METHODS TO DETECT ATMOSPHERIC AND SURFACE HEAT ISLANDS IN URBAN AREAS

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ABSTRACT. – Methods to detect atmospheric and surface heat islands in urban areas. Intensification of the urbanization process and its associated climatic effects is nowadays a major problem of large cities worldwide. One of these climatic effects is the urban heat island (UHI), that implies increased air and surface temperature values in the city when compared to the nearby rural areas. This phenomenon threatens the health of the population, especially during heat waves, affects the quality of the environment and the quality of life, and also generates significant costs to ensure the inhabitants' thermal comfort. In this study we present a review of the UHI concept and three of the main methods used to detect the atmospheric and surface urban heat islands. Satellite image data analysis seems an easier and time-saving solution, but due to its limitations, we consider that a combination of both surfaces and lower atmospheric layer temperature data analysis is the best choice in order to get accurate results of the intensity and spatial extension of the UHI.

Key words: urban heat island, atmospheric urban heat island, surface urban heat island, satellite data, direct measurements

1. INTRODUCTION

In the last decades, cities worldwide have experienced accelerated development. Besides the positive aspects of this process, the environmental impact of urbanization is nowadays a major problem in the urban development studies. One of the most important consequences of the urbanization process is the urban heat island (UHI). This phenomenon generates higher temperature values of the air (atmospheric urban heat island - AUHI) and of the surfaces (surface urban heat island – SUHI) when compared to nearby rural areas.

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The configuration of the urban area is very different in terms of albedo values, vegetation cover, moisture availability, and surface energetics when compared to the rural one. As a consequence, they act as islands of higher temperature related to the natural areas surrounding them (Sailor & William, 1995).

Cities usually have lower albedo values, abundant areas with impervious surfaces and low vegetation cover. These features, correlated with a high degree of anthropogenic heat, represent the ideal conditions for UHI development.

A lot of urban climate studies from the last decades focused on evaluation and mitigation of the UHI effects. By 2011, atmospheric heat island observations on 221 cities and towns from all over the world were reported in the literature, but many of them focuses on methodological and theoretical aspects (Stewart, 2011). In Romania, few studies were performed until now for Bucharest city, by using direct measurements as well as remote sensing data (Cheval et al., 2009; Cheval & Dumitrescu, 2015).

2. DATA AND METHODS

Five basic methods are commonly used in literature to measure the effects of development on the urban climate: fixed stations/points, mobile transverse, remote sensing, vertical sensing and energy balances (Gartland, 2008). In the present paper, only the first three of them will be presented: the AUHI detection by direct measurements (fixed stations and mobile transverse) and SUHI detection based on satellite image data.

2.1. Atmospheric Urban Heat Island detection by direct measurements

2.1.1. Measurement processes

The AUHIs are weak in the morning and the daytime, but they become more intense after the sunset and especially after midnight, as opposite from the SUHIs that are present day and nighttime but are more intense in the afternoon (Van Hove et al., 2011). In order to evaluate the maximum AUHI intensity, measurements should be performed during the nights with high pressure, clear sky and calm weather, in the relative thermal stability interval between 23.00 - 03.00, at 1.5...3.00 m above the ground level. Usually, those weather conditions are specific to anticyclones. The highest temperature differences between the city and the rural area nearby are supposed to be observed during the summer. In some cases, the summer maximum intensity is followed by the winter values, especially in the cities with a high degree of uninsulated high concrete buildings (compact high-rise areas).

To highlight the intensity of an UHI, we propose a mixed method that combines two of the commonly used methods in the literature for UHI detection: observations in representative fixed points (fixed stations) of the city with different types of urban architecture combined with measurements on different routes (profiles) along the city main streets.

To evaluate the AUHI using fixed points, measurement points located in urban and rural areas nearby must be used. Their number depends on the urban area extension and on the local climate zones (LCZ) distribution. It should be at least 10 points. The location of the points should be chosen in such manner so they highlight the temperature difference between different parts of the city and the nearby rural area. The fixed points in the urban area have to be representative for each type of urban tissue, which usually generate a specific LCZ, in order to get a detailed and confident configuration of the AUHI.

It is recommended but not mandatory for these points to have similar elevation. If the topography configuration of the city does not fit this condition, altitude correction of the collected data should be performed.

The temperature values in the fixed points have to be collected every 5 - 10 minutes and for higher accuracy, a meteorological shelter (portable) should be used.

These temperature values can be correlated with data collected along the street network, usually on the major roads of the urban area. In a mobile transverse study the data must be collected from at least two crossing profiles, one on the dominant wind direction and the other perpendicular to the first one. The routes of the profiles should be covered by car, public transportation, or even bicycle. The measurements can be continuous, when devices used can provide real time accurate temperature values. Otherwise, the temperature can be measured on profile points. The interval must be established by taking into account the structure of the LCZ and the temperature should be measured for each specific urban tissue type the profile crosses. Regardless of the method chosen, the location of the measurement points should be recorded using a GPS device or a GPS logger phone application, as *GPS Logger for Android*.

2.1.2. Data processing

In the data processing phase, the data have to be time and altitude corrected. The difference from the rural area reference point should be calculated for all the temperature values collected in fixed points and on profiles. The "primary" data can be obtained as a temperature difference between the measurement points in the urban area and the reference point outside. Afterwards, lapse rate based altitude corrections must be performed.

For the fixed points, only altitude corrections are needed as in (1).

$$T_{Bcor} = T_B + \frac{\Delta H}{100} \times 0.65 \qquad (1)$$

T_{Bcor} = corrected temperature in point B, located in the urban area (°C);
T_B = temperature measured in point B, located in the urban area (°C);

$$\Delta H = H_B - H_A \qquad (2)$$

H_B = altitude of the point where the temperature needs altitude correction (m);
H_A = altitude of the reference point (A), located in the rural area nearby the urban area (m);
0.65 = lapse rate (for 100 m), given in (°C).

When recording devices are used, no time correction is needed. The data processing continues with calculating the difference between the temperature recorded in each profile point and the reference point temperature at the same moment, as in (3).

$$D = T_{PX} - T_R \qquad (3)$$

D - the difference to be calculated for a point X (a point on the profile);
T_{PX} - temperature measured in point (X) of the profile at time t_X;

T_R - temperature measured in reference point at time t_X;
t_x - time when the temperature was recorded in point X of the profile, given in hour, minutes (and seconds, if recorded).

In case of a longer measurement period, mean values (hourly, monthly, seasonal, or even annual) of each point can be used in order to detect the intensity of the AUHI.

In case of employing non-recording devices for the profile measurements, the time correction is needed. In such situation, the best choice is to make measurements in fixed points (or at least in the reference point located in the rural area nearby) as often as possible. A step of 5 minutes could be appropriate. When measurements in a profile point and in the reference point are simultaneous, the difference is calculated between the two points temperatures (Table no 1).

When the measurement time for the point on the profile and the reference point does not coincide, the time correction is needed for the temperature in the fixed point as presented in (4).

$$C_t = (t_1\text{-}t_2)/n \times d \qquad (4)$$

C_t - time correction;
t_1 - temperature measured in the reference point before the measurement in the point on the profile;
t_2 - temperature measured in the reference point after the measurement in the point on the profile;
n - number of minutes between two consecutive measurements in the reference point;
d - number of minutes between the measurement in the profile point and the previous measurement in the reference point.

Each correction has to be added to the measured temperature, before calculating the differences between temperatures in the urban area points and in the reference point.

Technically, the easiest way to calculate those differences is to use a table template. First, new lines should be introduced in *Table no 1*, where the time of the measurement in profile points fits (lines in gray). Then, calculation of the corresponding temperature in the reference point for the time of each profile point measurement is needed (values in bold in column "Temperature in the RP"). Thus, one can get the time corrected values in the fixed point that are to be used in order to get temperature difference between the two points (the last column), that are to be used for mapping the AUHI.

Table no 1. Table filled in with data measured on the profile at different moments (RP - reference point)

Time of the RP	Temperature in the RP	Time of the measurements on the profile points	Temperature measured in the profile points	Latitude	Longitude	Difference calculated
0:00	14.0					
0:05	14.0	0:05	13.3	46.78065	23.67224	-0.7
0:10	13.8					
0:11	**13.8**	0:11	13.6	46.78339	23.66163	-0.2
0:15	13.6					
0:18	**13.6**	0:18	13.9	46.78437	23.65486	0.3
0:20	13.6					

Data from local meteorological stations can also be used in the interpolation process as long as they are located at the same altitude above the ground level, or have the altitude correction applied.

Once the data processed and the temperature differences between the points on the profile and the fixed point got, there are several interpolation methods that can be used to obtain a continuous surface of the air temperature values recorded in the fixed and profile points. In some studies, comparisons between the different interpolation methods have been made. Spatial interpolation procedures often have to be adapted to each case, lacking reproducibility (Kergomard, 2007). If the ArcGIS software is used for this step, the ESDA (Exploratory Spatial Data Analysis) tools can be very useful in order to choose the best interpolation method.

Since the temperature values in the field are unknown, to identify the best result, a cross validation should be performed where one data point is withheld and the remaining data points are used to predict the withheld point (Collins and Bolstad, 1996). Many interpolation types should be tested in order to find the most appropriate one, which gives the closest result to the measured value.

However, the Residual Kriging was found to give the most accurate results in the UHI mapping process (Szymanowski and Kryza, 2009).

2.2. Surface Urban Heat Island evaluation using satellite image data

Remote sensing and satellite image data processing have a long history as tools used in urban climate research. At the beginning of the 1970s the first initiative that used the satellite image data approach has been set up. Rao (1972) was the first researcher who used imagery from an environmental satellite (ITOS 1) to evaluate the urban heat island effect. In the next period a lot of studies that employed the remote sensing method have been performed (Roth et al., 1989, Lo & Quattrochi, 2003, Tomlinson et al., 2012).

In order to assess the UHI from satellite imagery, many studies used the land surface temperature (LST), which is a key parameter for the urban climate. It modulates the air temperature of the lowest layers of the urban atmosphere, focuses on the energy balance of the surface, helps to determine the internal climates of buildings, and influences the energy exchanges that affect the comfort of city dwellers (Voogt and Oke, 2003).

The satellites that collect the image data to be processed in order to obtain the LST, measure the energy (heat) emitted by objects in the thermal infrared domain of the electromagnetic spectrum ranging from 3.0 - 15.0 μm. However, due to spectral absorbtion (the sensors can acquire data only in certain atmospheric windows) and the capacity of the different sensors, the actual interval of the data used to compute the LST is much smaller.

In the last decades a lot of satellites equipped with thermal infrared sensors captured the radiation from the Earth's surface. In *Table no 2*, a list of satellites and technical details of their thermal bands are presented. In this paper we will address, however, only the evaluation of the SUHI from Landsat imagery, which is commonly used in the literature, as it is freely available and the most performant in terms of spatial resolution when compared to other types of free satellite image data.

In the literature, the retrieval of LST from Landsat data is performed differently depending on the sensor used to acquire the image. Few methods have been developed in order to obtain the LST such as the radiative transfer equation, the single-channel method

(Jiménez-Muñoz & Sobrino, 2003), the mono – window (Qin et al., 2001) and split - window algorithms (Wan & Dozier, 1996). The last mentioned method does not apply, however, to single channel Landsat products such as MSS (Landsat 3), TM or ETM+ as it involves the brightness temperature of two TIR bands in order to perform the atmospheric corrections. In this paper we present the methodology to obtain the LST from single channel Landsat products (MSS, TM, ETM+) and the split window algorithm for the images acquired by Landsat 8 TIRS.

2.2.1 Retrieval of LST from Landsat MSS (Landsat 3), TM, and ETM+

The Landsat MSS, TM, and ETM+ sensors detect the spectral response of the objects from the Earth's surface in certain wavelengths (the atmospheric windows) and store it as a Digital Number (DN), with values ranging from 0 to 255 (the grey level of the pixel). In order to compute LST, the calibrated DNs must be converted first to physical units - the at-sensor spectral radiance (5).

Table no 2. Technical details of the thermal bands for different types of sensors (available from http://usgs.gov; https://asterweb.jpl.nasa.gov/TerraLook_aster.asp)

Sensor	Wavelength (μm)	Spatial resolution (m)
HCMM (Heat Capacity Mapping Mission)	10.5-12.5	600
Landsat MSS (Multispectral Scanner)	10.4-12.6	68x83
Landsat TM (Thematic Mapper)	10.4-12.5	120
Landsat ETM (Enhanced Thematic Mapper)	10.4-12.5	120
Landsat ETM+ (Enhanced Thematic Mapper+)	10.4-12.5	60
Landsat TIRS (Thermal Infrared Sensor)	10.6-11.2 11.5-12.5	100
AVHRR (*Advanced Very High Resolution Radiometer)*	10.3-11.3 11.5-12.5	1100
MODIS (Moderate Resolution Imaging Spectroradiometer)	10.7-11.2 11.7-12.2	1000
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)	8.1-8.4 8.4-8.8 8.9-9.2 10.2-10.9 10.9-11.6	90

$$L_\lambda = L_{\min(\lambda)} + \frac{(L_{\max(\lambda)} - L_{\min(\lambda)})Q_{dn}}{Q_{\max}} \tag{5}$$

Where:
L_λ - spectral radiance for wavelength λ;
Q_{dn} - the grey level of the pixel;
Q_{max} - the maximum numerical value;
$L_{max(\lambda)}$ and $L_{min(\lambda)}$ - the minimum and respectively maximum spectral radiance for Q_{dn} = 0 and Q_{dn}= 255; these values can be found in the metadata file of each image.

Afterwards, the temperature of the blackbody (given in Kelvin) can be calculated by converting the spectral radiance based on Planck's equation (6).

$$T_b = \frac{K_1}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (6)$$

Where:
T_b - the temperature of the black body (in Kelvin)
L_λ is spectral radiance from (5)
K_1 ,K_2 - calibration constants (Table no 3)

The black body is, however, only a theoretical concept and in order to obtain the actual surface temperature, land surface emissivity corrections have to be performed depending on the land cover type (7). The difference between the black body temperature and the LST is very small therefore the black body temperature is just as adequate for use in surface temperature mapping from thermal infrared images, thus saving an extra computation step (Lo & Quattrochi, 2003).

Table no 3. Calibration constants for different Landsat missions

Sensor	K1 (watts/(meter squared ×ster×µm)	K2 (Kelvin)
Landsat 4	671.62	1284.30
Landsat 5	607.76	1260.56
Landsat 7	666.09	1282.71
Landsat 8 Band 10	774.89	1321.08
Landsat 8 Band 11	480.89	1201.14

$$LST = \frac{T_b}{1 + (\lambda T_b / \rho) \ln \varepsilon} \quad (7)$$

Where:
$\rho = h \times c / \sigma$ (1.438×10^{-2}mK)
h - Plank's constant (6.626×10^{-34}J s)
σ - Boltzman's constant (1.38×10^{23}J/K)
c - light velocity (2.998×10^{8}m/s)
λ - wavelength of emitted radiance
ε - emissivity of terrestrial objects (Table no 4)

Table no 4. Emissivity of terrestrial objects (after Lo & Quattrochi, 2003)

Land cover class	Emissivity
High Density urban	0.94
Low Density urban	0.95
Forest	0.96
Cultivated land	0.92
Water bodies	0.99
Grassland	0.95

The last operation is the temperature conversion from Kelvin to Celsius degrees (8). The equations that can be used in a model for the retrieval of LST are presented below:

$$T_c = T_b \,|\, 273 \quad (8)$$

2.2.2 Retrieval of LST from Landsat 8 TIRS

Landsat 8 TIRS measures the top of the atmosphere radiance (TOA), a mixing result of three different fractions of energy: emitted radiance from the Earth's surface, upwelling radiance from the atmosphere and downwelling radiance from the sky (Weng at al., 2004). Therefore, an accurate retrieval of the LST implies performing some atmospheric corrections.

The LST is obtained by applying a structured mathematical algorithm that uses both Landsat 8 thermal infrared bands. This method involves the use of radiances measured at two different wavelengths to determine the atmospheric attenuation and was developed by McMillin (1975) in his effort to derive the sea surface temperature (SST). This "split-window" algorithm was then adapted to be used in the estimation of LST.

The retrieval method presented here was developed by Sobrino et al. (1996). The main advantage of this technique is that only brightness temperature, emissivity, and atmospheric water vapor content are needed. The first two parameters can be estimated, while the last one can be derived from remote sensing products. The equation is presented in (9):

$$LST = TB_{10} + c_1(TB_{10} - TB_{11}) + c_2(TB_{10} - TB_{11})^2 + c_0 + (c_3 + c_4 w)(1-\varepsilon) + (c_5 + c_6 w)\Delta\varepsilon \qquad (9)$$

Where:
TB_{10} –brightness temperature of Landsat 8 TIRS band 10 (K);
TB_{11} – brightness temperature of Landsat 8 TIRS band 11 (K);
C_0 to C_6 – coefficient values (Table no 5);
ε – mean emissivity of TIR bands; $\varepsilon = 0.5\ (\varepsilon_{10} + \varepsilon_{11})$;
Δ ε – emissivity difference; $\Delta\varepsilon = (\varepsilon_{10} - \varepsilon_{11})$;
W – Atmospheric water vapor content (in grams per square centimeter).

Table no 5. Coefficient values (after Sobrino et. al, 1996)

Constant	Value
C_0	-0.268
C_1	1.378
C_2	0.183
C_3	54.30
C_4	-2.238
C_5	-129.20
C_6	16.40

In order to implement (9) into a model for LST retrieval, the brightness temperature, the emissivity, and the water vapor content should be known.

The brightness temperature (black body temperature) can be obtained with the same equation presented above for single-channel Landsat products (6) using the Landsat 8 specific calibration constants and the top of the atmosphere radiance (TOA). In this case, the radiance value to be used in the formula should be obtained using to following equation (10):

$$L_\lambda = M_L Q_{cal} + A_L \qquad (10)$$

Where:
L_λ - TOA spectral radiance (Watts/(m2 * srad * μm))
M_L - Band-specific multiplicative rescaling factor from the metadata
A_L - Band-specific additive rescaling factor from the metadata
Q_{cal} - Quantized and calibrated standard product pixel values (*DN*)

Land surface emissivity (ε) is a proportionality factor that scales blackbody radiance (Planck's law) to predict emitted radiance, and it is the efficiency of transmitting thermal energy across the surface into the atmosphere (Sobrino et al., 2008).

In order to calculate the mean emissivity and emissivity difference for LST retrieval using split-window algorithm developed by Sobrino et al. (2008), a land surface emissivity raster is needed for each of the Landsat 8 TIRS bands. To obtain this raster, the land cover should be classified in different land cover types. Afterwards, the band specific emissivity values should be set. These values can be identified using a tool such as the *Aster spectral library*.

The atmospheric water, which is the total atmospheric precipitable water vapor contained in a vertical air column, is a key parameter for climate study. It is one of the most important factors which cause the atmospheric effect on the thermal band (Zhang et al., 2008). The water vapor content can be either calculated using data from the local weather station with the Yang and Qiu method (Yang & Qiu, 1996) or derived from remote sensing products such as MODIS, based on the algorithm developed by Kaufmann & Gao (1992) that uses the reflectance of band 2 and band 19.

3. CONCLUSIONS

Direct measurements methods for AUHI detection are very difficult to be assessed as an important investment in equipment is needed. Also, the set up and the equipment security used for measurements is one of the most difficult problems to be solved for these methods.

Satellite image data processing is a very useful asset for the SUHI detection since it offers the possibility to compute the land surface temperature of large areas. It is the most cost-efficient technique for SUHI evaluation and we consider that the technique we presented gives more accurate results, especially for small and mid-extension cities, compared to those retrieved from MODIS images (Cheval et al., 2009, Cheval & Dumitrescu, 2015).

Besides its advantages, the remote sensing approach has some important limitations: the spatial resolution of the Landsat thermal band(s) that provide an accurate result only for homogeneous areas; inside the urban area a single pixel can include different land cover types (as asphalt, concrete, green spaces, water bodies); due to the temporal resolution of the Landsat products, the SUHI detection is possible only twice per month, when the satellite passes over the study area; requirement for clear ski implies a limited number of images available for processing, especially during spring, autumn and winter seasons; for single channel products, the atmospheric corrections due to the water vapor absorption and re-emission in the thermal infrared region of the electromagnetic spectrum cannot be performed.

Under these circumstances, even though satellite image analysis seems an easier and time-saving solution, we consider that a combination of both surfaces and lower atmospheric layer temperature data analysis is the best choice in order to get accurate results on the intensity and spatial extension of the UHI.

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