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URBAN HEAT ISLAND

Assessment techniques, mitigation and applications in a post-socialist city

Presa Universitară Clujeană

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List of Acronyms and Abbreviations

AC	Air conditioning
ADAC	Allgemeiner Deutscher Automobilclub
AHF_s	Anthropogenic Heat Fluxes
AHI	Anthropogenic Heat Intensity
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Advanced Thermal and Land Application Sensor
AVHRR	Advanced Very-High-Resolution Radiometer
AUHI	Atmospheric Urban Heat Island
BHE	Borehole Heat Exchangers
EEA	European Environment Agency
HCMM	Heat Capacity Mapping Mission
HIRI	Heat Island Reduction Initiative
HRV	High Resolution Visible
HW	Heat Waves
LCZ	Local Climate Zones
LSE	Land Surface Emissivity
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDBI	Normalized Difference Built-Up Index
NDBaI	Normalized Difference Bareness Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
PCM	Phase change materials
NOAA	National Oceanic and Atmospheric Administration
SPOT	Satellite Pour l'Observation de la Terre
SubUHI	Subsurface Urban Heat Island
SUHI	Surface Urban Heat Island
SVF	Sky View Factor
TES	Temperature Emissivity Separation

TIRS	Thermal Infrared Remote Sensing
TOA	Top of atmosphere
UHI	Urban Heat Island
USGS	United States Geological Survey

INTRODUCTION

The expansion without precedent of city boundaries determined the modification of the climatic conditions inside urban areas, with a direct impact on the environment and the population. Urban development implies fundamental changes in the natural setting, generating significant differences between the urban environment and the nearby areas in terms of meteorological parameters, air quality, and energy balance.

Over the last decades, cities worldwide have experienced accelerated development, urbanization being one of the most important dimensions of global change. Nowadays 54% of the world population lives in urban areas, being responsible for 76% of the energy consumption and emissions of greenhouse gasses (Grumbler et al. 2012). Moreover, by 2050 the urban population is expected to grow by 66% (United Nations and Department of Economic and Social Affairs 2014). This fact also implies the expansion of the urban fabric and a massive growth for built surface demand in the following decades (Seto et al. 2012; Song et al. 2016).

According to the European Environment Agency (EEA), in Europe alone, 73% of the population lives in cities (EEA, 2010), and it is expected to grow to 82% by 2020 (Akbari et al. 2016). In Eastern Europe, another important matter is the forced industrialization from the communist era which leads to a complex process of urban change. This change influenced the urban climate of post-socialist cities. In such cities, the urban landscape was radically transformed with the emergence of over-sized production units and "dormitory neighborhoods" meant to accommodate their personnel. The replacement of natural surfaces with the built, impervious ones (with distinct caloric properties and lower cooling rates), is known as one of the main factors that generate the urban heat island effect.

The topic of this book refers, therefore, to the urban heat island (UHI), as an example of climate change of anthropic origin, and to its atmospheric, biologic and economic impact (Yow 2007). The UHI phenomenon implies a temperature difference between the densely built urban areas and the nearby rural ones. It can manifest at the atmospheric air level (AUHI), the built surface level (SUHI), and the subsurface level (SubUHI). More recently, researchers have shown an increased interest in the subsurface heat island as well (Müller et al. 2014; Luo and Asproudi 2015; Benz et al. 2018).

UHI and the climatic effects induced by the continuous urbanization of cities worldwide represent major problems currently approached by scholars in the fields of applied climatology and urban development studies. Besides climatologists, the UHI phenomenon has gained the attention of the researchers from medical and social sciences, but most of all, the attention of the activists for environmental equity and environmental justice. Although both of these fields militate for the fair share of the natural resources and burdens that result from their exploitation, the environmental justice aims not only at the detection of the inequalities, but at their remediation as well (Cutter 1995).

The research performed in Phoenix, Arizona, by Harlan et al. (2007) highlights the increased possibility for the white population with high income to live in areas with more abundant vegetation (less affected from a climatic point of view) when compared to the Latin-American population with low income. The wealthy neighborhoods benefit from low temperature values and have a smaller risk in the summer, especially during heatwaves. Besides being warmer, poor communities do not possess the critical resources needed in the physical and social environment to face extreme heat. The research performed in Athens also confirms that the thermal stress is more pronounced for the underprivileged population during the warmer periods (Sakka 2012).

1

URBAN HEAT ISLAND. THEORETICAL ASPECTS.

1.1 UHI: Definition, classification, fluctuations.

The accelerated urbanization of the last decades materialized through the rapid expansion of city boundaries also determined the warming of the urban climate. This phenomenon involves the concentration of high air (but surface as well) temperatures in the shape of an island (Sailor 1995). The periurban and rural areas around the city stay cooler. If the structure is a multicellular one, we can even refer to an archipelago of urban heat (Unger 2004).

The configuration of urban areas is very different from the rural setting in terms of albedo, vegetation cover, humidity, and surface energetics. Cities usually have lower albedo values, large areas of impervious surfaces, and relatively little vegetation. These characteristics, correlated with a high degree of anthropogenic heat, represent the ideal conditions for the formation of UHI. The urban-rural temperature differences are more intense with the urbanization rate and with the number of inhabitants (Sailor 1995).

The UHI can manifest at the level of atmospheric air, surfaces (natural or built), and subsurfaces (soil, groundwater, and deep ground). In the first case, we can refer to atmospheric urban heat island (AUHI), in the second to the surface urban heat island (SUHI), a significant drop in the UHI intensity when the wind speed is higher than 4 m/s.

The research of Gedzelman et al. (2003) on the UHI in New York City indicates that the maximum intensity of the phenomenon appears in the nights with a clear sky, low humidity, and low wind speeds, two or three days after the passing of the cold front. Similar results have been obtained by Targino et al. (2013) regarding the phenomenon's dependence on the synoptic situation while analyzing the UHI of Londrina, Brazil. The highest intensity was observed during weather conditions specific to a high-pressure system. Average intensity values were recorded during cold anticyclones and low values during the passing of a cold front.

The geographic position also influences UHI. The presence of large water bodies near the cities affects the urban temperature and generates winds. Such air currents determine the convection of heat outside the urban areas. The mountains nearby can prevent the winds from reaching inside the cities or even create crossing patterns.

1.4 UHI impact on the environment and population

Even if the effect is mainly a negative one, UHI also implies some positive aspects. Such advantages are the faster flowering and the burgeoning of plants/trees inside the city, or even the apparition of new species of birds attracted by the more favorable climate of the urban habitat (Oke 2009).

Also, UHI determines the extension of the vegetative period of plants, these being less affected by the late spring frosts. Landsberg (1981) estimates that the apparition period is diminished with approximately 35 days in the urban environment as a consequence of the heat island. Another advantage is lower costs for house heating during the winter (especially inside colder cities from mid- and high latitudes and altitudes).

In the vast majority of cities, the phenomenon represents a problem for the human communities, with biological, ecological, and socio-economic implications.

UHI induces an unfavorable urban climate, especially if the city is located in a warm climate. After performing measurements in Salonic, Greece, Giannaros and Melas (2012) conclude that the increase of the island with 1.5 °C also determines an increase of 1 °C for the thermal discomfort index. The high-temperature values during the summer influence the health and the wellbeing of the city inhabitants both directly and indirectly. The human body produces heat during activity and during metabolic processes, receiving radiation from the sun (direct or reflected) as well as from objects with a higher temperature. The atmospheric air transfers heat to the human body through conduction (Kleerekoper and Salcedo 2012). If the air temperature is higher than the one of the human body, the thermal stress appears. The social categories that are more affected by the heat islands are older people, children, and the poor.

The presence of heatwaves and the UHI related increase in temperatures can affect the health of the inhabitants directly. It also influences the work productivity, while the use of air conditioning systems for fighting high temperatures and ensuring thermal comfort affects the inhabitant indirectly. Many studies from the last 20 years show that the occupants of buildings with AC usually have more symptoms than the occupants of the ones with natural ventilation. Some of the symptoms associated with the use of AC is mucosa irritation, breathing difficulties, skin irritations, as well as neurological symptoms like fatigue and headaches (Mendell and Smith 1990).

UHI determines critical consequences on the elements related to the local meteo-climate characteristics like the patterns of the local winds, snow frequency, number of electric discharge, and precipitation rate (Rasheed 2009).

The polluting substances from the circulation of cars, household

2

THERMAL INFRARED REMOTE SENSING. THEORETICAL BACKGROUND.

2.1 Introduction

Remote sensing can be defined as a complex of activities that aim to obtain from distance information in the form of conventional photos or raster (digital) images. This technique is based on the interaction between objects from the Earth's surface and electromagnetic radiation sensors (usually placed on board of planes and satellites) (Imbroane and Moore 1999).

Depending on the spectral domain where the electromagnetic radiation sensors capture the spectral response of objects, we can distinguish between remote sensing in the visible and infrared domain (VNIR), thermal infrared remote sensing (TIR, thermal) and microwave remote sensing.

The detection of thermal energy in thermal infrared is possible because all bodies with a temperature higher than absolute 0 (0 K or -273.15 °C) emit electromagnetic energy due to the oscillation of atoms and molecules (Block 1978). The radiant energy emitted as heat is called *thermal radiation*. The Earth absorbs a large part from the incident solar radiation (some reflected, other emitted) and behaves like a black body with the peak of emission around 9.7 microns. The shorter wavelengths are reflected, and the longer ones emitted (Kuenzer and Dech 2013).

A significant advantage of TIR remote sensing is the fact that image data can be acquired during the night as well, when collecting information in VNIR is not possible. This type of data is beneficial in detecting thermal anomalies like the ones induced by forest or coal fires. Also, the thermal images captured nighttime are not affected by the patchy heating of surfaces during the day (the diurnal cycle of temperature), determined mainly by the shading of surfaces.

2.2 TIR detectors. Data acquisition.

Thermal infrared data is acquired by a multitude of remote sensing instruments placed at ground level, or onboard planes and satellites. The thermal infrared domain sensitive sensors can record radiation, with the possibility of showing the kinetic temperature of the objects at the resolution of the sensor. The most common products obtained from thermal imagery are the land surface temperature (LST), sea surface temperature (SST), and the land surface emissivity (LSE). These are the only indicators that can be deducted directly from the data collected by a TIR sensor (Tang and Li 2014).

Even so, the data from thermal sensors has much more potential than the deduction of these indicators by standard procedures. They can be used in various fields and activities like detecting inflammation in medical imagery, detecting coal and forest fires, mapping UHI, geological surface differentiation, or the analysis of soil moisture (Kuenzer and Dech 2013).

The spreading of thermal infrared remote sensing is related

3

AUHI EVALUATION METHODS.

The presence of AUHI was first signaled at the beginning of the 19th century by Luke Howard in his study on the climate of London. Here, Howard observed an artificial heat excess compared to the nearby rural areas. Similar results were obtained afterward by Emilien Renou for Paris in the second half of the 19th century and by Wilhelm Schmidt for Viena at the beginning of the 20th century. In the US, the research on the topic started in the middle of the 21st century with Mitchell's research activity (Gartland 2008).

A lot of urban climate studies from the last decades are focused on the heat island assessment and mitigation. By 2011, observation of the phenomena in 221 cities around the world have been reported in the literature, even if many of them had theoretical and methodological flaws (Stewart 2011). In some situations, the researchers even reported different magnitudes for the same cities because they used different monitoring protocols.

Generally speaking, by using fixed stations, one could obtain much smaller values than by performing mobile transverses (Founda et al. 2015). In this context, Oke (2009) stressed the importance of adopting common protocols when researching the AUHI phenomena and their use in applied climatology. He draws attention on matters like scale, the experimental design, the classification of sites, instrument exposure. The absence of scientific rigor can lead to measuring or modeling errors.

The *local climate zone* (LCZ) is a concept introduced in the literature by Stewart and Oke (2010). It represents a classification system meant to provide the research methodology to study AUHI and to standardize the temperature observation change on a global scale. The AUHI evaluation consists of comparing simultaneous observations from urban and rural environments. The authors mentioned above noted that the definition of these terms differs from one area to another and from one study to another. Such variations are due to the difficulty of establishing a clear limit between urban and rural areas, in the context of accentuated urban expansion taking place in the last years.

The standardized evaluation system of AUHI with 16 classes was initially tested in three representative cities from Europe, East Asia, and North America (Stewart and Oke 2010). Stewart and Oke analyzed data collected by many researchers between 1976 and 2010 from Uppsala, Nagano and Vancouver. The preliminary results indicated that the system is close to its optimal shape. However, individual classes still required improvements. The final structure completed by the two authors includes 17 classes (Figure 3.1) with ten built types and seven land cover types.

Every LCZ should have a minimum diameter of 400-1000 m (Stewart and Oke 2012). The built types are composed of buildings disposed on a prevailing kind of land cover, paved or with small vegetation for compact types, and scattered trees for the open ones. If the urban fabric and the use of space are not uniform, subclasses can be created for heterogeneous types.

In the literature, the evaluation of the effects of development on the urban climate are traditionally obtained by five different methods, with direct or indirect data collection: fixed station/points, mobile transverses, energy balances, remote sensing, and vertical sensing (Gartland 2008). All these methods can be used for AUHI assessment,

5

UHI MITIGATION. CURRENT PRACTICES AND PROSPECTS.

If by 2011 observations of UHI from over 200 cities from all over the world were reported in the literature, in the last years, the urban climate studies published are focused more on UHI mitigation rather than evaluation. The objective of the present chapter is to identify sustainable solutions and practices to diminish the effects of development on the urban climate, but also results obtained after their implementation in different locations.

In the last years, the concept of „Green infrastructure" became very popular. It can be defined as an ensemble of anthropic elements that confer multiple ecological functions at the building level, but at an urban scale as well. From these functions, the reduction of energy consumption, ambient temperature, and UHI mitigation are major priorities (Pérez et al. 2014).

The heat islands develop in urban areas because they contain a large amount of impervious, non-reflective surfaces, like buildings, roofs, streets, and sidewalks, that slowly replaced the natural environment. Even if in Eastern Europe the phenomenon drew the attention of researchers only in the last years, in the US, mitigating the impact of UHI started at the beginning of the 90s with the federal program HIRI - Heat Island Reduction Initiative (Solecki et al. 2005).

The mitigation of UHI is closely related to the improvement of the energetic efficiency at the building level and the reduction of the energy consumption for the artificial increase/decrease of the indoor temperature. This final desideratum can be reached by combining modern alternatives of passive cooling and heating. A study performed in Los Angeles has shown that the need for air conditioning can be reduced up to 18 % for buildings with light color roofs and shadowed by trees (Solecki et al. 2005).

The design and building manner specific to the urban environment can be included among the factors that influence the increased energy consumption of settlements. The researchers identified the negative patterns that generated it and proposed sustainable strategies meant to reduce energy consumption. The structure of the street network with a specific orientation affects both sides of the road, setting an exposition that is usually unfavorable for the implementation of the solar techniques and other energy consumption reduction methods. The relation between the street front and the depth establishes the number of indoors with southern exposure. The densely built urban centers determine the obstruction of air currents and solar light by the walls of tall buildings. The absence of vegetation, replaced by concrete and asphalt, represents another factor influencing energy consumption. The plans and local urbanism regulations can determine the dimensions of a building and, therefore, the shape and position inside the parcel (Shahmohamadi et al. 2010).

The unsuitable orientation of buildings, their high density, and the shading degree can directly affect UHI because its genesis is related to high temperatures and weak winds. Efficient territorial planning and intervention in the design process can ensure better climatic conditions inside cities.

For the mitigation of UHI and the reduction of energy consumption, building, district, municipal, or even regional-level

European countries due to its large spatial extension. The continental climate is dominant in inland areas, with extremely cold winters. EEA indicated two cold climate types in northern Russia, continental and transitional. Summers, are, however, milder towards the south, closer to the Black and Caspian Seas. In the north and west, the country is exposed to Arctic and Atlantic influences, since there are no high and massive landforms to obstruct the air masses.

6.3 The literature on UHI in Eastern Europe

Local studies on UHI were performed in more than 35 unique from all over Eastern Europe, but their distribution is not uniform. In the former Soviet Socialist Republics, the literature is very scarce. Only one study is available for Ukraine, and no peer-reviewed articles in English were published for Belarus and Moldova.

The evaluation of the phenomenon at the near-ground air, surface, and subsurface levels employed methods such as fixed points, mobile transverses, image data processing from satellite and airborne sensors, borehole drilling, and vertical sensing based on passive microwave radiometry. The vast majority of the literature is focused on AUHI.

6.3.1 Research progress of UHI in Bulgaria

The UHI topic gained the interest of Bulgarian researchers only over the last years. Therefore, very few publications are available, and they focus solely on the capital of the country, Sofia, a city with more than 1.2 million inhabitants (Table 6.1). Here, the presence of neighboring mountains and the UHI effect lead to the formation of three types of temperature inversions: ground, elevated, and capping (Kolev et al. 2000).

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