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Microclimate Evaluation of the Hradec Králové City using HUMIDEX

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Abstract: Urban environment differs from the surrounding landscape in terms of the values of meteorological parameters. This is often referred to as the urban heat island (UHI), which in simple terms means higher air temperatures in cities. The cause of these changes lies in the different active surfaces in cities, which subsequently results in a different radiation balance. The higher temperatures, however, also affect the living conditions in the city and during very high temperature periods can have negative effects on the health of the city inhabitants. The results presented in this paper are based on measurements taken over several years at locations near Hradec Králové, which is surrounded by different surface areas. Environment analysis was performed using the Humidex index. The obtained results show that replacing green areas with built-up areas affects temperatures in the city, when air temperatures are very high they significantly increase the discomfort of the inhabitants. Differences in the frequency of discomfort levels are observed especially during periods of high temperatures, at lower temperatures these differences are not significant. Higher frequencies of discomfort are observed at locations with artificial surfaces (asphalt, cobblestones, concrete) and in closed spaces. In contrast, locations with lots of green areas almost always have the value of this index lower or more balanced. The results should therefore be a valid argument for maintaining and extending green areas in cities.

Key words: city, urban heat island, green areas, humidex, discomfort, Hradec Králové

1. Introduction

Weather conditions, and subsequently the climate, are significantly influenced by human activities. Probably the most significant factor is the

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building of cities. Studies that have been done for many cities all around the world have shown that significant improvement of the urban environment and decrease of air temperature can be achieved by the presence of green areas. These green areas have several functions, for example increasing water vapor content in the air or cooling down the environment.

Urban environment evaluations are based on analyses of the occurrence of extremes, calculations of feels like parameters and also air pollution. The differences between urban climate and countryside are due to the different surfaces. This results in different radiation balance because solar radiation is reflected and absorbed by solid objects differently (road surfaces, roofs etc.) than by green areas. The city surfaces heat up more when exposed to the sun and thus increase the air temperature and this also affects the air humidity. Different surface temperatures then affect the temperature regime during night-time as well, when the crucial values are the values of radiation (*Unger, 1999*).

In comparison to open landscape, urban environment does not only differ in the actual values of air temperature and humidity, but also in the dynamics of these parameters based on measurements from weather stations. Because air temperature affects how one feels like, it can be said that individuals living in urban environments are under much more significant stress. In locations where there are no green areas, only asphalt, this feeling then transforms into a feeling of discomfort. In extreme cases it can even lead to health problems. The effects of urban surfaces on human health are being studied in many cities all around the world with the goal to find a way of counteracting their negative impacts. One of the well-known facts is that great improvement is achieved by increasing the proportion of green areas in cities and dividing large artificial surfaces by green belts, or at least planting trees.

The so-called Urban Heat Island (UHI) effect is a phenomenon where higher temperatures are being observed in urban areas compared to the surrounding countryside. Urban heat island is a function of meteorological parameters (air temperature, precipitation, solar radiation, cloud cover, air flow, evapotranspiration) and the nature of the city itself (population, population density, terrain, elevation, proportion of water areas, surfaces – proportion of build-up areas, surface color, distance between buildings, building heights, surface resistance, city geometry – the so-called "city canyon", "anthropogenic heat production" from heating and industries, surface retention). In comparison to countryside areas, the air temperature during night-time can be even 10 °C higher, which has a direct effect on not just human health, but also affects the economy. Changing the geometry of active surfaces – increase in their total area and the proportion of vertical surfaces – leads to higher absorption of solar radiation and reflection.

Enclosed spaces between buildings reduce reflection of long-wave radiation at night and thus lower heat loss. Buildings have a relatively high heat capacity, which allows more heat to be absorbed during periods of positive energy balance and its release during negative energy balance periods. Not just the heat properties of active surfaces are different, but also the hydrological balance is changed. Dominance of impermeable surfaces leads to a decrease in available water amount for evapotranspiration and also decrease in latent heat flux and increase of turbulent flow.

Apart from higher temperatures, urban areas also have higher cloudiness and frequency of fogs, lower visibility (haze) and thus decreased solar radiation, higher rainfall amount and frequency of thunderstorms, lower wind speed and air humidity. The very first study that compared the course of temperature in urban areas with surrounding countryside was the Climate of London analysis published by *Howard (1833)*. UHI is most commonly observed and quantified by methods of ground thermal monitoring (IR sensors), remote sensing (thermal satellite images), eddy covariance methods etc. A classical method used to quantify the so-called Atmospheric Urban Heat Island (related to air temperature and humidity) compares the course of meteorological parameters from urban and non-urban stations. Atmospheric Urban Heat Island can be identified by measuring air temperature or humidity by standard weather stations, using special-purpose measurements within dedicated station networks, or for example by the so-called "measuring drives", which allow spatial quantification of thermal and humidity in the area of interest.

Particularly warm locations such as parking lots, industrial areas, roofs, asphalt roads etc., are defined as Micro Urban Heat Islands (MUHI). An extensive study of urban areas using the city of Brno as an example and based on special-purpose measurements from weather stations, was published by *Dobrovolný et al. (2012)*. The climate of Olomouc was analyzed in the same way (*Vysoudil et al., 2012*).

2. Methods

Hradec Králové is a city with annual air temperature normal (1961–1990) of 8.7 °C and average annual precipitation total of 600.2mm. Course of average monthly temperatures and their range is shown on Fig. 1. In accordance with climate of the Czech Republic, highest daily average temperatures are seen in summer months.

The immediate surrounding area is mostly arable land and suburban forests. For the purposes of analyzing the changes and horizontal variability in temperature and humidity conditions due to different surface types, a network of purpose-built measuring points was created in Hradec Králové in 2011. The sensors monitor air temperature and humidity in 10-minute intervals, which corresponds to the standard measuring practice in the network of climatological weather stations managed by the Czech Hydrometeorological Institute (CHMI). These CHMI stations serve as reference stations so that the differences in temperature and humidity course due to specific microclimate can be determined at the measuring points.

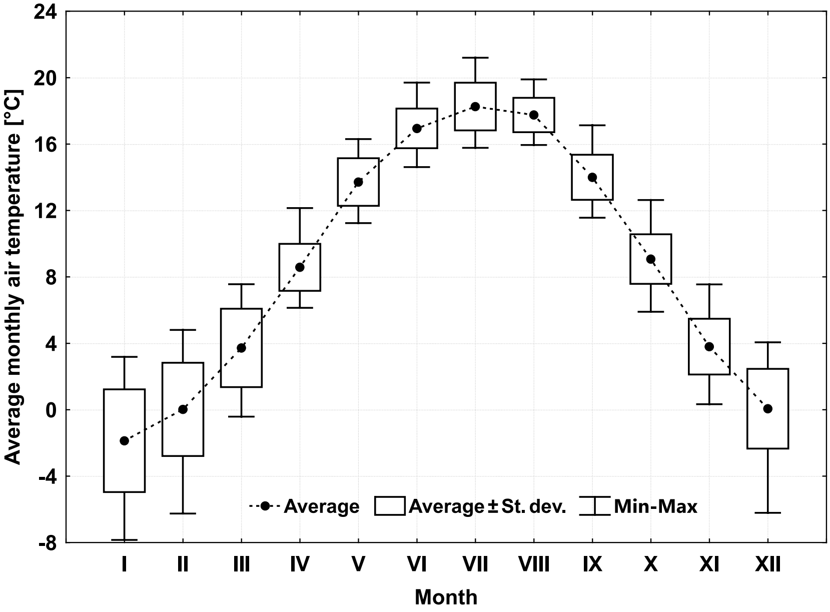

Fig. 1. Average monthly air temperature in Hradec Králové, period 1961–1990.

Temperature-humidity indexes are a commonly used characteristic used to describe the effects of meteorological conditions on thermal comfort of individuals staying at these places. More detailed overview of indexes that are suitable for use in the Czech Republic taking into account the available data sources and including their application on 4 weather stations in the area of Brno, is available in works by *Litschmann and Rožnovský (2009, 2012).* The evaluation in this paper uses Humidex as the temperature-humidity index (*Toy et al., 2007; Unger, 1999*). This index has already been used by *Tomáš (2012)* in a work within the same project for the area of the city of Olomouc, which is why it has also been chosen for this work. This index is in a way similar to the equivalent temperature, which was used in previous years for Slovakia by Čabajová (*Petrovič, 1979*).

The measured temperature and air humidity values in 10-minute intervals were first used to calculate hourly averages and these then used to find the Humidex index using the following equation:

$$\text{Humidex} = T + (0.5555) \cdot (e - 10.0)\,,$$

where T = air temperature [°C], e = actual water vapor pressure [hPa].

The values of current water vapor pressure e [hPa] were calculated from the temperature T [°C] and the relative air humidity φ [%] using the well-known and widely used relationships. Subsequent analysis consisted of finding the number of hours with Humidex values between 30 and 39 for each day (discomfort can be felt by sensitive individuals in this range) and above 40 (significant discomfort leading to limited physical activity). Humidex values above 45 were not observed in the analyzed period at any station so the evaluation only considered the first two categories.

3. Measuring points and used equipment

The course of air temperature and humidity and the differences between Hradec Králové urban area and its surrounding areas were studied based on purpose-built and standard weather stations depicted in Fig. 2 and described in detail in Table 1. Weather stations Hradec Králové Svobodné Dvory and Nový Hradec Králové are equipped with standardized equipment used in

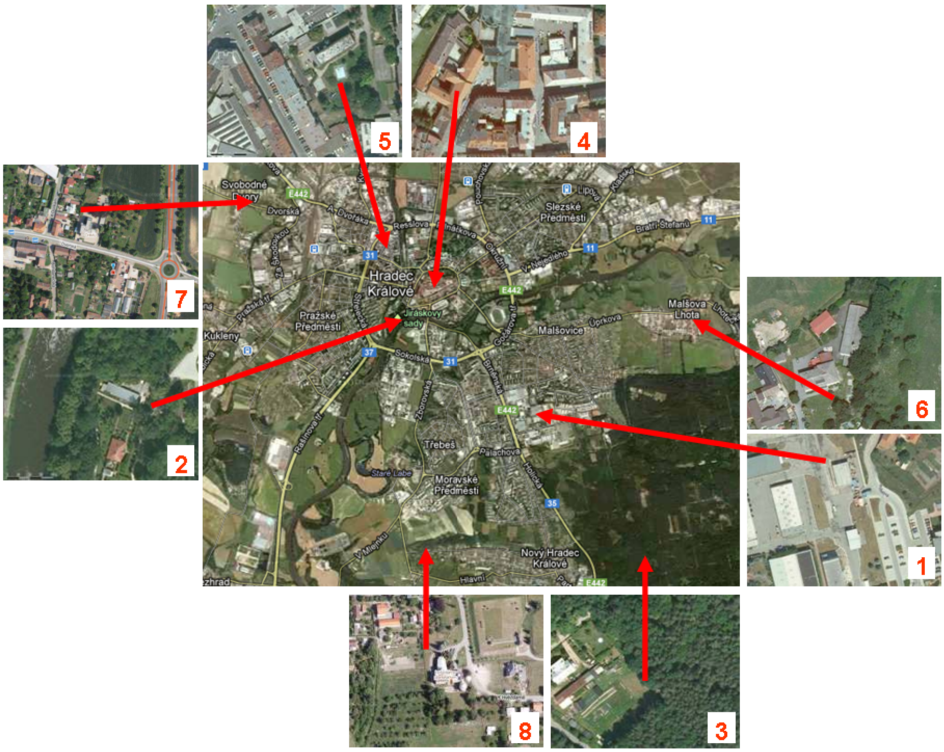

Fig. 2 Location of measuring points in the area of Hradec Králové.

CHMI automatic stations, placed in a Stevenson screen two meters above the ground (grass cover).

Measurements at the purpose-built points were also taken 2 meters above the ground by the surface sensor HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger U23-001, placed inside a radiation shield. Air temperature was measured in 10-minute intervals at all stations.

4. Results

Comparing the course of air temperature and humidity immediately gives a general idea of the differences. Results of measurements from June to

Table 1. Overview, location and specification of the measuring points.

Name, abbreviation and coordinates	**ID num.**	**Brief description of the area**
Technical Services (TS): 50°11'43.159"N, 15°51'18.336"E	1	Located on the city outskirts, significant proportion of horizontal concrete and asphalt surfaces, further away grass cover, exposed to sun shine all day
City Park – Jiráskovy sady (Park): 50°12'21.884"N, 15°49'31.925"E	2	Higher woody vegetation in the city center, high proportion of non-built-up shaded areas, grass cover, shaded all day, confluence of two major rivers nearby
City Forest (Forest): 50°10'39.974"N, 15°54'14.036"E	3	Middle-aged, predominantly coniferous trees, apart from afternoon hours mostly shaded by trees, absence of significantly large areas with artificial surfaces
Historical city center – Music hall (Music hall): 50°12'39.493"N, 15°49'55.767"E	4	Historical city center, enclosed space (courtyard) with vertical surfaces and limited air flow, artificial solid surface, situated under limited woody greens, exposed to sun from morning until afternoon
Průmyslová kindergarden (MŠ inner courtyard): 50°12'52.516"N, 15°49'32.781"E	5	Housing development (5-floor houses), woods and bushes in close vicinity of the measuring point, grass cover, pool nearby, mostly shaded, partly exposed to the sun during morning hours
Malšova Lhota kindergarden (MŠ Malšova L.): 50°12'29.911"N, 15° 53'6.672"E	6	Outskirts of suburban housing development, located in school garden, woods and bushes nearby, grass cover, shaded most time of the day, only exposed to the sun in the afternoon
CHMI station Svobodné Dvory (Svobodné Dvory): 50°13'21.367"N, 15°47'15.969"E	7	Standardized meteorological weather station situated on the outskirts of suburban housing development, woody plants nearby, horizontal artificial surfaces nearby, sensor placed inside a Stevenson screen
CHMI station Nový Hradec Králové (Nový Hradec): 50°10'39.01"N, 15°50'18.98"E	8	Standardized meteorological weather station, situated on the outskirts of suburban housing development, woody plants nearby, significant areas of grass cover in the vicinity, sensor placed inside a Stevenson screen

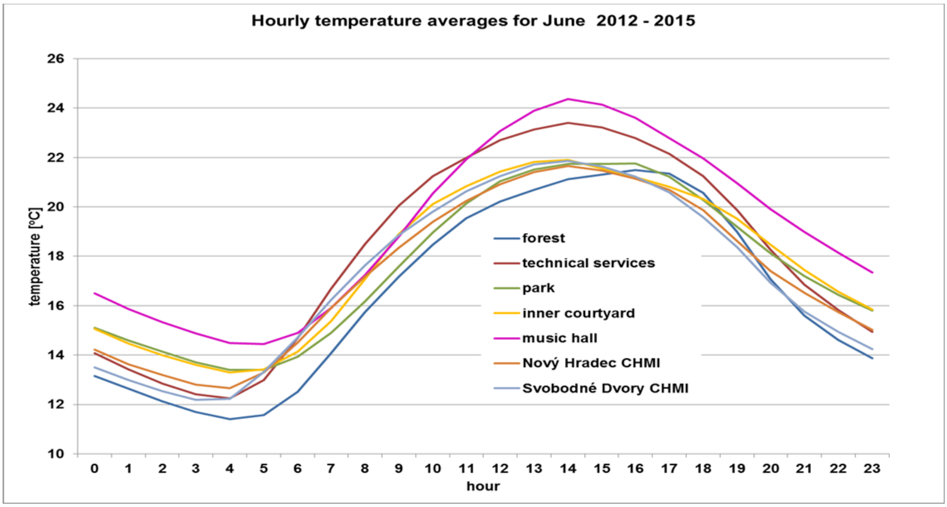

Fig. 3. June hourly temperature averages.

August 2012 to 2015 are used below as examples. The course of air temperature during the day for the individual months is shown in Figs. 3 to 5 and some similarities can be seen. However, more detailed analysis shows that indeed there are differences resulting from different microclimate conditions.

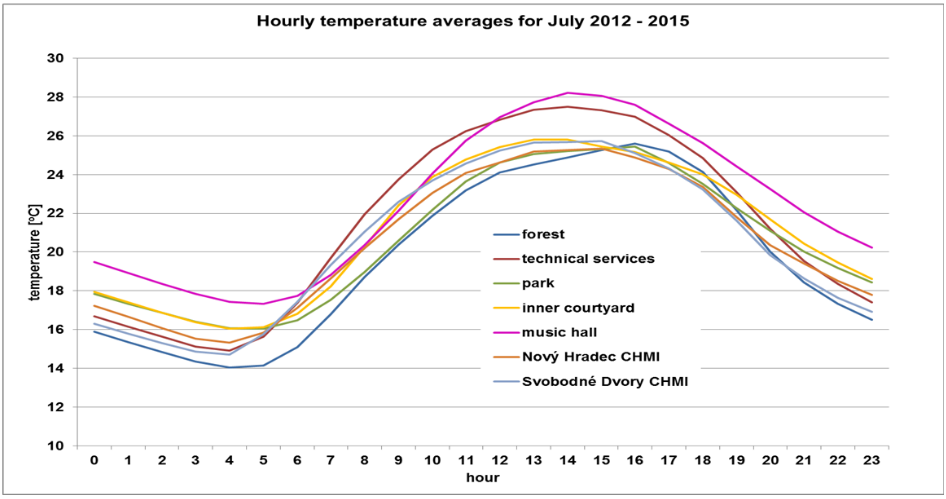

Fig. 4. July hourly temperature averages.

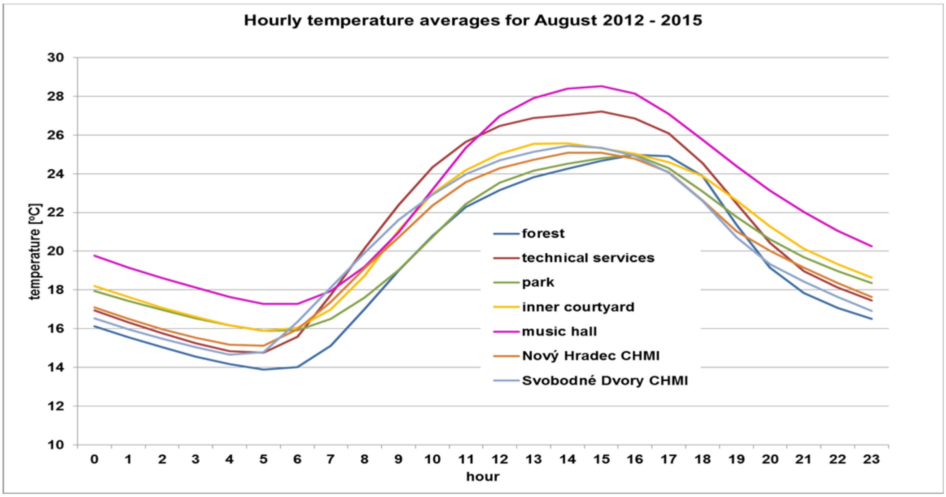

Fig. 5. August hourly temperature averages.

It can be said that at the time of sunrise, the temperatures are lowest in the forest and highest in the music hall. In the forest, this is caused apart from other factors by the fact that the soil surface is shaded during the day and does not warm up as much as other surfaces and so during night-time does not release so much accumulated heat to the surroundings that would warm up the air above it. Low temperatures are of course also caused by reduced air flow. On the other hand, in case of the music hall, high temperatures are caused by the relatively high heat capacity of surrounding buildings, which release this heat to the surrounding air, partly also in the form of long-wave radiation. The difference in average temperatures between these two locations in the period of interest is approximately 3 °C. The park is warmer than the forest at sunrise and is warmer than even the open space surrounding the technical services CHMI station. This is due to the position of this station in the city and the incoming warm air from the surroundings.

In the morning, especially in July and August, the effect of trees and water bodies becomes more profound at the station in the park and the temperatures get closer to non-urban locations, or the forest, thereby creating suitable conditions for the city inhabitants right in the city center. Extreme locations include the isolated area of the music hall and the technical services station, which can serve as an analogy to unshaded solid surfaces, typical for example for shopping malls located close to cities. These extreme locations are warmer than other places around noon, on average by about 2 to 3 °C. These higher temperatures in the park, compared to the forest and open space places, can especially during evening hours and colder days or months be welcomed and suitable for relaxation of the city inhabitants.

Daily course of air humidity in summer months in the period from 2012 to 2015 is shown in Fig. 6 to 8. The analysis shows that there are differences between the locations. Highest humidity throughout almost the entire day can be observed in places with enough green areas, i.e. the forest and the park. Especially during daytime, these two locations have similar humidity values, quite different from the remaining analyzed locations.

At night and in the morning hours, the relative air humidity at the individual stations depends on how much air they exchange with the surrounding areas and if there is a source of water for evaporation. The lowest humidity values are therefore observed in the music hall area, where there is lower water vapor content due to the surface type. Surprisingly, the relative air humidity at the Technical services station is higher than the one in the park.

Differences between the above mentioned locations in daily progress of

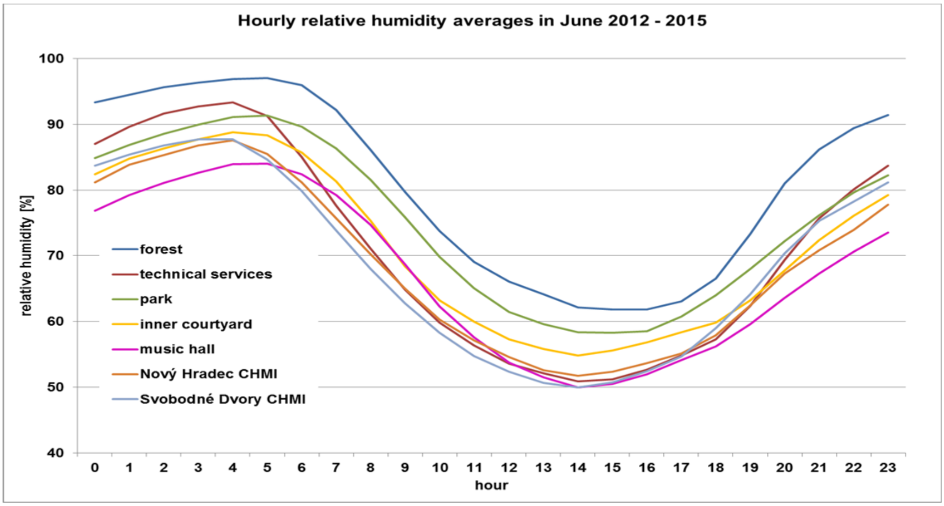

Fig. 6. June hourly relative air humidity averages.

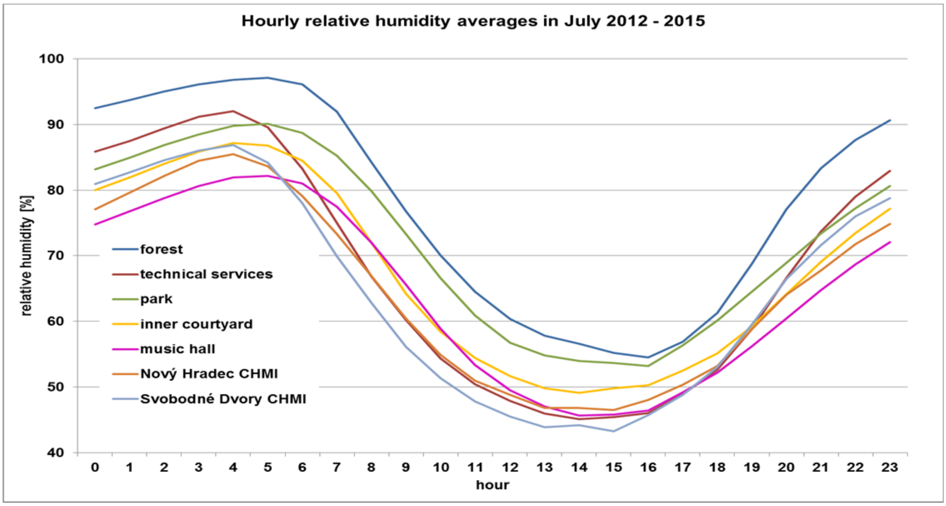

Fig. 7. July hourly relative air humidity averages.

air temperature and humidity can be further specified using the HUMIDEX index, which takes into account the combination of both of these meteorological parameters and their effect on humans. As expected, the highest HUMIDEX values were observed at locations with highest proportion of

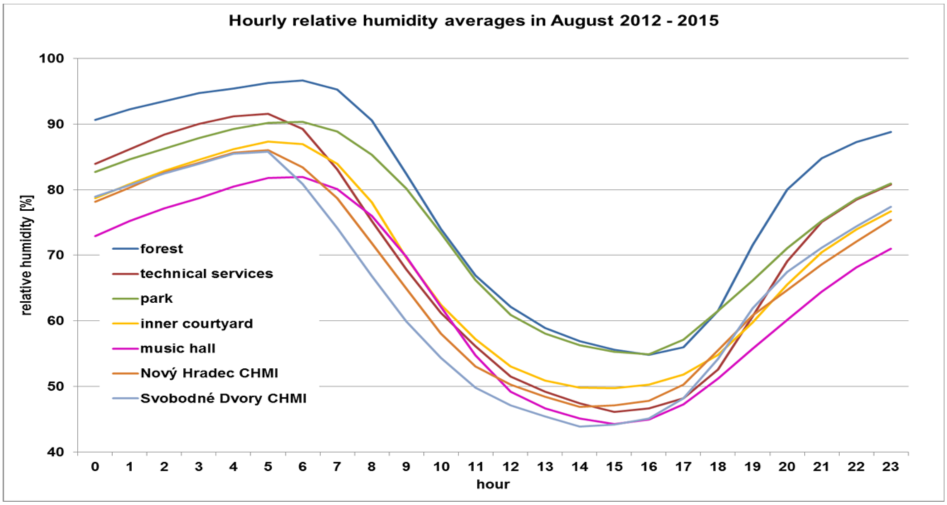

Fig. 8. August hourly relative air humidity averages.

artificial surfaces, i.e. the Technical services station and the music hall. A desirable fact is that critical HUMIDEX values were only observed in less than 25% of cases.

It turns out that July is a month when HUMIDEX index values most frequently fall into the discomfort (DSC) category, followed by August. The music hall courtyard is in this respect the most extreme location, followed by the Technical services station, surrounded by concrete and asphalt surfaces. It is also interesting to note that in July a relatively high frequency of values in this category also occurs in the park, MŠ Průmyslová station and the forest, while in August and other months the frequency of this category at these locations is more or less equivalent and close to the frequency observed at locations in the open space, represented by the CHMI stations.

Extreme discomfort category (EXDSC) is significantly less frequent, as can be seen in Fig. 9, increased frequencies were observed in the courtyard of the music hall in June and July, in August also in the inner courtyard. This category was otherwise not observed at any other station in any other month.

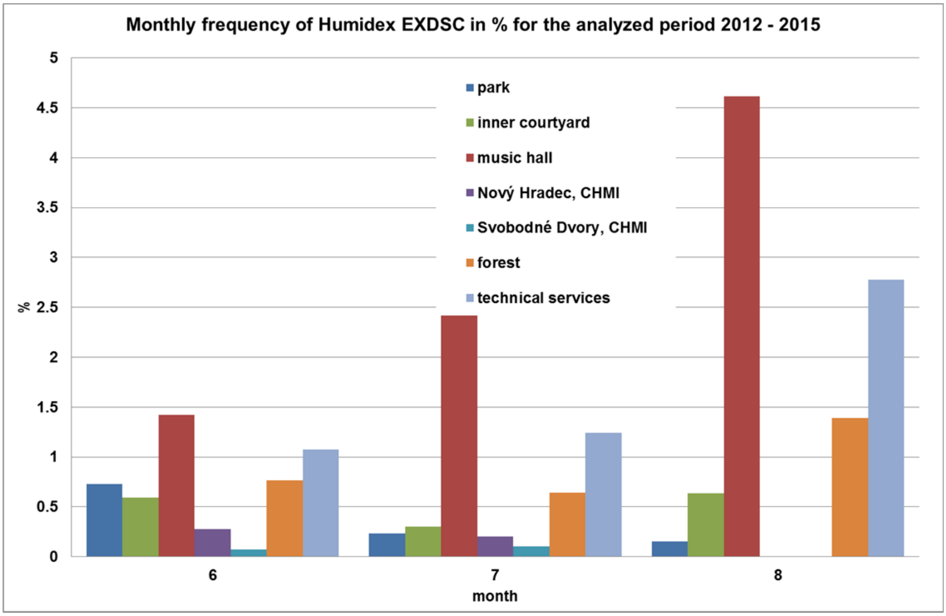

Fig. 9. Monthly frequency of HUMIDEX EXDSC in %.

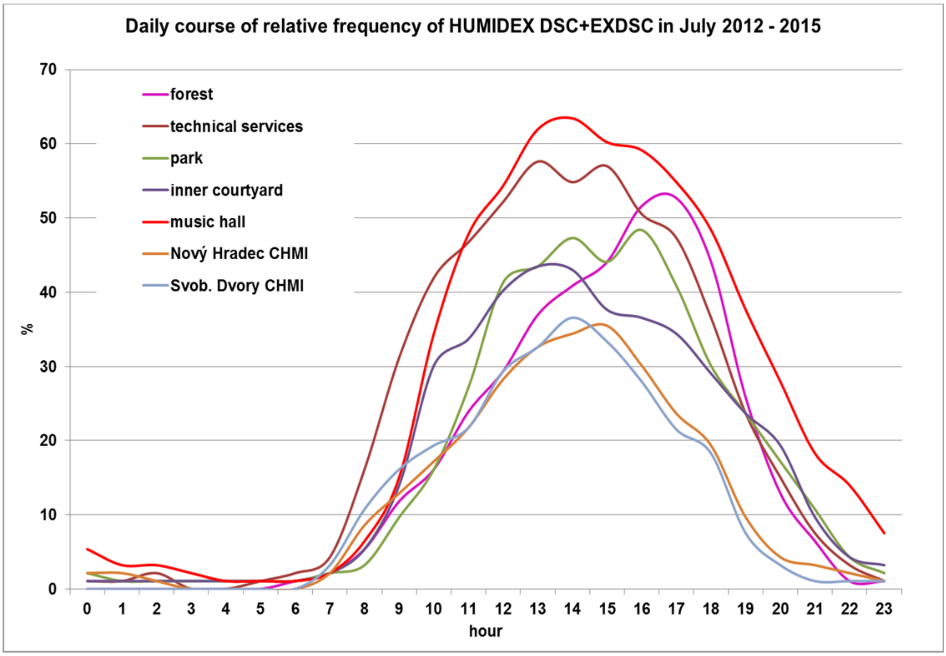

Fig. 10. Daily course of relative frequency of HUMIDEX DSC + EXDSC in July.

Differences between the individual locations are also in the daily course, which can be seen in Fig. 10, which shows the daily course for July, again relative to the overall count of analyzed hours. At places with artificial surfaces, such as the Technical services station, discomfort category values start to appear already in the morning and reach their maximum shortly after noon. This maximum value then remains until late in the afternoon. In the inner courtyard and the music hall, the discomfort category begins about an hour later because in early morning hours, these areas are shaded by the buildings surrounding them. In the relatively small area of the music hall courtyard, the period of discomfort in July lasts until late evening hours, when the heat accumulated in the walls of the surrounding objects starts to be released and also because of the limited air flow in these areas. The daily course of discomfort category in the forest area is quite interesting. Until noon it is the same as for the CHMI stations, however, in the afternoon, when this location is no longer shaded by trees, the frequency of discomfort category significantly increases. This also explains the overall higher number of hours of discomfort in this month. Similar course of discomfort category can also be observed in June and August.

In subsequent analysis, the number of hours with Humidex values in the range from 30 to 39 was determined for every day (DSC – discomfort can be felt by sensitive individuals) and above 40 (EXDSC – significant discomfort leading to reduced physical activity). Humidex values above 45 (danger) were not observed at any analyzed station in the analyzed period so the analysis only concentrated on the first two categories.

In July, the category labeled as "discomfort" reaches its maximum in the afternoon, the absolute highest values were observed in the music hall. At other stations, the occurrence of this category is relatively rare and its frequency ranges between 1% and 3% of all values analyzed. In August, at some stations this category was not observed at all, however higher frequency was at the station in the inner courtyard and for a short period of time in the afternoon also in the forest. One possible reason for this could be the change in energy balance of the active surface, where during some years one can for example expect higher and drier grass in August along the edges of the forest, which limits heat flux to the soil and the air therefore warms up quicker.

The results show that during the analyzed period, the least comfortable month in terms of human thermal comfort was August 2015, when the frequency of discomfort category was highest, the absolute highest values being observed in the music hall. Interesting fact to note is also the relatively high frequency of this category in the forest in August 2015 and partly also July of that year. This was caused by the fact that extremely warm air remained even until night hours in the forest environment, and by plants and soil saturating the air with water vapor, thus increasing the air humidity, which was higher than in the surrounding open space and locations without vegetation or with low air flow, and this caused the air being sultry at night. In contrast, it can be said that the summer of 2012 was relatively comfortable without any significant extremes. Very irregular course of weather was observed in 2014, when June and August were relatively cold compared to other years and with low frequency of discomfort category, however in July it was quite the opposite, with the frequency of discomfort category being very high.

5. Conclusion

The results are based on measurements across several years. It can be said that replacing green areas with artificial building materials indeed affects the thermal conditions in urban environments and at higher temperatures significantly increases discomfort felt by the inhabitants. Urban environment is composed of various active surfaces, which have different physical properties and are oriented in different ways, which means they also have different level of insolation and ventilation. The results of this analysis can be summarized as follows:

a) differences in the frequency of discomfort category between different locations are particularly significant at higher air temperatures, at lower temperatures the differences are less profound,

b) higher frequency of discomfort category is associated with artificial surfaces and closed spaces, however at particular weather conditions higher frequency of this category can also be seen at locations with purely natural surfaces that have a particular geometrical layout that limits air flow, for example forest edges,

c) in case of artificial surfaces, discomfort category starts to appear early in the morning already and at locations where heat can accumulate in surrounding objects (for example buildings) it remains until the evening,

d) discomfort category was most commonly observed during the afternoon hours.

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