A review of studies involving the effect of land cover and land use on the urban heat island phenomenon, assessed by means of the MUKLIMO model

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ABSTRACT The urban heat island phenomenon occurs in urban areas. It is characterized by increased temperature of both the air and ground surface, compared to the surrounding rural landscape, and is a typical feature of the urban climate. As this phenomenon may affect quality of life in the cities, a variety of scientific studies have been carried out. The article provides a review and evaluation of selected published studies devoted to the issue of the urban heat island, from the point of view of the application of land cover and land use data in the 3-dimensional microscale urban model. Part of the review brings into focus the MUKLIMO model, which computes the atmospheric conditions in urban landscapes and predicts thermal and other climatic characteristics. Evaluated studies confirmed the correlation between the land cover / land use classes and occurrence of the urban heat islands, i.e. a higher percentage of impermeable surfaces within the urban heat island causes more intensive thermal manifestation. The urban heat island effect diminishes when there are less impermeable surfaces and a greater representation of urban greenery in land cover / land use classes.

KEY WORDS local climate zone – land cover – land use – urban heat island – MUKLIMO model

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Introduction

Large urban areas face an ever greater risk of increasing surface and air temperature, particularly city centres. This is the result of the application of artificial construction materials (including concrete and paving asphalt). The physical properties of these construction materials (which accumulate rather than reflect solar radiation and possess a higher heat capacity and conduction) actively influence the temperature increase in the cities, in addition to increasing urban populations. At present, 75% of the European population live in the cities and this proportion is liable to increase to 80% before 2020. It is expected that by 2050, almost 70% of the population of the planet (about 6.3 billion) will live in the cities (Lauriola 2016). For this reason, research activities have concentrated on tracking and assessing the relationships between the expansion of areas of constructed, impermeable surfaces, the shrinkage of farmland and vegetation and the temperature increase in the cities, in terms of their micro and mesoclimate. Thorough knowledge of these relationships may contribute to the improvement of the quality of life in the cities and to energy saving, especially in connection with the use of air-conditioning and other cooling systems.

One manifestation of the changing heat conditions in a densely built-up urban environment is connected with urban heat islands, which is a phenomenon occurring in urbanised areas with typically higher air and surface temperature (Yow 2007) in contrast to the surrounding rural landscape (Oke 1995; Weng 2011; Lauriola 2016). This term is frequently used by authors involved with the theme. Stewart and Oke (2012) reported that the urban heat islands term emerged in the 1940s and Balchin and Pye (1947) were the first to use it when they assessed the relationship between a city's atmospheric heat and its environment. However, Howard identified virtually all of the factors that are responsible for urban heat islands in 1820 (Mills 2008). Kratzer (1956) described the city as an "island in the sea of cool air produced by the terrain". Manley (1958) used the term "heat island". Oke (1982) and Stewart and Oke (2012, p. 1881) associate the main causes of the origins of the urban heat islands effect with:

- Greater absorption of solar radiation (due to multiple reflection) by the walls of buildings and vertical surfaces in the city
- Greater absorption and slower release of heat by buildings and paved city surfaces
- A greater proportion of absorbed solar radiation at the surface is converted to sensible, rather than latent, heat forms
- Greater release of sensible and latent heat from the combustion of fuels for urban transport, industrial processing, and the heating and cooling of domestic space.

From the studies quoted, it is obvious that the subject of urban heat islands effect assessment is broad. The study presented here exposes the published sources devoted exclusively to the tracking of land cover and land use effects on urban heat islands and options for simulation of the heat characteristics of urban areas by means of the *Mikroskaliges Urbanes KLIma MOdell* (known as the MUKLIMO model). This model has been developed by DWD (German Meteorological Service) and has been used in several studies aimed at urban heat islands, mainly in Central Europe, e.g. Vienna (Žuvela-Aloise et al. 2014), Brno (Geletič, Lehnert, Dobrovolný 2016), Bratislava (Holec, Šťastný 2017), and Szeged (Gál, Skarbit 2017), or for the comparison of more central European cities (Bokwa et al. 2015).

The structure of the study was adapted to analyse the basic terms used in the study of heat characteristics of urban landscapes (Section 2), simulation of urban heat islands (Section 3), particularly by means of the MUKLIMO model (Section 4), documentation of selected projects involved with urban heat islands (Section 5), and a survey of views on the issue by applying two approaches:

- Meteorological and climatic approach (Section 6)
- Landscape-urban planning aspect and the land cover / land use effect on occurrence of urban heat islands (Section 7).

Section 8 looks at the significance of land cover and land use information and how their changes relate to the cognition of heat characteristics of urban landscapes.

The aim of the study is to provide the geographic community with a survey and evaluation of selected published studies devoted to the urban heat islands issue, from the point of view of application of the land cover and land use data in the MUKLIMO model which makes it possible to simulate and forecast heat and other climatic characteristics of urban landscapes.

Urban heat islands and the basic terms

Oke (1995) discerned three basic types of urban heat islands: air urban heat islands, surface urban heat islands, and sub-surface urban heat islands. Air urban heat islands is the synonym of the atmospheric urban heat islands. As far as the atmospheric urban heat islands is concerned, the layer close to the earth's surface between buildings below roof level, i.e. the urban canopy layer and the layer above it, i.e. the urban boundary layer are determined (see Fig. 1).

Voogt (2004) presented a similar classification, distinguishing three urban heat islands types: canopy layer heat island, boundary layer heat island, and surface heat island. The daily temperature cycle of the urban heat islands consists of a daytime urban heat islands and nocturnal urban heat islands depending on different dynamics, compared with the broader environment.

The detection of urban heat islands in the urban canopy layer is first carried out by *in situ* measurements from meteorological stations or ad hoc measurements and

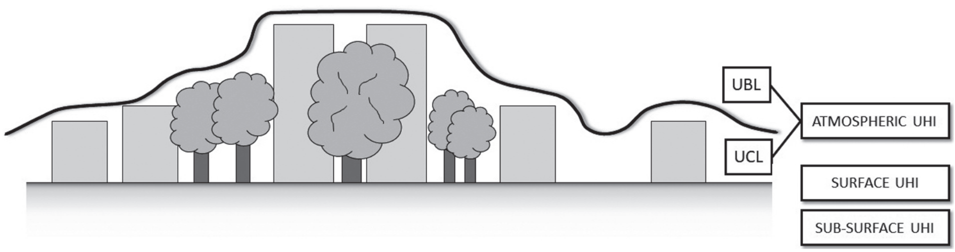

Fig. 1 – Schematic depiction of the commonly encountered urban heat islands types. UBL – urban boundary layer, UCL – urban canopy layer, UHI – urban heat island.

then, secondly, from data from sensors placed on vehicles such as cars, bicycles or trams. The urban boundary layer data are obtained by means of devices carried by balloons or aircraft (Majkowska et al. 2017). Voogt (2004) specified that while urban canopy layer reaches approximately to the height of the buildings, the height of urban boundary layer oscillates. It can reach up to a kilometre during the day but it drops to a level of several hundreds of metres during the night. While the air temperature measurement makes a direct urban heat islands quantification possible, surface urban heat islands assessments rely on remote sensing data. Land surface temperature is derived from the intensity of surface radiation. Land surface temperature is the basic input data for the majority of surface urban heat islands indicators quoted by Schwarz, Lautenbach, Seppelt (2011). Based on the analysis of fifteen studies, indicators may represent the difference between the mean land surface temperature of urban areas and land surface temperature of selected land cover / land use classes (for instance, farming areas or water bodies). Additional indicators can express the difference in mean land surface temperature of urban areas and the contiguous rural landscape (for example the 20 km wide buffer zone around the city), or extent of the area with land surface temperature higher than the mean land surface temperature. The standard deviation of land surface temperature and magnitude of land surface temperature may create other group of indicators.

Surface urban heat islands was identified from the ITOS-1 satellite data for the first time and this was documented in Rao's (1972) study, where higher temperatures in the cities in the east of the USA were pointed out. Anniballe, Bonafoni, Pichierri (2014) analysed the mutual relationship between surface urban heat islands and canopy layer heat island with consideration given to their differences in light of the spatial scope magnitude, orientation and temperature.

Shepherd et al. (2013) mentioned that many of the studies focussing on the analysis of the urban heat island effects (for instance, those on microclimate or public health) have evaluated this phenomenon in an isolated manner, i.e. for single cities. They proposed that in many cases (first of all in urban agglomerations) the effects of urban heat island are multiple with accumulated effects on the local landscape. They used the term 'urban climate archipelago'.

The opposite effect, related to surface urban heat islands, is that of surface urban cool islands and atmospheric urban cool islands which are influenced by the humidity of the earth's surface in green parts of cities (Chang, Li, Chang 2007; Rasul, Balzter, Smith 2015; Rasul et al. 2017; Shigeta, Ohashi, Tsukamoto 2009; Xiao et al. 2018).

Urban heat island modelling

There are several ways to study urban heat island. They include: appropriately designed, purposeful climatological networks (Herbel et al. 2016), remote sensing methods (Roth, Oke, Emery 1989; Tran et al. 2006; Fabrizi, Bonafoni, Biondi 2010), traverse (or mobile) measurement (Quitt 1978) or modelling (Atkinson 2003).

Three types of models can be used to study urban heat island (Fernando, ed. 2013):

- Physical scale models study selected properties of urban heat island by means of simplified conditions that neglect, for instance, the turbulent transference of heat during night hours or consider a simplified geometry of street canyons.
- Statistical models are suitable for their simplicity, but sufficient results are only received in the limited scope of the atmospheric conditions for which they were formulated. Normally, they work with a linear regression statistical approach, where the maximal intensity of urban heat island measured in ideal conditions (dependent variables) is associated with population number, geometrical and meteorological variables or data about the properties of the active surface (independent variables).
- Numerical models offer greater possibilities for simulation of the entire complexity and variety of cities and their environs, as well as ways of interacting with the surrounding atmosphere. They modify parameters of the city surface for better consideration of its properties (such as albedo of the surface, roughness of surface, heat capacity and heat conductance of individual materials or natural surfaces). They make it possible to assess the impact on the environment and are suitable for planning mitigation and adaptation to the changing climate.

MUKLIMO model

The numerical 3-dimensional microscale urban model (MUKLIMO) is used for the calculation of atmospheric conditions in an urbanised landscape. It has been developed for microscale applications dealing with the issue of urban climate and,

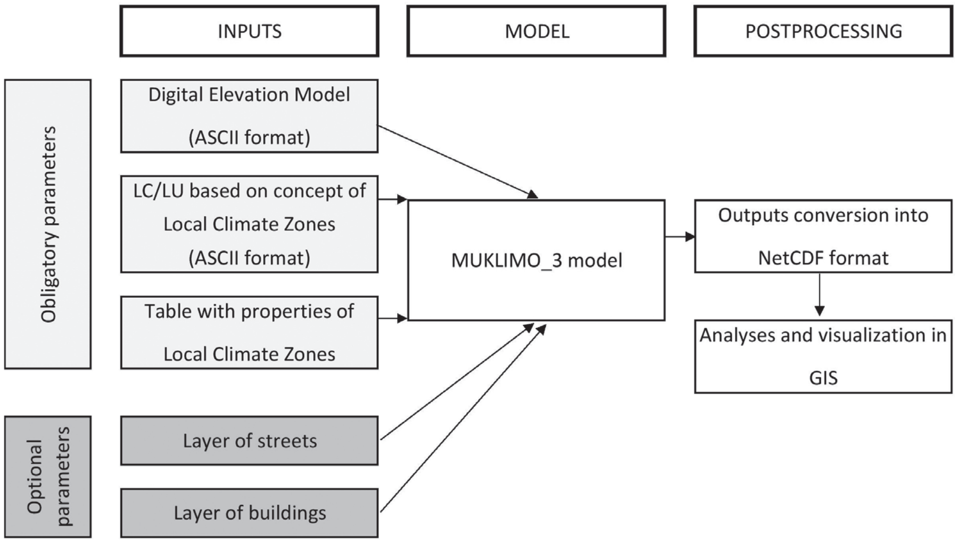

Fig. 2 – Inputs and outputs of MUKLIMO_3 model

primarily, for urban heat island analysis and assessment (Sievers, Zdunkowski 1986), by the German (DWD – Deutscher Wetterdienst 2014) and Austrian (ZAMG – *Zentralanstalt für Meteorologie und Geodynamik*) meteorological services. The current version of MUKLIMO-3 (Sievers 2012, 2016) is used in the urban heat island research. The algorithm of this model also includes prognostic equations for air temperature and humidity, parametrisation of unresolved buildings, short and long-wave radiation, soil temperature and moisture balance as well as a vegetation model. It also uses the categorisation of a proportion of surfaces of varied kinds by an established scale: built-up, impermeable and also permeable surfaces (vegetation cover and soil).

The particular input parameters of the model are: (1) a digital elevation model, (2) a land cover / land use layer using the concept of local climate zones (which are areas with a homogeneous surface, structure, material and human activities), i.e. quasi-homogeneous land cover / land use areas regarding the urban climate (Stewart, Oke 2012), (3) table with characteristics of the local climate zones used, which includes data about the density of the urban fabric, dimensions of building coverage of the ground by an impermeable surface, properties of building materials and properties of greenery. In addition, optional entry parameters are: (4) street layer and (5) layer of buildings (if this is not applied, then the properties of the buildings are included in the table of the local climate zones used (see Fig. 2). Important meteorological input consists of temperature, moisture and wind characteristics in the vertical profile of the atmosphere (below 1 km above the surface of the landscape). Other inputs that can be used are: temperature of urban water bodies, soil moisture, soil temperature, soil type and some other environmental properties.

The model provides outputs for air and soil surface temperature, air humidity and the wind field. It also offers the option to assess the effects of relief, land cover and land use and of weather on the urban climate. The model does not take into account changes in cloudiness and possible atmospheric precipitation. Therefore, its use is limited to cloudless days that are void of atmospheric precipitation. The usual grid size used by the model is between 20 and 500 metres. Depending on the resolution of the model and size of the particular territory, the calculation time varies between several hours and several days.

Projects focused on the urban heat island issue in Central Europe

The common need for monitoring of the urban heat island issue and proposals for mitigation and adaptation measures have led to the support of several international projects. For example, the European Union addressed the urban heat island phenomenon in *Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon – 3CE292P3*. The project was coordinated by the Regional Agency for Environmental Protection in Emilia Romagna, Italy with the participation of 17 partner organisations from Czechia, Hungary, Germany, Poland, Austria, Slovenia, and Italy. The aim was to obtain detailed information about the urban heat island phenomenon (analysis and assessment of the state-of-the-art scientific and legislative knowledge regarding it) and to adapt the models, in association with urban and landscape planning, in order to mitigate urban heat island effects on the urban landscape. The meteorological data obtained by measurements produced by the monitoring stations located in selected cities (Budapest, Ljubljana, Modena, Padua, Prague, Stuttgart, Warsaw, and Vienna) and their environs (as well as satellite images, land use data, and the digital relief model) were used and compared in this project (Lauriola 2016).

The Slovak Hydrometeorological Institute joined the international project *Urban climate in Central European cities and global climate change* in the years 2014–2015, which started modelling the temperature field of Bratislava by applying the MUKLIMO model (Bokwa et al. 2015).

The International Community Project WUDAPT (*The World Urban Database and Access Portal Tools*) is focused on the global collection of urban data from a climate point of view (Mills et al. 2015). The mapping is carried out by crowd-sourcing following the single scheme based on the local climate zones concept and it consists of three hierarchic levels. The input data for basic level mapping are the freely available Landsat satellite images and the methodology is based on the free SAGA GIS software (Bechtel et al. 2015). The data for the hierarchic levels which follow are specified more exactly, based on the experience and knowledge of people living in the cities or some other supplementary data (about buildings, for instance).

Urban heat island issues in meteorological and climatological studies

The identification of surface urban heat islands using the satellite data obtained in the thermal infrared part of the spectra with a small resolution, is associated with the launching of the NOAA (National Oceanic and Atmospheric Administration for global weather monitoring) in 1970 and Heat Capacity Mapping Mission satellites (HCMM) in 1978. These collected information about the thermal characteristics of objects on the earth's surface in the 1970s. A review of the published studies on these themes before 1989 was carried out by Roth, Oke, Emery (1989), who also analysed some methodological aspects of the interpretation and application of satellite data for the study of city climates. Progress in answering these methodological questions in the following decade was brought about by Voogt and Oke (2003), who summarised the use of data from the thermal part of the spectra in their 1988–2000 studies devoted to city climates. This was when the thermal spectral bands of the LANDSAT Thematic Mapper sensor with higher spatial resolution were also introduced.

Various models followed, the most frequently used numerical climate models assessing the urban heat island including Weather Research and Forecasting (WRF), Urban Boundary Layer Climate (UrbClim; De Rider, Lauwaet, Maiheu 2015) and the already mentioned MUKLIMO model. The non-hydrostatic numerical model, WRF, simulates climate at the medial to large scales. Brousse et al. (2016) simulated urban heat island by means of this model in the city of Madrid. Mitigation of the urban heat island effect by means of green and cool roofs was assessed based on the WRF model by Sharma et al. (2016).

The numerical UrbClim model can be applied, in medium scale cases, to simulate processes which take place in the Urban Boundary Layer. This model was applied, for instance, to the assessment of the seasonal urban heat island trends in the Greater London area (Zhou et al. 2016), and it reproduced the time shift of surface temperatures against the air temperatures in a reasonable way. Lauwaet et al. (2016) predicted urban heat island in the city of Brussels by means of the UrbClim model for the present and future climate conditions. Results of the future-modelled scenarios indicated a slight decrease of the urban heat island intensity due to global warming.

The MUKLIMO model has also been used for simulation of urban heat island in the cities of Brno (Geletič, Lehnert, Dobrovolný 2016) and Bratislava (Holec, Šťastný 2017). Žuvela-Aloise et al. (2014) offered an interesting comparison of the scope and intensity of urban heat island when they modelled urban heat island in Vienna by the MUKLIMO model using historical data from The First Military Survey. Modelling revealed that urban heat island with high intensity, but a small spatial scope might have already formed in a densely built-up city centre in the second half of the 18th century. On the contrary, the study of Žuvela-Aloise et al. (2018) concentrated on possible mitigation of urban heat island in future by the introduction of green roofs and the application of materials with high albedo. Simulation by means of the MUKLIMO model in the city of Vienna proved a potential cooling effect of these strategies in densely built-up areas. The MUKLIMO model is also applicable to the assessment of human heat comfort during heat waves, as is appreciable from the study carried out by Geletič et al. (2018) of the city of Brno.

The input parameters of numerical climate models usually consist of data regarding the altitude above sea level, a digital terrain model, land cover / land use data, building information and meteorological parameters. Such data are used by the MUKLIMO, WRF and Urban Multi-scale Environmental Predictor (UMEP) models. Comparison of the resuls of the WRF model using the local climate zones and standard land cover / land use data in the form of the Co-ORdination of INformation on the Environment (CORINE) Land Cover (CLC) layer showed more accurate results using local climate zones data (Brousse et al. 2016). A correct definition of local climate zones and their parameters is also crucial for the functioning of the MUKLIMO model (Geletič, Lehnert, Dobrovolný 2016). Simulations of heat patterns in the city of Brno, for instance, showed that the model primarily reflects the effect of sea level altitude that is particularly evident in the afternoon, evening and night-time hours. On the other hand, the model does not reflect the variability in density of the urban fabric, i.e. the amount and effect of accumulated heat. This is the reason why the authors admit the possibility that the local climate zones concept is too general for modelling on a detailed level.

A review of urban climate studies with an overview of the methods used in various cities across the world is provided by Grimmond (2006).

Effect of land use/land cover classes on urban heat island in studies focused on landscape and urban themes

One of the first analytical works about the relationship between temperature and land cover / land use was that of Chandler (1965), where the author defined three principal determinants affecting the specific climate in cities as follows: (1) General climate of a given locality; (2) Effects of the local geomorphological situation, and (3) Proper modifications generated by the clustering of buildings and roads into an urban complex (where the height, density, composition and structure of buildings, rate of impermeable soil sealing by concrete, size, character and spatial location of parks and other spaces, form and amount of produced heat of anthropogenic origin, and intensity of traffic are taken into account). Based on these parameters, four zones with different density or urban fabrics were defined in the city of London. Differences in air temperature obtained by measurements from twenty meteorological stations and auxiliary mobile measurements in selected transects were tracked in these four zones. In the interpretation of the obtained results, the author pointed out the effects of the settlement greenery and spacious parks on the local temperature. Explaining the obtained urban heat island data, he also concentrated on differences in heat capacity and conductance of materials, presence of haze, fog/mist (altered reception of sun radiation), air mixing (regarding terrain with heterogeneous geomorphology) and night radiation uptake (Grimmond 2011).

As land cover / land use is one of the key factors influencing urban heat island, several authors attempted the purposeful classification of a city which might reflect the potential effect of the given locality on microclimate. Oke (2004) proposed a simple classification of urban climate zones. Until then, *climatope* was the term used in a similar context in several studies (for example, Wilmers 1991, Scherer et al. 1999). Steward and Oke (2012) then defined local climate zones, characterising the urban landscape and other landscape types.

In their study, Roth, Oke, Emery (1989) demonstrated the use of data taken by the Advanced Very High Resolution Radiometer sensor from the NOAA satellite for identification of surface urban heat islands in the cities of Vancouver, Seattle and Los Angeles; these were then visually compared with the land use maps. The results proved a strong relationship between the day-time temperatures and land use mosaics, while the warmest areas had an industrial landscape and the coolest were those covered by vegetation and those in the vicinity of water. Dousset (1991) interpreted the surface urban heat islands data of the city of Los Angeles (obtained by the Advanced Very High Resolution Radiometer sensor) as functions of land cover and classified based on multispectral *Satellite Pour l'Observation de la Terre* (SPOT) satellite images. Surface urban heat islands significantly correlated with industrial and densely built-up areas while the local, cool islands coincided with golf courses and urban parks with large areas of water.

Records from satellite sensors with greater spatial (around 100 m) and shorter time resolution, such as Landsat or ASTER, are more appropriate for the analysis of surface urban heat islands distribution. The Lougeay, Brazel, Hubble (1996) study concentrated on the analysis of the land cover / land use samples with land surface temperature identified by means of Landsat satellite images of the rapidly sprawling, urban landscape of Phoenix, Arizona. The results confirmed a significant correlation between land surface temperature and the presence of water-covered areas and biomass which provide a cooling effect by evaporation. Almutairi (2015) used thermal data from Landsat 8 for the identification of ten urban heat islands in the vicinity of the city of Riyadh, which were cartographically presented using isotherms. The author confirmed the correlation between land cover / land use types and the identified urban heat islands.

Unger et al. (2001) analysed the correlation of selected land cover classes (particularly built-up areas, water bodies and other surfaces) and the urban heat island in the city of Szeged. Built-up areas were classified by four intervals of density of urban fabric which were compared with isotherms indicating the urban heat islands. The results show a distinct effect of the density of urban fabric on the temperature dynamics in the city and localities with tall prefab houses had a similar effect.

Articles by Rodriguez-Alvarez (2013, 2016) presented the analysis and assessment of the effect of land cover / land use classes (represented by data from the European Urban Atlas project on the intensity of urban heat islands at Madrid, Barcelona, Berlin, Cologne, London, and Brussels). The data was obtained by the MODIS satellite sensor from the Aqua satellite and the European Urban Atlas data were aggregated into five basic classes: built-up areas, settlement vegetation, forests, farmland, and surface waters. The results confirmed the correlation between the density of urban fabric represented by land cover / land use classes and the urban heat islands. They also proved that the presence of parks and water bodies has potential cooling effects on the urbanised landscape. On the other hand, one of the decisive factors positively influencing the urban heat island effect is high population density, which manifests itself in the concentration of tall buildings in the settlement structure.

The traditional approach to urban heat island detection based on *in situ* point measurement does not facilitate a detailed analysis of the spatial structure of this phenomenon. Majkowska et al. (2017) believe it is the main reason that the surface urban heat islands is detected by means of remote sensing data. Rao (1972) published the first conceptual frame for implementation of satellite data in the assessment of surface urban heat islands. Satellite data were used in the study of urban heat island in the cities of Houston (Streutker 2003), Paris (Dousset, Gourmelon 2003), Rome (Fabrizi, Bonafoni, Biondi 2010), Madrid (Fabrizi, De Santis, Gomez 2011), and Brno (Dobrovolný 2013).

The effect of the composition and configuration of land cover / land use on the formation of urban heat island has also been tracked using selected indicators in the territory of Shanghai (Li et al. 2011). Land surface temperature was analysed in relation to the normalised differentiated vegetation index, vegetation fraction and percentage of impervious surface areas based on the Landsat ETM+ data. The results showed a strong correlation between land surface temperature and vegetation, as well as impermeable surfaces. Residential zones participated most in the formation of urban heat islands, followed by industrial areas with the highest land surface temperature. However, industrial land has a limited contribution to the overall surface urban heat island due to its small spatial extent in Shanghai. Wang et al. (2017) assessed changes of land cover / land use in Shanghai from the years 2002 to 2013 in the context of the changing urban heat island. They assessed the surface urban heat islands intensity in relation to four classes: built-up areas, water, vegetation and the remaining areas (mostly soil without vegetation). The results confirmed a strong positive correlation between land surface temperature and impermeable surfaces and a negative correlation between land surface temperature and vegetation and water. A strong positive correlation of land surface temperature with impermeable surfaces was also found in the territory of Changchun (Yang et al. 2017). The authors analysed land cover / land use changes over the course of thirty years (1984–2014) with relation to the surface urban heat islands changes. Land cover / land use was classified into eight classes: paddy land, dry land, woodland, urban land, rural settlement, other built-up areas, water, and unused areas. Regarding the mean annual values of normalised land surface temperature, the highest values corresponded to urban areas and other built-up areas and the lowest values were found for water and forest areas. The above-quoted correlations are not universally valid, however. Xiao et al. (2018) demonstrated that, in the case of the city of Madrid, urbanised areas may appear as cool islands amidst hot surroundings in arid regions.

Geletič and Lehnert (2014) investigated the effect of the distribution of industrial areas and shopping centres on the spatial variability of land surface temperature in the city of Olomouc. An increase in land surface temperature was found in all built-up localities in the city. Meteorological measurement revealed that some of the complexes warm their environs during sunny days by several degrees Celsius. Sedlák, Prislinger, Vysoudil (2010) calculated mean land surface temperature in different land use / land cover types from two Landsat images of Olomouc. The highest mean temperature of 24 °C corresponded to built-up areas and some roads but the authors point out that a more detailed investigation of surface urban heat islands requires images with a higher spatial resolution to be able to study temperature variations not only between land cover / land use classes but also within them.

Dobrovolný and Krahula (2015) chose a different approach. They assessed spatial variability of the night air temperature in the city of Brno, as detected by mobile measurement in the context of selected factors: altitude, vegetation density, and density of buildings and roads. Vegetation density (represented by normalised differentiated vegetation index values) and building density (which explained almost 50% of temperature variability) proved to be the most important ones.

The Geletič et al. (2016) model of the urban heat island for the city of Brno also revealed an interesting fact: the daily air temperature in large parts of the city was not always higher than in the neighbouring farming landscape, where fields were more prevalent. This was stated by Houet and Pigeon (2011) as well.

Majkowska et al. (2017) applied Landsat data to urban heat island detection in the city of Poznan in 2008 to 2013 and they particularly focused on detecting correlations between land cover classes according to CLC 2006. The greatest anomalies in relation to the mean surface temperature were found in the class *continuous settlement fabric* (3.4 °C) and the lowest values were taken for the class *broad-leaved forest* (−3.1 °C). Higher urban heat island intensity was confirmed in warmer periods (April to September). Schwarz et al. (2012) tracked differences in the morning and evening land surface temperature values and air temperature according to individual European Urban Atlas classes in the city of Leipzig. Statistically significant deviations were also found between these classes, in terms of land surface temperature and air temperature. Correlation analyses were processed for the cities of Vienna and Madrid, based on the European Urban Atlas data and Landsat 8 OLI data with an emphasis on the assessment of the relationship between surface temperature and land cover / land use at different scales, using a square grid of different dimensions from 90 m to 990 m (Xiao et al. 2018).

One of the most recent studies in this field is that of Chapman et al. (2017) which provides a detailed review of published articles devoted to the assessment of the effect of increasing size and sprawl of the cities and climate change on urban air and surface temperatures (presented in °C) in the context of the monitored cities. The study tries to answer questions about whether changes in anthropogenic heating, in response to climate change, will impact on urban temperatures and how increases in urban density may affect future urban heat stress. The study also asks how the spatial configuration of urban growth could impact on future changes to the urban heat island phenomenon and how heat stress vulnerability could change in urban areas in the future, considering both climate change and urban growth.

Importance of information about changes of land cover / land use in relation to temperature characteristics of the urban landscape

Assessment of the above-described studies makes it possible to formulate the following generalisations:

- One of the basic statements pointed out by Almutairi (2015) is confirmation of the correlation between land cover / land use classes and the occurrence of urban heat island (a higher percentage of impermeable surfaces, particularly in densely built-up city centres, in the frame of land cover / land use, leads to a more intensive manifestation of urban heat island); this correlation has also been confirmed by Majkowska et al. (2017) and Žuvela-Aloise et al. (2014, 2018) and they associate the uninterrupted urban fabric with the top value of urban heat island. They ascribe the lowest value of urban heat island to forest, urban greenery and materials with high reflectivity.

- Land cover / land use classes representing settlement greenery (parks) and water areas and their spatial distribution mitigate the urban heat island effects (for example, Roth, Oke, Emery 1989).
- Occurrence of the urban heat island effect is associated with the occurrence of land cover / land use classes with high concentrations of high-rise buildings and the accompanying high population density (Rodriguez-Alvarez 2013, 2016).
- Other land cover / land use classes which influence spatial variability of urban heat island are the industrial and commercial areas which cause a similar increased urban heat island effect, not only within them but also in their surroundings, as demonstrated by Sedlák, Prislinger, Vysoudil (2010) and Geletič, Lehnert (2014).
- Li et al. (2011) stressed the role of landscape composition and configuration on urban heat island based on the analysis of land surface temperature in relation to a normalised difference vegetation index, vegetation fraction, and the percentage of impermeable surface area.
- Geletič, Lehnert, Dobrovolný (2016) came to the conclusion that, when applied to the MUKLIMO model, the input data about local climate zones are too general for the simulation of temperature characteristics of an urban landscape on a detailed level.

Conclusions

The results reported and verified in the cited studies confirm that the urban heat island is a phenomenon with a distinct manifestation in the urban landscape. Its effect is observed not only in real time (by measured temperature characteristics of the surfaces of landscape objects and those of air temperatures in different heights above the surface) but may be accurately simulated by using temperature characteristics of urban landscapes for different time horizons, for instance, in the MUKLIMO modelling framework, whose brief characteristics are quoted here. The appropriateness of urban heat island assessment within the framework of different land cover / land use classes was approved by various case studies, as listed in our review.

The MUKLIMO model relies on high-resolution land cover / land use datasets in order to assess the microclimatic conditions. The necessity of high resolution urban land use data was confirmed by the clear correlation between temperature characteristics and presence of land cover / land use classes with a high share of impermeable surfaces and the small extent of urban greenery. Thus, if the land cover / land use classification used in some of the studies is too general, this may significantly hamper the model accuracy.

We have presented a complex review that summaries the current state-of-the art of urban heat island modelling. By considering such models in urban planning, the quality of life in the built-up environment may be significantly improved, particularly with regard to global warming.

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