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# ABSOLUTE MOISTURE CONTENT IN MID-LATITUDE URBAN CANOPY LAYER, PART 2: RESULTS FROM SZEGED, HUNGARY

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**Summary:** This study gives a comprehensive picture on the air humidity observation and mapping in urban canopy layer in Szeged, Hungary, analyzing three-year long vapor pressure dataset (*e*) calculated from observations of a 22-station urban network. The analysis was divided into two directions, namely the urban-rural and intra-urban ones where the latter was partly based on the local climate zone approach. (i) The general features of the annual and diurnal variations of urban-rural absolute humidity difference in cities with mid-latitude climates are also detectable in the case of Szeged. (ii) In the annual and seasonal *e* means there is no clear zone sequence that would follow the differences in the compactness or building height of the zones and even the built-up versus land cover distinction. (iii) The highest e values and their differences among stations appear in summer, while the lowest ones in winter and the values of transitional seasons are between them. In certain cases the intra-zone differences can exceed the inter-zone ones since the effect of microscale environment is essential. The decisive factors are the permeability of the surface and the vegetation cover. (iv) The diurnal course of the *e* pattern in normalized 4-hour time steps does not show a regular shape, the patterns are mosaic-like: in all time steps the driest and wettest areas are mainly in the north-western and south-eastern parts, respectively.

**Keywords:** vapor pressure, urban network, long dataset, urban-rural, intra-urban, local climate zones

## 1. INTRODUCTION

The first part of our study dealt with the main results of earlier studies related to urban absolute moisture content of the urban canopy layer (*UCL*) in mid-latitude climate regions (see Unger et al. 2018).

Our work in this second part presents a development in this research field compared to the previous ones as it is based on a rather long and spatio-temporally detailed intra-urban dataset from Szeged (Hungary). We analyze three-year long relative humidity and temperature data from 22 stations of an urban meteorological network, the installation of which was based on the surface classification scheme of Local Climate Zone (LCZ) system proposed recently by Stewart and Oke (2012). The applied dataset from the period of 2014–2017 provides a reliable basis for examining the seasonal and annual features, as well as the diurnal dynamics of the urban absolute moisture content in and around the city.

Based on the vapor pressure values calculated from relative humidity and temperature data of the urban network our analysis applies two approaches, namely the urban-rural and intra-urban ones:

(1) In the first approach the annual and diurnal variations of mean urban-rural humidity differences are analyzed comparing them to the earlier results mentioned by Oke et al. (2017);

(2) During the second approach (a) the mean annual and seasonal humidity conditions of LCZs, (b) the mean diurnal variation of humidity of LCZs by seasons and (c) the mean diurnal variation of intra-urban humidity patterns in summer are evaluated.

## 2. STUDY AREA, DATA AND METHODS

Szeged is located in the south-eastern part of Hungary (46.25°N, 20.15°E) at 79 m a.s.l. on a flat terrain with a population of 162,000 within an urbanized area of about 40 km$^2$. According to Kottek et al. (2006) it is in Köppen's climatic region Cfb (warm temperate climate, no dry season, warm summer) with annual mean temperature of 10.9°C, sunshine duration of 2049 hours and annual amount of precipitation of 514 mm (1981–2010, OMSZ 2015). Its urban area is characterized by a densely built midrise core, with openly spaced blocks of flats in the east-northern part of the city, as well as family homes and warehouses on the outskirts. The rural surroundings are mostly croplands (wheat, maze) with few scattered trees (Skarbit et al. 2017).

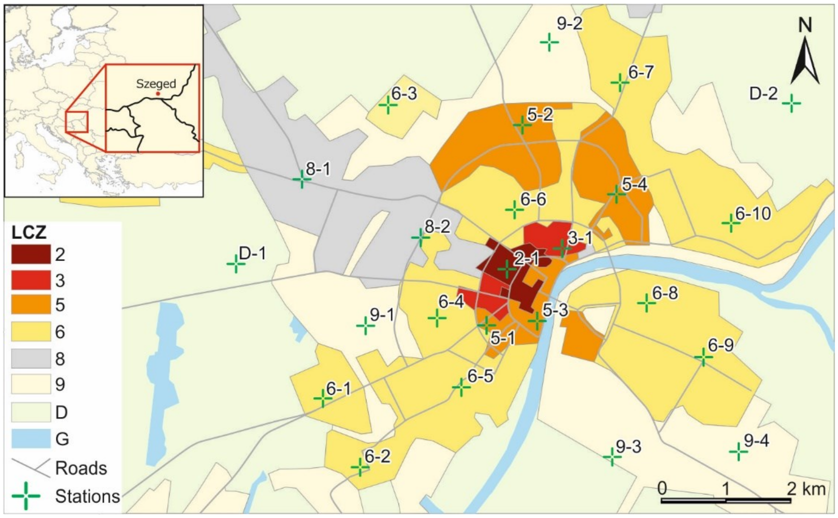

Fig. 1 Geographical location of Szeged and local climate zone map of the study area with station sites of the urban meteorological network (marked by green crosses and digits referring to the zones)

Within the framework of an EU project (URBAN-PATH 2018) an urban meteorological network with 24 stations was set up in Szeged representing different LCZs occurring in and around Szeged (Fig. 1). Two stations represent the rural area and 22 stations the different built-up areas (different LCZs) of the city (for more details see Unger et al. 2015). The network provides air temperature (*T* in °C) and relative humidity (*RH* in %) datasets of high temporal and spatial resolution across various weather conditions. In this analysis two stations (5-1, D-1) were excluded from the original network because of technical reasons. The remaining 22 stations represent the built and land cover LCZs occurring in Szeged with one exception: LCZ G, as there is no measurement station near the small water bodies in the area. Thus, the data used in the present study relate to LCZs 2 (compact midrise), 3 (compact low-rise), 5 (open midrise), 6 (open low-rise), 8 (large low-rise), 9 (sparsely built) and D (low plants) (Fig. 1).

As a first step, we calculated ten-minute averages of the measured 1-minute *T* and *RH* data of 22 stations from June 1, 2014 to May 31, 2017. In order to avoid the problem related to the effect of temperature on relative humidity (see Unger et al. 2018) and present the absolute moisture content of the urban canopy layer, the vapor pressure ($e$) values were calculated from the *T* and *RH* data, as a second step. During this procedure the vapor saturation pressure ($e_s$) was determined by:

$$e_s = A \cdot 10^{\left(\frac{m \cdot T}{T+T_n}\right)}$$

where $A$, $m$ and $T_n$ are constants depending of the state of water (Vaisala 2013). After, using the obtained ten-minute *RH* and $e_s$ values the $e$ was calculated by the following equation:

$$RH = \frac{e}{e_s} \cdot 100\%$$

To compare the general humidity modifying effects of different LCZs in Szeged, monthly hourly means, monthly and seasonal means, as well as seasonal minimum and maximum means were used. In case of LCZs 2, 3 and D the averages derived from data of only one station, however, for LCZs 5, 6, 8 and 9 the average of data from several stations were used according to the size of these zones.

We used data from selected stations to examine and compare the diurnal variation of seasonal averages by LCZs. In this analysis LCZs 2, 3 and D were represented by one station. Similarly, from the LCZ 8 we used also one station (8-2) because the other station has large data gaps in autumn, winter and spring. From the zones where this was possible more than one station was selected in order to reveal the intra-zone differences which may occur in $e$ variations. These stations were 5-2 and 5-4 from LCZ 5, 6-1, 6-3 and 6-9 from LCZ 6 as well as 9-2 and 9-4 from LCZ 9.

During the investigation of the temporal dynamics of the seasonal humidity patterns normalized time steps were applied in order to avoid the disturbing effect of different length of nights. It means that the time period from sunset to sunrise was divided into 12 parts and from sunrise to the next sunset also into 12 parts called them as ‘normalized hours’. The diurnal change of the seasonal $e$ pattern was examined in 4-normalized-hour time steps: at sunrise, four and eight hours after sunrise as well as at sunset, four and eight hours after sunset, but only in summer as an example. The patterns were based on the above mentioned 22 stations’ data using Kriging interpolation method with 100 m resolution.

## 3. RESULTS AND DISCUSSION

### *3.1. Annual and diurnal variations of mean urban-rural humidity differences*

In the first part of our study (Unger et al. 2018) we already mentioned three statements of Oke et al. (2017) about the common characteristics of the urban-rural moisture differences in cities with mid-latitude climates. To confirm their statement (iii) they cited an example from the results of Hage (1975) who evaluated a 13-year dataset of an urban-rural station pair in Edmonton (Canada) having continental climate with cold winters (Köppen type D, Kottek et al. 2006). Based on this example (see also their Fig. 9.4) they mentioned three features of

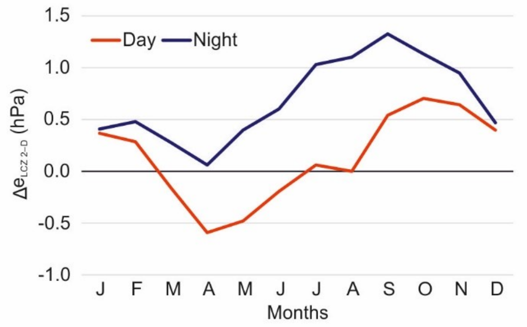

Fig. 2 Annual and diurnal variations of mean urban-rural ($LCZ_{2–D}$, 2-1↔D-2) vapor pressure difference in Szeged (June 2014 – May 2017)

the annual and diurnal variations of urban-rural absolute humidity difference as typical ones for mid-latitude cities. We now compare these features with those of Szeged using data also from a station pair based on our three-year dataset: station 2-1 from the city center and station D-2 represents the urban and rural conditions, respectively (Fig. 2).

According to Oke et al. (2017) the "nocturnal absolute humidity difference is positive throughout the year with largest differences in August and the smallest in winter and spring" is the first feature. The *e* variation at night in Szeged is consistent with this feature except for the time of the maximum difference (September instead of August) because of the longer warm season. The second feature is the following: "Annual course of daytime difference changes from a deficit (city drier) in the warmer part of the year, to excess in the colder part." Similarly, in our case the city is drier between March and July, then the urban-rural daytime difference disappears and from September to February it changes its sign that is the rural areas are drier. The third feature, that is, "in winter there is a little diurnal change in the magnitude of the excess, but mid-summer there is a strong diurnal shift from a large daytime deficit to an equally large nocturnal excess" is also valid in Szeged with certain time deviations. Namely, the largest daytime deficit and the largest nocturnal excess occur in April and September, respectively.

So the general features of the annual and diurnal variations of urban-rural absolute humidity difference in cities with mid-latitude climates are also detectable in the case of Szeged.

### *3.2. Inter-zone comparison of mean annual and seasonal humidity conditions*

Based on the three-year dataset we calculated annual and seasonal means, as well as means of maximum and minimum vapor pressure by LCZ classes. Table 1 contains these *e* means, the maximum differences between the zones ($\Delta e_{max}$) and information about the zones between which this maximum occurred.

As expected the largest *e* means occur in summer while the smallest ones in winter (Table 1). In the transitional seasons the values are between them with a bit higher *e* means in autumn followed the warmest period of the year. The largest mean difference (1.3 hPa) appears in the daily minimum vapor pressure in summer as a difference between urban (LCZ 3) and rural (LCZ D) areas while the smallest one (0.3 hPa) is in winter also between the *e* minimums.

There is no clear zone sequence neither in the seasonal nor in the annual means that would follow the differences in the compactness or building height of the zones and even the built-up versus land cover distinction. Furthermore, there is no detectable order of sequence between the zones that would be valid for all seasons.

Table 1 Annual and seasonal vapor pressure (*e*, hPa) means by LCZs in Szeged, Hungary (June 2014 – May 2017)

| **Means (2014–17)** | | **LCZ class** | | | | | | | **$\Delta e_{max}$** | **max** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **2** | **3** | **5** | **6** | **8** | **9** | **D** | | **$LCZ_{X–Y}$** |
| Summer | $e_{s\ mean}$ | 17.9 | 17.5 | 17.8 | 18.1 | 17.8 | 18.1 | 17.2 | 0.9 | 6, 9 – D |
| | $e_{s\ mean\ max}$ | 20.2 | 19.8 | 20.1 | 20.7 | 20.1 | 21.0 | 20.4 | 1.2 | 6 – 3 |
| | $e_{s\ mean\ min}$ | 15.7 | 15.2 | 15.5 | 15.6 | 15.5 | 15.3 | 14.4 | 1.3 | 3 – D |
| Autumn | $e_{a\ mean}$ | 12.1 | 11.3 | 11.7 | 11.9 | 12.2 | 11.8 | 11.6 | 0.9 | 8 – 3 |
| | $e_{a\ mean\ max}$ | 13.9 | 13.0 | 13.6 | 13.9 | 14.1 | 13.9 | 13.8 | 1.1 | 8 – 3 |
| | $e_{a\ mean\ min}$ | 10.5 | 9.9 | 10.1 | 10.1 | 10.6 | 9.8 | 9.7 | 0.9 | 2 – D |
| Winter | $e_{w\ mean}$ | 6.4 | 6.1 | 6.2 | 6.2 | 6.2 | 6.2 | 6.5 | 0.4 | D – 3 |
| | $e_{w\ mean\ max}$ | 7.3 | 6.9 | 7.1 | 7.2 | 7.1 | 7.1 | 7.5 | 0.6 | D – 3 |
| | $e_{w\ mean\ min}$ | 5.5 | 5.2 | 5.4 | 5.3 | 5.3 | 5.2 | 5.5 | 0.3 | 2, D – 3,9 |
| Spring | $e_{sp\ mean}$ | 10.3 | 10.0 | 10.3 | 10.4 | 10.3 | 10.3 | 10.2 | 0.4 | 6– 3 |
| | $e_{sp\ mean\ max}$ | 11.9 | 11.7 | 12.0 | 12.2 | 12.0 | 12.2 | 12.3 | 0.6 | D – 3 |
| | $e_{sp\ mean\ min}$ | 8.7 | 8.4 | 8.7 | 8.6 | 8.6 | 8.4 | 8.2 | 0.5 | 2, 5 – D |
| Annual | $e_{an\_mean}$ | 11.6 | 11.1 | 11.5 | 11.7 | 11.8 | 11.6 | 11.4 | 0.7 | 8 – 3 |

### *3.3. Inter- and intra-zone comparison of mean diurnal course of humidity by seasons*

Figs. 3-5 present the seasonal daily variations of vapor pressure by LCZs based on normalized hourly means. In order to reveal any intra-LCZ deviations that may arise as a result of local circumstances we selected data from more than one station from the zones where this was possible (two, three and two stations from LCZ 5, 6 and 9, respectively).

In summer the highest mean values approach the 20 hPa and their range is 4.3 hPa (15.4–19.7 hPa) during the day (Fig. 3). As expected, summer has the highest values and the largest range among the seasons. The smallest values are at sunrise, but the upward trend in the first part of the daytime breaks at about 4 hours after sunrise showing an early morning peak in almost all zones. This peak is the diurnal one except of station 9-2. Then a local decline can be observed until sunset. Then a slight increase appears, forming a second maximum in most cases (e.g. 5-4, 6-9, 9-4). In the case of remaining stations the decline continues until sunrise (e.g. 2-1, 3-1, 5-2). Appearance of the two peaks is caused by the daily dynamics of the urban boundary layer (*UBL*). At morning the insolation rapidly in-creasees the evapora-tion, later the near surface moisture is transported to the higher part of the *UBL* by convection. Near sunset when the *UBL* collapses due to the cessation of insolation this moisture of the higher part of the *UBL* descends near to the surface.

The stations in the suburb (9-2, 6-9) have the largest values during the whole 24-hour period while the smallest values can be found partly in the rural area (low plants, D-2) and partly, for surprise, in the housing estate (compact midrise, 5-2).

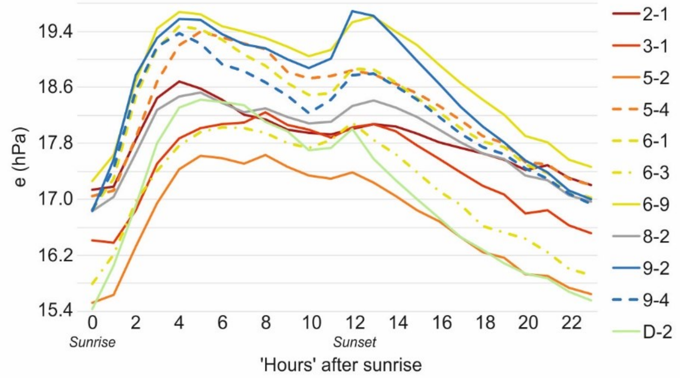

Fig. 3 Daily variations of normalized hourly mean vapor pressure (*e*) in summer by LCZs in Szeged, Hungary (June 2014 – May 2017)

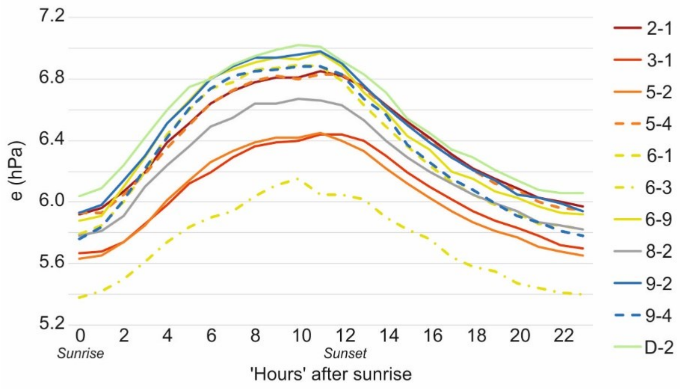

Fig. 4 Daily variations of normalized hourly mean vapor pressure (*e*) in winter by LCZs in Szeged, Hungary (June 2014 – May 2017)

Considering the intra-zone differences in LCZ 5 the hourly *e* means of station 5-2 are much lower (~2.5 hPa) during the whole day than the means of station 5-4. The reason of this deviation is the difference in the microscale environments, as station 5-2 is surrounded by mostly impervious surface, while the immediate environment of station 5-4 is dominated by vegetation, particularly by trees.

In LCZ 6 stations 6-9 and 6-1 have almost equal values until 6 hours after sunrise, after that the maximal deviation between them is only 0.8 hPa. Station 6-3 has lower values than stations 6-9 and 6-1 with about 1.6 and 1.1 hPa in average, respectively. These differences are also caused by the vegetation nearby the stations since stations 6-1 and 6-9 are surrounded by more dense vegetation than station 6-3.

As far as LCZ 9 is concerned values of stations 9-2 and 9-4 are almost equal except in the period from sunrise+6 hours to sunset+4 hours with a maximum difference of 0.9 hPa at sunset. Station 9-4 is located near to dense vegetation and in its close proximity there is a partly swampy area (former river bed) thus the alteration of increased evaporation at this time causes the momentary higher values (Fig. 3).

In winter, compared to summer, the *e* values are much lower (they are smaller than 7.1 hPa) and the range is more narrow (1.6 hPa) (Fig. 4). The diurnal courses follow a fairly regular shape from a sunrise minimum to a sole peak between 10 hours after sunrise and sunset in all zones. It is remarkable that the two peaks of the daily cycle disappear. In this season the moistest zone is the rural one (D-2), this is followed by the outer zones (LCZs 9 and 6, except station 6-3) with the compact and open midrise zones (stations 3-1, 5-4). The extended and compact low-rise zones (stations 8-2, 3-1) have smaller values, then, as a real exception, the station 6-3 in the north-western part of the city follows with its extra small values distinctly separating from the others. The absence of the two peaks indicates that the daily development and collapse of the *UBL* is not as dynamic as in summer.

To examine the intra-zone differences two zones can be considered (LCZs 5 and 6) as in LCZ 9 there is minor deviation in the diurnal course between stations 9-2 and 9-4. In LCZs 5 and 6 larger differences appear, which are 0.3–0.4 hPa and 0.4–0.9 hPa, respectively. In this season values of stations 6-1 and 6-3 are almost equal all of the hours. The appearing alteration is attributable to the differences in the impervious/pervious surfaces and vegetation in the microscale environments. The small variation inside zones highlights that in winter the micro scale differences of water availability and transpiration sources are not as important factors as in summer. The basic reason of this phenomenon is the more humid conditions (due to the less energy for evaporation) in this season (Fig. 4).

In the transitional seasons the *e* values are a bit higher (1.5–2 hPa) in the autumn following the summer, as in the spring following the winter (Fig. 5). Their values are between 8.6 and 13.4 hPa with the almost equal ranges (2.8 hPa and 3.2 hPa in spring and autumn, respectively). The highest daytime values in autumn (in LCZs 6 and 9) have two peaks similar to the summer ones while the peaks in spring are less pronounced. The appearance of two peaks indicates that in the transition seasons the daily cycle of *UBL* is similar to the summer situation.

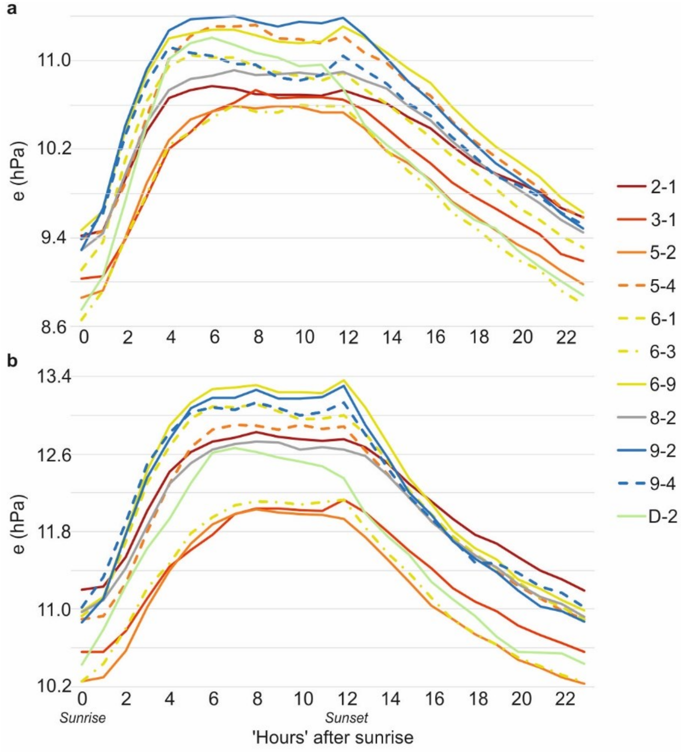

Fig. 5 Daily variations of normalized hourly mean vapor pressure (*e*) in spring (a) and in autumn (b) by LCZs in Szeged, Hungary (June 2014 – May 2017)

The intra-zone variations are more noticeable compared to winter, since in the transition seasons the increase (or decrease) of energy income of the surface will lead to increase (or decrease) the humidity difference in various micro environments, and, additionally the availability of evaporable water is not equal within the whole urban area (even within a zone).

In LCZ 5 the character of the difference between the two stations is similar to the summer one in both seasons but the deviation is smaller, it does not exceed 0.8 hPa and 1 hPa in spring and autumn, respectively (Fig. 5). In case of LCZ 6 the daily courses of stations 6-9 and 6-1 are more separated in spring, the maximum difference is of 0.5 hPa, while the values of station 6-3 are not much lower than the ones of station 6-1 with the difference ranging from 6-9 is 0.7–1.1 hPa. It can be assumed that the changing vegetation causes the different seasonal differences. Considering LCZ 9 there is minor deviation (< 0.1 hPa) in the diurnal course between stations 9-2 and 9-4 in autumn but in spring the deviation is a bit larger, mainly in the daylight hours (0.3–0.6 hPa) due to the more active vegetation life (Fig. 5).

### *3.4. Mean diurnal variation of intra-urban humidity patterns in summer*

According to the previous section the largest mean seasonal LCZ-difference in *e* appears in summer (4.3 hPa) which means that the most picturesque intra-urban deviations are expected in the summer urban patterns based on the dataset from 22 stations mentioned in Section 2. Therefore, now we present the mean diurnal course of intra-urban humidity patterns only in summer as an example.

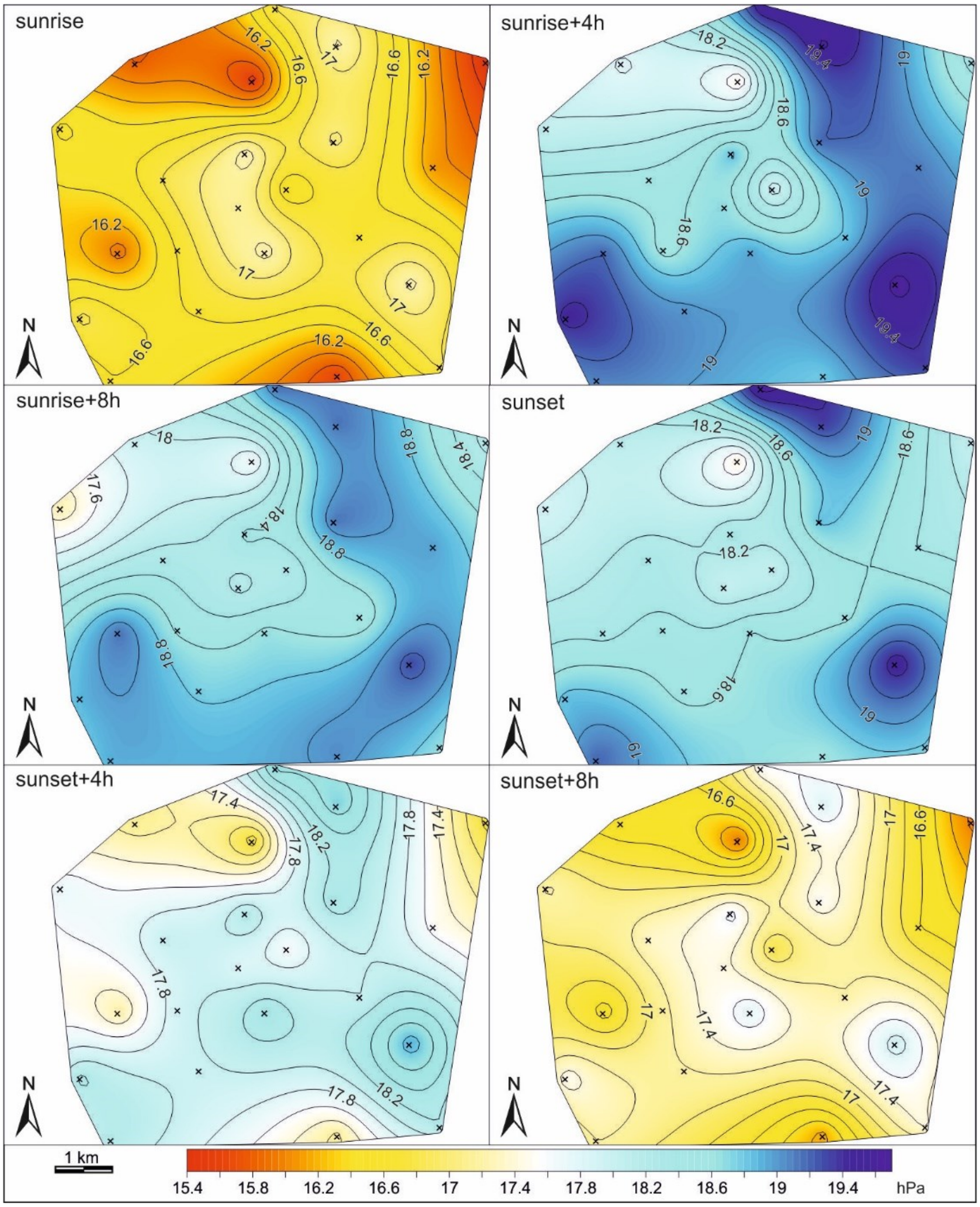

Fig. 6 Diurnal course of the mean summer patterns of vapor pressure in the urban area of Szeged, Hungary in normalized 4-hour time steps (June 2014 – May 2017)
(station sites are marked by crosses)

Fig. 6 shows this diurnal course in normalized 4-hour time steps from sunrise to 4 hours before the next sunrise. Generally, as in the mean summer case (see Fig. 2 in Unger et al. 2018), the distribution of *UCL* vapor pressure does not show a regular shape, the *e* pattern is mosaic-like: in all time steps the driest and wettest areas are in the north-western and south-eastern parts, respectively. That is, there are no detectable trace of the urban dry island phenomenon. This result confirms the statement of Unger et al. (2018), namely the urban dry island is a phenomenon that is mostly caused by the areal change of temperature dependent relative humidity.

As the dew formation on the gradually cooled surface during the night removed some of the moisture from the near-surface air the driest situation occurs at sunrise. At this time the lowest values (< 15.6 hPa) can be found in the north-western outskirts and north-eastern rural areas, while the highest ones (> 17.2 hPa) are in the city center as well as in the northern and south-eastern outskirts.

Then, due to the intensive evaporation from the wet surface supported by the rising sun, the moisture content of the air increased drastically until 4 normalized hours after sunrise to reach the highest values in the 24-hour period (18–19.6 hPa). The areas with highest humidity appear in the eastern and south-western outskirts while the inner and north-western areas are a bit drier.

Similar patterns can be observed after 8 hours and at sunset but with a bit lower air moisture content: the *e* values range between 17.4 and 19.2, as well as between 17.6 and 19.4 hPa, respectively.

After sunset, due to the increasingly cool surface, the moisture is partially extracted from the air resulting very similar patterns to the first one at sunrise, although their *e* values are not at the minimum: they ranges between 16.8 and 18.8 hPa, as well as between 16 and 17.8 hPa, respectively (Fig. 6).

## 4. CONCLUSIONS

In this study the seasonal and annual, as well as the diurnal absolute moisture contents were analyzed in the urban canopy layer of Szeged, Hungary. The analysis consisted of two approaches, namely urban-rural and intra-urban ones, the latter was partly based on the local climate zone surface classification system. The general features of the annual and diurnal variations of urban-rural absolute humidity difference in Szeged are consistent with the features of mid-latitude cities. The nocturnal absolute humidity difference is positive throughout the year while the diurnal course changes its sign. The largest daytime deficit and nocturnal excess occur in April and in September, respectively.

The largest *e* means occur in summer while the smallest ones in winter and in the transitional seasons the values are between them with a bit higher *e* means in autumn. There is no clear sequence in the annual and seasonal mean values of local climate zones that would follow the differences in the compactness or building height of the zones and even the built-up versus land cover distinction. The intra-zone differences can be larger than the inter-zones. Consequently, the effects of the microscale environment of the measurement sites are crucial. The permeability of the surface and vegetation cover of the immediate surrounding can cause the different values of the stations within the same zones. The higher impervious surface indicate lower, while natural surfaces, mostly the proximity of trees indicate higher values.

The mean diurnal course of intra-urban humidity patterns in summer shows mosaic-like ones. In all time steps the driest and wettest areas are mainly in the north-western and south-eastern parts, respectively. The driest situation occurs at sunrise and after that, due to the intensive evaporation from the wet surface supported by the rising sun, the moisture content of the air increases. The city core is drier from 4 hours after sunrise to 4 hours after sunset than the outskirts. After sunset, due to the cooling surface the *e* patterns are very similar to the first one at sunrise.

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