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Surface urban heat island and buildings energy: visualization of urban climatic flows

Abstract

The Surface Urban Heat Island (SUHI) effect can be defined as the relative warmth of urban surfaces compared with its surroundings due to the difference in their respective cooling rates. Classic studies have demonstrated that urban warming is a regional and occasional phenomenon whose occurrence depends on weather conditions and characteristics of the urban fabric. Satellite imagery and GIS are combined in this paper to unveil patterns in thermal variations across cities and relate air temperature to density or land cover. Six European regions were selected: Madrid (40°N, 3°E), Cologne (50°N, 6°E), Barcelona (41°N, 2°E), London (51°N, 0.5°W), Brussels(50°N, 4°E) and Berlin (52°N, 13°E). Images with information on surface temperature were obtained from Modis Satellite database. Over 120 files were scrutinized to select 6 winter and summer days and nights. From these, six summer nights are presented as they offer the clearest land surface temperature distribution. The spatial correlation between air temperature, density and land cover was analysed in GIS and plotted as citywide cross sections. The strongest correspondence was found between density and land cover. Finally, the influence of SUHI in the energy demand of domestic buildings in London and Barcelona was investigated. This analysis showed the greater relative impact of this phenomenon in warmer regions.

Keywords

Surface Urban Heat Island. MODIS. Urban morphology. Remote sensing. GIS.

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ISLA DE CALOR URBANO SUPERFICIAL Y DEMANDA ENERGÉTICA: VISUALIZACIÓN DE LOS FLUJOS CLIMÁTICOS URBANOS

Resumen

El efecto de isla de calor urbana (ICU) se puede definir como el calentamiento relativo de las ciudades en comparación con su entorno rural. Numerosos estudios han demostrado que el calentamiento urbano es un fenómeno regional y ocasional cuya ocurrencia depende de las condiciones climáticas y las características del tejido urbano. La teledetección ha permitido analizar este fenómeno en relación con la forma y actividades urbanas. Este trabajo utiliza imágenes de satélite y sistemas de información geográfica para analizar los patrones de variaciones térmicas y relacionar la temperatura en las zonas urbanas con parámetros espaciales, tales como a la densidad o los tipos de superficie. Seis regiones han sido seleccionadas para representar diferentes variantes en el contexto europeo: Madrid (40ºN, 3ºE), Colonia (50ºN, 6ºE), Barcelona (41ºN, 2ºE) Londres (51ºN, 0.5ºW), Bruselas (50ºN, 4ºE) y Berlín (52ºN, 13ºE). Las imágenes con información sobre la temperatura de la superficie se obtuvieron de la base de datos del satélite Modis. Más de 120 archivos fueron examinados para seleccionar 6 días y las noches de invierno y verano. De estos, sólo se presentan las seis noches de verano, ya que ofrecen una distribución más clara de la temperatura de superficie. Las imágenes fueron procesadas en gvSIG y las extensiones Sextante y Teledetección. A continuación se obtuvo Información sobre densidad y cobertura del suelo para los mismos casos de estudio. La correlación espacial entre las tres variables (temperatura superficial, densidad y cobertura del suelo) fue analizada numérica y gráficamente, siendo representada aquí como secciones transversales de toda la ciudad. La correspondencia más fuerte se encontró entre temperatura y cobertura del suelo, mientras que la influencia de la densidad en la ICU fue menos consistente en las diferentes regiones. Por último, se investigó la influencia de la ICU en la demanda energética de los edificios domésticos en Londres y Barcelona. Este análisis sugiere que el mayor impacto relativo de este fenómeno se produce en las regiones más cálidas.

Palabras clave

Isla de calor urbana. MODIS. Forma urbana. Teledetección. GIS.

ILHA URBANA DE CALOR SUPERFICIAL E A ENERGIA DAS EDIFICAÇÕES: VISUALIZAÇÃO DOS FLUXOS DO CLIMA URBANO

Resumo

O efeito de ilha de calor urbana superficial (SUHI) pode ser definida como o aquecimento relativo da temperatura das superficies nas cidades comparado com o do entorno dessas cidades devido as respectivas diferenças nas taxas de resfriamento. Estudos clássicos demonstraram que o aquecimento urbano é um fenômeno regional e ocasional, cuja ocorrência depende de condições de clima e das características do tecido urbano. Imagens de satélite e de GIS são combinadas nesse artigo para revelar padrões de variações térmicas nas cidades e relacionar temperatura do ar com densidade construída e taxa de ocupação. Seis regiões de cidades européias foram selecionadas: Madri (40ºN, 3ºE), Colonia (50ºN, 6ºE), Barcelona (41ºN,2ºE) Londres (51ºN,0.5ºW), Bruchelas (50ºN,4ºE) e Berlim (52ºN,13ºE). Imagens com informação sobre temperaturas superficiais foram obtidas da base de dados Modis Satélite. Mais de 120 arquivos foram análisados para selecionar seis dias e noites de verão. Seis noites de verão são apresentadas aqui, pois oferecem a visão mais clara da distribuição de temperaturas superficiais. A correlação espacial entre temperatura do ar, densidade e taxa de ocupação urbana foi analisada em GIS e marcadas em cortes do espaço da cidade. A correlação mais forte encontrada foi entre a densidade e a taxa de ocupação. Finalmente, a influência da Ilha Urbana de Calor (SUHI) na demanda energética das edificações em Londres e Barcelona foram investigadas. A análise mostrou um impacto significativo desse fenômeno em regiões de clima mais quente.

Palavras-chave

Ilha de calor. MODIS. Morfologia urbana. Medição remota. GIS.

Introduction

According to the IPCC predictions, the Earth's average temperature is likely to increase over two degrees by the end of the century (STOCKER et al., 2013, p. 60). Anthropogenic heat and the alteration of land use and surface properties have decisively contributed to modify the global energy budget. The increased concentration of greenhouse gasses in the atmosphere limits the planet's cooling capacity, while changes in surface porosity, albedo and roughness enhance regional warming (FOLEY et al., 2005). Recent observations have shown an overall increase in the frequency of warm days, heat waves and extreme precipitation episodes in Europe, which are deemed as consequences from global warming (HARTMANN et al., 2013, p. 211). Most scenarios predicted by the IPCC describe further environmental hazards, which may derive in social strain (ROAF et al., 2009).

Although peak demand for heating fuels may decline in northern latitudes due to the rise in temperature (WATSO et al., 1997), the spreading of air conditioning and relentless urban growth in tropical megalopolis will counterbalance any potential energy savings globally. Moreover, peak temperature and extreme weather conditions pose a great risk to human health, especially for the most vulnerable groups, elderly, children and the poorer sectors of the population. Climate change scenarios predict, in sum, that buildings and cities will be exposed to a warmer environment in a context of fewer fossil fuel resources (EDWARDS, 2010, p. 86).

Global warming is enhanced locally by the effect of distinct urban climatic patterns as cities play an important role in the shaping of local climates. Pioneer studies on urban climatology were conducted in the 19th century by Luke Howard in London (MILLS, 2014). The relationship between climate and urbanisation was already an issue of concern for town planning magazines in the early 20th century Germany (HEBBERT, 2014). However, systematic studies on urban climatology began in the 1950s (BARRY; CHORLEY, 2003). Early observations reported urban-rural temperature differences, whose magnitude was found to be related with the size of the city and weather conditions. Chandler made a thorough analysis of the spatial and temporal variation of air temperature on his classic book on the climate of London (CHANDLER, 1965). This phenomenon was already referred to as an Surface Urban Heat Island in this book, a term that would successfully settle. Chandler used an equipped car, together with data from some twenty weather stations, to map the spatial distribution of temperature and humidity across London (CHANDLER, 1965, p. 25-33). In the following decades, the Surface Urban Heat Island (SUHI) was widely studied and thus identified as an important factor in the shaping of urban environments (OKE, 1987; SPIRN, 1984; DOUGLAS, 1983).

A number of studies have been conducted since the last quarter of the 20th century to understand the relationships between urban climate and the spatial attributes of cities. New analytical techniques, enabled by satellites, sensors and telecommunication technologies, have allowed researchers to obtain data of land surface temperature for almost any location at any time. Complex analysis can be performed with Geographic Information Systems (GIS) to identify correlations between different spatial variables. In this article, the potential application of these tools for the study of urban climate and its connections to urban planning will be further explored. Land surface temperature in six European regions will be compared against density and land cover to establish the relationships between local climate and the physical attributes of those regions.

A definition of the surface urban heat island effect

The Urban Heat Island (UHI) can be defined, in few words, as *"the characteristic warmth of a settlement compared with its surroundings"* (GRIMMOND, 2011) that results when *"rural cooling rates are greater than urban cooling rates"* (OKE, 2011). It is generated by the various processes that occur in the surface-atmosphere interface and their modification by urban features:

• **Incoming solar radiation.** Urban surfaces have, in general, a low albedo, which enhances the absorption of heat. The increase of surface temperature is particularly intense in roofs and large parking lots due to their high exposure and the use of dark materials.

• **Incoming long wave radiation.** Pollution, greenhouse gasses and aerosols reduce the visibility in the atmosphere above the city, in the urban boundary layer**.** These particles are not as cold as a clear sky and they may emit downward infrared radiation.

• **Outgoing long wave radiation**. The heat that is absorbed during the day can be partly released by outgoing radiation. The sky is the best available heat sink to reduce land surface temperature, especially under clear conditions. However, the urban canyon reduces wide the sky view factor and hence the potential of night radiative cooling.

• **Convection.** Winds are dragged down by the roughness of the urban skyline. The average air velocity tends to be lower in urban areas than in the rural environment. For the same climatic conditions, the wind reduction due to the urban geometry is around 30% (CIBSE, 2006). The dragging effect of urban roughness diminishes the potential of convective cooling.

• **Evaporation**. While natural ground has the capacity to retain some rainwater in its porous system, the surface of artificial pavements dries out fast. The water content of the ground evaporates during warm weather, producing a cooling effect in the immediate environment. Waterproof surfaces prevent the evaporation and consequently, the potential evaporative cooling.

• **Heat storage**. Urban surfaces tend to have a moderate to high thermal storage capacity. It means that they can absorb heat during the warmer hours of the day to release it, gradually, over the night. Moreover, building elevations provide additional surface area (i.e. walls and façades) for heat storage. The high thermal inertia softens daily fluctuations and reduces peak temperatures in cities.

• **Anthropogenic heat**. The heat produced by human activities is emitted to the urban environment, either by direct exhaustion (exhausts, chimneys...) or indirectly by heat transfer through building envelopes. The aggregate heat waste is a considerable contributor to the Surface Urban Heat Island. According to measured data, anthropogenic heat could reach over 1000 watts per square meter in dense, developed cities during cold periods and around 100 watts in warmer seasons (ICHINOSE et al.,1999)

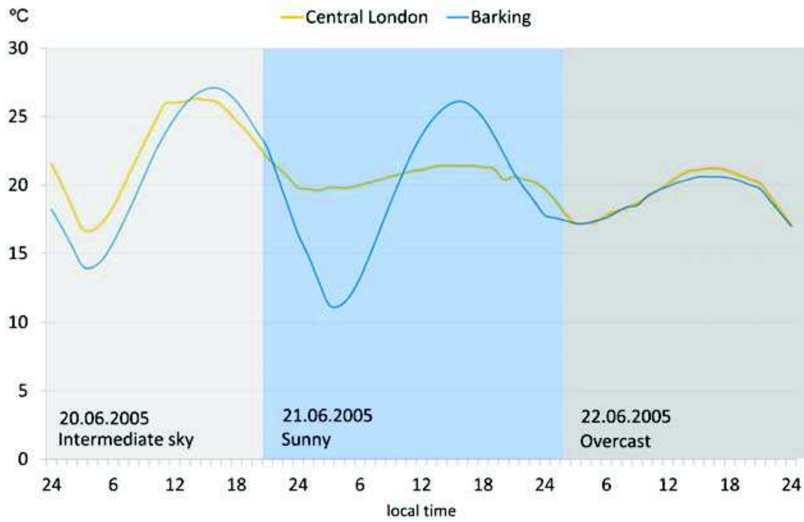


Figure 1: Daily variation of UHI in Central London during three consecutive days in summer 2005. It can be noticed how the intensity of UHI is strongly determined by sky conditions Source: Meteonorm.

Most of these processes are highly dynamic, as they vary with time and space. Weather conditions and urban geometry determine the fabric's warming and cooling rates. Clear sky and the absence of wind in a dense urban environment are favourable conditions for the occurrence of the UHI (fig. 1). Typically, during summer cloudless nights, rural areas get cooler by dissipating heat to the sky, whereas urban canyons obstruct the sky view thus reducing outgoing radiation. Warmth will be retained within the city's fabric, hence preventing any sharp decrease of night temperature. Conversely, buildings also obstruct direct solar radiation into the urban canyon during daytime, which has a softening effect on diurnal temperature. As a result, thermal daily fluctuation tends to be softer in cities than in rural areas.

There are distinct types of heat islands associated with the different elements of the urban boundary layer. By default, the UHI refers to the atmospheric thermal variation between rural and urban areas. However, similar phenomena have been observed for underground and surface temperature (SUHI). The surface heat island can be examined by satellite-based sensors that measure the thermal radiation emitted by exposed surfaces at ground level. Although it is considered an indirect measurement, as it requires substantial post-processing (VOOGT; OKE, 2003), it offers a continuous spatial pattern, in contrast to the extrapolation that is required when using in situ observations.

Objectives

The contribution of urbanization to the heat island effect has been long associated with the characteristic urban geometry and surface materials (HOUGH, 2004; LANDSBERG, 1981; OKE, 1987). Field studies identified high density (OKE, 2011) and impervious surfaces as factors that enhance urban warmth (ARNFIELD, 2003). It is considered that the geometry of the urban canyon has a greater influence in the urban canopy layer, whereas the sensible heat input from urban surfaces determines the warming on the boundary layer (BARLEY; CHORLEY, 2003, p. 343).

Classical measurements of the UHI had to rely on a finite number of weather stations or traverses of vehicle-mounted sensors to reveal climatic patterns

(GRIMMOND, 2011). These field observations were limited by the influence of surrounding features and the need for precise timing to represent broad areas. The development of thermal remote sensing technology has enabled monitoring surface temperature in entire regions, providing new analytic possibilities. However, satellite-based measurements require consideration of the atmospheric and surface properties that may interfere with the information received by the sensor.

Voogt and Oke (2003) provide a thorough review of UHI studies and methods based on remote sensing, identifying three main thematic areas. The first group focused on the examination of the spatial structure of urban thermal patterns and their relation to land cover types. The second group explored the application of thermal remote sensing to the study of the urban energy balance. Finally, a third category covered the relation between atmospheric heat islands and surface heat islands (SUHI).

These investigations aimed to inform urban climatic models, to predict microclimatic variations within urban regions and metropolitan areas. Planners, architects and designers could then use the information provided by the models to optimize planning prescriptions, design solutions or material specifications. However, the penetration of urban climatology in planning practice has taken a slow pace (OKE, 1984; SCHILLER; EVANS, 1991). Planners appeal to climatologist for simpler tools and solid arguments to influence planning decisions (ELIASSON, 2000). The elaboration of urban climatic maps has been useful to overcome communication issues, although still few countries had conducted bespoke climatic cartographies for their main cities (CHAO et al., 2010). Urban designers' confidence grows at the micro-scale. The association between urban form and environmental variables becomes straightforward at this level. A number of tools and pre-design methodologies have been systematically adopted to perform detailed site analysis (LITTLEFAIR et al., 2000). Moreover, environmental assessment methods, such as BREEAM for Communities or LEED ND contemplate local mitigation measures of the heat island as part of their evaluation system (CABRITA; RODRÍGUEZ-ÁLVAREZ, 2011). However, the gap between research and practice remains large at the regional scale. Despite growing evidences about the connections between urban form and urban climate, planners have important difficulties to convey sound arguments that exert a practical influence in strategic planning decisions.

This study aims to combine remote sensing with GIS analytic and visualization capacity to explore and effectively communicate the connections between urbanization and the heat island effect at regional scale. The study followed the classical approach of connecting thermal measures with morphological attributes with the difference that data were obtained from satellite based sensors and geographic information datasets. A substantial amount of post processing work was required to transform the raw data into meaningful graphic information, legible for planners and decision makers while tractable and rigorous. The objective is to exemplify a relatively simple methodology to visualize aspects of the urban climate by using readily available resources. This information could be used to illustrate potential variations in temperature across regions or as an initial layer to create comprehensive urban climatic maps. Accurate urban climatology is critical to create energy efficient buildings and comfortable urban spaces.

Methodology

Six European regions were selected in order to identify consistent patterns across different case studies (Figs. 2 and 3). They are located between latitudes 40º and 52º and longitudes 3ºW to 13ºE. Therefore, climatic variations can be taken into consideration within a relatively uniform geographical context. Madrid and Barcelona are situated in the subtropical region of Europe; whereas the other four cases are in a temperate zone:

- Madrid (40ºN, 3ºW)
- Cologne(50ºN, 6ºE)
- Barcelona(41ºN, 2ºE)
- London(51ºN, 0.5ºW)
- Brussels(50ºN, 4ºE)
- Berlin(52ºN, 13ºE)

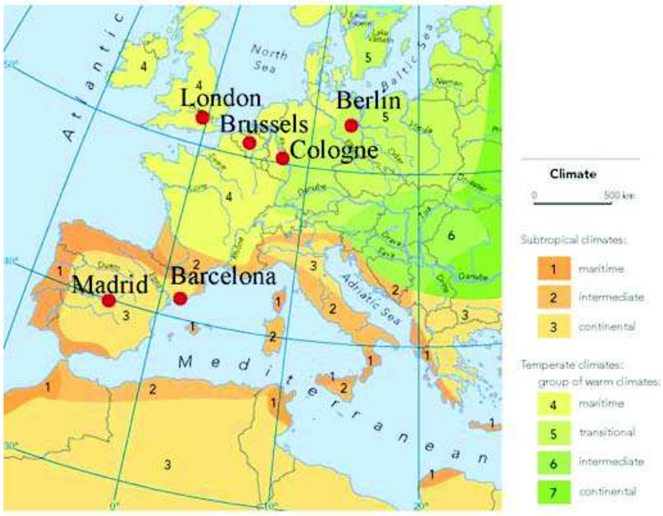


Figure 2: Location of the selected regions in relation with the main climates of Europe. Source: after EEA, 2012

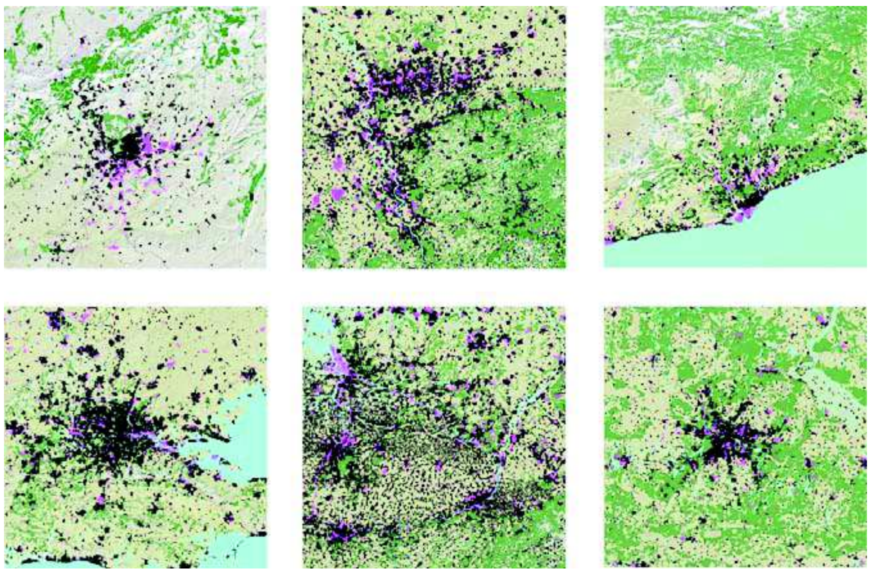


Figure 3: Selected regions. From top left, clockwise: Madrid, Cologne, Barcelona, Berlin, Brussels and London. Source: Rodríguez-Álvarez, 2014

To explore the intensity of Surface Urban Heat Island in these regions, satellite images with information of land surface temperature were used. Satellite Aqua (2013) transports MODIS (Moderate Resolution Imaging Spectroradiometer), an instrument that combs the entire globe on a daily basis to send images of the land and ocean surfaces in 36 different groups of wavelength. The specific product that contains data about land surface temperature is the MOD 11A2, which has a global resolution of 1 and 5 Km. Images can be downloaded from the Earth Explorer engine of the US Geological Survey (EARTH EXPLORER, 2013). Information on the accuracy and quality checks of the data is provided in a Quality Assurance metadata and in a Quality Control Scientific Dataset (SATELLITE AQUA, 2013). To visualize the data in a GIS application, it needs to be previously reprojected. A reprojection tool is freely available from the USGS site. The data is organized in a grid format where each tile covers a surface of 10 by 10 degrees. Six tiles were needed to cover the six regions. It is important to point out that MODIS can only retrieve good data of Earth surface under cloudless sky. Otherwise clouds interfere with its observations and black patches will appear on the image. For this reason, it was necessary to download data for a number of different periods in order to select those intervals with better visibility and fewer gaps. The selected datasets contained averaged values for night time and day time Land Surface Temperature. Overall, over 120 files were inspected to select 6 winter and 6 summer days and nights. From these, only the six summer nights are presented in this paper as they offer clearer conditions. The images depict land surface temperature for the average summer night in the fourth week of July 2004, except for Madrid and Berlin, in which case data from the first week of June was used due to the better quality of the observations on that night.

The next step after retrieving satellite data was to process it in a GIS application. GvSIG, Sextante and the Remote Sensing plug-in were used for this exercise. The tiles were merged to delimitate the urban regions. Thermal data were then scaled to transform absolute values (i.e. 21 or 23ºC) into relative values to a reference minimum in each area. It was considered that it would enhance comparisons between regions. Finally a colour code was applied for a range of 12K temperature scale (fig. 4).

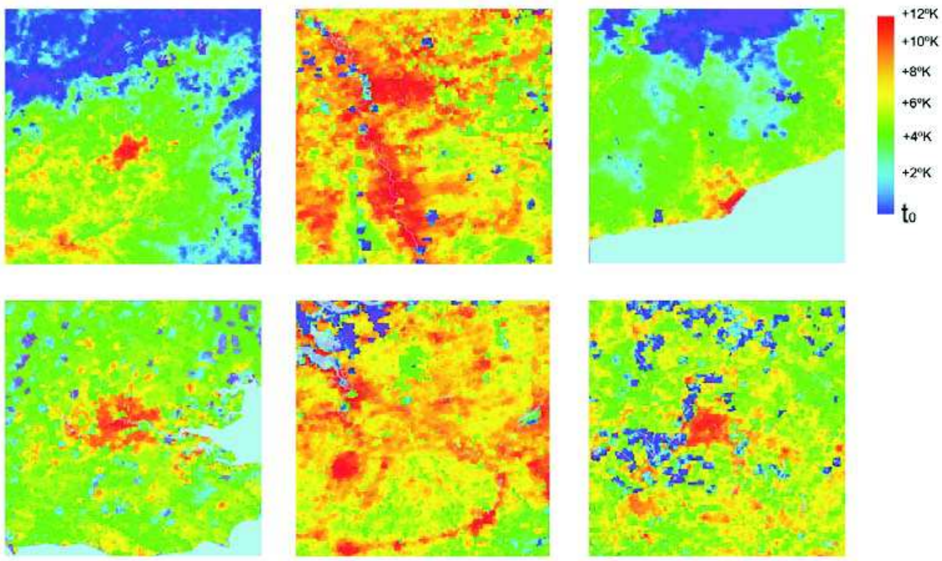


Figure 4: Surface temperature for a summer night in six European capitals. Clockwise: Madrid, Köln, Barcelona, Berlin, Brussels, London. Source: Satellite Modis (data processed and plotted in GvSIG as described in the text.

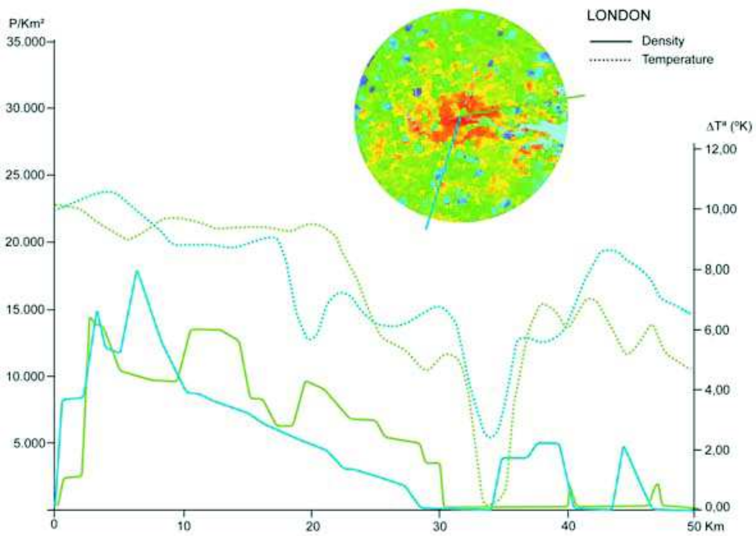
The processed images were used for the analysis of the spatial distribution of SUHI and its correlation with urban spatial characteristics. Land use and population density patterns on the six regions were superimposed to the thermal maps. In order to facilitate visual analysis, cross sections of the data were plotted in two different directions from the city centre to a distance of 50km. Population density values were obtained from the European Environment Agency and they correspond to Census 2001 (EUROPEAN ENVIRONMENT AGENCY, 2013a). Land cover information was obtained from GMES Urban Atlas (EUROPEAN ENVIRONMENT AGENCY, 2013b) and processed in GvSIG. For each metropolitan area, a 50 by 2 km band was delimited, crossing the entire city. The bands were divided into 500x500m cells in order to match the resolution of MODIS imagery. For each cell, the area that corresponded to different land types was measured. As a result, the bands had 100 rows and 4 columns of data, which were taken for the elaboration of longitudinal sections depicting land cover breakdown. Results from Barcelona, Cologne, London and Berlin were reported in this second analysis.

Observations

Population density and Surface Urban Heat Island in the six European regions

The contour of the cities can be quickly identified in the thermal images as they stand out intensely as warm areas. Surface temperature decreases gradually when moving from urban centre outwards. Suburban values are shown around 6K lower and the difference is greater for rural zones (about 8K cooler). The presence of geographic features, such as large water bodies or mountains, induce further variations, up to 12K, as observed in the maps. The correlation between urbanization and surface temperature seems evident in these maps. In order to obtain a more detailed analysis, cross sections of land surface temperature and gross residential density across the cities were plotted. Residential density is an indicator of the intensity of urbanization and it has been used repeatedly in Surface Urban Heat Island studies (OKE, 1981).

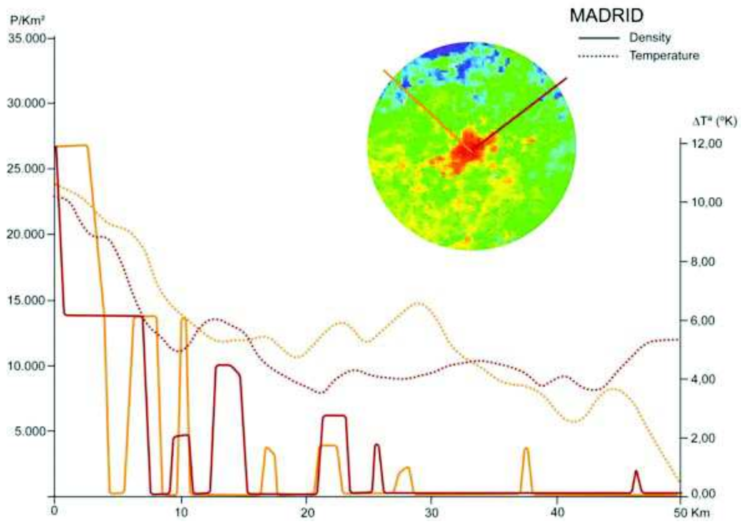
Figure 5: SUHI and population density in London. Source: Rodríguez-Álvarez, 2014



The study of population density to temperature profiles reveals a close correspondence in London and Madrid, while results are not totally conclusive in the regions of Brussels or Cologne.

In London, residential density peaks are not at the centre, but at the inner suburban ring, 4 to 7 km from the Saint Paul cathedral (symbolic centre and core of the City). In those residential boroughs, density rises above 15,000 persons per square kilometre while temperature goes up to 10K higher than the reference value. The two cross sections in London traverse the city eastwards and southwards respectively, in both cases the decrease of density is relatively steady, although slightly more irregular to the East, where industrial estates and residential suburbs are intertwined. Population decreases sharply when sections at 30 away Km from the centre. This is where the Green Belt was designated by the Greater London Plan in 1944. The territory marked by the sections is predominantly rural beyond the Green Belt, except for several satellite towns in the southern axis. The effect of the old the Green Belt can be also detected in the thermal profile. Land surface temperature drops between kilometres 30 and 40, to then rise smoothly beyond the Green Belt.

Figure 6: SUHI and population density in Madrid. Source: Rodríguez-Álvarez, 2014



Madrid, which could be described as a compact city, locates the maximum residential density at its central districts, reaching up 25,000p/km² (fig. 6). The first conurbation which extends from 5 to 15 km from the centre is still dense, with an average of 15,000p/km². Satellite towns can be spotted in the graph as density peaks between kilometres 20 and 30. Cross sections were taken for the Northeast and Northwest axis as they are aligned with two important corridors that connect the Spanish capital with northwest and northeast regions. These axes have absorbed a substantial part of the urban growth in the last decades. Land surface temperature data confirm that the central districts are around 5K warmer than the suburban rings. Rural regions were consistently cooler during the observation periods.

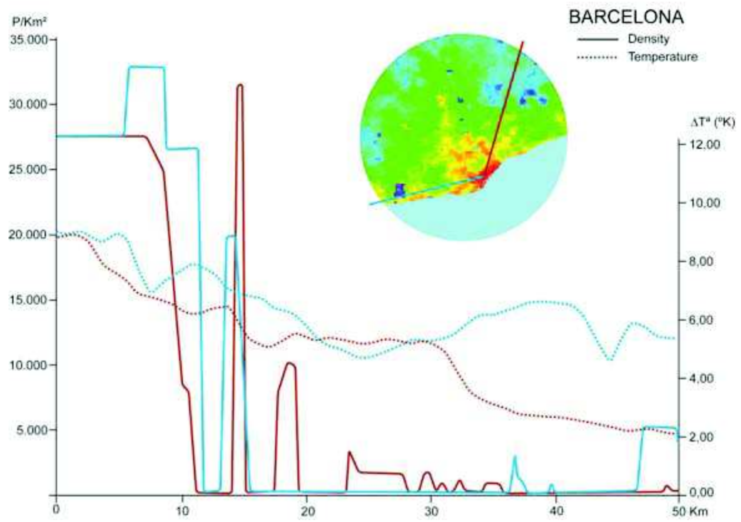


Figure 7: SUHI and population density in Barcelona. Source: Rodríguez-Álvarez, 2014

Likewise, Barcelona concentrates most of its population on the central quarters, where population density peaks above 30,000p/km². Its coastal character and the hilly terrain have determined a compact and dense urban pattern. The first analytical section was drawn along the coast, from Barcelona to the southwest, while the second one connects Barcelona and the hinterland, crossing the hills, as well as several satellite towns. Thermal fluctuations are softer than in Madrid (about 2-3K difference between the centre and rural areas), although the central districts are still reported as warmer than rural zones. The presence of the sea is likely to produce a stabilizing effect in temperature.

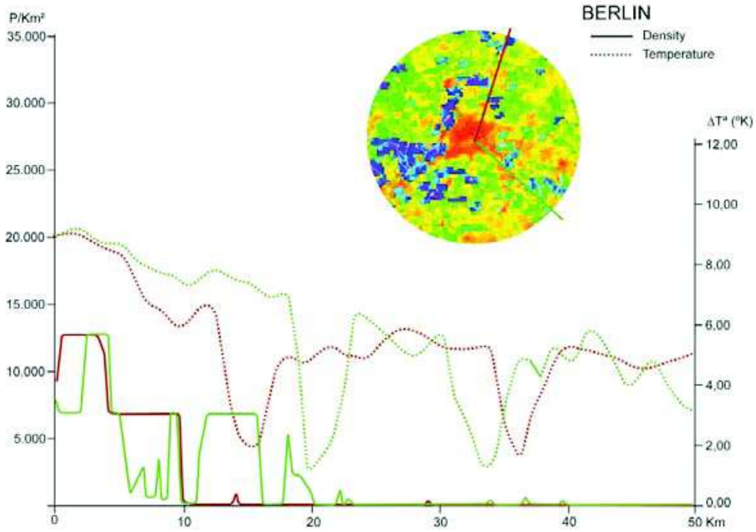


Figure 8: SUHI and population density in Berlin. Source: Rodríguez-Álvarez, 2014

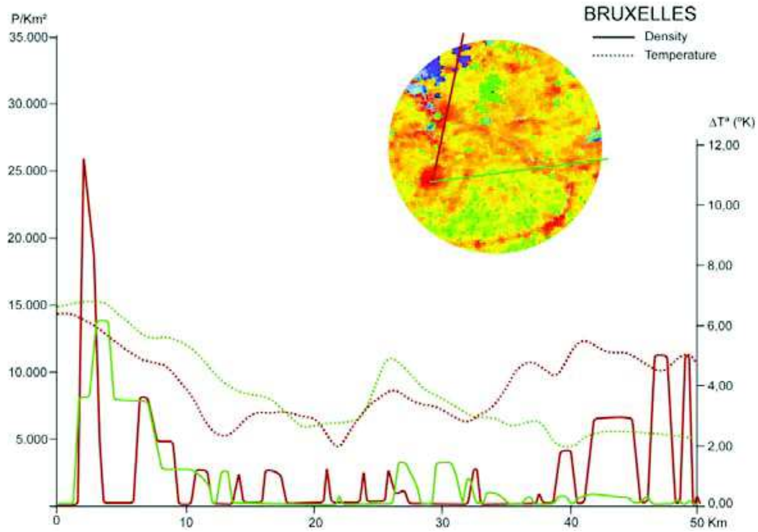


Figure 9: SUHI and population density in Brussels. Source: Rodríguez-Álvarez, 2014

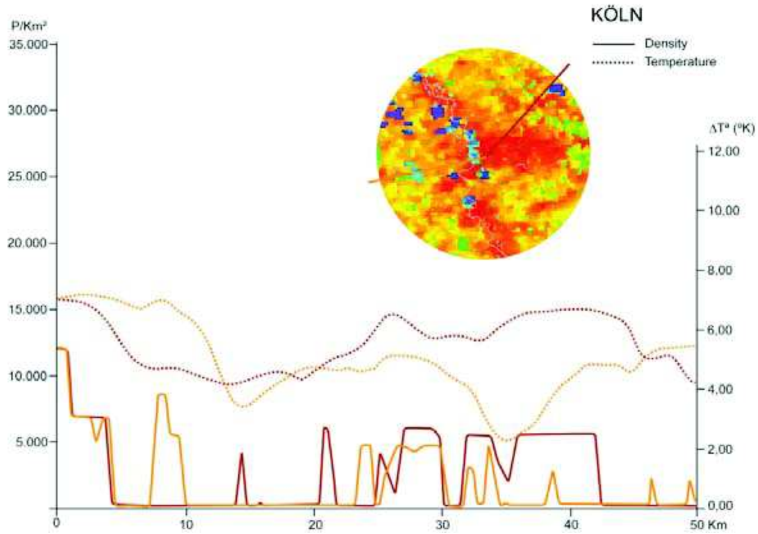


Figure 10: SUHI and population density in Cologne. Source: Rodríguez-Álvarez, 2014

Berlin's urban centre portrays a characteristic star-like shape with eight lobes that project along the main transport corridors. Central densities are moderate, about 12,000p/km² in the inner ring and 7,000p/km² on the first periphery, up to 15 km outwards. Beyond that distance, densities drop dramatically, with only scattered villages punctuating an otherwise flat profile. The depicted sections go along the northern and southeastern lobes respectively. The whole region is predominantly flat. Land surface temperature is relatively even, it barely drops 3-4K between Berlin's urban centre and the surrounding countryside. More pronounced dips can be explained by the presence of large water bodies such as lakes or reservoirs.

Brussels (fig.9) and Cologne (fig.10), present similar patterns, both in their urban structure and thermal profiles. Population sprawls over the entire regions as it can be observed in the population density sections. Scattered towns, with densities beyond 2,000p/km² leave few gaps for rural patches. In the region around Cologne, the urban continuum forms an extensive blanket with multiple centres (Cologne has one million inhabitants while Dortmund, Essen, Duisburg and Düsseldorf are above half million each). Although Brussels presents a stronger hierarchy, Antwerp and Genk also play a complementary role as industrial and communication nodes of this densely populated triangle. In both cases, land surface temperature presents a rather flat profile with smooth fluctuations. However, a typical warming can be noticed in dense areas (i.e. Brussels) and medium sized cities, whose presence can be inferred on the thermal curves.

Land cover and Surface Urban Heat Island

The previous analysis has shown the relationship between residential density and SUHI intensity. High population densities are associated with taller buildings and narrow urban canyons, which are factors that enhance the Surface Urban Heat Island. However, regarding land surface SUHI, the characteristic properties of surface material is a critical aspect as it determines aspects such as albedo or the moisture content. The second stage of the analysis looked into different land cover types to understand how dominant features influenced temperature. Given the morphological similarities of Barcelona and Cologne respect to Madrid and Brussels respectively, only the former were considered, together with London and Berlin in this second stage. For each metropolitan area, a 50 by 2 km band was delimited. Unlike the previous sections, the selection is not radial but diametrical, this is, it starts from one extreme of the metropolitan area and it finishes at the opposite border, after going through the city centre. Although the original dataset contained 21 different land use types, they were grouped into five categories, while land without designated use was left blank:

- Artificial land includes buildings, industry and transport networks (roads, railway tracks, etc...)
- Green urban, stands for parks, gardens and open field sport facilities (football, cricket pitches..)
- Forests
- Agricultural land represents farmland, pasture and semi-natural features
- Water bodies include all accountable presence of water; rivers, lakes, channels or open sea

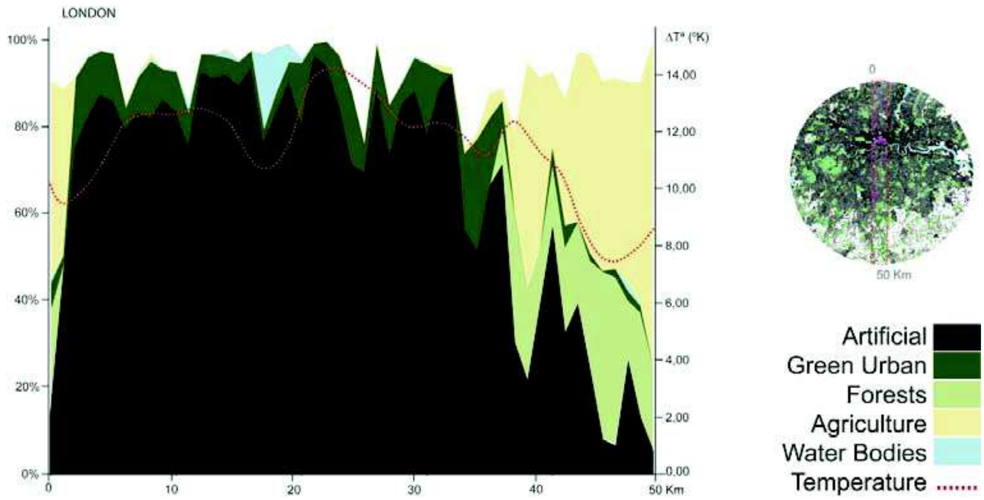


Figure 11: SUHI and land cover in London. Source: Rodríguez-Álvarez, 2014

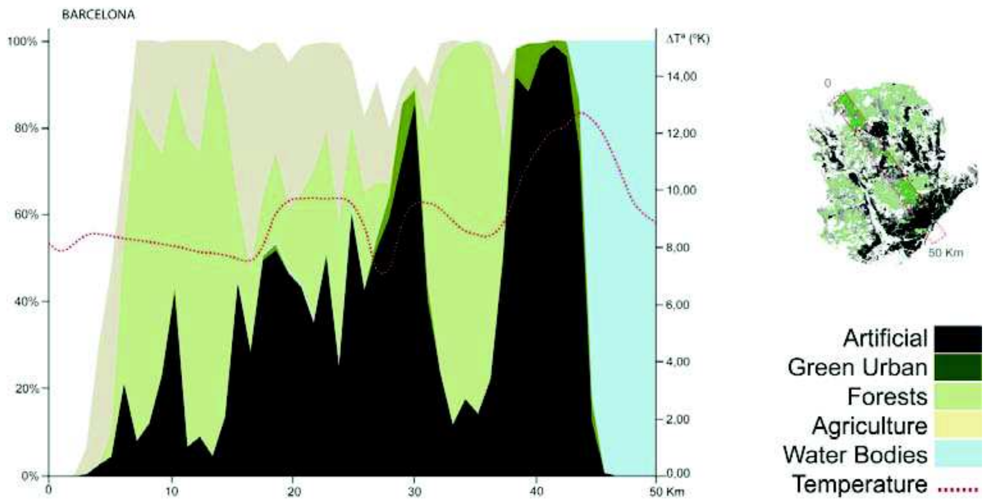


Figure 12: SUHI and land cover in Barcelona. Source: Rodríguez-Álvarez, 2014

In the four cases, land surface temperature follows the variations in artificial land cover ratio (in black). Variations up to 6K in less than 5Km are reported in Berlin, in areas where the degree of urbanization dropped dramatically from 40% to 90%. In London, the River Thames or the Green Belt can be spotted as thermal depressions in the graph. In Barcelona, both the city and the satellite towns can be clearly identified as warmer spots in the graphs. Finally, Cologne presents no dramatic fluctuations along its thermal profile. Although the most highly urbanized area concentrates in the central 15km, the whole territory is splattered with settlements of moderate density, which may prevent sharp temperature variations.

Figure 13: SUHI and land cover in Berlin. Source: Rodríguez-Álvarez, 2014

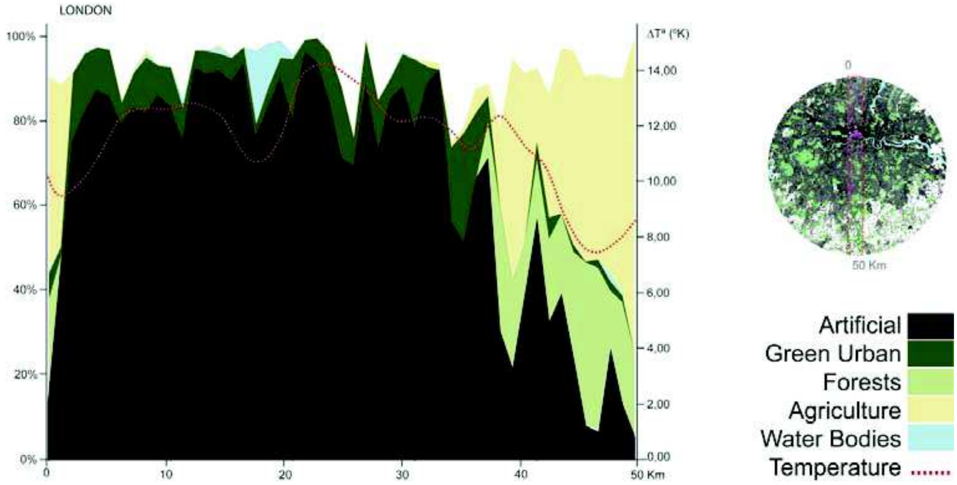
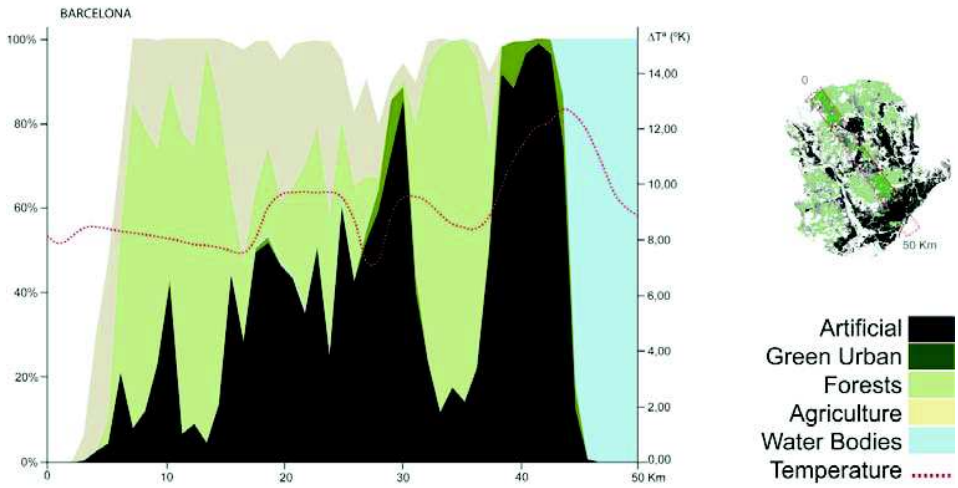


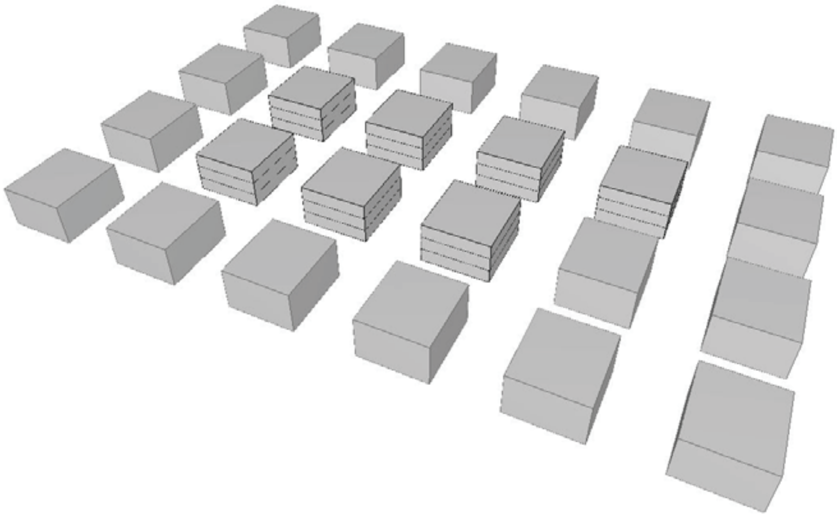
Figure 14: SUHI and land cover in Cologne. Source: Rodríguez-Álvarez, 2014



Surface Urban Heat Island and energy consumption

The heat island has manifold consequences on air quality, health, comfort or the energy consumption of urban areas. In cold climates, sustained urban warmth can potentially reduce space heating needs. However, in temperate and warm latitudes, where overheating may be only displaced at a high energy cost, additional heat gains should be prevented for most building types and for a great part of the year. The effects in energy consumption induced by the influence of planning decisions on urban climate should be carefully considered. Moreover, when the influence of Surface Urban Heat Island is not taken into consideration in energy studies, estimated loads for cooling and heating in buildings may be misleading. Although availability of local weather has greatly increased in recent years, the definition of rural and urban locations is still ambiguous (STEWART; OKE, 2012). A simple exercise was

Figure 15: Urban sample used for the energy predictions (source: author, own elaboration).



conducted as part of this study to evaluate the differences in energy predictions between two scenarios: [a] considering the SUHI in central urban locations and [b] using data from a suburban weather station.

The results are shown in figure 16, which illustrates the variations in energy loads for cooling and heating for the two scenarios. The calculations were performed for an urban development defined by the following characteristics: It was a squared area of 500 by 500 meters, the Ground Floor Coverage was 40% and the Floor Space Index was 1.00m²/m². Buildings formed regular blocks of 15x15m and were homogenously spaced. The streets were 12 wide, thus creating an urban canyon of proportions close to 1:1. The heating and cooling loads of this sample were calculated for the climates of suburban and central London and Barcelona respectively in order to reveal variations in different latitudes. Simulations were carried out with the Urban Energy Index for Buildings, a tool that has been developed to perform rapid energy assessments of large urban areas (RODRÍGUEZ-ÁLVAREZ, 2016). The base scenario did not consider the SUHI factor, as climatic data were obtained from airport weather stations, at the outskirts of both cities (METEONORM, 2013). For the second scenario, data from weather stations located at the city centre was used instead. The average annual temperature was 0.5K higher in central London, with cold peaks of -6K (the city centre was cooler) and hot peaks of +6K (the city was warmer than the suburban station). In Barcelona, the annual average increase at the city centre was + 1.8K, with fluctuations respect to the suburbs ranging from -3.8K to + 8.3K.

The comparison of the energy loads in the different scenarios showed divergent patterns in the two cities. In London, the SUHI makes a modest contribution to space heating, inducing savings up to thirteen percent respect to the base case. In contrast, in Barcelona, the impact upon cooling loads was substantial, especially for residential buildings, whose demand increased over 30% due to urban warming. Although savings in heating loads were also reported, they do not compensate the increase in cooling as it has to be taken into that electricity requires a larger amount of primary energy than typical heating systems. This analysis can be deemed as a conservative estimate, but it shows how energy consumption due to the SUHI is likely increases in warmer climates.

Figure 16: Variation in primary energy for heating and cooling when the effect of SUHI is considered. Source: Rodríguez-Álvarez, 2013

Conclusions

This study looked into the interconnections between population density, climate and energy. A causal relationship between the attributes of the city and urban warming, especially during cloudless summer nights, has been found and graphically illustrated. Moreover, the potential effect of Surface Urban Heat Island in the energy demand of buildings has been explored. The following remarks could be concluded:

- The use of satellite imagery to elaborate climatic cartography is a useful resource that can facilitate the consideration of environmental information on planning decisions. This data can be used in a number of ways, from accurate urban climatic maps to predictive models and exploratory analysis to reveal and present the relationship between SUHI and planning decisions.

- The elements that determine the intensity of the SUHI can be divided in two main categories: urban attributes and climatic variables. Although urban attributes induce distinct microclimates in the city, the intensity of the SUHI is ultimately determined by weather conditions. Lack of wind, clear sky and warm daytime temperature are favourable conditions to induce sharp thermal variations between the city and rural areas.

- The comparison between land surface temperature and spatial characteristics, particularly gross population density and land cover, confirmed the connections between anthropogenic activities and SUHI. This phenomenon is intense in densely populated zones with a greater proportion of artificial surfaces (concrete, asphalt...). The presence of natural features, such as parks, gardens or large water bodies have a potential to generate cool spots. However, their effect is limited, and it is barely noticeable beyond few blocks. Mitigating measures should be, therefore, regularly distributed over the city, so that their combined effect could have a global impact on urban temperature.

- The influence of SUHI in energy consumption is determined by centrality within the urban system and the buildings' sensitivity to the climate. Assuming typical construction and typologies, a rough estimation was done to compare these effects in two notional urban typologies located in London and Barcelona, with and without the SUHI into consideration. Results suggest that SUHI does not have a substantial effect in the former, where the hot season is both mild and short. However, a potential increase in energy demand was found in Barcelona.

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