Heat Island and Urban Morphology:
Observations and analysis from six European cities

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ABSTRACT: The Urban Heat Island (UHI) effect can be defined as the relative warmth of cities 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. Current technology offers new opportunities to analyze this phenomenon and its connections with urban form. Satellite imagery and GIS are combined in this paper to unveil patterns in thermal variations across cities and eventually, relate temperature in urban areas to density or land cover. Six European regions were selected to represent a varied range of form, climate and topographic context: Madrid (40ºN, 3ºE), Cologne (50ºN, 6ºE), Barcelona (41ºN,2ºE) London (51ºN,0.5ºW), Brussels(50ºN,4ºE) and Berlin(52ºN,13ºE) together with their surrounding regions have been selected for this study. 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, only the six summer nights are presented as they offer the clearest land surface temperature distribution. Images were processed in GvSIG and plug-ins Sextante and Remote Sensing. Density and land cover information were obtained for the same regions. The spatial correlation between the three variables was analyzed in GIS and plotted as city-wide cross sections. The strongest correspondence was found between density and land cover, whereas the influence of density on UHI was less consistent across regions.
Keywords: Urban Heat Island, MODIS, urban morphology, remote sensing, GIS

INTRODUCTION

The Urban Heat Island (UHI) effect is a widely studied phenomenon. It has been defined as "the characteristic warmth of a settlement compared with its surroundings"[1] that occurs when "rural cooling rates are greater than urban cooling rates"[2]. Consequently, urban buildings are exposed to different climatic conditions respect to nearby rural areas. This difference may eventually affect the energy demand from urban living and working environments. Conversely, buildings also play an active role in the formation and intensity of urban microclimates. Their location, shape, materials and arrangement within the urban fabric contribute to gradual variations in temperature, wind or humidity across the city. Some of these alterations induced by urbanization may have a positive effect in certain places during a certain period of the year, for instance raising air temperature in cold winters, but the observation of UHI at global scale has reported an important burden for the metabolic and environmental performance of cities.

The physical processes behind the UHI are basically those involved in the surface-atmosphere interface (short and long wave radiation, convection, evaporation, heat storage, anthropogenic heat...) that are altered by the presence of features which are genuinely urban (dark sealed surfaces, deep canyons, pollution...). The connection between urban morphology and temperature has been thoroughly studied since the last quarter of the 20th century. Oke identified the influence of density and urban canyon in heat island intensity in the seventies [3]. The broad range of tools that are currently available, provide sophisticated analytic techniques to obtain further insights. The combination of satellites, sensors and telecommunication technologies allow researchers to obtain data of land surface temperature for almost any given location at anytime of the year. Comparative analysis of combined data and spatial attributes can be performed for large areas with the aid of Geographic Information Systems (GIS). This paper explores the potential application of these tools to the study of urban climate. Land surface temperature will be compared against spatial characteristics, such as density or land cover to verify the connection between urban form and UHI.

A DYNAMIC EFFECT

The processes that shape the UHI are dynamically and spatially changing. As a consequence, the UHI intensity varies not only with location but also over time. A combination of conditions can either decelerate urban fabric's cooling rate or accelerate heat inputs. A clear sky, the absence of wind and a densely populated urban environment are favourable conditions to heighten thermal variations (fig. 1). The gradient becomes more pronounced during summer cloudless nights. In this scenario, rural areas can take full advantage of the sky as a heat sink, whereas the obstruction induced by buildings in the city will partly obstruct outgoing radiation. The degree of obstruction is determined by the proportion of street width to building height. Tall structures will block a greater portion of the sky thus undermining the capacity to cool down street surfaces by the effect of night time radiation. The heat will be stored in the fabric, hence stabilizing temperatures. Conversely, those same tall buildings prevent direct solar radiation into the urban canyon, which may soften diurnal surface temperature. As a result daily temperature fluctuation will be, in general, less pronounced in cities than in rural areas.

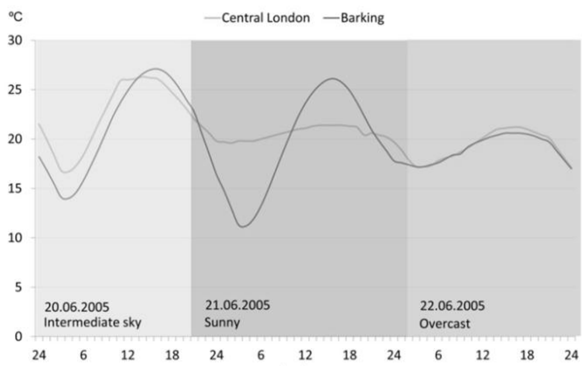

Figure 1: Daily variation of UHI in Central London. It can be noticed how the intensity of UHI is strongly determined by sky conditions. Data from Meteonorm [4]

SELECTED SAMPLES AND CITY FORM

From the previous paragraph, it can be inferred that urban thermodynamics are very much determined by climatic variables. However, certain spatial attributes are also necessary for UHI occurrence. Despite the degree of uncertainty of climatology, comparative analysis can unveil the interdependence between morphology and thermal spatial patterns in cities and regions. Six European regions were selected to represent a cross section of urban models, trying to cover different forms, climates and topographic contexts. Madrid (40ºN, 3ºE), Cologne (50ºN, 6ºE), Barcelona (41ºN, 2ºE), London (51ºN,0.5ºW), Brussels(50ºN,4ºE) and Berlin(52ºN,13ºE) were the capital cities of the selected regions. Various morphological classifications could be drawn from this set of European territories, depending on the parameters that were considered:

- In terms of metropolitan structure, at least two regions could clearly adhere to the concept of polycentric metropolis (Cologne with Dusseldorf and Dortmund on one hand and Brussels with Antwerp, Charleroi, Liege and the Walloon region on the other one). Madrid, Barcelona, London and Berlin present a more hierarchical structure with a core capital, of various sizes and densities, and a radial transport network that connects the capital with much smaller satellite towns.

- Regarding the residential structure, there would be a gradient from purely compact high dense cities (Barcelona and Madrid) to relatively contained models (Berlin and London in this order) to, finally, an sprawl model (Cologne and Brussels)

- According to classical classifications of city forms [5], Berlin and London would be qualified as a star or radial models, Madrid and Barcelona as core, monolithic and compact examples, and finally Brussels and Cologne respond to the concept of constellation or galaxy.

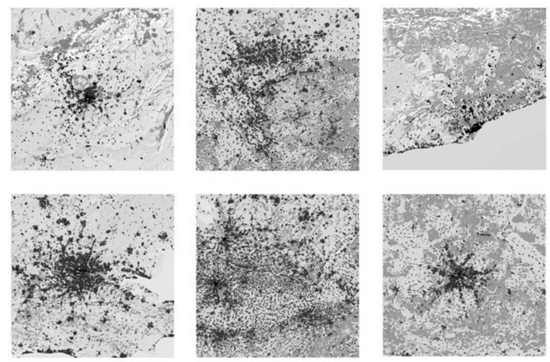

Figure 2: Selected regions. From top left, clockwise: Madrid, Cologne, Barcelona, Berlin, Brussels and London.

IMAGE PROCESSING

To explore the intensity of Urban Heat Island in these regions, satellite images with information of land surface temperature were used. Satellite Aqua [6] 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 [7]. To visualize the data in a GIS application, it needs to be reprojected before. 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 in the image. For this reason, it was necessary to download data from many different days in order to select those intervals with better visibility and fewer gaps. The selected product contained averaged values for night time and day time Land Surface Temperature. It gives a more representative view than single days. 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 here as they offer the clearest conditions. The last step before the analysis was to process the data in a GIS application. GvSIG, Sextante and the Remote Sensing plug-in were used for this exercise. The images were combined and temperatures were scaled so that instead of absolute values (i.e. 21 or 23ºC) they became relative values to a reference, which was the lowest temperature in the region (i.e. +2º or +4 ºK) This allows easier comparison between regions, as the absolute temperature may vary among them. Finally a colour scale was applied in a range of 12K temperature difference. The processed images are presented in figure 3 (as greyscale image).

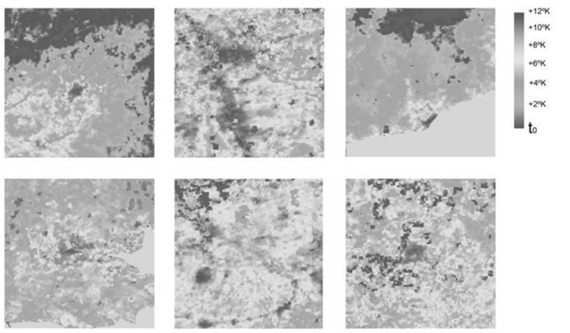

Figure 3: Surface temperature for a summer night in six European capitals. Clockwise: Madrid, Köln, Barcelona,Berlin, Brussels, London (data extracted from Satellite Modis, processed and plotted in GvSIG)

DENSITY AND URBAN HEAT ISLAND

The processed images were used for the analysis of the spatial distribution of UHI and its correlation with urban features such as density or land use. 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 contour of the cities can be quickly identified as they stand out intensely in the tones that represent warmer areas. Surface temperature decreases gradually when moving from urban centres outwards. Suburban values are 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 explains the deep differences, up to 12K, observed in the maps. The correlation between urbanization and surface temperature results obvious from these satellite images. However a more precise analysis was required to explore the factors that have greater influence in urban warming.

Land use and density patterns of the six cities were superimposed to the heat maps in order to find correlations between UHI and spatial aspects. To facilitate visual analysis, data were plotted as cross sections, in two different directions from the city centre to a distance of 50km. Density values were obtained from the European Environment Agency and they correspond to Census 2001 [8]. The study of density to temperature profiles reveals certain correspondence, although results are not totally conclusive. Temperature decreases as density values go down, especially in London (fig.4) and Madrid (fig. 5), where some parallel sections can be observed in the profiles.

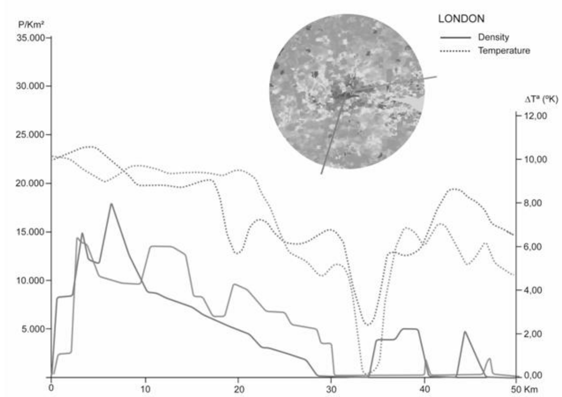

Figure 4: UHI and density in London

In London, residential density peaks are not at the centre but at the inner suburban ring, 4 to 7 km from Saint Paul cathedral (symbolic centre and core of the City). The density on those areas gets around 15,000 persons per square kilometre and temperature is up to 10K higher than the reference value. The two cross sections in London move 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. The population rate decreases sharply at 30Km 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 dips between kilometres 30 and 40, and then it rises again smoothly beyond the Green Belt.

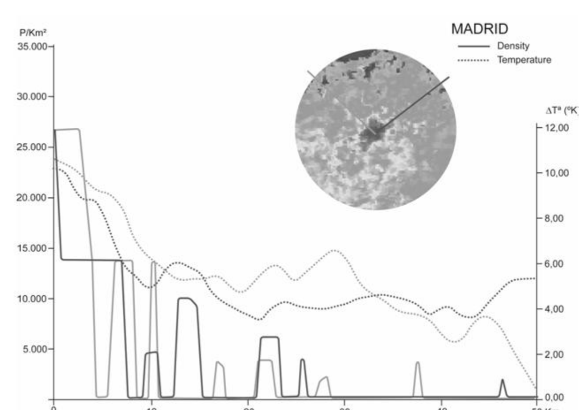

Figure 5: UHI and density in Madrid

Madrid represents a more compact model (fig.5). Central density reaches 25,000 p/km² in the inner ring (five kilometres) and it keeps over 15,000 p/km² in the first conurbation, which extends up to 15 km from the centre. Satellite towns can be noticed as density peaks between kilometres 20 and 30. Beyond that point, the rural landscape dominates. Cross sections were taken for the Northeast and Northwest axis as they are aligned with two important corridors that connect the Spanish capital with Galicia (North-Atlantic shipping node) and Catalonia (Mediterranean port and gate to central Europe) regions. These axes have absorbed a substantial part of the urban growth in the last decades. Land surface temperature presents warmer temperatures in the central districts, which are 5K higher than suburban rings. The different performance between the suburban fringe belt and the countryside is better represented by the northeast axis. The thermal gradient in this case barely reaches 2K. Sharper fluctuations on the Northwest extreme are explained by Navacerrada Mountains, which elevates 1,000 meters above sea level.

Barcelona is frequently quoted as a compact city model (fig. 6). It concentrates a great proportion of its population on central quarters, with peak density above 30,000 p/km². The proximity to the sea and a hilly terrain have determined the location of the main urban settlements either in the coastal line or inner valleys. Two cross sections were selected for the analysis to portray those two scenarios; the first axis goes along the coast, from Barcelona to the southwest, while the other axis connects Barcelona and Montseny, a mountain range to the North of the city, crossing industrial and satellite towns in Vallés and Granollers. Thermal fluctuations are softer than in Madrid (about 2-3K between the centre and rural areas), due to the sea capacity as thermal buffer and moisture generator.

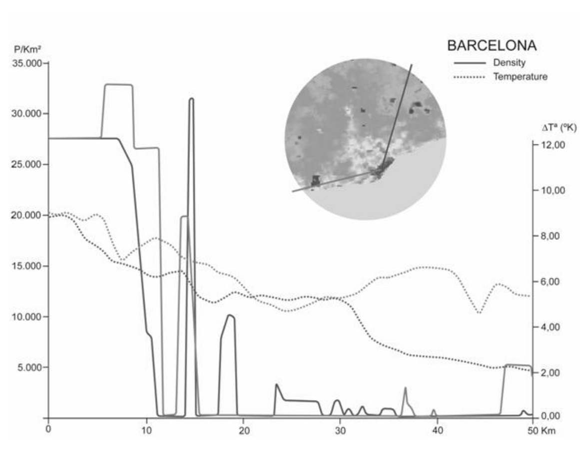

Figure 6: UHI and density in Barcelona

Berlin can be considered as another compact example (fig.7). It presents an star-like shape with eight lobes that project along the main transport corridors. Central densities are moderate, about 12,000 p/km² in the inner ring and 7,000p/km² up to 15 km outwards. Beyond that distance, densities drop to minimum values, with the exception of scattered villages which are connected to the Berliner ring, the ring road that runs around the capital at an approximate distance of 20km. The sample sections go along the northern and south-eastern lobes. The former is within Barnim district, an sparsely populated region that contains large natural areas. Natural features also characterize the southern axis, along the Dahme-Spreewald, a district that contains large woods and numerous lakes. The whole region is predominantly flat. Land surface temperature is relatively even, it barely drops 3-4K between Berlin's urban centre and surrounding countryside and greater fluctuations can be only explained by the presence of large water bodies such as lakes or reservoirs.

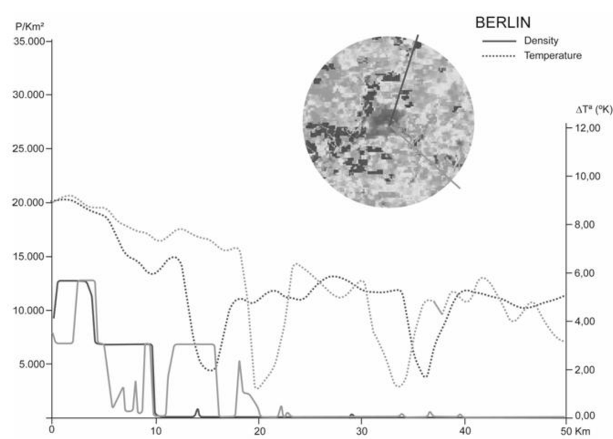

Figure 7: UHI and density in Berlin

Brussels (fig.8) and Cologne (fig.9), or rather Flanders and Rhine-Rurh regions, present similar patterns both in their urban structure and in their thermal profiles. Population sprawls over the entire regions as can be observed from density lines. Scattered towns, with densities beyond 2,000p/km² leave few gaps for rural patches. In the case of Rhine-Rurh region, the urban continuum forms an extensive blanket with multiple centers (Cologne has one million inhabitants and Dortmund, Essen, Duisburg and Düsseldorf are above half million each). Whereas in Belgium, Brussels has a stronger hierarchy, Antwerp and Genk play a complementary yet essential 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, the typical increase in dense areas (i.e. Brussels) and the presence of medium sized cities can still be inferred from the reading of the thermal curves.

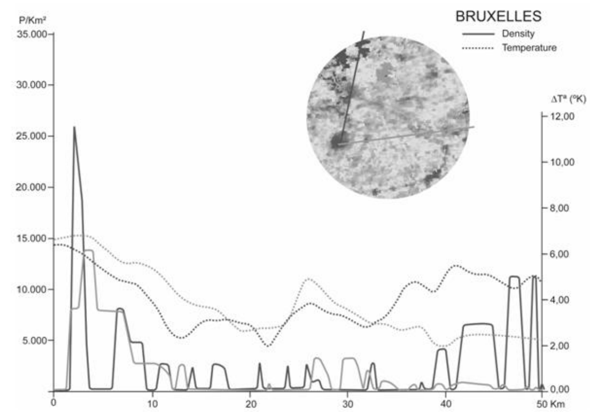

Figure 8: UHI and density in Brussels

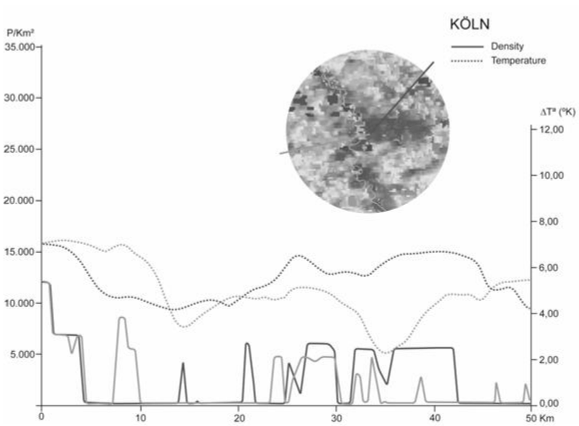

Figure 9: UHI and density in Cologne

LAND COVER AND URBAN HEAT ISLAND

The previous analysis has shown the correlation between density and UHI intensity. However, other factors may have a stronger influence in urban warming. In the case of land surface UHI, surface properties and land cover are critical elements as they determine aspects such as albedo or moisture content. The second stage of the analysis looked into different land cover types to understand how dominant features influenced temperature. Data of land cover was obtained from GMES Urban Atlas [9] and processed in GvSIG, Open Office and MS Excel. For each metropolitan area, a 50 by 2 km band was delimited. Unlike the previous sections, the study area was not radial but diametrical. This is, it starts from one extreme of the metropolitan region and it finishes at the opposite border, after crossing the city centre. The second methodological difference lays in the use of 2km wide bands instead of linear sections. 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 are reported in this second analysis.

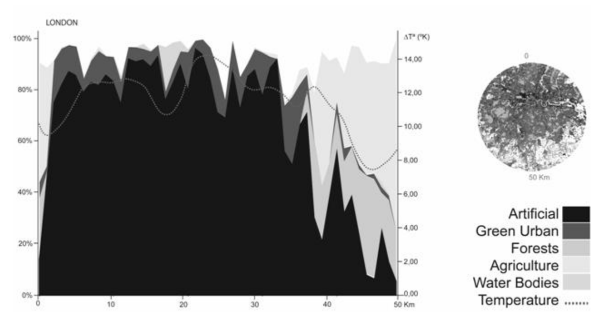

Figure 10: UHI and land cover in London

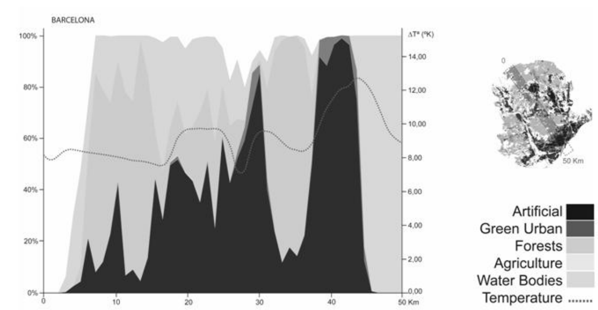

Figure 11: UHI and land cover in Barcelona

The plotted graphs (figs. 10 to 13) revealed not only insights about UHI but also broader urban aspects, such as the provision of green areas (significantly low in central Barcelona) or the dimension and intensity urbanized land. If we define urban zone as the area where artificial land takes over 80% of the total, Barcelona could be said to extend over barely 10 km, whereas London, in contrast, extends over 30km. In all cases, surface temperature is warmer on urbanized areas. Variations up to 6K in less than 5Km are shown in Berlin, in areas where the degree of urbanization changed dramatically, from 40% to 90%. In London, the thermal depression caused by Thames River in the central city can be clearly read in the graph. The green belt is also highlighted as a marked decrease at kilometre 38 approximately. In Barcelona, the uneven terrain and the presence of the sea influence surface temperature. However, both the city and Vallés valley "technoburb" can be clearly identified as respective hotspots, being 4K and 2K warmer that their surroundings. 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 scattered with suburban villages and industries, which prevents sharp temperature variations.

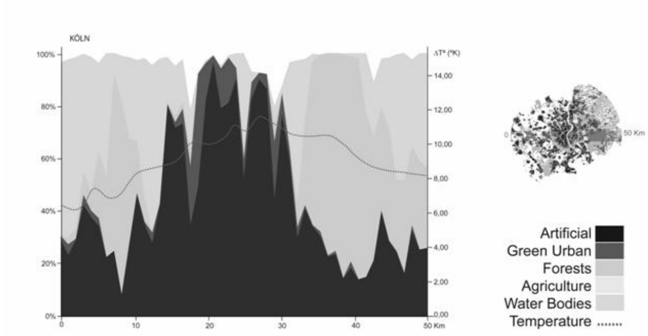

Figure 12: UHI and land cover in Berlin

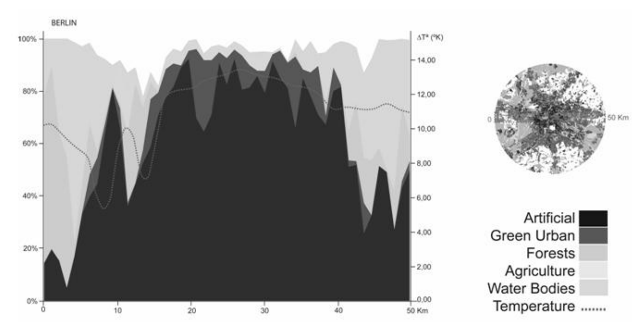

Figure 13: UHI and land cover in Cologne

CONCLUSION

The interconnections between urban form and climate have been explored in previous paragraphs. A causal relationship between the attributes of the city and the temperature of the urban fabric, especially during cloudless summer nights, has been found. The following remarks could be concluded from the previous observations:

- The direct extrapolation of rural weather station climatic data may be inaccurate for urban locations, particularly in large dense cities due to the UHI effect.

- The elements that determine the intensity of the UHI can be divided in two main categories: city attributes and weather conditions. Certain urban attributes generate microclimates in cities but, according to observations and satellite imagery, the intensity of the UHI is ultimately determined by weather conditions. Lack of wind, clear sky, warm daytime temperature and strong vertical solar radiation are favourable conditions to induce sharp thermal variations between the city and rural areas.

- The comparison between land surface temperature and spatial characteristics such as density or land cover confirmed the correlation between urban form and UHI. The presence of mitigating elements within the city fabric (parks, lakes, rivers...) have a potential to generate cool spots but their effect is limited to a short distance and is barely noticeable beyond few blocks. Mitigating measures should be regularly distributed over the city, so that their combined effect could have a global impact on urban temperature.

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