 2008). But this method has significant limitations at night. The NDVI overvalues vegetation when it considers the canopy of trees. This overestimation is not a serious problem during the day, when the shade of trees limits the incident radiation on the ground. However, it is critical at night. At night, the application of the standard method for determining emissivity underestimates the land surface radiation in areas with abundant tree vegetation. The result is critical on the streets and in parks with a significant degree of canopy. For this reason, this paper used the methodology suggested by (Arellano & Roca, 2021) to estimate the degree of vegetation and soil moisture. Based on this estimation, the emissivity was determined and consequently the nocturnal LST. In this paper, winter NDVI was used instead of summer NDVI, as it better represents the degree of vegetation at ground level. The tree canopy plays a smaller role due to the deciduous nature of the trees in the study area. At night, when solar radiation is non-existent, long-wave radiation from the ground is not significantly affected by the tree canopy.

4. Modeling the spatial distribution of the LST. The methodology used in this work has been to develop a "hybrid" OLS model, with geographical (longitude, latitude, altitude, slope, orientation and distance to the sea) and urban-territorial (such as NDVI, NDBI, albedo, imperviousness, land covers, …) explanatory variables. The MODIS LST is also included in the model. Said "hybrid" model enables not only LST downscaling (from 1000 meters, MODIS, to 30 meters, Landsat), but also the possible application to other moments in time to those of the date of acquisition of the image.

5. On the other hand, directly modeling the existing information on the land surface air temperature resulting from the meteorological stations. The LSAT is obtained (for the date of the Landsat 8 image) based on the methodology developed by (Serra et al, 2020). The daily MOD11A1 LST measured by MODIS Terra, including daytime (LSTd) and nighttime (LSTn) with 1 km2 spatial resolution, has been used in this study. Besides Satellite variables LSTd, LSTn, NDVI and NDBI, other six geographical and topographic variables are considered: latitude, longitude, distance to coast, altitude, orientation and slope of the terrain for every meteorological station and pixel. Furthermore, the calendar day (cd) has been transformed into a new calendar day (cd*) according to a cosinus transformation (equation 1). These variables are used to fit an OLS model, with the air temperatures obtained from the meteorological stations as the dependent variable. This model makes it possible to know (at a resolution of 1 km / pixel) the spatial distribution of the air temperature.

$$cd^* = \cos\frac{2\pi(cd - cd_{max})}{365} \quad (1)$$

6. Once the air temperature model developed from the meteorological stations has been obtained, said model can be merged with the information resulting from the high-resolution satellite sensors (Landsat 8). In this way, the UHI derived from the air temperature can be visualized in much more detail. Therefore, to downscale the multiregression model developed in section 5, the variables (NDVI, NDBI, LSTn, albedo, ...) are used at a resolution of 30 m/p (obtained from Landsat).

7. The study of the spatial distribution of the Urban Heat Island of the Barcelona Metropolitan Area in August 2015 will allow determining the health risk posed by high temperatures derived from heat waves.

8. Determine the green areas of the MAB through the use of remote sensing (Sentinel 2), as well as study the degree of urban greenery of the different landscapes. Sentinel 2 offers a higher spatial resolution (10 meters/pixel) than Landsat 8 (30 m/p), which helps to more accurately delimit green spaces. NDVI has been used as an indicator of vegetation quality. Spaces with a surface area greater than 1,000 m^2 and an NDVI greater than or equal to 0.3 have been considered "urban parks".

9. And finally, model the effect of greenery in the nocturnal UHI as well as quantify the effect that the increase in green spaces (measured by greenery characteristics and distance to parks) would have on temperature regulation.

3. RESULTS

3.1 Heatwaves and Mortality

Figure 2 shows the (official) weather stations existing in the Barcelona Metropolitan Area. Among them stands out, due to its high temperatures, the Raval station.

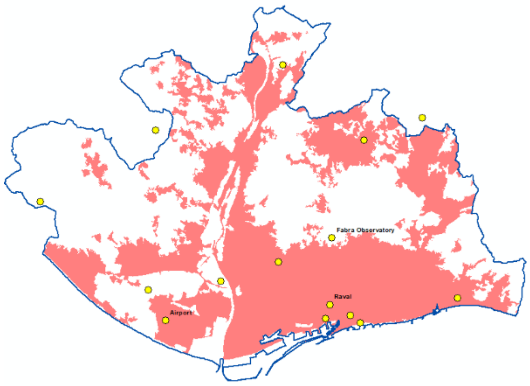

Figure 2. Weather stations

The European Union's Copernicus program highlights two climatic indicators: summer days, when the temperatures exceed 25 degrees, and tropical nights, when the minimum temperature does not drop below 20 degrees. For the period of 1971 to 2020, the Raval was the weather station with the highest number of summer days per year: 114.04. Almost four months/year were summer days. Regarding tropical nights, the Raval on average between 1971 and 2020 reached 66.94 nights or over 2 months a year.

The application of the criteria for defining heatwaves in Barcelona, which is at least 3 consecutive days with a maximum temperature (DHW) or a minimum temperature (NHW) higher than the 95th percentile for the months of July and August in the period 1971 to 2000, gave us the thresholds of 32.49ºC by day and 23.86ºC by night for Raval station (located in the old city). Applying these thresholds, 18 daytime heatwaves would have been produced in the center of Barcelona, with 76 extremely hot days between 1971 and 2020. The Raval station would have endured 70 nighttime heatwaves and 577 very hot nights (table 1).

Years	NHW	HN
1971-1980	0	3
1981-1990	4	28
1991-2000	8	66
2001-2010	24	192
2011-2020	34	288
Total	70	577

Table 1. Nighttime Heat Waves and Hot Nights (Raval)

As can be seen, NHW and extremely hot nights (HN) increased almost exponentially, the first from 0 (1971 to 1980) to 34 (2011 to 2020), and the second from 3 (1971 to 1980) to 288 (2011 to 2020). If the growth continues at the current rate, it could lead to 140 extremely hot nights per year in the center of Barcelona in 2050.

As we have previously indicated, it is during the night when excess temperature can generate more negative effects on health, causing an increase in premature deaths. Using the daily mortality data for Barcelona provided by the Barcelona Public Health Agency (ASPB), from January 1 to December 31, 2018, this study seeks to assess the effects of high temperatures on premature mortality. Figure 3 shows the daily deaths in the city of Barcelona in relation to the minimum temperatures (Tm). The minimum temperature threshold that marks the minimum deaths is located at 21.3ºC.

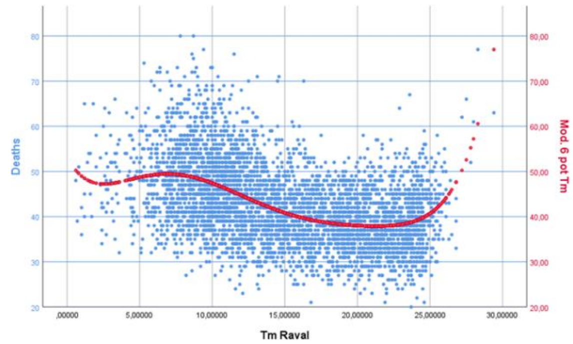

Figure 3. Deaths vs. Minimum Temperatures (2007-2018)

A total of 852 days between 2007 and 2018 experienced night temperatures above 21.3 degrees, which represented an increase in mortality that can be estimated at 995 additional deaths in the same period. Between 20 and 23.86 degrees Celsius (the limit at which a nocturnal heatwave is identified), the increase in mortality is very low (1 additional death). However, above this limit, mortality multiplies exponentially: at 25 degrees (the threshold that we call a torrid night) there are 2.81 additional deaths, which increases to 5.83, 10.98, 19.34, 32.27 and 51.57 for each additional degree. The warming forecasts for the Barcelona area, established in the previous subsection and in the event of no human adaptation to the climate (and the massive installation of air conditioning systems in homes), may lead to a very marked increase in premature mortality due to night heat.

3.2 Nighttime LST

To proceed with the analysis of daytime and nighttime LST, Landsat 8 images relative to the month of August 2015 were used (8/3, 8/28). To obtain a completely cloud-free image of the study area, the night thermal images of 8/28 and 9/13 were combined. Figure 4 compares the August 2015 AMB LST day and night images from MODIS and Landsat.

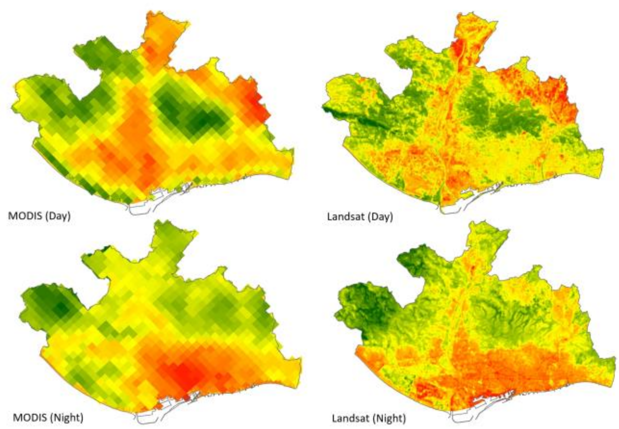

Figure 4. MODIS vs. Landsat LST (day and night)

As is well known, the low spatial resolution of MODIS contrasts with the better resolution of Landsat. However, the few nighttime thermal images from Landsat have made detailed knowledge of nighttime LST difficult. This study focused on heatwave events occurred in August 2015, for which there are nighttime Landsat images, which make it possible to study the LST-UHI at night.

Figure 4 shows the big difference between UHI during day and night. The UHI appears very clearly, especially when compared to the daytime LST (on the left in the figure). While during the day the UHI does not stand out, at night the greater thermal inertia of the urban materials, buildings and roofs determines the greater heat gradient of the built-up area compared to the rural ones. The metropolitan mean of the LST reaches, at night, 22.6°C, confirming that we are faced a Night Heat Wave event. Nighttime UHI is very pronounced: 2.9 degrees higher between rural (21.23°C) and urban (24.10°C) land covers, means a 13.5% higher. It can be affirmed that a significant part of urbanized landscapes had a temperature typical of a "torrid night" in the date of study (August, 2015).

Figure 5 presents the result of modelling nighttime temperature. This model explains 90.9% of the variation in nighttime land surface temperatures, with all significant variables. Table 2 shows this "hybrid" model. Among the explanatory variables, winter NDVI and MODIS LST stand out. These two variables alone explained 88.1% of the spatial variation of Landsat LST. The inclusion in Step 3 of the variable artificialization raised the R^2 to 0.892. However, in Step 4 the variable distance to the coast was incorporated into the model, with the sign changed due to its interaction with artificialization. These four variables accounted for over 90% of the explanatory power of the OLS model.

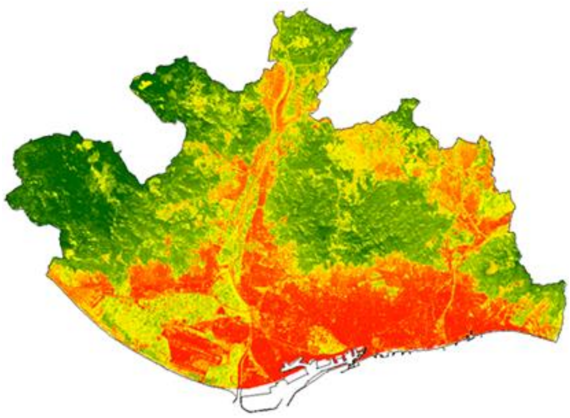

Figure 5. Nighttime LST-UHI model

Model		B	Error Desv	Beta	t	Sig.
1	(Constant)	60,960415	1,759		34,658	,000
	NDVI_L8_20150201	-4,428146	,006	-,456	-702,660	,000
	longitude	2,899694E-5	,000	,125	74,717	,000
	Latitude	-3,836431E-5	,000	-,151	-97,066	,000
	Dist_coast	1,077118E-5	,000	,032	21,042	,000
	Water	,098431	,008	,007	12,163	,000
	Artificial	,596092	,002	,157	275,360	,000
	NDBI	-,018922	,011	-,001	-1,772	,076
	ALBEDO	,171031	,034	,003	5,098	,000
	Imperviousness	,003747	,000	,071	116,462	,000
	Altitude	-,000945	,000	-,066	-91,455	,000
	Orientation	-,000108	,000	-,005	-14,972	,000
	Slope	,011514	,000	,059	115,269	,000
	MLST20150712AMB_N	,008517	,000	,331	393,162	,000

a. Dependent variable: LST_night_2015

Table 2. "Hybrid" OLS model oh nighttime LST

3.3 Modelling Land Surface Air Temperature

Once the nocturnal LST has been obtained, the air temperature is modeled. A multi-regression model has been developed with night air temperature (obtained by weather stations) as dependent variable, and nighttime and daytime LST (obtained by MODIS), latitude, longitude, altitude, slope, orientation, distance to the sea, calendar day* (cd200), NDVI and NDBI as independent variables. The model has been developed throughout the extended Metropolitan Area of Barcelona for all non-cloudy days of the year. The MAB only has 13 weather stations (see figure 2). We have used the 20 stations closest to the city center to improve the significance of the regression model.

The model, with 1832 observations, reaches an R^2 of 0.943, with 7 significant variables. The most significant variable is the MODIS nighttime LST, followed by distance to the sea (-), slope (+), longitude (-), NDVI (-), NDBI (+) and calendar day* (cd200). Altitude and latitude are not incorporated into the best model due to their high collinearity with the variable distance to the sea. The NDVI and the NDBI with the correct sign. In step 7 the variable calendar day* (cd200) is incorporated; its relatively low significance (student's t = 6.579) is due to its high collinearity with the MODIS LST (Pearson's coefficient = 0.911). Table n. 3 presents the regression coefficients of the model.

Model		B	Desv. Error	Beta	t	Sig.
7	Constant	9,812662635	,842		11,657	,000
	LST_night	,8004063728	,017	,805	47,731	,000
	Sea_distance	-,0001221436	,000	-,118	-18,810	,000
	NDBI	3,788099386	,833	,046	4,546	,000
	Slope	,0517143536	,004	,090	12,534	,000
	lon	-3,14697651	,348	-,054	-9,046	,000
	NDVI	-4,54919549	,539	-,090	-8,442	,000
	Cd200	1,038166245	,158	,108	6,579	,000

Table 3. Nighttime Air Temperature Model (MODIS, 2015)

Figure 6 shows the air temperature model obtained by MODIS, merging it with Landsat 8 information (urbanized land, line blue). This fusion allows to see with great detail the LSAT-UHI of the Metropolitan Area of Barcelona (with a resolution of 30 meters / pixel).

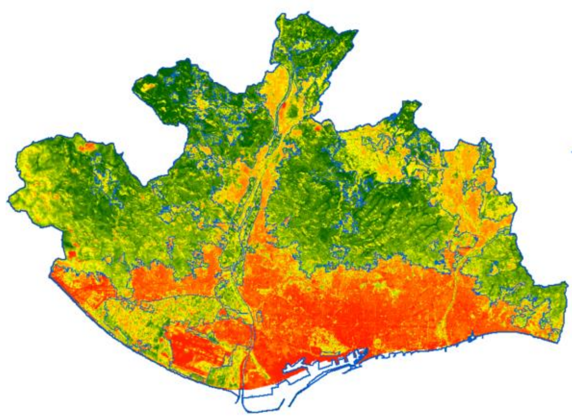

Figure 6. Nighttime LSAT-UHI model

The metropolitan mean of the LSAT reaches, at night, 20.00 degrees Celsius, with 18.34°C in rural covers and 21.89°C in urban ones, 19.4% higher.

Figure 7 shows the metropolitan air temperature of Barcelona (August 2015):

- In white, areas with an air temperature below 20 degrees Celsius. This area basically coincides with rural, nonurbanized areas.

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- Also below 20°C some of the main parks and green areas of Barcelona, such as Montjuich, the Citadel or the Tres Turons.
- In pink, the areas with an air temperature between 20 and 22 degrees, characterized therefore by having a relatively cool "tropical" night. This degree of heat makes it difficult to rest at night, but it has no relevant effects on health. None of these areas is located in the urban continuum of Barcelona, characterized by its high density. Only the Urban Sprawl areas, located on the northern slope of the Collserola mountain chain, reach this temperature.
- In red, the areas with an air temperature between 22 and 24-25 degrees Celsius. This degree of heat does not only imply discomfort. It also has a significant effect on health, representing the threshold above which premature deaths due to heat increase significantly. These areas correspond to the urban continuum of Barcelona. Neighborhoods characterized by their high density.
- Finally, in dark brown, the areas with a temperature above 24-25 degrees. Temperature that represents serious problems for human health ("torrid" nights) if there is no air conditioning installation in the homes. These areas coincide with the urban center of the city ("Ensanche"), as well as, above all, in the historic center of Barcelona ("Ciutat Vella").

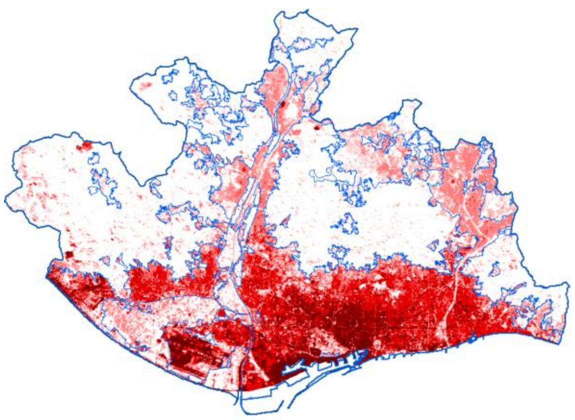

Figure 7. Nighttime LSAT and Risk

3.4 Urban greenery and Urban Heat Island

As mentioned above, the increase and improvement in vegetation measured by the NDVI among other indicators is a fundamental element of urban cooling. In this work, several models have been developed to evaluate the effect of urban vegetation on the night air temperature of the urbanized land of Barcelona Metropolitan Area. The model with only the NDVI as the explanatory variable explained 60.5% of the spatial variation of LSAT, which implied that an increase of 0.1 in the NDVI represented nighttime cooling of 0.7 degrees Celsius.

In addition to the NDVI, proximity to parks had a relevant effect on urban heat. However, to determine to what extent vegetation enhancement actually affects urban climate, it is necessary to determine what is really green in terms of impact on human health and well-being. In this study we considered parks to be green areas (public or private) with a winter NDVI greater than 0.3, and an area > = 1,000 m^2. To better resolve what was "really green", the Sentinel 2 images (10 meters/pixel) that were closest in time were used. Figure 8 shows these "parks" in the city of Barcelona.

More than 80% of the inhabitants who live in the central city of Barcelona are more than 200 meters from a true urban green area. In fact, the standard of green spaces per inhabitant does not reach 5 m^2 per inhabitant (if Collserola park, located outside the urban continuum, is excluded). Only in areas of lower density, of urban sprawl, in the metropolitan periphery is the proximity to greenery less than 200 meters.

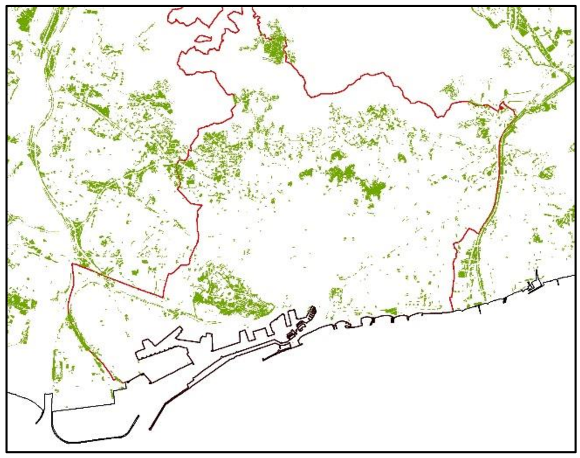

Figure 8. Green areas (>1000 m^2)

In addition to the NDVI, or others vegetation indexes (like Soil Adjusted Vegetation Index - SAVI, Enhanced Vegetation Index - EVI, Leaf Area Index - LAI, FAPAR, Fcover, …), proximity to parks has a relevant effect on Urban Heat Island. Usually, the parks' cooling effect is calculated by its extent and intensity. The cooling intensity (ΔT) is the difference between the temperature of the parks (PT) and the surrounding urban areas (SUT), calculated as SUT - PT. The cooling effect shows positive ΔT values. The cooling extent limit (Lmax) is the maximum distance reached by the microclimatic influence of the park. A positive cooling effect implies lower temperatures near to the park and a gradual increment with increasing distance. In a fitted dataset of temperature of urban spaces ordered by distance to a park, the cooling effect generates a "cooling curve", which ends at the maximum ΔT (ΔTmax) and defines the Lmax point. Although this methodology is usually applied at local scale, showing the extent and intensity of the cooling generated by each urban green area, in this paper a statistical approximation was made for the entire metropolitan area, thus obtaining the average extent of park cooling of the entire the metropolis.

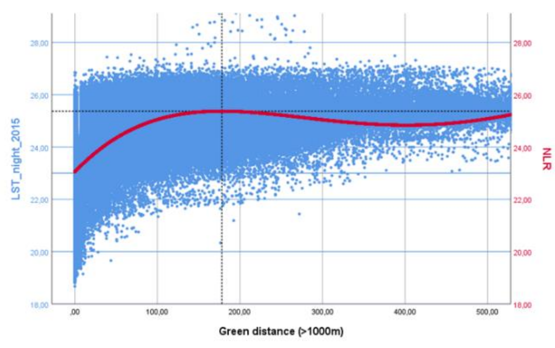

Figure 8. Temperature vs. Distance to Green Areas

Figure 8 shows the land surface temperature in relation to the distance to the green areas of the urbanized land in the Barcelona Metropolitan Area. The adjustment by means of non-linear regression (NLR) of a fourth-degree polynomial model, helps to understand the cooling effect generated by urban greenery.

By itself, the distance to urban greenery explains 43.6% (R^2) of the spatial variation in temperature. The adjustment of the model allowed the deduction of an average extension of cooling of the parks of 178 m. Given that in the city of Barcelona most of the inhabitants live more than 200 meters from a park, the beneficial climatic effect of green areas on the population is limited.

The adjustment of an explanatory linear model of the temperatures, with only the distance to the green area as an independent variable, showed that for every 1,000 away from the parks, there was a cooling of 5.7 degrees. However, as indicated, the cooling effect of parks is not linear. In addition, there is collinearity between the distance and the NDVI, so an OLS model is developed with the NDVI and the distance to greenery, to evaluate more precisely the beneficial effect of proximity to greenery.

The adjustment of an explanatory linear model of the temperatures, with NDVI and distance to greenery, allows evaluation of the beneficial effect of vegetation and proximity to greenery. This joint model explains 61.6% of the spatial variation of the LST, suggesting that an increase in 0.1 points in NDVI would represent a reduction in temperatures by - 0.645ºC. Table 4 shows this model. A distance of up to 1,000 from the parks would imply a temperature increase of 1.438ºC. Therefore, urban policies can be developed that reduce the risks of excess heat on human health. Urban greening, together with land perviousness, is especially relevant to prevent high temperatures.

Model		B	Desv. Error	Beta	t	Sig.
1	(Constant)	25,3828864	,004		7118,541	,000
	NDVI_L8_20150201	-6,4469826	,011	-,715	-567,534	,000
	Green distance (>1000m)	,0014380	,000	,123	97,672	,000

Table 4. Nighttime Air Temperature Model (MODIS, 2015)

Therefore, the models suggest that an improvement in urban vegetation that represents a significant increase in NDVI and a significant reduction in the distance from homes to parks would have very beneficial effects on health and well-being. Night cooling would undoubtedly reduce the risk of premature death in heatwave events. Especially in an area as dense and sparse in vegetation as the city of Barcelona.

4. CONCLUSIONS

In this paper, we analyzed the significant role of the urban heat island due to the increase of global warming in the spatial field of study, Barcelona Metropolitan Area. We also verified the extent of warming since the middle of the last century. An increase in heatwaves and extreme temperatures was detected. We tried to demonstrate the effect of this progressive warming on health, and especially on mortality, since the rise in temperatures in the warm months of July and August has the main effect of increasing premature mortality, in addition to aggravating various other health effects.

The starting hypothesis of the paper was that the main adverse health effects occur at night, due to the difficulty of adapting the body (in the context of a built-up area without widespread access to air conditioning) to the night heat. In cases of high nighttime temperatures, heat stress persists and is aggravated by the fact that the human body cannot rest at night. The most common impact of hot nights on human health is on sleep and rest. Heat, along with other factors, can cause sleep disturbances and deprivation due to the necessary thermoregulation processes. In the context of climate change, in Mediterranean towns there has been a notable increase in the number of tropical and torrid nights.

Given the relevance of temperatures during the night, this study focused on the study of extreme heat phenomena that occurred in Barcelona Metropolitan Area, defining the scope of heatwaves and extreme temperatures at night. In this context, UHI increase the effects of heatwaves, and represent a serious inconvenience to human health and comfort. Consequently, the spatial distribution of LST at night was studied to define the concept of night UHI, using the information from various space sensors, and especially from Landsat 8. At night and during the warm months of the year, there is a high correlation between the LST and the air temperature supported by humans (LSAT). Therefore, knowledge of the LST is of vital importance due to its decisive role in the climate process and as a real indicator of air temperature, which is what really affects human health and comfort.

For this reason, a model of the spatial distribution of the LSAT was also developed using the information provided by MODIS. Said LSAT model confirmed the main role played by the LST in explaining nighttime air temperatures, in addition to allowing downscale the model to 30 m/p. Change of resolution of the LSAT model that allowed better visualization of the UHI. And also to evaluate the health risk of nocturnal heat waves in the different urban landscapes of the Barcelona metropolis.

In this context, the research has aimed to demonstrate the important role played by urban vegetation in adaptation to Global Warming and Urban Heat Island. Green areas have lower temperatures than other land uses and generate a cooling effect that extends to its surroundings creating a "cool island" effect. The second hypothesis, therefore, has been aimed at demonstrating said cooling role in a heat wave context in the case study, the Barcelona Metropolitan Area. The pronounced scarcity of vegetation, as well as the high nighttime temperatures (often above the comfort threshold) make the city of Barcelona a place that is not very resilient to Global Warming, as well as to Heat Waves.

The development of an explanatory model of the role played by vegetation in the UHI makes it possible to determine the effect of urban green on temperatures, and therefore to design urban policies aimed at increasing adaptation to climate change and thus reducing negative impacts on health and the comfort. The adjustment of the model allowed the deduction of an average extension of cooling of the parks of 178 m. Given that in the city of Barcelona most of the inhabitants live more than 200 meters from a park, the beneficial climatic effect of green areas on the population is limited.

The lack of green areas in the city of Barcelona is very pronounced. In fact, the standard of green spaces per inhabitant does not reach 5 m^2 per inhabitant. This fact demonstrates the low resilience of the city in the face of global warming and the progressive increase in heat waves. Therefore, the models suggest that an improvement in urban greenery that represents a significant increase in NDVI and a significant reduction in the distance from homes to parks would have very beneficial effects on health and well-being. Night cooling would undoubtedly reduce the risk of premature death in heatwave events. Especially in an area as dense and sparse in vegetation as the city of Barcelona.

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