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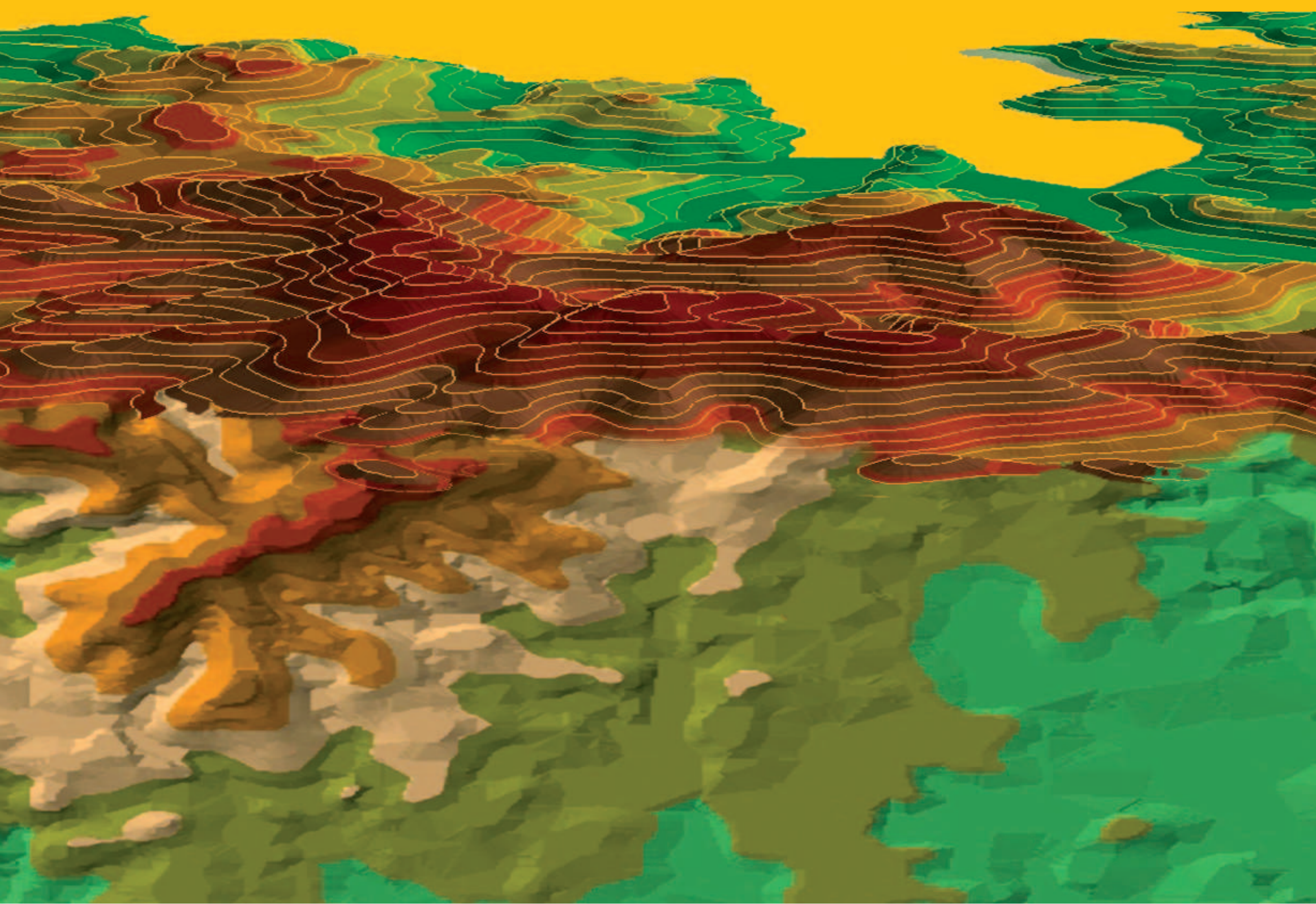

Fig. 2: Selected meteorological stations in Brno city (Photos: P. Dobrovolný). Note: a – Hroznová Street, Brno-Pisárky, b – Botanic garden on Kotlářská street; c – Institute of Geonics on Drobného Street, d – Garden of the Augustinian monastery at the Mendel square

Illustrations related to the paper by P. Dobrovolný and L. Krahula

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Articles:

Urban space and climate: Introduction to the Special Issue

Miroslav VYSOUDIL [a *]

An urban climate refers to the fact that atmospheric conditions tend to be different in a city compared to the surrounding rural environment. In addition, urban areas constitute those locations most at risk among those affected by potential global climate changes. Studies concerning the impact of global changes on the local climates of cities are of great significance for the health and wellbeing of urban residents. In contrast to the cities of Western Europe, however, urban areas in Central Europe developed in a significantly different way after World War II because of political and economic conditions. Urban structures, then, also tend to be different, and urban climate studies must include those specific features.

This Special Issue of the Moravian Geographical Reports (MGR) includes selected, revised and updated original papers by climatologists and related scientists from the Central European region. Considering the broader geographic focus of the MGR, this issue includes works dealing with urban climate studies from several perspectives, including spatial aspects. The purpose of these introductory remarks is to contextualize this research area in general terms, opening up the field for the reader.

An urban area is a specific geographic space exhibiting many features, including the regime of most meteorological elements and climatic characteristics. According to Landsberg (1981), an urban area, in comparison with a suburban one, is mainly characterised by the following factors: a lower average wind speed; higher daily and annual average air temperatures; lower relative humidity; reduced visibility; a higher value of air pollution because of higher emissions of air pollutants; a reduced value of solar radiation; a higher value of cloudiness; a higher value of total precipitation; an increased frequency of storms; a higher frequency of fog in winter; and a shorter heating season.

These differences manifest themselves most clearly in cities with more than one million inhabitants, but they have also been demonstrated in the smaller towns that are typical of Central Europe (Beranová and Huth, 2006; Bottyán et al., 2005; Bokwa, 2011; Dobrovolný et al., 2012; Unger et al., 2001; Vysoudil et al., 2012). The specific character of the urban climate is also influenced by other more general factors. According to Oke (1981), the most important factors include the thermal and radiation properties of active surfaces, their mostly impermeable character, the geometrical arrangement of active surfaces, waste heat production and pollution of the urban atmosphere.

The study of urban climates is a relatively 'young' field, about two hundred years old. The scientific basis of studies of the climate in cities was established by an English chemist and meteorologist, Luke Howard (1772–1864), who sorted the records of meteorological measurements in London for the period 1797–1831 and in 1833 published the results in his book "Climate of London Deduced from Meteorological Observation" (Howard, 1833). With respect to the further development of urban climatology, it was essential that Howard did not confine himself to monitoring the temperature conditions of London itself, but also observed any differences in comparison with its surroundings. The importance of Howard's contribution to studies of urban climate was emphasised by the Second Edition of his publication by the International Association for Urban Climate (Howard, 2007). The work of Luke Howard has a special place in the history of the field because he was the first to recognise the existence of urban heat islands (UHI) and because his analysis proved to be so prescient. His theory of the manifestations of a warmer urban climate still remains valid today, and Howard is therefore rightly regarded as the principal founder of urban climatology.

The dynamic development of urban climate studies from the mid-20th century to the present day has been influenced not only by the development of measurement techniques and statistical and mathematical-physical methods of research, but also by the gradual development of space technology, GIS methods and information technologies in general. The attention of scientists has gradually shifted to the study of all meteorological elements and meteorological processes responsible for the formation and character of the urban climate.

The studies of urban climate from the mid-20th century to the present can be characterised in a broad fashion in the following stages:

- 1960s: employment of statistical methods to test hypotheses, moving towards an energy budget approach and explanations;
- 1970s: application of computer techniques in modelling, observations of energy fluxes, a more rigorous definition of the urban "surface", urban scales and observing urban effects;
- 1980s: adoption of common urban forms for modelling and measurement, the use of so-called physical models, measurement of fluxes in different cities;
- 1990s: establishing relationships between urban forms and their climatic effects, urban field projects examined by research teams; and
- 2000s+: improved models of urban geometry, increased links between modelling and measurement programs.

The most distinctive contributor to urban climatology in second half of 20th century is probably the Canadian climatologist T. R. Oke, who extended the traditional descriptive approach of studies of urban climate to encompass studies of the actual climate-forming processes characteristic of urban areas, and further outlined directions leading to more efficient urban climate research (Oke, 2006a, 2006b). Research in the field of urban climatology therefore pays particular attention to the key area of collecting relevant data needed for subsequent analysis.

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The development of space technology has enabled the use of satellite images from the remote sensing of the Earth in both the microwave and long-wave heat thermal parts of the electromagnetic spectrum for the needs of climatological and environmental research (Adams and Gillespie, 2006). A systematic review of the possibilities of using remote sensing data in urban climatology is presented by Weng and Quattrochi (2007). For the study of spatial-temporal changes in urban heat islands, thermal satellite images have been used by climatologists in virtually all geographic regions (Mesev, 1998; Nichol, 1998; Ozawa et al., 2004; Van, 2007; Weng et al., 2004; Weng, 2009; Yamaguchi and Kato, 2007), and recently also by Czech researchers (Dobrovolný, 2013; Geletič and Vysoudil, 2012; Sedlák et al., 2010).

The absence of historical and recent meteorological data from stationary measurements is a common problem in urban climate studies. Therefore, in the second half of the 20th century mobile measurements began to be used systematically as a new method for obtaining operational meteorological data. Schmidt and Peppler may be considered as the founders of these methods, according to Yoshino (1975). The key work in the field of mobile measurements was presented by Sundborg (1950), whose contribution ranks highly among the methods of studying urban climate, i.e. mobile measurement using a thermometer placed on an automobile. The pioneer of these methods in Central Europe was undoubtedly the Czech climatologist Quitt (1956, 1972).

Oke (1987) states that these methods allowed a better definition and quantification of surface urban heat islands (SUHI) and atmospheric urban heat islands (AUHI). Mobile measurements also allowed UHI to be identified in smaller agglomerations, regardless of their areal extent (Kopec, 1970). They also made possible a detailed understanding of important processes in urban spaces, especially the energy balance (Terjung, 1970). The effectiveness of an integration of multi-level measurement methods, including mobile ones, and the use of different data sources (Hart and Sailor, 2009), has also been demonstrated.

Studies based on mobile measurements are frequent in Central Europe, as evidenced by the following examples. Unger et al. (2001) identified the time of the most prominent manifestation of the UHI in Debrecen (Hungary). The structure of the urban heat island of Ljubljana (Slovenia) was described by Jernej (2000). Mobile air temperature measurements were used to study the links between the fields of temperature, orography and type of active surface in Krakow (Poland) and its outskirts (Bokwa, 2011). Mobile measurement in a study of the influence of orography and spatial structure on the urban climate of the city of Košice and its surroundings (Slovakia) was employed by Šťastný (1996). Similarly, Polčák and Soták (2002) studied the climate of Banská Bystrica (Slovakia). In 2010–2012, mobile measurements and stationary measurements also took place simultaneously in the Czech Republic (Olomouc, Brno), where, for example, they enabled the point of origin of the potential climatic effects to be located (Vysoudil, 2010). A similar study was published by Dobrovolný et al. (2012), using the case of Brno (Czech Republic).

The lack of meteorological data from standard measurements is to some extent compensated by measurements from purpose-built networks of stations. The organisational and financial demands on measurements in purpose-built station networks often result in their being operated for only a short time. In Central Europe, such short-term measurements have been realised, for example, in Slovenia (Ljubljana), Austria (Graz), Poland (Krakow) and Hungary (Debrecen). The long-term existence of station networks suitable for the needs of urban climate studies is rather rare. One example in Central Europe is the network of urban stations in the Czech Republic (Vysoudil et al., 2012; Dobrovolný et al., 2012).

In recent decades, dynamic computerisation, increasingly sophisticated mathematical-physical and statistical methods, digital equipment and measurement technologies, have all contributed to the creation of numerical climate models (Kusaka et al., 2001; Lemonsu et al., 2004; Mills, 1997). Because of their increasing spatial resolution, they are applicable even at the level of the meso-, local and micro-scales, i.e. the spatial levels that are usual for the study of urban climate (Baklanov and Nuterman, 2009). Even the majority of the first 2D models from the period 1970–2000 enable city heat islands to be determined in a reliable manner.

Recently these models have been refined and 3D models are becoming standard. They are irreplaceable, especially for the study of urban circulation resulting from the complicated morphographies of urban relief (Bornstein et al., 1993; Yoshikado, 1992) and their spatial structures (Swaid, 1993). The most comprehensive models used in UHI studies use 3D parameters including the shapes of urban development, which allows the energy balance to be studied in detail and separately for individual parts of buildings both in relation to the actual active surface (2D) or to the adjacent layers of the atmosphere (3D): see Masson et al. (2002), Kusaka et al. (2001) and Souch and Grimmond (2006). Simultaneously, empirical models have been developed that are applicable for the study of relationships between cities and their surroundings (e.g. Haffner and Kidder, 1999).

Current models provide a tool for understanding the mechanisms of the formation of urban and suburban climates, including their mutual links, especially their energetic relationships (Masson, 2006). When modelling the urban climate in Central Europe, an often-used micro-scale numerical model is ENVI-met, mesoscale model WRF, and also 2D model MUKLIMO (Sievers and Zdunkowski, 1986), or its 3D version MUKLIMO-3 (Sievers, 1990, 2014). Many of today's models used layers or matrices for modelling. On the scale of a city, their use may be problematic as a result of the large spatial variability of the urban environment and the factors that affect it. Boufidou et al. (2011) therefore distinguish static factors (reflecting the nature and properties of surfaces and objects) and dynamic ones (measured using instruments). Both groups of factors and their role in the formation of urban climates have been described in detail, for example by Kay and Davies (2008) and Stewart and Oke (2009a, 2009b). The majority of current models have the capacity to be used in 3D modelling. A representative survey of modelling processes in the atmosphere at the meso-scale level (cities) is provided by Pielke (2013).

Currently, knowledge about radiation and energy balance seems to be necessary to understand the temperature field of cities and their surroundings. The findings on the energy balance of the city and the spatial structure of the urban atmosphere, as described by Oke (1987), are still applicable. Oke defined the so-called "urban canopy layer – UCL" as the ground layer of the atmosphere immediately above the active surface, with its upper limit approximately at the height of the roofs. Above the UCL, he defined the so-called "urban boundary layer – UBL", creating the urban boundary layer of the atmosphere. In the field of the energy balance of a city, Oke's work has been developed by many other researchers (e.g. Gleugh and Oke, 1986; Grimmond, 1992).

Following current views on the formation and nature of the urban climate, it cannot be described only on the basis of the values of measured elements. It must be observed in the context of the character of the surrounding geographic environment of the stations and specific local features. In the last two decades, the description and classification of urban climate has been based on the definition of urban climate zones (UCZ), or local climate zones (LCZ). The classification is based, among other things, on the standardisation of meteorological stations in purpose-built networks. One of the possible ways of standardising stations according to the structure of the city around them is the definition of LCZ elaborated by Stewart and Oke (2009, 2012). The current classification of LCZ suggested by Steward and Oke (2012) includes 10 classification parameters, including values of geometric and surface cover properties as values of thermal, radiative and metabolic properties. This approach to urban climate classification has been applied gradually in the (Central) European area (e.g. Houet and Pigeon, 2011; Lehnert et al., 2014; Savić et al., 2013; Unger et al., 2014).

Urban climatology includes application layers (urban planning, urban design, urban environmental adaptation, and others). The study of the impact of extreme weather conditions on the health of urban populations is currently very important, and not only in the context of global climate changes. Probably the most frequent topic is the impact of heatwaves, whose frequency has rapidly increased in Europe since 1990 (Solomon et al., 2007). The relationship between heat extremes and increased mortality of the urban population, combined with the UHI effect, has been described by many authors all over the world (inter alia: Gabriel and Endlicher, 2011; Páldy et al., 2005; Smoyer et al., 2000). It has gradually become clear that the risk group in connection with extremely high temperatures is the urban population, but on the contrary, that low temperatures represent an increased danger for the rural population (Conlon et al., 2011; Gómez-Acebo et al., 2010). The impacts of adverse weather conditions on health may be amplified by socio-economic and demographic factors (e.g. Hattis et al., 2012; Sheridan and Dolney, 2003; Wu et al., 2010). These factors are associated with increased mortality in urban populations at both the global and local levels (Dessai, 2002; Karl and Knight, 1997; Schär et al., 2004). Their manifestations and impacts in the Czech Republic can be found, for example, in the work of Huth et al. (2000), Kyselý and Dubrovský (2005), and Kyselý and Kříž (2008).

In the sense of the activities of the IAUC (International Association for Urban Climate), the current trends in urban climatology include the following research topics: (i) climate change mitigation and adaptation in urban environments; (ii) transfer of urban knowledge to urban planners; (iii) the study of urban climate; (iv) geospatial datasets; (v) new observational and modelling techniques and methods to study urban climates; (vi) bioclimatology and the public; (vii) urban design that takes climate into consideration; (viii) urban planning that takes climate into consideration; and (ix) an interdisciplinary approach.

Contextualized by these topics, this Special Issue is also related to the increased activities of Czech climatologists in the topic of urban climatology, and in the context of the research project: "*Multilevel analysis of the urban and suburban climate taking medium-sized towns as an example*" (Reg. CZ 205/09/1297). This research project was developed by means of an effectively close national collaboration in research on urban climate, with the idea of supporting international cooperation not only in the Central European area but also beyond.

The Editors of MGR consider this monothematic issue a contribution to the IX International Conference on Urban Climate, Jointly with the XII Symposium on the Urban Environment, held in July 2015 in Toulouse (France). In a broader sense, this Special Issue of MGR develops monothematic issues devoted to urban climate published in recent years in Central Europe in Geographia Polonica 2014, 87(4) and Geographica Pannonica 2013, 17(3).

When selecting articles, a preference was afforded to those papers that addressed some of the major problems in modern urban climatology.

In the first three articles, the authors represent more strictly areas of research in climatology. In the first paper, Petr Dobrovolný and Lukáš Krahula investigate the spatial variability of air temperature and nocturnal urban heat island intensity in the city of Brno, Czech Republic, with respect to a number of factors such as altitude, quantity of vegetation, density of buildings and the structure of the transportation (road) system. The main information sources consist of mobile air temperature measurements and a relevant geographical database.

The second article presents a comparative case study of air temperature in three major urban settlements in Italy, Slovenia and Croatia, using 100-year trends, evaluated by Darko Ogrin. Differences in trends between Ljubljana (Slovenia) and Zagreb (Croatia) result in part from different measurement histories, but the impact of urban climates is also presented. The lowest air warming trends occur in the maritime climate of Trieste (Italy), where measurements were continuously performed in the densely built-up section of the city.

In the third paper by Katja Vintar Mally and Matej Ogrin, the data from two measuring campaigns throughout the city of Ljubljana (Slovenia) during the summer of 2013 and the winter of 2014, were used for an analysis of spatial variations of NO_2 concentrations. Since the main source of NO_2 in Ljubljana is road transport, three types of urban space have been identified (urban background, open space along roads, and street canyon), and their NO_2 pollution levels were measured using Palmes diffusive samplers at a total of 108 measurement points. The results of both measuring campaigns allowed a precise estimation of the pollution levels of different types of urban space.

The subsequent four papers represent broader aspects of climatological research in East Central Europe, with work related to urban areas. The paper by Márton Kiss, Ágnes Takács, Réka Pogácsás and Ágnes Gulyás presents the problems of natural system responses to reducing pollution in urban space. The effects of differences in tree management on the chosen ecosystem services were investigated by comparing two pairs of tree alleys in the town of Szeged (Hungary).

A contribution to the topic of social system responses to the specific climate in urban space is presented in the article by Hana Středová, Tomáš Středa and Tomáš Litschmann, which deals with role of smart tools of urban climate evaluation for smart spatial planning. Data over the period 2011–2014 were collected, analyzed, and used for comparison and modelling purposes. As commonly accepted, the use of standard climate information has a low priority for urban planners. Hence, the authors calculated the HUMIDEX index, as information that could be more understandable with respect to temperature conditions for urban planners.

On a related topic, Dalibor Výberči, Marek Švec, Pavol Faško, Henrieta Savinová, Milan Trizna and Eva Mičietová explore heat-related human mortality for the total population, as well as within selected population groups, in Slovakia over the period 1996–2012, for the case of summer heat events. This paper is one of the first of its kind focusing on the given population and sub-groups in Slovakia.

The final paper in this Special Issue is by Lívia Labudová, Pavol Faško and Gabriela Ivaňáková, who discuss some of the larger-scale changes in different climatic regions for the case of Slovakia. Most studies comparing recent climate conditions to the past, use as the reference period the years from 1961 to 1990. In this article, the authors to point out the probable characteristics for the next reference period from 1991 to 2020. Finally, changes in the climate regions in Slovakia are analysed, comparing the spatial distributions in both reference periods.

The articles presented in this Special Issue illustrate both the theoretical and empirical aspects of urban spaces and their specific climates. In summary, the global climate is changing and this reality is reflected in the changes in urban climates, which also contribute to global changes.

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The spatial variability of air temperature and nocturnal urban heat island intensity in the city of Brno, Czech Republic

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Abstract

This study seeks to quantify the effects of a number of factors on the nocturnal air temperature field in a medium-sized central European city located in complex terrain. The main data sources consist of mobile air temperature measurements and a geographical database. Temperature measurements were taken along several profiles through the city centre and were made under a clear sky with no advection. Altogether nine sets of detailed measurements, in all seasons, were assembled. Altitude, quantity of vegetation, density of buildings and the structure of the transportation (road) system were considered as explanatory variables. The result is that the normalized difference vegetation index (NDVI) and the density of buildings were the most important factors, each of them explaining a substantial part (more than 50%) of overall air temperature variability. Mobile measurements with NDVI values as a covariate were used for interpolation of air temperature for the entire study area. The spatial variability of nocturnal air temperature and UHI intensity in Brno is the main output presented. Air temperatures interpolated from mobile measurements and NDVI values indicate that the mean urban heat island (UHI) intensity in the early night in summer is at its highest (approximately 5 °C) in the city centre and decreases towards the suburban areas.

Keywords: *urban heat island, mobile measurements, air temperature, Brno, Czech Republic*

1. Introduction

The urban heat island is possibly the most important specific characteristic of urban climate, a phenomenon that relates to the higher temperatures that prevail in urban areas compared to the surrounding rural environment (Arnfield, 2003). No matter how the intensity of UHI is defined (Stewart, 2011), the same general set of factors create UHI and influence its intensity. Local geography, prevailing categories of land use and their spatial distribution, the thermal properties of materials used for surfaces and buildings, the geometry of the constructions themselves, and anthropogenic heat production are among the most important of these (Landsberg, 1981; Oke, 1981; Grimmond, 2006). The role and importance of individual factors may differ significantly from city to city, however, depending on geographical position, size, number of inhabitants, etc. More specific knowledge of the most important factors impacting upon UHI intensity may contribute significantly to mitigation of its negative effects. Such effects are largely related to the occurrence of heat waves that may be of longer duration and more intense in an urban climate, with direct impacts on human health (Kyselý, 2010; Dousset et al., 2011), including increasing urban fatalities (Peng et al., 2011; Laidii et al., 2012).

Air temperature in urban areas and UHI intensity vary widely in time and space. Whereas the highest positive intensity of atmospheric UHI occurs during the night, UHI may be weakly expressed during daylight hours, or even negative, due to shadowing effects (Hart and Sailor, 2009). Other factors, however, such as land-cover and availability of soil moisture may contribute to negative UHI (Georgescu et al., 2011). The spatial distribution of air temperatures in urban areas is highly complicated, as is the spatial structure of UHI intensity. Most of the factors that modify energy balance and air temperature conditions in cities arise out of the highly different thermal properties of the urban environment relative to its natural surroundings. Improved knowledge of the spatial distribution of air temperature in urban areas and UHI intensity may be achieved by consideration of two elements in particular: spatially-detailed air temperature measurements, together with a detailed spatial database of the factors affecting urban air temperatures.

Standard meteorological measurements, even supplemented by special-purpose measurements from a dense network of automatic stations, often prove insufficient to describe and understand fully the spatial variability of air temperature in urban areas (Hart and Sailor, 2009; Dobrovolný and Krahula, 2012). Some of the limitations of stationary measurements may be overcome by various types of mobile measurement made by thermometers attached to vehicles. The first systematic mobile measurements were taken in Vienna as early as 1927 (Yoshino, 1984). These methods were further developed in Sweden (Sundborg, 1950), and in Czechoslovakia, Quitt (1972) used thermometers mounted on automobiles and trams to record air temperature variability in the city of Brno (now the Czech Republic). Recently, Unger et al. (2001) and Bottyán et al. (2005) used mobile measurements to investigate temperature conditions in the Hungarian cities of Szeged and Debrecén. Hedquist and Brazel (2006) compared the results of stationary and mobile temperature measurements in Phoenix, Arizona (USA). Hart and Sailor (2009) analysed the spatial variability of air temperature in terms of both land use and a number of surface characteristics in Portland (USA) by means of regression trees applied to the results of

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mobile measurements. Mobile campaigns have a particular advantage over a network of stations when analysing the spatial variability of urban climate, since mobile traverses provide a significantly higher density of measurements and thus offer better initial conditions for more precise spatial interpolation. The higher number of measuring points is rendered all the more valuable in urban environments of high heterogeneity.

In this contribution, mobile temperature measurements taken in the medium-scale city of Brno are analysed. The study aims to establish the main factors that correlate with air temperature measurements; the air temperatures and these covariates are then used to construct the urban temperature field. Finally, the nocturnal UHI intensity in the study area is estimated.

2. Study area and data

The study area is situated in the south-eastern part of the Czech Republic (Fig. 1). Brno (49.2N, 16.5E) is the second-largest city in the country (population 400,000, cadastral area 230 km^2), and is characterized by a basin position with complex terrain. Altitudes range from 190 m to 479 m, with the higher elevations lying largely in the western and northern parts of the region. Lower and flatter terrain is typical of the southern and eastern parts of the study area. There is a large water reservoir (area approximately 2.6 km^2) located on the north-west border of the built-up part. The study area lies in one of the warmest and the driest regions in the Czech Republic. Mean annual temperature stands at 9.4 °C, while mean annual precipitation is around 500 mm (1961–2000 reference period).

The city's location at the confluence of two rivers and a complex relief with several deep valleys and hills predispose the area to a complicated spatial distribution of land-cover categories. The highest density of built-up areas occurs in the historical city centre. These are largely residential (20% of the cadastral area). There are several industrial zones and large shopping centres with high percentages of impervious surfaces (area almost 14% of total). Several large parks are located relatively close to the city centre. Further from the centre, individual land-cover categories form a mosaic of different surface types, such as blocks of flats, gardens, allotments and agricultural fields. Arable land and grasslands cover 34% of the study cadastre and are situated mostly in the south, while forests take up 29% of the cadastre and are to be found largely west and north of the built-up area, at higher elevations. Percentages of individual land use categories were calculated from interpreted LANDSAT satellite imagery at an original spatial resolution of 30 m (Dobrovolný, 2012).

Mobile air temperature measurements were taken along a number of profiles that ran though the city centre and also in various suburban environments (Fig. 1). Altogether, nine sets of measurements were made between April 2011 and January 2012, covering every season. Each set of measurements was around 90 km in length and lasted 3.5 hours. Elevation varied along the profile from 200 m to 410 m. Since the most distinct air temperature differences between urban and rural environments start to build up in the early hours of the night (Oke, 1981; Alcoforado and Andrade, 2006; Fortuniak et al., 2006), measurements were taken at this time. A special resistance thermometer, featuring a NiCr-Ni sensor with a rapid response time of 0.8 second for up to 90% of temperature change, was employed. The sensor was mounted on the left of an automobile, on the roof, approximately 1.8 m above ground level. Air temperature was recorded every five seconds. At a mean vehicle velocity of 30–40 km.h^{-1} and in view of the length of the profile, each set of measurements comprised approximately 2,000 temperature readings taken at 40–50-metre intervals. The precise position of the automobile was recorded by GPS synchronized with the thermometer over time.

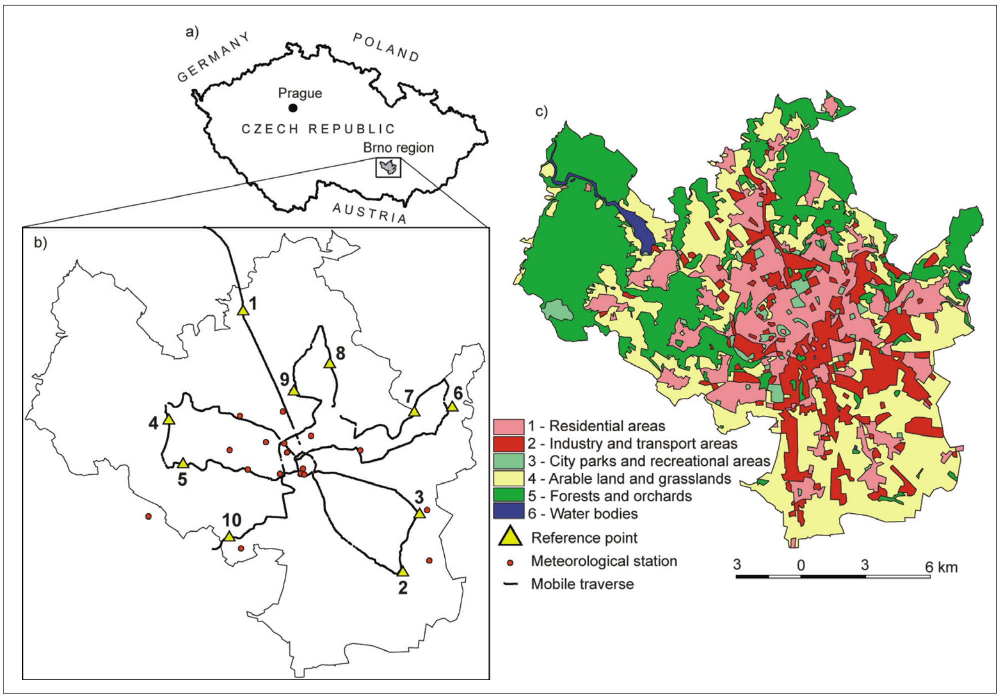

Fig. 1: Study area: a) position of Brno in the Czech Republic; b) route followed when taking mobile measurements; c) main land cover categories. Triangles 1–10 mark the beginning/end of sections with prevailing character of land cover type and serve for orientation within the measurement profiles (see Fig. 2).
Source: authors' calculations

3. Methods

Raw measured air temperature data and GPS coordinates were pre-processed to suppress possible sources of noise. First, the general drop in temperature over time that occurred during the period of measurement was controlled for, using 10-minute-interval temperature readings from 16 special-purpose meteorological stations located in the Brno area (Fig. 1, selected stations – see Fig. 2 in cover p. 2). Station temperature measurements were taken at two metres above ground level, slightly higher (0.2 m) compared to the mobile measurements. A simple linear regression equation was fitted to each station air temperature at the time mobile measurements were being taken. The slopes of the regression lines for all stations were averaged and the mean regression coefficient then represented mean temperature drop per time unit (correction factor). By multiplying raw measured temperatures by time interval from the beginning of the mobile measurements, and using the correction factor, we conrolled for any general drop in temperature over time. One may assume that there may be a strong vertical gradient on quiet nights that may introduce differences between mobile and station measurements. As the slope of the regression line was used as a correction factor and not absolute temperature values, however, the above-mentioned 0.2 m height difference should not influence the results. Precise coordinates from GPS measurements were used to remove all temperature readings that had been taken at obligatory stops at traffic lights and crossroads, which might have been influenced by surrounding traffic, or were otherwise rendered redundant. Because certain GPS measurements proved impossible for a number of segments near the city centre with tall buildings, these were interpolated by calculations from the number of temperature readings and the topographical map. Finally, time-corrected temperatures were smoothed with a 3-point average filter to further suppress noise related to the high sensitivity of the sensor and random influences from the surrounding environment.

The factors that affect air temperature variability in the urban environment were described in terms of four variables. The degree of urbanization and extent of impervious surfaces were expressed as density of buildings (BUILD) and density of roads (RDS). The normalized difference vegetation index (NDVI) quantified the occurrence of natural pervious surfaces. The natural environment was also characterized by altitude (ALT). These parameters were included because they have been used successfully in similar studies (see for example: Unger et al., 2001; Bottyán et al., 2005; Hart and Sailor, 2009). Moreover, these parameters cover the study area continuously, which is important for subsequent spatial interpolation of an urban temperature field. Other parameters, such as anthropogenic heat and sky view factor, were not included since their values were available for only a few locations. The study area was divided into a regular grid of 300 × 300 m and values for the above factors were calculated for each 300-m grid cell. The ZABAGED geographical database, provided by the Czech Office for Surveying, Mapping and Cadastre (www.cuzk.cz), a digitalized topographical map at 1:10 000 scale, was employed for input data. The density of buildings was expressed as a percentage derived from the ground plan area of buildings in each grid cell. Similarly, RDS consisted of the overall area of the roads in each grid cell. NDVI was calculated from available LANDSAT TM satellite imagery, combining visible red and near-infra-red bands in a standard formula that may be found elsewhere (Dobrovolný, 2012). Because NDVI is a suitable measure of the quantity and vigour of vegetation, it is frequently used in urban climate studies to characterize the spatial distribution of pervious natural surfaces in a city environment (Dousset et al., 2003; Weng, 2009). The mean elevation of each grid cell (ALT) was calculated from an elevation model derived from the topographical map.

The size of the grid (300 m square) was chosen with reference to similar studies. According to Oke (2006), the circle of influence of environmental parameters, such as building density, upon temperature measurements may have a radius of about 0.5 km, depending on local conditions. Unger (2004) characterized relationships between surface geometry and the urban heat island in Szeged (Hungary) with a 500-m grid, and Hart and Sailor (2009) quantified the influence of land-use and surface characteristics on urban temperatures in Portland (USA) using a 300-m grid. Sampling at a 300-m grid size was also selected for this study in view of the relatively high heterogeneity of the environment, especially in the suburbs (Fig. 3).

To evaluate the relative importance of individual factors for the spatial variability of air temperature, corrected temperatures from mobile measurements were aggregated to the same 300-m grid. Mean temperature for each 300-m grid cell through which the measurement profile passed was calculated as a simple arithmetical mean from all temperature readings performed within this grid-cell. The degree of temperature variance explained by individual factors was assessed by correlation analysis. Significant covariates were further used for spatial interpolation using geostatistical methods. The compiled air temperature fields were transformed to temperature anomalies that facilitated calculation of the intensity of UHI. As there was a clear correlation structure within some of the factors under consideration, their combinations and/or their principal component (PC) transformations were also tested for the extent of explained variance and for air temperature field construction.

4. Results

As follows from Table 1, each measurement campaign took place after sunset during the first half of night, in radiation-driven weather conditions. These were characterised by an almost clear sky, minimum cloud cover, and weak advection (Tab. 1). Such conditions are generally favourable to UHI formation. All four seasons were covered with at least two campaigns, providing a broad range of temperature regimes within the study area. Mean air temperatures during traverses varied from – 8.0 °C at the end of January to 22.0 °C in July. While relative variability was at its lowest in summer, it was highest in November and January. Air temperatures along the profiles varied by 5.0 °C–6.0 °C in the winter months and by more than 10.0 °C in July.

In spite of very different temperature conditions for individual days, several common features emerged from the temperature records from all campaigns (Fig. 4). In particular, three air temperature profiles from the first three segments (1–2, 3–4, 5–6), which traversed the city centre, exhibit the convex shapes typical of positive UHI, with higher temperatures in the city centre and distinctly lower temperatures in suburban areas with higher percentages of natural surfaces. Conversely, segments traversing typically rural conditions (2–3, 4–5, 6–7) exhibited lower temperatures. The minimum temperatures for each period were recorded at the beginning of the route,

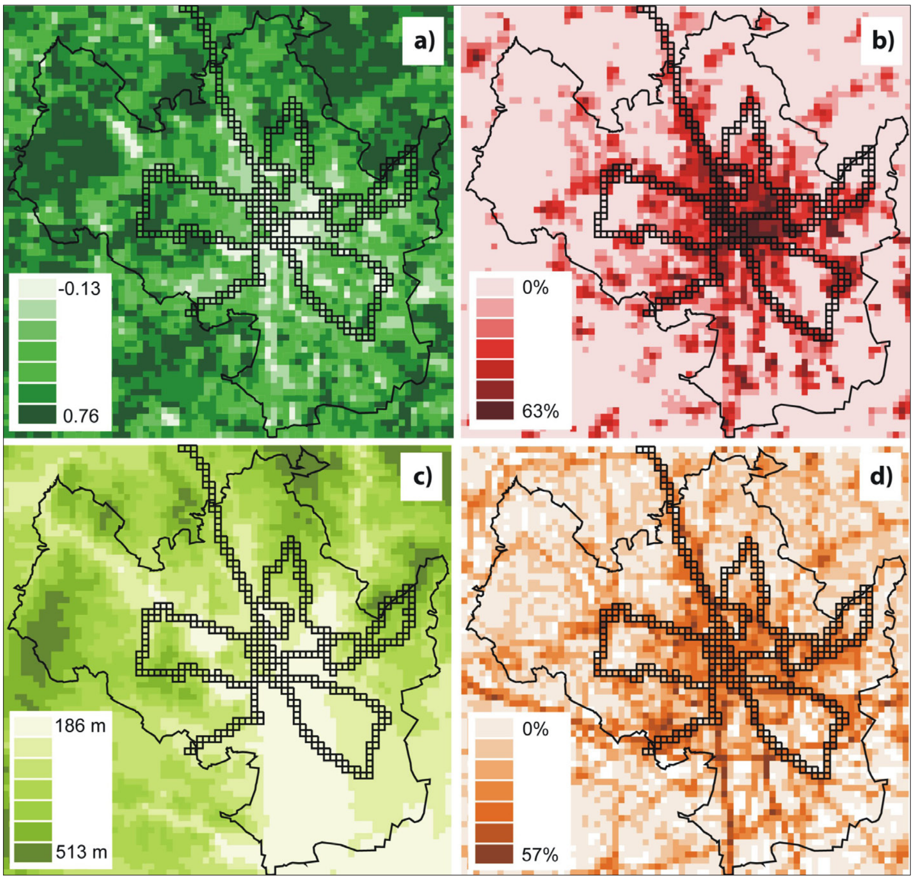

Fig. 3: Spatial distribution of selected factors affecting air temperature variability in the Brno area: a) Normalized difference vegetation index (NDVI); b) density of buildings (BUILD); c) altitude above sea level (ALT); d) density of roads (RDS). The solid black line delimits the Brno cadastral area. Source: authors' calculations

Day	Time (h:min)	Cloud cover [tenths]	Wind speed [m.s^{-1}]	Wind direction [deg.]	t_{avg} [°C]	t_{min} [°C]	t_{max} [°C]	t_{range} [°C]	SD** [°C]	CV** [%]
19.4.2011	20:31–23:28	1	4	360	13.5	7.5	16.4	8.9	1.5	11.1
9.5.2011	20:15–23:04	0	3	30	16.2	10.3	19.5	9.2	1.9	11.8
8.7.2011	20:58–23:54	1	3	60	22.0	16.3	26.0	10.6	1.6	7.2
3.8.2011	20:21–23:40	1	3	40	21.1	15.8	24.0	8.2	1.4	6.8
13.9.2011	20:12–23:03	2	1	260	21.2	15.6	24.5	8.9	1.6	7.7
27.9.2011	20:03–23:19	1	1	350	17.3	12.6	20.0	7.4	1.5	8.6
1.11.2011	20:28–23:53	1	2	70	5.7	1.9	8.4	6.4	1.2	21.6
3.1.2012	20:11–23:28	4	2	180	3.6	0.1	5.1	5.0	0.8	22.4
31.1.2012	20:24–23:54	0	1	70	– 8.0	– 12.2	– 5.6	6.5	1.0	12.2

*Tab. 1: Basic information related to individual mobile measurements recorded in the Brno area**
Source: authors' calculations
*Notes: *The time period refers to Central European Summer Time; data on cloud cover, wind speed and wind direction are means for the time period of the traverses recorded at the meteorological station at Brno, Tuřany airport. ** SD – standard deviation; CV – coefficient of variance*

the farthest segment of the route from the urban area, and especially at the end of the route (beyond point No. 10 in Fig. 4). Here the lowest temperatures are related to the basin position of the locality and to conditions favourable to the characteristic formation of a 'lake' of cold air.

As higher air temperatures are related to lower positions (and vice versa) along the urban parts of the route, however, there appears to be a negative correlation between temperature and height above sea level. Variability of air temperature in this part of the study area is a typical example of mutual interactions in complex orography and urban/rural land cover, forming either hot or cold spots in the urban temperature field. More detailed quantification of these effects, however, would need more detailed measurements including vertical temperature profiles.

The importance of individual factors for air temperature variability was estimated by correlation analysis (Fig. 5). NDVI emerged as the most important factor, especially in spring and summer, when it explained 20%–50% of air temperature variability. Although the importance

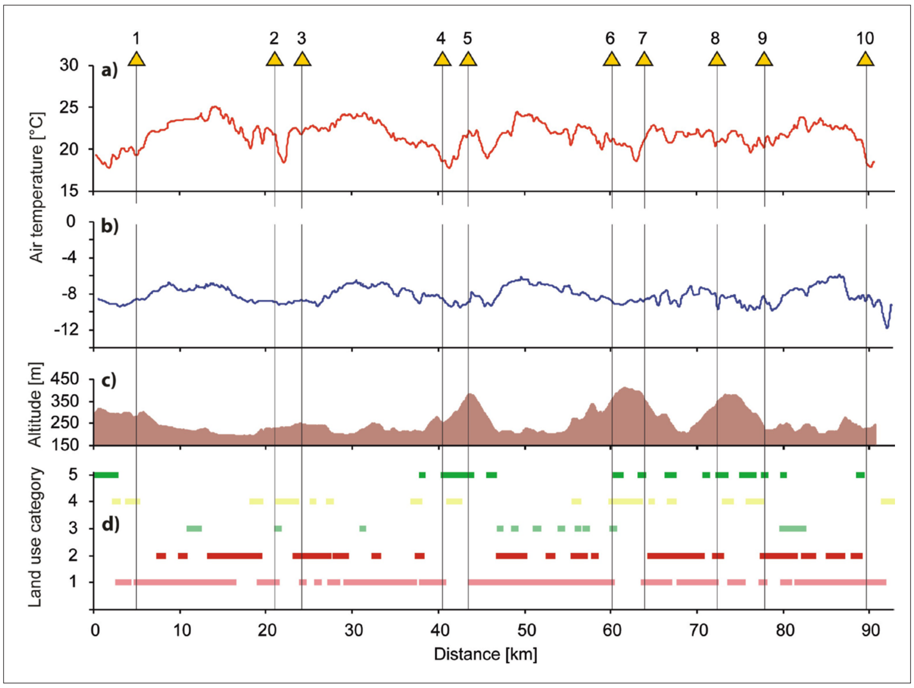

Fig. 4: Air temperature variability along mobile transects: a) 8 July 2011; b) 31 January 2012; c) elevation profile; d) distribution of main land use categories. Verticals 1–10 indicate the positions of reference points from Fig. 1: see Fig. 1 for land use categories. Source: authors' calculations

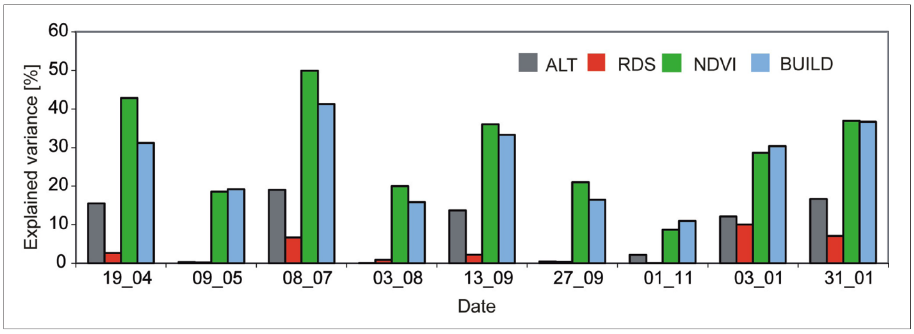

Fig. 5: Air Temperature variability explained (r^2) in terms of: height above sea level (ALT); density of roads (RDS); normalized difference vegetation index (NDVI); and density of buildings (BUILD), in the Brno area in nine different periods from April 2011 to January 2012.

of the BUILD parameter increased in winter, r-squared coefficients (r^2) for NDVI and BUILD were comparable even in winter (30%–40%). The correlation between air temperature and percentage of roads (RDS) was low and generally non-significant. This may be related to the fact that RDS represents only a fraction of the impervious surfaces and its spatial distribution does not reflect the degree of anthropogenic transformation well, compared to the BUILD parameter. High or low RDS values may be found in different parts of the study area depending on the spatial configuration of the transportation system. Ambiguous results were found for altitude (ALT). There were high and significant negative correlations in five measuring terms; however, the amount of explained temperature variance was less than 20% in all terms.

The results of the correlation analysis demonstrated that the two most important factors are the quantity of vegetation and the percentage of built-up areas. Relatively high and significant correlations also facilitate the construction of a regression model conducive to air temperature interpolation from NDVI values, since NDVI covers the whole study area. Even though the mobile temperature measurements provide relatively good coverage, especially in the centre of the study area, interpolation based on only mobile temperature measurements would be partly biased, especially farther from the city centre. In order to overcome this bias and utilize the correlation analysis results, NDVI was used as a covariate within co-kriging of spatial interpolation. Co-kriging is a geostatistical approach to interpolation that makes for better estimation of the values of the main variable of interest (in this case, air temperature) if the distribution of one or several secondary variables is known more precisely due to, for example, better sampling (Cressie, 1993). In co-kriging, autocorrelation of the main variable of interest and all cross-correlations between the main and secondary variables are used to make more reliable predictions.

In the first step, mobile temperature measurements aggregated to the 300 grid cells were standardized to z-scores of zero mean and unit variance. This was done for all nine measurement terms analysed. Standardization allowed direct comparison of temperature measurements taken in different seasons under different temperature regimes. After this, standardized values from individual terms were interpolated using co-kriging and the NDVI map as the most significant covariate. Finally, all nine interpolated fields were averaged to a single map (Fig. 6).

A typical air temperature distribution places the highest values in the central part of the city with the least vegetation cover and highest density of buildings. Temperatures drop radially, in general, from this core towards peripheral areas. The decreasing trend is less marked towards the north and east, in parts of the city with a relatively higher density of surfaces of anthropogenic origin. The lowest values occur in the western part of the study area, where elevations are higher and a higher proportion of natural surfaces prevails. Relatively lower z-scores occur in the deeper valleys not far from the central part of the study area. Markedly higher values are related to densely-populated suburbs even when these are situated at relatively higher elevations than the central part of the city. The mean spatial distribution of air temperature (Fig. 6a) is completed with the mean variability computed from all measurement campaigns as well (Fig. 6b), and this map may partially validate our model. Less variable and thus more precise air temperature estimates are typical for the city centre, while higher variability occurs on the periphery.

The mean distribution of the z-scores from Fig. 6, presenting the relative variability of air temperature, may be combined with the real temperature regime disclosed by mobile measurements (summarized in Table 1). The two pieces of information may then be used for estimation of the typical temperature distribution during the evening hours and also to establish UHI intensity in the Brno area. As follows from Table 1, three out of nine campaigns (July 8, August 3, and September 13) took place in hot weather, when mean temperatures measured along the profiles reached 21 °C–22 °C, with non-significant differences in temperature variability in terms of an F-test (standard deviations ranged between 1.4 °C and 1.6 °C). Moreover, the main features of the synoptic situation during these three periods were associated with a low-pressure system over Western Europe, contributing to the transport of relatively warm air to central Europe from the south-west. Such situations, especially when they are prolonged by a blocking anticyclone in central and Eastern Europe, are favourable to the occurrence of hot days in central Europe and to the formation of UHI in urban environments. Z-score maps from the three periods were averaged and transformed back to real temperatures using 21.5 °C as a mean and a standard

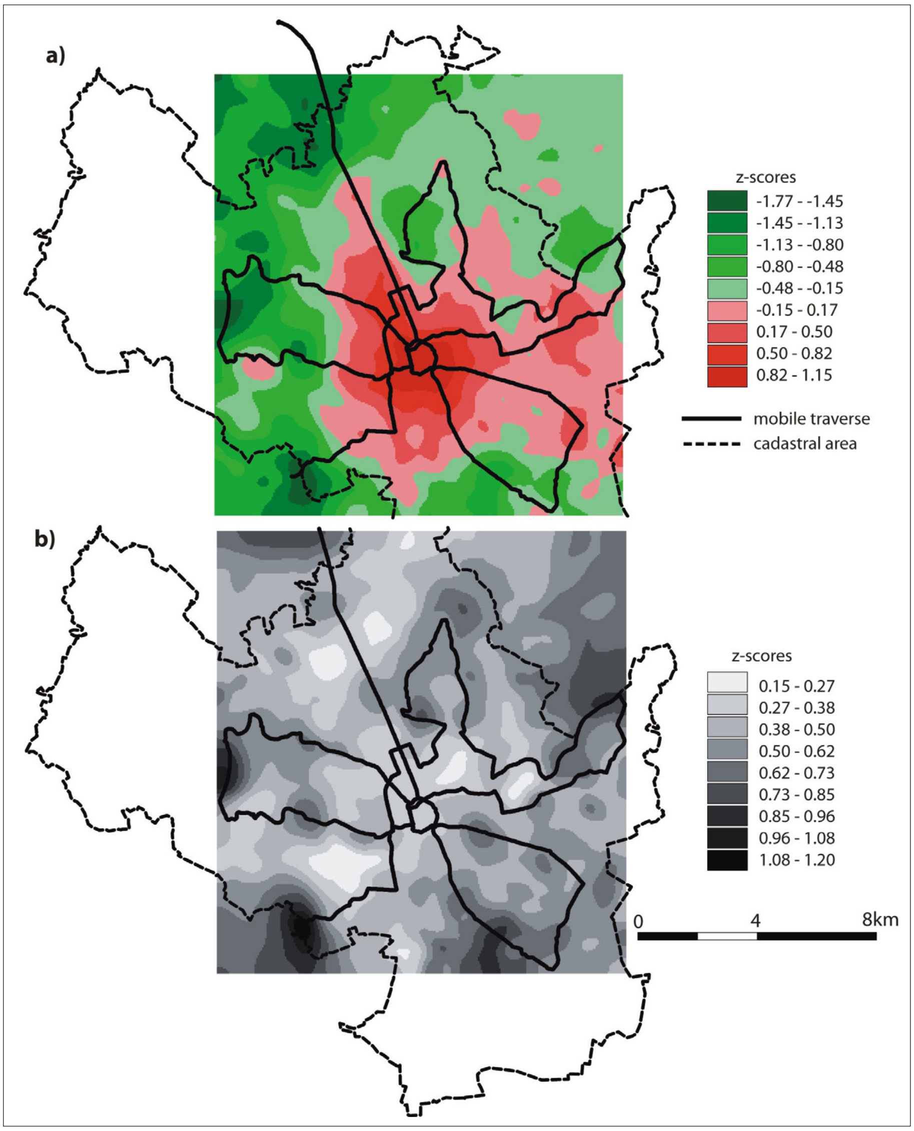

Fig. 6: a) Spatial distribution of early-night air temperatures in the Brno area (calculated as a mean from nine mobile measurements); b) Temperature variability. Interpolated temperatures and their variability are expressed in the form of standardized values (z-scores). Source: authors' calculations

deviation of 1.5 °C. The resulting map was expressed in the form of temperature anomalies calculated as the difference between temperatures of individual grid-cells in the whole study area and the mean temperature of all grid-cells outside the cadastral area, representing the rural environment; the cadastral area is shown in Fig. 3. This map (Fig. 7) may be considered as an assessment of UHI intensity that occurs during the evening hours on typically hot days in the summer in the Brno area.

The overall features of the spatial distribution of temperature anomalies in summer are largely identical to those presented in the form of the mean field constructed for all nine mobile measurements in Fig. 6. The highest temperatures concentrate around the city centre and extend from there towards the north-west. Local maxima are clearly distinguishable for most of the suburbs. The lowest values occur in a number of spots in the western part of the Brno area. Calculations derived from the temperature anomalies indicate that the city centre may be around 2 °C warmer than the peripheral parts and about 5 °C warmer than rural areas in the immediate environment.

5. Discussion

Carefully pre-processed temperature measurements and a relatively detailed spatial dataset for four different variables allowed us to evaluate the effects of the latter factors on the spatial variability of air temperature in a medium-sized city in central Europe. Our results are in agreement with similar studies that conclude that the quantity of vegetation (represented by NDVI), and partly the percentage of built-up areas, are the most important factors affecting the spatial distribution of air temperature in urban areas (Unger et al., 2011). The crucial influence of vegetation cover on the spatial variability of air temperature within an urban environment has been confirmed, for example, by Hedquist and Brazel (2006). They used a Soil Adjusted Vegetation Index rather than NDVI for analysis of the temperature field in Phoenix (Arizona). According to Hart and Sailor (2009), canopy cover represented by NDVI was the primary factor in a tree-structured regression model for UHI intensity estimate in the Portland (Oregon) metropolitan area. More relevant results for direct comparison with this study may be found for Szeged (Hungary). Bottyán et al. (2005) used NDVI as a key factor in categorising the main land-cover influences on forming UHI intensity, but they did not quantify the role of NDVI directly.

As the vegetation distribution in cities may be mapped relatively easily and repeatedly from remotely-sensed data, this finding may have important consequences for practical applications in urban climatology, such as the identification of hot-spots and the prediction of air temperature. It may also help to optimize processes in regional planning. Areas with low vegetation (lowest NDVI values) and densely built-up areas (highest BUILD values) clearly highlight the warmest parts of the city. Moreover, their spatial distribution agrees with an analysis of the spatial distribution of land surface temperatures and with surface urban heat island intensity derived from satellite thermal imagery (Dobrovolný, 2012).

In this study, we placed emphasis on making the best possible use of information concerning the extent of impervious areas, combining two original variables (density of buildings and density of roads) into one. This new variable, however, does not provide a higher percentage of explained variance in comparison with the original variables. The sum of built-up areas and road areas explained from 15% to 38% of air temperature variability. Further improvements in UHI estimates in the near future may consider other factors that characterize the geometry of constructions (Dobrovolný and Krahula, 2012).

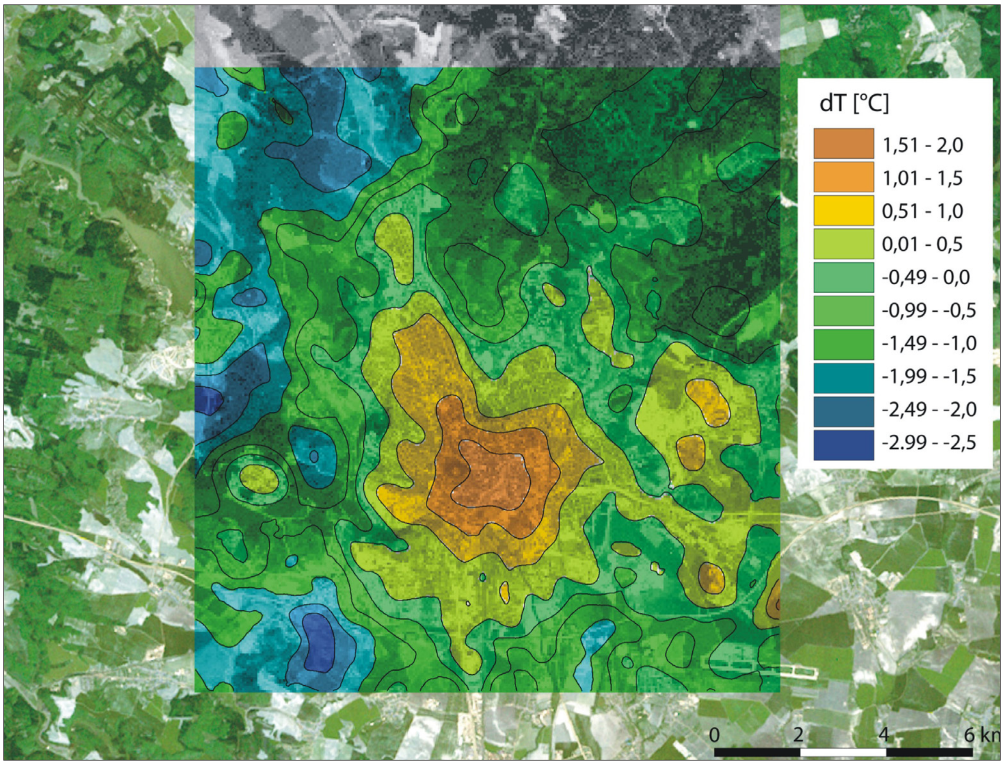

Fig. 7: Spatial distribution of air temperature in the central part of the Brno area in the early night hours: Air Temperature is expressed as deviation (dT) from the mean value of the study area. It is typical of clear, calm weather in the course of a hot day in summer. Source: authors' calculations

A closer look at our correlation analysis reveals that there exists a clear correlation structure between the explanatory variables used in this study. There exists a highly significant negative correlation between NDVI and BUILD as explanatory parameters. Similarly, there is a significant positive correlation between BUILD and RDS because both measure the degree of anthropogenic influence on local climate. To utilize these cross-covariances, we transformed the original variables to principal components (PC) and tested their relationship to air temperature variability. This type of explanatory data transformation, however, did not provide better correlations to air temperature compared with NDVI. This implies that our air temperature interpolation, based on NDVI values, provided an optimal result considering the available geographical database. Moreover, the simple model of temperature field construction satisfies the principle of parsimony and thus avoids the multicolinearity problem that is typical of multiple regression models. Clearly one source of uncertainly in our approach may be related to the size of the grid employed for unification of all data sets to the same spatial resolution. The 300-m grid may partly smooth local effects and influence correlations. However, this value is comparable to, or even finer than, the grid sizes used in similar studies (Oke, 2006; Unger, 2004; Hart and Sailor, 2009). The relatively weak effect of altitude on air temperature variability suggests that the role of natural factors may be partly suppressed by anthropogenic factors. Moreover, even in the complex terrain of the Brno area, altitudes vary within a relatively low range (less than 250 m), rendered even lower in the 300-m grid resolution. Thus the low variation in altitude hampers the establishment of a strong signal.

6. Conclusions

Improved knowledge of the effects of selected geographical factors on the spatial variability of air temperature facilitated the use of interpolated air temperature maps for estimation of the UHI intensity that may occur during the early night hours of a typical summer day-cycle. As discussed in Stewart (2011), figures for UHI intensity depend strongly on the methodology used for UHI identification and for its estimation. As our estimate is based on an interpolated temperature field and not on individual sites, this may be considered as a robust feature of this contribution. Our estimate of UHI intensity may also be considered conservative, since it is derived from partly-smoothed data. The instantaneous temperature ranges measured in the course of individual campaigns were mostly higher, reaching 8 °C–10 °C in total in five time periods. The results of this study may be used in various decision-making processes on the part of the Brno city authorities, particularly in the fields of urban planning and regional development, and in various programs addressing urban ecology and the quality of life, especially health.

According to the Fifth Assessment IPCC Report, more frequent and more intense extreme events such as heat waves can be expected in the near future in response to recent climate change (IPCC, 2013). Intensity and duration of heat waves may be further enhanced due to the UHI effect in urban environments, and thus heat waves may have negative impacts, especially on city dwellers. At the same time, the IPCC Report attributes only medium or low confidence to expected future changes in extremes, because of a lack of studies together with data quality issues. This means that many more case studies in various urban areas, based on special-purpose air temperature measurements and detailed geographical databases, are needed. Our study identifies factors that significantly contribute to higher air temperatures, describes spatial and temporal parameters of UHI formation, and finally it estimates UHI intensity in a typical medium-sized central-European city. In summary, we believe that our findings may contribute to a better understanding of urban climate processes and extreme events under recent climate change.

Acknowledgement

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Long-term air temperature changes in Ljubljana (Slovenia) in comparison to Trieste (Italy) and Zagreb (Croatia)

Darko OGRIN [a*]

Abstract

The cities of Ljubljana, Trieste and Zagreb are proximate in terms of distance but differ in terms of geographical and climatic conditions. Continuous meteorological measurements in these cities began in the mid-19th century. The 100-year trends of changes in mean annual and seasonal air temperatures for these cities are presented here, evaluating the differences between them which result from their different geographical and climatic positions. Differences in trends between Ljubljana and Zagreb that result from different measurement histories and the impact of urban climate are also presented: the impact of city growth on air temperatures in Ljubljana after 1950 was not completely eliminated in the process of data homogenization. The lowest air warming trends occur in the maritime climate of Trieste (mean annual air temperature: + 0.8 °C × 100 yr^{-1}), where measurements were continuously performed in the densely built-up section of the city. The strongest trends occur in Ljubljana, mainly due to city growth (mean annual air temperature: + 1.1 °C × 100 yr^{-1}). Comparing the linear trends in Zagreb-Grič and in Ljubljana, the impact of Ljubljana`s urban heat island on the 100-year warming trend was assessed at about 0.2 °C, at 0.3–0.4 °C for the trend after 1950, and if non-homogenized data are used, at about 0.5 °C.

Keywords: *climate change in the instrumental period; long-term temperature trends; urban heat island; Ljubljana (Slovenia); Trieste (Italy); Zagreb (Croatia)*

1. Introduction

During the last 25 years, much attention has been devoted to historical climatology, which investigates climates of the past. One of the main reasons for this increased interest can certainly be sought in contemporary global and regional climate changes and oscillations, manifested in various ways. In Slovenia, for example, such changes began to occur towards the end of the 1980s, initially as green and mild winters, then followed by a period of very hot and dry summers, and recently, in addition to a general increase in temperatures, an ever greater frequency of exceptional weather events has been observed. In order to properly evaluate these events – to establish whether they already anticipate a changed climate or whether they are just the result of normal weather and climatic variability, and to prepare scenarios of the future climate and its (possible) impacts on natural and social environments - it is necessary to be intimately acquainted with the history of the climates, both in the pre-instrumental period and in the instrumental period, for which measurement and observational data from meteorological stations are available.

To establish the changeability of climate in Slovenia during the instrumental period of over one hundred years, four meteorological stations can primarily be taken into account. Two of them have been operated on Slovenian territory, i.e. Ljubljana and Maribor, and two in the direct vicinity, i.e. Trieste and Zagreb. These stations began with measurements and observations in the mid-19th or the second half of the 19th century and have collected continuous series of data of sufficient quality. Temperature and precipitation data have been collected in Trieste since 1841, in Ljubljana since 1851, in Zagreb since 1862, and in Maribor since 1876. Trieste exemplifies very well climatic changes in Slovenian areas with moderate Mediterranean climate, while for Ljubljana areas with the sub-Alpine variety of the moderate continental climate of central Slovenia, and Maribor and Zagreb exemplify the moderate continental climate of east Slovenia (sub-Pannonian climate) (Ogrin, 1996; Ogrin and Plut, 2009). Measurements in the mountainous regions began only after World War II, e.g. at Kredarica (2,537 m a.s.l.) in 1954 (Povše, 1984). Data from Villacher Alpe in Austrian Carinthia (2,160 m a.s.l.) are applicable for establishing climatic changes in the Slovenian Alps from the mid-19th century onwards. The series was composed of the data from the two high-elevation stations of Hochobir and Villacher Alpe, and homogenized within the framework of the HISTALP project (www.zamg.ac.at/histalp/). The data were used in several studies dealing with the eastern part of the Alps (e.g. Auer et al., 2007; Brunetti et al., 2009; Colucci and Guglielmin, 2014; Gabrovec et al., 2014).

The main goal of this research was to establish the changes in mean annual air temperatures (MAAT) and mean seasonal air temperatures (MSAT) as the regional response of Ljubljana to global warming, with a comparison to Trieste and Zagreb. The emphasis is on the comparison of 100-year temperature trends. The three cities are located in close vicinity: Ljubljana is located about 100 km either from Trieste or from Zagreb. These cities are either medium-sized (Ljubljana: 279,000 inhabitants; Trieste: 205,000 inhabitants), or larger (Zagreb: 780,000 inhabitants), and they differ in their geographical and climatic positions (see Fig. 1). Trieste lies on the northernmost rim of the Adriatic, i.e. the Mediterranean Sea, and has a moderate variety of Mediterranean climate. Ljubljana is situated on the continental side of the Alpine-Dinaric barrier, where the features of mountain and continental climates combine. Due

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to its position on the western rim of the Pannonian Basin, Zagreb has more pronounced continental climate features. Similar climatic conditions to those of Zagreb also occur in Maribor, but preference was given to Zagreb because its data series is longer and of a higher quality. Additionally, data from Maribor were studied recently (Žiberna, 2011). Meteorological measurements in Ljubljana, Trieste and Zagreb began in the mid-19th century, or in the second half of the 19th century. The history of measurements differs in the three cities; the largest changes in measurement conditions occurred in Ljubljana, and the smallest in Zagreb. Since the impact of city growth in Ljubljana after 1950 was not eliminated in data homogenization, another aim of the research was to assess the impact of the Ljubljana urban heat island on the 100-year temperature trends.

Temperature and precipitation series for Ljubljana, Trieste and Zagreb have been studied individually in the scholarly literature at different times: for Ljubljana – Manohin (1952, 1965), Gams and Krevs (1990), Kajfež-Bogataj (1990, 1992), Ogrin (1994, 2003, 2012), Vysoudil and Jurek (2005), Bertalanič et al. (2010), and Dolinar et al. (2010); for Trieste – Polli (1944), Stravisi (1976, 1987), and Brunetti et al. (2006: in the framework of regional data series for the Po plain); and for Zagreb – Goldberg (1953), Šegota (1970, 1981), Juras (1985), Penzar et al. (1992, 1992a), Radič et al. (2004), and Zaninović (2006). Hence, it follows that changes in climate and establishing the trends of these changes have been topical questions not only in recent decades, when opinions have prevailed that humans are the main culprits of current changes, but also that these issues became a subject of research soon after a sufficiently long series of climate data became available. Regardless, a comparison between the hundred-year temperature trends as they occurred in Ljubljana, Trieste and Zagreb has not yet been made.

2. Data series and methods

Data series that had been homogenized within the framework of the HISTALP project (www.zamg.ac.at/histalp) served as the basis for the analysis of air temperature changes in Ljubljana, Zagreb and Trieste. In this work, MAAT and MSAT were employed. Average values, standard deviations, linear trends, and 20-year moving averages and extreme values were calculated or assessed using the Excel package. Statistical significance of the trends was tested by means of the Mann-Kendall test (XLSTAT, Addinsoft 1995–2014). The data series are as follows: the 1851–2010 period for Ljubljana, 1841–2009 for Trieste, and 1862–2010 for Zagreb-Grič.

To establish the impact of the urban climate of Ljubljana on the 100-year trends, non-homogenized data were also used. Their database was composed of published series of data over many years for Ljubljana (Krevs, 1986; Klimatografija Slovenije, 1995), Trieste (Polli, 1944; Stravisi, 1976) and Zagreb (Penzar et al., 1992). The database was completed for Ljubljana over the last 20 years with the data from the archives of the National Meteorological Service at the Slovenian Environment Agency (Agencija RS za okolje/ARSO). The 1986–2009 data for Trieste were obtained from the Institute of Marine Sciences in Trieste (Istituto Talassografico Sperimentale di Trieste/ISMAR),

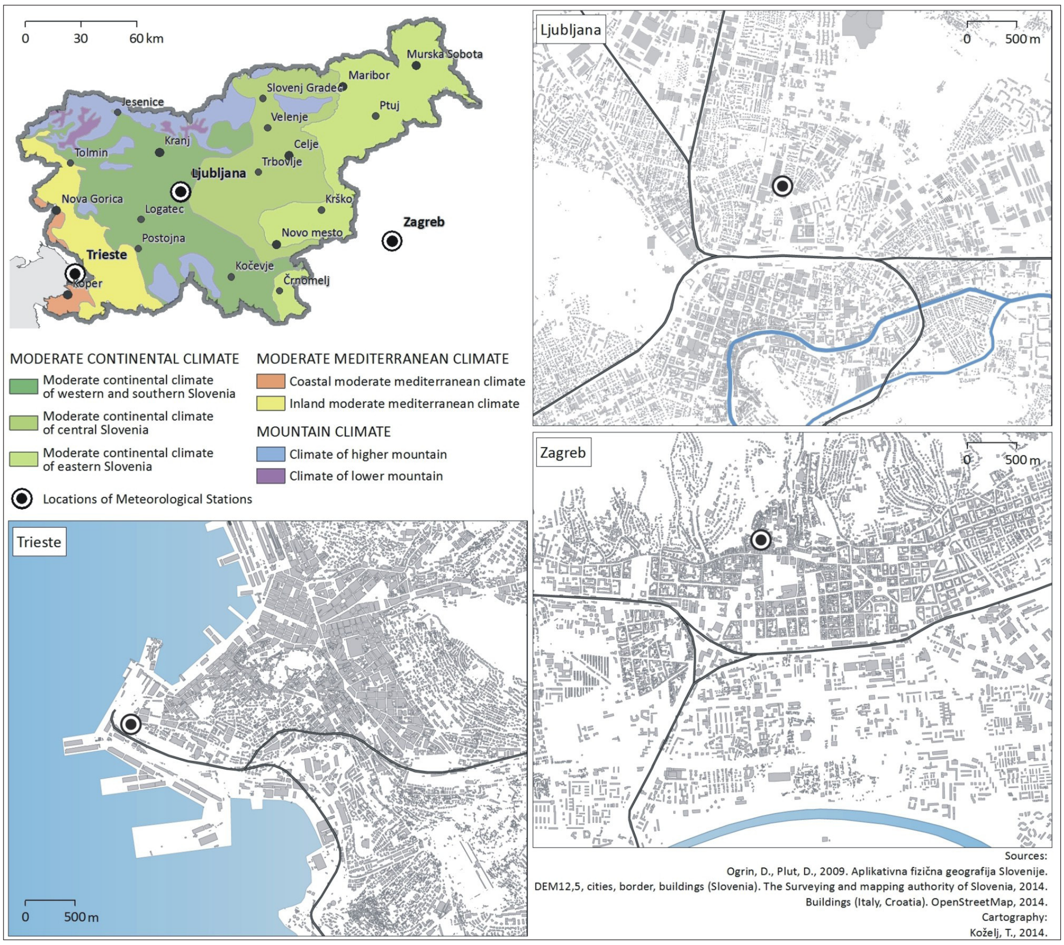

Fig. 1: Climate Types in Slovenia and Locations of Meteorological Stations in Ljubljana, Trieste and Zagreb

and the 1990–2010 data for Zagreb from the archives of the Hydrometeorological Institute of Croatia (Državni hidrometeorološki zavod Republike Hrvatske).

The basic problem in analysing the series of climate data over many years and in establishing changeability and climatic trends arises from the lack of homogeneity in the data series. In order to obtain reliable results, the meteorological stations should have operated at the same places all of the time, their surroundings should not have significantly changed, nor the technology and methodology of measurements or observations. If this is not the case, it is then essential to have detailed information (i.e. metadata) about the history of observations, the methodologies used for any given weather station, and any time lags.

The stations of Ljubljana and Trieste have changed their locations and instrumentation several times in their history, while the Zagreb station has only changed its micro-location and instrumentation. With respect to the homogeneity of data series, the best station is the one in Zagreb because it has operated at Grič (157 m a.s.l.) throughout the study period. Due to extending the Royal Secondary Modern School there, only in the initial period of measurements was the Stevenson screen moved from the northern to the southern wing of the building; however, it was at all times located on the northern side, on the first-floor window sill. It was mainly due to the world-famous geophysicist Andria Mohorovičić that the station was not moved; on the basis of his own observations he was familiar with the characteristics of the city's climate and was aware of the impact that moving the station could have on the homogeneity of the measured data (Mohorovičić, 1897; Herak et al., 2011). The Zagreb-Grič station has a complete series of temperature (and precipitation) data, since its operation did not stop even during the First and the Second World Wars, despite certain troubles (Katušin, 2011).

The stations of Ljubljana and Trieste were both moved longer distances within the two cities. The Trieste station has an advantage over the one in Ljubljana with respect to data homogeneity, however, because it was moved only within the continuously built-up quarter of the city, and the history of its temperature measurements in individual periods is also better documented. On the grounds of this evidence, the basic series of temperature measurements was rectified and homogenized also in the past, so that it corresponds to measurements such as they would have been if the station had operated all the time in the present location in the centre of the city, not far from the sea (Polli, 1944; Stravisi, 1976).

In spite of the corrections made for Ljubljana, its data are the least homogeneous, due to a more varied history, a somewhat poorer knowledge of measurement circumstances in individual periods, and a greater number of interpolated values. Above all it is due to moving the station after the Second World War to the northern fringe of the city (Bežigrad, 299 m a.s.l.). According to Trontelj (2000), after the station was moved in 1948, measurements were carried out on a "large meadow" which was gradually built-up in the following decades, and thus the measurement circumstances were significantly changed. Therefore, in the temperature series for Ljubljana the impact of urban climate is still present also in the case of homogenized data, with more explicit trends in the latest decades. This was used to advantage in the estimation of the impact of the urban heat island on the air warming trend.

3. Climate types in Slovenia

Due to its position in temperate latitudes at the transition of the Alps to the Dinaric range and of the Mediterranean to the Pannonian Basin, Slovenia has an explicit transitional type of climate, which results from the interaction between maritime and continental air masses. As well, local climate conditions are rather strongly influenced by the very strong diversity of landforms and differences in heights. As a result, there are contacts between the mountain (Alpine), Mediterranean and continental (Pannonian) climates, which interact in Slovenia. These three climate types are

Ljubljana*	Trieste**	Zagreb-Grič***
1850–1852: Telegraph office of the Railway station, 1st floor – east, then at the fringe of the city, 298 m a.s.l.	1841–1856: Imperial-Royal Academy of Commerce and Maritime Studies, 4th floor – north, 20 m a.s.l.	1861–1864: The Great secondary School, 1st floor – north wing of the building
1853–1895: Prečna ulica street, 295 m, 298 m, 290 m a.s.l.; data for 1863 and 1864 are missing, city centre	1856–1868: Imperial-Royal Academy, 5th floor, north, 24 m a.s.l.	1864: Stevenson screen relocated to the 1st floor of the south wing
1895–1919: precipitation measurements, Levstikova ulica street, 297 m a.s.l.	1868–1902: Marine observatory (the roof of Academy, north, 27 m a.s.l.	1861–1891: meteorological measurements and observations managed by I. Stožir
1895–1924: Secondary school in Vegova ulica street, station relocations within the building, 306 m, 304 m, 297 m a.s.l.; city centre 1921–1922: parallel air temperature measurements at Šiška and in Šlajmerjeva ulica street	1902–1919: Marine observatory (villa Basevi), Stevenson screen, 67 m a.s.l.	1892: observations taken over by A. Mohorovičić, gradual replacement of instruments
1921–1948: the University building, Institute of Geography, station relocations within the building, 309 m, 305 m, 295 m a.s.l; town centre	1919–1938: Royal Oceanographic Institute, Passeggio S. Andrea, Stevenson screen, 10 m a.s.l.	1896: Secondary School moves to a new location, Meteorological observatory remains in its original location
1948– : Bežigrad, Celjska (Vojkova) ulica street, 299 m a.s.l.; fringe of the city, later densely built-up	1938– : Oceanographic Institute, a cluster of buildings was built on its eastern side, 10 m a.s.l.	Uninterrupted daily recording of climate elements since 1861, 157 m a.s.l.

*Tab. 1: Overview of the history of meteorological observations in Ljubljana, Trieste and Zagreb. Note: * Gavazzi, 1925; Trontelj, 2000; ** Polli, 1944; Stravissi, 1976; *** Katušin, 2011; Herak et al., 2011*

characterized by atypical features if compared to 'proper' mountain, Mediterranean and continental climates, whose main characteristics are combined; therefore, the three types often receive the prefix "sub" in Slovenia (sub-Mediterranean, sub-continental, sub-Alpine climates) or they are defined as "moderate" (Mediterranean, continental, mountain) (Ogrin, 1996; Ogrin and Plut, 2009, p. 88). Because of this explicit transition of climate types, climatic division and the determination of borders between climate types and sub-types, as well as their naming, are difficult. In general, with increasing distance from the Alps and the High Dinaric plateaus in the direction towards the east and northeast of Slovenia, continental climate features are intensified; towards the south and southwest the Mediterranean features increase; while with increasing altitude in the Alps and the High Dinaric plateaus, the characteristics of mountain climate begin to prevail.

To the south and southwest of the Alpine-Dinaric barrier, the moderate Mediterranean climate prevails, due to the landforms that open towards the Adriatic and the Mediterranean. This area has the greatest number of days with sunshine in Slovenia (2,100–2,400 h × yr^{-1}), thus the greatest number of clear days and the lowest number of cloudy days. The mean air temperature of the coldest month is above 0 °C, and over 20 °C of the warmest month. Due to the influence of the sea, autumn and winter temperatures are mainly higher if compared to those inland. The precipitation amount ranges from 1,000 mm along the coast to 1,700 mm towards the inland. Most of it usually falls in October or November, a secondary maximum occurs at the turn of spring into summer (May, June), while in July and August, drought usually occurs. In the lower-lying areas along the Gulf of Trieste, where the city of Trieste is located, average January temperatures are above 4 °C and July temperatures above 22 °C (coastal sub-type of moderate Mediterranean climate). The inland sub-type has slightly lower temperatures and a larger precipitation amount. All the data referred to above relate to the period 1971–2000.

The moderate continental humid climate is typical of the larger part of Slovenia. Because continental characteristics combine with the highland and Mediterranean ones, and because continental features intensify in the direction from the Alps and High Dinaric plateaus towards the east and northeast, three sub-types of moderate continental climate can be discerned. The moderate continental climate of west and south Slovenia, including Ljubljana, is – due to their position in the sub-Alpine mountains and in the area of the Dinaric barrier (therefore also sub-Alpine climate) – characterized by large precipitation amounts (1,300–2,500 mm of annual precipitation, 1971–2000), with the precipitation maximum in autumn. The moderate continental climate of east Slovenia occurs in the hilly and lowland areas in the east and northeast of the country which opens towards the Pannonian Basin, on the margin of which Zagreb is located. The temperature and precipitation regimes are the most continental-like in this part of Slovenia. The lowlands warm up intensely in summer, and cool in winter. Spring temperatures are on the level of autumn temperatures or even slightly higher. If compared to the overall situation in Slovenia, these areas receive little precipitation – from 800 to 1,000 mm annually (1971–2000) – since the air masses that reach them are rather dry because they are located at the lee of the Alpine-Dinaric barrier. In spite of the summer precipitation maximum, summers in east and northeast Slovenia are at the verge of drought due to the relatively low amounts of precipitation and high temperatures.

The mountain (Alpine) climate that prevails in the Alpine world and the Pohorje range, as well as in the highest areas of the High Dinaric plateaus, is characterized by the average air temperature of the coldest month dropping below − 3 °C, and of the warmest month – up to the timberline – rising to more than 10 °C. The mountain climate in Slovenia could also be defined as sub-Alpine (sub-mountain), since the region is less massive and lower than the Central Alps for example, and it also lacks a real nival zone. Due to lower altitudes and less massive features, and because of the very small central mountain mass, the timberline in Slovenian mountains runs at lower heights than in the Central Alps. It is also greatly influenced by the limestone-dolomite base, which is the cause of great height differences in landforms and steep slopes, as well as by intense windiness, cloudiness and a lot of precipitation on the southernmost and SW rims of the Alps and High Dinaric plateaus. In the most massive central part of the Julian Alps, the timberline runs at about 1,900 m, and in the slightly lower and less massive Kamnik-and-Savinja Alps it runs between 1,700 m and 1,800 m; on the southern and SW rims of the Julian Alps it drops to 1,600–1,700 m and on the highest ridges of the Dinaric plateaus to 1,450–1,600 m (Lovrenčak, 2007). The timberline is the demarcation between the climates of the higher and the lower mountain types. The climate of the lower mountain world occurs also in some mountain valleys, basins and high-lying karst depressions, where July temperatures equal those in continental Slovenia, whereas January temperatures, mainly because of intense temperature inversions, are lower than − 3 °C. Insolation is poor in summers because of convective cloudiness but, in contrast, winters on the mountain peaks are very sunny. An outstanding feature is the large precipitation amount (from 1,700 to over 3,200 mm of annual precipitation, 1971–2000) which decreases towards the east.

4. Results and discussion

4.1 The trends of mean annual and seasonal air temperatures in Ljubljana, Zagreb and Trieste

Mean annual air temperature (MAAT) shows the same variability in Ljubljana and Zagreb but is slightly lower in Trieste. The differences in seasonal variability between these cities are larger. Winter temperatures in Ljubljana and Zagreb typically exhibit greater variability, whereas in Trieste greater variability in temperatures is specific to spring and winter. Generally, the winters (and in Trieste also the springs) manifest the most explicit air warming trends since the mid-19th century.

Of the three cities, Ljubljana shows the most distinctive air warming trends (see Tab. 2), although it was initially anticipated that such trends would prove to be higher in Zagreb, due to its more explicit continental character of temperature regime.

Trends in the three cities are shown in Figure 2. Without exception, seasonal air temperatures in Ljubljana have been rising since the mid-19th century. The warming trend is most obvious in winter (by + 1.4 °C × 100 yr^{-1}), which means that winter temperatures have increased since the mid-19th century by slightly more than 2 °C. Until the beginning of the 20th century, winters were below the average, but in the middle of its first half, a series of warm winters occurred, and in the following decades winter temperatures were on the level of about the 150-year average. From the 1980s onwards an explicit trend of winter temperature increase was observed. Winter is followed by spring (+ 1.1 °C × 100 yr^{-1}), and the same trend is also demonstrated in the increase of MAAT. Summer temperatures have increased more intensely in the last 25 years, when the mean summer temperature has been 1.5 °C higher than the average over 160 years, and the linear trend for the whole period amounts to + 0.8 °C × 100 yr^{-1}. All the trends are statistically significant.

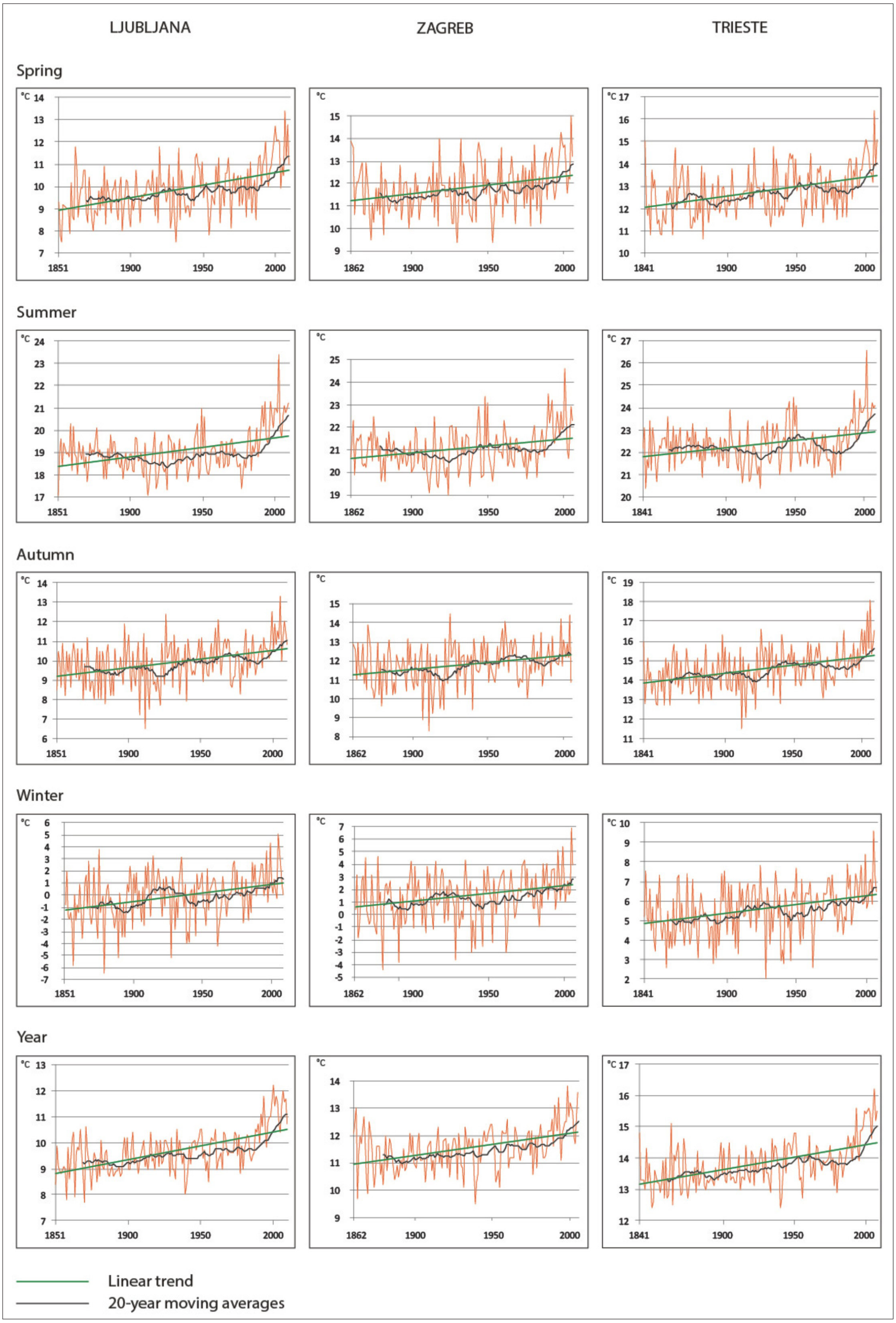

Fig. 2: Changes in Mean Air Temperatures in Ljubljana (1851–2010), Zagreb (1862–2010) and Trieste (1851–2009)

	Mean	Standard deviation	Lowest temperature	Highest temperature	Trend*: °C × 100 yr^{-1}	Four warmest seasons/years	Four coolest seasons/years
Spring	9.9	1.1	7.5 (1932)	13.4 (2007)	+ 1.1	2007, 2009, 2000, 2002,	1932, 1853, 1955, 1958,
Summer	19.0	1.0	17.1 (1851, 1913)	23.4 (2003)	+ 0.8	2003, 1994, 1998, 2010,	1851, 1913, ** 1926, 1918, 1978,
Autumn	9.9	1.1	6.5 (1912)	13.3 (2006)	+ 0.9	2006, 2000, 1926, 1963,	1912, 1908, 1915, 1922,
Winter	– 0.1	1.8	– 6.5 (1879/80)	5.1 (2006)	+ 1.4	2006/07, 2000/01, 1876/77, 1997/98,	1879/80, 1857/58, 1890/91, 1928/29,
Year	9.7	0.8	7.7 (1871)	12.2 (2000)	+ 1.1	2000, 2007, 1994, 2002,	1871, 1858, 1864, 1940,

*Tab. 2: Changes in Air Temperatures in Ljubljana in the period 1851–2010 (in °C). Note: * All trends are statistically significant according to the Mann-Kendall test (α = 5%); ** Two seasons have the same mean air temperature*

The coldest year in the studied period was 1871, and the warmest was 2000. Very warm years have mainly occurred in a row since 2000. The coldest winters were in the first 100 years of measurements. Very warm winters are typical above all for the last two decades (the warmest winter 2006/07) and of the early 20th century, when they were followed by a period of fast decrease in winter temperatures. The warmest summer occurred in 2003. In addition to the hot summers of the past two decades, some had already occurred at the beginning of measurements and in the mid 20th century. In contrast, cool summers in Ljubljana occurred at the beginning of measurements and in the first half of the 20th century.

Zagreb shows similar tendencies in air temperature changes to Ljubljana, but the trends are less explicit (see Tab. 3). Even in this case, winters have warmed most in the past 150 years (trend + 1.2 °C × 100 yr^{-1}) and they have been 1.8 °C warmer in recent years than in the 1860s. They are followed by the springs (+ 0.8 °C × 100 yr^{-1}). MAATs in recent years have been one degree higher than those at the beginning of measurements. The warming trend is registered at + 0.9 °C × 100 yr^{-1}. All the trends are statistically significant. Most of the warmest years in Zagreb have also occurred in the last 15 years, whereas the coolest years were in the 19th century, and one in the 20th century, i.e. 1940.

Air warming trends in Trieste, where maritime climate features prevail, are slightly weaker than those in Ljubljana and Zagreb (Tab. 4). Both Ljubljana and Zagreb - the latter more markedly – have a continental position; besides, the impact of urban climate on temperature regime is more explicit in Ljubljana. The biggest differences occur in winter temperatures, which show that the winter warming trend in Trieste is 0.3 °C smaller than that in Zagreb, and 0.5 °C smaller than that in Ljubljana. These differences are also smaller in the case of the other seasons. The linear trend of MAAT in Trieste is + 0.8 °C × 100 yr^{-1}, which equals the level of the 100-year trends in the major part of Europe (Beniston et al., 1998); however, it does not apply to Ljubljana because its warming trend explicitly exceeds these values.

The coldest year in Trieste was 1940, whereas all other very cold years occurred in the second half of the 19th century. As well, the coldest winters occurred during the first 80 years of measurements, with the coldest one in 1928/29 which is well remembered for the great damage done by frost to olive trees. After this frost, the number of olive groves in the littoral part of Slovenia radically declined, and in some regions (Goriška brda) olive growing was dropped until the 1980s (Ogrin, 2007). The severe cold of the winter of 1928/29, particularly in February 1929, also affected the mainland of Slovenia. There are numerous reports on frosts that caused damage to fruit trees and forest trees, many rivers froze, livestock in stables froze as well as wine and field products in cellars, people ran short of fuel, transport was blocked due to the cold, railway transport in particular because steam locomotives froze, schools were closed, etc. (Trontelj, 1997). The hottest summer in the history of measurements in Trieste occurred in 2003. Very hot summers occurred in Trieste in the last decade and in the mid-20th century. Cool summers, in contrast, occurred at the beginning of the measurements,

	Mean	Standard deviation	Lowest temperature	Highest temperature	Trend*: °C × 100 yr^{-1}	Four warmest seasons/years	Four coolest seasons/years
Spring	11.8	1.1	9.4 (1932, 1955)	15.0 (2007)	+ 0.8	2007, 2009, 2000, 1920, 1934**	1932, 1955, 1875, 1883,
Summer	21.1	0.9	19.0 (1926)	24.6 (2003)	+ 0.7	2003, 1992, 1950, 1994,	1926, 1913, 1919, 1940**
Autumn	11.8	1.1	8.3 (1912)	14.5 (1926)	+ 0.7	1926, 2006, 2000, 1963,	1912, 1908, 1915, 1921, 1941,
Winter	1.5	2.0	– 4.4 (1879/80)	6.9 (2006)	+ 1.2	2006/07, 2000/01, 1997/98, 2008/09,	1879/80, 1890/91, 1928/29, 1939/40,
Year	11.5	0.8	9.5 (1940)	13.8 (2000)	+ 0.9	2000, 2007, 1994, 2008, 2009**	1940, 1864, 1871, 1933,

*Tab. 3: Changes in Air Temperatures in Zagreb in the period 1862–2010 (in °C). Note: * All trends are statistically significant according to the Mann-Kendall test (α = 5%); ** Two seasons/years have the same mean air temperature*

	Mean	Standard deviation	Lowest temperature	Highest temperature	Trend*: °C × 100 yr^{-1}	Four warmest seasons/years	Four coolest seasons/years
Spring	12.8	1.4	10.6 (1883)	16.4 (2007)	+ 0.9	2007, 2001, 2009, 1841,	1883, 1845, 1853, 1861,
Summer	22.4	0.9	20.4 (1843)	26.6 (2003)	+ 0.6	2003, 1994, 1950, 1998,	1843, 1926, 1851, 1913,
Autumn	14.6	1.0	11.5 (1912)	18.1 (2006)	+ 0.8	2006, 2004, 1926, 1987,	1912, 1915, 1922, 1851, 1856**
Winter	5.5	1.3	2.0 (1928/29)	9.6 (2006)	+ 0.9	2006/07, 2000/01, 1987/88, 1997/89,	1928/29, 1857/58, 1867/68, 1890/91,
Year	13.8	0.7	12.4 (1940)	16.2 (2007)	+ 0.8	2007, 2003, 1994, 2006, 2009**	1940, 1850,** 1864,1858, 1860,

*Tab. 4: Changes in Air Temperatures in Trieste in the period 1841–2009 (in °C). Note: * All trends are statistically significant according to the Mann-Kendall test (α = 5%); ** Two seasons/years have the same mean air temperature*

in the second decade of the 20th century, and at the end of the 1970s and beginning of the 1980s. The period after the mid-1980s typically has seen a tendency towards a rapid increase in air temperature.

4.2 Estimation of the urban heat island (UHI) impact on air warming trends in Ljubljana

The distinctive trend of air warming in Ljubljana – particularly in the last 30 years – that greatly exceeds the world average (Dolinar and Vertačnik, 2010) is the result of several factors. Due to the complex history of the meteorological station, it is not possible to exclude completely the influence of the several relocations of the measuring station and the way measurements were taken on the result, in spite of the data homogenization that was carried out. All of the circumstances of measurements in individual periods are not known, especially those in the initial decades when air temperature was measured at non-standard times. The expansion of the city in the second half of the 20th century was certainly the main reason, however, since this factor could not be eliminated in data homogenization (Bertalanič et al., 2010). After the relocation of the meteorological station to the margin of the city in 1948, the surrounding areas became densely built up in the following decades and were thus transformed from a suburban to a completely urban environment, which resulted in the measurements falling under the impact of the UHI. According to the research carried out by Jernej (2000), Ljubljana has a single-cell and stable heat island, where the city centre is warmer than its surroundings by about 1 °C for the annual average, by 1.2 to 1.5 °C in the summer months, and by 0.4 to 0.5 °C in winter. Differences between the highest temperatures in the centre and the lowest ones in the southern marshy outskirts of Ljubljana are from 5 to 7 °C, and on clear winter nights and the subsequent emergence of fog, when snow cover still lies outside the city, they can even reach 10 °C.

The impact of the UHI in Ljubljana on temperature trends can be estimated by means of a comparison of trends in Ljubljana and Zagreb before and after 1950, when intense urbanization of the surroundings of the Ljubljana meteorological station began (Tab. 5). Between 1862 and 1950, both in Zagreb and Ljubljana, a gradual rise of air temperatures occurred, whether of MAAT or winter, autumn and spring temperatures. Only summer temperatures showed no trend. The warming was somewhat more intensely expressed in Ljubljana, but the differences in trends, with the exception of winter, were not bigger than 0.2 °C. Besides, no trend is statistically significant in Zagreb, while trends in winter and MAAT are statistically significant in Ljubljana. After 1950, the increase in air temperatures soared, in Ljubljana in particular. Its linear trends range between + 1 °C × 50 yr^{-1} (autumn) and + 2.1 °C × 50 yr^{-1} (summer). Except in winter, the Zagreb trends are markedly weaker, and the autumn months do not show a statistically significant trend.

If winters, which warmed slightly more in Zagreb than in Ljubljana, are ignored, the differences between Ljubljana and Zagreb in the warming trends after 1950 range between 0.4 and 0.7 °C in the seasons, and 0.4 °C in MAAT – to the 'benefit' of Ljubljana. If non-homogenized data are used, the difference in MAAT is higher by another tenth of one degree C (Tab. 5). It is not surprising that the difference between the two cities is greater in the summer, since according to the findings of Jernej (2000) the intensity

	1862–1950 (°C × 100 yr^{-1}) Homogenized data		1862–1950 (°C × 100 yr^{-1}) Non-homogenized data		1951–2010 (°C × 50 yr^{-1}) Homogenized data		1951–2010 (°C × 50 yr^{-1}) Non-homogenized data	
	Ljubljana	Zagreb	Ljubljana	Zagreb	Ljubljana	Zagreb	Ljubljana	Zagreb
Spring	+ 0.4*	+ 0.3	+ 1.1*	+ 0.7	+ 2.0*	+ 1.6*	+ 2.1*	+ 1.7*
Summer	+ 0.05	+ 0.05	+ 0.2	+ 0.3	+ 2.1*	+ 1.4*	+ 2.2*	+ 1.5*
Autumn	+ 0.6	+ 0.4	+ 0.4	+ 0.8	+ 1.0*	+ 0.4	+ 1.2*	+ 0.5
Winter	+ 0.9	+ 0.4	+ 1.5	+ 1.3	+ 1.9*	+ 2.0*	+ 1.7*	+ 1.6*
Year	+ 0.4*	+ 0.2	+ 0.8*	+ 0.8*	+ 1.7*	+ 1.3*	+ 1.8*	+ 1.3*

*Tab. 5: Comparison of linear trends of air temperatures in Ljubljana and Zagreb in the periods 1862–1950 and 1951–2010. Note: * Statistically significant trends according to the Mann-Kendall test (α = 5%)*

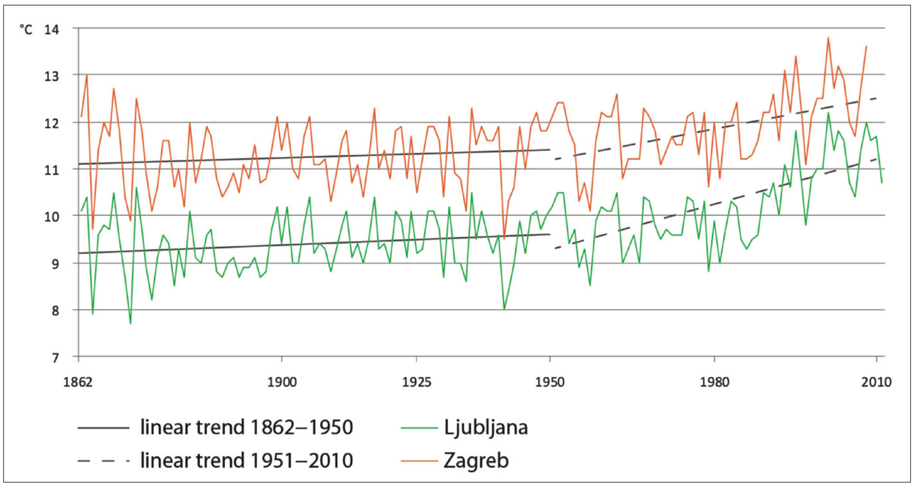

Fig. 3: Linear trends of MAAT in Ljubljana and Zagreb in the periods 1862–1950 and 1951–2010

of the Ljubljana UHI is highest during this season. Also in other cities of a similar size and structure as Ljubljana, the UHI is most intense in summer, e.g. in Brno in the Czech Republic (Dobrovolný et al., 2012). In our opinion, most of the differences between the warming trends of Ljubljana and Zagreb after 1950 can be ascribed to the impact of the UHI or the expansion of Ljubljana and the increased building densities in the surroundings of the meteorological station (see Fig. 3). If these factors are taken into account, the values of the 100-year trends in Ljubljana are slightly higher than the warming trends in most of Europe, but they are more comparable to them.

5. Conclusions

The comparison between the 100-year temperature trends in Ljubljana, Zagreb and Trieste has shown that air warming trends are the least explicit in Trieste and the most explicit in Ljubljana. The increasing trend in MAAT was + 1.1 °C × 100 yr^{-1} in Ljubljana, + 0.9 °C × 100 yr^{-1} in Zagreb, and + 0.8 °C × 100 yr^{-1} in Trieste. In all three cities it was the winters that warmed the most, but it should be noted that the warming trend of winters in Trieste equals the warming trend of spring temperatures. The lowest warming trends occur in summer and autumn air temperatures.

The results for Trieste had been anticipated, since warming trends in maritime climate areas are generally less explicit than those in continental climate areas, even though the maritime character of Trieste climate is less explicit. The city is located at the northernmost rim of the Adriatic, which cuts deep into the European continent, but the Northern Adriatic is a shallow sea and has poor water exchange with the South Adriatic or the Mediterranean. Consequently, the water temperature regime in the Gulf of Trieste is to a certain degree closer to a larger lake than a sea. The weaker maritime character of the Trieste climate is also evident from the comparison of trends in Trieste with those in Padua, where the warming trend of MAAT at the end of the 19^{th} century and in the 20^{th} century is 0.5 °C lower than that in Trieste (+ 0.34 °C × 100 yr^{-1}: see Cocheo and Camuffo, 2000).

The warming trend in Ljubljana, after 1950 in particular, is more explicit than the warming trend in Zagreb, although the latter city's climatic features are more continental than those in Ljubljana. The Ljubljana trend of the last 30 years also greatly exceeds the world average (Dolinar and Vertačnik, 2010). The main reason can be seen in the lateral expansion of the city in the second half of the 20^{th} century, and the urbanization of the surroundings of the meteorological station. Its original suburban position was transformed into an urban one and the station fell intensely under the impact of the UHI. However, it was not possible to take account of this impact in data homogenization (Bertalanič et al., 2010). Through comparison of the trends in Zagreb before the year 1950 with those after that year, the impact of the UHI on the warming trend in Ljubljana after 1950 was assessed at 0.3–0.4 °C (with non-homogenized data, at 0.5 °C), and on the 100-year trend at about 0.2 °C.

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Spatial variations in nitrogen dioxide concentrations in urban Ljubljana, Slovenia

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Abstract

Ambient nitrogen dioxide (NO_2) concentrations are regularly measured at only two monitoring stations in the city centre of Ljubljana, and such scanty data are inadequate for drawing conclusions about spatial patterns of pollution within the city, or to decide on effective measures to further improve air quality. In order to determine the spatial distribution of NO_2 concentrations in different types of urban space in Ljubljana, two measuring campaigns throughout the city were carried out, during the summer of 2013 and during the winter of 2014. The main source of NO_2 in Ljubljana is road transport. Accordingly, three types of urban space have been identified (urban background, open space along roads, and street canyon), and their NO_2 pollution level was measured using Palmes diffusive samplers at a total of 108 measuring spots. This article analyses the results of both measuring campaigns and compares the pollution levels of different types of urban space.

Keywords: *road transport, air pollution, nitrogen dioxide, diffusive samplers, Ljubljana, Slovenia*

1. Introduction

Air pollution from road transport in urban areas is a serious problem, both in central cities as well as elsewhere in urban regions, as the traffic volume and congestion on roads are increasing. Nitrogen oxides are among the most important pollutants produced by transport and are released as fuel is burned in internal combustion engines, as well as in industrial and energy production processes. The group of nitrogen oxides (NO_x) includes nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Nitrogen oxides have a negative impact on human health, particularly on liver, lung and spleen functions, and on the blood as well (EU-28 – Air pollution fact sheet 2014, 2014, p. 3).

Nitrogen oxide emissions also contribute to acid rain and the eutrophication of water and soil (EU-28 – Air pollution fact sheet 2014, 2014, p. 3), and are a significant component of photochemical smog, which affects the formation of ozone. In 2012, 45% of nitrogen oxide emissions in the European Union came from transport, and 39% of it from road transport. Transport is thus the second most important source of this pollutant, after energy production (ibid., p. 6). During this same time period, 8% of the urban population was exposed to excessively high concentrations of nitrogen dioxide; this figure, however, is 5.1% lower than in 2010 (ibid., p. 10).

In Slovenia air quality is further diminished by poor ventilation in low-lying areas, especially in the cities in the interior of the country. Ljubljana is among these poorly-ventilated cities, where there are no steady strong winds, which reduces the self-cleaning capacity of the air. Since it is located in a basin, temperature inversions during times of clear weather are frequent and pronounced (Ogrin, 2010; Ogrin and Plut, 2009). Recent data indicate that emissions from transport in Slovenia have been reduced, but transport nevertheless remains one of the major sources of air pollution.

In 2012, road transport contributed 53% of nitrogen oxide emissions (Logar, 2014; Slovenia – Air pollution fact sheet 2014, 2014, p. 6), and the whole transport sector: 55% (Logar, 2014). But judging from official data from the national air quality monitoring network, the urban population in Slovenia in the 2010–2012 period was not exposed to excessive concentrations of nitrogen dioxide (Slovenia – Air pollution fact sheet 2014, 2014, p. 10). It should be noted, however, that these estimates are based on only six monitoring stations in the urban environment of Slovenia. This means that these data do not capture the heterogeneity of urban space, which is usually high. There are many different types of land use in urban areas, settlement is dense, and the density of roads and other transport routes is high as well. It is therefore necessary to set up a dense network of measuring points, and to repeat these measurements many times, in order to gain an accurate picture of spatial pollution patterns and of the change in concentrations in urban space.

In this article we closely examine nitrogen dioxide air pollution in Ljubljana in the summer 2013 and the winter 2014, using a much denser spatial network. Similar studies in the past have indicated that in this way a rather different and, above all, a more complete picture of air pollution in the urban environment can be obtained. A study of nitrogen dioxide pollution in Genoa thus showed that concentrations in particular areas of the city can differ from the average values by more than 70% (Gallelli et al., 2002). Fluctuations in concentrations are also high in smaller areas, as can be seen from a study of air quality at Aberdeen Harbour (Marr et al., 2007): average concentrations in summer were in a range from 15 to 36 ppb v/v, and this was in a relatively small area. Similar studies have also been conducted in the area of Ljubljana in the past (Ogrin et al., 2006; Ogrin, 2008; Ogrin and Vintar Mally, 2013), in which the findings were similar and serve to confirm the thesis regarding the need

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Fig. 1: Research area – the location of the City Municipality of Ljubljana (orange coloured area).
Source: GURS, 2012

for a dense spatial network of measuring points, especially in urban environments. This article shows the air pollution in Ljubljana in summer 2013 and winter 2014 in a dense spatial network in different types of urban space using the method of diffusive samplers (in literature also referred to as diffusion tubes or passive diffusion samplers).

2. Theoretical background and methods

The use of diffusive samplers to identify spatial patterns of pollution in Ljubljana has already been shown by earlier studies (Ogrin et al., 2006; Ogrin, 2008) to be a suitable method for determining air quality, and we therefore also used them in the 2013/2014 study presented here, thereby enabling easier comparability of our results with those of previous investigations.

Diffusive samplers are used to sample certain substances in the air through passive sampling, and are therefore also called passive samplers. This means that we do not need pumps for the supply of air into the samplers: they are simply exposed to the air. The level of sampling is monitored through the level of diffusion of the pollutant in the air within the sampler, as determined by Fick's law of diffusion, which accounts for the name of the sampler.

There are several different types of diffusive samplers; in our study we used Palmes samplers, which have been in use since the 1970s (Palmes et al., 1976). They have a 7.1 cm long tube with an internal cross-sectional area of 0.71 cm^2 and a metal mesh at the closed end coated with a reagent that acts as a sorbent. At one end the tube is closed and at the other end it is open during the sampling period. Outside air enters through this opening during the time of sampling, bringing with it also pollutants. When the pollutant in the tube reaches the membrane and reacts with the reagent, a new substance is formed that remains on the membrane. Thus the concentration of the pollutant that is being sampled is equal to zero in the immediate vicinity of the membrane, since the sorbent binds it to itself and changes it. A gradient of concentration is therefore always formed in the tube whenever the concentration of the sampled pollutant of the entering air is greater than zero, and due to molecular diffusion this causes a flow of molecules towards the membrane with the reagent. At the end of the sampling the sampler closes, and the membranes are sent for chemical analysis, where the mass and hence also average concentration of the pollutant is determined by chemical analytical methods.

It is worth noting some of the important advantages of the method of sampling using diffusive samplers, in particular their flexibility and practicality. The samplers are simple and quick to set up and this can be performed by one person. The samplers and shelters are small, lightweight, and durable when cared for properly. Several hundred can be set up in one day, which greatly increases the quality of information on air pollution and also enables a dense spatial grid of measurements. Because of their low cost, we can repeat the measuring campaign frequently and more easily tolerate losses of samplers due to vandalism (Cape, 2009; Ogrin and Vintar Mally, 2013, p. 58).

On the other hand we must also consider the disadvantages of carrying out measurements and interpreting results using this sampling method. First of all we are interested in the comparability of this method with the reference method. The use of diffusive samplers compared with the reference method approved by the European Commission was performed by Warren Spring Laboratory (Campbell et al., 1994) and researchers found that the use of diffusive samplers gave about 30% higher values, with the differences being higher in more heavily polluted environments. A possible source of the elevated concentrations could be wind effects, shortening the diffusion path in the diffusion tube (Campbell et al., 1994). Several studies (Heal et al., 1999; Heal and Cape, 1997) show the higher concentrations of nitrogen dioxide to be the result of change in the atmospheric photostationary state within the tube, where there is a reaction between nitrogen monoxide and ozone that is no longer balanced by the dissociation of nitrogen dioxide. In a study in Edinburgh Heal and Cape (1997) found that in urban areas this excess reached 28% in summer, while in rural areas and in winter in urban areas it was 8–14%. On the other hand, Moschandreas et al. (1990) note that low temperatures (251–283 K) lead to an underestimation of NO_2 concentrations due to anomalies in the behaviour of triethanolamine below the freezing point for this substance, which is at 294 K.

The time at which the samplers are exposed can also influence measurement results. Bush et al. (2001) cite cases of studies in which four-week concentrations were noticeably lower than two-week ones, especially in the summer months. Among other things, this is assumed to be the result of the photodegradation of triethanolamine, which is more pronounced in the warm and sunny summer months. On average over a six-month period, four-week samples had a value that was 18% lower than two-week ones. Based on their own research, these authors found that for areas with an urban background the differences among measurements with diffusive samplers and the reference chemiluminescent measurements in longer periods, were within the general uncertainties of the chemiluminiscent measurements, and so corrective factors of the values measured in the diffusive samplers are not required. The authors further found that the use of shelters and shaded samplers, which reduce the penetration of turbulence into the diffusive sampler, also affect the lower overestimation of the concentrations measured.

A disadvantage of the method using diffusive samplers is also the fact that they provide only information about average pollution, and not maximum, hourly, multi-hourly, or daily values on which legally determined threshold values are based. Moreover, the method is not suitable for monitoring air quality in real time, since the results are available only after a time lag, once the final chemical analysis of the samplers has been performed, and this can last from several days to several weeks.

Measurement based on the use of the Palmes diffusive samplers is also less suitable for shorter periods; it must last for at least a few days and preferably for one to three weeks, during which time there can also be a problem due to the photodegradation of the reagent in the sampler, as mentioned above.

In the research described here as well as in previous studies, we placed the samplers in special shelters made by the manufacturer of the samplers (Gradko International) (Fig. 2), which reduces turbulence in the area surrounding the sampler and consequently also inside it. After both measuring campaigns, the samplers were sent to the Gradko International laboratory for chemical analysis. "Nitrogen dioxide is absorbed as nitrite by triethanolamine. Nitrite reacts with the added reagent to form a reddish purple azo dye, which is measured spectrophotometrically (ultra-violet/visible) at 542 nanometres. Concentrations as μg on tube are calculated by reference to a nitrite calibration curve prepared from certified reference standards. The concentrations are converted to ugm^3 and parts per billion nitrogen dioxide in air using exposure data and a constant derived from the coefficient of diffusion and sampling rate" (Gradko Environmental, 2015).

The measurement uncertainty, as specified by the laboratory, was in both cases ± 7.8%. The details of the Nitrogen Dioxide Proficiency Scheme for the year 2014 provided by Gradko International, are specified in Table 1.

During each campaign, a set of three blank (unexposed) samplers was used and sent for analysis in order to subtract the values of blank samplers from the results of the exposed samplers. Additionally, the results were always corrected using a correction factor obtained from the relationship between the values measured with the six diffusive samplers and the reference method at the Ljubljana city monitoring station of the Slovenian Environment Agency. The correction factor for the summer campaign was small (1.07) and, as such, also within the measurement uncertainty. The correction factor for the winter campaign turned out to be larger, reaching 1.27.

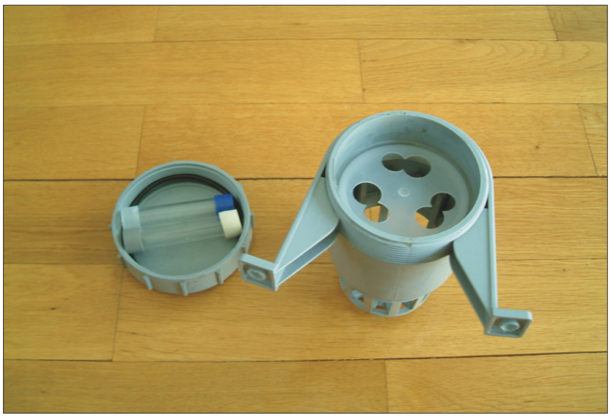

Fig. 2: Diffusive samplers and shelter (Photo: M. Ogrin)

Fig. 3: Measuring point in the urban background at Ljubljana Castle (Photo: K. Vintar Mally)

Fig. 5: The measuring point along Zaloška Street was classified as the type open space along roads (Photo: K. Vintar Mally)

Since the research area is rather small (around 6–9 km in diameter) and the reference monitoring station is almost in the middle of this area, we have decided to use this correction factor for all measurements. We are aware, however, of the possibility that these factors could somewhat differ across the whole network. At each measuring spot the shelter (containing three diffusive samplers) was mounted on a streetlight, a traffic sign, a traffic light, the roof gutter of buildings or in similar place. Samplers along roads were placed at a height of about three meters from the ground,

Proficiency scheme – Nitrogen dioxide 2014								
Date	Round	Assigned value	Camspec M550 – GLM 7			QuAAttro –GLM 9		
			Measured concentration	z-Score	% Bias	Measured concentration	z-Score	% Bias
Feb-14	WASP 124-1	0.90	0.91	0.14	1.2	0.91	0.06	0.6
Feb-14	WASP 124-2	2.24	2.25	0.09	0.5	2.31	0.41	2.9
Feb-14	WASP 124-3	2.24	2.25	0.07	0.4	2.33	0.58	4.2
Feb-14	WASP 124-4	0.90	0.93	0.46	2.9	0.92	0,32	1.9
May-14	AIR PT 1-1	1.39	1.44	0.48	3.6	1.43	0.38	2.9
May-14	AIR PT 1-2	1.36	1.44	0.78	5.9	1.40	0.39	2.9
May-14	AIR PT 1-3	0.97	0.95	– 0.27	– 2.1	0.98	0.14	1.0
May-14	AIR PT 1-4	0.99	0.97	– 0.27	– 2.0	0.99	0.00	0.0
Aug-14	AIR PT 3-1	1.84	1.84	0.00	0.0	1.87	0.22	1.6
Aug-14	AIR PT 3-2	1.71	1.71	0.00	0.0	1.72	0.08	0.6
Aug-14	AIR PT 3-3	1.66	1.65	– 0.08	– 0.6	1.69	0.24	1.8
Aug-14	AIR PT 3-4	1.83	1.87	0.29	2.2	1.88	0.36	2.7
Nov-14	AIR PT 4-1	2.00	1.99	– 0.07	– 0.5	2.05	0.33	2.5
Nov-14	AIR PT 4-2	1.98	1.95	– 0.20	– 1.5	2.01	0.20	1.5
Nov-14	AIR PT 4-3	1.15	1.15	0.00	0.0	1.16	0.12	0.9
Nov-14	AIR PT 4-4	1.14	1.14	0.00	0.0	1.15	0.12	0.9

Tab. 1: Proficiency Scheme for NO_2 measurements in year 2014. Methods: GLM 7 – Camspec M550 Spectrophotometer, GLM 9 – QuAAtro Continuous Flow analyser.
Source: Gradko Environmental, 2014

usually 0.5–3.0 m from the edge of the road, exceptionally even more. After the chemical analysis, the average value of nitrogen dioxide concentration at each measuring spot was calculated, using only the nearest two measured values and excluding the third one. This allowed for the exclusion of unusually large or small values, which can occur from unknown or known reasons (for example contamination from the ingress of insects or spiders).

In Ljubljana, measuring points were determined with respect to three pre-defined types of urban space: urban background, open space along roads, and street canyons (see Fig. 6, below). For measuring points in the urban background, it is the case that sources do not affect the flow of concentrations directly but rather with a lag. Daily fluctuations in pollutants are significantly lower than along roads (where there are fluctuations in the degree of traffic congestion), and the average concentrations are lower. These areas are usually residential neighbourhoods, parks, gardens and similar places, and are usually more distant from major roads and other sources that would directly affect the path of concentrations. Any pollution in these areas is an especially important problem, since people spend time in them more frequently and for longer periods, including spending their free time there, and such areas are generally regarded by people to be more peaceful and less polluted. With respect to pollution from primary pollutants, these areas are usually less polluted.

Street canyons are a particular spatial category (Figs. 4a,b – see cover p. 4). They are narrow, densely built-up or walled areas, usually in city centres, where arterial roads converge in squares and large parking areas, or lead to a major road that runs through the centre of the city. Traffic is often congested and slow-moving along street canyons. Although they usually have a lower volume of traffic than arterials on the outskirts of the city or ring roads, they are nonetheless quite busy. Since the self-cleaning capacity of the air in street canyons is severely diminished, the concentrations of primary pollutants are greater, and in some places very high. It is also important to note that nitrogen dioxide is only partly a primary pollutant. Only about 10% of this gas is exhausted directly from vehicles, the rest is produced with oxidation of nitrogen monoxide and ozone. In street canyons, ozone concentrations are often too small to react with all the nitrogen monoxide available. Eventually, nitrogen monoxide reaches the urban background, where it usually reacts with ozone to create nitrogen dioxide. This can result in lower concentrations of nitrogen dioxide in street canyons than what one might expect.

For the third type we placed measuring points in open space along roads. Sampling was performed along arterial and other roads outside street canyons in order to gain an insight into the air quality and its degree of pollution from nitrogen dioxide along roads where pollutants are not concentrated due to topography, but pollution is instead dependent on the volume of traffic and the speed of vehicles using them.

3. Results and discussion

Measurements of nitrogen dioxide using diffusive samplers were carried out in the city of Ljubljana over three weeks in the summer of 2013 (from 26th August

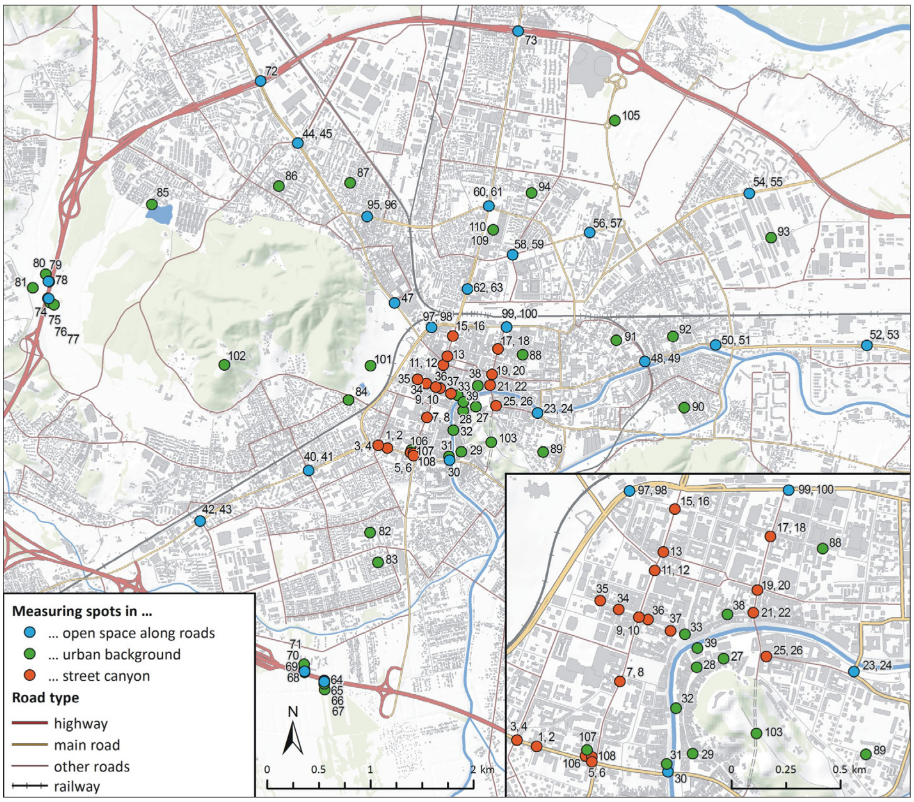

Fig. 6: Measuring spots for nitrogen dioxide in the summer and winter measuring campaigns in Ljubljana
Sources: GURS, 2012 and MKGP, 2013 for GIS data; authors' survey for NO_2 measurements

to 16th September 2013), and for three weeks in winter 2014 (from 15th January to 6th February 2014), at 108 different measuring spots, classified into the three pre-defined types of urban space (Fig. 6). In the urban background, the sampling was conducted at 35 measuring spots, in the open space along roads at 43 measuring spots (of which in 16 cases measuring spots were paired in locations along both sides of a main road, while the remaining spots were distributed in the immediate vicinity of the ring road), and in street canyons at 30 measuring spots (likewise in pairs on both sides of the street, with the exception of four locations along pedestrian zones in the city centre and one location where we further placed samplers at two different heights above the main road). In the cases where the measuring spots were placed in a pair on each side of the street (in street canyons as well as in open space along roads), we combined them into one measuring point. The concentration of nitrogen dioxide for these measuring points was calculated as the arithmetic mean of the concentrations from each measuring spot in the pair. In this way, we eliminated the influence of wind on the final value along the road. Since wind in the urban background and at a greater distance from main roads does not have a significant influence on the result of the measurement, measuring points there were composed of just one measuring spot.

In this account we provide the results of measurements of nitrogen dioxide for 35 measuring points in the urban background (Fig. 7), 27 measuring points in open space along roads (Fig. 8) and 18 measuring points in street canyons (Fig. 9). For both measurement campaigns we

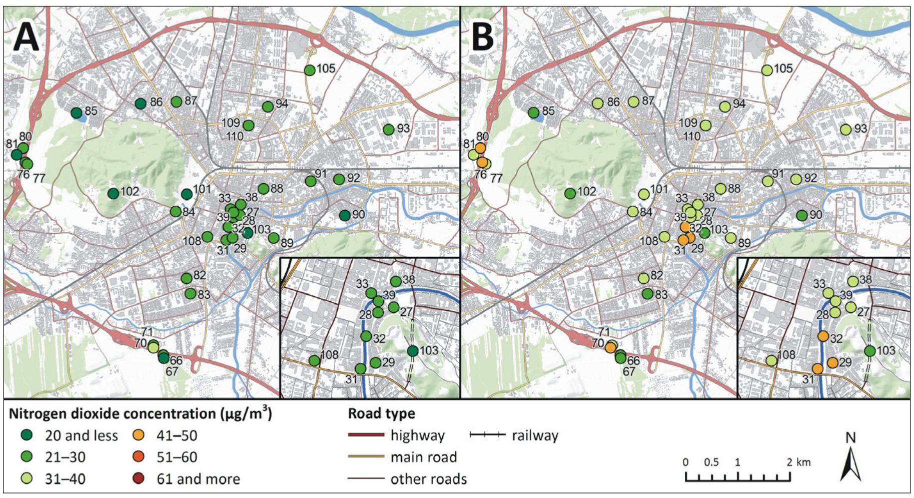

Fig. 7: Concentrations of nitrogen dioxide in the urban background in the summer (A) and winter (B) measuring campaigns. Sources: GURS, 2012 and MKGP, 2013 for GIS data; authors' survey for NO_2 concentrations

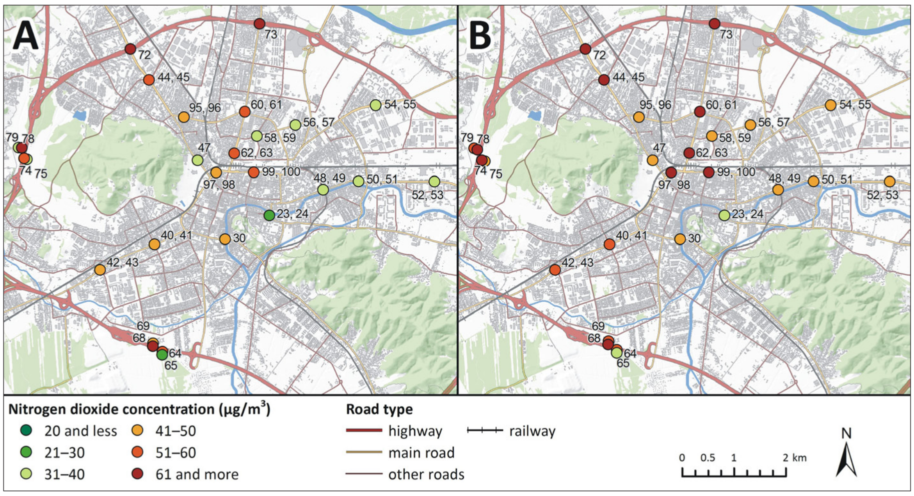

Fig. 8: Concentrations of nitrogen dioxide in open space along roads in the summer (A) and winter (B) measuring campaigns. Sources: GURS, 2012 and MKGP, 2013 for GIS data; authors' survey for NO_2 concentrations

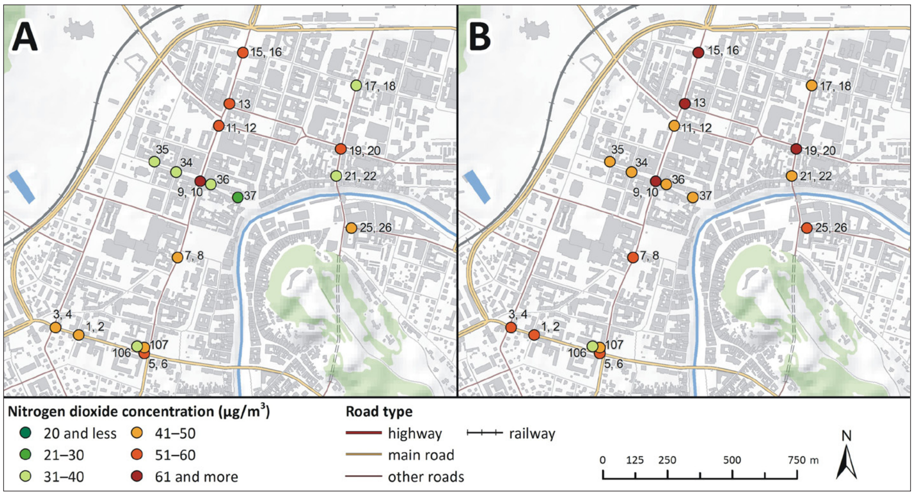

Fig. 9: Concentrations of nitrogen dioxide in street canyons in the summer (A) and winter (B) measuring campaigns Sources: GURS, 2012 and MKGP, 2013 for GIS data; authors' survey for NO_2 concentrations

Type of urban space	Concentrations (μg/m³)		Absolute difference (μg/m³)**	Relative difference (%)***
	Summer measurements	Winter measurements		
Urban background				
Highest value	31	45	19	112
Lowest value	15	23	2	8
Average of all measuring points	23	35	11	50
Open space along roads				
Highest value	67	81	22	65
Lowest value	29	37	3	7
Average of all measuring points	46	56	9	22
*Street canyons**				
Highest value	72	67	12	27
Lowest value	38	45	– 7	– 10
Average of all measuring points	52	57	5	11

*Tab. 2: Comparison of nitrogen dioxide concentrations in the summer and winter measuring campaigns in different types of urban space in Ljubljana. Note: *Altogether 12 measuring points in four street canyons (Aškerčeva, Slovenska, Resljeva, and Poljanska street canyon) with motor vehicle traffic were taken into account (Fig. 9); **Absolute difference = winter concentration – summer concentration; ***Relative difference = (winter concentration – summer concentration)/summer concentration × 100*
Source: authors' survey and calculations

make use of the results for 106 different locations, since measuring spots 109 and 110 were placed in the same location (directly adjacent to the automatic reference station of the Slovenian Environment Agency, in order to check the accuracy of measurements). Measuring spots at locations 14 and 46 are not included in the comparison; the diffusive samplers there were stolen during one of the measuring campaigns. Measuring point 104 could not be set up. The measured values of the concentrations of nitrogen dioxide in the summer and winter measuring campaigns can (with respect to the duration of the measurements) be compared only with the annual threshold value (40 $\mu g/m^3$), which is the only determined threshold value for nitrogen dioxide under Slovenian law for a period longer than one or three hours (Bolte and Murovec, 2013, p. 9).

Measuring points for the urban background were located in city parks and recreation areas, in the pedestrian zone in the city centre, side streets in peaceful residential neighbourhoods, and other areas where people often gather and spend their free time, since city residents generally believe that these areas are less polluted. At a greater distance from main roads, daily fluctuations in the concentrations of pollutants are in fact lower and the levels of concentrations are also lower. Thus in the summer as well as the winter measuring campaign, the lowest values of concentrations of nitrogen dioxide in Ljubljana were measured in the urban background: in summer these were from 15 to 31 $\mu g/m^3$, and in winter from 23 to 45 $\mu g/m^3$ (Tab. 2). In the summer measuring campaign the concentrations measured were nowhere higher than the annual threshold value of 40 $\mu g/m^3$, but in the winter measuring campaign this occurred at six measuring points, in the city centre and near the city ring road (Fig. 7). The fact that in winter concentrations of nitrogen dioxide in the urban background, with the exception of seven measuring points, were everywhere higher than 30 $\mu g/m^3$, including in the city park of Tivoli (measuring point 101) and in the pedestrian zone in the city centre (for example, measuring points 27, 28, 29, 32, 33), is a cause for concern. In both measuring campaigns the lowest concentrations were measured in the city districts of Koseze (85) and Kodeljevo (90), and on two hills above the city – on Rožnik (102) and on Castle Hill (103). These two measuring points also indicate lower concentrations of nitrogen dioxide in somewhat higher layers of the air or, rather, the retention of polluted air at ground level.

Higher concentrations of nitrogen dioxide were measured at all measuring points in the urban background in the winter measuring campaign than in the summer measuring campaign, greater on average by 50%, or 11 $\mu g/m^3$. The difference is alarmingly high, although it is in any case expected since winter weather conditions reduce the self-cleaning capacity of the air in the city and increase the use of energy for heating; fuel consumption by vehicles is also higher. The winter air pollution measured at background level indicates a generally present pollution of the air in the city, even far from sources of pollution, which practically cannot be avoided, and it is also a sort of basic level of pollution in street canyons and along other roads.

The second type of measuring points covered locations in open space along roads that are the most heavily travelled in Ljubljana. Measurements were conducted along the city ring road, arterials and other main roads that do not have the characteristics of a street canyon. In this type of space, air pollution is dependent on the number and type of vehicles and their speed. In the summer measuring campaign concentrations of nitrogen dioxide measured in open space along roads were from 29 to 67 $\mu g/m^3$, and in the winter measuring campaign from 37 to 81 $\mu g/m^3$. In summer the average concentration in open space along roads (46 $\mu g/m^3$) was twice the average concentration in the urban background (23 $\mu g/m^3$), while the winter average concentration of 56 $\mu g/m^3$ in open space along roads almost reached the average concentration of nitrogen dioxide of the most heavily polluted type, i.e. street canyons (Tab. 2).

The concentrations measured in open space along roads exceeded the legally defined annual threshold value of 40 $\mu g/m^3$ at two-thirds of the measuring points in summer and at 25 measuring points of a total of 27 in winter. The highest concentrations were measured along the city arterials Celovška Street (measuring points 72, 44–45) and Dunajska Street (73, 60–61, 62–63) and directly beside the ring road (64, 68, 74, 78), as well as along the main bus station in the city centre (99–100). In this type of measuring points we also included two so-called 'hot spots' in the investigation – measuring points 72 and 73, where a city arterial runs above the ring road and the concentrations of nitrogen dioxide were among the highest in both measuring campaigns, as expected. In the winter measuring campaign the highest values in the whole of the study were measured at these two locations: 81 $\mu g/m^3$ at measuring point 72 and 78 $\mu g/m^3$ at measuring point 73.

The other main roads in the city, along which non-motorized traffic also travels, are immediately adjacent as bicycle paths and sidewalks usually run right alongside, and they were also found to be relatively heavily polluted, especially in winter. Thus pedestrians and cyclists, in addition to car and bus passengers, are also exposed to excessive concentrations of nitrogen dioxide.

In the centre of Ljubljana we identified several street canyons, characterized by dense, slow-moving traffic through a space along the street with a high density of buildings, usually tall. Although they normally have a lower volume of traffic than arterials on the outskirts of the city or ring roads, high concentrations of primary pollutants are to be expected because of the poor self-cleaning capacities of the air in the canyon. For nitrogen dioxide, which is mainly a secondary pollutant, higher concentrations are expected only if enough ozone is available for the reaction with nitrogen monoxide as the primary air pollutant. Measuring points were set up in four street canyons along which traffic flows: the Aškerčeva street canyon (measuring points 1–2, 3–4, 5–6), the Slovenska street canyon (7–8, 9–10, 11–12, 13, 15–16), the Resljeva street canyon (17–18, 19–20, 21–22), and the Poljanska street canyon (25–26). A fifth canyon was selected for comparison, between Cankarjeva Street and Čopova Street (34, 35, 36, 37), which is for the most part closed to automobile traffic, but this traffic runs along cross streets, including Slovenska Street. Concentrations measured in this canyon were indeed considerably lower than in other canyons, reaching 27 to 36 $\mu g/m^3$ in summer and 41 to 48 $\mu g\ m^3$ in winter (Fig. 9).

The average winter and summer concentrations of nitrogen dioxide obtained from the other four street canyons showed that street canyons are the most polluted type of urban space. On average the most polluted was the Slovenska street canyon, where the highest summer concentration in the city was also measured (72 $\mu g/m^3$ at measuring point 9–10). In the winter of 2014 measured concentrations increased in comparison to summer values at all measuring points in street canyons, except for measuring points 9–10 and 11–12 in the Slovenska street canyon, since the city closed this section of road to passenger cars in the fall of 2013, and since that time only public transit and deliveries are permitted. Concentrations of nitrogen dioxide in the canyon mentioned nevertheless significantly exceeded the annual threshold value, which also holds true for the other street canyons in winter.

Only in the Resljeva street canyon in summer were concentrations lower at two measuring points, amounting to 38 $\mu g/m^3$ (measuring point 21–22) and 39 $\mu g/m^3$ (measuring point 17–18). In the Aškerčeva street canyon at measuring point 5–6, diffusive samplers were also exceptionally mounted at heights of 11 meters (measuring point 106) and 26 meters (107) above the street, in order to observe how concentrations of nitrogen dioxide in the street canyon change in a vertical direction. In both measuring campaigns, the concentration fell significantly with increasing height: in winter, for example, from 59 $\mu g/m^3$ at a height of three meters to 41 $\mu g/m^3$ at 11 meters above the street, and 31 $\mu g/m^3$ at 26 meters above the street. Future studies will need to give greater attention to these types of measurements since not only pedestrians, cyclists, and users of motorized transport are endangered, but also residents and employees in nearby buildings, who are exposed to elevated concentrations for many hours a day.

4. Conclusions

Measurements of nitrogen dioxide taken using diffusive samplers in the city of Ljubljana in the summer of 2013 and winter of 2014 showed heavy pollution of the air in certain parts of the city, and also great variety in the degree of pollution, which confirms the thesis on the need for a dense spatial network of measurements.

In general, concentrations in both measuring campaigns were lowest in the urban background and highest in street canyons, although measuring points in the open space along roads category on average did not show a significantly more favourable situation than that in the street canyons. It should be emphasized, however, that the air quality in open space along roads is strongly dependent on the volume of traffic, and pollution along roads that are not busy can be very low. But in a street canyon the air becomes strongly polluted even with a considerably lower volume of traffic, and this pollution just increases as traffic increases. In Ljubljana the air was most polluted from nitrogen dioxide along arterial roads (especially at overpasses above the ring road), directly adjacent to the ring road, and in the centre of the city where there are street canyons, the area around the main bus station and the main roads with the most traffic. We also found a relatively high level of nitrogen dioxide concentrations in the urban background, as a result of which, for example, in winter the air was constantly polluted at a level of about 35 $\mu g/m^3$, and the contamination increases with the proximity of local sources of pollution, as shown by measurements in the space along more heavily travelled roads and in street canyons.

Here it should be emphasized that measurements in both measuring campaigns took place in rather untypical weather conditions that were more supportive of the self-cleaning capacities of the air, with above average precipitation, greater mixing of air, and an absence of longer temperature inversions, and in winter it was also unusually warm. As a result, we expect significantly greater pollution of the air than that measured, especially in winter, with stable, calm, and colder anticyclonic weather. The latter is also supported by the comparison of winter concentrations of nitrogen dioxide as measured in three consecutive years with the reference method at the Ljubljana city monitoring station of the Slovenian Environment Agency. Although the Agency has in 2014 temporarily moved the monitoring station from its usual place for about 650 m, it remained in the same type of urban space (i.e. urban background) with similar characteristics and without any important influence on the results. Over the same three-week period in winter 2013 and winter 2015, the average concentrations of nitrogen dioxide were 40 $\mu g/m^3$, which is 25% higher than during our measuring campaign in winter 2014 (32 $\mu g/m^3$). This is not only indicative of the meteorological conditions in the winter of 2014 but also supports the conclusion that average conditions may usually be worse than those presented in this discussion.

High concentrations of nitrogen dioxide are a caution to the city of Ljubljana and the country of Slovenia, drawing attention to the urgency of implementing measures for sustainable mobility: for example, expansion of the bicycle path network, reduction of parking areas for private cars, strengthening (the competitiveness of) public transit, encouragement of walking and non-motorized traffic, education of the population, preparation of mobility plans for public institutions, etc. Above all, perhaps, this work points to the need for restrictions on traffic in the city centre, the introduction of vehicles with cleaner technologies, especially for public transit, and for spatial planning that will protect road users and residents from the negative impacts of polluted air and raise the general quality of life in the city.

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The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary)

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Abstract

The evaluation of ecosystem services can provide essential help in incorporatating the multifunctionality of urban ecosystems in planning and management processes. Two important regulating services of urban trees, carbon sequestration and air pollution removal, are evaluated in this article for different types of tree stands (streets, parks) in the city centre of Szeged (Hungary). The necessary calculations were carried out by an adaptation of the targeted model (i-Tree Eco), based on a large complete tree inventory dataset. The analyses revealed the main tendencies in differences between tree species considering the tree condition, which affects the service-providing capacity to a high degree. The effects of differences in tree management on the chosen ecosystem services were investigated by comparing two pairs of tree alleys. Based on our observations, clear cuts and complete tree alley changes are not advisable from an ecosystem service point of view.

Keywords: *urban ecosystem services, carbon sequestration, air pollution removal, Szeged, Hungary*

1. Introduction

The rapid growth of urban populations and global climate change call for the elaboration and evaluation of different adaptation and mitigation strategies in these antropogenically-modified climatic circumstances. Among these strategies, one of the most important is the planting and maintenance of trees and other green spaces. On the one hand, vegetation is directly effective through shading and evapotranspiration, improving the quality of life of the resident population by decreasing heat stress. Several investigations have been carried out on such issues at micro- and local scales, based on field measurements, models or remotely-sensed data (Cao et al., 2010; Lee et al., 2013; Lehmann et al., 2014). On the other hand, urban tree stands modify the city's climatic characteristics and air quality by the sequestration of carbon dioxide and the removal of various air pollutants, and by reducing stormwater runoff (Jim and Chen, 2008; Kirnbauer et al., 2013; Nowak et al., 2013). Furthermore, trees in particular are considered to have significant aesthetic and eco-psychological values (O'Campo et al., 2009; Tyrväinen et al., 2003). Studies have been carried out also to express the monetary value of these effects, using the methodologies of hedonic pricing (Donovan and Butry, 2011; Sander et al., 2010), choice experiments (Giergiczny and Kronenberg, 2014) and travel costs (Teknomo, 2005).

The multifunctionality of urban ecosystems is a well-known fact (Haase et al., 2014), and a methodology for the evaluation of ecosystem sevices could play an important role in its promotion and its incorporation into decision-making processes. The essence of this approach, originating primarily from the fields of landscape ecology and ecological economics, is to quantify those goods and services of ecosystem and landscape elements that contribute directly or indirectly to human well-being (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013; Gómez-Baggethun et al., 2013). Due to the integrated approach and monetary quantification (which can be carried out for some of the services), this methodology could play an important role in furthering the interests of nature conservation. This is indicated by several significant international policy documents, and the foundation of IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services: MEA, 2005; Perrings et al., 2011; TEEB, 2010a,b).

The evaluation of climate- and air quality-related ecosystem services of urban trees is an important task. As an example, heat stress mitigation is a service which is perceived directly by inhabitants, and it has a strong effect on the use of urban public spaces (Égerházi et al., 2013). As well, the significance of the service of air pollution removal is highlighted by the fact that changes in air pollutant concentrations can be quantitatively related to the occurence of some diseases and to mortality rates, which means that this service is directly contributing to human well-being (Nowak et al., 2014).

These evaluations can be carried out relatively easily using allometric and growth equations of different tree species (based on data from forestry practice). Using such findings, several targetted models have been developed using these data to calculate some of these services, mainly carbon sequestration and air pollution removal, completed sometimes with monetary evaluations (i-Tree, 2014; Peng et al., 2008). These have been used in many cities in the world, and sometimes they are an integral part of the official urban tree management processes (City of Melbourne, 2012; Rogers et al., 2011). At this point in time,

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however, we are not aware of any studies published on assessments of climate- and air quality-related ecosystem services, based on large tree inventories from the wider region of Central Eastern Europe.

As described above, urban trees can alter the climatic conditions of cities considerably, even though, as a reverse effect, the built environment and anthropogenic heat surplus create a special environment for the trees. A weaker tolerance to urban circumstances may result in worse (less healthy) tree conditions in the case of certain species, which can be observed from the referring tree attributes in the field, or can be calculated by models. In the case of worse tree conditions, the trees provide less services.

Besides the main vegetation type and species characteristics, the services provided by certain ecosystems are influenced strongly by land management intensity. The evaluation and modelling of these effects are in the focus of recent ecosystem service research (Petz and van Oudenhoven, 2012). This approach is becoming more important in the case of urban tree stands as well. Some of the important management-related questions are: How long should the rotation cycle be in the case of urban tree stands? What kind of tree maintenance works should be used to keep the trees' service-providing capacity as high as possible? There are some published results aimed at the comparison of different-aged, differently-managed tree stands, mainly from the U.S. (Martin et al., 2012; McPherson, 2003; McPherson and Kendall, 2014). To date, however, we have rather few empirical studies on the effects of different species selection policies and treatment practices from the point of view of ecosystem services. Using the methodology proposed in this study, we can express some of the important regulating services in monetary value, which can facilitate their incorporation into urban planning and management.

As a result of these research needs, we provide and discuss the results of an individual-based ecosystem service assessment, based on a complete tree inventory. The analyses refer to tree stands in the centre of Szeged (Hungary). Our first goal was to investigate the significance of the urban trees from the point of view of two services, carbon sequestration and air pollution removal, given the Central European climatic circumstances. This was achieved with the adaptation of a targetted model (i-Tree Eco). Another goal was to assess the service-providing capacity of different species, with relation to their general condition. This also needed the complete inventory, where data representing stands of different species were available for comparison. The significance of protected trees compared with other stands in terms of ecosystem services, is an important issue in the green space management of the city. Some preliminary empirical results are presented, from a case study using differently managed tree alleys, which are nonetheless situated in similar built environments and which are originally of about the same age.

2. Data and methods

2.1 Study area

The general study area was located in the centre of Szeged, situated in South-East Hungary. The city is characterized by a dry-warm continental climate. Szeged is the administrative centre of Csongrád county, with ca. 170,000 inhabitants. Because of its size, the urban heat island effect and air pollution are considerable, and these have been studied in detail in previous research (Kántor et al., 2012; Makra, 2005; Unger et al., 2014). The structure of the city is characterized by radial avenues and three boulevards. The downtown area, which is located inside the innermost boulevard, constituted the main area for this investigation.

The entire investigated stand (i.e., total urban forest) is composed of 2,846 trees, situated mainly in tree lines, while the rest are park stands on squares. About one-third of the trees are protected (by local regulation of the municipality). An important element of legal protection, from the point of view of our analysis, is that in protected tree alleys clearcuts are prohibited, trees can be cut down and substituted only inidvidually, due to 'bad' condition or for safety reasons. The differences between protected and non-protected stands are

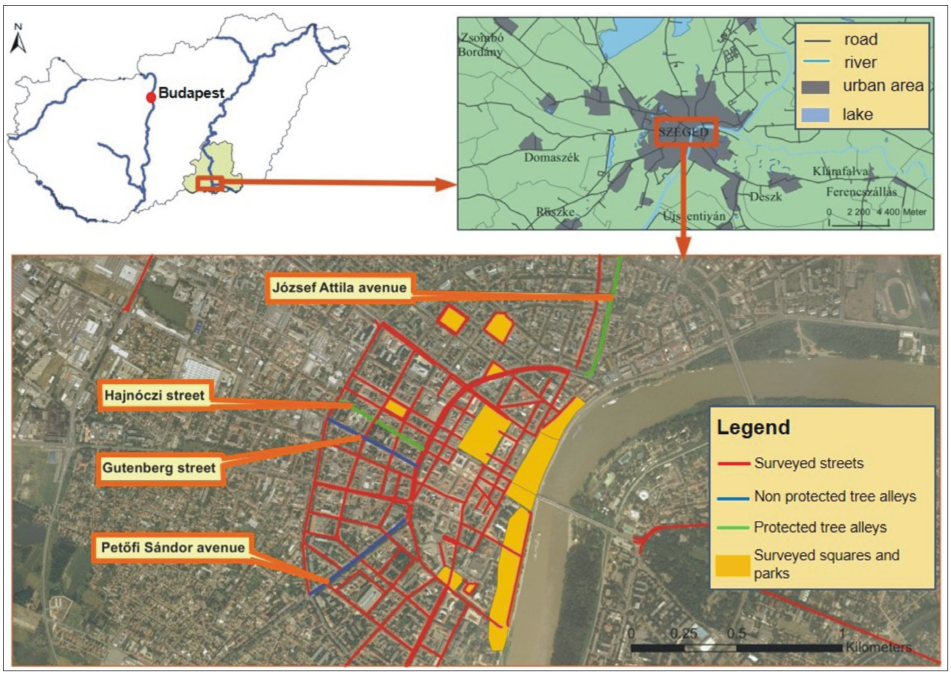

Fig. 1: The surveyed streets and squares, and the four case study areas in Szeged (Hungary)
Source: author's elaboration

primarily due to age differences. Therefore, to evaluate some of the effects of management differences, we chose stands which are of about the same age originally, situated in similar urban morphological zones that represent the characteristic built environments of the downtown of Szeged, and which are 'special' from a management aspect.

The tree alleys of boulevards and avenues are very important elements of the townscape and of the green infrastructure as well. One of them (József Attila avenue) is protected in its full length, and this was the main reason that it could be preserved in an almost completely undisturbed form during a large infrastructure development project in the 2000s (Szentistványi, pers. comm.). In contrast, in the tree alley of the Petőfi Sándor avenue (which is situated in a similar environment to the József Attila avenue, and is approximately the same age), large parts of the tree crowns and a considerable number of whole trees were cut down. The protected Sophora japonica tree alley of the Hajnóczi street is situated in a central part of the city centre (mostly under heritage protection). In the parallel Gutenberg street, a very similar Sophora japonica tree alley (of the same age, but without legal protection) was cut down entirely and substituted with a young Tilia tomentosa tree line.

2.2 Data and materials

The analyses are based on a field-based complete tree inventory, that had been produced in the vegetation period of 2012 and 2013, with the strong cooperation of the municipal public utility company responsible for green space management. The exact locations of the trees were available from a baseline GIS database of the city, which considerably aided the field survey. For the latter, we applied the protocol of the i-Tree model (i-Tree, 2014). We recorded the attributes of every street and park trees in the study area, if its diameter at breast height (DBH) exceeded 5 cm. The height of the tree, the height to base of live crown and the crown diameter were measured using the Vertex III ultrasonic hypsometer. The diameter was recorded at 1.37 m (breast height), under which, in case of multi-stemmed individuals, every stem was measured which exceeded 5 cm in DBH. The ratio of canopy missing and ratio of branch dieback in crown data are used to rate tree condition and to adjust downward leaf area and biomass data, which are calculated with the help of allometric equations (Nowak et al., 2008). The percent of canopy missing and dieback data were recorded in 5-percent intervals in the field. The growth of a certain individual is corrected with the crown light exposure (CLE) data (number of sides of the tree receiving sunlight – maximum of five). The data collected in the field were primarily imported and stored in "Greenformatic" software, which was developed in Hungary specifically for urban tree registers and which is capable of storing i-Tree datasets. From Greenformatic, we exported the data into MS Access format, which is the required format of the applied model.

2.3 The i-Tree Eco model

The elements of the i-Tree software suite are tools used world-wide for calculating climate- and air quality-related ecosystem services of urban trees. From the tools of the i-Tree (formerly UFORE – Urban Forest Effects Model) suite (i-Tree Eco, Streets, Hydro, Design), Eco is the most suitable for international use. The model calculations are based on well-defined allometric relationships between indicators of the relevant ecosystem services (amount of biomass, leaf area) and measured size parameters of the trees. The first part of the model results cover the most important structural characteristics of the urban forest (leaf area, canopy cover, tree condition, etc.). The tree condition categories are given based on the proportion of branch dieback in crown data (excellent: < 1%, good: 1–10%, fair: 11–25%, poor: 26–50%, critical:51–75%, dying: 76–99%).

The second main part of the results include the estimates on the investigated ecosystem services. Carbon storage is quantified with the help of the above-mentioned allometric equations. Annual growth (from which annual carbon sequestration is calculated) estimates are based primarily on standardized growth rates (that take into account climatic characteristics of the study area), which are adjusted based on tree condition and crown light exposure data (which represent forest or open-growth conditions). The air pollution removal (dry deposition) calculations are carried out using pollutant concentration datasets of the study area, by calculating deposition velocities, for which detailed meteorological datasets are needed from the study site.

The i-Tree model has to be adapted for use outside the U.S. It needs the integration of some basic geographical data, information on the growth characteristics of the tree species specific to the study area, and local meteorological and air pollutant datasets. As all of the species in our inventory can be found in the i-Tree Eco species database (partly because of their American origin), no additional species information was needed. The general climatic characteristics of the area (e.g., number of frost-free days) affect the annual growth rates, while meteorological data with high temporal resolution is needed for the calculation of deposition velocities of pollutants. The meteorological datasets employed here are from the meteorological station of Szeged (run by the Hungarian Meteorological Service). Air pollution removal was calculated for CO, NO_2, PM10, SO_2 and O_3, their hourly concentration datasets were provided by the local station of the Hungarian National Air Quality Network. After compiling and properly formatting the above-mentioned datasets (together with the tree inventory), the data processing was carried out by the US Forest Service. The model was implemented for the year 2012 (meteorological and air pollution datasets for 2012 were used). The monetary value of carbon sequestration was calculated based on the marginal social cost of carbon data (Tol, 2008), while that of air pollution removal was estimated using country-specific median externality values (PowerConsult, 2010). As these values could be found only for earlier years, the values were converted to the study year using Producer Price Indices of the subsequent years (ÁKK, 2014).

3. Results

In this section, the characteristics of the forest structure are described, followed by the results for the two investigated services. The total tree stand is described mainly with respect to the share of different species, while the comparison of stands with management differences is carried out partly with DBH categorisation.

3.1 Forest structure

3.1.1 Structural characteristics of the total tree stand

The total urban forest of the city is characterised by high species diversity: exactly 100 species can be found in this area, slightly larger than 2 km^2. Some of them, about one-half (48%), are native in Hungary. The major elements of the urban forest consist of street tree lines, but the tree populations in parks are also planted stands. The ten most common species amount to 70% of the whole urban forest (1,992 individuals, Tab. 1.), and most of our analyses of the total tree stand are related to the characterization and comparison of the populations of these species.

For most species, there is a dominant size range (which can be described with the standard deviation of DBH, Tab. 1). This shows that in recent years, different species were preferred when planting tree lines. More than half of the species (53) have less than 10 individuals, these were planted partly when diverse parks were created or if individuals of formerly homogeneous tree alleys were substituted with new species.

Leaf area is one of the most important state indicators of the investigated ecosystem services, therefore examining the weight of different species within the total population is necessary (Fig. 2). The *Platanus hybrida* stand is outsanding in leaf area (37.7% share in the total leaf area), followed by the populations of *Celtis occidentalis* (10.1%) and *Sophora japonica* (9.1%). The order from the point of view of the species' share in the number of trees is slightly different (*Platanus hybrida* is first with 10.7%, the second is *Tilia cordata* (10.4%), third is *Sophora japonica* (9.7%) and *Celtis occidentalis* was ranked only the fourth (8.9%)). The population of *Tilia tomentosa* has very small amount of leaf area, compared to its share in the number of individuals.

The health condition of the populations of different species might be a factor that affects the amount of leaf area to a strong degree. It can be said that the total studied stand is considerably "good" in terms of its condition, as most of the individuals were classified into "excellent" or "good" categories (Fig. 3). This is partly a consequence of the design of the model, but proper management also plays a significant role (trees in very bad health status are replaced relatively quickly). Large differences between species, however, can also be observed from the point of view of tree condition, which highly influences the amount of provided services. For example, the populations of *Platanus hybrida* and *Acer platanoides* are in a good general condition (only 14.7% and 19.5% of their individuals are in worse (fair or worse) tree condition). The same situation applies to *Tilia tomentosa* and *Fraxinus ornus* stands (60.9% of the individuals are in "excellent" condition in both populations). In contrast, considerable parts of the populations of two native *Tilia* species (*Tilia cordata*, *Tilia platyphyllos*) are ranked as 'worse' health categories (27.4% and 24.8%), and similar observations can be made of the individuals of the *Sophora japonica* population (19% and 31.2%).

3.1.2 Structural attributes of the stands with different management regimes

To evaluate the characteristics of ecosystem services provided by different stands, it is necessary to investigate their main structural characteristics, in a similar fashion to the total urban forest. We provide summarized data for these stands in Table 2.

The tree alley of the József Attila avenue has the largest trees among the four subsamples chosen for this case study, with an average DBH of 43.7 cm, higher than the same value of the total urban forest. From the investigated stands, it has the largest leaf area, even if there are more trees on Petőfi avenue. The values of 3.6% (dieback) and 10.8% (canopy

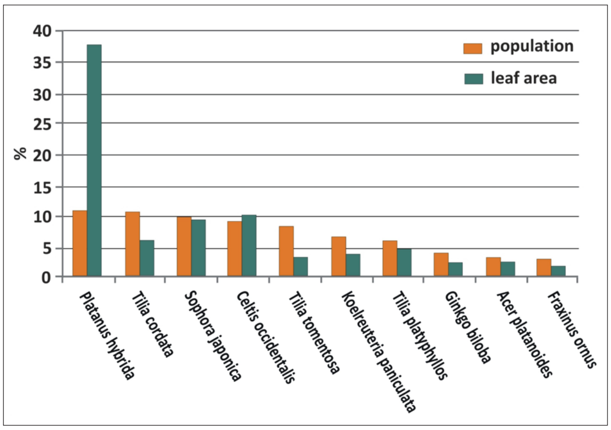

Fig. 2: Percentage of the ten most common species and their share in the whole leaf area
Source: author's calculations

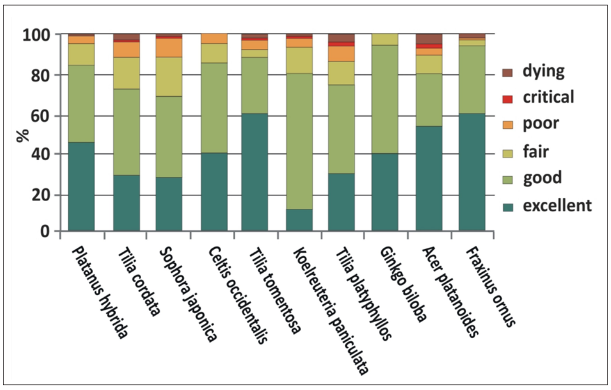

Fig. 3: Tree conditions in the populations of the ten most common species. Source: author's calculations

Species	Number of trees	Canopy cover (m^2)	Leaf area (m^2)	Avg. DBH (cm)	Std. dev. of DBH
Platanus hybrida	305	58,697.4	229,455.5	63.0	25.2
Tilia cordata	295	8,080.0	36,249.4	28.4	16.7
Sophora japonica	276	23,635.1	55,252.7	47.5	18.6
Celtis occidentalis	252	16,210.4	61,215.2	36.2	17.5
Tilia tomentosa	235	4,375.1	19,355.9	18.0	14.1
Koelreuteria paniculata	184	8,097.5	21,567.1	29.4	9.7
Tilia platyphyllos	165	7,119.1	27,978.8	28.2	13.9
Ginkgo biloba	111	5,164.1	14,737.5	33.2	16.8
Acer platanoides	87	3,014.9	13,547.9	20.3	13.9
Fraxinus ornus	82	3,216.1	9,807.0	22.1	11.9

Tab. 1: Characteristics of the ten most abundant species in the urban forest of Szeged. Source: author's calculations

	Average DBH (cm)	Total leaf area (m^2)	Average percent of missing crown (%)	Average percent of crown dieback (%)	Number of trees
József A. avenue	43.7	39,805.5	10.8	3.6	103
Petőfi S. avenue	33.8	14,374.2	34.3	23.5	123
Hajnóczi street	31.4	8,033.2	36.2	16.0	95
Gutenberg street	8.1	666.3	1.6	0.5	110

Tab. 2. Structural characteristics of investigated stands with different management regimes
Source: author's calculations

missing) are much lower than the city averages (8.4% and 17.9%). Due to protection and homogeneous management, the József Attila tree alley consists of only four species (with dominance of *Platanus hybrida* and *Quercus robur "Fastigiata"*).

The alley of Petőfi Sándor avenue boasts the highest number of trees. During transportation development works, some individuals of the non-protected original tree line of *Tilia tomentosa* (which was approximately the same age as the József Attila alley and was in a good condition originally) were cut down. In the locations of the cut *Tilia trees*, trees of several species were planted (there are 15 species now). The average percent of missing crown (34.3%) and crown dieback (23.5%) are well above the total urban forest averages.

Hajnóczi street is a characteristic, quite narrow street, bordered by 2–3-storey buildings. Despite the small area, the tree alley consists of quite large individuals, most of which are *Sophora japonica* trees (77 trees). The amount of leaf area is considerably low, compared to the realatively high average DBH of the individuals. This is connected to the fact that the average percent of missing crown value is extremely high (34.3%), and the average crown dieback (23.5%) is also much higher than the total urban forest average.

Gutenberg street is the neighbouring street, with similar neighbouring buildings and a "building height:street width" ratio. There was a tree alley like the one on Hajnóczi street, which was cut down and substituted with an almost homogeneous young *Tilia tomentosa* tree line. The young individuals are in 'good' condition, with low values of percent of missing crown and dieback.

3.2 Ecosystem service provision

3.2.1 Carbon sequestration and air pollution removal in the total tree stand

Differences between species in carbon sequestration and storage capacity are mainly determined by the differences in size distribution. The *Platanus hybrida* population can be characterized by an extremely high annual sequestration, which can reach 60 kg/year or even more for the largest individuals. The 305 *Platanus hybrida* trees store 428.9 tons of carbon, which is more than one third of the total stored carbon (1,169 t) of the studied urban forest. *Sophora japonica* have the second largest annual carbon sequestration values (23.5 kg/tree on average), and the third is *Celtis occidentalis* (15.8 t/yr). The economic value of carbon sequestration per tree is between 0.1–0.2 €/yr for most species, but the values of the species with highest sequestration rates are above that. The total carbon sequestration of the whole studied urban forest amounted to 720 €/yr in economic value. The order of the species based on carbon storage, is obviously mostly parallel with the one based on the leaf area (both

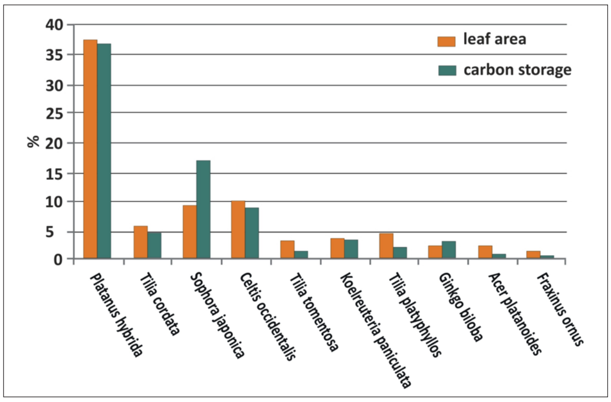

Fig. 4: The share of the ten most common species in the whole leaf area and in the amount of stored carbon
Source: author's calculations

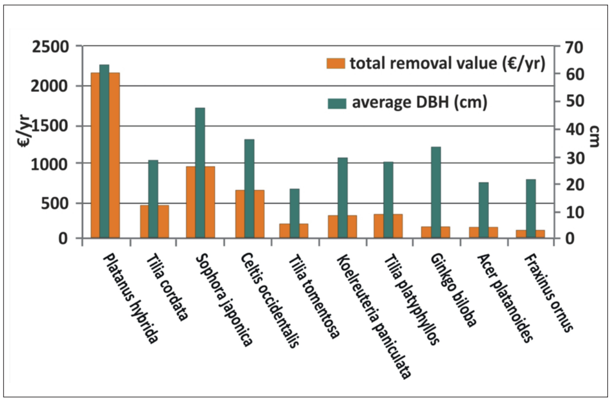

Fig. 5: Total monetary value of air pollution and average diameter at breast height (DBH) for the ten most common species.
Source: author's calculations

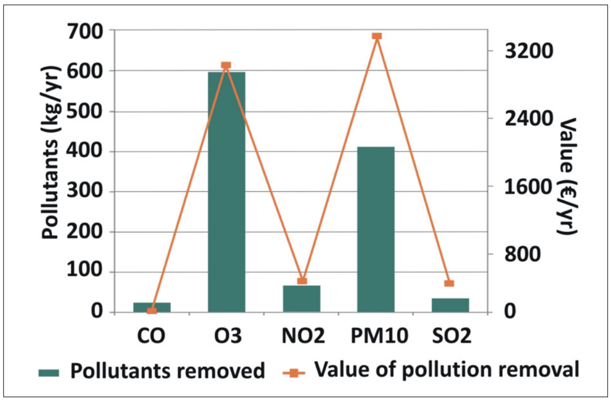

Fig. 6: Total amounts of removed pollutants (CO, O_3, NO_2, PM10, SO_2) and their economic value
Source: author's calculations

have strong connection with primary production). In some cases, however, slight differences can be detected which may indicate the health status of the species. For instance, the *Sophora japonica* population clearly has a relatively small leaf area compared to its carbon storage capacity (Fig. 4).

The differences in air pollution removal between species and its relation to the average diameter at breast height are basically parallel with the previously-described leaf area – carbon storage relations (Fig. 5), as leaf area is the ecosystem indicator with respect to the quantification of the service. The average removal per tree (calculated by summarizing the values of all of the pollutants) ranges between 200–400 g/yr for most species (1–2 €/yr in monetary value); this is outweighed only by *Platanus hybrida* (1059.1 g/yr; 6.9 €/yr) and *Sophora japonica* (556.8 g/yr; 3.4 €/yr).

If we examine the different pollutants separately, it is clear that the highest amounts are removed (with the highest economic values) from those pollutants that have the highest concentrations in the city in general. In the investigated urban forest in Szeged, where there are no considerable industrial emissions, the highest removal values can be observed in the case of O_3 (~600,000 g/yr in total) and PM10 (~400,000 g/yr), which are mainly from traffic (Fig. 6).

In the concentrations of the latter, dust coming from the neighbouring landscapes as a result of wind erosion may also have a significant role (Szatmári, 2005). The total economic value of air pollutant removal was 7,127 € for 2012, which is quite high, almost ten times the amount of the economic value of carbon sequestration.

3.2.2 Comparison of service provision by the investigated stands

The amount of the two provided services and their economic value for the four places can be seen in Tab. 3. The compared street and avenue pairs are similar in the number of trees, but, due partly to management-related interventions, they are different in size distribution. Therefore, the comparisons of the stands are more informative with categorisation based on DBH (Martin et al., 2012).

In the smallest diameter class (1–15 cm), the József Attila stand, and in the largest diameter class (> 76 cm), both avenues have such a small amount of trees (below 10), which make comparisons impossible. In the case of carbon storage and sequestration, the average values of József Attila avenue are higher in every diameter classes, and in the economic values as well. The relations are mainly the same in the case of air pollution removal. In the smallest diameter class that was considered, however, in spite of the higher percentages of average canopy missing and dieback of the trees in the József Attila avenue, air pollution removal appeared to be much lower than that of the trees in the same diameter class in Petőfi Sándor avenue. In the other diameter classes, clearly larger carbon sequestration and air pollution removal values can be observed for the trees of József Attila avenue. The differences in economic value of the two services can reach 2–5 €/year per tree.

The tree alleys of the two smaller streets are not suitable for this kind of comparison, as the population of the Gutenberg street belongs to only one diameter class.

DBH (cm)	Average carbon storage per tree (kg)	Average carbon sequestration per tree (kg/yr)	Average value of carbon sequestration per tree (€/yr)	Average removal amount (g/yr)	Average removal value per tree (€/yr)
József Attila avenue					
1–15	22.4	4.4	0.1	44.4	0.2
16–30	130.6	11.3	0.2	105.5	0.3
31–45	335.8	17.9	0.3	241.5	0.7
46–60	810.7	28.3	0.5	877.7	3.7
61–75	1,380.1	41.4	0.7	1,350.6	5.7
61–76	1,269.1	39.3	0.7	1,540.8	6.5
76+	2,092.1	56.7	1.0	1,490.3	6.2
Petőfi Sándor avenue					
1–15	13.2	2.6	0.01	151.3	0.5
16–30	81.9	6.7	0.1	171.1	0.6
31–45	237.5	9.5	0.2	248.7	0.9
46–60	512.3	16.0	0.3	414.4	1.5
61–75	971.0	23.9	0.4	260.9	0.9
61–76	675.8	21.7	0.4	145.2	0.5
76+	1,450.9	32.8	0.6	402.6	1.5
Hajnóczi street					
1–15	23.9	3.9	0.1	80.4	0.3
16–30	134.8	10.2	0.2	170.5	0.6
31–45	340.1	16.3	0.3	256.8	0.9
46–60	723.8	24.3	0.4	669.3	2.0
Gutenberg street					
1–15	5.7	1.7	0.01	8.5	0.0

Tab. 3: Ecosystem services provided by the investigated stands, by diameter class (cm). Source: author's calculations

In fact, the comparison of these two streets rather mean the quantification of the effects of the tree removal on ecosystem services (see, e.g. Pothier and Millward, 2013). The total amount of stored carbon in the trees of Hajnóczi street is 24,520.4 kg, while the same data for the Gutenberg street (total stored carbon in the small Tilia tomentosa trees) is 629.4 kg. The average annual carbon sequestration is 13.2 kg/tree at Hajnóczi street (with an economic value of 0.24 €/yr), and 1.72 kg/tree for Gutenberg trees (economic value: 0.03 €/yr). Considering air pollution removal, the total annual removal in the case of Gutenberg street was observed to be 936 g/yr (with an economic value of 4.8 €/yr), while in Hajnóczi street it was 22,314.6 g (with an economic value of 73.5 €/yr).

4. Discussion

The structural characteristics of the urban forest in Szeged are similar in principle to those of other East Central European cities. The share of non-native species recorded as 50% or even more is typical of other cities as well, where i-Tree analyses were carried out (e.g., Chaparro and Terradas, 2009; Rogers et al., 2011). The American and Asian species, which were introduced as ornamental trees in previous times, are sometimes more urban tolerant than native species. This can be observed in better tree conditions in the analyses and may result in better ecosystem service-providing capacity. The consequence of the parallel use of native and non-native species is a very high species diversity within a considerably small area. The species selection in urban areas and the resulting forest structure depend to a strong extent on the ownership characteristics and on the species selection policy of the forest managers.

In the investigated urban forest in Szeged, there is a small number of planting activities by the inhabitants, besides the work of the urban public enterprise which is responsible for urban tree management. Apart from that, the very high tree species diversity in urban, institutional environments appears in the results of other analyses as well (Pothier and Milward, 2013). As a consequence, there is also a high diversity in the services provided, owing to the different growth and leaf area production capacities of the different species. The system of i-Tree can handle this, as allometric equations for hundreds of species that are native in different continents, are stored in the species database of the model. And the modules which are used in this analysis (calculations of urban forest structure, carbon sequestration and air pollution removal) are suitable for use outside the U.S. in different climatic zones, after proper model adaptation.

The greater or smaller weight of particular species compared to their number of individuals, is a consequence primarily of the size distribution. For instance, the oldest tree alleys of the city, where the oldest trees are present, consist mainly of *Platanus hybrida* individuals; this is the reason for the very high share of the species in the total leaf area. Meanwhile, a huge part of the *Tilia tomentosa* population form a newly-planted, homogeneous tree line in the city centre, thus it is represented with hundreds of individuals but with considerably low leaf area. The share of different species in the total leaf area provides information on the performance of the populations from an ecosystem service point of view. The tree condition is calculated automatically by the i-Tree Eco software, and a quite large share of "good" and "excellent" categories was reported in other i-Tree studies as well (Martin et al., 2012). The main reason for this is that this categorisation is based on the percentage of branch crown dieback in the crown data. This may result in better tree condition categories than the trees' real health status, because "poor", "critical" or "dying" categories are given only if the dieback is above 25%. This occurs very rarely, because if there is such a large amount of dead branches and foliage, those parts are cut off by the management company, or if that is the case for several neighbouring trees, the solution is sometimes the complete replacement of the tree alley.

But there are some species-specific differences even with this type of categorisation, which could provide valuable information for species selection. As an example, in the urban forest of the city centre of Szeged, the "worse" condition of two native *Tilia species* (*Tilia cordata*, *Tilia platyphyllos*) was detected, which refers to their lower urban tolerance, and calls attention to the need for further research specific to these trees. The good condition of the *Platanus hybrida* population contributes to the extremely high amount of leaf area, and it is a popular species planted mainly in tree alleys in Hungary and many countries in Europe. The good tolerance of urban circumstances and the large amount of leaf area provided by these trees is indicated by the fact that more than half of most of the services were connected to this species, in the analysis of Rogers et al. (2012). The good health state of the individuals of *Tilia tomentosa* indicates the relatively complete canopies in the newly-planted tree line. The adequate general condition of *Acer platanoides* trees appears also in other studies. In the contribution of Pothier and Millward (2013) on an urban forest analysis in Toronto, the individuals of this species appeared to be the best from the point of view of carbon sequestration and air pollution removal (due partly to the good tree condition of the population). Thus, this species might be considered suitable for urban planting in the climatic circumstances of this study, without regard to nativeness.

From the investigated ecosystem services, the results of carbon sequestration can be compared more easily to the results of other studies, as air pollution removal is calculated based on hourly meteorological data and on pollutant concentrations, which have very strong variability between different cities. The average carbon storage of 410.8 kg/tree and yearly carbon sequestration of 14.01 kg/tree (referring to the complete urban forest in Szeged) are close to the results of Wälchli (2012), obtained for Zürich (Switzerland) with i-Tree Eco analysis (348.9 kg and 12.97 kg/yr), and to the results of Russo et al. (2014) for Bolzano (Italy), calculated with allometric equations (377.4 kg and 12.1 kg/yr). In the latter publication, the species composition of the urban forest was quite similar to the one in Szeged. From the main species, the Platanus hybrida population can be characterized with roughly similar size distribution (mean DBH: 64.5 cm) to the London planes of Szeged (mean DBH: 63 cm). We obtained 1406.2 kg as the average carbon storage per tree, and 35.9 kg/yr as average carbon sequestration per tree for Szeged. These values were slightly above 1,500 kg and 35 kg/yr (allometric equation-based calculations).

We are not aware of published carbon sequestration estimates for DBH classes from European cities. Martin et al. (2012) published results referring to an institutional environment (university campus) for the city of Auburn (Alabama, USA), which is situated in the same wider climatic zone (Köppen's Cfa) as Szeged. From the climatic characteristics, the number of frost-free days is most important for the carbon calculations of i-Tree. The carbon sequestration estimates were (in the DBH categories used in our study as well: 1–15 cm, 16–30 cm, 31–45 cm, 46–60 cm, 61–75 cm, 76+ cm): 3, 8, 15, 22, 32, 54 kg/yr, respectively. The values for the same categories in the total tree stand of Szeged (in a little colder and drier climate in general) are: 2, 7, 13, 24, 36, 54kg/yr. A review of carbon storage and sequestration values referring to U.S. cities is given by Nowak et al. (2013). The results which are suitable for comparison, are expressed as an average on a unit area basis (kgm^{-2} canopy cover); the values of Boston, MA (0.231 kgm^{-2}), New York, NY (0.230 kgm^{-2}) and Atlanta, GA (0.229 kgm^{-2}), are very close to the average value for Szeged (0.232 kgm^{-2}).

The work of Nowak et al. (2006) is a similar study on air pollution removal in U.S. cities, with values given for canopy cover unit area (gm^{-2}). The total amount of removed pollutants in Szeged is 6.5 gm^{-2} and the values of Charleston, WV (6.7 gm^{-2}) and Minneapolis, MN (6.2 gm^{-2}) are close to it. From European studies, the results for Victoria (London) and Barcelona (10.9 gm^{-2} and 9.3 gm^{-2}) are much higher than those for Szeged, which is due to the fact that these are crowded capital cities. There are also some differences if we look at the amounts of different pollutants separately, e.g. in Barcelona, the share of NO_2 is higher (17.87%) than in Szeged (6.5%), where PM10 and O_3 represent almost 90% of the total amount of pollutants removed.

The economic value of carbon sequestration is not very high compared to some other services of urban tree stands. This was stated by other authors as well (Soares et al., 2012). The ecosystem service of carbon sequestration by trees in an average European city is small compared with the total greenhouse gas emissions, but it is considerably higher if we compare it with the emissions derived from the sectors that are directly managed by the city council (Baró et al., 2014).

Air pollution removal provides much greater returns in monetary value. The levels of air pollution have been shown to be statistically associated with health status in Szeged, and it has been demonstrated as well in the case of O_3 and PM10 (Matyasovszky et al., 2011), which are the pollutants removed in the largest amounts in Szeged. It should be noted that the air pollution concentration dataset could be obtained from only one monitoring station in the city. The station is situated not far from the city centre, but not inside it, thus the concentration values do not refer exactly to the most polluted sites' values. The significance of this service is also very high because a small change in air quality parameters can result in a strong improvement in environmental status, which has particular importance in city centres.

The structural attributes of the tree alleys in the case studies are mainly the direct results of the species composition and management characteristics. The low values of canopy missing and dieback for the trees of József Attila avenue are a consequence mainly of the protection of the tree alley during infrastructure development projects in previous years. In comparison, in Petőfi Sándor avenue, huge parts of the crowns were cut off during infrastructure development activities, even for some of the remaining trees as well, and the building works caused a deterioration in tree condition, in terms of crown dieback in some parts of the stand. The low "leaf area:average DBH" ratio in the case of the *Sophora japonica* trees of Hajnóczy street (which is parallel to the low "leaf area:carbon storage" ratio, as observed in the service provision section) is a result of frequent pruning. It is needed because of the characteristic airy, loose crown structure of the species, which calls for such maintenance. This problem is even more serious on Hajnóczy street because of the nearby high buildings. The high values of crown dieback are caused by the dying of lower branches of the large trees, which get too low amount of light.

The reason of the lower air pollutant removal values in the 16–30 cm DBH category in the case of József Attila avenue is that most of the trees in this diameter class belong to the population of an oak species with a columnar appearance (*Quercus robur "Fastigiata"*). The lateral distribution of the crown of this species is much lower than in the case of other species, which results in very small leaf area values, even if there are no large missing or dead parts in the crown.

With the comparison of the stands under different management regimes, our aim was to provide some preliminary results for a problem that needs further studies. The legal protection status that we used to differentiate between the chosen street pairs does not always result in characteristic management differences. For safety reasons, pruning and other small maintenance activities are allowed for the protected stands too, and many of the non-protected stands are in very good condition. The amount and growth of biomass and leaf area of trees (consequently, the provision of services) in a given DBH class is strongly affected by the growth characteristics and tolerance of urban circumstances of different species, besides management-related interventions. Although the investigated stands are in a very similiar built environment, there are also slight differences in crown light exposure, which also affects the amount of leaf area. Therefore, the differences in service provision can not be explained only by management differences. These complex interactions need further, targeted investigations, where, besides further empirical studies, simulation-based calculations may also play an important role in differentiating the effects of the above-mentioned factors.

With the comparison of the two neighbouring streets, of which one was the location of a complete tree alley replacement some years ago, we wanted to show the effects of tree clearcuts during building public space development projects on the amount of ecosystem services. In the place of the non-protected stand (Gutenberg street), a new tree line was planted. But even from our results it is clear that old-growth trees provide climate- and air quality-related ecosystem services to a very great extent. The maintenance costs of old-growth trees are generally higher, but in McPherson's (2003) results, for example, it is clear that for many of the investigated species, the cost-benefit ratio increased drastically for the older trees but the economic value of services was still greater than the increased costs.

Besides the two services investigated in our study, there is also the case for the service of microclimate regulation (through shading and evapotranspiration), which might also be expressed in economic value (e.g., through energy savings in buildings). The homogeneous tree line of newly-planted small trees obviously can not regulate microclimate in the same way as the former large trees with huge leaf area. Such streets remain street canyons with extreme heat load in the summers for many years to come. And people can be emotionally bound to big trees that are present in a certain place for long time, which means that old-growth trees provide important cultural services (aesthetic value, sense of place). These observations suggest that complete tree alley changes are not advisable from an ecosystem service point of view.

Meanwhile, it should be noted that the tree alley of Hajnóczi street consists mainly of *Sophora japonica* trees, with the management problems described previously (bad condition, frequent pruning). This type of tree alley was the previous one in Gutenberg street, which might have contributed to the decision to clearcut. This also shows that before planting trees of different species, it is worth investigating their general condition and service-providing capacity in the city. For such purposes, creating and maintaining a tree cadastre database and analyses of ecosystem services similar to the ones presented in this study, may be advisable in as many cities as possible. The characteristics of different species' populations, their life cycles, the services provided during this time, and the benefit-cost relationships can be monitored in the best way if all management activities are also registered on a per tree basis.

5. Conclusions

In this study, we carried out the first tree individual-based urban ecosystem service assessment in Central Eastern Europe, based on a large complete tree inventory. This was achieved with an adaptation of the i-Tree Eco model (developed in the U.S.), which is a targeted tool to evaluate climate- and air quality-related ecosystem services of urban trees. The adaptation process required meteorological data collected by the national meteorological service, and air pollution data, which is collected in a measurement system that is owned by the ministry and which is available to the public. This means that the adaptation process can definitely be carried out in other countries of the CEE region, with similar responsible institutions.

With the help of i-Tree model, the actual state of smaller tree stands or even huge urban forests can be assessed, and the effects of tree removal losses in different development scenarios can also be quantified. Besides these practical applications, several research questions can be investigated based on the i-Tree results (together with the baseline tree cadastre database). In our study, we pointed out that such analyses may help forming urban tree species selection policies. Management-related interventions (such as pruning, which can also be affected by the protection status) can result in a decline in service provision (due to biomass removal), but its exact quantification and differentiation from other relevant factors need further, focused investigations.

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Smart tools of urban climate evaluation for smart spatial planning

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Abstract

Air temperature and humidity conditions were monitored in Hradec Králové, Czech Republic, by a network of meteorological stations. Meteorological sensors were placed across a representative variety of urban and suburban environments. The data collected over the 2011–2014 period are analysed in this paper. The data from reference standard meteorological stations were used for comparison and modelling purposes. Air temperatures at the points of interest were successfully modelled using regression relationships. The spatial expression of point measurements of air temperatures was provided by GIS methods in combination with CORINE land cover layer, and satellite thermal images were used to evaluate the significance of these methods. The use of standard climate information has low priority for urban planners. The impact of the urban heat island on city residents and visitors was evaluated using the HUMIDEX index, as it is more understandable for urban planners than temperature conditions as such. The aim of this paper is the modification, description and presentation of urban climate evaluation methods that are easily useable for spatial planning purposes. These methods are based on comprehensible, easily available but quality data and results. This unified methodology forms a theoretical basis for better urban planning policies to mitigate the urban heat island effects.

Keywords: *urban heat island, city development plan, HUMIDEX, Hradec Králové, Czech Republic*

1. Introduction

The urban population in 2014 accounted for 54% of the total global population, and is expected to grow by approximately 1.64% per year between 2015 and 2030. The rate of urbanization is especially important for low- and middle-income countries, as 70% of the world population is forecasted to live in cities by 2050 (WHO, 2013). From this point of view, urban climate research ranks highly as a current topic in recent climatology, largely due to the growing number of city inhabitants together with the significant effects of climatic conditions on their health and the risk of damages caused by extreme weather events.

In the case of air temperature, the city centre could be about several degrees centigrade warmer than suburban landscapes. It directly influences not only human health but also causes negative economic consequences (Oke, 1997). The urban heat island is a function of meteorological factors (air temperature, precipitation, solar radiation, cloud cover, air flow, evapotranspiration, etc.) and the character of the city itself: the number of inhabitants and population density; topography; altitude; water bodies; land cover – built-up area; surface colour – their albedo; distances between buildings; building heights; surface resistance; the surface geometry of the city – the so-called "street canyon"; the "anthropogenic heat" of heating and industry; surface retention; the thermal capacity of materials; thermal conductivity and humidity, etc. (Oke, 1997; Voogt, 2002; Landsberg, 1981). The urban heat island effect becomes stronger during warm, windless and cloudless days (Oke, 1982). An urban area with a unique temperature regime (e.g. due to parking lots, industrial objects, flat roofs, asphalt roads, etc., i.e. isolated urban locations that produce “hot spots” within a city) is occasionally referred to as a "micro-urban heat island" (Aniello et al., 1995; Ekşi and Uzun, 2013; Smargiassi et al., 2009; Stathopoulou et al., 2004).

Knowledge of local geographical conditions and the surface temperature regime allows for the identification of places with thermal and/or thermodynamically-related local climatic effects (Vysoudil et al., 2009). Ellefsen (1991) identified 17 types of urban terrain zones (UTZ) to classify the physical structure of cities. The method of urban morphometry, that uses aerial photography, is applicable to cities all over the world. Oke (2006) designed a simple and generic classification of city zones to improve the siting of meteorological instruments in urban areas. A simplified classification of distinct urban forms according to their ability to impact local climate is used to divide city terrain into seven homogenous regions called “urban climate zones” – UCZ (Srivanit, 2013). The “local climate zone” (LCZ: Stewart and Oke, 2012) classification system provides a research framework for urban heat island studies and standardizes the worldwide exchange of urban temperature observations. Lehnert et al. (2014) have set up a classification of existing stations within local climate zones (LCZ) for conditions of the Czech Republic.

Vysoudil and Ogrin (2009) present some possibilities of application of a portable infrared camera for topoclimatic research, especially for establishing the differences in temperatures of the active surface layer. The impact of relief is expressed in a much higher urban heat island intensity in a city located in a valley bottom (including the city centre) than in cities of comparable size but located in flat areas (Bokwa, 2011). Satellite images, radar measurements and aviation technology are widely used for studying urban

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climates (e.g. Voogt and Oke, 2003). Aerial and satellite imagery can help researchers describe surface heterogeneity and its influence on microclimate.

The quantification of urban heat island effects on mesoclimate, and their possible influence on human beings with respect to the size of the agglomeration, the level of built-up areas and features of their surfaces etc., is a principal current research question. Significant spatial variability in the environment is the main obstacle to modelling the urban climate because the natural surface vegetation overlaps infrastructure and buildings. Bottyán and Unger (2003) and Souch and Grimmond (2006) claimed that besides meteorological conditions (radiative or advective), factors such as the characteristics of the built-up area, land use, topography and the presence of large water bodies, markedly shape the spatial differentiation of meteorological elements in a city.

The negative influence of the urban heat island on the microclimate will likely increase. Urban development standards need to be created by using existing knowledge and developing tools for urban planning over long-term periods (Jendritzky et al., 2003). This study provides knowledge of standard and advanced microclimatic monitoring methods as a helpful tool for urban planning.

2. Study rationale

The relations between extreme weather situations (extreme temperatures, heat waves, etc.) and particular health complications for a city's inhabitants are clear. An evaluation of satellite thermal images and mortality data showed that a direct connection exists between mortality risk and high surface temperatures on extremely hot days. Mortality is strongly associated with the duration of heat waves in summer, demonstrated in many locations: Tan et al. (2007) for Shanghai; Karl and Knight (1997) for Chicago; Dessai (2002) for Lisbon; Schär et al. (2004) for Paris; and Smargiassi et al. (2009) for micro urban heat islands in Montreal. The effect of relief and land use on heat stress in Kraków (Poland) was evaluated by Bokwa and Limanówka (2014). These authors' results suggest that in cities located on concave landforms, relief is at least as equally important as land use in controlling the spatial pattern of heat stress. Pokladníková et al. (2009) demonstrated another significant characteristic of the urban climate in which heat waves are more frequent and longer compared with suburban areas, based on a study of medium-sized cities in the Czech Republic. Středa et al. (2014) analysed the number of "hot wave" days in Hradec Králové from 1961 to 2007; such days increased by two days per decade. The term "heat wave" is relative to the climatic conditions at a specific location. Therefore, the World Meteorological Organization recommended that a heat wave be defined as the period during which the daily maximum air temperature over five consecutive days is at least 5 °C higher than the normal average daily maximum for a given period (Frich et al., 2002). The frequency, intensity and duration of heat waves did not generally increase during the 20th century. In the 21st century, however, and particularly in the second half, the situation will likely be dramatically altered.

Traditional studies of heat islands typically do not include bioclimatic aspects; therefore, these studies are of limited use to urban planners. An evaluation of the effects of anthropogenic changes on the thermal environment that are related to human health and wellbeing is needed (Jendritzky and Nübler, 1981). Numerous indices can evaluate the influence of temperature, moisture and wind on human bodies. For example, d'Ambrosio Alfano et al. (2011) proposed the main comfort and stress indices caused by the thermal environment. In addition to temperature- and moisture-based indices, more complex indices account for factors such as wind speed and global radiation. The use of these metrics, however, is limited by the wide variability in these factors in the urban environment (e.g. shaded or sunny streets, perpendicular or parallel to wind direction, etc.).

Appropriate urban planning and building design provides measures to reduce heat stress for individuals living in cities and reduces the urban heat island effect. The heat load becomes more extreme if the human body is directly irradiated by solar radiation. Planning measures that provide shade for pedestrians (e.g. trees, arcades and narrow streets) can therefore reduce the heat load (Jendritzky, 1988). Szűcs (2013) investigated the extent to which urban planning and the resulting morphology of the built environment in Dublin influenced the microclimate that was created by the wind regime.

To maximize thermal comfort in urban areas, climatic aspects should be considered at all scales, from the design of individual buildings to regional planning. The type of housing, its density and optimal distances between buildings, the geometric configuration and orientation of buildings, building heights, the properties of the building materials and colours of external surfaces, the orientation and size of windows, settlement shading and radiation control, the use of open space, and the functions and location of land use, all of these factors might be considered during the urban planning process to improve the urban microclimate (Koppe et al., 2004).

Microclimate tools have recently been used for the simulation of microclimate in urban conditions, with respect to the cooling effects of greening on urban microclimates, but in-situ measurements of meteorological conditions for model verification are necessary. Some possible uses of numerical microclimate simulation tools (ENVI-met) for urban spatial planning have been described for instance by Srivanit and Hokao (2013). The average maximum temperature would be decreased and be reduced by as much as 2.27 °C in the peak of the summer when the quantity of trees was increased by 20%. Similarly, an analysis in the United States on the potential of vegetation to reduce summer cooling loads in residential buildings in cities found that an additional 25% increase in urban tree coverage saved 40% of the annual cooling energy cost in Sacramento (Huang et al., 1987).

The development of Hradec Králové was planned by the architect Josef Gočár (1880–1945) in the early 1920s. His regulation of the city, which commenced in 1925, included the concept of using a significant amount of green spaces. The implementation of the city development plan was recently addressed in an evaluation of the impact of land cover changes on the city microclimates. Therefore, the results from the current study might be a helpful tool for urban planning in Hradec Králové and for preparing regional city planning in areas with similar conditions. Stewart (2011), however, has warned us that "If climate modelers, weather forecasters, city planners, urban engineers and building architects are to be convinced of the serious environmental and social implications behind the urban heat island effect, heat island researchers must first produce results that can be trusted". Such results should be based on comprehensible, easily available but reliable quality data.

They can be used when public vegetation planning and nurturing is under discussion, as well as for negotiations with other administrative bodies (the river authorities, the road and motorway directorate, energy companies, etc.).

3. Data and methods

Hradec Králové is a city with a population of nearly one hundred thousand inhabitants and an area of 105.6 km^2, which makes it among the ten largest cities in the Czech Republic. The landscape is predominantly flat with an average altitude of 235 m a.s.l. The mean annual temperature (1961–1990) is 8.7 °C, and the mean annual total precipitation is 600.2 mm. The warmest months are July (18.3 °C) and August (17.8 °C) (Fig. 1). The ALADIN-Climate/CZ model predicted for the simulation period 2021–2050 an increase in the mean annual temperature of up to 9.9 °C. August was predicted to be the warmest month, with a mean temperature of 21.0 °C. The surrounding area is dominated by arable land and suburban forests, such that the area of green vegetation per inhabitant is one of the highest among large Czech cities. In addition, the confluence of the Labe and Orlice Rivers in the city centre significantly influences surrounding climatic conditions.

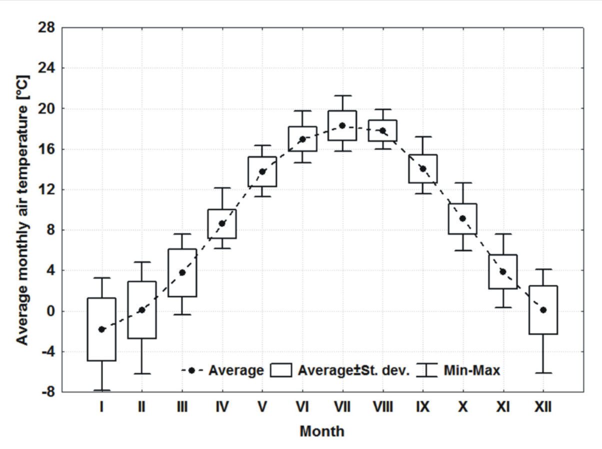

Fig. 1: Mean annual temperature in Hradec Králové during the period 1961–1990.
Source: Czech Hydrometeorological Institute

3.1 Evaluation of urban (bio)climatic conditions as a five-step process

Step I: A network of spatial monitoring points was established in Hradec Králové in August 2011 to analyse the influence of surface properties (land cover and land use) and their horizontal effects on temperature and humidity conditions (Tab. 1; for geographic locations, see Fig. 6). Temperature and humidity were monitored using sensors located across a representative variety of urban and suburban environments. The special network used U23 HOBO Pro V2 sensors located within a radiation shield at a height of two meters above the ground. The measurement interval at all stations was ten minutes.

Location of measurement	Label	Brief characteristics of the environment	Ellefsen (1991) UTZ classification	Stewart and Oke (2012) LCZ classification	Oke (2006) UCZ classification
Industrial zone 50°11'43.159"N, 15°51'18.336"E	1	significant proportion of horizontal concrete and asphalt surfaces, partial grassland, sunlit spaces all day	Do4	LCZ 8_B (large low-rise with scattered trees)	UCZ 4
City park 50°12'21.884"N, 15°49'31.925"E	2	woody vegetation in the city centre, grass cover, full shade, near the confluence of two major rivers	Unclassifiable	LCZ B (scattered trees land cover type)	Unclassifiable
Suburban forest 50°10'39.974"N, 15°54'14.036"E	3	middle-aged, predominantly coniferous forest, shaded by trees (except in the afternoon), absence of significant artificial surfaces	Unclassifiable	LCZ A (dense trees land cover type)	Unclassifiable
Historic city centre 50°12'39.493"N, 15°49'55.767"E	4	the historical part of the city centre, enclosed area (courtyard) with vertical surfaces and limited air flow, artificial solid surfaces, insolation from morning until afternoon	A2	LCZ 3_2 (compact low-rise with mid-rise built type)	UCZ 2
Urban residential zone 50°12'52.516"N, 15°49'32.781"E	5	location surrounded by residential buildings five stories high, woody and shrubby vegetation in the immediate vicinity of the measurement location, grass cover, small summer swimming pool, partially sunlit afternoons	Dc3	LCZ 2_B (compact mid-rise with scattered trees)	UCZ 3
Reference climatological location 50°13'21.367"N, 15°47'15.969"E	6	located according to the principles of meteorological station establishment, the sensors are placed in a meteorological shelter	Do3	LCZ 9 (sparsely built – built type)	UCZ 5
Reference climatological location 50°10'39.01"N, 15°50'18.98"E	7	located according to the principles of meteorological station establishment, the sensors are placed in a meteorological shelter	Do3	LCZ 9 (sparsely built – built type)	UCZ 5

Tab. 1: Location of the measurement stations and characteristics of the environment
Source: authors and references in heading

Data from standard meteorological stations of the Czech Hydrometeorological Institute (CHMI) were used as reference points. The CHMI stations at Locality 6 and Locality 7 are standard meteorological stations at which the air temperature and humidity are monitored at a height of two meters above a grassland.

Step II: Data from the special meteorological points were compared with the data from the reference climatological stations of CHMI using regression analysis. Regression relationships can be used for spot modelling of temperature and humidity under urban climate conditions. Based on the climatological data from the reference meteorological stations, it is possible even without direct measurements to estimate temperature and moisture conditions at the measuring points. The ten-minute data over 2011–2014 were evaluated using linear regression methods.

Step III: The impact of the local urban and micro-urban heat island on city residents and visitors was evaluated using the HUMIDEX index. HUMIDEX was used for the first time in 1965 in Canada to describe how hot the weather feels to the average person by combining the effect of heat and humidity. The index provides an indication of a citizen's perception of the outdoor air as a consequence of a lack of evaporation of perspiration during hot and humid weather (Ghanghermeh et al., 2013).

The following equation was used to calculate HUMIDEX:

$$HUMIDEX = T + (0.5555) \times (e - 10.0),$$

where T = air temperature (°C) and e = actual vapour pressure (hPa).

An evaluation was conducted from August 2011 to September 2014. Only the months June, July and August were considered because temperature increases that might indicate potential discomfort did not occur in the remaining months.

Ten-minute temperature and humidity data were used to calculate hourly averages, and HUMIDEX was calculated based on the hourly averages. The actual vapour pressure e [hPa] was calculated from the temperature T [°C] and relative humidity φ [%] data using well-known relationships. The HUMIDEX scale used in this study is presented in Tab. 2.

Step IV: Point measurements of air temperature and humidity (see Step I above) were interpolated using standard GIS methods (ArcGIS 10.3, ESRI, Redlands, California, USA). The layer of Coordination of Information on the Environment (CORINE) land cover (Heymann et al., 1994) from 2006 was converted into raster. The raster was then reclassified by attaching every single pixel to one of the six categories according to the supposed effect on air temperature and humidity. This method is commonly employed in climatology for the spatial expression of climatological variables. The method is based on the calculation of raster values from point measurements by regression relations between the investigated variable and the reclassified CORINE layer (Van Weverberg et al., 2008). The universal linear kriging method (Papritz and Stein, 2002; Zhang et al., 2011) was applied to interpolate the measured values of the temperature and the values calculated from the regression dependence. The resulting raster was then smoothed by a low pass filter.

HUMIDEX range (°C)	Degree of comfort
Less than 29	Comfort
30–34	Some possible slight discomfort
35–39	Some possible moderate discomfort
40–45	Possible strong discomfort
46–53	Possible very strong discomfort
Over 54	Danger of death; imminent heat stroke

Tab. 2: HUMIDEX scale (after Baum et al., 2009)

Step V: Spatial heterogeneity was evaluated by using thermal satellite imagery. The output from thermal remote sensing was compared with and evaluated by ground monitoring results.

Surface temperature data were processed using a mono-window algorithm, which considers a single frame in a thermal spectrum. The mono-window algorithm for processing images from the LANDSAT-8 (TIRS sensor) satellite consists of two steps (Weng et al., 2004). In this case, the brightness temperature represents the temperature of an absolutely black body at a given wavelength and radiation intensity. Within a selected range, however, the earth does not behave as an ideal emitter, and its emissivity is extremely variable over space. Therefore, a correction is necessary. In accordance with Mallick et al. (2008), the emissivity correction used CORINE Land Cover 2012 (CLC 2012) classes with known average emissivity values.

4. Results and discussion

4.1 Step I

Table 3 shows that Locality 4 was warmest according to most of the temperature variables. This locality thus showed the highest urban heat island. Incoming solar radiation caused intensive warming of artificial surfaces at Localities 4 and 1. The coldest point in terms of mean values was Locality 3 (by up to 5 °C). However the outstanding feature of this locality is higher thermoregulation of vegetation cover and thus the absolute minimum value was recorded in Locality 1 due to the surface emissivity.

Locality 2 had the most intense cooling effect during extremely high temperature episodes and had the smallest temperature amplitude. Locality 1 had the highest extreme values due to artificial surfaces. The (ir)regulation of solar radiation, albedo, emissivity and air temperature on the temperature of asphalt surfaces and near-surface air layer was previously reported in detail (Středa et al., 2011). The asphalt temperatures surpassed 70 °C, particularly on days with significantly high levels of radiation.

The relative humidity is shown in Table 4. Humidity at the typically humid Locality 3 rarely dropped below 40%, and values higher than 95% prevailed. The typical night-time (day-time) value of 100% (lower than 100%) at Locality 1 is associated with rapid cooling (warming) of the air. The dew point temperature was attained as a result of the cooling.

The evolution of the air temperatures and their differences on an extraordinary hot day are shown in Figure 2. The positive effects of the land cover at Localities 2, 3 and 5 on extreme temperature reductions are obvious. The air temperatures at Localities 1 and 4 were significantly higher than those measured at the CHMI reference station.

4.2 Step II

The relationship between the air temperature at the CHMI meteorological station (Locality 7) and the meteorological measurement in the city centre with the highest air temperature (Locality 4) was determined. The relationship ($r^2 = 0.9765$) was characterized by the linear

Locality	N valid	Avg.	Median	Min	Max	1^{st} quart.	3^{rd} quart.	1^{st} perc.	99^{th} perc.	Range	St. Dev.
1	22323	11.0	10.8	*– 22.6*	39.5	3.8	17.6	– 7.5	32.1	**62.2**	9.2
2	22320	10.6	11.0	– 19.1	*35.7*	3.6	17.0	– 7.0	*29.1*	*54.8*	*8.5*
3	22102	*9.7*	*9.6*	– 22.5	37.3	*2.7*	*16.0*	*– 8.1*	29.9	59.7	8.8
4	22319	**12.0**	**12.1**	**– 17.7**	**41.1**	**4.7**	**18.6**	**– 6.6**	**33.3**	58.8	**9.3**
5	22320	11.0	11.2	– 18.6	36.2	4.2	17.4	– 7.1	30.0	*54.8*	8.7
6	22322	10.4	10.6	– 20.1	36.8	3.6	16.9	*– 8.1*	30.0	56.9	8.8
7	22024	10.7	10.8	– 18.4	37.2	4.0	17.0	– 7.5	30.0	55.6	8.7

Tab. 3: Basic statistical analysis of the air temperature over the entire period (August 2011–October 2014). Note: maxima are in bold, minima are in italics. Source: authors

Locality	N valid	Avg.	Median	Min	Max	1^{st} quart.	3^{rd} quart.	1^{st} perc.	99^{th} perc.	Range	St. Dev.
1	20782	79	85	18	100	66	95	31	100	**85**	**19**
2	20779	83	88	**23**	100	72	97	**39**	100	*77*	*17*
3	22044	**85**	**91**	19	100	**76**	**98**	36	100	81	*17*
4	20778	75	*79*	18	100	63	89	*29*	100	82	18
5	20779	78	83	20	100	67	92	35	100	80	*17*
6	22322	*74*	*79*	*16*	100	64	*88*	30	100	81	18
7	22287	75	*79*	19	100	*62*	90	32	100	81	18

Tab. 4: Basic statistical analysis of the air humidity over the entire period (August 2011–October 2014). Note: maxima are in bold, minima are in italics. Source: authors

regression equation Y = 1.0594 × X + 0.7285 (where Y = air temperature at the measurement point, and X = air temperature at the CHMI standard meteorological station). As shown, air temperature can be quite easily modelled by regression models based on nearby meteorological stations, if available. Due to the low density of meteorological stations, air temperature modelling in small cities also requires sophisticated models employing variables such as: distance to the urban area, topographic position, land-cover diversity, building density and northness index (Ivajnšič et al., 2014).

The relationship between air humidity at these stations was defined by the linear regression equation Y = 0.9503 × X + 3.229 (where Y = air humidity at the measurement point, and X = air humidity at the CHMI standard meteorological station). The dispersion values around the linear trend line were significantly larger compared with the air temperature. The coefficient of determination was high (r^2 = 0.8812), indicating a close relationship; however, modelling the relative humidity (based on simple regression using data from the reference station) resulted in significant errors and, therefore, the use of this procedure is limited.

4.3 Step III

In Step III, the HUMIDEX index was calculated for all sites during the months of June, July and August. Graphical and basic statistical evaluations are given in the box-plots (Fig. 3). The highest values were obtained at localities with

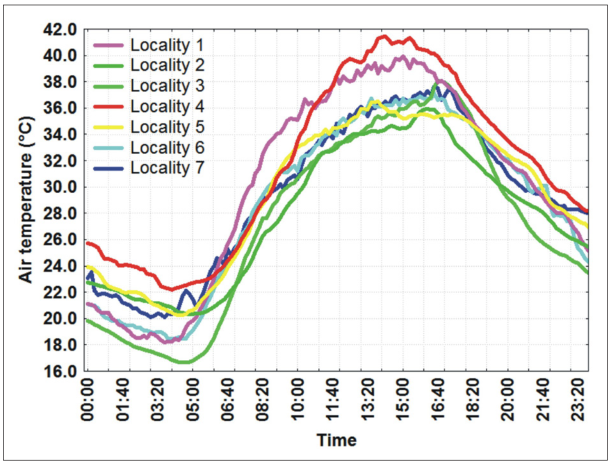

Fig. 2: Evolution of the air temperature during the hottest day (28^{th} July 2013) Source: authors

the highest proportion of artificial surfaces (Locality 1 and Locality 4), as expected. The critical values were achieved only in rare extreme cases (less than 25% of all cases).

HUMIDEX limits of 35 °C and 40–45 °C have been proposed in Europe and Canada, respectively, to reduce the risks of excessive heat. Some results, however, show that HUMIDEX frequently results in an underestimation of the potential danger in the workplace and an unreliable comfort prediction occurs when this index is used in indoor situations (d'Ambrosio Alfano et al., 2011).

The differences in the daily HUMIDEX between the sites are shown in Figure 4. In Locality 1, discomfort over artificial surfaces was first recorded in the early morning and then peaked in the afternoon. Discomfort in Locality 4 started approximately one hour later because enclosed spaces were shaded by buildings early in the morning. The daily evolution of discomfort in the forest (Locality 3) is interesting: until noon, the discomfort was identical to the CHMI stations, while in the afternoon, when the sensor was no longer overshadowed by trees, the frequency of discomfort increased significantly. This result corresponds fairly well with the findings of Litschmann and Hadaš (2003) and Mayer (1996). Mayer (1996) evaluated the effect of trees in street canyons in Munich (Germany) by comparing street canyons (north–south) with and without trees. This author reported a small effect on air temperature measured at a height of 1.10 m above ground level, but the physiologically equivalent temperature was reduced from 46 °C to 31 °C, which reduced the heat stress by 40%.

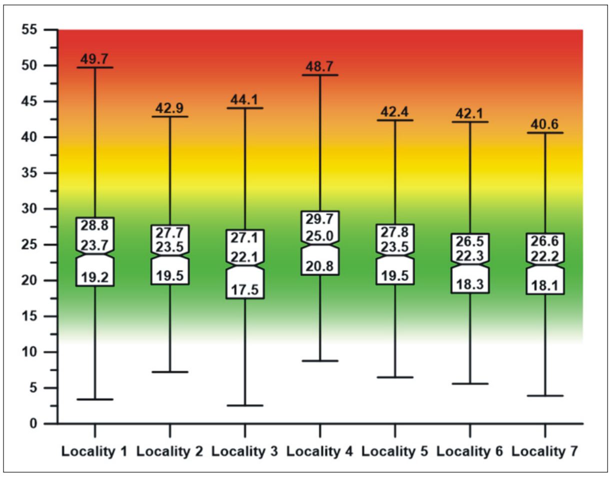

Fig. 3: The range of HUMIDEX values for each locality during July and August 2011–2014 (hourly data) and associated descriptive statistics (i.e., median, minimum, maximum, first quartile, and third quartile); plotted with Software Grapher, Golden Software, Colorado
Source: authors

July had the highest incidence of discomfort based on the HUMIDEX index. Locality 4 contained the most extreme places, similar to the concrete and asphalt in Locality 1. August 2013 was the worst month in terms of thermal comfort (Tab. 5). In contrast, the summer of 2012 was characterized as relatively pleasant without significant extremes. Erratic values were recorded in 2014. Compared with other years, June and August were relatively cool with a low incidence of discomfort, while July was characterized by the highest frequency of discomfort.

4.4 Step IV

Detailed measurements of meteorological conditions in a heterogeneous urban environment are very expensive. Additionally, the meteorological components of a city cannot be measured at the level of detail required for bioclimatological assessments. Modelling appears to be the most appropriate method to generate the data needed for urban planning purposes with the aim of creating and safeguarding healthy conditions. Re-designing a city on a large scale is typically illusionary, however, and planning measures are usually restricted to a small part of a city (Koppe et al., 2004).

The spatial expression of point measurements of air temperature is obtained using the CORINE layer and GIS interpolation method, as shown in Figure 5. Although the expression generalizes the air temperature distribution, the air temperature difference between the city centre and

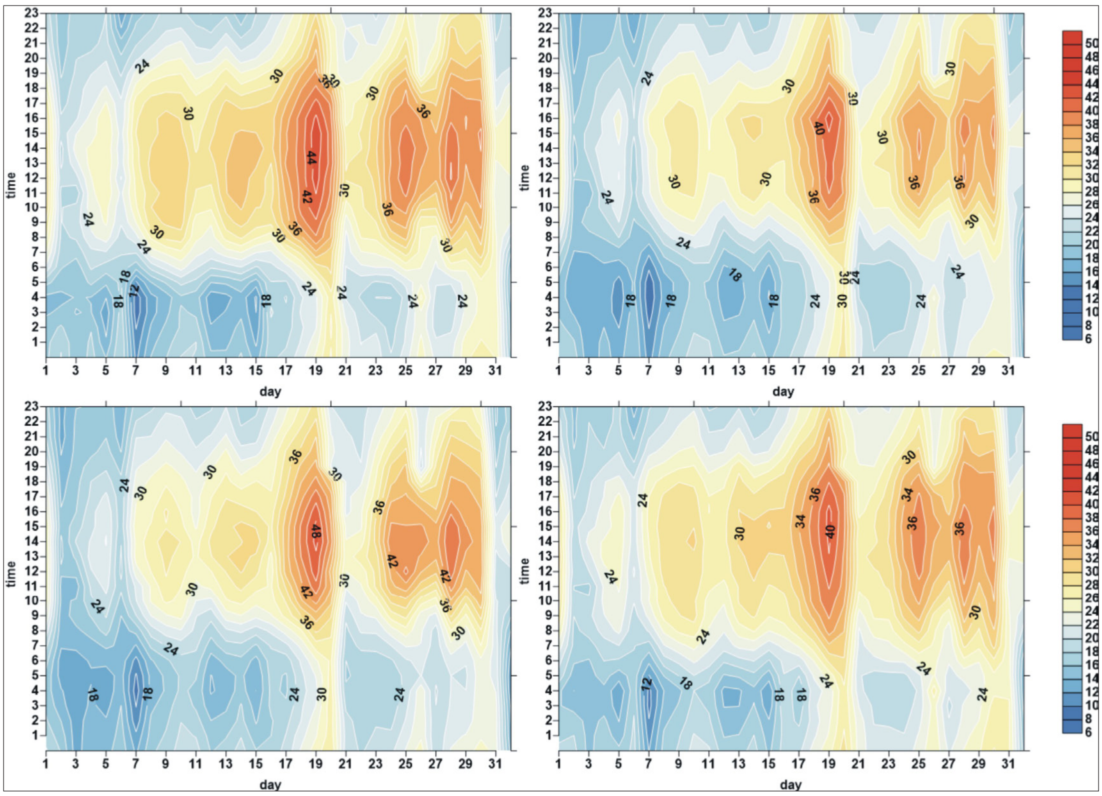

Fig. 4: 24-hour HUMIDEX values (Y axis) at selected locations (Locality 1 – upper left, Locality 2 – upper right, Locality 4 – bottom left, and Locality 6 – bottom right) from July 10, 2013 – August 10, 2013 (X axis); plotted with Software Surfer, Golden software, Colorado. Source: authors

Year	Month	Locality 1	Locality 2	Locality 3	Locality 4	Locality 5	Locality 6	Locality 7	Average
2011	VIII	15	14	7	23	17	14	15	**15**
2012	VI	11	11	10	15	10	8	8	**10**
2012	VII	19	15	15	19	14	12	12	**15**
2012	VIII	19	12	11	23	13	10	10	**14**
2013	VI	14	10	10	17	10	8	9	**11**
2013	VII	24	16	15	28	15	9	10	**17**
2013	VIII	39	33	31	41	36	31	30	**34**
2014	VI	8	6	7	11	7	6	6	**7**
2014	VII	27	22	21	32	23	14	14	**22**
2014	VIII	9	5	6	10	6	4	4	**6**
Average		**18**	**14**	**13**	**22**	**15**	**12**	**12**	**15**

Tab. 5: Relative frequency (%) of HUMIDEX categories relating to "some possible moderate discomfort", "possible strong discomfort" and "possible very strong discomfort" in individual months.
Source: authors

surroundings is obvious. The cooling effect of vegetation and water bodies is also shown. Manik and Syaukat (2015) applied a similar approach (i.e. GIS interpolation of in-situ monitoring data and CORINE layer with subsequent comparison with remote sensing – see Step V) in their analysis of the spatial distribution of air temperature in Bandar Lampung and Jakarta. With respect to urban environment heterogeneity, its area and relatively low number of meteorological stations, however, the mapping expression and distribution of temperature or air humidity using the CORINE layer is only generalized output with simple orientation information value. To maximize the informative value, more punctual data of land cover in GIS are needed. The precise modelling of urban microclimate requires a combination of in-situ measurement with microclimate simulation tools.

During a hot day (20th August 2012; Fig. 5), the daytime air temperature difference between central and suburban parts of Hradec Králové exceeded 5 °C and 4 °C during the night. As a comparative example, the maximum night difference between central Łodź and nearby suburban areas reached 8 °C in winter (Fortuniak et al., 2006).

4.5 Step V

The spatial heterogeneity of the surface temperature in Hradec Králové and its surroundings was evaluated using remote sensing. The results of the satellite thermal-image evaluation (July 27, 2013, 9:53 GMT) are presented in Table 6 and Figure 6. The absolute highest surface temperature (39.9 °C) was recorded at Locality 5, and the lowest (31.9 °C) was recorded at Locality 2.

The surface temperature at Locality 5 was influenced by an industrial zone, highways and building surfaces. The characteristics of the residential area and greenery, however, reduced the air temperature at ground level.

An analysis of the surface characteristics, as represented by the amount of vegetation cover, demonstrates the control of the land surface temperature variability (56–67% of the explained variance) by the degree of urbanisation, which was represented by building density (37–40% of the land surface temperature variance), following Dobrovolný (2013).

A correlation analysis revealed a relationship between both the surface temperature and immediate air temperature, where r = 0.784 or r = 0.985, respectively, upon exclusion of Locality 5 (i.e. the locality with a heterogeneous habitat; therefore thermal remote sensing is likely to be influenced by the sensor resolution). The correlation coefficient between surface temperature and the air temperature sum (Kyselý et al., 2000) and air average temperature (from midnight to 9:53 GMT) was 0.696 and 0.707, respectively. The correlation coefficient between the immediate and average air moisture was – 0.519 and – 0.475, respectively. A similar temperature pattern was

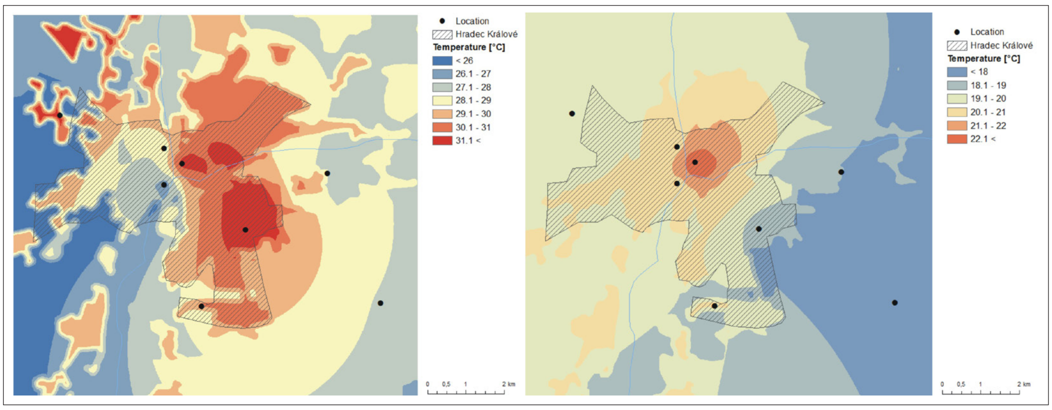

Fig. 5: Average air temperature during the day (left) and night (right) of a hot day
Source: authors

	Locality 1	Locality 2	Locality 3	Locality 4	Locality 5	Locality 6	Locality 7
Instantaneous air temperature (°C)	35.3	29.8	30.1	34.1	32.1	31.8	31.6
Instantaneous air humidity (%)	34	53	48	40	44	36	37
Air temperature sum (°C)	1502	1413	1299	1582	1489	1418	1448
Average air temperature (°C)	22.8	21.4	19.7	24.0	22.6	21.5	21.9
Average air humidity (%)	73	77	83	65	70	70	66
TRS surface temperature (%)	38.7	31.9	32.9	37.4	39.9	35.3	33.8

Tab. 6: Meteorological conditions of measurement localities in terms of thermal remote sensing (TRS)
Source: authors

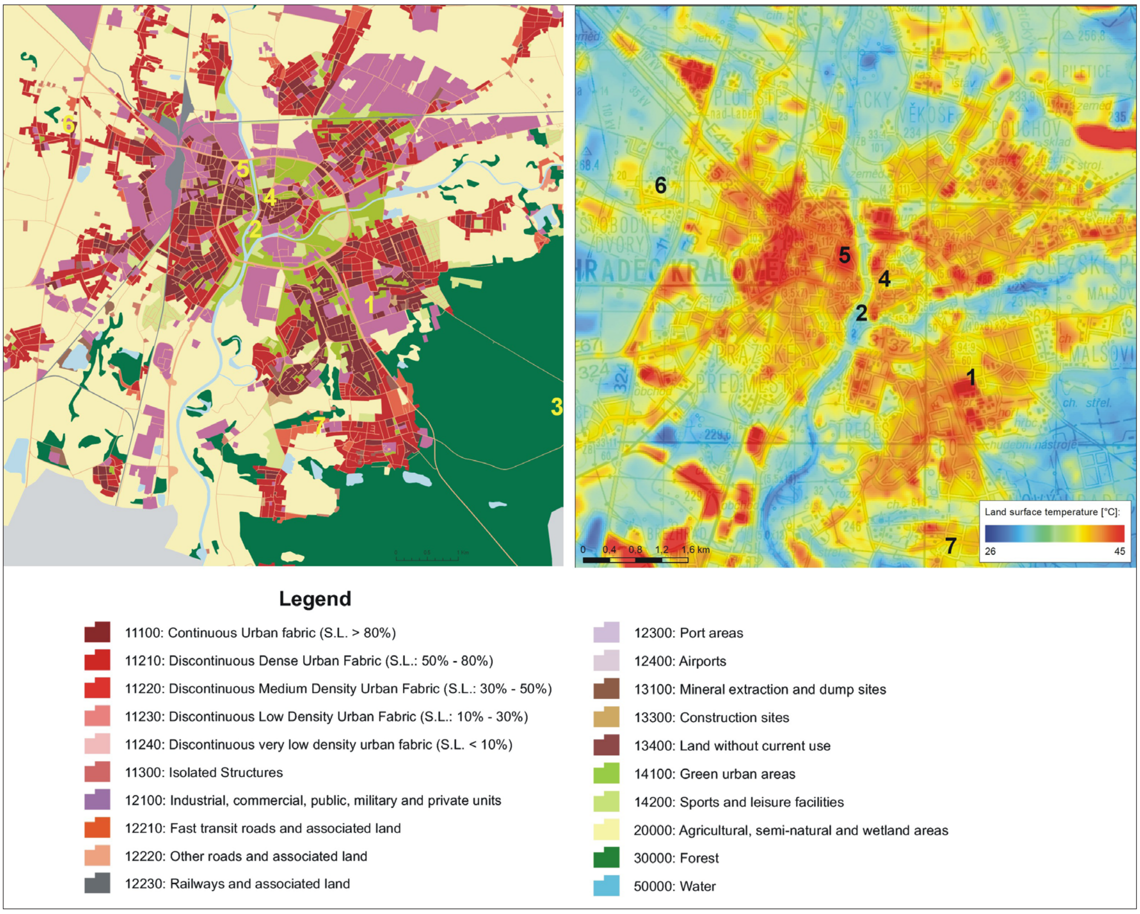

Fig. 6: Satellite thermal image of Hradec Králové and adjacent surroundings with measurement locality network (right part) and land cover map (left part)
Source: Left part with legend: CORINE layer; Right part: LANDSAT-8, scene LC81910252013208LGN00 and authors

obtained by interpolating point measurements (Fig. 5). In contrast, Geletič and Vysoudil (2012) compared the surface temperature field with the air temperature recorded at weather stations within and near the city of Olomouc. Their analysis showed that the description of spatial differences in surface temperatures of a city and its surroundings, based on an evaluation of thermal imagery, was inconclusive. Soil temperature data series measured at selected stations of the same metropolitan station system of Olomouc were analysed by Lehnert (2013), but the impact of the urban landscape on the soil temperature regime was not demonstrated.

5. Conclusions and policy implications

Local governments have limited possibilities of influencing climate change mitigation, with measures such as education, taxes, a fee policy, and other economic instruments (incentives or disincentives). The greatest influence of local governments, however, is evident in their decisions on urban form, primarily through urban planning and land use regulation. The methodology for urban climate study demonstrated here, with the necessary data processing, should be a worthwhile tool for local authorities. Such a unified methodology can be employed to develop a theoretical basis for better urban planning policies to mitigate the urban heat island effects.

Some of the constituent activities could be as follows:

a. Pre-screening based on thermal images and land-use to determine the crucial places for direct monitoring;

b. Establishment of a monitoring network, monitoring as such (for at least two years), and subsequent use of regression analysis with the existing (reference) measurements. In-situ meteorological monitoring is indispensable for precise meteorological monitoring and model verification as well. Air temperatures at locations of interest can be subsequently modelled with a high degree of reliability using regression relationships. In addition, the effect of land cover was reflected in the humidity relationships, although modelling relative humidity using only simple regression results in relatively large errors;

c. Calculation of climatological variables including bioclimatological ones (with direct connections for humans) such as the HUMIDEX index. Climate considerations often have little effect on urban planning. Although urban planners are interested in climatic aspects, the use of climate information has low priority. This is why taking the HUMIDEX values into consideration can change practice, as its influences on humans are more understandable than temperature conditions as such; and

d. The spatial expression of point air temperature and humidity measurements is enabled by GIS methods, but with limited accuracy due to urban environment heterogeneity and the density of the monitoring network.

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The effects of the 1996–2012 summer heat events on human mortality in Slovakia

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Abstract

The impacts of summer heat events on the mortality of the Slovak population, both in total and for selected population sub-groups, are the foci of this study. This research is the first of its kind, focusing on a given population, and therefore one priority was to create a knowledge base for the issue and to basically evaluate existing conditions for the heat-mortality relationship in Slovakia. This article also aims to fill a void in current research on these issues in Europe. In addition to overall effects, we focused individually on the major historical heat events which occurred in the summers of 2007, 2010 and 2012. During the heat events, a non-negligible negative response in mortality was recorded and fatal effects were more pronounced during particularly strong heat events and periods which lasted for two or more days. In general, females and the elderly were the most sensitive groups in the population and mortality was characterized by several specific effects in individual population groups. The most extreme heat periods were commonly followed by a deficit in mortality, corresponding to a short-term mortality displacement, the pattern of which varied in specific cases. In general, displaced mortality appeared to compensate for a large part of heat-induced excess deaths.

Keywords: *weather extremes, weather stress, heat events, mortality, Slovakia*

1. Introduction

Heat is the deadliest of all atmospheric phenomena (Changnon et al., 1996; Sheridan and Kalkstein, 2004). Heat-related mortality can be defined as the incidence of deaths which would not occur in the absence of heat stress (Zaninović and Matzarakis, 2014). Only a small portion of heat-related deaths is caused directly by hyperthermic conditions (overheating, heatstroke, etc.); high temperatures, however, contribute to a more pronounced pathogenesis of other, in the end deadly illnesses, especially of the circulatory and respiratory systems (e.g. Keatinge, 2003; Kenney et al., 2014).

Possible negative impacts of hot weather on the health status of the human population came to light under the current conditions of a changing climate, expressed, inter alia, by increases in the general occurrence of very high temperatures. Even in Slovakia, the trends of long-term variability in characteristics of excessive heat stress have changed significantly (Labudová et al., in press) and this is also confirmed by the findings of several other studies (e.g. Faško et al., 2013; Kolláriková et al., 2013). It should be noted that after the dissolution of the Institute of Human Bioclimatology in Bratislava in 1994, however, research in the area of human biometeorology was practically non-existent in Slovakia. Therefore, no new expert studies concerned with weather influences on the health status of the Slovak population were conducted. This contribution thus represents a pilot initiative in this area of research after two decades. Its parallel objective is to create a knowledge base for this research issue in Slovakia.

The paper focuses on the impacts of summer heat events on human mortality during a 17-year period, with the entire population of the Slovak Republic being the object of interest. Unfortunately, due to the extent of available mortality data, the analysis did not include some relatively recent exceptional heat situations. Such periods of prolonged hot weather occurred mainly in the summers of 1992 and 1994, during which mortality increased considerably in the neighbouring states, for example, in the Czech Republic (Kyselý, 2004) or in Poland (Kuchcik and Degórski, 2009). Even in the period analyzed in this study (1996–2012), however, several summers with remarkably long durations of heat events were recorded, in which the Slovak population was exposed to a number of extremely hot episodes. Our intention was to evaluate both overall mortality during the heat events, as well as during the major individual historical heat events and most severe summers. In the absence of research in this area, both approaches represent useful sources of information, e.g. for potential public health measures during severe heat episodes in the future. Apart from evaluating the magnitude of heat impacts, we have also focused on the evaluation of other selected aspects of the heat-mortality relationship. Because of the existing "spatial gap" in the research of this issue, we turned our attention to complex comparisons of our results with a summary of findings in a broader geographical context, mainly that of Central Europe.

2. Theoretical background

Under current climate conditions, the issue of high temperatures impacts on human mortality has received

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greater attention from scientists, especially due to the occurrence of some unprecedented extreme heat waves. Recently, since 2000, the exceptional mortality crisis was caused by heat waves in the extremely hot summer of 2003 (Kosatsky, 2005; García-Herrera et al., 2010), in which Western and Southwestern Europe were most severely affected, mainly in the first two weeks of August. During that summer there were almost 75,000 excess deaths in 16 European countries, from Spain to Poland and from Denmark to Italy (Robine et al., 2008). France was particularly affected, with nearly 15,000 excess deaths recorded just during the strongest August crisis (Fouillet et al., 2006; Toulemon and Barbieri, 2008). According to de Bono et al. (2004), with regard to the number of victims, the summer heat waves of 2003 were one of the worst natural disasters in Europe in the last 100 years, and absolute worst in the last 50 years. It is logical that this so-called 2003 big European heat wave has become an example of what a typical heat wave in a warmer climate might be like (Gosling et al., 2009).

In the summer of 2010, another anomalously hot period affected the European part of Russia in particular. Here, according to some estimates, in comparison to previous years mortality increased by 54,000 cases in July and August, approximately 11,000 of which were in Moscow. Taking into account the size of the affected population, it is stated that this heat wave was 2.4 times more dangerous than the 2003 European heat wave (Revich, 2011; Shaposhnikov et al., 2014).

In recently published studies, excess mortality has also been evaluated separately during other extreme summer heat waves in various parts of Europe: for example in 2006, it was mainly in Western Europe (Fouillet et al., 2008; Monteiro et al., 2013; Knobová et al., 2014); in 2007, mainly in Central and Southeastern Europe (Overcenco, 2010; Páldy and Bobvos, 2010; Opopol et al., 2012; Bogdanović et al., 2013; Corobov et al., 2013; Stanojević et al., 2014); and in Central Europe, most recently in 2011 and 2012 (Páldy and Bobvos, 2012).

The largest increase in mortality during heat episodes is recorded mainly on days with the most uncomfortable temperature conditions (Matzarakis et al., 2011). Special attention is dedicated to situations with an extended duration of heat stress. Despite the capacity of the human organism to tolerate extreme heat stress for short periods of time, periods with longer duration represent a different group of stressors associated with a larger risk of death, as a sequence of consecutive hot days puts a higher strain on the human thermoregulatory system (e.g. Gosling et al., 2009; Kenney et al., 2014).

There was a particularly higher risk of death found in persons within several specific population groups, which have logically become a centre of interest in the corresponding analyses. Proper identification of these groups is decisive for possible public health interventions and their effectiveness (Hajat and Barnard, 2014).

Most European studies confirm that females are usually a more vulnerable group (Kovats and Hajat, 2008), and in Central Europe this situation is quite consistent (e.g. Hutter et al., 2007; Kyselý and Plavcová, 2012; Páldy and Bobvos, 2012). The results of several European research publications have shown somewhat higher long-term sensitivity in females during heat waves when taking into account variations in age structure as well (Matzarakis et al., 2011; Hajat and Barnard, 2014).

From the physiological point of view, the organism in old age can not fully compensate meteorological effects in a natural way due to a multitude of factors (Morabito et al., 2012). Indeed, increases in mortality of the elderly tend to be among the largest in heat episodes (e.g. Basu, 2009; Oudin Åstrom et al., 2011; Yu et al., 2012; Kenney et al., 2014). This can be essential information in the context of population ageing, which is, in both the short- and the long-term, an important current problem in the Slovak population as well (Mládek and Káčerová, 2008). As the elderly are expected to be potentially more susceptible to heat exposure, an aging population is logically more at risk (e.g. Gosling et al., 2009; Kenney et al., 2014). This hypothesis was confirmed in the Czech Republic (Kyselý and Plavcová, 2012), and it could also apply to Slovakia where population ageing shows an exceptionally high degree of similarity to that of the Czech Republic (Káčerová et al., 2012).

People suffering from circulatory system diseases are often found to be at the highest risk in relation to higher air temperatures in biometeorological research (e.g. Basu, 2009; Hajat and Barnard, 2014; Kenney et al., 2014). Slovakia belongs to the set of European countries with high mortality rates from diseases of this group (Baráková, 2009; Helis et al., 2011; Šprocha et al., 2015).

To determine true (net) heat-related mortality, investigators must account for a compensating effect of mortality displacement (also known as harvesting) (Saha et al., 2014). The basic principle of this phenomenon is that an extreme weather event (such as a heat period) mainly affects people with poor health, who would die in a very short period of time anyway, regardless of the weather (Gosling et al., 2014). In other words, a negative weather event kills some of those people who would have died soon under normal weather conditions. This means that an extreme weather event in fact does not cause true excess mortality, but only a short-term shift in deaths among terminally-ill people (Martiello and Giacchi, 2010), and a period of elevated mortality is followed by a compensatory period with a deficit of deaths.

As already suggested, the issue of hot weather influences on human mortality has been frequently analysed over the last years, and in the European context this is valid mainly for the most developed Western European countries. Although research in this field has improved lately, it is still somewhat less common in the wider region of Central European countries. Several contributions have focused on the population of the Czech Republic (e.g. Kyselý, 2004; Kyselý and Huth, 2004; Kyselý and Kříž, 2008; Kyselý and Plavcová, 2012; Knobová et al., 2014), as well as Austria (Hutter et al., 2007; Muthers et al., 2010a,b; Matzarakis et al., 2011), Switzerland (Grize et al., 2005), Poland (Kuchcik and Degórski, 2009), Hungary (Páldy et al., 2005; Páldy and Bobvos, 2010, 2012), Croatia (Zaninović and Matzarakis, 2014), Serbia (Bogdanović et al., 2013; Stanovejić et al., 2014), and Moldova (Overcenco, 2010; Opopol et al., 2012; Corobov et al., 2013). In several cases, and this is also valid in global terms, most of the studies were aimed specifically at populations of larger cities or metropolitan areas where a higher risk of death can be generally expected due to a higher sensitivity of the population as a consequence of climate (urban heat island, higher air pollution, etc.) and socioeconomic (e.g. certain lifestyle) factors. Therefore, studies focused on large areas and entire countries are still rare in Central Europe.

In several publications (e.g. Gosling et al., 2009; Plavcová and Kyselý, 2014) there are discussions that some of the analyses in biometeorological research cover a relatively short time period (most often individual heat waves and individual hot summers), or the research is commonly established on relatively small population samples from single or only a small number of hospitals (this is how the latest research has been done in Slovakia as well: see Štvrtinová et al., 1990; Čabajová et al, 1999; Čabajová, 2005). One advantage of this group of investigations, for example, is a higher quality-determined cause of death of a person based on a medical or autopsy record, compared to cases when the official cause of death is determined only on the basis of the examining doctor's report. Nevertheless, the collection of clinical data from larger territories with larger population samples is usually complicated, and it is also necessary to consider that people do not always die in hospitals or undergo autopsies.

3. Material and methods

3.1 Meteorological data

Data on daily mean air temperature and daily mean water vapour pressure (the latter, for discussion purposes only) was used. Daily means are calculated from actual temperatures observed at 7, 14, 21 hrs local time.

Data series from 23 climatological stations (Fig. 1) over the period 1996–2012 were provided by the Slovak Hydrometeorological Institute. The stations represent the whole territory and include the various climatic regions of Slovakia. Likewise, the stations represent various altitudes except for the mountain and high mountain ranges, in which permanent settlements are not located or where there is a negligible number of inhabitants. In the end, the stations represent practically all of the most densely populated areas (Fig. 1) and, at the same time, take into account the distribution of the Slovak population in terms of the absolute number of inhabitants in the studied time period.

3.2 Identification of heat events

According to Robinson's (2001) general definition, a heat wave is an extended period of unusually high atmospheric-related heat stress, which causes temporary modifications in lifestyle and which may have adverse health consequences for the affected population. Based on this definition, the author specifically mentions that heat waves can not be evaluated without considering their impacts on human society. Robinson further states that a definition of heat wave must include the combined effect of weather elements and effects which affect the thermal sensation of the human body. Also, defined thresholds have to consider the effects of both daytime high and night-time low air temperatures, respecting the variability of climatic conditions in the given area. The effect of duration also needs to be included (Robinson, 2001), which also results from another general definition by Gosling et al. (2014), according to which a heat wave is a period of extreme high temperature that lasts several days. Due to the fact that not all of the above-mentioned criteria were respected precisely in our analysis, we prefer more simple terms rather than "heat wave" in our terminology.

Furthermore, a specific universal definition to determine a heat wave has not been generally accepted in the scientific literature (e.g. Robinson, 2001; Kuchcik, 2006; Gosling et al., 2009). Likewise, heat episodes still do not have an official definition in Slovak meteorological and climatological practice nor in public health, and they are not monitored in Slovakia to create an early warning system (Koppová, 2011). In our analysis, we applied the quantile approach (cf. Gosling et al., 2009) to identify "heat days" as the days when the daily mean air temperature anomaly from normal exceeded the value of the 90th percentile of its empirical distribution in the summer months (June, July, August) over the full period of interest (1996–2012). To evaluate the effects of the most extreme temperatures, we also similarly determined the days with anomalies above the 95th percentile value – we define these as "strong heat days".

An advantage of using anomalies from normal is that it effectively removes the mean temperature variation between stations (effects of various elevations, specific locations, etc.). Anomalies were specifically set for each of the stations and consequently an average value representing the entire Slovak territory was calculated. When calculating temperature normals, the annual cycle was smoothed by 7-day centred moving averages. This type of smoothing was chosen from several alternatives as optimal, because it preserves the annual cycle singularities to a suitable degree and simultaneously it smoothes its irregularities (large day-to-day variability). In addition, 7-day moving averages correspond well with the mean duration of a natural synoptic period (Sobíšek, 1993).

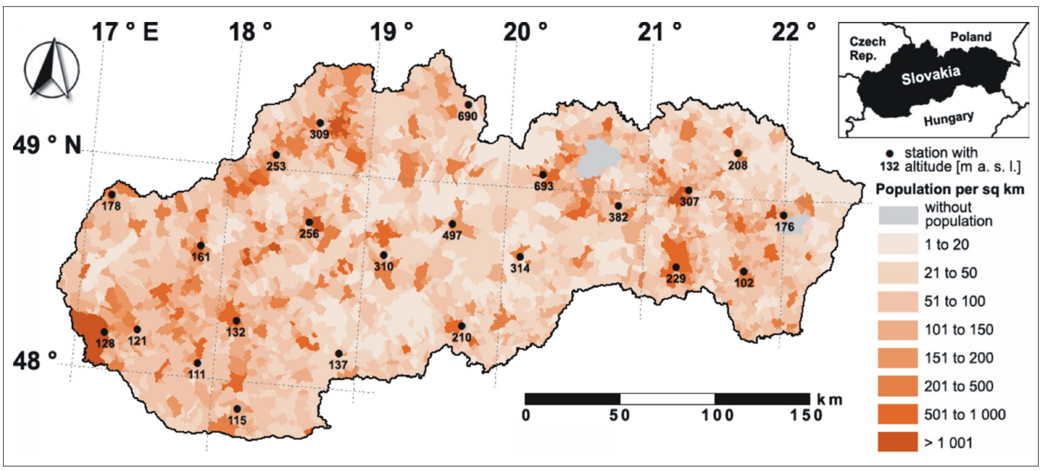

Fig. 1: Location of climate stations and population density in Slovak communes (according to the 2001 Population and Housing Census)
Source: Prepared following Kusendová and Tomášiková (2006)

We use the term 'heat events' for the compact episodes of heat in this paper. 'Heat events' were classified according to their duration. Our main focus was on the events with duration of two or more "heat days", and we define these situations as multi-day "heat periods", while 'isolated heat day' refers to a one-day heat event. According to Kyselý and Plavcová (2012), hot spells of at least 2 days result in a much higher response in mortality than isolated hot days. At least two-day duration is also recommended by Robinson (2001), and last but not least, such a selection is more suitable with respect to duration criterion as specified in general definitions of heat episodes. Multiple heat events, separated by only one non-heat day with a slight drop of temperature anomaly below the threshold, were evaluated together as a single heat period. In our terminology please note that 'strong heat events' relate to 'strong heat days', but their further classification based on duration was not used.

There are several reasons why we prefer applying the simple daily mean air temperature variable as the mortality predictor rather than any of the biometeorological indices (de Freitas and Grigorieva, 2015). Based on their analysis, Barnett et al. (2010) recommend the use of simple air temperature characteristics when assessing heat-related mortality due to practical reasons such as their long-term availability, the smaller number of missing data in time series, and good spatial coverage of the studied area. The authors of that study did not find any significant differences between the usage of simple air temperature characteristics and biometeorological indices, and state that the selection of the mortality predictor is much less important than some other tasks. Daily mean temperature is an equivalent alternative, and in the case of an evaluation of heat-related mortality it shows similar results as various biometeorological indices according to other studies as well (Kim et al., 2011; Vaneckova et al., 2011). Urban and Kyselý (2014) also confirmed this finding in Central Europe when evaluating heat effects on cardiovascular mortality in the neighbouring Czech Republic.

3.3 Mortality data

A database of deaths for the years 1996–2012 was provided by the Public Health Authority of the Slovak Republic based on datasets of the Statistical Office of the Slovak Republic. Each death record includes the date of death. Based on this information, daily death counts were established. Each record also includes information on the sex and age of the deceased, as well as the cause of death. After reviewing the quality of these data, in addition to total (all-cause) mortality, mortalities of three specific population sub-groups were also analysed: by sex, both males and females; and by age, the elderly aged 70 years and older. Country-wide mortality was evaluated: the whole country population is usually exposed to heat situations, which tend to be spatially extensive events, so they easily impact the entire territory of Slovakia (~49,000 sq km).

For the purpose of mortality evaluation, we applied the procedure of calculating deviations of death counts from baseline (expected) mortality (cf. Gosling et al., 2009); this procedure is known as indirect standardization. Baseline daily mortality values were calculated based on the methodology used over a longer period of time in the biometeorological research in the Czech Republic (e.g. Kyselý, 2004; Kyselý and Kříž, 2008; Kyselý and Plavcová, 2012; the latest exact procedure is described in detail, for example, in the study by Hanzlíková et al., in press).

Daily baseline mortality $M_0(y,d)$ for year y and day d was calculated as follows:

$$\mathbf{M_0(y,d) = M_0(d) \times W(y,d) \times Y(y)}$$

where $M_0(d)$ denotes the mean annual cycle of mortality in the period of interest determined as the average number of deaths in the given day of the year; $W(y,d)$ is the correction factor for the weekly cycle of mortality for individual days of the week, defined as the ratio of mean mortality on a given day of the week to the overall mean daily mortality, with the influence of public holidays eliminated; and $Y(y)$ is the correction factor for year-to-year changes in mortality, defined as the ratio of number of deaths in the given year to the mean annual number of deaths during the analysed period.

The correction factors $W(y,d)$ and $Y(y)$ were calculated over the period May–September, outside the season of influenza, influenza-like illnesses and acute respiratory infections, which could significantly affect mortality. This modification in the selection of time period for calculating correction factors was our only adjustment in the process of mortality data standardization presented in the source publication (cf. Hanzlíková et al., in press), resulting from the unavailability of necessary epidemiological data.

Deviations of observed mortality from baseline (expected) mortality were calculated for each day and summed (absolute characteristics)/averaged (relative characteristics) over the relevant time periods of heat events. Immediate direct effects on mortality (without lags) were considered. The 95% confidence interval was selected to evaluate the statistical significance of deviations. Confidence intervals of deviations were calculated based on the procedure suggested by Morris and Gardner (1988) for a Poisson-distributed variable. This method is suitable for the approximation of larger statistical samples with more than 20 observed cases.

This complete methodological approach of calculating baseline mortality and of following the establishment of mortality deviations is appropriate when analysing longer time series, as such an approach takes into account both long-term (reflecting especially overall socioeconomic changes) and short-term changes in mortality (Gosling et al., 2009; Hanzlíková et al., in press).

3.4 Target population

In terms of the number of inhabitants, Slovakia represents a mid-sized European population. Between 1996 and 2012, the mid-year population on July 1^{st} fluctuated around the value of 5.4 million (Statistical Office of the Slovak Republic, 2014). In the summer months of 1996–2012, the average daily total number of deaths was 137.2, of which 64.5 (47.0% of total mortality) of the deceased were females, 72.7 (53.0%) males, and 82.5 (60.1%) the elderly aged 70 years and older. A more detailed picture of the corresponding mortality trends in Slovakia in the long term can be found in the recent study by Šprocha et al. (2015).

4. Results

4.1 Basic evaluation of overall (long-term) impacts of the heat events on mortality

Daily mean air temperature anomaly, necessary for classification of situations as heat days (strong heat days), was 3.90 (4.97) °C. The average anomaly during heat events (strong heat events) was 5.23 (6.01) °C. We would like to emphasise that all of the presented temperature anomalies represent spatial averages calculated from a larger number of stations (see Fig. 1 and Section 3.2: Identification of heat events, above).

In the 17-year period under investigation, more than 2,160 excess deaths in total were recorded in Slovakia during the identified heat events (157 days in total). This value represents a total relative increase of 9.9% (95% CI: 8.5% to 11.3%) compared to expected mortality. The mortality increase was more pronounced among females (11.4%; 95% CI: 9.4% to 13.5%) in comparison with males (8.5%; 95% CI: 6.6% to 10.5%). An excess mortality of 11.3% (95% CI: 9.5% to 13.2%) was found in the elderly at the age of 70 and older. The approximate proportion of excess deaths in total excess mortality was 55% for women and 69% for the elderly.

If we focus only on strong heat events (79 days in total), increases in relative deviations of mortality were even higher by 3 to 5%. In total mortality, it was 13.9% (95% CI: 11.9% to 15.9%), i.e. more than 1,530 deaths. This means that approximately 70% of all heat events-induced excess deaths were recorded during strong heat events. In individual population groups, mortality increased by 13.3% (95% CI: 10.6% to 16.1%) for males, by 14.5% (95% CI: 11.6% to 17.4%) for females, and by 16.2% (95% CI: 13.6% to 18.8%) for the elderly. The approximate proportion of excess deaths in total excess mortality during strong heat events was 50% for women and 71% for the elderly.

4.2 Mortality during the major heat events

An overview of most severe individual multi-day heat periods and their impacts on mortality is shown in Table 1. Annual statistics of summer heat events and corresponding mortality are presented in Figure 2. Selected summers are separately shown in Figure 3.

The longest total duration of heat events in the analysed period occurred in 2012. During 21 days of summer heat events in this year, a 13.0% (95% CI: 9.2% to 17.0%) increase in total mortality was recorded, accounting for more than 370 excess deaths. Within individual 2012 heat periods, a large part of the excess deaths was caused by the period that began on the very last day of June. In relation to heat events in the first half of the summer of 2012, a remarkable deficit in mortality occurred between the 13th and 23rd of July, which may correspond to a mortality displacement effect. In total mortality, this 11-day reduction was statistically significant (– 13.5%; 95% CI: – 18.2% to – 8.7%) and it compensates for more than 200 deaths from the total of approximately 230 excess deaths recorded during heat events in the first half of summer 2012.

Total mortality during the 2010 summer heat events exceeded the expected value by 13.6% (95% CI: 9.2% to 18.3%), i.e. almost 300 excess deaths during the 15 days of heat events. The heat peaked in an extreme one-week heat period in mid-July with a highly significant increase in mortality. Shortly after this period, another short period with lower impacts on mortality occurred, followed by a significant – 5.1% (95% CI: – 8.9% to – 1.0%) deficit between the 24th July and 9th August, which is equivalent to more than 120 displaced deaths. Even though a higher sensitivity of females was characteristic both in general, as well as during the majority of individual heat events, a much higher excess mortality of males was recorded for the most severe heat period in July 2010. This finding generally applies to all 2010 heat events as well: an excess of 15.0% (95% CI: 9.0% to 21.7%) was found in the case of men, while for women: 12.2% (95% CI: 5.8% to 18.7%).

During the summer heat events of 2007 (13 days), a total mortality increase of 12.4% (95% CI: 7.6% to 17.3%) was recorded in Slovakia. In the dominant extreme heat period in July, the most fatal day (19th July 2007) of the entire analysed period was recorded, with both the highest absolute (almost 65 excess deaths) and relative (44.4%; 95% CI: 25.4% to 65.4%) deviation of total mortality. A large significant increase during this 8-day heat period, accounting for around 220 excess deaths, was followed by an extended period of reduced mortality. Between the 25th July and 17th August 2007, total mortality was – 3.8% (95% CI: – 7.1% to – 0.4%) below the baseline, meaning a deficit of around 125 deaths. The next compact period of time with mortality well below the expected level was recorded in the first half of September 2007, when during the first thirteen days of the month the deviation of mortality reached negative values in all but two days (not shown). The deficit was statistically significant as well (– 4.9%; 95% CI: – 9.4% to – 0.3%), accounting for approximately 90 displaced deaths.

During the very hot summer of 2003, a long total duration (17 days) of heat events was recorded. With the exception of the period at the beginning of June, however, these were just isolated heat days or 2-day heat periods. Altogether, 2003 summer heat events caused only a moderate increase in total mortality by 6.0% (95% CI: 1.8% to 10.3%) compared to the expectation. Other remarkable individual heat periods (Tab. 1) and summers (Fig. 2), respectively, with significant impacts on mortality, were recorded in 1998, 2000 and 2006. In addition to the situations in 2010 and 2012 described above, among the last three analysed years, 2011 summer heat events (12 days in total) also resulted in a significant increase (11.1%; 95% CI: 5.8% to 16.3%) in total mortality.

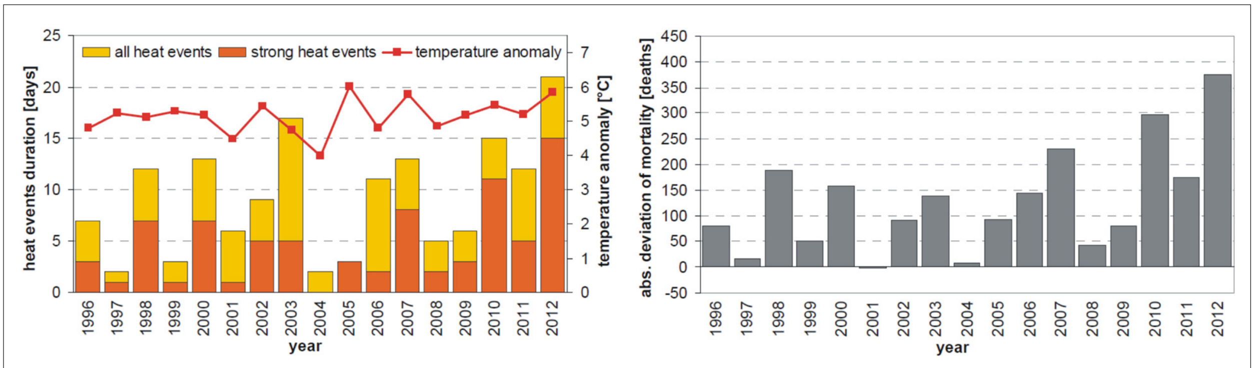

Fig. 2: Duration of heat events, average value of daily mean temperature anomaly (left chart) and total mortality deviations (right chart) during 1996–2012 summer heat events in Slovakia.

Onset date–End date	Total duration [days]	Number of included strong heat days	Average of daily mean temperature anomaly [°C]	Relative deviation of mortality (95 % confidence interval) [in %]			
				Total mortality	Male	Female	The elderly aged 70 years and older
20 Jul 1998–23 Jul 1998	4	3	4.97	22.8 (14.0 to 32.2)	20.7 (8.8 to 33.5)	25.6 (12.4 to 39.6)	14.2 (3.1 to 26.3)
11 Jun 2000–14 Jun 2000	4	3	5.55	15.3 (6.6 to 24.6)	7.1 (–4.3 to 19.9)	24.2 (11.1 to 38.2)	24.5 (12.8 to 37.1)
19 Jun 2002–23 Jun 2002	5	2	5.34	6.6 (–0.9 to 14.7)	10.4 (–0.1 to 21.5)	2.3 (–8.4 to 14.1)	4.3 (–5.4 to 14.6)
4–9 Jun and 11–12 Jun 2003	8	3	4.66	10.4 (4.2 to 16.8)	10.2 (1.8 to 19.0)	10.8 (1.7 to 20.2)	12.7 (4.6 to 21.0)
25 Jun 2006–28 Jun 2006	4	2	5.43	15.6 (7.0 to 24.8)	11.7 (0.2 to 24.2)	20.2 (7.4 to 34.0)	14.4 (3.7 to 26.2)
15 Jul 2007–22 Jul 2007	8	7	6.46	19.2 (13.0 to 25.7)	18.2 (9.8 to 27.3)	20.1 (11.2 to 29.8)	21.0 (12.9 to 29.3)
9 Jun 2010–12 Jun 2010	4	3	5.90	12.0 (3.6 to 20.9)	14.6 (3.1 to 27.6)	9.3 (–2.8 to 21.9)	13.6 (2.9 to 25.0)
11 Jul 2010–17 Jul 2010	7	7	5.72	18.2 (11.7 to 25.2)	22.1 (13.0 to 32.3)	13.9 (4.7 to 23.8)	17.6 (9.2 to 26.3)
23 Aug 2011–27 Aug 2011	5	4	5.98	17.9 (9.8 to 26.5)	10.2 (–0.6 to 22.0)	26.0 (14.0 to 39.0)	25.3 (14.3 to 36.4)
17 Jun 2012–21 Jun 2012	5	5	6.16	8.9 (1.3 to 17.0)	3.3 (–6.7 to 14.6)	14.9 (3.7 to 27.1)	13.2 (3.3 to 23.7)
30 Jun 2012–8 Jul 2012	9	8	6.44	13.7 (7.8 to 19.7)	11.4 (3.3 to 19.7)	16.2 (7.8 to 25.3)	15.2 (7.9 to 23.0)

Tab. 1: Selected severe multi-day 1996–2012 summer heat periods in Slovakia and their impacts on mortality. Note: Multiple heat periods, separated by only one non-heat day with a slight drop of daily mean temperature anomaly below the threshold, were evaluated as a single heat period.

4.3 Mortality during isolated heat days and multi-day heat periods

Twenty-one isolated heat days (with average daily mean temperature anomaly of 4.56 °C) and forty multi-day heat periods (5.33 °C) were recorded. The increase in mortality was much higher during the multi-day periods, while it was even statistically not significant for the isolated heat days (Tab. 2). From the total amount of 2,160 excess deaths, more than 96% were recorded during multi-day heat periods.

4.4 Mortality regime related to multi-day heat periods

In the period 1996–2012, 2.35 multi-day heat periods occurred per year on average, with average duration of 3.4 days. Since the multi-day periods were responsible for the vast majority of total excess deaths, we analysed a typical regime of mortality in the time sequence of 5 days (day – 5) before the onset of a heat period, up to 30 days (day 30) after the onset (Fig. 4).

On average, there was a slight, but only in a few cases statistically significant, increase in mortality prior to the onset of a heat period on almost all days of the 5-day pre-sequence. At the beginning of a heat period (day 0), mortality rose significantly and remained markedly high for several following days. Soon afterwards, a decrease to below-baseline level was observed and negative deviations of mortality persist until the end of the whole 30-day sequence after the onset of a heat period. This indicates the effect of mortality displacement.

Mortality effects are in line with the results presented earlier, being more pronounced in females and the elderly. With a focus on the following most critical days, male mortality was more pronounced on the initial day of a heat period (day 0). The highest relative deviation of mortality from baseline was reached for the whole population and both gender groups one day (day 1) and for the elderly two days (day 2) after the onset of a period. Another interesting finding is that deviations of mortality stayed consecutively positive, on average, for a week (days 0 to 6) of a heat period in all population groups, with the exception of males in which mortality was above the baseline for just the first five days (days 0 to 4) of a period.

5. Discussion

5.1 Overall long-term heat impacts on mortality

Despite differences in methods and the time periods used, overall increases in mortality during heat events in Slovakia are in accordance with the results of studies from neighbouring countries analyzing mortality over longer time periods (e.g. Kyselý, 2004; Hutter et al., 2007; Kyselý and Kříž, 2008; Matzarakis et al., 2011; Stanojević et al., 2014). The highest relative increases during the individual heat periods exceeded 20%, which is also similar to other Central European studies (Kyselý, 2004; Páldy et al., 2005).

5.2 Summer heat in 2003

Although the 2003 May–August season was extremely hot in Slovakia (Faško et al., 2003) and the corresponding summer was, in terms of average temperature, the hottest in the history of meteorological observations at several stations across Slovakia, the 2003 summer heat events were associated with only a moderate 6% increase in total mortality. In spite of the diversity of applied methodologies, this value corresponds very well with the results of other studies confirming less dramatic heat impacts of the summer

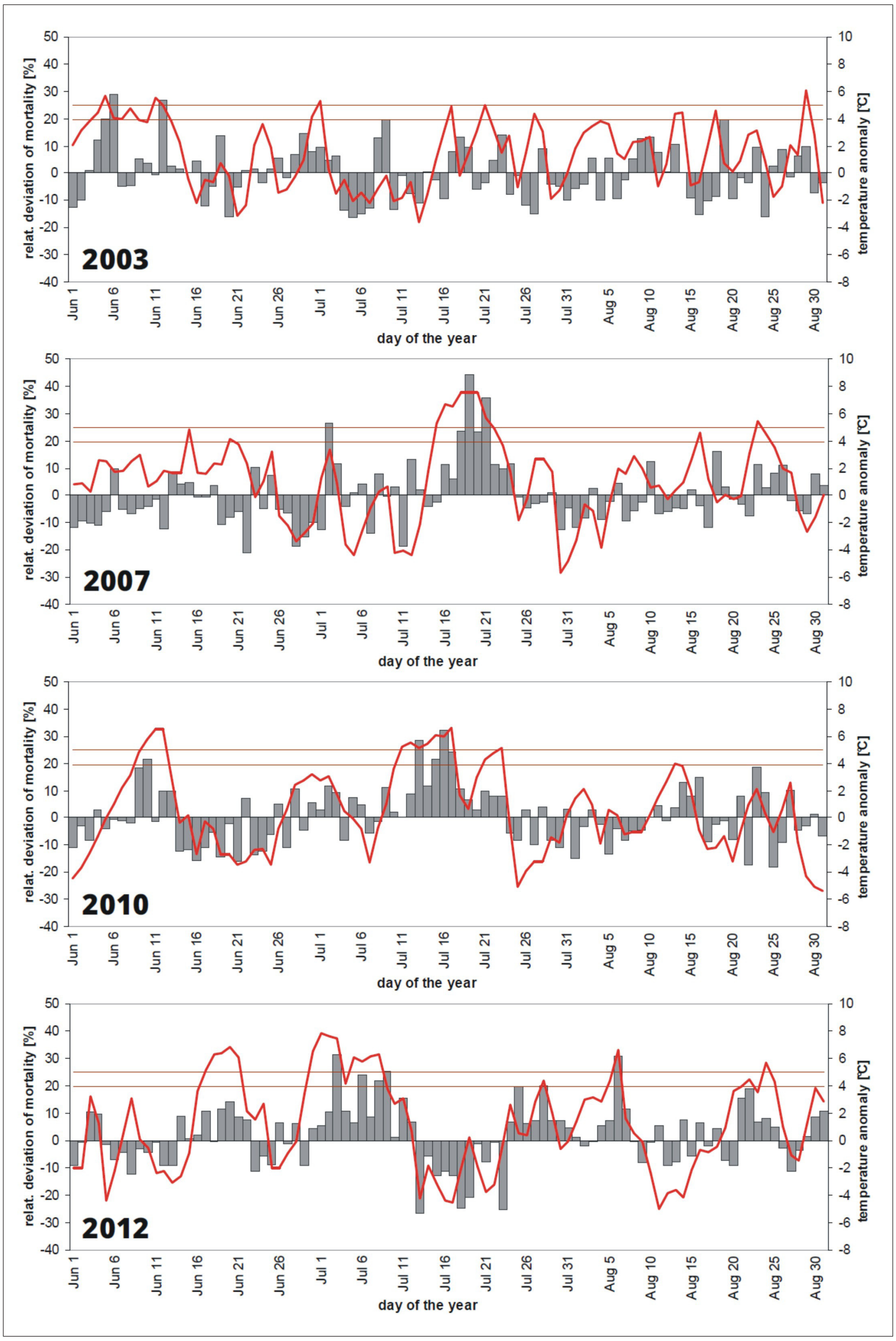

Fig. 3: Temperature conditions (lines) and total mortality (bars) in selected summers in Slovakia. Note: The red curve shows daily mean temperature anomalies; horizontal lines represent the threshold values of daily mean temperature anomaly for the classification of heat and strong heat days, respectively.

	Isolated heat days	Multi-day heat periods
Total mortality	2.8 (–0.9 to 6.5)	11.0 (9.5 to 12.5)
Male	1.6 (–3.4 to 6.7)	9.6 (7.6 to 11.7)
Female	4.0 (–1.3 to 9.6)	12.6 (10.4 to 14.8)
The elderly aged 70 years and older	3.7 (–1.0 to 8.6)	12.4 (10.6 to 14.5)

Tab. 2: Relative deviations of mortality [%] from baseline during isolated heat days and multi-day heat periods in Slovakia, 1996–2012. Note: Multiple heat events, separated by only one non-heat day with a slight drop of temperature anomaly below the threshold, were classified as a single heat period; values in brackets represent 95% confidence intervals of deviations.

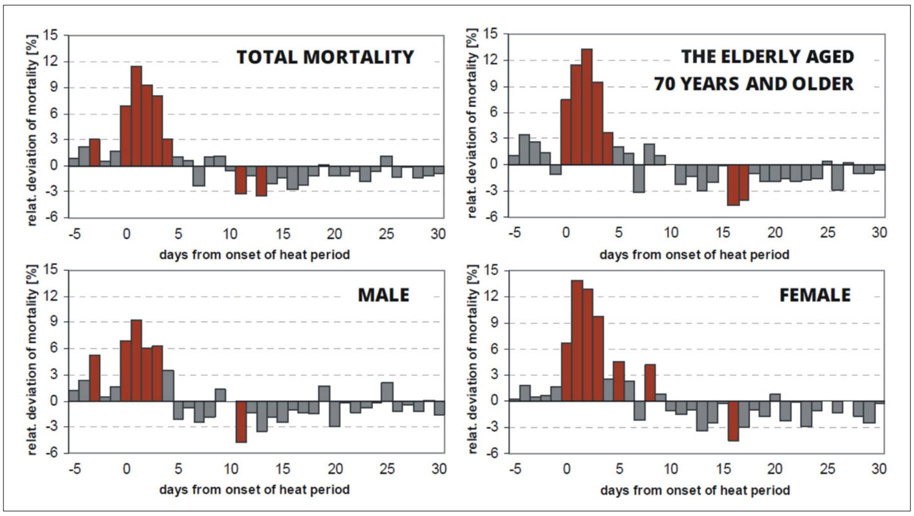

Fig. 4: Mortality regime related to multi-day summer heat periods in Slovakia, 1996–2012. Note: The brown bars indicate statistically significant values at the 95% level (based on the relevant confidence interval); multiple heat events, separated by only one non-heat day with a slight drop of temperature anomaly below the threshold, were classified as a single heat period.

of 2003 on the mortality of Central European populations. For example, an excess total mortality of 2.9% during four heat waves was recorded in the Czech Republic (Kyselý and Kříž, 2008). In Prague, the increase during an extended heat peak period between the 2nd and 22nd of August was 3.2% (Knobová et al., 2014), in Vienna 5% for the entire summer (Hutter et al., 2007) and in Switzerland 6.9% for the entire summer (Grize et al., 2005). These values are considerably lower than those for the majority of the Western European countries (cf. Kosatsky, 2005; Robine et al., 2008; García-Herrera et al., 2010), where the heat was much more severe in meteorological terms. During the first half of August, when heat waves and the mortality crisis peaked in the most impacted countries in Western Europe, no remarkable heat period was recorded in Slovakia. At the least, relatively low values of excess mortality in Slovakia could have been attributable to more comfortable humidity conditions (lower values of water vapour pressure) and also to the fact that heat events were distributed evenly throughout the summer (Fig. 3), which likely contributed to a gradual improvement in the physiological and behavioural seasonal acclimatization of the population to the persisting hot weather.

5.3 Summer heat in 2007

The extreme heat of 2007 was primarily concentrated in Southeastern Europe and also some parts of Central Europe (Corobov et al., 2013). In Central Hungary, including Budapest, mortality during the hottest days rose by 12% (Páldy and Bobvos, 2010), which is a comparable value with the results of our analysis (12.4%). A particularly extreme heat spell occurred in the second half of July 2007. During this episode, mortality increased by 38% in Belgrade (Bogdanović et al., 2013) and by 32.9% in Central Hungary (Páldy and Bobvos, 2010), and these values are much higher than in Slovakia (Tab. 1). It is necessary, however, to take into consideration the metropolitan character of Belgrade and Budapest with possibly higher mortality risks. Nevertheless, the severity of this extreme heat period is indisputable for the case of Slovakia, as this was the period during which the highest national temperature on record was observed (40.3 °C in Hurbanovo on the 20th of July). It was the only severe heat episode in the summer of 2007 and this could play a role in a very high excess mortality recorded during this period.

No significant deficit in mortality, corresponding to mortality displacement, was recorded immediately after the July heat period in Moldova (Corobov et al., 2013), Serbia (Bogdanović et al., 2013), or in Hungary (Páldy and Bobvos, 2010). The authors of the cited Moldavian study, however, noticed markedly negative excess mortality in September 2007 and they stated that this was a reduction related to post-heat mortality displacement. In Slovakia, we observed a moderate, statistically significant mortality deficit in the period of approximately three weeks after the extreme heat period in July (Fig. 3), and a similar situation occurred in the first half of September. These deficits are most likely attributable to the mortality displacement effect. In contrast to the above-mentioned studies, an apparent extended short-term mortality displacement was observed as the result of 2007 heat events in Slovakia.

5.4 Summer heat in 2010, 2011 and 2012

Only a small number of European studies have dealt with the influence of the 2010–2012 heat episodes on mortality. In Slovakia, heat events in these summer seasons occurred with higher frequency and their response in mortality was remarkable: each year the relative deviation of total mortality from the baseline exceeded 10%.

The centre of 2010 heat was in the European part of Russia. According to Shaposhnikov et al. (2014), total mortality in Moscow was 90% above the selected baseline for the 44-day July–August heat wave. In the same location, total mortality in July and August 2010 increased by 59.6% compared to 2009. A similar comparison for the 43 administrative regions of European Russia, including Moscow, showed an excess mortality of 19.5% and 32.6% in July and August of 2010, respectively (Revich, 2011). It is clear that the excess during the 2010 heat episodes was much higher in Russia than in Central Europe. In Frankfurt, the total mortality increase during the 2010 summer heat waves was 22.7% (Heudorf and Schade, 2014), and the increase during heat events identified in Slovakia (13.6%) was not negligible either. We believe that this high value may have been positively influenced by air humidity, as 2010 was by far the most extreme year in terms of record-breaking precipitation in Slovakia. Precipitation totals exceeded long-term averages practically in each month. They were especially extreme in April, May and June, and there were also large regional floods at the turn of May and June (Pecho et al., 2010); but rainfall was also frequent in July and August. Therefore, the pre-existing high soil humidity led to a higher evaporation and water vapour pressure (the country-wide spatial average was 20.65 hPa during the 15 days of heat events). Consequently, people were exposed to a greater temperature-humidity discomfort on the hottest days, and such conditions might have caused a more negative response in mortality.

The only European publication analysing the effects of 2011 and 2012 heat on mortality that we are aware of is a Hungarian study by Páldy and Bobvos (2012). During the relevant hot days in the summer of 2011, total mortality in Hungary increased by approximately 13%, which roughly corresponds with the 11.1% increase observed in Slovakia. Similar results for the next year show that the 2012 summer heat spells had larger impacts on mortality in Hungary. Total mortality increased by approximately 20% in comparison with 13% during the heat events identified in Slovakia. The difference appears to be quite prominent. It is most likely the consequence of temperature conditions as heat was more intense in the regions southward from Slovakia (Hungary, Serbia, Romania, etc.).

A further difference between the results presented in our study and the results of the Hungarian study is the observation of mortality displacement in 2012. While a marked deficit in mortality was recorded in Slovakia after the major June–July heat period, this phenomenon was not observed in Hungary (Páldy and Bobvos, 2012).

It was the period at the turn of June and July 2012 which was the most remarkable individual 2010–2012 summer heat event from a meteorological point of view. Despite the fact that mortality increased significantly during this heat period, it did not reach the high value of a comparable heat period in July 2007. A partial reason for that could be an earlier heat period in June 2012, which could have influenced mortality in the following period due to mortality displacement and positive seasonal acclimatization to heat.

5.5 Mortality displacement

We have shown that short-term mortality displacement was well expressed after the heat periods in Slovakia (Fig. 4), particularly the most extreme individual ones (Fig. 3). There is no general consensus about the length of the period over which mortality displacement can be expected (Toulemon and Barbieri, 2008; Saha et al., 2014). This was the main reason why we have not defined the exact time frame during which the effect was evaluated. In Slovakia, the pattern of mortality displacement also varied in individual situations. Reduction in mortality was in some cases rapid, occurring immediately after the period of anomalously hot weather, but in other cases daily mortality deficits were smaller and remained as such for a longer period of time.

The role of mortality displacement is probably less important in situations where deaths associated with heat stress do not occur predominantly among terminally ill people (very old, suffering from chronic diseases, etc.). This is typical during most extreme heat episodes when a larger proportion of deaths might occur for otherwise immune individuals (e.g. García-Herrera et al., 2010; Hajat and Barnard, 2014; Saha et al., 2014). As has been shown (Figs. 3 and 4), displaced mortality accounted for a large part of excess mortality during heat periods in Slovakia, and this was also the case for the most severe individual heat events. This finding is in accordance with studies focusing on the populations of the Czech Republic (Kyselý, 2004; Kyselý and Plavcová, 2012) and Budapest (Gosling et al., 2007), i.e. other populations from transforming Central European countries.

With regard to displacement, there is an assumption of a true favourable impact of a lower temperature range on mortality after a period of very hot weather. On average, no unusually negative values of daily mean temperature anomaly over the days following heat periods were found (not shown). Thus, mortality displacement seemed to be a dominant factor for the extent of post-heat mortality reduction in Slovakia.

5.6 Heat impacts on selected population groups

For the Slovak population, we can confirm that the elderly are among the most sensitive population groups during heat episodes. Generally, higher risk of death was identified in females compared to males in Slovakia, although in some cases, for example, during the summer heat events of 2010, male mortality was more pronounced. The risk of death in otherwise less-sensitive males increased during the strong heat events.

Some interesting aspects of the mortality regime of the selected population groups were observed in Slovakia during the multi-day heat periods (Fig. 4). Despite the fact that males are generally less sensitive, their mortality was better expressed on the very first day of a heat period; this suggests that men are more sensitive to the onset of extremely high temperatures. On the other hand, the most negative response in male mortality vanished in a shorter period of time in comparison to females and the elderly, in the case of which the most fatal impacts of hot weather persisted for a few more days.

5.7 Mortality related to multi-day heat periods

Multi-day heat periods were accompanied by a much higher negative response in mortality in the Slovak population, and the longest individual periods were usually the most severe events from this point of view (Tab. 1). Generally, exceptions to this situation can be caused by several factors. The number of days with particularly strong heat stress within a multi-day sequence seems to play an important role. Within-season acclimatization to high temperatures may also have an effect, i.e. negative impacts decrease in each subsequent hot period of a season due to improved physiological short-term adaptation to heat, positive changes in population behaviours during heat episodes, and possibly also due to mortality displacement (e.g. Basu and Samet, 2002; Kyselý and Plavcová, 2012). This hypothesis partially explains the different impacts of the extreme July 2007 and June–July 2012 heat periods on mortality in Slovakia. Both of these periods were similar in terms of duration, the number of included strong heat days, or mean temperature anomalies, while the 2012 period was characterized by a higher humidity discomfort (higher average values of water vapour pressure). The observed impacts during the 2012 period, however, were markedly lower (although still fairly negative).

In relation to the multi-day heat periods, it was interesting to note that there was already a slight increase in mortality in the days before their onset (Fig. 4). Five to two days before onset, mean temperature anomaly ranged from – 0.28 to 0.67 °C, and it was even not considerably different from its long-term summer value in non-heat days (– 0.51 °C).

This means that temperature conditions in the days before the onset of a heat period did not appear to have a crucial effect on elevated mortality on these days. Moreover, one day before the onset of a period, mean temperature anomaly apparently increased to 2.64 °C; however, the deviation of mortality on that day did not increase greatly and it even dropped into negative values for the elderly. Larger anomalies from the usual values in the days before the beginning of a heat period were not recorded for the water vapour pressure either. Therefore, one could discuss whether mortality was influenced by other meteorological factors besides temperature and humidity, or whether it was true pre-heat excess mortality among the most sensitive humans, perhaps associated explicitly with the weather change (i.e., the onset of warm advection).

5.8 Limitations

When assessing mortality, immediate direct effects of heat were considered, i.e. without possible lags in mortality. The strongest correlation of extreme high temperatures and elevated mortality is usually observed with lags ranging from 0 to 3 days (e.g. Basu and Samet, 2002; Gosling et al., 2009; Hajat and Kosatky, 2010; Martiello and Giacchi, 2010). According to some of these authors, the analysis of mortality lags should be a compulsory part of heat-related mortality assessment. Hence, not taking the mortality lags into account could be considered as a certain limitation of our study.

Our analysis also does not include the possible impact of air pollution, which can play a significant role in heat-related mortality (e.g. Basu, 2009; Analitis et al., 2014; Hajat and Barnard, 2014).

This study presents the first results of the 'high temperatures-mortality' investigation in Slovakia. We have attempted to cover a number of aspects in this relationship, but due to the complexity of the issue, of course, there is room to assess more of them in the future. In addition to the already-mentioned factors, others include, for example, determining temperature thresholds at which mortality begins to increase, a more accurate assessment of mortality displacement, etc.

5.9 Potential target population groups based on cause of death

Our original intention was to analyse mortality during heat events by also taking into account causes of death, specifically focusing on mortality from circulatory system diseases (CSD). Following a detailed study of the relevant literature, we eventually decided to omit CSD (and any other cause-specific) mortality from our analysis. The rationale for this decision is that there is a long-term, unreliable determination (miscoding) of causes in death certificates in Slovakia, with a high rate of errors, which leads to an incorrect statistical classification of death causes following the International Classification of Diseases (ICD) subgroups and chapters (Baráková, 2011). Despite some gradual improvement, 10% of randomly selected causes of 2010 deaths, and 12% of all officially determined causes of 2011 deaths were incorrectly classified into a different ICD chapter; it is equivalent to 5,400 and 6,200 deaths, respectively, for the entire population (Baráková et al., 2012, 2013). It is obvious that a high number of errors in the source data would undoubtedly lead to a considerable distortion in the obtained results. As a consequence, cause-specific mortality analysis seems highly problematic in Slovakia at this time.

6. Conclusions

Our study, the first of its kind focusing on the Slovak population, presents a basic insight into the issue of heat impacts on mortality of the population, both overall (long-term) as well as during the major individual events.

The effects of heat events on human mortality in Slovakia fit well into the Central European context. Compared to expected values, the overall mortality of the Slovak population apparently increased during the summer heat events in the period 1996–2012. In this period, there were several extremely hot episodes in Slovakia with mortality very significantly above the baseline; especially remarkable were the summer heat events of 2007, 2010 and 2012. A higher risk of death was found in females compared to males, and in the elderly. Multi-day heat periods had significantly larger negative impacts, and they were also characterized by differences in the mortality regimes within the examined individual population groups. Short-term mortality displacement after the end of heat periods was well expressed, and it seemed to represent a large portion of heat-induced excess deaths.

In any case, the results clearly show that heat events cause non-negligible negative responses in the mortality of the Slovak population. For this simple reason alone is it highly desirable to restart biometeorological research in the country. In addition to heat, this would be also appropriate for other weather effects on population health. In the European context, research in this area may be particularly important in transition countries (such as Slovakia), which have still not reached the level of actions as in some of the most developed countries, where successful efforts to minimize the negative effects of heat (and weather in general) on their populations have already been made (e.g. Pascal et al., 2006; Fouillet et al., 2008; Lowe et al., 2011; Bittner et al., 2013). These results could therefore be particularly useful for future public health interventions, the implementation of which is below an adequate level in Slovakia.

Even after reaching a satisfactory state of overall social adaptability, however, unprecedented extreme heat episodes will still be associated with very large negative effects and excess mortality, even in the developed countries, and their probability is expected to rise in a changing climate (Kyselý and Plavcová, 2012). Therefore, assessments of the 'high temperature-human mortality' relationship remain of high importance worldwide, and it is extremely important in Slovakia which is positioned at the beginning of new research in the area of human biometeorology.

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Changes in climate and changing climate regions in Slovakia

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Abstract

In the context of climate change, scientists discuss the relevant reference periods for the assessment of changes in climate. Recently, many studies have been published comparing recent conditions with the last reference period 1961–1990. In this paper, the trends of annual, seasonal and monthly average air temperature, as well as annual, seasonal and monthly precipitation totals in Slovakia, are presented to point out changes which will probably show up in the next reference period 1991–2020. In the second part of paper, changes in the climate regions in Slovakia are analysed, comparing spatial distributions in the period 1961–1990 and in the period 1961–2010.

Keywords: *temperature, precipitation, trend analysis, climate regions, Konček's climate classification, Slovakia*

1. Introduction

The trends of meteorological variables in the context of climate change are of high interest in current climate research. Since the 1980s, many such studies have been published world-wide. Some of this research has dealt with climate changes in Central Europe.

CARPATCLIM, a complex research project focused on climate analysis in the Carpathian region, was active in the years 2010–2013 and used gridded data with a horizontal resolution 0.1 ° × 0.1 °, which were obtained from observational data in the period 1961–2010 using interpolation methods. Considering the whole region, annual precipitation was reported as positive anomalies in the 1960s and the 1970s, negative anomalies in the 1980s and positive anomalies again after 1995. The results showed that altitude plays an important role in the trends of climatic variables. In the Carpathian Mountains less significant trends were observed than in surrounding areas, especially in spring and summer. A positive significant trend in annual precipitation was observed across the borders between Slovakia and Czech Republic and between Romania and Ukraine (Spinoni et al., 2014; Cheval et al., 2014). On the other hand, the trend of maximum, minimum and average temperatures increased on an annual scale and in all seasons, except autumn. Only over the Carpathian Mountains did the maximum air temperature in summer record no significant trend (Cheval et al., 2014).

More studies were focused on a single country. Hundecha and Bárdossy (2005) identified the 90th percentile daily maximum and the 10th percentile daily minimum temperatures as showing increasing trends (except autumn) for the majority of station-based datasets in south-west Germany, and many of them were significant. The highest average increase in the 90th percentile daily maximum temperature was observed in winter: + 2.7 °C in the period 1958–2001. The fact that extreme daily minimum temperature is increasingly less extreme was confirmed by the decreasing number of frost days. On the other hand, extreme heavy precipitation became even more extreme, both in terms of magnitude and frequency, in winter and in the transition seasons. The increase of air temperature during the second half of the 20th century was also observed for 146-year observational data in Poland. But the totals and the frequency of winter precipitation increased in Krakow in the period 1863–2008, while annual precipitation decreased in lowland regions (Twardosz et al., 2012). On the contrary, Niedzwiedz et al. (2009) identified no trend in precipitation, using long-term datasets from the seven oldest meteorological stations in Central Europe. Primarily, such differences are explained by the high variability of precipitation in this region.

Several studies have been published in the Czech Republic (e.g. Brázdil et al., 1995; Pišoft et al., 2004; Brázdil et al., 2009; Brázdil et al., 2012). The analysis of gridded Czech temperature series using wavelet transformations demonstrated an increasing trend in air temperature during the last century (Pišoft et al., 2004). It was noted that the warming tendency in Prague started ca. 1850 and in Brno at the end of the 19th century, using long-term observational data. An important acceleration of temperature increase was confirmed from the 1970s by Brázdil et al. (2012), with one exceptionally cold year in 1996 (Brázdil et al., 2009). Most of the other selected stations observed no significant trends in precipitation, which is in agreement with previous studies (Brázdil et al., 2009; Brázdil et al., 2012).

Since the late 1990s, most studies dealing with air temperature and precipitation were focused on the comparison of observational data with climate scenarios from climate models, but information about the trends of some studied climatic variables can be found, as well. In Slovakia, according to Lapin and Melo (1999), precipitation decreased significantly, mostly in the south west in the warm half-year, but average air temperature and evapotranspiration increased significantly in their study period from 1881 to 1998. The highest increase was observed in the months from January to August. A comparable

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evolution in the future was expected according to the results of the Canadian coupled GCM model, which was downscaled for the territory of Slovakia. These trends were replicated at the meteorological station at Hurbanovo in later studies by Melo et al. (2007a) and Pecho et al. (2008). The average annual air temperature in Hurbanovo increased about 1.4 °C in the period 1871–2006 (Melo et al., 2007b). This change resulted in the first occurrence of a very dry climate region, according to Konček's climate classification from the period 1951–1980. This classification was established by Konček and Petrovič (1957) and is described below.

The drying trends in the Danubian lowlands during the entire 20th century were also confirmed by Pecho et al. (2008), Melo et al. (2007b) and Lapin et al. (2009). The shift in climate conditions towards the climate of southern regions (e.g. Hungary) can be shown by changes in the occurrence of insect species in south-western Slovakia. Significant changes in Hurbanovo occurred also in the number of days with an average air temperature below or equal to 0 °C. This value significantly decreased in the period 1901–2006, while the number of days with average air temperatures ≥ 15 °C and ≥ 20 °C significantly increased (Melo et al., 2007b).

According to Faško et al. (2009), nearly all GCMs downscaled for Slovakia in the period 1991–1995 recorded only small increases in annual precipitation totals. No change, or even some decrease, was expected only in the southern lowlands. The highest increase in precipitation totals was expected in winter and in the mountainous northern part of Slovakia (up to 30%). Summer precipitation seemed to be very irregular (more frequent drought spells and flooding events) in the future, and winter precipitation seemed to occur mostly as rain up to 800 m a.s.l. Newer regional climate models were used in Lapin and Melo (2012).

In the context of climate change, scientists discuss the attribution of reference periods to the assessment of climate. Recently, many studies have been published comparing recent conditions with the last reference period 1961–1990. In this paper, the trend of annual, seasonal and monthly average air temperature, as well as annual, seasonal and monthly precipitation in Slovakia, is presented to record changes which could probably be shown in the next reference period 1991–2020. The first GCM was used in Slovakia in 1991 (quite late in comparison to western countries), and some other GCMs at the end of the 1990s and at the beginning of 2000s. At present, then, we can partly verify if their trend projections for the beginning of 21st century were correct. Additionally, this paper shows that the reference periods did not show such differences in the past as will probably be forthcoming, in comparing the reference periods 1961–1990 and 1991–2020. Changes in temperature and precipitation in different regions, not only the lowlands but also the high mountains, result in the changes of climate regions in Slovakia. Some climate regions in Slovakia demonstrate some significant changes as presented in this paper. Such changes should support the existence of climate change in this region as these changes are sometimes still disputed.

2. Methods

2.1 Temperature and precipitation data

This study was prepared using average monthly air temperature and monthly precipitation totals from 14 meteorological stations in Slovakia (Fig. 1) over the period 1931–2014. The selection of the stations was conditioned by complete observed datasets in the database of the Slovak Hydrometeorological Insitute. The only exception was the station Lomnický štít peak, which had missing data from January 1931 to September 1940 and in the years 1945 and 1946. The data from the database, from the publications Zborník prác SHMÚ Nr. 23 (Petrovič and Šoltís, 1984) and Klíma Tatier (Konček, 1974), were homogenized and missing values were imputed using the software MASHv3.03 (Szentimerey, 2003). This process resulted in a dataset without discontinuities, some of which occurred due to the moving of stations, changes of observers, or changes in station equipment, etc.

The selected meteorological stations represent lowland, valley and mountainous parts of the country. After homogenisation, the data were analysed on monthly, seasonal and annual time scales. The spatial average temperature values for all of Slovakia were calculated as averages from 11 stations with weight 1 and from three stations with weight 0.1 (mountainous stations Lomnický štít peak, Štrbské pleso lake and Skalnaté pleso lake). This method corresponds with the established calculation of spatial average temperature in Slovakia (Lapin et al., 1995). The linear model was used for trend analysis. The significance

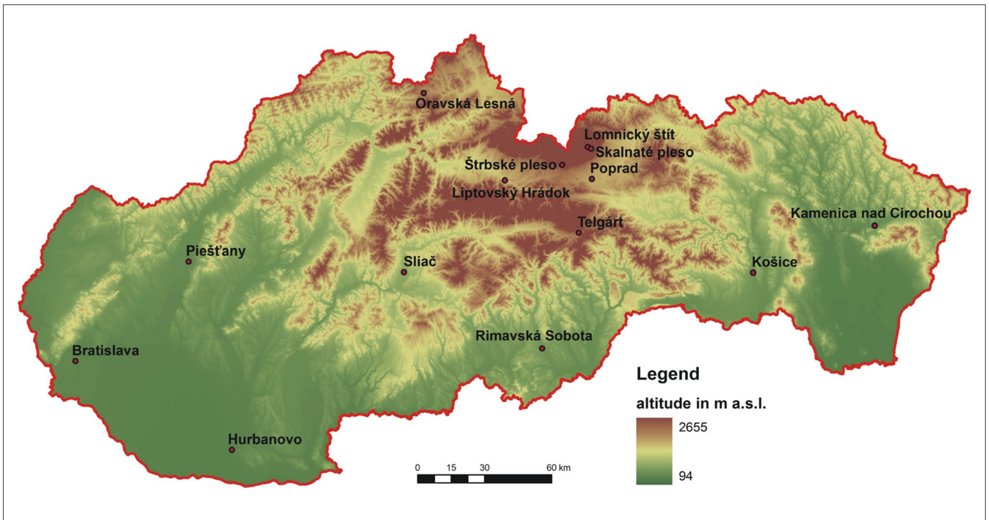

Fig. 1: Location of selected meteorological stations in Slovakia.
Source: authors, digital terrain model by Slovak Environment Agency

of the trend was tested using F-statistics at significance level $\alpha = 0.05$. To demonstrate not only changes in average air temperature, but also in its maximum and minimum, the occurrence of "summer" and "tropical" days in the spring months was determined, as well as the occurrence of "ice"and "arctic" days in winter months. A "summer" day is defined in the official Meteorological dictionary (Sobíšek, 1993) as a day with a maximum daily temperature greater than or equal to 25 °C. The definition of "tropical" day is very similar, but the temperature threshold is set at 30 °C. The "ice" day occurs when the maximum daily temperature is less than 0 °C and, similarly with respect to a threshold, a maximum daily temperature below − 10 °C denotes the occurrence of an "arctic" day.

The spatial average precipitation totals can be used to characterize precipitation conditions in a selected region. This value was obtained from precipitation data for each station using a double weighted average method. The result was the dataset of spatial monthly precipitation totals for the entire country. It represents a quite conservative value, which is proper for the analysis of precipitation trends (Šamaj and Valovič, 1982). The data for each station were analysed on monthly, seasonal and annual time scales. Again, the linear model was used for trend analysis. The significance of the trend was tested using F-statistics with the significance level $\alpha = 0.05$.

The long-term characteristics of meteorological variables, including averages for the reference periods, comprise basic research activities in climatology. The reference period is defined as a 30-year dataset of meteorological observations. The World Meteorological Organisation (WMO) established the reference periods 1901–1930, 1931–1960 and 1961–1990. Such defined conditions enable comparisons at larger regional scales, to quantify changes in meteorological variables, and to objectively assess the recent status of the climate.

2.2 Classification of the climate regions in Slovakia following Konček and Petrovič (1957)

Slovakia can be characterised as a very complex landscape, which can result in different climate conditions within a small area. On the other hand, it was not possible to use methods for clapssification of large areas, because they were too coarse for the area of the country – Czechoslovakia as then defined. Therefore, Konček and Petrovič (1957) established a new classification of the climate regions of Czechoslovakia. The classification consists of three main regions – warm, moderately warm and cold regions. They tested many different criteria based on continentality and temperature characteristics, e.g. average annual temperature amplitude, the ratio between months with maximum and minimum precipitation, cumulative temperature sums for periods with average daily temperature above 5 °C, 10 °C or 15 °C. These characteristics have been shown to be inappropriate or bringing no new information other than isolines representing the number of summer days. This characteristic differentiates regions with different continentality quite well, as continentality is caused by different factors in the Czech Republic and in Slovakia (Konček and Petrovič, 1957).

Additionally, the isoline of 50 and more summer days corresponds to isoline bounding region with the first harvest day of winter rye till 15th July. Therefore, it was established as a threshold isoline for a warm climate region, where the production of warmth-requiring crops (e.g. maize or tobacco) is possible. Another very important characteristic was the isoline of average temperature in July equal to 16 °C, which is located approximately at the same altitude (700 m a.s.l.) in the whole country. Spring is quite short in areas up to this isoline and late frosts occur quite often. For this reason only the production of less warmth-requiring crops is suitable in this area. Therefore, the isoline of average temperature in July equal to 16 °C was set as the upper threshold of moderately-warm climate regions. The rest of country is allocated to the cold climate region.

Each region has several sub-regions, which are further classified according to average temperatures in January and July, as well as Konček's moisture index and altitude (Tab. 1).

Konček's moisture index is an empirical estimate of the water balance in the warm half-year (April–September). It is estimated according to the equation:

$$I_z = 1/2R + \Delta r - 10 \times T - (30 + v^2)$$

where

I_z = Konček's moisture index, R = precipitation total in warm half-year (WH), Δr = precipitation surplus above 105 mm in winter, T = average temperature in WH; and v = average wind speed measured at 2 p.m. in WH.

The advantage of this index is primarily in considering precipitation in the warm half-year, which is the most important for vegetation as the months from April to September comprise almost the entire growing season. The authors assumed that half of the total precipitation in this period is evaporated and the rest results in run-off. The index also considers winter precipitation, but only its surplus, which improves water balance at the beginning of the growing season. The threshold (105 mm) represents the amount which is usually run-off or evaporated in March and hence cannot support the water balance in April (Konček and Petrovič, 1957). This index provides very similar information about moisture conditions to those reached using Thornthwaite's moisture index (Thornthwaite, 1948).

The differences in average winter temperature throughout the country are very clear. They led to the establishment of average temperature in January (T_{Jan}) as another criterion for the sub-division of sub-regions. Another important criterion is altitude, which plays an important role in the regime of climatic variables. The last characteristic, dividing sub-regions in the cold climate region, is again average temperature in July (T_{July}). The production of oats is possible in areas up to an isoline of T_{July} equal to 12 °C. This sub-region is described as moderately cold. The isoline of T_{July} equal to 10 °C represents the upper threshold of forest and this sub-region is described as cold mountainous. Above this isoline are areas of alpine meadows and rocks. This classification describes in strong detail various climate differences in Slovakia, where one can find regions from semi-steppe to precipitation-very rich areas, as well as from warm areas to cold areas, where the growth of vegetation is not possible.

This moisture index was used in the original methodology of land evaluation units, which describe units with similar climatic and soil features. The index, however, is not so well suited for operational monitoring, but it reflects climate changes quite well (e.g. Melo, Kružicová, 2011; Melo et al., 2007a). This classification was used in the Landscape Atlas of the Slovak Republic (2002). In this paper, we compare the results of a climate classification in the period 1961–1990, published in Landscape Atlas of

Sub-region		Climate conditions
Warm region (50 or more summer days per year)		
T1	warm, very dry, with mild winter	$T_{Jan} > -3$ °C, $I_z < -40$
T2	warm, dry, with mild winter	$T_{Jan} > -3$ °C, $-20 > I_z \geq -40$
T3	warm, dry, with cold winter	$T_{Jan} \leq -3$ °C, $-20 > I_z \geq -40$
T4	warm, moderately dry, with mild winter	$T_{Jan} > -3$ °C, $0 > I_z \geq -20$
T5	warm, moderately dry, with cold winter	$T_{Jan} \leq -3$ °C, $0 > I_z \geq -20$
T6	warm, moderately humid, with mild winter	$T_{Jan} > -3$ °C, $60 > I_z \geq 0$
T7	warm, moderately humid, with cold winter	$T_{Jan} \leq -3$ °C, $60 > I_z \geq 0$
T8	warm, humid, with mild winter	$T_{Jan} > -3$ °C, $120 > I_z \geq 60$
T9	warm, humid, with cold winter	$T_{Jan} \leq -3$ °C, $120 > I_z \geq 60$
Moderately warm region (less than 50 summer days per year and 16 °C ≤ T_{July})		
M1	moderately warm, moderately humid, with mild winter, upland	$T_{Jan} > -3$ °C, $60 > I_z \geq 0$, altitude ≤ 500 m a.s.l.
M2	moderately warm, moderately humid, with very cold winter, valley/basin	$T_{Jan} \leq -5$ °C, $60 > I_z \geq 0$
M3	moderately warm, moderately humid, upland to highlands	-5 °C $< T_{Jan} \leq -3$ °C, $60 > I_z \geq 0$
M4	moderately warm, humid, with mild winter, upland to planes	$T_{Jan} > -3$ °C, $120 > I_z \geq 60$
M5	moderately warm, humid, with cold to very cold winter, valley/basin	$T_{Jan} \leq -3$ °C, $120 > I_z \geq 60$, altitude ≤ 500 m a.s.l.
M6	moderately warm, humid, highlands	$T_{Jan} \leq -3$ °C, $120 > I_z \geq 60$, altitude > 500 m a.s.l.
M7	moderately warm, very humid, highlands	$I_z \geq 120$
Cold region (T_{July} < 16 °C)		
C1	moderately cold	12 °C ≤ T_{July} < 16 °C
C2	cold mountainous	10 °C ≤ T_{July} < 12 °C
C3	very cold mountainous	T_{July} < 10 °C

Tab. 1: The classification of climate regions in Slovakia
Source: Landscape Atlas of the Slovak Republic (2002), re-worked by authors

the Slovak Republic (2002), with the results of our updated classification, which is published in the Climate Atlas of the Slovak Republic (2015).

3. Results

3.1 Temperature trends

The period 1991 to 2014 is characterised by an increasing trend of air temperature characteristics. In Slovakia most of the trend analyses in recent years were carried out and published for single meteorological stations separately. In this paper, the motivation was to determine if the significant increasing trend is comparable for the entire territory.

Climate conditions in Slovakia are very complex due to the higher oceanicity in the western part, but higher continentality in the eastern part of the country. Climate contrasts exist also in the north-south direction, as colder climate dominates in the north and warmer climate in the south. Despite these differences within a fairly small area, a comparable increasing trend in annual air temperature is recorded in the dataset of each station. The average annual air temperature increased in the period 1991–2014 from about 0.9 °C (e.g. in Piešťany, Lomnický štít, Skalnaté pleso, Kamenica nad Cirochou, Telgárt, Sliač, Rimavská Sobota, Oravská Lesná) to 1.1 °C in Bratislava, Košice and Liptovský Hrádok, in comparison to its average value in the period 1961–1990. On the other hand, a difference only 0.1 °C was reached comparing average annual air temperature in the periods 1931–1960 and 1961–1990. Thus, the total increase in the whole study period reached at least 1 °C.

These results are confirmed by the spatial average value of annual air temperatures for the whole of Slovakia. It reached an increase of about 1 °C in the period 1991–2014 compared to its average value in the period 1961–1990 (Fig. 2).

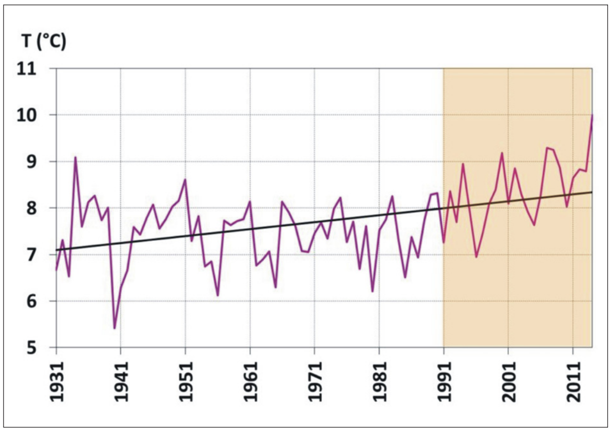

Fig. 2: Spatial average annual temperature in Slovakia in the period 1931–2014. Source: authors

Considering spatial average monthly air temperatures, the increasing trend of average monthly temperature in each month reveal different intensities. The highest increase was observed in the months of January, June, July and August (Tab. 2). The trend in all these months is statistically significant. The spatial value of average monthly air temperature increased about 1.5 °C in January and June and about 1.7 °C in July and August, comparing the periods 1961–1990 and 1991–2014. But comparing the periods 1931–1960 and 1961–1990, the increase reached at most 0.6 °C in July.

Similar trends are recorded in the months of the transitional seasons and in December, but they are not as evident as those mentioned above, except March, April and May (Fig. 3). Most of them are statistically insignificant, again except March, April and May. The differences between the average for 1961–1990 and the average for 1991–2014 reached at most 0.6 °C.

The significant increasing trend in April can be explained by the shorter snow cover duration and its smaller spatial extent in March (Pecho et al., 2010a). This situation enables faster warming processes at the surface, which results in higher air temperatures in the second half of spring. A comparable trend was observed in May. There are several known cases when short periods with maximum daily air temperatures above or equal to 30 °C were recorded at the beginning of May (Fig. 4). Their occurrence has been noted several times since the last decade of the 20th century. Such cases were very rare in the past and they referred to single days.

Recently, short episodic heat waves, or single heat days have been recorded even at the end of April. They occurred frequently in Slovakia at the beginning of the 2010s (Výberči, 2012). A good example is the number of summer ($T_{max} \geq 25$ °C) and tropical days ($T_{max} \geq 30$ °C) in Hurbanovo. The increase of tropical days since the last decade of 20th century is most evident in May (Fig.4). In the case of summer days, it is interesting to note that they are recorded more often in May months, when the maximum temperature was higher than 25 °C during more than one half of its days. Since 1991, five of such May months have occurred (in the years 1993, 2000, 2001, 2003 and 2012), while such a case was noted only once (in 1958) during the previous sixty years (1931–1990). This trend was most notable in Bratislava, where monthly average temperatures in April increased about 1.3 °C when compared to the periods 1961–1990 and 1991–2014. It is an incomparably higher increase than at Lomnický štít peak, where the difference reached "only" 0.8 °C (Fig. 5).

The increase at Lomnický štít peak was only slightly higher in May, when it reached the value of 0.9 °C. But the difference, compared to the previously-mentioned periods, is much higher when considering the summer months, as average monthly temperatures in July and August increased about 1.8 °C and 1.6 °C, respectively. Such values were also observed in the lowland parts of Slovakia. It appears from this finding that snow cover impacts as a barrier during spring warming not only in the lowlands, but also in mountainous regions (Pecho et al., 2010b). When the snow cover is missing, the warming has the same intensity as that found in the lower parts of country (Fig. 6).

With respect to the highest parts of Slovakia, the warming acceleration is higher than in the lowlands, when assessing the warming dynamic over the last 25 years. This warming process began in the lowlands in the 1990s, but it occurred with some delay in high mountainous regions in the 2000s and 2010s. Besides circulation factors, this trend demonstrates that the lowest parts of the atmosphere are warmed from the surface first, and the warmth is then transported into higher levels of the atmosphere through atmospheric processes (Matejovič, 2011).

At the beginning of the period 1991–2014, record temperatures (temperature exceeding the highest observed value) were concentrated in the southwestern part of Slovakia. Recently, they have occurred in northern and eastern regions. It is interesting to note that their occurrence

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	Spring	Summer	Autumn	Winter
Bratislava-Letisko	0.36	0.23	0.25	0.19	0.16	0.18	0.18	0.19	0.00	0.08	0.09	0.10	0.17	0.20	0.18	0.06	0.23
Liptovský Hrádok	0.38	0.29	0.24	0.18	0.16	0.20	0.18	0.18	– 0.03	0.12	0.12	0.13	0.18	0.19	0.19	0.07	0.27
Hurbanovo	0.37	0.26	0.25	0.21	0.16	0.13	0.15	0.15	– 0.02	0.08	0.10	0.11	0.17	0.21	0.14	0.06	0.25
Kamenica n/C.	0.38	0.21	0.24	0.19	0.12	0.13	0.17	0.15	– 0.03	0.07	0.06	0.04	0.15	0.18	0.15	0.03	0.22
Košice-Letisko	0.32	0.23	0.25	0.23	0.15	0.17	0.21	0.18	0.02	0.09	0.08	0.00	0.16	0.21	0.19	0.06	0.18
Lomnický Štít	0.23	0.14	0.05	0.15	0.14	0.12	0.17	0.18	– 0.02	0.09	0.11	0.08	0.12	0.11	0.15	0.06	0.15
Oravská Lesná	0.38	0.22	0.19	0.16	0.15	0.13	0.16	0.15	– 0.04	0.06	0.10	0.02	0.14	0.16	0.14	0.04	0.21
Piešťany	0.27	0.16	0.20	0.14	0.12	0.10	0.14	0.17	– 0.03	0.06	0.06	0.06	0.12	0.15	0.14	0.03	0.16
Poprad	0.39	0.20	0.23	0.19	0.12	0.14	0.16	0.19	– 0.05	0.06	0.09	0.07	0.15	0.18	0.16	0.03	0.21
Rimavská Sobota	0.37	0.23	0.20	0.21	0.15	0.16	0.17	0.21	– 0.04	0.09	0.04	0.09	0.16	0.19	0.18	0.03	0.23
Skalnaté Pleso	0.29	0.19	0.13	0.22	0.18	0.14	0.19	0.17	– 0.01	0.15	0.16	0.15	0.16	0.18	0.16	0.10	0.22
Sliač	0.35	0.18	0.18	0.20	0.17	0.15	0.14	0.18	– 0.01	0.08	0.07	0.02	0.14	0.18	0.16	0.04	0.18
Štrbské Pleso	0.31	0.25	0.15	0.20	0.19	0.14	0.17	0.19	– 0.02	0.10	0.10	0.08	0.16	0.18	0.17	0.06	0.22
Telgárt	0.31	0.20	0.20	0.18	0.11	0.12	0.16	0.16	– 0.07	0.04	0.10	0.01	0.13	0.16	0.15	0.03	0.18
Slovakia	0.35	0.22	0.22	0.19	0.14	0.15	0.17	0.17	– 0.03	0.08	0.08	0.06	0.15	0.18	0.16	0.04	0.21

Tab. 2: Increase of average monthly, seasonal and annual temperature in °C per decade in the period 1931–2014 (bold values are statistically significant). Source: authors

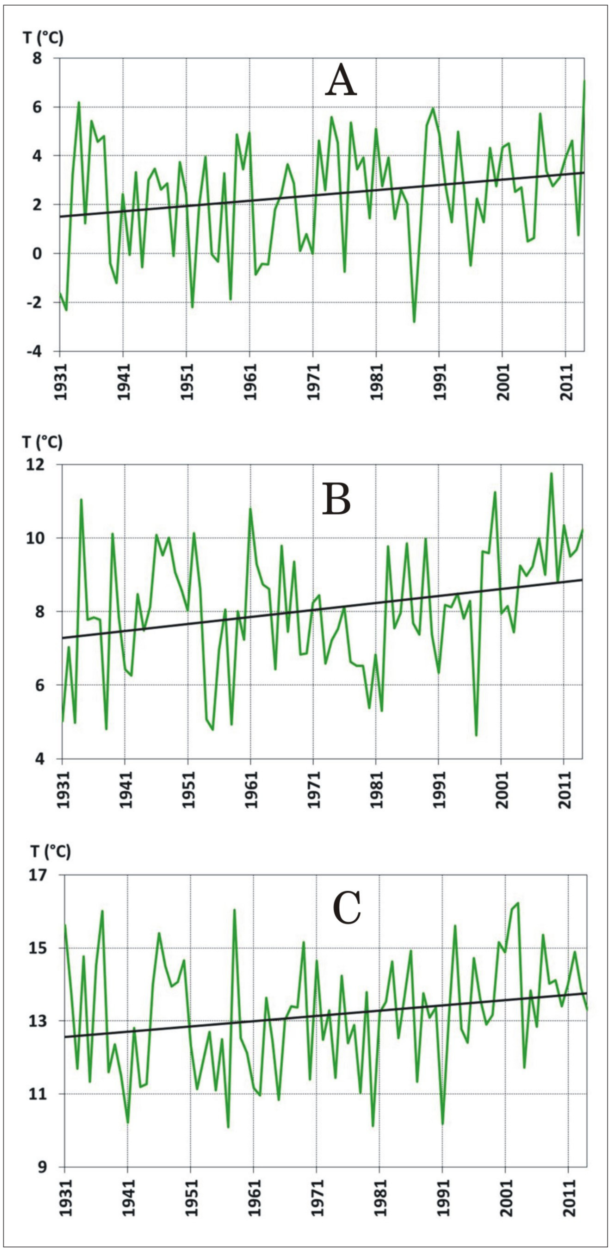

Fig: 3: Spatial average value of monthly temperature in March to May (A to C) in Slovakia in the period 1931–2014. Source: authors

is higher there than in the traditionally warmer southwestern part of country. Due to this, the area with occurrence of record temperatures has become less heterogeneous. To some degree, one notes a parallel to temperature changes in mountainous areas, but in this case we can speak about latitudinal zonality.

The different intensities of increasing trends in each month result in similar differences in each season and in the warm and cold half-years. Only a small increase is observed in autumn due to the slow increasing trend in the months September and October, probably due to large-scale circulation over Europe. Spring shows only a slightly higher trend in average temperatures than autumn; nevertheless, the increasing trend in April and May is high. It is balanced out by only a low trend in March at some stations. There is a similar situation in winter, when the trend in January is as high as in the summer months, but the months of December and February show only a low increasing trend. Similar impacts are expressed in the number of ice ($T_{max} \leq 0$ °C) and arctic days ($T_{max} \leq -10$°C), which decreased the most clearly in January in Hurbanovo. The last arctic day in Hurbanovo was recorded in 1987.

These findings are in very good agreement with meteorological experiences at the end of the 20th century and at the beginning of the 21st century (Faško et al., 2013). The transitional seasons are not very outstanding. On the other hand, it is unusually warm at those times when winter should be ending. The notable results are the changes from late summer into winter weather in a short time period during autumn. Similar changes are recorded during spring, when winter weather at the end of March and the beginning of April turns into summer weather in the second part of April (Pecho et al., 2010a).

The most notable increasing trend is observed in the summer for the whole country. The difference, in comparison to other seasons, reached + 1 °C, considering spatial average values. The same dominant trend is visible comparing warm and cold half-years (Fig. 7). All months with the highest increasing trend of average monthly temperatures (April, May, June, July and August) are concentrated in the warm half-year, while comparable trends in the cold half-year are identified only in January.

3.2 Precipitation trends

With respect to air temperature trends since 1931, it is also interesting to identify precipitation trends. Differences between air temperature and precipitation as meteorological variables are commonly known. Research on precipitation is more difficult in this sense, whether considering an annual or other periodic regime, as well as its spatial distribution.

The long-term averages of spatial precipitation totals for the reference periods show only small changes in each month, season, half-year and year, opposite to the temperature trends. The only exception is the month of July, even though it is not statistically significant.

In the 1990s and 2000s, some notable precipitation weather conditions were recorded, which resulted in floods. It is probable, as well, that an important role was played by a greater spatial extent of rain storms and their intensity, which caused flash floods (Faško et al., 2006).

Differences between the reference periods, or long-term precipitation averages for each station, represent some specifics. They are conditioned by the location of the meteorological station with respect to the air masses bringing precipitation, but also by the enhancing or the weakening of the precipitation significance of these masses, respectively (Lapin et al., 1995). These conditions resulted in increased precipitation totals in the months from January to March in the period 1991–2014 in northwest Slovakia (Fig. 8), when compared to the reference periods 1931–1960 and 1961–1990. The increasing trend in these months is higher than in July. Although the increasing trend in winter precipitation is not statistically significant, the highest increase was recorded at high altitudes. These results are in good agreement with Cheval et al. (2014). The higher precipitation totals in these months were not caused just by humid air masses from the northwest, as temperature conditions in this region were important as well (Lapin, 2015). For example, winters after 1991 were not as cold as in the past, which resulted more often in the occurrence of mixed and liquid precipitation (Pecho et al., 2009). The higher temperatures in the period from January to March also supported the higher precipitation totals.

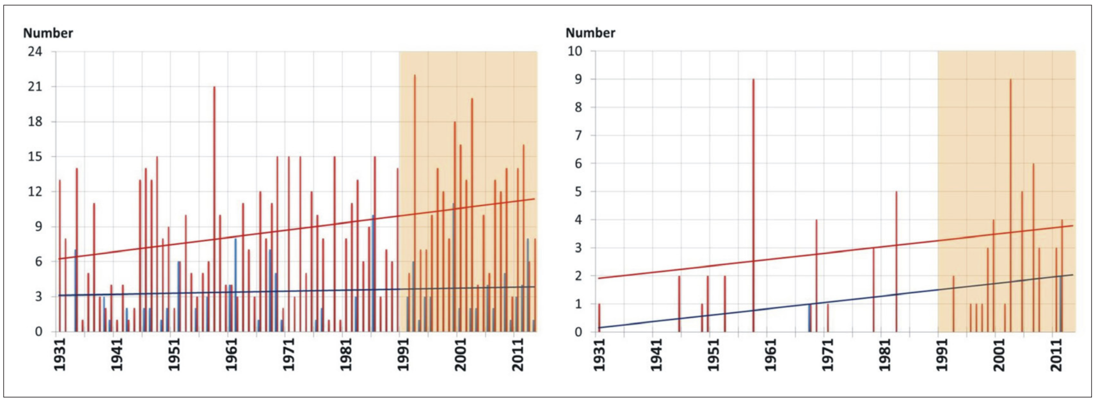

Fig. 4: Number of summer (T_{max} ≥ 25°C, left) and tropical days (T_{max} ≥ 30°C, right) in the months of April and May in Hurbanovo since 1931. Source: authors

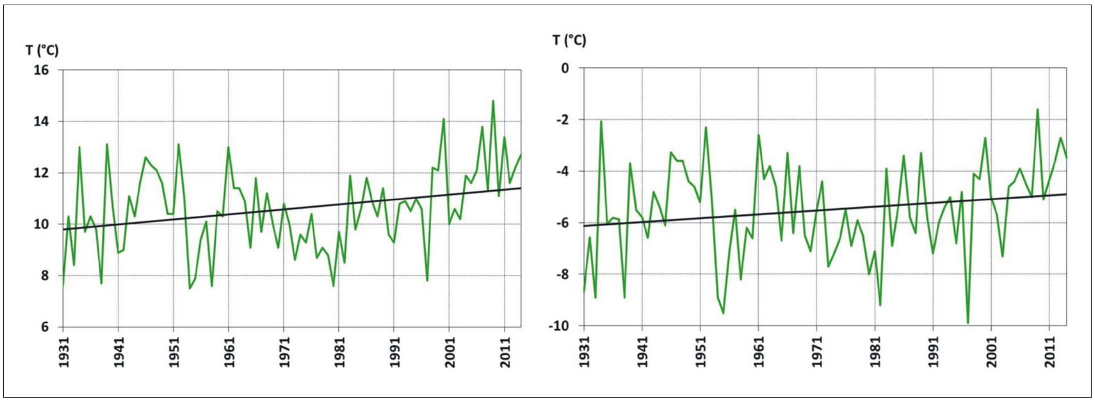

Fig. 5: Average monthly temperatures in April in Bratislava (left) and at Lomnický štít peak (right) in period 1931–2014. Source: authors

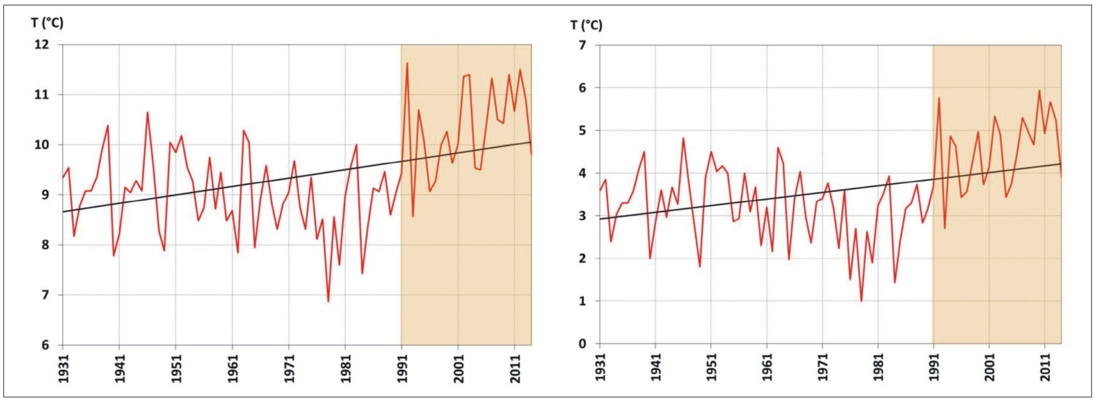

Fig. 6: Average air temperature in summer at Skalnaté pleso lake (left) and at Lomnický štít peak (right) in period 1931–2013. Source: authors

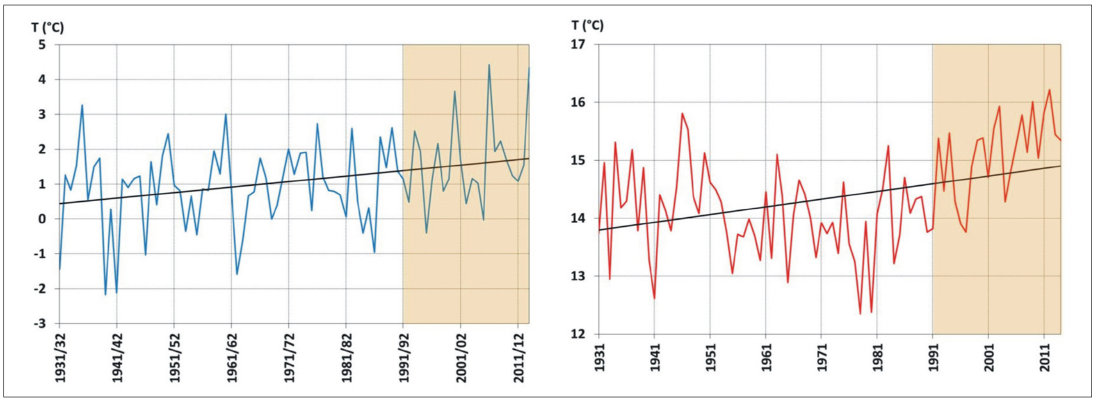

Fig. 7: Spatial average air temperatures in the cold (left) and warm half-year (right) in Slovakia, 1931–2014. Source: authors

At the end of 2000s and at the beginning of 2010s, the weather situations which originated in pressure lows over the Mediterranean, participated in precipitation totals in a more important way (Pecho et al., 2010). This situation led to record-breaking annual precipitation in the southern part of Slovakia (Fig. 9). Due to similar synoptic conditions, the winter season in 2012/2013 was characterized by higher precipitation in the southwest of the country and in the southern part of central Slovakia. Some parts of these regions recorded an extraordinary height of snow cover (Matejovič and Pecho, 2013).

From the data presented above, precipitation and air temperature trends are different. Firstly, the precipitation trend is much less notable than the temperature trend.

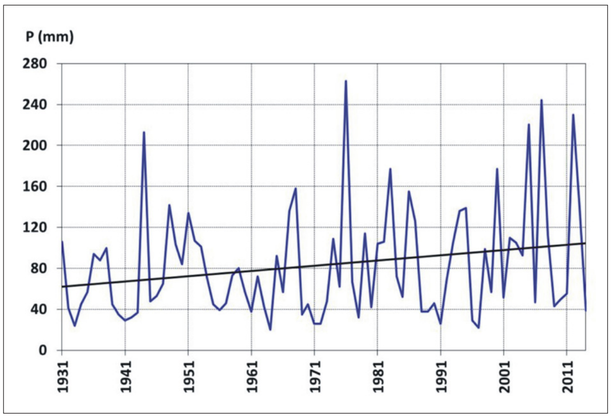

Fig. 8: Monthly precipitation totals in January in Oravská Lesná in the period 1931–2014. Source: authors

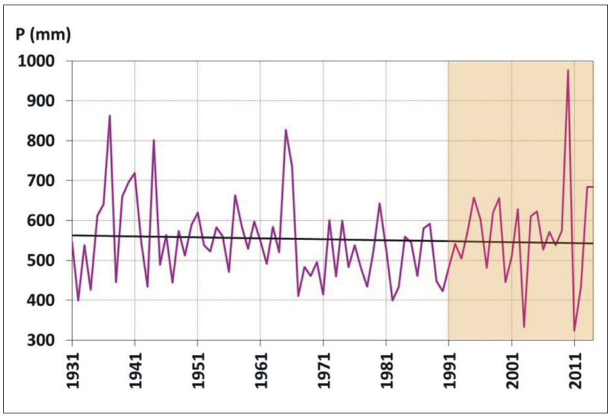

Fig. 9: Annual precipitation total in Hurbanovo in the period 1931–2014. Source: authors

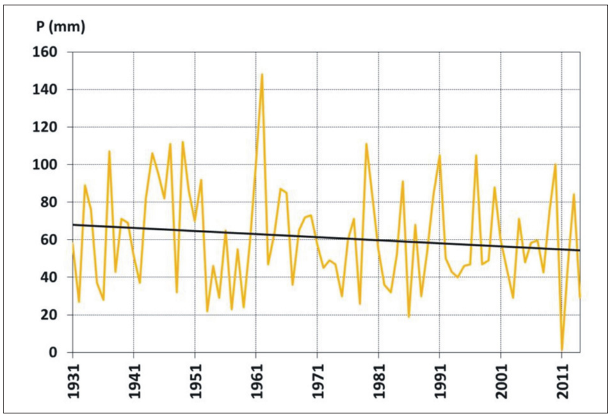

Fig. 10: Spatial precipitation total in Slovakia in November in the period 1931–2014. Source: authors

Precipitation reached a higher intensity during its occurrence compared to the past. It leads to the occurrence of months with extremely below normal and extremely above normal levels of precipitation (Faško, 2012; Falťan et al., 2014). Therefore, the comparison of dry and wet periods seems to be in high contrast. Considering precipitation totals in the reference periods, it might seem that there are no changes, but the annual regime of precipitation has changed.

Considering periods without precipitation or with deficit precipitation, tendencies in precipitation are similar for the whole country, as in the case of air temperature. The spatial extent of these periods has also spread into the traditionally wetter regions of northern and northeastern Slovakia (Matejovič, 2011). As one example, we could mention November 2011, in which extremely low precipitation totals were recorded over the entire country (Fig. 10).

3.3 Changes in climate regions

As noted above, Konček and Petrovič (1957) presented a new classification of the climate regions of Czechoslovakia: three main regions – warm, moderately warm and cold. From a comparison of climate regions in Slovakia published in the Landscape Atlas of the Slovak Republic (2002) and in the Climate Atlas of the Slovak Republic (2015), it is obvious that important changes in some regions and sub-regions have occurred. The changes have resulted from two major trends: the increase of monthly average temperature and the drying trend in some regions.

The warm region, earlier established in the Váh river basin up to the town of Ilava, has expanded northward through the Váh river basin and today includes the town of Žilina (Fig. 11). A similar extension of the warm region has appeared in the Hron water basin. These changes are primarily due to warmer conditions in summer, which resulted in a higher number of summer days in these river basins. Both river basins still have enough precipitation in the areas within the extended warm region, which results in Iz values above 60. Therefore, two new sub-regions occur in Slovakia. The first of them, T8 – warm, humid sub-region with mild winter, is located in the middle part of the Váh river basin. The second sub-region, T9 – warm, humid sub-region with cold winter, is recorded northeastward from Kamenica nad Cirochou (northeastern Slovakia) and in the Hron river basin eastward from Banská Bystrica. At these sites, the average monthly temperature in January is still quite low, in contrast to sub-region T8.

The change in temperature conditions, concretely the increase of average monthly temperature in January, results in a change of sub-region in the Východoslovenská nížina lowland (Fig. 12), but also in areas near the towns of Lučenec, Tornaľa and Rimavská Sobota, and in the southern part of the Košická kotlina basin. In these areas, the warm dry sub-region with cold winter (T3) changed to a warm, dry sub-region with mild winter (T2).

The driest sub-region T1 moved northward and it covers the whole of the Podunajská nížina lowland today (Fig. 13), except for the Hronská pahorkatina upland and the Ipeľská pahorkatina upland. Drying was also identified in the eastern part of the Záhorská nížina lowland, where the warm, moderately humid sub-region T6 was reclassified into the warm, moderately dry sub-region T4.

The moderately warm region is recorded as a spatial extension at the expense of the cold region. It is the most visible in the Liptov region (located around the towns of

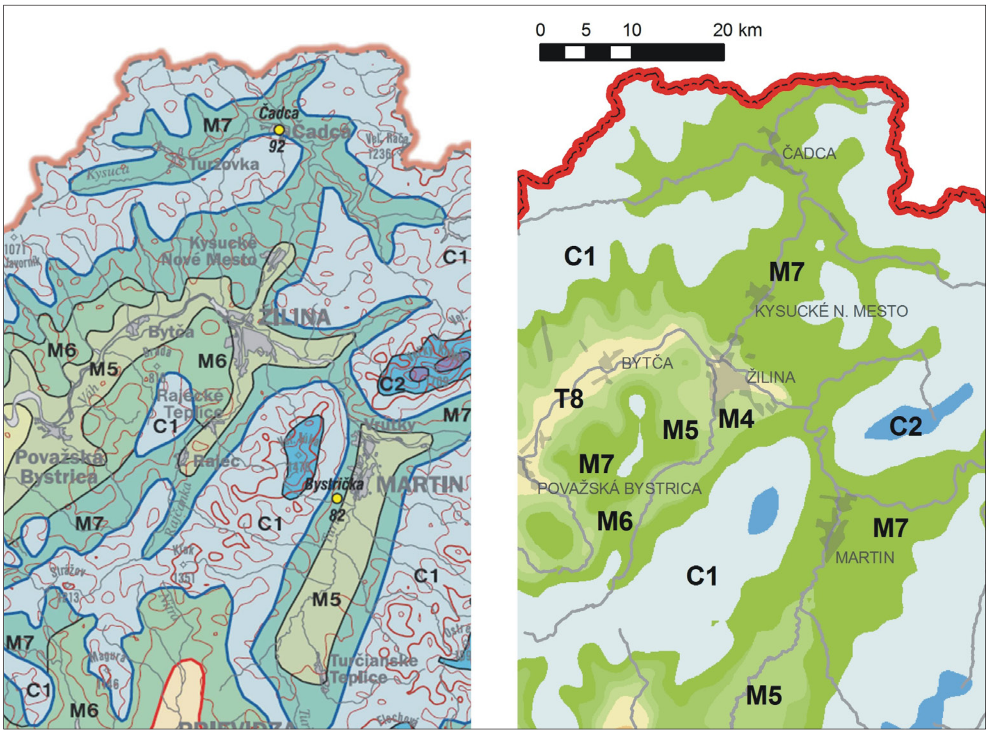

Fig. 11: Climate sub-regions near the town of Žilina in the period 1961–1990 (left), and in the period 1961–2010 (right). Source: Landscape Atlas of the Slovak Republic (2002), authors

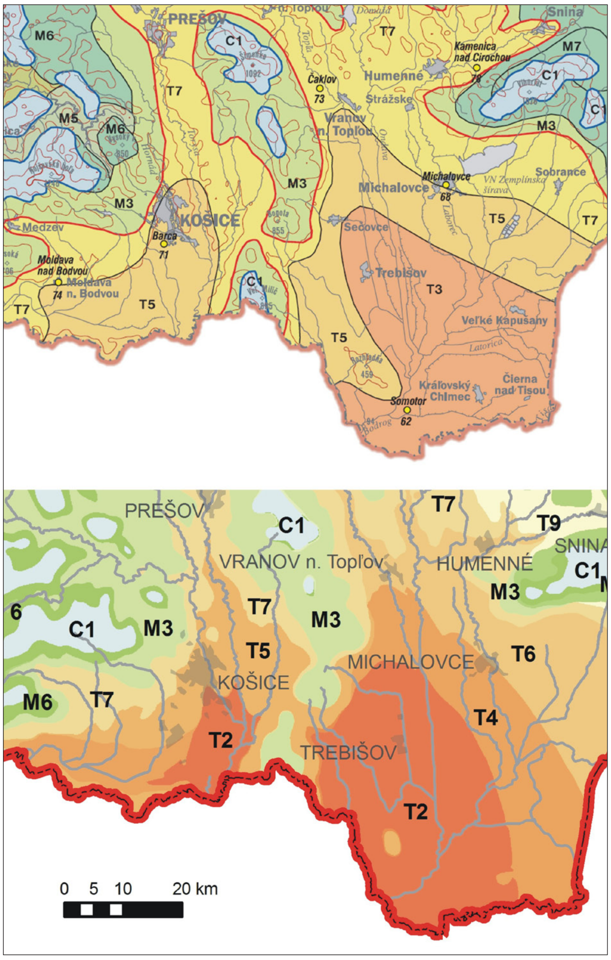

Fig: 12: Climate sub-regions in the Východoslovenská nížina lowland in the period 1961–1990 (top), and in the period 1961–2010 (bottom).
Source: Landscape Atlas of the Slovak Republic (2002), authors

Liptovský Mikuláš and Ružomberok), in the upper part of the Hron river basin, as well as extending northward in the Orava and the Kysuca water basins. The sub-region M2 (moderately warm, moderately humid, with very cold winter) has totally disappeared due to the increase in the average monthly temperature in January. It was located in the Hornádska kotlina basin in the period 1961–1990, but now this area is assigned to the sub-region M3, which is characterised by milder temperature in winter. Some smaller changes due to climate drying are also recorded in the moderately warm region, more concretely in the north-eastern part of Slovakia.

The smallest part of Slovakia is classified as "cold region" and it is still shrinking. It is most apparent near the Piľsko and the Babia hora peaks (the northern part of Slovakia), in the Malá Fatra Mountains, the Veľká Fatra Mountains, the Štiavnické vrchy Mountains and the Javorie Mountains. The coldest sub-region, C3, totally disappeared from the Ridge of Malá Fatra Mountains, and is in slow regression in the Tatra Mountains.

4. Discussion and conclusions

An analysis of the air temperature characteristics in Hurbanovo (Faško and Švec, 2013) was the impulse for the research reported above: the question was whether similar tendencies exist also in the temperature datasets of other meteorological stations in Slovakia. The trend from the temperature dataset in Hurbanovo was clearly identified in other regions, even in higher altitudes. In this context, an increasing air temperature trend is more notable at high altitudes and in the northern and northeastern part of Slovakia than in its southwestern part in the 21st century. This trend was sharper in the southwest of country at the end of the 20th century (Bochníček et al., 2015). Comparing these results to those from GCMs scenarios for the beginning of 21st century, the temperature trend is in very good agreement with CGCM3.1 (Faško et al., 2009). The same

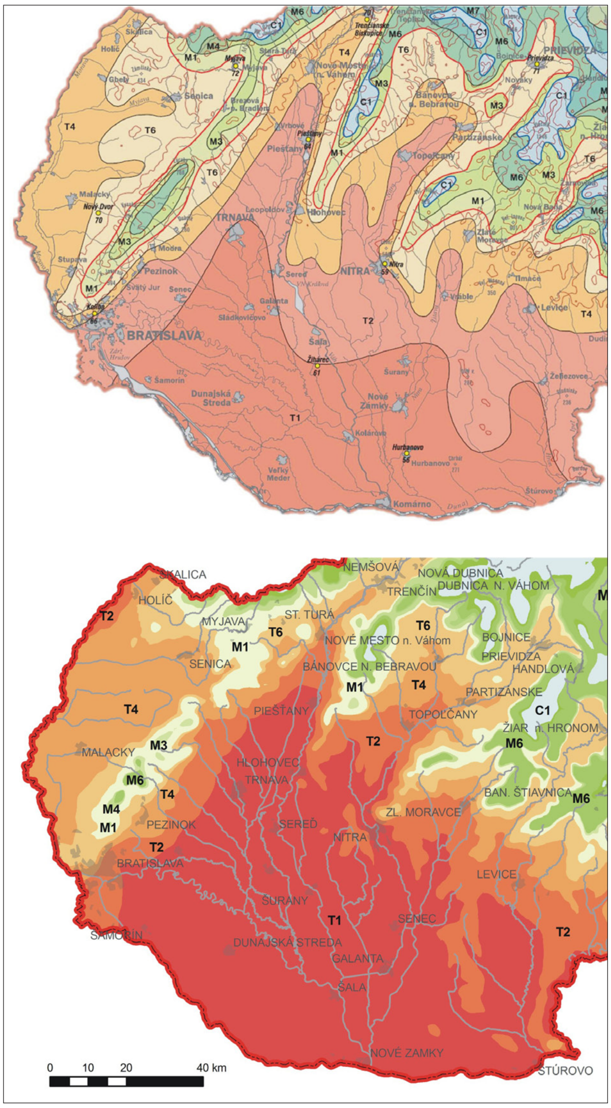

Fig. 13: Climate sub-regions in the Podunajská nížina lowland in the period 1961–1990 (top) and in the period 1961–2010 (bottom). Source: Landscape Atlas of the Slovak Republic (2002), authors

situation is registered by using CCCM 1997, which expected a high temperature increase in summer and smaller in winter (Melo and Lapin, 2000). Our results show that the increase is comparable in these two seasons. On the other hand, a precipitation trend from CGCM2 was not confirmed. A trend that is more similar was reached using GISS 1998, even though the trend in autumn months was not confirmed as well (Faško et al., 2009). All these models were downscaled for Slovakia in 1990s and 2000s.

The precipitation trend is more complex than the temperature trend. It is influenced by particular regional effects, oceanity (or continentality), annual precipitation regime and zonality (or meridionality), in the circulation of air masses bringing precipitation. Overall, changes in precipitation totals and their variability are not as crucial as changes in annual precipitation regime and the contrast variation between wet and dry periods (Faško, 2012).

Even though Konček's moisture index describes moisture conditions in Slovakia very well in the long-term view, the need to modify it is required due to climate change. Modifications are due to the fewer number of days with precipitation, but with higher precipitation intensity at the same time (Melo et al., 2007; Pecho et al., 2008). The result is higher surface runoff, but lower infiltration of water into the soil. Therefore, the water from intense precipitation is less effective for ecosystems. These changes of precipitation regime are not reflected in the results of the index. Another parameter which should be changed is the precipitation surplus above 105 mm in winter ($\Delta r > 105$ mm). Approximately, 60% of Slovakia has altitudes higher than 300 m a.s.l., but only 5.4% of its territory has altitudes higher than 1000 m a.s.l. In the context of climate change, areas with a persistent snow cover shrink relatively quickly, and occasional snow cover with liquid precipitation in the middle of winter expands over the territory of Slovakia (Lapin and Melo, 2012). Such conditions result in the higher participation of winter precipitation in winter runoff, not in spring runoff as in the past. Therefore, water reserves in spring are low even after winter, which was rich in precipitation. From these findings, the parameter $\Delta r > 105$ mm seems to be unsustainable and should be increased with the increasing average air temperature in winter. Lapin and Melo (2012) suggested to skip this parameter, if average winter temperature is higher than or equal to 2 °C. In other cases, when the average winter temperature is lower than 2 °C, the parameter should vary from $\Delta r > 150$ mm to $\Delta r > 105$ mm, according to the temperature (minus 2 mm for each 0.1 °C under 2 °C).

Despite the fact that modification of Konček's moisture index has not been carried out at present, it is suitable for the assessment of climate changes in Slovakia in such a context. Additionally, it enables the comparison of the results with any earlier published distribution of climate regions in the country. According to the comparison described above, we record the changes in sub-regions due to the increase of average monthly temperature and the drying tendencies in lowlands and surrounding lower parts of Slovakia. These drying tendencies are not caused by the decline of precipitation, but by increasing temperature, which enhances evapotranspiration. These results are in good agreement with Pecho et al. (2008) and Melo et al. (2007b), who identified such drying trends in earlier periods. The changes in the distribution of regions are also due to the increasing air temperature in January, which is most apparent in the south and east of Slovakia. It must be noted that the map of climate regions in the Landscape Atlas (2002) was made without the GIS system and was digitized manually for publication. Therefore, some small differences in climate regions could be the result of different interpolation techniques. On the other hand, this paper presents changes and shifts in climate sub-regions which are clearly not the result of interpolation, but of changes in climate.

Acknowledgment

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MORAVIAN GEOGRAPHICAL REPORTS

Aims and Scope of the Journal

Moravian Geographical Reports [MGR] is an international peer-reviewed journal, which has been published in English continuously since 1993 by the Institute of Geonics, Academy of Sciences of the Czech Republic, through its Department of Environmental Geography. It receives and evaluates articles contributed by geographers and by researchers who specialize in related disciplines, including the geosciences and geo-ecology, with a distinct regional orientation, broadly for countries in Europe. The title of the journal celebrates its origins in the historic land of Moravia in the eastern half of the Czech Republic. The emphasis for MGR is on the role of 'regions' and 'localities' in a globalized society, given the geographic scale at which they are evaluated. Several inter-related questions are stressed: problems of regional economies and society; society in an urban or rural context; regional perspectives on the influence of human activities on landscapes and environments; the relationships between localities and macro-economic structures in rapidly changing socio-political and environmental conditions; environmental impacts of technical processes on bio-physical landscapes; and physical-geographic processes in landscape evolution, including the evaluation of hazards, such as floods. Theoretical questions in geography are also addressed, especially the relations between physical and human geography in their regional dimensions.

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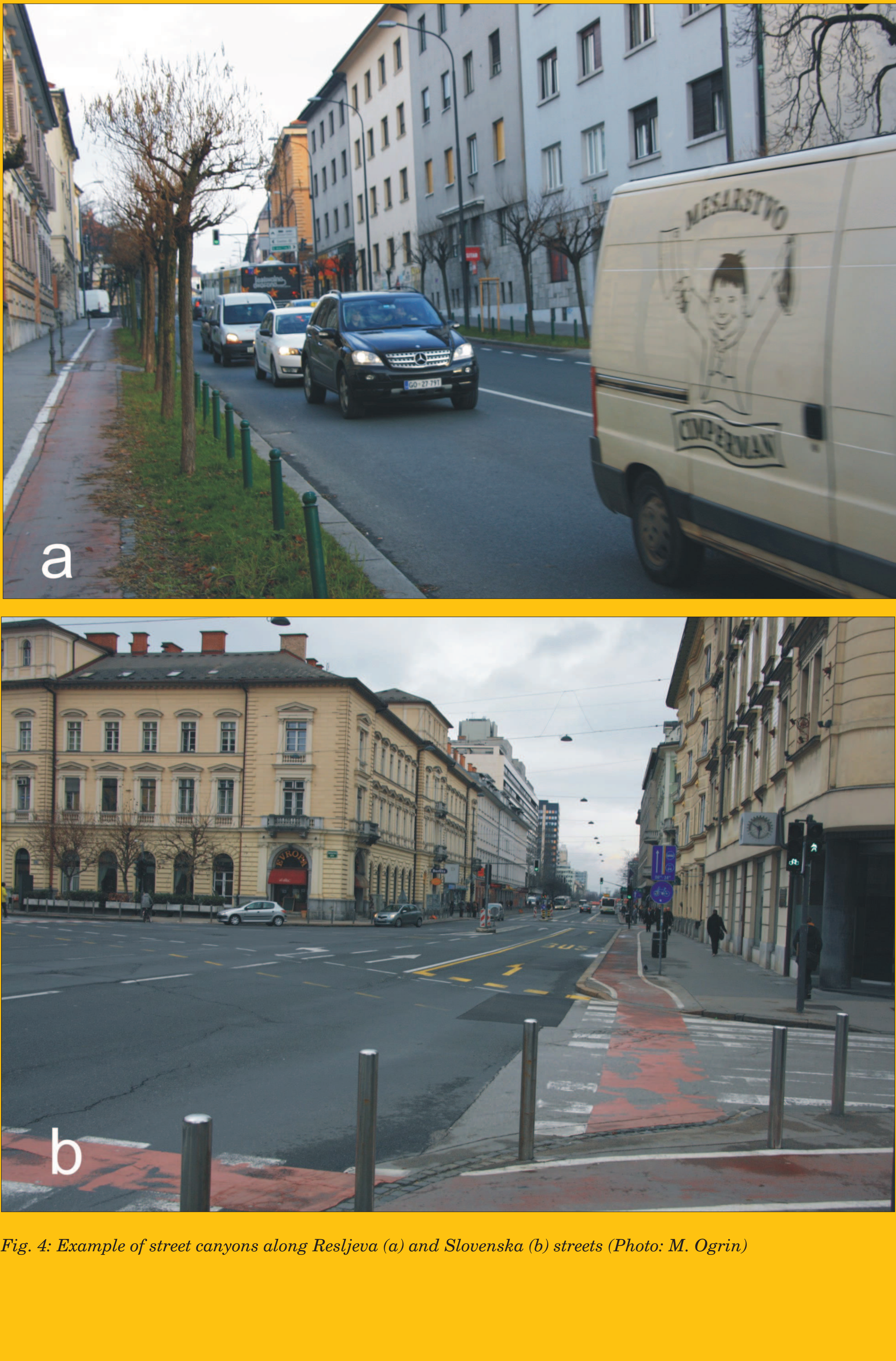

Fig. 4: Example of street canyons along Resljeva (a) and Slovenska (b) streets (Photo: M. Ogrin)