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Spatio-temporal variability of moisture conditions within the Urban Canopy Layer

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With 10 Figures

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Summary

Re-analysed data from an urban climate research project in Munich, Germany, were used to investigate the spatio-temporal variability of moisture conditions (expressed here in vapour pressure VP) within the Urban Canopy Layer UCL. The results, which apply to three main sites and additional subsidiary ones, cover both summer and winter months. The summer month variation of VP is characterised by higher monthly mean values of VP for all three sites, howbeit with considerable inter-site differences. The temporal variability of mean VP values at diurnal time scales is also examined. With respect to the UCL, they reveal different amplitudes and times of occurrence of their extreme values. In addition, results of car traverses performed during clear sky conditions in downtown Munich show a remarkable small-scale spatio-temporal variability of VP.

In relation to a sealed downtown site within a courtyard in Munich, a time-dependent urban moisture excess (UME) was formed. A positive correlation between UME and the urban heat island (UHI) could be verified in general. However, it was slightly negative with a very low coefficient of determination in the summer month when the maximum UME preceded the maximum UHI up to 5 hrs. As example for the effects of air moisture on the urban climate within the UCL, the role of VP on a thermal index (physiologically equivalent temperature PET) was investigated. Based on one-year data from another urban climate project in Munich, a positive correlation between PET and VP was found, although the coefficient of determination was somewhat low. However, during a human-biometeorological case study on a typical summer day in the northern downtown of Freiburg, a medium-sized city in southwest Germany, PET and VP showed a negative correlation (possibly because the specific temporal course of VP at the measuring points was mainly influenced by thermally induced turbulence).

1. Introduction

The urban heat island (UHI) is the most well-known phenomenon of the urban climate (Arnfield, 2003). Looking more closely on a city, UHI gives way into an urban heat archipelago (UHA). Compared to numerous investigations on UHI or UHA, only a few papers on the moisture conditions within urban areas are available (Chandler, 1967; Kopec, 1973; Goldreich, 1974; Hage, 1975; Fiedler, 1979; Henry et al., 1985; Kawamura, 1985; Brazel und Balling, 1986; Ackerman, 1987; Adebayo, 1991; Lee, 1991; Unkaševic, 1996; Jauregui und Tejeda, 1997; Holmer und Eliasson, 1999; Unger, 1999; Deosthali, 2000; Unkaševic et al., 2001). Based mostly on data measured at screen level, i.e. at the bottom of the Urban Canopy Layer UCL, they discussed the temporal variability of moisture differences between cities and their surroundings. Different variables such as relative, absolute or specific humidity as well as vapour pressure are used for the analysis of the moisture conditions within the UCL. Nearly all investigations show a time-dependent urban moisture excess UME at night which can be explained by the mass balances for water vapour in the urban and rural atmosphere. Among others influencing factors are the location and structure of a city as well as the current weather and climate conditions.

Moisture in the urban atmosphere has diverse effects on the urban climate. For example, the radiative properties of water vapour imply that UME will produce a radiative force that ought to influence the UHI development (Holmer und Eliasson, 1999) and could result into the reduced formation of radiation fog in cities (Sachweh and Koepke, 1995). Moisture has a significant impact on the latent heat fluxes of the energy balance of an urban surface and the energy balance of an urban air volume. Moreover, moisture is a major influencing factor on the human energy balance and, therefore, affects the thermal comfort conditions of city dwellers (Berglund, 1997; Höppe, 1999).

The objectives of this study are (1) to improve the understanding of the spatial and temporal behaviour of the vapour pressure VP within the UCL as well as the relationship between UME and UHI and (2) to analyse the role of VP with respect to thermal perception of people within different urban microclimates.

2. Mass balance for water vapour in the urban atmosphere

According to Fiedler (1979), the mass balance of the moisture field within the urban air mass can be expressed as the mass balance for water vapour in the urban atmosphere:

$$\frac{\partial \mathrm{M_{VP}}}{\partial \mathrm{t}} + \vec{v} \cdot \nabla \mathrm{M_{VP}} = -\nabla \cdot \vec{\mathrm{E}}_{\mathrm{VP}} \qquad (1)$$

where $\frac{\partial \mathrm{M_{VP}}}{\partial \mathrm{t}}$ is temporal variation of water vapour mass in an urban atmosphere volume, $\vec{v}$: is three-dimensional wind vector, and $\vec{\mathrm{E}}_{\mathrm{VP}}$ is turbulent flux of water vapour. For urban areas the water balance is given by (Grimmond and Oke, 1991; Arnfield, 2003):

$$\mathrm{P + F + L = E_0 + R} \qquad (2)$$

where P represents precipitation, F denotes water released due to anthropogenic activities (e.g. combustion processes), L is piped water supply, $\mathrm{E_0}$ represents water vapour mass released by evaporation at the surface, and R is runoff (of precipitation and waste water).

Integrating Eq. (1) over the whole urban volume, neglecting vertical advection and horizontally turbulent diffusion of water vapour, considering only averages over the complete urban area, and using Eq. (2), the mass balance for water vapour in the urban atmosphere is (Fiedler, 1979):

$$\frac{\partial \mathrm{M_{VP}}}{\partial \mathrm{t}} + \Delta \mathrm{A} = -\mathrm{E}_{\mathrm{z}*} + \mathrm{P + F + L - R} \qquad (3)$$

where ΔA is net advection of water vapour, and $\mathrm{E}_{\mathrm{z}*}$ is turbulent flux of water vapour (removal or supply) through the upper boundary z^* of the urban atmosphere volume. All terms of Eq. (3) have the unit $\mathrm{kg\,m^{-2}\,s^{-1}}$ or $\mathrm{mm\,hr^{-1}}$.

Fiedler (1979) showed for Karlsruhe, a city in southwest Germany with 250,000 residents and emissions mainly from motorcar traffic and industry (refineries), that approximately twice the amount of the annual precipitation is supplied to the urban atmosphere by other sources (e.g. F). The natural evapotranspiration in a city is reduced by the high portion of sealed surfaces, but the missing water vapour is partly compensated by anthropogenic water vapour sources. Energy necessary for the production of anthropogenic water vapour does not come from the sun but from other processes.

3. Data base

This investigation is based on data recorded (1) within the scope of the research programme *Urban Climate in Bavaria* which was carried out in the first half of the eighties of the last century mainly in Munich (Bründl et al., 1986; Mayer, 1988), (2) during the urban climate project *KLIWUS* (April 1989 to March 1990) in Munich (Mayer and Matzarakis, 1997), and (3) during a human-biometeorological case study in Freiburg in July 1999. Data from *Urban Climate in Bavaria* and *KLIWUS* have been re-analysed with respect to the urban heat archipelago (Matzarakis, 2001).

During the *Urban Climate in Bavaria* programme, a temporary network of 20 climate stations was set up at different urban sites within Munich recording air temperature $\mathrm{T_a}$ and relative

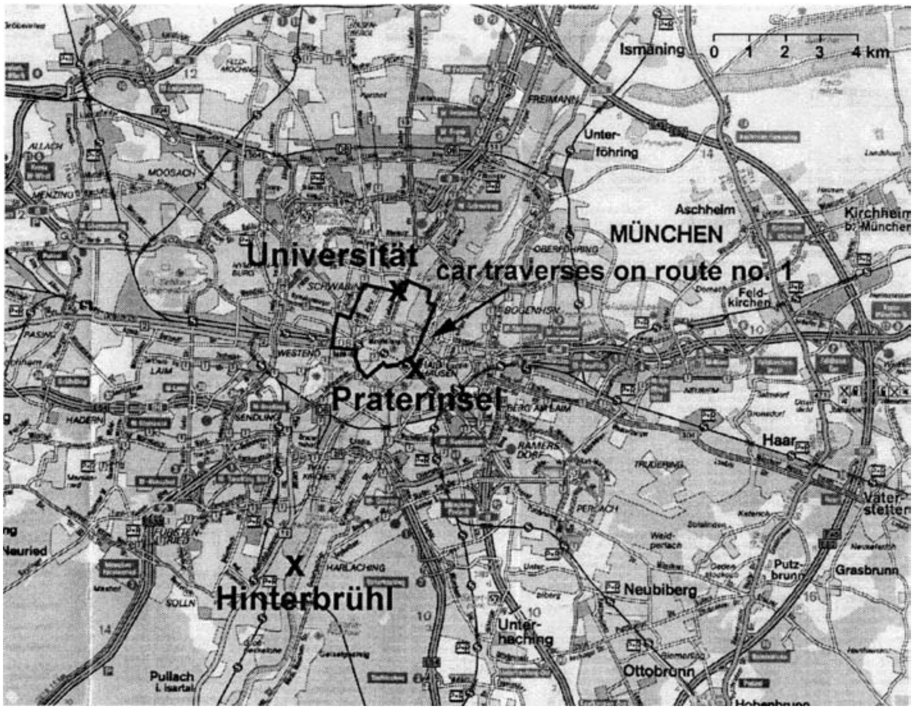

Fig. 1. Location of the sites "Universität", "Praterinsel" and "Hinterbrühl" of the urban climate network within the Urban Canopy Layer during the research programme *Urban Climate in Bavaria* in Munich as well as route no. 1 for car traverses

humidity RH (at 2 m above the ground) from July 1981 to December 1984. The sensors used at the 20 stations were of the same type (thermo-hygrographs) and calibrated at regular intervals at each site. Therefore, an accuracy of the hourly mean values of T_a and RH could be obtained, which was in the order of 0.2 °C and 3%, respectively. Due to the strong dependence on T_a, RH had to be ruled out for the investigation on the moisture within the UCL and was replaced by VP which could be calculated as hourly mean values with an accuracy of at least 0.2 hPa. The discussion of the results is restricted to the following three main sites (Fig. 1) which represents typical urban land cover types of European cities:

- "Universität" (hereafter referred to as CDA): courtyard in the northern downtown; sky view factor $SVF = 0.25$; surroundings: block buildings with low residential green areas; sealed area in a circle with a radius of 100 m around the site: 80%.
- "Praterinsel" (hereafter referred to as PDA): park in the downtown with old deciduous trees; $SVF = 0.15$ (growing season), 0.65 (winter); surroundings: park areas with block buildings at the borders; sealed area: 20%.
- "Hinterbrühl" (hereafter referred to as GSO): green space (dominant: short lawn) at the southern outskirts; $SVF = 0.55$ (growing season), 0.80 (winter); surroundings: green areas (grassland with trees and shrubs) as well as single and row houses; sealed area: 5%.

The horizontal differences between these measurement sites are 2.3 km (Universität – Praterinsel), 8.2 km (Universität – Hinterbrühl) and 6.5 km (Praterinsel – Hinterbrühl).

The main objective of the experimental *KLIWUS* project was the human-biometeorological assessment of small-scale climate effects within different urban structures (Mayer and Matzarakis, 1997). A specific mobile human-biometeorological measurement unit was compiled for recording the data. During cloudless days with low wind speeds, the measurements were sequentially carried out at selected points on short routes which led through different urban microclimate zones within Munich. Values of VP for these subsidiary sites were calculated from measured dry and wet bulb temperatures and reached an accuracy of 0.1 hPa.

The case study in Freiburg, a medium-sized city in southwest Germany, was performed on a typical summer day (19 July 1999). The objective of the investigation was the human-biometeorological assessment of the small-scale climate manipulation formed by a group of chestnut trees near a crossing in the northern downtown (Matzarakis, 2001). Values of VP were again determined on the basis of dry and wet bulb temperatures and had an accuracy of 0.1 hPa. The physiologically equivalent temperature PET calculated after the method by Mayer and Höppe (1987) was used as assessment index for the thermal environment.

4. Results

4.1 Seasonal variability of VP

To get an impression on the spatial magnitudes of VP within the UCL in different seasons, mean VP values were calculated for a typical summer (August 1981) and winter month (January 1982). Due to the increased availability of energy at the three sites in summer, the average VP level was clearly higher at all three sites in August 1981 (Table 1). In January 1982, the mean VP values amounted to approximately 30% of the mean August values. Mean VP values showed nearly no significant spatial variation in the winter month, whereas a decrease of mean VP values was observed in the summer month from the site CDA to the other two sites. Its magnitude from CDA to PDA ($-0.304\,\mathrm{hPa\,km^{-1}}$) was higher than from CDA to GSO ($-0.171\,\mathrm{hPa\,km^{-1}}$), indicating that VP does not decrease linearly from downtown to the surroundings. This could be that the horizontal variation of VP depends strongly on the pattern of the urban land cover and, therefore, is slightly irregular. Assuming no clear differences of the mean monthly values of P, L and R from Eq. (3) between the three sites, the combined effect of reduced air mass exchange, elevated water vapour supply from anthropogenic processes in the vicinity and evapotranspiration from the small green spaces was mainly responsible for the comparatively high mean VP value at the site CDA in August 1981. Compared to the site PDA, the site GSO was exposed to a stronger ventilation which led to a lower mean VP value.

Table 1. Mean values of vapour pressure VP (in hPa) for a typical summer month (August 1981) and winter month (January 1982) at three sites (2 m above the ground) in Munich

Site	August 1981	January 1982
Downtown, courtyard (CDA)	14.8	4.3
Downtown, park (PDA)	14.1	4.2
Southern outskirts, green space (GSO)	13.4	4.2

4.2 Diurnal variability of VP

To analyse the temporal behaviour of VP within the UCL in the typical summer month of August 1981, Fig. 2 presents mean diurnal cycles of VP at the three urban sites in Munich. They have the

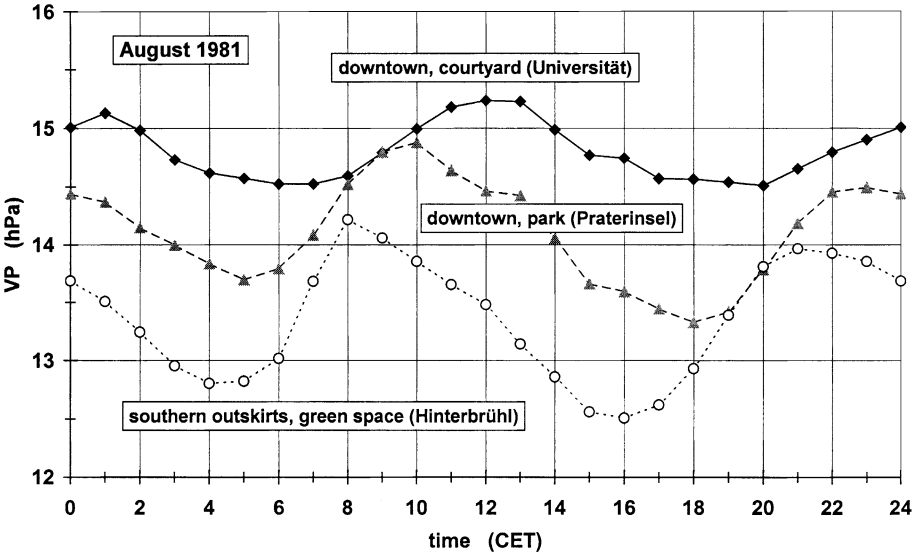

Fig. 2. Mean diurnal cycles of vapour pressure VP (2 m above the ground) at three different sites in Munich for a typical summer month (August 1981)

Table 2. Mean diurnal occurrence of extreme VP values for a typical summer month (August 1981) and winter month (January 1982) at three sites (2 m above the ground) in Munich

	Site		
	Downtown, courtyard CDA (CET)	Downtown, park PDA (CET)	Southern outskirts, green space GSO (CET)
August 1981			
1st max VP	12	10	8
2nd max VP	1	23	21
1st min VP	20	18	16
2nd min VP	6, 7	5	4
January 1982			
max VP	15	14	15
min VP	3	5	7

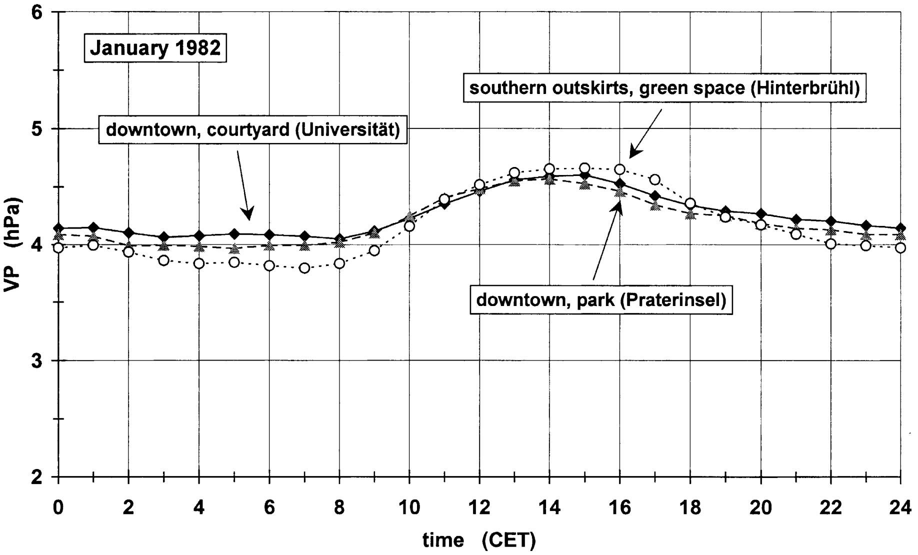

Fig. 3. Mean diurnal cycles of vapour pressure VP (2 m above the ground) at three different sites in Munich for a typical winter month (January 1982)

form of a double wave with the extreme values occurring at different times over the sites (Table 2). The higher the mean VP level was, the later the extreme values were observed during the day. The sudden ending of the increasing trend of VP in the morning at GSO, which occurred at PDA in alleviated form about two hours later, can be explained by the beginning of convection processes which were more pronounced at GSO due to the higher sky view factor. The following loss of water vapour could not be completely replaced by the net advection of water vapour or latent heat flux (Eq. 3). The diurnal cycles of VP in the typical winter month of January 1982 had more the form of a sine curve (Fig. 3) with maximum values in the early afternoon and minimum values in the early morning. The magnitude of the amplitudes of the mean diurnal VP cycles depended on the specific sites. CDA which had the highest mean VP values in both months revealed the lowest amplitudes of the mean VP cycles (Table 3). By contrast, GSO with the

Table 3. Ranges (in hPa) of the mean diurnal VP cycles for a typical summer month (August 1981) and winter month (January 1982) at three sites (2 m above the ground) in Munich

Site	August 1981	January 1982
Downtown, courtyard (CDA)	0.7	0.5
Downtown, park (PDA)	1.6	0.6
Southern outskirts, green space (GSO)	1.7	0.9

lowest mean VP values in both months showed the greatest amplitudes of mean VP cycles.

The mean hourly variations of the vapour pressure $\Delta VP/\Delta t$ which are addressed in Eq. (3) can also be explained by the site conditions with respect to air mass exchange, evapotranspiration and VP supply due to anthropogenic activities for both winter and summer months. Like the diurnal cycles of the mean hourly VP values, they had the form of a double wave in August 1981 (Fig. 4) and a sine curve in January 1982 (Fig. 5) with higher values in the summer than in the winter month. Due to energetic reasons, the ranges of $\Delta VP/\Delta t$ were higher in the summer than in the winter month. With respect to the different urban sites, the highest mean hourly increase and decrease rates of VP were observed in both months at the site GSO (Table 4), which had the highest sky view factor and, therefore, the most pronounced ventilation conditions, whereas the lowest comparable values were determined for CDA. In the winter month, the extreme values of $\Delta VP/\Delta t$ occurred nearly at the same time, i.e. the highest values around 11 CET and the lowest values between 17 and 18 CET. In the summer month, however, the occurrence of the extreme values of $\Delta VP/\Delta t$ showed a more pronounced disparity between the three sites.

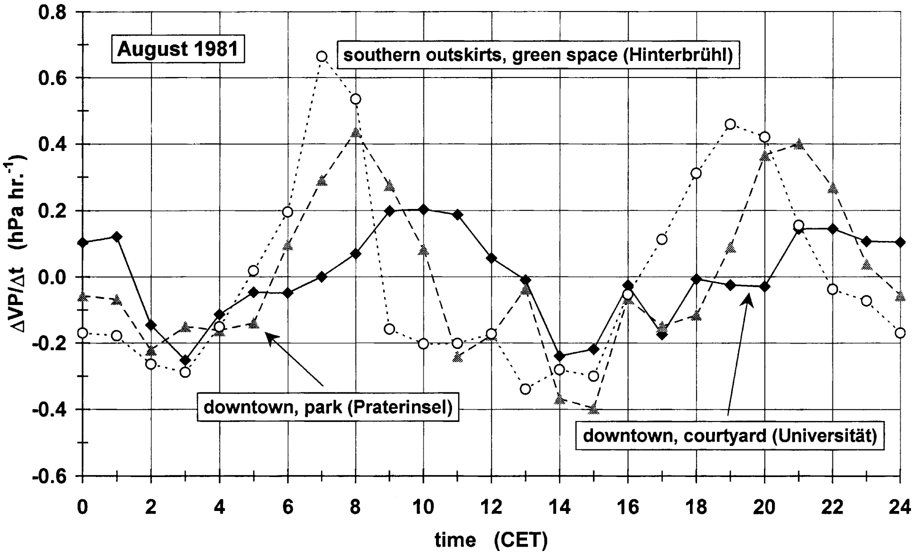

Fig. 4. Mean hourly variations of vapour pressure $\Delta VP/\Delta t$ (2 m above the ground) at three different sites in Munich for a typical summer month (August 1981)

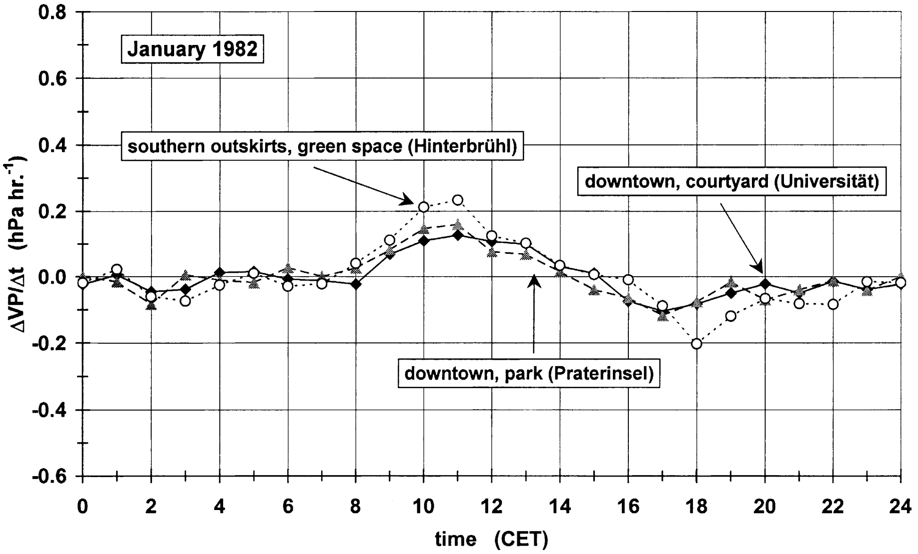

Fig. 5. Mean hourly variations of vapour pressure $\Delta VP/\Delta t$ (2 m above the ground) at three different sites in Munich for a typical winter month (January 1982)

Table 4. Extreme values of mean hourly VP variations $\Delta VP/\Delta t$ (in hPa h^{-1}) and times of their occurrence for a typical summer month (August 1981) and winter month (January 1982) in the UCL (2 m above the ground) of Munich

Site	August 1981				January 1982			
	$(\Delta VP/\Delta t)_{max}$		$(\Delta VP/\Delta t)_{min}$		$(\Delta VP/\Delta t)_{max}$		$(\Delta VP/\Delta t)_{min}$	
	Value	*Time (CET)*	Value	*Time (CET)*	Value	*Time (CET)*	Value	*Time (CET)*
Downtown, courtyard (CDA)	0.20	*10*	−0.25	*3*	0.13	*11*	−0.10	*17*
Downtown, park (PDA)	0.44	*8*	−0.40	*15*	0.16	*11*	−0.12	*17*
Southern outskirts, green space (GSO)	0.66	*7*	−0.34	*13*	0.23	*11*	−0.21	*18*

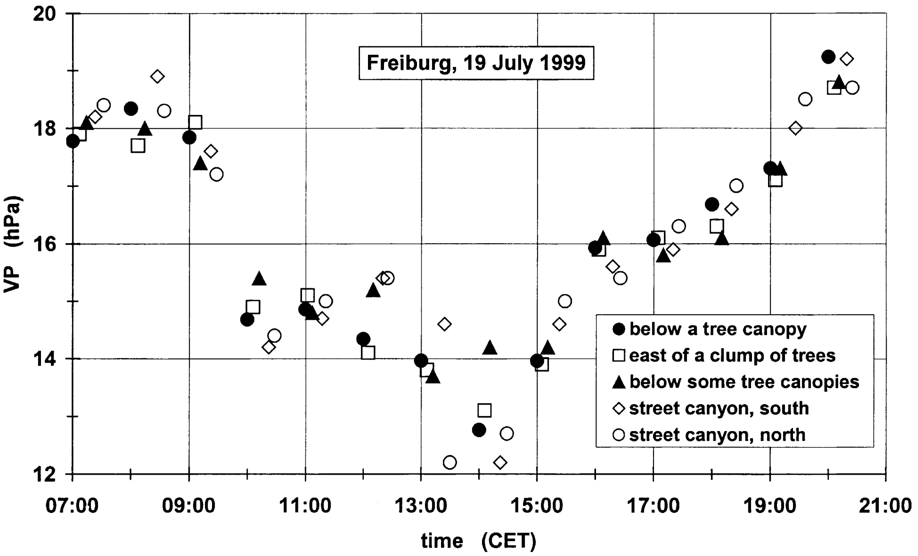

Fig. 6. Vapour pressure VP (1.1 m above the ground) at five different sites in northern downtown of Freiburg for a typical summer day (19 July 1999)

In reality, current diurnal cycles of VP within the UCL can widely differ from mean monthly diurnal cycles. An example of this is taken from the Freiburg case study on a typical summer day (19 July 1999). The results (Fig. 6) show instantaneous values of VP (in the human-biometeorologically significant height of 1.1 m above the ground) at different measuring points (within a circle with a radius of 50 m in the northern downtown). The measurements were sequentially carried out by use of the specific mobile measurement unit from the *KLIWUS* project. Though a thermally induced scattering of the VP values was observed in the early afternoon, the most striking feature is that the lowest VP values occurred at all measuring points around 14 CET. This phenomenon was mainly caused by the intense thermally induced turbulence at all sites. According to Eq. (3) water vapour produced by the evapotranspiration of the chestnut trees was transported upwards by convection, whereas air masses with lower vapour pressure contents arrived at the measuring points within the street canyon and below the tree canopies.

4.3 Spatial variability of VP

An example of the spatio-temporal micro-scale behaviour of VP is shown in Fig. 7, which contains VP values at 2 m above the ground, taken during different car traverses on the same route (Fig. 1) through downtown Munich during the *Urban Climate in Bavaria* Programme. The length of the route was 11.2 km. Measuring points fixed at the planning of the route were located about every 300 m. The psychrometric method based on special Pt100 sensors suited for car traverses was applied to calculate VP values. More details about all car traverses during the *Urban Climate in Bavaria* Programme

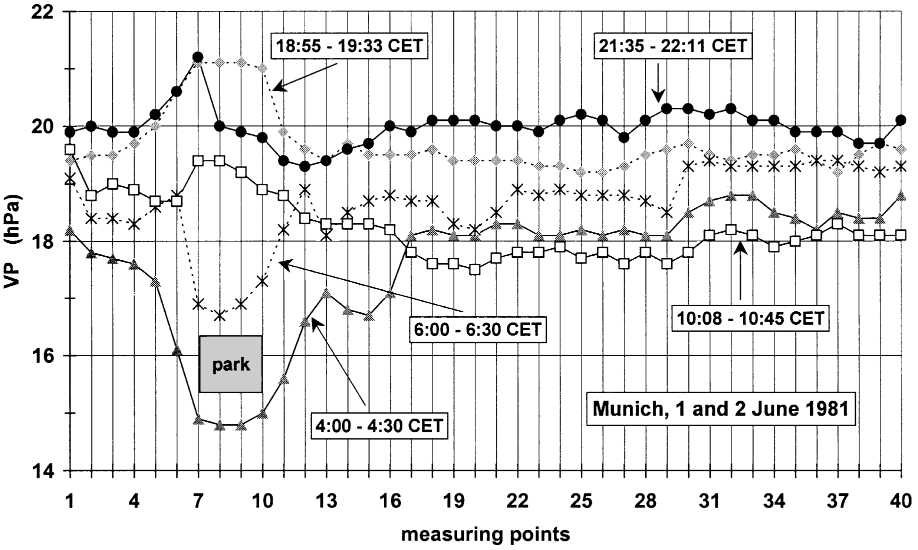

Fig. 7. Vapour pressure VP (2 m above the ground) at selected measuring points on a profile route obtained by car traverses through downtown Munich before, during and after a clear night at early summer (1 and 2 June 1981)

are documented by Bründl et al. (1996) and Mayer (1987). The car traverses of Fig. 7 were performed before, during and after a clear night at early summer with mean values of air temperature T_a (at 2 m above the ground) of 24 °C (1 June 1981: 19:00 CET), 21 °C (1 June 1981: 22:00 CET), 16 °C (2 June 1981: 4:15 CET), 17 °C (2 June 1981: 6:15 CET) and 25 °C (2 June 1981: 10:30 CET). The route started at the site CDA, cut through different urban structures including a large park ("Englischer Garten") and ended at the starting point.

The results showed a combined dependence of VP on time and pattern of urban land cover. Both factors influence the mass balance for water vapour (Eq. 3) within different volumes in the urban canopy layer. The most pronounced variation of VP was found at the transition between sealed surfaces and the park. Due to the enhanced evapotranspiration, the urban park had higher VP values in the daytime than its sealed surroundings. Lower VP values in the park at night (up to 3 hPa) were mainly caused by the formation of dew which removed water vapour from the UCL. From the literature (e.g. Spronken-Smith and Oke, 1998; Upmanis et al., 1998; Eliasson and Upmanis, 2000), the phenomenon of a nocturnal airflow created by urban parks is known, which have an impact on the fields of air temperature and moisture in the vicinity of parks. Although no suited wind measurements were performed during the car traverses, the results for VP within and in the vicinity of the park (Fig. 7) also point out the existence of such a local airflow.

4.4 Urban moisture excess and urban heat island

According to Kratzer (1956), the urban atmosphere is frequently more moist than the rural atmosphere, particularly at night. Investigations on this phenomenon, which is called urban moisture excess UME, by Holmer and Eliasson (1999), Unger (1999) and Unkašević et al. (2001) showed that UME has to be discussed more precisely taking into consideration suited variables for moisture, seasons, current weather, climate zone of a city and pattern of urban land cover. Against this background, VP data of the three sites in Munich enabled a further investigation of UME. In relation to the site CDA, UME showed the known dependence on the season with higher values in summer and lower values in winter (Table 5). The spatial differentiation of UME by use of VP data from the two green sites yielded higher mean values of UME in the summer month, when VP values from the site GSO were taken. In the winter month, the same mean UME values were obtained for both green sites. For comparison, mean values of the urban heat island UHI within the UCL were included in Table 5. They display nearly the same qualitative behaviour like UME.

In addition to the diurnal cycles of mean UHI values, those of mean UME values are also

Table 5. Mean urban moisture excess UME (in hPa) and mean urban heat island UHI (in °C) for a typical summer month (August 1981) and winter month (January 1982) in the UCL (2 m above the ground) of Munich

Site	August 1981		January 1982	
	UME	UHI	UME	UHI
Downtown, courtyard (CDA) – downtown, park (PDA)	0.7	2.1	0.1	0.9
Downtown, courtyard (CDA) – southern outskirts, green space (GSO)	1.4	3.5	0.1	1.6

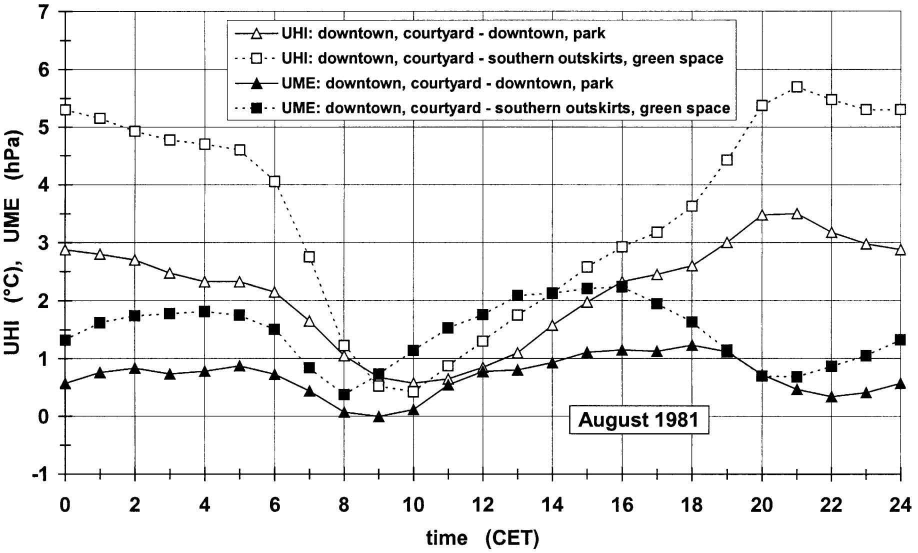

Fig. 8. Diurnal cycles of the mean urban moisture excess UME and mean urban heat island UHI (2 m above the ground) for a typical summer month (August 1981)

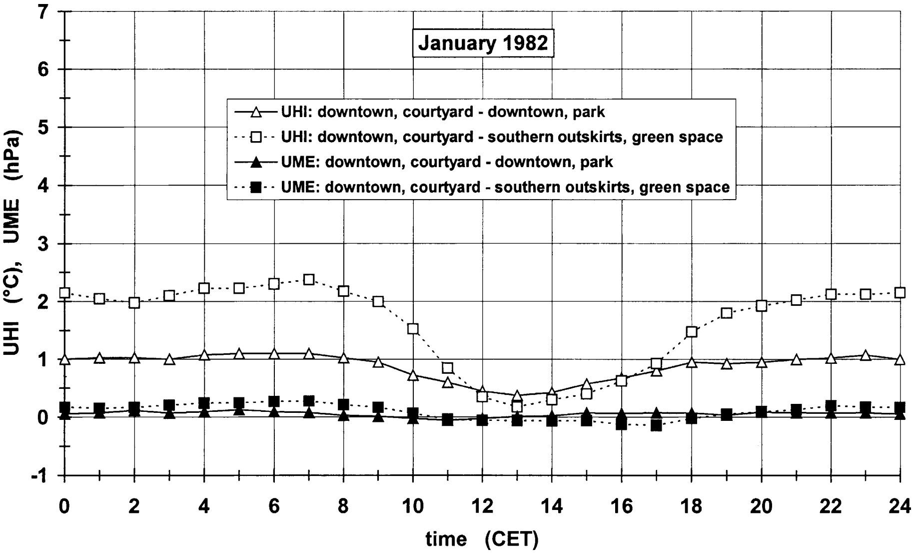

Fig. 9. Diurnal cycles of the mean urban moisture excess UME and mean urban heat island UHI (2 m above the ground) for a typical winter month (January 1982)

presented in Figs. 8 (August 1981) and 9 (January 1982). Due to the behaviour of the mean VP values, they had the form of a double wave in both months, but with a more pronounced shape in the summer month. The mean UME values were always positive in the summer

Table 6. Highest mean urban moisture excess UME_{max} (in hPa) and highest mean urban heat island UHI_{max} (in °C) and times of their occurrence for a typical summer month (August 1981) and winter month (January 1982) in the UCL (2 m above the ground) of Munich

Site	August 1981				January 1982			
	UME_{max}		UHI_{max}		UME_{max}		UHI_{max}	
	Value	*Time* (*CET*)	Value	*Time* (*CET*)	Value	*Time* (*CET*)	Value	*Time* (*CET*)
Downtown, courtyard (CDA) – downtown, park (PDA)	1.2	*18*	3.5	*21*	0.1	*5*	1.1	*5–7*
Downtown, courtyard (CDA) – southern outskirts, green space (GSO)	2.2	*16*	5.7	*21*	0.3	*7*	2.4	*7*

month, i.e. the mean VP values at CDA were higher than the mean VP values at both green sites. As the diurnal cycles of the mean UHI values had the form of a single wave, only magnitudes and times of occurrence of the first UME maximum values are discussed (Table 6). While the mean UHI maximum in August 1981 was observed at 21 CET, the mean UME maximum occurred 3 to 5 hours earlier. In the winter month January 1982, UME was positive only at night. Compared to the site CDA, slightly higher mean VP values, particularly at GSO, caused negative mean UME values in the daytime. In contrast to the summer conditions, the times of occurrence of the mean maximum values are similar between UME and UHI.

Lee (1991), Holmer and Eliasson (1999) and Unkaševic et al. (2001) analysed the linear relationship between UHI (in °C) and UME (in hPa):

$$\mathrm{UHI} = \mathrm{a} \cdot \mathrm{UME} + \mathrm{b} \tag{4}$$

where a and b are the regression coefficients. According to Holmer and Eliasson (1999), the physically based positive correlation between UHI and UME can be explained by similar but not identical atmospheric processes, which influence both UHI and UME similarly. Using the mean UHI and UME data of the analysis for Munich, the general validity of this relationship could be examined. In agreement with Lee (1991), Holmer and Eliasson (1999) and Unkaševic et al. (2001), the results in Table 7 show a positive correlation between UHI and UME for three cases, but it was negative for the case "Munich, August 1981: CDA–GSO".

Table 7. Coefficients a and b from the relationship $\mathrm{UHI} = \mathrm{a} \cdot \mathrm{UME} + \mathrm{b}$ and the corresponding coefficient of determination R^2 for different sites; results for London from Lee (1991), for Göteborg from Holmer and Eliasson (1999) and for Belgrad from Unkaševic et al. (2001)

Site	a	b	R^2
Munich, August 1981, mean hourly values: downtown, courtyard (CDA) – downtown, park (PDA)	0.91	1.54	0.115
Munich, August 1981, mean hourly values: downtown, courtyard (CDA) – southern outskirts, green space (GSO)	−0.30	3.96	0.008
Munich, January 1982, mean hourly values: downtown, courtyard (CDA) – downtown, park (PDA)	3.53	0.68	0.442
Munich, January 1982, mean hourly values: downtown, courtyard (CDA) – southern outskirts, green space (GSO)	5.21	1.11	0.840
Göteborg: clear and calm nights in summer 1994	0.25	0.41	0.520
Belgrade, 1976–1980: downtown – rural site	2.08	1.25	0.291
Belgrade, 1976–1980: downtown – suburban site (airport)	2.08	1.34	0.306
Belgrade, 1976–1980: downtown – suburban site (low hill)	−1.97	0.72	0.643
London: monthly mean values in the period 1979–1988	3.23	0.87	0.697

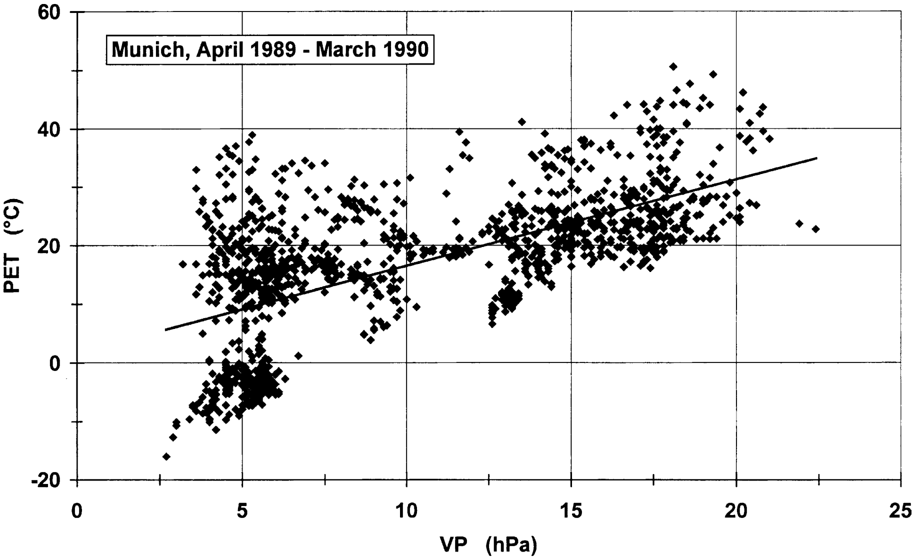

Fig. 10. Relationship (confidence level p = 0.95) between the physiological equivalent temperature PET (1.1 m above the ground) and the vapour pressure VP (1.1 m above the ground) on the basis of different case studies during the *KLIWUS* project in Munich (April 1989 to March 1990)

However, the latter relationship is not significant, since the value of R^2 (coefficient of determination) is extremely low (Table 7). A negative correlation between UHI and UME was also found for one case in the Belgrade study which was mainly caused by the vertical difference of 111 m in altitude between both sites. Altogether, the relationship between UHI and UME are characterised by a pronounced spatial and temporal dependence (see different values of the regression coefficient a in Table 7).

4.5 Effect of vapour pressure on the human thermal comfort

As an example of the effects of VP on the urban climate, the role of VP on the human thermal comfort within urban microclimates will be discussed in this section. Thermal indices derived from the human energy balance are the current standard to assess the thermal conditions of climate in a human-biometeorologically significant manner (Mayer, 1993; Höppe, 1999; Matzarakis et al., 1999; Spagnolo and de Dear, 2003). Besides mean radiant temperature of the surroundings T_{mrt}, air temperature T_a and wind speed v, vapour pressure VP belongs to the meteorological parameters necessary to calculate thermal indices such as PMV, PET or OUT_SET*.

To evaluate the role of VP with respect to thermal comfort, data of the urban climate project *KLIWUS* were used. Under the physiological point of view, the physiologically equivalent temperature PET as a thermal index and VP should have a positive correlation. This hypothesis can be confirmed by the *KLIWUS* results in Fig. 10. But the scattering around the linear regression line and the low coefficient of determination (Table 8) indicate for mid-latitude cities like Munich, that on a yearly basis VP is only a minor influencing factor on PET, whereas T_{mrt} dominates. Besides the macroclimate background, the order of the thermophysiological importance of meteorological parameters depends on the seasons, too. As exemplarily demonstrated by the results for the human-biometeorological case study on a typical summer

Table 8. Linear relationships (confidence levels p = 0.95) between the physiological equivalent temperature PET (in °C) and mean radiant temperature of the surroundings T_{mrt} (in °C), air temperature T_a (in °C) as well as vapour pressure VP (in hPa), instantaneous data (1.1 m above the ground) from the urban climate project *KLIWUS* in Munich and an urban climate case study on a summer day in the northern downtown of Freiburg

Linear relationships	R^2
Munich, April 1989–March 1990 (KLIWUS)	
$PET = 0.632 \cdot T_{mrt} + 1.56$	0.851
$PET = 1.217 \cdot T_a - 2.64$	0.815
$PET = 1.483 \cdot VP + 1.69$	0.394
Freiburg, 19 July 1999	
$PET = 0.585 \cdot T_{mrt} + 6.95$	0.893
$PET = 1.083 \cdot T_a + 1.31$	0.162
$PET = -1.585 \cdot VP + 54.97$	0.251

day (19 July 1999) in Freiburg, the influence of VP on PET was a little higher than of T_a (Table 8). At first sight, the minus sign of the regression coefficient in the relationship between PET and VP may be unexpected, but it is the consequence of the specific diurnal cycle of VP during the Freiburg case study (Fig. 7).

5. Discussions

It could be expected that moisture affected by urbanization is lower in a city when compared to the rural environment (Adebayo, 1991). However, as investigated in this study with vapour pressure VP, the reality displays a more different behaviour. The basis to understand the moisture conditions within and outside a city is the mass balance for water vapour in the urban atmosphere (Eq. 3). It combines all mass fluxes which determine both the spatial and temporal variability of VP within the UCL. Factors affecting the distribution of VP within the UCL are mixing influences of surface roughness and thermal fields, reduced evapotranspiration due to limited vegetation and extensive impervious surfaces, emissions of water vapour by anthropogenic processes and transpiration, advection, vertical turbulent transfer, removal of water vapour by precipitation, dew, deliquescence of hygroscopic aerosols and surface materials as well as chemical reactions in the atmosphere (Holmer and Eliasson, 1999; Grimmond and Oke, 2000; Unkaševic et al., 2001; Richards and Oke, 2002).

The re-analysis of data from the research programme *Urban Climate in Bavaria* enabled a specific investigation of VP within the UCL at selected sites in Munich. The two downtown sites are contrasting examples for the variability of small-scale structures within cities. Although the site GSO was located within a green space at the southern outskirts, it was assumed that rural conditions were approximately represented, because the area south of GSO is characterised by large green spaces (mainly forests). A completely rural station of the German Weather Service would have been an alternative to GSO, but such a station is not available in the direct vicinity of the city of Munich.

Different magnitudes of the mass fluxes in Eq. (3) were responsible for site specific VP conditions in August 1981 and January 1982 leading, for example, to higher mean VP values at the site CDA than at both green sites. In addition, results from car traverses indicate a pronounced small-scale variation of VP at changes between sealed and green surfaces. The diurnal cycles of VP in the winter month had nearly the same form at the three sites, whereas clear distinctions could be observed in the summer month which was not addressed in earlier investigations. They refer to the amplitudes of the diurnal cycles of the mean VP values, the times of the occurrence of their extreme values as well as the increase and decrease rates $\Delta VP/\Delta t$. Compared to GSO, CDA was characterised in August 1981 by a (1) 59% lower VP amplitude, (2) temporally delayed occurrence of the extreme values of the VP double wave, (3) 70% lower increase rate of VP, and (4) 26% lower decrease rate of VP. The form of the diurnal cycle of current VP values can differ widely from the form for mean VP values, which was demonstrated for a typical summer day in Freiburg. Due to the different magnitudes of the terms of the mass balance for water vapour in the urban atmosphere (Eq. 3), the lowest VP values occurred in the early afternoon.

Nearly all investigations on the urban moisture excess (UME) conclude that the urban atmosphere is more humid than the rural at night in all months and during the day in winter and spring, while during summer days, the urban atmosphere is less humid. The magnitude of UME depends on the mass fluxes for water vapour in Eq. (3) at the reference sites, which themselves are influenced by many factors such as weather and climate conditions, pattern of urban structures or location of the measuring points for the determination of UME. In this investigation, mean monthly UME values were highest in the summer month August 1981 and ranged from 0.7 hPa (CDA–PDA) to 1.4 hPa (CDA–GSO). In January 1982, mean monthly UME values amounted to 0.1 hPa in both cases. Based on mean monthly values of VP obtained four times daily in the period 1979 to 1988 from a site in central London and an airport approximately 40 km to the south of London, Lee (1991) found clear seasonal and diurnal patterns of UME with mean monthly values (central London – airport) between 0.9 and −0.3 hPa. Unger (1999) investigated UME in Szeged, a medium-sized city in the Great Hungarian Plain, using VP data taken four times a day in the period 1978 to 1980. His mean monthly values of UME ranged from 4.3 hPa in August to 0.8 hPa in February. Unkaševic et al. (2001) used VP data obtained three times daily during the period 1976 to 1980 from one urban station, two suburban stations at the city border and one rural station near Belgrade. They reported monthly mean values of UME between 0.9 and −1.1 hPa.

Due to the many factors which influence UME, it is not surprising that results up to now for the diurnal and seasonal variations of UME are different. Henry et al. (1985) reported, that city atmospheres are usually drier than rural atmospheres during the afternoon and early evening hours, but are often more moist than rural areas at night. Unger (1999) found that the city centre is more humid than the rural area both by day and at night for the duration of the whole year. Unkaševic et al. (2001), however, observed, that the urban atmosphere is drier than the suburban and rural ones at 2 p.m. throughout the year, whereas the urban atmosphere contains more moisture compared to the suburban and rural ones at 7 a.m. and 9 p.m. from September to February. The results for the formation of UME in Munich show a mean positive UME for the whole typical summer month August 1981 and a partly mean negative UME mainly in the daytime of the typical winter month of January 1982.

On the basis of VP data from an urban site with a sky view factor (SVF) of 0.99 in the middle of Göteborg and a 9 km remote rural site with SVF = 1.0, Holmer and Eliasson (1999) investigated UME during clear and calm nights in summer 1994. They found out, that the maximum UHI preceded the maximum UME by 2 to 5 hours and the maximum UME was as high as 7 hPa during some nights. Due to lower SVF values at all three sites and in consideration of diurnal cycles of mean monthly VP values, the current study for Munich comes to a different conclusion. In the typical summer month of August 1981 (Table 6), the mean maximum UME reached 1.2 (CDA–PDA) and 2.2 hPa (CDA–GSO) and preceded the maximum UHI (21 CET) by 3 (CDA–PDA) resp. 5 hrs (CDA–GSO).

As moisture affects human comfort in a number of ways both directly and indirectly (Berglund, 1997), the influence of VP on the thermal index PET was analysed using data of a one-year human-biometeorological measurement campaign within the UCL in Munich. In mid-latitudes cities, heat stress in summer is the extreme thermal perception of city dwellers which should be minimized by suited methods of urban planning. Though mean radiant temperature is most responsible for the thermal sensation throughout the year, the effect of VP should not be underestimated, particularly in tropical cities (Adebayo, 1991). In general, a positive correlation exists between PET and VP, whereby the significance of VP is nearly in the same dimension like T_a. This correlation can be explained thermophysiologically (Berglund, 1997). In case studies within the UCL during distinct weather conditions, however, negative correlations between PET and VP are possible, because the diurnal course of VP within the UCL can strongly differ from the usual form of the diurnal VP cycle which is known from investigations over vegetation surfaces with high sky view factors and which is characterised by comparatively high VP values in the afternoon. A negative correlation between PET and VP cannot be explained using any thermophysiological background and, therefore, is to be evaluated as a specious correlation. This type of correlation indicates, for the specific case, that another meteorological parameter with a more pronounced influence on PET increases when VP becomes lower.

6. Concluding remarks

Moisture belongs to the parameters of the urban climate without a first-order importance. But there are some processes of urban climate which can be better understood, when the moisture is taken into consideration. In this study, vapour pressure VP was used as a measure for the urban air moisture. Altogether, the results show a pronounced dependence on three groups of factors which are involved in the mass balance for water vapour. The first group refers to the specific site conditions within the UCL. The second group covers the current weather and climate zone of the city under investigation. Time of day and season constitutes the third group, because they control energetic processes which are relevant for the emission or condensation of water vapour.

The tendency of the results of this study agrees quite well with the results of other comparable investigations. But to obtain results with a still higher level of accuracy, further systematic investigations on both spatial and temporal variability of the moisture are necessary. They should take into account: (1) results from both measurements and model calculations, (2) the three dimensionality of the UCL, (3) cities in different climate zones, particularly in the subtropics and tropics, (4) cities of different size and (5) regional distinctions of the pattern of urban structures. In addition, a stronger emphasis should be placed on processes and phenomena of the urban climate which are related directly or indirectly to the site-dependent moisture within the UCL.

References

Ackerman B (1987) Climatology of Chicago area urban–rural differences in humidity. J Climate Appl Meteor 26: 427–430

Adebayo YR (1991) Day-time effects of urbanization on relative humidity and vapour pressure in a tropical city. Theor Appl Climatol 43: 17–30

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol 23: 1–26

Berglund L (1997) Thermal and non-thermal effects of humidity on comfort. J Human-Environm System 1: 35–47

Brazel WS, Balling RJ (1986) Temporal analysis of long term atmospheric moisture levels in Phoenix, Arizona. J Climate Appl Meteor 25: 112–117

Bründl W, Mayer H, Baumgartner A (1986) *Urban climate in Bavaria* – final report of the partial programme "Climate measurements in Munich". Bavarian State Ministry for Regional Development and Environmental Affairs, series materials No. 43 (in German)

Chandler TJ (1967) Absolute and relative humidities in towns. Bull Amer Meteor Soc 48: 394–399

Deosthali V (2000) Impact of rapid urban growth on heat and moisture islands in Pune City, India. Atmos Environ 34: 2745–2754

Eliasson I, Upmanis H (2000) Nocturnal airflow from urban parks – implications for city ventilation. Theor Appl Climatol 66: 95–107

Fiedler F (1979) Modifikation der Luftfeuchte in einem Stadtgebiet. Promet 4'79: 12–16

Goldreich Y (1974) Observation on the urban humidity island in Johannesburg. Israel J Earth Sciences 23: 39–46

Grimmond CSB, Oke TR (1991) An evapotranspiration-interception model for urban areas. Water Resources Research 27: 1739–1755

Grimmond CSB, Oke TR (2000) Variability of evapotranspiration rates in urban areas. In: de Dear RJ, Kalma JD, Oke TR, Auliciems A (eds) Biometeorology and urban climatology at the turn of the Millenium. Selected Papers from the Conference ICB-ICUC'99, WCASP-50, WMO/TD No. 1026, pp 475–480

Hage KD (1975) Urban–rural humidity differences. J Appl Meteor 14: 1277–1283

Henry JA, Dicks SE, Marotz GA (1985) Urban and rural humidity distributions: Relationships to surface and land use. J Climatol 5: 53–62

Holmer B, Eliasson I (1999) Urban–rural vapour pressure differences and their role in the development of urban heat islands. Int J Climatol 19: 989–1009

Höppe P (1999) The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol 43: 71–75

Jauregui E, Tejeda A (1997) Urban–rural humidity contrasts in Mexico City. Int J Climatol 17: 187–196

Kawamura T (1985) Urban–rural humidity differences in Japan. Geog Rev Japan 58: 83–94

Kopec RJ (1973) Daily spatial and secular variations of atmospheric humidity in a small city. J Appl Meteor 12: 639–648

Kratzer PA (1956) The climate of cities. Braunschweig: Vieweg (in German)

Lee DO (1991) Urban–rural humidity differences in London. Int J Climatol 11: 577–582

Matzarakis A (2001) The thermal component of the urban climate. Ber Meteor Inst Univ Freiburg No. 6 (in German)

Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. Int J Biometeorol 43: 76–84

Mayer H (1987) Results from the research program STADTKLIMA BAYERN. Mitt Geogr Gesellsch München Nr 72: 119–160 (in German)

Mayer H (1988) Results from the research program 'STADTKLIMA BAYERN' for urban planning. Energy and Buildings 11: 115–121

Mayer H (1993) Urban bioclimatology. Experientia 49: 957–963

Mayer H, Höppe P (1987) Thermal comfort of man in different urban environments. Theor Appl Climatol 38: 43–49

Mayer H, Matzarakis A (1997) The urban heat island seen from the angle of human-biometeorology. Proc. Int. Symp. Monitor. Managem. Urban Heat Island, Fujisawa, pp 84–95

Richards K, Oke TR (2002) Validation and results of a scale model of dew deposition in urban environments. Int J Climatol 22: 1915–1933

Sachweh M, Koepke P (1995) Radiation fog and urban climate. Geophys Res Lett 22: 1073–1076

Spagnolo J, de Dear R (2003) A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Australia. Building and Environment 38: 721–738

Spronken-Smith RA, Oke TR (1998) The thermal regime of urban parks in two cities with different summer climates. Int J Remote Sensing 19: 2085–2104

Unger J (1999) Urban–rural air humidity differences in Szeged, Hungary. Int J Climatol 19: 1509–1515

Unkaševic M (1996) Analysis of atmospheric moisture in Belgrade, Yugoslavia. Meteorol Z NF 5: 121–124

Unkaševic M, Jovanovic O, Popovic T (2001) Urban–suburban/rural vapour pressure and relative humidity differences at fixed hours over the area of Belgrade city. Theor Appl Climatol 68: 67–73

Upmanis H, Eliasson I, Lindquist S (1998) The influence of green areas on nocturnal temperatures in a high latitude city (Göteborg, Sweden). Int J Climatol 18: 681–700

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