ACTA CLIMATOLOGICA 51-52: 37-45 (2018)
https://doi.org/10.14232/acta.clim.2018.52.2

ABSOLUTE MOISTURE CONTENT IN MID-LATITUDE URBAN CANOPY LAYER, PART 1: A LITERATURE REVIEW

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Summary: This part of the study on absolute moisture content in the mid-latitude urban canopy layer first gives a comparison on intra-urban relative and absolute humidity patterns showing an example based on a long dataset. The comparison clearly demonstrates the usefulness of the utilization of absolute measure opposite to the temperature dependent relative one. This supports the earlier statements found in the literature albeit these statements are based on only case studies or short datasets. Then a short overview follows which presents the main results of studies about urban absolute moisture content. These studies focused mainly on urban-rural and less on intra-urban humidity differences. The scale differences are used for the grouping of studies based on the number of available measurement sites as well as their spatial distribution and density in the investigated urban regions.

Key words: relative humidity, vapor pressure, other humidity measures, urban-rural differences, intra-urban differences

1. INTRODUCTION

Urban regions modify the originally natural landscapes which means transformation in their radiative, thermal, moisture and aerodynamic characteristics reflecting in datasets of different climate parameters (temperature, humidity, precipitation, wind, etc.) (Oke 1987). It has long been known in the related literature that the relative humidity (*RH*, %) is generally lower in the near-surface air in the built-up areas (urban canopy layer, *UCL*) relative to their surroundings, especially in the evening/night hours because of the temperature-dependence of *RH*. It is mainly explained by the developing urban heat island phenomenon, that is the momentary urban *RH* pattern is the mirror image of this and it is calling as "urban dry island – *UDI*" (Moriwaki et al. 2013, Cuadrat et al. 2015). Therefore, the extent of this negative *RH* deviation is closely related to the strength of the heat island and its daily variation (e.g. Ackerman 1987, Oke et al. 2017).

In contrast, if we are interested in not the relative but the absolute amount of air moisture (moisture content of air) and its urban-rural or intra-urban differences or patterns, we need to use other measures (e.g. vapor pressure – e, dew point temperature – T_d, absolute humidity/vapor density – p_v, specific humidity – q) having other units instead of % (hPa/mmHg/mb, °C/°F, gm^{-3}, gkg^{-1}, respectively) (Oke et al. 2017). Moriwaki et al. (2013) summarized the importance of the spatial and temporal distribution of air moisture mentioning that local severe rainfall is occasionally caused by the urbanization induced convergence of water vapor, as well as the humidity level can influence the plants life, the thermal comfort and health of people living in urban environment.

As our study has general and specific aims we split it into two parts. The first (recent) part is organized as follows:

(1) Presentation of the mean summer patterns of relative and absolute amount of air humidity (in parallel to temperature) in a city's *UCL* as an example in order to compare the two types of vapor content measures and their usefulness.

(2) Compilation of a short overview on the main results of earlier studies related to urban absolute moisture content of cities in mid-latitude climate regions (Köppen types C and D, Kottek et al. 2006). These studies are divided into two groups according to their scales. Studies in the first group are on urban-rural (larger scale) differences while the second group contains studies on humidity patterns and their intra-urban (smaller scale) differences.

In the second part of our study we will show the results about the absolute moisture content of the urban canopy layer in Szeged, Hungary based on a rather long (three years) and detailed intra-urban dataset (see Unger et al. 2018).

2. COMPARISON OF URBAN PATTERNS OF MEAN RELATIVE AND ABSOLUTE MOISTURE CONTENT

In this section we compare the mean summer patterns of relative and absolute amount (vapor pressure) of air humidity as well as temperature.

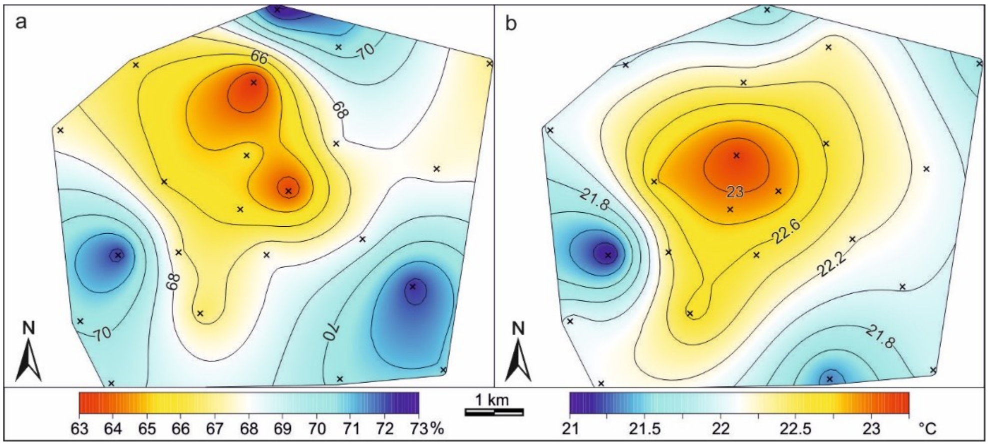

Fig. 1 Mean summer patterns of (a) relative humidity and (b) temperature in the urban area of Szeged, Hungary (June 2014 – May 2017)

As we mentioned in the previous section the urban *RH* pattern is the mirror image of the urban thermal field in the *UCL*, since the *RH* is the ratio of the vapor pressure and the vapor saturation pressure and the last one is the function of the temperature (*T*). Now we support this statement, not just based on a momentary situation, but taking the averages of a longer period (nine months) based on a three-year dataset of an urban meteorological station network from Szeged, Hungary (June 2014 – May 2017). These averages of *RH* and *T* were calculated from ten-minute records of 22 stations situated on a study area of about 8 km × 5.5 km. For the derivation of *e* averages we used the measured *T* and *RH*. For more details about the study area and data source see Unger et al. (2018).

The patterns of the three-summer *RH* and *T* averages have also mirror-like pictures (Fig. 1): dry/warm areas in the central parts and moist/cool areas in the western, northern and south-eastern parts of the study area. Additionally, the island-like shape of the patterns is clearly recognizable with highest *T* and lowest *RH* values in the middle then the decreasing *T*s and increasing *RH*s toward the edges. Based on Fig. 1, we could reach the deceptive conclusion that the city core is drier than the rural areas.

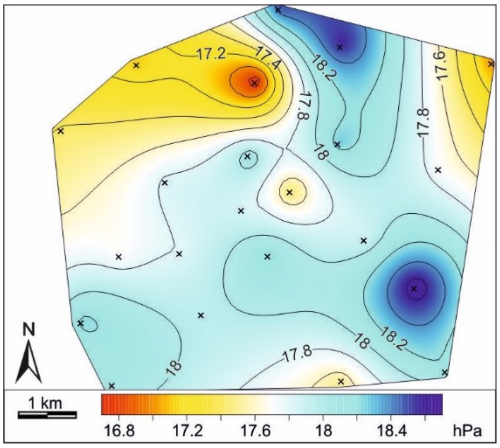

Fig. 2. Mean summer pattern of vapor pressure in the urban area of Szeged, Hungary (June 2014 – May 2017)

On the contrary, the distribution of vapor pressure in the *UCL* does not follow the thermal field and differs radically from the previous ones (Fig. 2). It does not show a regular shape, the pattern of *e* is mosaic-like: the driest and wettest areas are in the north-western and south-eastern parts, respectively, but smaller dry and moist areas can be found in the city center, too. Furthermore, there are moist areas in the north and the south-eastern parts, while dry areas appear in the north-western, north-eastern and southern edges. This mosaic-like behavior of *e* implies that the moisture content distribution in *UCL* does not have any contact with the thermal pattern developed there but primarily depends on the smaller scale local moisture sources (irrigated parks, traffic, households, district heating plants, manufactories, etc.) and on the local conditions that inhibit or assist in air mixing promoting moisture accumulation or dilution.

Comparing Figs. 1 and 2 it is clearly visible that the usage of *RH* in intra-urban analysis hides the real spatial distribution of moisture in the city. Precisely, on the basis of the mean patterns on Figs. 1 and 2 we can state that the investigation of urban *RH* patterns is not really useful since it does not give any valid information about the actual moisture content distribution of the urban air. It is more proper to turn our attention to the studies investigating the absolute measures (e, T_d, P_v and q) of air moisture in urban environment.

3. SHORT OVERVIEW ON STUDIES ABOUT ABSOLUTE MOISTURE CONTENT IN MID-LATITUDE CITIES

In the following, starting with a short historical review, we look at the findings of the absolute moisture amount in the *UCL* based on studies in cities located at mid-latitudes. For the first time, Kremser (1908) stated that humidity changes in the city air. Based on his investigation of 14-year data series from Berlin (Germany) and its surroundings, *e* was smaller in the city with 0.2 mmHg on average. Lessmann and Zedler's (1936) mobile measurement on a November day in 1935 gave rise to the first mapping of areal distribution of *e* with a largest difference of about 1.6 mmHg in Berlin.

Subsequently, according to our knowledge, no progress was made until Chandler's (1962) study in London (UK). Then the development has accelerated, both in terms of the growing number of studies and in their versatility. It is not always possible to compare the urban effects identified in different cities as different humidity measures were utilized and insufficient information were given to convert them to a common measure (Oke et al. 2017).

Below we describe the main characteristics and key findings of the studies related to urban-rural differences (first group) as well as to humidity patterns that is to intra-urban differences (second group). These distinction by scales is based on the number of available measurement sites as well as their spatial distribution and density in the investigated urban regions.

3.1. Urban-rural differences

According to Oke et al. (2017) the urban-rural moisture differences in cities with mid-latitude climates have the following common characteristics:

(i) “They are best displayed in ‘ideal’ (calm, clear) weather.”

(ii) “They are largest and spatially coherent at night but, during daytime they are complex and patchy.”

(iii) “There is a seasonal shift in the diurnal pattern; in summer, urban air is less moist than in the countryside by day, but more moist at night and in winter a city is commonly more moist at all times.”

The main features of studies in the first group are summarized briefly in Table 1. These studies are different regarding their measurement methods (fixed sites, mobile), the studied measures (e, T_d, p_v) and the length of the examined period (from one night to 33 years). In addition we indicate which statements of Oke et al. (2017) are supported by the mentioned studies.

Chandler (1962) states that the cellular morphology of cities may trap pockets of air (in case of favorable conditions for urban heat island development). In this situation the *UCL* is free from excessive mixing, thus the high daytime humidity will be maintained. It was proven by the distribution of mean T_d values for about 23:30. In the central London T_d was exceptionally high.

According to Hage (1975) Edmonton (Canada) was found to be dry in the daytime but moist at night in all but especially in winter months. In winter p_v is usually higher in the city on the whole day. Annual maxima in p_v differences were found in March and August (moist) and in daytime in July (dry).

The *UCL* air in Chicago (US) could be more or less humid than that in the surrounding rural areas (Ackerman 1987). This study also found diurnal and seasonal cycles. The average urban-rural differences were positive at night and negative only in the forenoon in late spring and in early summer afternoons.

Lee (1991) found obvious seasonal and diurnal patterns of urban-rural humidity differences in case of London (UK). The mean monthly differences were between +0.9 and -0.3 hPa. The *UCL* is more humid than the rural area all day long in winter and spring while less humid only during daytime in summer.

Szeged (Hungary) was found to be more humid than its surroundings during the whole year (Unger 1993, 1999). The minimum of increased humidity is at 01 h and its maximum is at 19 h in the summer months. This type of regular diurnal variation does not exist except in case of these summer situations. The humidity difference increases from January–February to August and then decreases until November–December.

Holmer and Eliasson (1999) revealed that the urban moisture excess (*UME)* in Stockholm (Sweden) could develop from three different combinations of rural and urban nocturnal *e* changes. This observation proves that different physical processes have effect on urban humidity, and these processes have different relationship with each other and the resulted *e* changes. They identified evaporation and condensation as an important factor for the development of *UME* but they also pointed out that the dry air advection caused by the urban heat island circulation could also modify the values.

Table 1 Main characteristics of studies focused on urban-rural humidity differences in absolute terms in chronological order (*fine* – clear and calm weather conditions, *e* – vapor pressure, T_d – dew point temperature, p_v – absolute humidity), as well as their confirmation of one or more statements by Oke et al. (2017)

Reference	**Measurement type**	**Studied measure**	**Number of events, time**	**Confirm (i), (ii) or (iii)**
Chandler (1962)	mobile traverse	T_d (°C)	1 night (October)	(i)
Hage (1975)	urban-rural station pair	p_v (gm^{-3})	13 years	(iii)
Ackerman (1987)	urban-rural station pair	*e*, T_d (mb, °C)	7 years	(iii)
Lee (1991)	urban-rural station pair	*e* (mb)	10 years	(iii)
Unger (1993, 1999)	urban-rural station pair	*e* (mb, hPa)	3 years	-
Holmer and Eliasson (1999)	urban-rural station pair	*e* (hPa)	53 *fine* summer nights	-
Unkašević et al. (2001)	1 urban, 2 suburb, 1 rural stations	*e* (hPa)	5 years	(iii)
Charciarek (2003)	urban-rural station pair	*e* (hPa)	5 years	(iii)
Mayer et al. (2003)	3 urban stations, mobile traverses	*e* (hPa)	August, January	(iii)
Richards (2005)	urban-rural station pair	p_v (gm^{-3})	24 days June-July (rain-free weather conditions biased toward fine and stable weather)	(ii)
Fortuniak et al. (2006)	urban-rural station pair	*e* (hPa)	6 years	(ii), (iii)
Sakakibara et al. (2006)	mobile traverses	*e* (hPa)	50 *fine* nights, 22 cloudy nights, 48 *fine* days (1 year)	(i), (iii)
Kuttler et al. (2007)	urban-rural station pair	*e* (hPa)	1 year	(iii)
Liu et al. (2009)	urban-rural station pair	*e* (hPa)	33 years	(ii), (iii)
Pongrácz et al. (2016)	intra-district mobile traverses, 1 suburban station	T_d (°C)	1 summer day	

Unkašević et al. (2001) manifested clear seasonal and diurnal patterns of urban-rural moisture differences in Belgrade (Serbia). They found humidity surplus in *UCL* compared to suburban and rural air at 07 and 21 h, autumn and winter, while in spring and summer the humidity had lower values in the *UCL*. They also clearly identified that at 14 h the *UCL* is drier in the whole year.

In case of Lodz (Poland) Charciarek (2003) found clear daily and seasonal cycle in *e* between urban and rural areas. In urban area the *e* is higher at nighttime, and in daytime only in the winter half-year. Maximal moisture surplus of urban area was measured after midnight in November and June, and in the afternoon and evening hours in November.

Mayer et al. (2003) could not find any significant spatial variation of *e* in the winter months in Munich (Germany). However they found that the summer variation of *e* is characterized by higher monthly mean values for all of their three measurement sites and the inter-site differences are considerable. Mayer et al. (2003) revealed that the diurnal variability of mean *e* values has different amplitudes and times of occurrence of their extreme values. The readings of their car traverses before, during and after a clear night showed an obvious small-scale spatio-temporal variability of *e* as a combined dependence on time and pattern of urban land cover.

In the case of Vancouver (Canada) there are no clear trend of urban humidity values, the urban-rural differences are between 1.7 and –3.3 gm^{-3} (Richards 2005). Median values for Δp_v between urban and rural sites were all negative, however, there was some tendency in the urban moisture island between 0 and 04 h.

Fortuniak et al. (2006) stated that urban-rural differences (Δe) in winter were usually around 1 hPa, but in summer they exceeded 5 hPa in extreme cases in Lodz (Poland). The highest negative differences occurred at night with a magnitude similar to the positive ones. They also found that it is very difficult to predict which type of humidity contrast will occur. According to their results the appearance of the highest positive Δe is at late night and the highest negative Δe is at early morning.

Based on the measurements in six different cities in Japan, Sakakibara et al. (2006) found that urban *e* had usually lower value than in rural areas. Urban-rural *e* differences on days with clear and calm daily weather conditions were two times larger than on cloudy or calm nights. They found that the mean value of *e* differences in summer was nearly twice as large as in winter. They also revealed that the connection between mean *e* differences and settlement population size is logarithmic.

Kuttler et al. (2007) revealed weak and intense *UME* during the year but the frequencies per month were different in Krefeld (Germany). A diurnal course of *UME* was also found only for summer. Weak or intense *UME* events usually occurred in the second half of the night. Most of these events had a duration of one hour, but in few occasions they found longer duration of weak and intense *UME* events up to 14 and 12 h, respectively.

In case of Beijing (China) annual urban-rural *e* differences were high at night and low in the morning and afternoon (Liu et al. 2009). In winter, for the 08, 14 and 20 hours urban *e* was higher than rural area and lower in the other seasons. They stated that the difference usually reached its maximum in summer, on the other hand, at 02 hours the difference was marginal. Based on their measurements urban *e* was basically higher than the rural one.

Pongrácz et al. (2016) revealed that T_d values in the afternoon are usually lower than in the evening in Budapest (Hungary). The difference relative to the suburb station decreased from 3–5°C (at about 14 h) to 1–2°C (at about 21 h).

3.2. Intra-urban patterns

The following is an overview of the main results that have been achieved so far related to the absolute humidity patterns in the urban areas. So now we turn to the studies in the second group that are more related to our recent investigation in Szeged (see Unger et al. 2018). The main features of studies of this group are summarized briefly in Table 2.

In case of Leicester (UK) Chandler (1967) proved that nighttime absolute humidity values were frequently higher in cities than in the rural areas nearby. There is also a remarkable conformity between the distribution of *e* and the extent and form of the city.

Kopec (1973) revealed that in clear and calm weather situations the humidity in urban area of Chapel Hill (US) were higher at night as well as lower in the morning and afternoon compared to suburban and rural areas. Based on their measurements, the maximal differences and the most complex patterns were in late afternoon and in contrary, and there were the minimal differences and less complex spatial patterns at night.

Table 2 Main characteristics of studies focused on urban humidity patterns in absolute terms in chronological order (e – vapor pressure, T_d – dew point temperature, q – specific humidity, p_v – absolute humidity)

Reference	Measurement type	Studied measure	Number of events, time
Chandler (1967)	mobile traverse	e (mb)	3 nights (August)
Kopec (1973)	mobile traverse	T_d (°F)	6 (midnight, morning, afternoon) (Sept., Oct.)
Goldreich (1974, 1999)	mobile traverse	q (gkg^{-1})	48 (morning, afternoon) (June, Dec.)
Henry et al. (1985)	mobile traverse	T_d (°C)	45 (morning, afternoon, evening) (Aug. – Oct.)
Moriwaki et al. (2013)	21-station network	p_v (gm^{-3})	16 months (from July to next Oct.)
Dou et al. (2015)	24-station urban + 20-station nonurban networks	q (gkg^{-1})	summer (5 years)

According to Goldreich (1974, 1999) a distinct *q* island was found above the Central Business District in Johannesburg (South Africa) in summer and winter, especially at sunrise and in the early afternoon. The *q* island was most pronounced in the daytime in winter.

Henry et al. (1985) stated that over undeveloped land the T_d was higher in the morning and afternoon in Lawrence (US). In contrary, residential and educational-institutional land use categories had negative correlation with T_d values, while in the evening the significance of this relationship was minimal.

In Matsuyama Plain (Japan) the *UDI* was identified in the daytime during favorable weather conditions (Moriwaki et al. 2013). They explained this phenomenon by the difference in water vapor fluxes at urban and rural sites. Their measurements showed obvious appearance of *UDI* in the morning and late afternoon, when the sea breeze and land breeze altered each other and the wind speed declined. Their study also revealed that *UDI* intensity was larger in summer than in winter. They explained their results with the small latent heat fluxes and strong NW monsoon effect in winter, which enhanced the mixing of humidity.

In Beijing (China) the urban *q* values were lower than in the surrounding regions (Dou et al. 2015). Their measurements clearly illustrated that a multicenter distribution occurred and it was connected to the spatial distribution of urban impervious surfaces. According to their results these surfaces decrease the evapotranspiration and increase the runoff, thus decrease urban *q* levels. They also highlighted that the usually warmer urban boundary layer in the daytime is also more convective than the rural one, and it could increase upward moisture fluxes, resulting lower *q* in *UCL* than in the nearby rural areas.

4. CONCLUSIONS

Our results help to draw the attention to the deceptive use of *RH* in urban climate studies. With the usage of absolute vapor characteristics (e.g. e, T_d, p_v, q) it is more likely possible to reveal the real moisture characteristics of urban areas.

Our literature review revealed the contradictions and knowledge gaps in the field of urban moisture behavior. There are some basic tendencies in the urban-rural characteristics, as Oke et al. (2017) summarized, however the studies could not prove all of them in the same urban area. We also found some studies where none of these general tendencies could be find. In case of intra-urban patterns we could find only a few studies, and based on their results it is hard to outline any general characteristics. We can state that the highest moisture differences occur in late afternoon, the differences disappear at night and there are some connection between the most vegetated urban surfaces and moisture content.

Essentially, the results of this systematic review show the necessity of a detailed analysis of the urban moisture patterns. This evaluation should use long data series in order to represent various weather situations, and it has to obtain readings from numerous different built-up areas of an urban environment in order to identify the possible factors what leads different moisture content in the basically same urban land use situations. In the second part of our study (Unger et al. 2018) we aim to present an analysis that is capable to accomplish these criteria.

Acknowledgement: This study was supported by the Hungarian Scientific Research Fund (OTKA K-111768).

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