ANALYTICAL STUDY OF THE IMPACT OF GREENERY AND PUBLIC SPACE DISTRIBUTION ON LAND SURFACE TEMPERATURE IN MID-SIZE CITIES OF POLAND

ADAM ZWOLIŃSKI[1] and AGNIESZKA WOCHNA[2]
[1] *West Pomeranian University of Technology in Szczecin, Poland*
[1] *azwolinski@zut.edu.pl*
[2] *University of Gdańsk, Poland*
[2] *agnieszka.wochna@ug.edu.pl*

Abstract. The focus of the article is the impact of urban geometry and greenery on the surface temperature in a city and the Urban Heat Islands (UHI) effect. The research problem discussed in the article is to define optimal combination of such parameters as urban geometry, greenery and the LST to enhance the temperature comfort and reduce the UHI effect. The methodology combines CAD and GIS environments. Vector data of 1:10000 scale, from the National Database of Topographic Objects (BDOT10k) is used to analyse urban structure. GIS data include rasters derived from remote sensing: Land Surface Temperature (LST), Digital Surface Model (DSM) and Digital Terrain Model (DTM). The analysis covers areas in Szczecin and Gdynia, two mid-sized cities in Poland. The results indicate a more distinct dependence of LST on greenery parameters than on buildings. The main contribution of the article is the development of a uniform data grid based on CAD and GIS data, allowing for an objective analysis of the city's temperature comfort based on the parameters of buildings, greenery and LST.

Keywords. Urban Heat Islands; Land Surface Temperature; Urban morphology; Greenery in cities.

1. INTRODUCTION

The size, shape and spatial features of urban space evolve due to social, economic, and climate changes. Nowadays, climate plays an increasingly important role in the shape of cities. The interest in examining the phenomenon of urban space warming started already in 1980s. The standard UHI (Urban Heat Island) model, presented by Oke, assumes that the temperature of urban space grows proportionally to the intensity of buildings and population, from rural areas, through suburbs, and towards the city centre (Oke, 1987). The temperature peak appears above the most urbanized area of the city and the magnitude of the UHI is defined as a difference between the temperature in the city and temperature in suburbs. Considering Oke's UHI zones, the article focuses on the urban areas (Fig. 1).

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 2, 437-446.

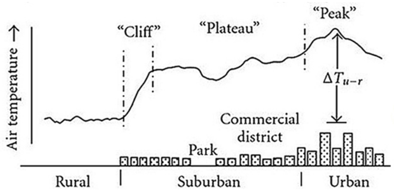


Figure 1. Typical cross section of the Urban Heat Island (UHI) effect vs temperature variations over different land-use areas. Source: Oke, 1987.

The UHI effect has been described in a separate publication by the US EPA (United States Environmental Protection Agency, 2014). The publication indicates, that differences in LST between rural and urban areas can reach about 15°C. Bonan (Bonan, 2002) considers meteorological phenomena and urban space parameters to be the main causes of the UHI effect. Description of UHI factors, such as heat generated from human activities, greenhouse effect, reduced air flow in streets, urban materials, emission and reflected heat can be found in publications in 1991 (Oke et al., 1991). These publications also use the term of 'urban canyon' whose size and proportions determine the UHI effect.

The cooling effect of greenery within streets has been studied in Athens (Tsiros, 2010) and the reduction of the LST is up to 2.2°C in daytime. The review of studies on the impact of trees in urban areas (Bowler et al., 2010) proves that the reduction of the LST is nearly identical regardless the number of trees. Li et al. research touches upon various factors contributing to the UHI effect (Li et al., 2020). Each one of them has a different impact on temperature in city space (Takebayashi and Senoo, 2018) and consequently on the comfort of living. Measurement tests and experiments regarding the impact have been described in the literature (Kaplan, Peeters and Erell, 2016). The extended specification of UHI factors, including those selected for the article, has been studied by Ryu and Baik (Ryu & Baik, 2012).

This article discusses mutual relations and optimal configuration of 3 UHI factors: urban geometry (morphology), greenery and land surface temperature (LST). These are expressed by building coverage, buildings height, greenery coverage, greenery height and LST distribution (Fig. 2). Research questions in the context of the selected parameters are: what and how strong is relationship between buildings and greenery intensity with LST in urban area of the two cities? What combination of buildings and greenery helps to reduce the UHI effect? In terms of data the question is how to combine remote sensing and vector data to get objective information for the UHI effect in the city scale.

UHI SELECTED FACTORS			
MEANS OF EXPRESSION	URBAN PARAMETERS	GREENERY	TEMPERATURE
GENERAL ANALYSIS	URBAN DENSITY AVERAGE BUILDING HEIGHT	% OF GREEN AREA AVERAGE GREENERY HEIGHT	LAND SURFACE TEMPERATURE (LST)
DETAILED ANALYSIS	% OF BUILDING AREA URBAN MORPHOLOGY SCHEME	DISTRIBUTION OF GREENERY	TEMPERATURE DISTRIBUTION
SOURCE DATA	BDOT10k VECTOR DATA	ELEVATION RASTER	LANDSAT 8

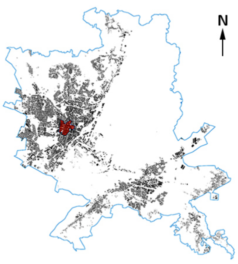
Figure 2. Selected UHI factors with measurement methods and source data. Source: authors.

Based on the combination of CAD and GIS data, the article presents original methodology of analysis and imaging of specific parameters. The methodology has been used in a case study of selected areas in Szczecin and Gdynia, two mid-size cities in Poland. Research findings have been examined from two points of view: general trends and the relationship between parameters and thorough analysis of characteristic areas of cities.

2. METHODOLOGY

2.1. RESEARCH AREA

The research area comprises Gdynia and Szczecin, two mid-sized cities in Poland. The cities were chosen due to similarities in their cityscapes and characteristic urban structure of their city centres. Moreover, both cities share the same cityscape features (location on water body and surrounded by forests). Yet another factor was authors' affiliation and familiarity of urban space from the point of its user. General data range is limited to administrative boundaries of the cities. The detailed analyses focused on two urban units designated SZN_01 and GDY_01 in centres of Szczecin and Gdynia (Fig. 3). The two units are selected based on their homogenous city centre urban structure and diverse configuration of open space (street canyons, squares, interiors).



SZCZECIN	CITY	GDYNIA
SZN_01	URBAN UNIT NAME	GDY_01
129.96	UNIT AREA [ha]	52.02
1444	NUMBER OF RASTER CELLS	578
37.3	BUILDING COVERAGE [%]	34.0
9.26	VEGETATION COVERAGE [%]	6.03
36.7-43.3	TEMPERATURE RANGE [°C]	32.8-36.8
6.7	TEMPERATURE SPREAD [°C]	4.0
40.6	AVERAGE TEMPERATURE [°C]	35.1
2020.08.13	DATE OF SATELLITE IMAGE	2020.08.15

Figure 3. Research area: Urban units SZN_01 and GDY_01 located in the city centers of Szczecin and Gdynia with specification of analytic data (PL) Source: authors.

2.2. URBAN DENSITY

The delimitation of examined urban units has been based on building density. It was determined using BDOT10k vector data and the method of clustering, namely DBSCAN (Density Based Spatial Clustering of Applications with Noise) (Ester et al., 1996). The assumption was to delimit homogeneous areas within city centres in terms of the distance between buildings. In BDOT10k database, buildings are reflected as single features. Building polygons have been converted into points by generating centroids within building envelopes. The layer of points were processed the DBSCAN analysis with search point distance of 20 m. Developed clusters of points indicated areas of homogenous development in terms of density and morphology (distances and scale of buildings). These areas were used to delimit SZN_01 and GDY_01 units for further analysis (Fig. 4). The single-colored dots represent homogeneous urban structures.

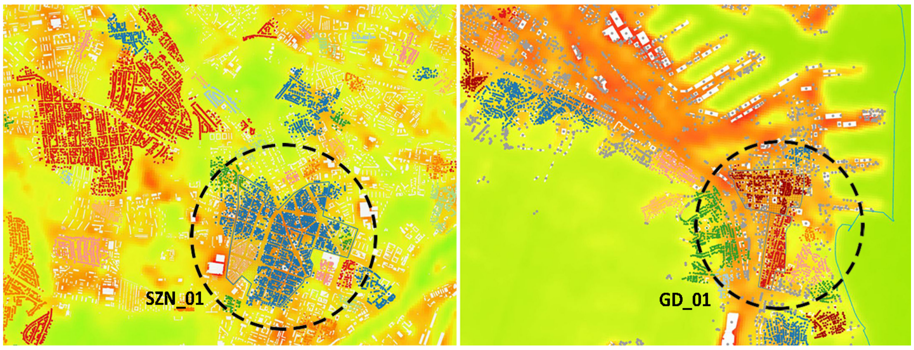


Figure 4. Delimitation of urban units SZN_01 (Szczecin) and GDY_01 (Gdynia) by the density-based clustering methodology. Source: authors.

2.3. DATA PROCESSING

To determine building and greenery intensity, a number of parameters have been calculated for each urban unit (SZN_01 and GDY_01). The diagram of data processing is presented in figure 5. In the first step, the difference between the Digital Surface Model (DSM) and Digital Terrain Model (DTM) was calculated to get the heights of elements above ground level and this was rounded to integers according to mathematical rules. Then heights were assigned to buildings based on BDOT10k vector data, what required combining raster data (1 m cell size) and buildings of several hundred square metres. We decided to assign a median of all pixels with heights within the polygon of a building, since the mean value could have been distorted by pixels of incorrect low (in case of pixels at ground level) or high values (trees above low buildings). Each building with high difference between median and mean was visually checked and frequently divided into several features. Most often, the difference was caused by differences in height of particular parts of buildings, whereas in BDOT10k it was reflected as one feature.

It was assumed that all differences between DSM and DTM above 0.5 (rounded to 1) that were not buildings represent vegetation. As a result it was crucial to investigate the map of differences to find all build-up terrain with heights exceeded 0 m above ground level and treat it as buildings. It helped to identify several hundred objects, most often low utility buildings, such as garages, which previously have not been included in the BDOT10k database and correct any inaccuracies. They all were digitized to vector data and added to the buildings database.

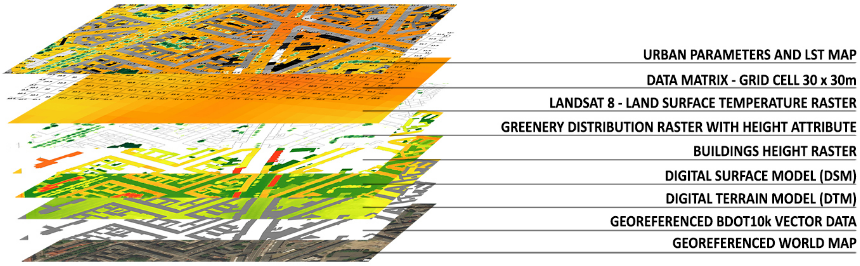


Figure 5. Diagram of data processing. Combination of CAD and GIS data. The final map of the analyzed parameters at the top. Source: authors.

All steps described above helped to develop a raster layer of buildings, including their height, and a raster layer of greenery with height, both with 1 meter spatial resolution. Temperature for UHI studies was downloaded from USGS website as a Landsat 8 Collection 2 level-2 Product - already corrected Earth surface temperature resampled to 30m resolution, and calculated with multiplicative and additive scale factors (Landsat 8 Collection 2 Level 2 Science Product Guide, 2020), then converted to Celsius degrees by subtracting 273.15. In research we used satellite derived LST for summer days - 15.08.2020 for Szczecin and 13.08.2020 for Gdynia. To combine temperature of spatial resolution 30m with building and vegetation data, a square vector mesh was developed overlapping with pixels of a satellite image resulting 1444 cells in Szczecin and 578 cells in Gdynia. Calculations for each cell of the mesh included: coverage with buildings, coverage with greenery, and the average height of buildings and greenery in each cell. The temperature rounded to 0.1°C was added and we obtained a set of parameters describing buildings urban geometry, greenery and temperature.

The relationship between the Land Surface Temperature (LST) and above-mentioned parameters have been examined after averaging values of density and height of buildings and vegetation in all cells of a given temperature.

3. RESULTS

3.1. TRENDS

Temperatures in two analysed cities differ much, as mean temperatures are 35.1°C in Gdynia and 40.6°C in Szczecin. The difference between maximum and minimum temperatures in Szczecin and Gdynia were 4.0°C and 6.7°C, respectively. The percentage of both building and vegetation area is higher in Szczecin (Fig. 3).

We have determined general trends in LST fluctuation depending on the intensity of buildings and vegetation by calculating Spearman correlation coefficients for particular parameters (Tab. 1). In Gdynia, we found outliers of exceptionally low and high temperatures. Outliers are defined as values that differ from the mean value by at least 2 standard deviations. In this case, the outliers included temperatures below 33.7°C and above 36.5°C. In Szczecin, no such outliers were found, most probably due to a different character of the area studied, variety of data and larger standard deviation. Since outliers caused no correlation between parameters, we tried to analyse relationships between selected cells. Table 1 shows correlation values including and excluding outliers.

Table 1. Spearman correlation coefficients, for Gdynia with and without outliers (3 cells of highest and 18 of lowest values). Source: authors.

Urban units	LST vs % of building coverage	LST vs mean buildings height	LST vs % of vegetation coverage	LST vs mean vegetation height
SZN_01	**0.64 *** **	**0.68 *** **	**-0.83 *** **	**-0.80 *** **
GDY_01 no outliers	**0.26**	**0.04**	**-0.46** **	**-0.08**
GDY_01 all	**0.05**	**-0.12**	**-0.31 * **	**0.26**
****p<0.01; **p<0.05; *p<0.10*				

Both in Szczecin and Gdynia, we can see a relationship between the percentage of vegetation area and the LST, but in Szczecin this relationship is stronger. Moreover, while in Szczecin there is a significant correlation between the buildings (both coverage and height) and temperature, in Gdynia no such trend can be determined. Szczecin shows stronger relationship of temperature with density and height of greenery, than with buildings (Tab. 1).

In cells of a higher vegetation coverage, temperatures are visibly lower (Fig. 6AB) in Szczecin. However, there is a visible concentration of points on the vegetation coverage and LST scatterplot (Fig. 6A) which is characterized by a high drop in temperature with an increasing vegetation coverage. The Spearman correlation just for these points equals -0.89, and the points represent 91% of the area analysed.

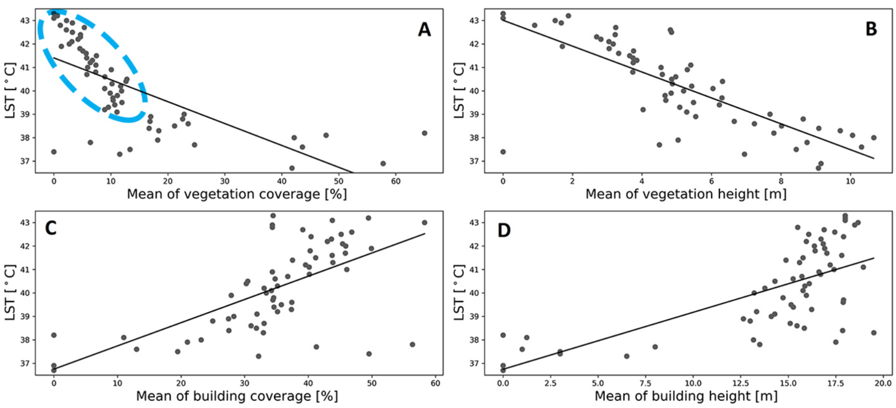


Figure 6. Scatterplots of LST and vegetation coverage [%] (A) and height [m] (B) and building coverage [%] (C) and height [m] (D) in Szczecin. Blue ellipse includes cells of high decrease of temperatures examined more closely. Source: authors.

In the case of three highest temperatures in Szczecin (above 43°C) - area located around crossroads surrounded by high buildings, the density of greenery is 0.2%, building intensity is 42.6% and 18 m height, whereas the two lowest LST values (below 37°C) are in cells located in a park with no buildings and high vegetation coverage (49.7%, 9.1m)

3.2. SPECIAL CASES

Apart from general trends and correlations between specific parameters, the study identified special cases showing the influence of building and greenery coverage on city space temperatures.

The first case involves two typical streets in Szczecin. Both of them are the main arterial roads playing a similar role in the traffic system (Fig. 7). However, they differ in their geometry and greenery coverage. The first arterial road (pixels A and B) is an avenue with double rows of trees and lawn strips. The second one (pixel C) is a densely developed street with single trees. The analysis of temperature in these cells show a significant variation of 3.2°C between the part of the avenue with trees (pixel A), and the second street deprived of greenery (pixel C). The height of greenery is less important in this case. For pixel A, the average height is 9.2 m, and pixel B 7.8 m. The building height for both streets is very similar. Additionally, the width of streets corresponds the general level of temperature (about 2°C difference). In the case of an avenue with trees (pixels A and B), the H/W ratio is 0.33 (18.5m / 55m), whereas in the case of the second street H/W= 0.61 (18.5m / 30m).

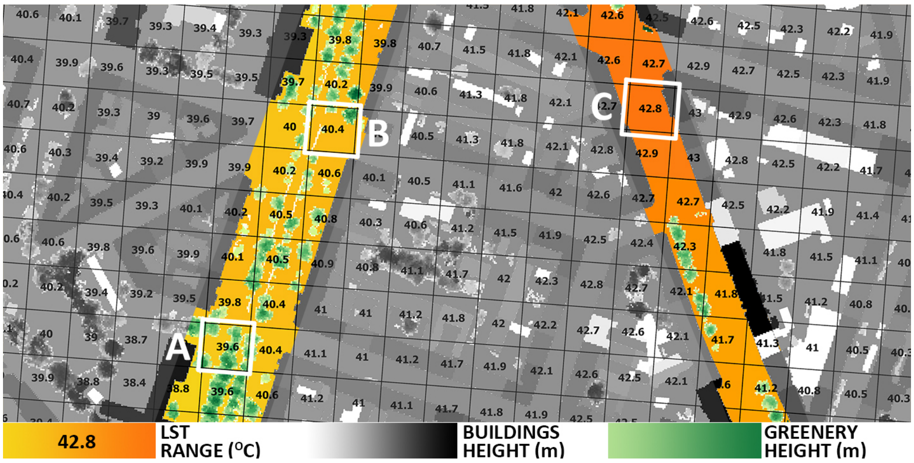


Figure 7. Case 1 – Two street in Szczecin. Values of LST / %greenery / %building coverage for pixels A, B, C: A(39.6 / 58.0 / 0.0), B(40.4 / 19.2 / 0.0), C(42.8 / 0.0 / 11.4). Source: authors.

In the second case, the analysis focused on the character of build-up development and the level of temperatures in city quarters defined as SZN_01 and GDY_01 (Fig.8). A detailed analysis included the level of temperature in areas of 3x3 pixels in interiors of city quarters (SZN_01, areas D and E) and the relationship between the interior of a quarter and the street (GDY_01, area F).

Figure 8. Case 2 – City quarters in SZN_01 (areas D and E) and GDY_01 (area F). Comparison of temperatures in 19th cent. closed residential quarters in Szczecin (area E) and partially open modernist quarters in Gdynia (area D). Source: authors.

Areas D and E show visible differences in LST levels (ca 1.5°C) to the disadvantage of the closed quarters in area E (42.4°C / 29.3%). The partial opening of the city quarters in area D (41.2°C / 43.7%) translates into a better air circulation and lower temperatures. In the case of area F in Gdynia, temperatures in residential quarters are the same as in the street. This is the result of a larger internal space of the modernist quarters in Gdynia and better wind flow.

4. DISCUSSION

Temperatures and ranges of temperatures in two analysed cities differ a lot: mean temperature is almost 5°C lower and ranges is almost 3°C lower in Gdynia (Tab. 1). Moreover, correlations with building and vegetation intensity, as expected (Li et al.,2020, Tsiros, 2010) and clearly visible in Szczecin, in Gdynia is limited to significant correlation with vegetation coverage but below 0.5 Spearman correlation coefficient. Such large differences in temperatures and correlations between examined parameters result from a close distance to the sea and frequent winds in the seafront district (Papanastasiou et al., 2010) of Gdynia. Czarnecka and Nidzgorska-Lencewicz, 2014, analysed the impact of sea breeze in neighbouring city (Gdańsk) on air pollution and UHI and the same phenomenon surely occurs in Gdynia. Frequently appearing sea breeze in summer causes ventilation of the city, daily movement and air exchange causing a drop of temperatures and its amplitudes (Miller et al., 2003).

The relationship between vegetation and its height in Szczecin was expected (Bowler et al., 2010) however on the scatterplot we can see a high drop of LST where vegetation coverages increases from 0 to 13%, what is marked with blue ellipse. Such greenery intensity is typical in that city as this range covers 91% of cells. The decrease of LST is from the highest - 43°C to 39°C- below the average.

The cooling effect of vegetation seems effective - 1°C over each 3% of vegetation coverage what is higher than was noticed in Toronto (Wang et al., 2015). The vegetation in our research includes only above 0.5 meters in height as a result of methodology, so it includes mainly trees and higher bushes.

The grid overlapping pixels in the satellite image allowed for calculations of vegetation and building in each cell and an objective analysis of relations of those parameters with the LST. However, as can be seen from a deeper analysis of special cases, we need to take the neighbourhood into consideration as well. A 3x3 cell window should be taken into consideration as in the city quarters analysis that showed a strong correlation between the formation of heat islands and building height, and consequently size and proportions of open space. This can also be done by the extraction of objects (streets, squares, quarters) for which other properties may be calculated, such as the W/H ratio as in the case of two streets in Szczecin where the temperature difference is about 2.5°C and the W/H ratio difference is about 0.3. Parameters assigned to objects may simplify the interpretation of results.

5. CONCLUSIONS

The article combines vector data with GIS remote sensing data. This allowed for the generation of a uniform objective grid of parameters: building coverage and height, vegetation coverage and height, LST. The application of the method indicated, that for individual cell of the grid it would be important to include infomation about its neighbourhood.

The investigated case of Szczecin emphasized a greater role of greenery than the building parameters for temperature comfort. Within the increase of concentration of the vegetation up to 13% of coverage, the temperature drops by 1°C for every 3%.

The research clearly indicates the role of furnishing street canyons with trees in city centre areas, as well as in poorly ventilated enclosed urban quarters.

The research also confirmed the contribution of other factors on the shaping of UHI effect (air flow, openness of urban geometry, transportation heat etc.). In the case of seaside Gdynia, the breeze significantly affects the temperature. It makes the correlation of LST with greenery and buildings weak. These factors could be added to the data grid in future studies.

In the context of data, the next step would be to increase the accuracy of the data grid (30x30m). This would be possible with drone measurements using a thermal camera. A natural continuation of the method would be to simulate the results in a 3d city model taking into account additional parameters. (Czyńska, 2015).

6. REFERENCE LIST

References

"Landsat 8 Collection 2 (C2) Level 2 Science Product (L2SP) Guide" : 2020. Available from <https://www.usgs.gov/media/files/landsat-8-collection-2-level-2-science-product-guide> (accessed 10.02.2021).

Bonan, G.B.: 2016, *Ecological climatology : concepts and applications*, Cambridge University Press.

Bowler, D.E., Buyung-Ali, L., Knight, T.M. and Pullin, A.S.: 2010, Urban greening to cool towns and cities: A systematic review of the empirical evidence, *Landscape and Urban Planning*, **97**, 147-155.

Czarnecka, M. and Nidzgorska-Lencewicz, J.: 2014, Intensity of Urban Heat Island and Air Quality, *Polish Journal of Environmental Studies*, **23**, 329-340.

Czyńska, K.: 2015, Application of Lidar Data and 3DCity Models in Visual Impact Simulations of Tall Buildings, *ISPRSInternational Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **XL7/W3**, 1359-1366.

Geletič, J., Lehnert, M. and Dobrovolný, P.: 2016, Land Surface Temperature Differences within Local Climate Zones, Based on Two Central European Cities, *Remote Sensing*, **8**, 788.

Johnson, G.T., Oke, T.R., Lyons, T.J., Steyn, D.G., Watson, I.D. and Voogt, J.A.: 1991, Simulation of surface urban heat islands under ?IDEAL? conditions at night part 1: Theory and tests against field data, *Boundary-Layer Meteorology*, **56**, 275-294.

Kriegel, H., Kröger, P., Sander, J. and Zimek, A.: 2011, Densitybased clustering, *WIREs Data Mining Knowl Discov*, **1**, 231-240.

Miller, S.T.K., Keim, B.D., Talbot, R.W. and Mao, H.: 2003, Sea breeze: Structure, forecasting, and impacts, *Review of Geophysics*, **41**(3), 1-31.

Mohammed, Y. and Salman, A.: 2018, Effect of urban geometry and green area on the formation of the urban heat island in Baghdad city, *MATEC Web of Conferences*, **162**, 05025.

Muniz-Gäal, L.P., Pezzuto, C.C., Carvalho, M. and Mota, L.T.M.: 2020, Urban geometry and the microclimate of street canyons in tropical climate, *Building and Environment*, **169**, 106547.

Oke, T.R.: 1987, *Boundary layer climates*, Methuen.

Oke, T.R., Johnson, G.T., Steyn, D.G. and Watson, I.D.: 1991, Simulation of surface urban heat islands under ?ideal? conditions at night part 2: Diagnosis of causation, *Boundary-Layer Meteorology*, **56**, 339-358.

Papanastasiou, D.K., Melas, D., Bartzanas, T. and Kittas, C.: 2009, Temperature, comfort and pollution levels during heat waves and the role of sea breeze, *International Journal of Biometeorology*, **54**, 307-317.

Ryu, Y.H. and Baik, J.J.: 2012, Quantitative Analysis of Factors Contributing to Urban Heat Island Intensity, *Journal of Applied Meteorology and Climatology*, **51**, 842-854.

Takebayashi, H. and Senoo, M.: 2018, Analysis of the relationship between urban size and heat island intensity using WRF model, *Urban Climate*, **24**, 287-298.

Tsiros, I.: 2010, Assessment and energy implications of street air temperature cooling by shade tress in Athens (Greece) under extremely hot weather conditions, *Renewable Energy*, **35**, 1866-1869.

Voogt, A.: 2000, Image Representations of Complete Urban Surface Temperatures, *null*, **15**, 21-32.

Wang, Y., Berardi, U. and Akbari, H.: 2015, The urban heat island effect in the city of toronto, *Procedia Engineering*, **118**, 137-144.