Original article

Evaporation from water surfaces in urban environments, using Prague and Pilsen (Czech Republic) as examples

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ABSTRACT

The subject of this study is an evaluation of the amount of evaporation from water surfaces (VVH), measured using EWM devices in two cities of different sizes, and located approximately 80 km from each other – Prague and Pilsen. The results were analyzed in the context of urban phenomena, which are pronounced especially in Prague, and also in the context of meteorological and morphological conditions in those locations. It was found that higher amounts of evaporation were measured at the meteorological station in Pilsen. The difference between the average sum of VVH per season (1st May to 30th September) between 2005 and 2014 for the two locations is 33.3 mm. The difference between daily average values was 0.2 mm. Given the suburban nature of the two locations where measurements were taken, it was not possible to draw any conclusions about the effect of the urban heat island on the rate of evaporation and values of VVH. Factors significantly influencing VVH are surface roughness, which is higher in urban environments than in open landscapes. Based on the results it was concluded that at both a regional and a local scale, the rate of evaporation is more affected by wind speed than thermal conditions. The measured VVH values differ, not just because of the urban dimension of the two cities compared, but especially as a result of different topoclimatic location of the two stations.

KEY WORDS: urban climate, amount of evaporation, EWM, water balance

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1. Introduction

Evaporation is one of the major components of hydrological balance and significantly affects the thermal balance of the Earth's surface and adjacent air. In this respect, evaporation also includes the formation of water vapour by sublimation. Evaporation is a meteorological parameter, which corresponds to the amount of water that evaporates in a defined time span from various surfaces (evaporation) or from plant bodies (transpiration), or both (evapotranspiration) (SOBÍŠEK, 1993). In meteorology, evaporation is usually expressed as either potential (sometimes also referred to as maximum possible) or real (sometimes also referred to as actual or effective). According to BRUTSAERT (1982), the actual evaporation, to a great extent, depends on the amount of water that is available at that particular location at that particular time, and can vary significantly especially in urban

conditions. Evaporation from water surfaces can be considered as very similar to potential evaporation, not limited by water availability and therefore only dependent on current weather conditions at that particular location.

The geography of urban locations has some unique climatological features, which make it different from rural environments or open landscapes. The most significant and well documented phenomenon is the urban heat island (UHI), which arises as a result of several factors, which include artificial active surfaces that retain long-wave radiation, smaller leaf area, higher surface roughness, which limits the speed of air flow, and artificial heat sources (OKE, 1982). These factors together lead to an increase in air temperature compared to the surrounding, non-urban areas. Another significant environmental impact of urbanization is also modification of the water cycle (COUTTS ET AL., 2013). Drainage of

water from active surfaces to sewage significantly reduces actual evaporation and thus also leads to higher air temperatures. Urban areas with extensive impervious surfaces have generally more runoff than their rural counterparts. The runoff water drains quickly and, in the long run, less surface water remains available for evapotranspiration, thus affecting the urban surface energy balance (GRIMMOND & OKE, 1999). Warm conditions, which are more frequent in urban areas, are usually negatively perceived by humans and cause uncomfortableness and health problems for some individuals (STEENEVELD ET AL., 2011). In order to improve the bioclimatic conditions of urban areas it is therefore necessary and desirable in cities in cold and dry regions to try to increase air humidity and enhance the evaporation processes, for example by designing and building green areas on roofs, green facades and creating artificial water bodies (BOWLER ET AL., 2010). In terms of water management in cities, it is also necessary to determine the rate and variability of potential evaporation in the urban environment.

The evaluation of evaporation is most commonly done using model outputs, for example using the FAO (Food and Agriculture Organization) methodology (ALLEN & PRUITT, 1991; BOS ET AL., 1996), which is based on the Penman-Monteith equations, or through an analysis of the energy balance of active surfaces and Bowen ratio (for example FISCHER ET AL., 2013) or applying the covariance method to assess the flow of water vapor and thus evaluate evaporation (for example SIEDLECKI ET AL., 2012; VAN KERSETEREN ET AL., 2013). However, very valuable are also results from direct evaporation measurements, which form the basis of all empirical and other indirect methods and allow verification and assessment of accuracy of the above mentioned model outputs.

Evaporation measuring stations are usually located outside urban areas, however, there are some that are, to a lesser or greater extent, influenced by the urban climate. In the Czech Republic, such stations are for example the one in Prague-Libuš and in Pilsen-Mikulka, two cities of different sizes, approximately 80 km apart. The subject of this study was to analyze the evaporation from water surfaces (VVH), measured at these two stations using an EWM device (manufactured by Asys Develop, modified by CHMI employees). The results obtained were analyzed in the context of urban phenomena, which manifest especially in Prague (BRÁZDIL & BUDÍKOVÁ, 1999; BERANOVÁ & HUTH, 2005; SKALÁK ET AL., 2015), and also in the context of other factors, which have some effect on the evaporation

regime. Meteorological parameters which most influence evaporation include air temperature, air humidity, wind speed and solar radiation. Other factors which must also be taken into account are elevation and terrain. The aim of this paper was to make a comparison of evaporation characteristics of the two afore mentioned weather stations and to perform an analysis of the factors that determine the VVH in urban environments.

2. Materials and methods

VVH measurements within the Czech Hydrometeorological Institute (CHMI) climatological stations network began in 1968, but at that time data were obtained using the manual GGI-3000 device (KRŠKA & ŠAMAJ, 2001). Since 2000, the GGI-3000 devices were gradually replaced with a more sophisticated, automatic evaporimeter EWM (MOŽNÝ, 2003; BAREŠ ET AL., 2006).

The EWM evaporimeter consists of a stainless circular tank with a cross-sectional area of 3000 cm² and depth of 60 cm. This tank is placed in the soil so that the water level corresponds to the level of the surrounding terrain (Fig. 1). The actual measuring device is placed in a cylindrical stainless tank with a diameter of 7.5 cm and a lid, connected with the tank of the evaporimeter. Due to the effect of connection of the tanks, the water levels balance out in the evaporation and measuring tanks. The water level in the measuring tank is recorded and the position of the float is monitored by a digital optical sensor with a resolution of 0.025 mm. There is continuous monitoring of the decrease in water level as a result of evaporation and an increase in water level due to precipitation. The resulting value is then given by the sum of differences between the levels and the precipitation amount measured by the automatic rain gauge. The daily evaporation total is measured from 7.00 CET of the previous day until 7.00 of the current day, similar to how precipitation is measured. The Pt100 sensor is used to measure the temperature of the water surface in the tank (LIPINA ET AL., 2014).

The water level in the evaporation tank is automatically regulated at selected intervals (-17 mm to +17 mm). In case of increase or decrease in water level above, or below, the specified threshold, the pump refills or pumps off the corresponding amount of water to maintain the "initial zero level". This level is set every day at 7AM CET as part of the daily calibration of the module. The storage tank has a capacity of 50 l and this tank also includes a filter in its lid. This means the water is filtered every day during the calibration process (BAREŠ ET AL., 2006).

Fig. 1. Automated EWM evaporimeter at the weather station in Prague-Libuš (source: CHMI)

The VVH evaluation was performed based on measurements from the stations in Prague-Libuš and Pilsen-Mikulka during the period from 1st May to 30th September, between 2005 and 2014. Data was validated and missing values filled by methods used in previous works of the team of authors (KOHUT ET AL., 2015). Both daily and monthly VVH amounts were analyzed in detail. The statistical analysis was performed using the climatological application ProClimDB (<http://www.climahom.eu>), see ŠTĚPÁNEK (2008).

Location of the two stations of interest is shown in Figure 2. Basic information about the location of both stations is given in Table 1.

Fig. 2. Location of the two stations compared, Prague-Libuš and Pilsen-Mikulka (source: CHMI)

Table 1. Basic information about the location of the two compared stations in Prague-Libuš and Pilsen-Mikulka

Weather station	Elevation	Longitude	Latitude	Population	Total Area
Prague-Libuš	302 m above sea level	14°26'53"	50°00'30"	1 259 079 (2015)	496 km ²
Pilsen-Mikulka	360 m above sea level	13°22'44"	49°45'53"	169 033 (2015)	138 km ²

The Prague-Libuš weather station is located on the Prague plateau in the Brdský region, at an elevation of 302 meters above sea level, in the southern part of Prague, the capital of the Czech Republic. It belongs to the River Vltava basin. Based on Quitt's classification it is situated in the W2 warm region, based on the Atlas podnebí ČSR (Atlas of the climate of Czechoslovakia) published in 1958 it is found in a slightly warm region and slightly humid subregion (slightly warm, slightly humid district) B3 (TOLASH ET AL., 2007). The weather station in Pilsen-Mikulka is located in the region of the Polabské hills, part of the Pilsen hilly

area, and belongs to the River Mže basin. The station lies 360 meters above sea level and is situated in the northern outskirts of the city of Pilsen, surrounded mostly by built-up areas. Based on Quitt's classification, it belongs to slightly warm region MW11, based on the classification used in Atlas podnebí ČSR, it is found in a slightly warm region and slightly dry subregion (slightly warm, slightly dry district) B2 (TOLASH ET AL., 2007). The location of both weather stations and the level of urbanization in their surroundings is depicted in Figures 3, 4 and 5.

Fig. 3. Location of the two stations in the context of urbanization – Prague-Libuš (A) and Pilsen-Mikulka (B) (source: mapy.seznam.cz)

Fig. 4. Weather station in Prague-Libuš. View from the West (A), meteorological garden (B) (source: CHMI)

Fig. 5. Weather station in Pilsen-Mikulka. View from Southeast (A), view from Southwest (B) (source: CHMI)

3. Results

The analyzed stations are relatively far from each other, therefore, it can be expected that the correlation between the daily VVH values will not be very high. This was indeed proven by the correlation coefficient value calculated from the daily evaporation amount from the two stations, which was equal to just 0.73.

The daily VVH amounts at the station in Prague-Libuš measured between 2005 -2014 (1st May to 30th September) ranged from 0.1 mm to 7.7 mm (3rd August 2013), the lowest value of 0.1 mm has been observed four times. The long-term daily average amount (2005-2014) was 2.5 mm (Table 2). The interval with the highest frequency of values was between 2.1 mm and 3.0 mm (31.3% of measurements), followed by 1.1 mm to

2.0 mm (28.1 % of measurements) and 3.1 mm to 4.0 mm (20.1 % of measurements), see Figure 6.

The basic statistical analysis derived from the measured daily VVH values is given in Table 2. Lowest monthly VVH amounts were observed in September, with the highest in July. Long-term monthly VVH amounts at this station ranged from 47.9 mm to 99.0 mm, long-term average for the whole period from 1st May to 30th September was 387.1 mm per season.

The graph in Figure 7 shows the variability in VVH amounts during the period from 1st May to 30th September, averaged from data from the years 2005 to 2014. The highest value of 456.8 mm was observed in 2007 and in contrast the lowest, 338.3 mm, in 2014.

Table 2. Prague-Libuš, basic statistics of daily evaporation from water surface for the individual months and overall (May-September) (2005-2014)

Prague – Libuš	V	VI	VII	VIII	IX	V-IX
Average daily sum	2.28	2.94	3.19	2.62	1.60	2.53
Average monthly sum	70.76	88.13	98.98	81.30	47.92	387.09
Standard deviation	1.060	1.147	1.156	0.992	0.745	1.170
Coefficient of variation	46.430	39.040	36.204	37.819	46.650	46.245
Skewness	0.301	0.097	0.183	0.682	0.543	0.425
Kurtosis	-0.348	-0.111	-0.417	1.714	0.054	-0.062
Daily minimum	0.1	0.1	0.3	0.5	0.1	0.1
Daily maximum	5.4	6.9	5.9	7.7	4.3	7.7
Date of observed maximum	24 May 2011	3 Jun 2012	3 Jul 2008 12 Jul 2010 28 Jul 2013	3 Aug 2013	13 Sep 2008	3 Aug 2013
1 st decile (10%)	0.95	1.30	1.65	1.30	0.70	1.10
Lower quartile (25%)	1.50	2.10	2.40	1.90	1.10	1.60
Median	2.20	2.90	3.20	2.60	1.50	2.50
Upper quartile (75%)	3.00	3.70	3.90	3.10	2.10	3.30
10 th decile (90%)	3.70	4.50	4.90	3.80	2.70	4.10

Fig. 6. Prague-Libuš, frequency of daily evaporation totals from water surface for the specified intervals (2005-2014)

Fig. 7. Prague-Libuš, evaporation from water surface between 1st May and 30th September (2005-2014)

Daily VVH between 2005 and 2014 (1st May to 30th September) at the weather station in Pilsen-Mikulka, ranged between 0.0 mm (September 19, 2006) to 7.4 mm (June 28, 2010 and August 3, 2013). The long-term daily average (2005-2014) was 2.8 mm (Table 3). The highest frequency interval was 2.1 mm to 3.0 mm (31.8% measurements), followed by 1.1 to 2.0 mm (23.3 % measurements) and 3.1mm to 4.0 mm (22.9 % measurements), see Figure 8. Basic statistical analysis of VVH is provided in Table 4. Lowest

monthly VVH was in general observed in September, with the highest in July. The long-term monthly average VVH total was between 56.3 mm and 102.6 mm, with an average value for the whole analyzed period (May to September) of 420.4 mm.

The graph in Figure 9 shows the variability in VVH from May to September between 2005 and 2014. The absolute highest total for the entire season was 452.0 mm (2012), while the lowest observed value was from 2005, of 363.7 mm.

Table 3. Pilsen-Mikulka, Basic statistics of daily evaporation from water surface for the individual months and overall (May-September) (2005-2014)

Pilsen-Mikulka	V	VI	VII	VIII	IX	V-IX
Average daily sum	2.53	3.21	3.31	2.81	1.88	2.75
Average monthly sum	78.35	96.14	102.62	86.94	56.32	420.37
Standard deviation	1.109	1.163	1.179	1.042	0.848	1.191
Coefficient of variation	43.886	36.287	35.619	37.148	45.178	43.341
Skewness	0.371	0.284	0.005	0.144	0.624	0.334
Kurtosis	0.510	-0.207	-0.447	0.465	0.415	-0.139
Daily minimum	0.1	0.8	0.1	0.2	0.0	0.0
Daily maximum	7.2	7.4	6.1	7.4	5.1	7.4
Date of observed maximum	13 May 2011	28 Jun 2010	2 Jul 2008 10 Jul 2013	3 Aug 2013	3 Sep 2008	28 Jun 2010 3 Aug 2013
1st decile (10%)	1.10	1.70	1.70	1.50	0.90	1.20
Lower quartile (25%)	1.80	2.35	2.50	2.10	1.20	1.90
Median	2.50	3.25	3.35	2.80	1.80	2.70
Upper quartile (75%)	3.20	4.00	4.10	3.60	2.40	3.50
10th decile (90%)	4.00	4.70	4.90	4.15	3.00	4.30

Fig. 8. Pilsen-Mikulka, frequency of daily evaporation sums from water surface in the specified intervals (2005-2014)

Table 4. Average values of basic meteorological parameters at the stations in Prague-Libuš and Pilsen-Mikulka (1st May to 30th September 2005-2014)

Parameter	Prague-Libuš	Pilsen-Mikulka
Sunshine duration	209.4 (h)	208.8 (h)
Air temperature	17.4 (°C)	16.7 (°C)
Relative air humidity	67.2 (%)	67.9 (%)
Wind speed	2.2 (m/s)	2.8 (m/s)
Total precipitation	383.7 (mm)	346.3 (mm)
VVH sum	387.1 (mm)	420.4 (mm)

Based on the comparison between VVH measured at the two weather stations in Prague and Pilsen, it can be seen that higher totals are observed at the station in Pilsen-Mikulka. Daily values in the interval between 0.1 mm and 1.0 mm and 1.1 mm and 2.0 mm are more frequent in Prague, while in Pilsen, the intervals 2.1 mm to 3.0 mm; 3.1 mm to 4.0 mm and 4.1 mm to 5.0 mm were more common. The highest daily value of VVH, equal to 7.7 mm, was measured in Prague on August 3rd 2013. That same day a record value was also observed in Pilsen, but there it was 0.3 mm less.

It was a tropical day with a maximum air temperature of 37.9°C in Prague-Libuš and 37.3°C in Pilsen-Mikulka. Relative air humidity at 14:00 CET was approximately 14% in Prague-Libuš and 20% in Pilsen-Mikulka. During the day there was a light breeze gusting at 6.2 m/s in Prague-Libuš and 8.0 m/s in Pilsen-Mikulka. Such a situation, however, in the period between 2004 and 2015 was quite rare. A daily total VVH over 7.0 was only measured once in Prague-Libuš, and in Pilsen-Mikulka three times (Fig. 10).

Fig. 9. Pilsen-Mikulka, evaporation from water surface between 1st May and 30th September (2005-2014)

Fig. 10. Relationship between daily evaporation amount from water surface at the stations in Prague-Libuš and Pilsen-Mikulka (2005-2014)

The annual progress of VVH totals is similar at both stations, higher values being observed in Pilsen. The overall average for the entire season from 1st May to 30th September is 33.3 mm higher in Pilsen compared to Prague. The most profound difference during the period analyzed was in the year of 2009, when the overall seasonal VVH was 82.0 mm higher in Pilsen. In contrast, a lower VVH in Pilsen compared to Prague was only seen in 3 years – 2005, 2007 and 2011.

4. Discussion

The results of the analysis show that the station in Pilsen-Mikulka has conditions favorable for higher evaporation compared to Prague-Libuš. Differences in VVH total are due to geographical location and due to specific regional and local factors discussed below.

The difference in latitude between the stations is negligible. Both stations belong to the Podberounská subprovince. Elevations of both stations differ only by approximately 60 m, but the terrain is more variable in the region of the Plaská hills, where the station in Pilsen is found. Analysis of evaporation at other evaporation measuring stations in the Czech Republic shows that stations with a higher morphological variability tend to have a higher average wind speed and as a result also higher values of VVH are usually observed. This was found in a study conducted by KOHUT ET AL. (2015) in which they studied data from 14 evaporation measuring stations in detail. The station in Pilsen-Mikulka is one such station.

It is located on a hillside, with possible formation of anabatic flow. In contrast, the weather station in Prague-Libuš lies in a flat region. The results of this analysis suggest that the factor with the most profound effect on VVH total from a regional perspective is wind speed.

Other important factors that determine VVH are climatic effects in local scale. The intensity of the urban heat island, associated with lower air humidity, enhances evaporation in urban regions (UNGER, 1999). The urban heat island is very apparent in Prague, which is also supported by the most recent studies performed as part of a project focused on developing a strategy to decrease, or prevent risks and manage urban heat islands in central Europe (<http://eu-uhi.eu/cz>). The intensity of the urban heat island in Prague was estimated to be 1.6 K (MUSCO, 2016). In 2014, VACÍK estimated the intensity of the urban heat island in Prague as 0.3 K (VACÍK, 2013). It must be said, however, that both weather stations are located outside the immediate area affected by the urban heat island. The station in Prague-Libuš lies 7 km from the centre of the capital, while the station in Pilsen, is found approximately 2 km from the city centre. Pilsen, however, is a much smaller city. Based on the suburban nature of the immediate surroundings of the station, no conclusions can be made as to how much the urban heat island affects the value of VVH at those particular two stations.

Another phenomenon typical for urban regions is higher surface roughness, compared to the open landscape. The build-up zones substantially limit wind speed in the boundary layer of the

atmosphere (DAVENPORT ET AL., 2000). Based on the GLOBAL WIND ATLAS (<http://globalwindatlas.com>), this effect of surface roughness is more pronounced in Prague compared to Pilsen, due to prevailing winds. For Prague-Libuš, the model used by the GLOBAL WIND ATLAS estimates the parameter of roughness length during dominant, westerly winds (25% frequency) and the second most common southwesterly winds (20% frequency) to be 0.5 m. For other wind directions, the parameter of roughness length is estimated to be between 0.3 m and 0.75 m. For the station in Pilsen-Mikulka, the roughness length during dominant, south-westerly winds (26% frequency) is estimated to be 0.3 m, and during the second most common, northerly winds (16% frequency) as 0.75. The remaining directions have a roughness length of 0.3 m to 0.5 m. This is also supported by the comparison of wind speeds measured at both stations at a standard height of 10 m above the ground. The average wind speed in Prague-Libuš is 0.6 m/s lower than in Pilsen-Mikulka (Tab. 4). In conclusion it can therefore be said that wind speed has a substantial effect on the value of VVH.

Apart from the topological conditions, VVH is also affected by many other climatological factors. When looking at the climate characteristics for both stations for the period between 1st May and 30th September 2005-2014, it can be seen that on average in Prague there is longer sun shine duration, higher average air temperature, but lower average air humidity and lower average wind speed, compared to the station in Pilsen-Mikulka (Tab. 4). The average daily precipitation amount is higher in Prague, while the average VVH sum is lower. When comparing the precipitation sum with the VVH sum for both stations, one can see that the water balance during the analyzed period was positive in Prague, while there is a water deficit in Pilsen, where evaporation amount was higher than precipitation amount. It must, however, be emphasized that the above statement is only based on data from the five warmest months (May-September). During winter months evaporation is much lower than precipitation, but the overall annual water balance cannot be determined in those areas because the EWM device measures evaporation from free water surface, which is not possible to perform when the water freezes. In conclusion, the difference between the average VVH sum during the analyzed period from May to September 2005-2014 at the two stations in Prague-Libuš and Pilsen-Mikulka, was 33.3 mm. The average difference in daily values was 0.2 mm.

Analyses of evaporation were also done in other European cities and their results can be

found in scientific literature. One study in the Netherlands compared evaporation in the city of Rotterdam (600 000 residents) and Arnhem (150 000 residents) and found that the differences in daily evaporation sums between April and September were between 0.5 to 1.0 mm (JACOBS ET AL., 2015). These values pretty much correspond to the results from this analysis of Czech cities, even though different methodologies were used to evaluate the evaporation amounts.

The results presented in this paper analyze the amount of evaporation from free water surfaces in urban environments for the stations in Prague and Pilsen. One characteristic of urban regions is a large variability of active surfaces, many of which are artificial. It is important to note that there are significant differences in the intensity of evaporation from surfaces with different humidity. Tang & Etzion (2004) compared the rate of evaporation from solid, humid surfaces and from water surfaces and found that the determining factor in the level of evaporation is wind speed. At low wind speeds, evaporation is higher from humid surfaces compared to water surfaces. At higher wind speeds, however, it turned out to be the other way around. In a study by STARKE ET AL. (2011), it was found that the aggregate size of active surfaces has a substantial effect on the evaporation intensity, regardless of their permeability. Impervious surfaces have lower evaporation intensity. The conclusion of this study on evaporation from water bodies in urban regions, however, was, that although open water in the city also contributes to urban evaporation, the effect of water bodies on mitigating heat in the city is less clear (VAN HOVE ET AL., 2015; STEENEVELD ET AL., 2014). Monitoring evaporation is expected to become more significant in the future because of urbanization, climate change and their impact on outdoor thermal comfort.

5. Conclusion

The presented study provides results from an analysis of VVH measured in two Czech cities of different sizes – Prague and Pilsen – in the period between 1st May to 30th September, 2005 to 2014. Based on the differences in the VVH totals it was found that the measured values differ not just because of the urban dimension of the compared cities, but more importantly as a result of different topoclimatic locations of the two weather stations. Despite the fact that Prague is a much larger city than Pilsen, the VVH measured in Prague was lower and it was found that at both regional and local scales, the level of evaporation

is to a larger extent determined by the wind speed, rather than temperature. Wind speed has the most profound effect on the level of VVH compared to other weather parameters.

It has also been found that at the weather station in Pilsen-Mikulka, from May to September, the VVH is higher than the total precipitation amount, which shows a water deficit – a problem often cited in literature as a serious issue in urban regions. Urban surfaces can absorb less water vapour than other surfaces and represent a sink for the precipitated water as well. Therefore, evaporation from urban surfaces is reduced as well which leads to lower humidity over urban areas. Estimating the relationship between evaporation and precipitation, including the amount of recycled water, supports water management issues, while also improving the understanding of the role of urban design in water budgets. Numerous studies, expert meetings and public relations activities are dedicated to forward-looking use of rainwater (rainwater management), particularly with the aim to raise the rate of evaporation (MUSCO, 2016). In the context of climate change, i.e. the expected increase in air temperature, drought occurrence and frequency of heat waves, it is expected that an ideal solution to the melioration of urban climate is to increase the amount of vegetation between active surfaces. Green roofs and building walls can create a cooling effect, which spreads to the surroundings and improves the thermal comfort of the inhabitants (BOWLER ET AL., 2010; OLIVIERA ET AL., 2011). Evapotranspiration can help to create city “oases”, which are 2 to 8 degrees Celsius cooler than the surrounding areas (TAHA, 1997).

In conclusion it should be emphasized that as part of trying to solve the problems related to water balance in urban regions, much closer attention should be paid to monitoring evaporation both in urban and natural areas. In addition, it is also very important to further develop and calibrate the evaporation models, which is substantially supported by direct measurement of VVH using automated devices such as the EWM.

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References

Allen R.G., Pruitt W.O. 1991. FAO-24 reference evapotranspiration coefficients. *J. Irrig. Drainage Eng., ASCE*, 117(5): 758-773.

- Bareš D., Možný M., Stalmacher J. 2006. Automatizace měření výparu v ČHMÚ. [in:] *Bioklimatológia a voda v krajině, Bioklimatologické pracovné dni 2006* [online]. [cit. 16. 8. 2011] http://www.cbks.cz/sbornikStrecno06/prispevky/PosterI_clanky/P1-16.pdf
- Beranová R., Huth R. 2005. Long term changes of the heat island of Prague under different synoptic conditions. *Theor. Appl. Climatol.*, 82: 113-118.
- Bos M.G., Vos J., Feddes R.A. 1996. CRIWAR 2.0. *A simulation model on Crop Irrigation Water Requirements*. Wageningen. ILRI publ., 46.
- Bowler D.E., Buyung-Ali L., Knight T.M., Pullin A.S. 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landsc. Urban Plan.*, 97: 147-155.
- Brázdil R., Budíková M. 1999. An urban bias in air temperature fluctuations at the Klementinum, Prague, The Czech Republic. *Atm. Environ.*, 33, 24-25, 4211-4217.
- Brutsaert W. 1982. *Evaporation into the Atmosphere*. D. Reidel Publ. Co., Dordrecht.
- Coutts A.M., Tapper N.J., Beringer J., Loughnan M., Demuzere M. 2013. Watering our cities: the capacity for water sensitive urban design to support urban cooling and improve human thermal comfort in the Australian context. *Prog. Phys. Geog.*, 37: 2-28.
- Davenport A.G., Grimmond C.S.B., Oke T.R., Wieringa J. 2000. *Estimating the roughness of cities and sheltered country*. 12th Conf. on Applied Climatology, 8-11 May 2000, Asheville, NC, Am. Meteorol. Soc.
- Development and Application of Mitigation and Adaptation Strategies and Measures for Counteracting the Global Urban Heat Island Phenomenon*. The framework of EC Operation Programme Central Europe (3CE292P3), <http://eu-uh.eu/cz>.
- Fischer M., Trnka M., Kučera J., Deckmyn G., Orság. M., Sedlák P., Žalud. Z., Ceulemans R. 2013. Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech-Moravian Highlands. *Agr. Forest Meteorol.*, 181: 43-60.
- Global Wind Atlas*, DTU Wind Energy. <http://globalwindatlas.com>
- Grimmond S., Oke T. 1999. An evapotranspiration-interception model for urban areas. *Water Res. Res.*, 27: 1991-1739.
- Jacobs C., Elbers J., Broolsma R., Hartogensis O., Moors E., Rodríguez-Carretero, Márquez M.T., Van Hove B. 2015. Assessment of evaporative water loss from Dutch cities. *Build. Environ.*, 83: 27-38.
- Kohut M., Rožnovský J., Knozová G., Brzezina J. 2015. Měření výparu z vodní hladiny automatizovaným výparoměrem EWM v České republice. *Práce a studie* (in print), ČHMÚ, Praha.
- Krška K., Šamaj F. 2001. *Dějiny meteorologie v českých zemích a na Slovensku*. 1 vyd. Praha: Univ. Karlova v Praze. Nakl. Karolinum.
- Lipina P., Kain I., Židek D. 2014. *Návod pro pozorovatele automatizovaných meteorologických stanic*. Metodický předpis č. 13a. ČHMÚ Praha.
- Možný M. 2003. Automatizace měření výparu z volné vodní hladiny. *Meteorol. Zpr.*, 56, 5: 150-155.
- Musco F. (ed.) 2016. *Counteracting Urban Heat Island Effects in a Global Climate Change Scenario*. Springer.
- Oke T.R. 1982. The energetic basis of the urban heat-island. *Q J Roy. Meteorol. Soc.*, 108: 1-24.
- Oliviera S., Andrade H., Vaz T. 2011. The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. *Build. Environ.*, 46: 2186-2194.
- Siedlecki M., Fortuniak K., Pawlak W. 2012. Porównanie wybranych metod określania parowania w Łodzi. *Przegl. Geofiz.*, 2: 211-221.

- Skalák P., Žák M., Zahradníček P., Helman K. 2015. Příspěvek projektu UHI k poznání klimatu Prahy. *Meteorol. Zpr.*, 68, 1: 18-23.
- Sobíšek B. (ed.) 1993. *Meteorologický slovník výkladový a terminologický*. MŽP ČR, Praha.
- Starke P., Wallmeyer C., Röhlvera S., Göbel P., Coldewey W.G. 2011. Development of a new laboratory evaporation measurement device as decision support for evaporation-optimized building. *Build. Environ.*, 46: 2552-2561.
- Steenneveld G.J., Koopmans S., Heusinkveld B.G., Theeuwes N.E. 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. *Landsc. Urban Plan.*, 121: 92+96.
- Steenneveld G.J., Koopmans S., Heusinkveld B.G., Van Hove L.W.A., Holtslag A.A.M. 2011. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *J. Geophys. Res-Atmos.*, 116, D20129.
- Štěpánek P. 2008. ProClimDB – software for processing climatological datasets. CHMI, regional office Brno. <http://www.climahom.eu/ProcData.html>.
- Taha H. 1997. Urban climates and heat islands: albedo, evaporation, and anthropogenic heat. *Energ. Build.*, 25: 99-103.
- Tang R., Etzion Y. 2004. Comparative studies on the water evaporation rate from a wetted surface and that from a free water surface. *Build. Environ.*, 39, 77-86.
- Tolasz R. et al, 2007. *Atlas podnebí Česka*. Praha, Olomouc: Český hydrometeorologický ústav, Univ. Palackého v Olomouci, ISBN 978-80-86690-26-1.
- Unger J. 1999. Urban –Rural air humidity differences in Szeged, Hungary. *Int. J. Clim.*, 19: 1509-1515.
- Vacík P., 2013. Statistický model charakteru u tepelného ostrova středoevropských měst. Diplomová práce, Univ. Karlova v Praze. Přírodovědecká fakulta, Katedra fyzické geografie a geoekologie, Praha.
- Van Hove L., Jacobs C.M.J., Heusinkveld B.G., Elbers J.A., Van Driel B., Holtslag A.A.M. 2015. Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Build Environ.*, 83: 91-103.
- Van Kesteren B., Hartogensis O.K., Van Dinther D., Moene A.F., De Bruin H.A.R. 2013. Measuring H₂O and CO₂ fluxes at field scales with scintillometry: Part I–Introduction and validation of four methods. *Agr. Forest Meteorol.*, 178-179: 75-87.
- <http://www.climahom.eu>
<http://eu-uhi.eu/cz>