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Urban/rural atmospheric water vapour pressure differences and urban moisture excess in Krefeld, Germany

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Abstract:

Urban/rural humidity differences were analysed by means of a climate station pair in Krefeld (51°20′N, 6°33′E), Germany, during the period from 11/2001 to 10/2002, on the basis of hourly averages of water vapour pressure. Focus was put upon on the examination of frequency, timing and duration of the Urban Moisture Excess (UME) ($\Delta e_{u-r} > 0$ hPa). It was found that the urban site was more humid (0 hPa $< \Delta e_{u-r} \leq 0.5$ hPa; weak UME) in 31.4% of the cases investigated and was only rarely significantly more humid ($\Delta e_{u-r} > 0.5$ hPa; intense UME) in 4.6%. Weak and intense UME occur during every month of the year with different frequencies per month. A diurnal course of UME was found for summer but not for winter. Weak and intense UME events show frequency maxima in the second half of the night. Most of them are characterized by durations of 1 hour, in few cases several hours duration were observed for weak (up to 14 h) and intense UME (up to 12 h).

The main reason for formation of UME events might be that the surface dew point at the rural station was reached more often, earlier and lasted longer in comparison to the urban environment. Copyright © 2007 Royal Meteorological Society

KEY WORDS atmospheric humidity; water vapour pressure; UME; UHI; urban climate

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INTRODUCTION

In the course of an increased number of basic research studies in the field of urban climatology, a growing interest in the behaviour of humidity within the urban atmosphere can be observed. A detailed knowledge about the behaviour of humidity within the urban canopy layer is not only important in order to better quantify and understand the dynamics of the urban energy balance (e.g. Weber and Kuttler, 2005) but also for the formation of the urban heat island (UHI) (Lee, 1991), urban radiation fog (Sachweh and Koepke, 1995), as an important factor and control parameter for the human energy balance and thermal comfort (Mayer, 1993) and in the context of emission of precursor gases for the development of photochemical smog by evaporation of dew in the morning (Yaalon and Ganor, 1968; Rubio *et al*., 2002). Furthermore, knowledge of urban dew properties is important in the assessment of deposition rates of trace gases since wet surfaces result in larger deposition velocities and therefore increased absorption of gases in comparison to dry surfaces (e.g. Mulawa *et al*., 1986).

Urban areas are generally characterized by lower air humidity in comparison to the non-built surroundings (Chandler, 1967; Landsberg, 1981). However, especially during clear and calm summer nights with weak wind speeds higher urban humidity levels are temporarily observed (e.g. Ackerman, 1987). Those positive water vapour pressure differences, indicating the urban area to be moister than the rural surroundings, are defined as Urban Moisture Excess (UME) (e.g. Holmer and Eliasson, 1999) or Urban Moisture Island (UMI) (Richards, 2005). In this paper we stick to the term UME which is widely used within scientific publications on urban/rural humidity differences.

Different reasons for the development of UME are discussed in literature, however, only few authors quantified those processes they identified for UME formation. There is consensus that the following processes are directly or indirectly related to UME formation (Hage, 1975; Nunez and Oke, 1977; Shreffler, 1978; Tapper, 1990; Grimmond and Oke, 1999; Richards, 2005; Fortuniak *et al*., 2006):

- Absent, reduced or delayed dewfall in the city compared to the rural environment,
- promoted evapotranspiration in the city during night and inhibited condensation associated with the nocturnal UHI,
- premature snowmelt in cities compared to rural areas and
- anthropogenic sources of water vapour in the city (combustion, traffic, households, power plants).

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The first reason seems to be the main factor identified in UME formation. So far, UME was studied in several cities in different climate zones with an emphasis on cities in the mid-latitudes. However, analysis of the different parameters of UME is scarce (e.g. intensity, frequency, duration of UME events, diurnal and annual courses and seasonal behaviour). To contribute to the discussion we analysed humidity data that was gathered during a 1-year study period from two stations in the city of Krefeld, Germany. The aim of this study was to analyse the temporal behaviour of UME and influences by ambient meteorology.

LITERATURE

Scientific interest in studies on the spatio-temporal behaviour of urban/rural humidity differences generally started with the essential works of Chandler (1965, 1967) in London and Leicester. However, the state of air humidity in cities was already studied before (Kratzer, 1956, see earlier references summarized therein), but only in the context of cities as 'dry islands' in comparison to the moister rural atmosphere.

Studies on urban/rural air humidity differences were mainly performed in North America and Europe, but also in Middle America and Asia. Attention was put upon the detection of the UME, a term, that was apparently invented by Ackerman (1987). The authoress characterized higher urban humidity as the 'urban excess'. However, 20 years before, Chandler (1965) termed higher nocturnal urban humidity as 'humidity islands' which was confirmed by long-term data sets from other mid-latitude cities during clear and calm summer nights (e.g. Hage, 1975; Lee, 1991). In tropical-subtropical cities UME is coupled to the rain seasons (Adebayo, 1991; Jauregui and Tejeda, 1997). Table I shows an overview of cities in which studies on urban air humidity were carried out according to authors' knowledge.

UME values (hourly averages) reached 2–3 hPa on average (Fortuniak *et al.*, 2006), while occasionally 5 hPa and up to 7 hPa were measured (see Holmer and Eliasson, 1999, for a summary of different studies).

Supplementing stationary measurements an increasing number of mobile measurements were performed which allow for mapping of local-scale moisture fields within an urban area (Chandler, 1965, 1967; Kopec, 1973). Those data is complemented by near-surface mobile traverses (e.g. Richards, 2005), aircraft (Sisterson and Dirks, 1978) and helicopter (Bornstein *et al.*, 1972) or tethersondes measurements (Tapper, 1990).

However, comparison of studies suffers from different measurement periods (days, months, seasons, years) and different measured quantities (relative humidity, absolute humidity, dew point). Also differences in urban surface cover, building density, variations in measurement sites, climate zone and weather conditions complicate the comparison of data sets. Further, some of the studies rely on data that was gathered at sites (urban, rural) that were not installed for the reason of analysing humidity differences but for general use (e.g. urban climate analysis).

STUDY AREA

The city of Krefeld (51°20′N, 6°35′E, 39 m above sea level (asl), area = 140 km^2, 238 000 inhabitants) is located in the western part of the federal state of North-Rhine Westphalia near to the Dutch–German border and on the western side of the river Rhine. The conurbation 'Ruhrgebiet' is situated at a distance of 40 km to the NE of Krefeld.

Krefeld is characterized by level terrain with surface heights of 23 m asl at the edge of the river Rhine in the east of Krefeld rising to 40 m asl in the western parts of the city. Land use consists of residential areas (25%), agricultural lands and forests (44%), green spaces (11%),

Table I. Selected studies of urban-rural humidity differences in chronological order.

City	References	City	References
Lodz	Fortuniak *et al.*, 2006	Christchurch	Tapper, 1990
Vancouver	Richards, 2005	Chicago	Ackerman, 1987
Cairo	Robaa, 2003	Phoenix	Brazel and Balling, 1986
Tokyo	Yamazoe, 2003	Munich	Bründl *et al.*, 1986
Munich	Mayer *et al.*, 2003	Jap. Cities	Kawamura, 1985
Wroclaw, Sosnowiec	Brys *et al.*, 2003	Shanghai	Chow and Chang, 1984
Lodz	Charciarek, 2003	Lawrences, Kansas	Henry, 1981
Belgrade	Unkasevic *et al.*, 2001	St. Louis	Hilberg, 1978; Sisterson and Dirks, 1978
Pune, India	Deosthali, 2000	Edmonton	Hage, 1975
Vancouver	Richards	Johannesburg	Goldreich, 1974
Göteborg	Holmer and Eliasson, 1999	Chapel Hill – North Carolina	Kopec, 1973
Szeged	Unger, 1999	New York	Bornstein *et al.*, 1972
Mexico City	Jauregui and Tejeda, 1997	Chicago	Ackerman, 1971
Ibadan, Nigeria	Adebayo, 1991	Leicester	Chandler, 1967
London	Lee, 1991	London	Chandler, 1965

industry and trade areas (11%) as well as traffic (5%) and water areas (4%).

The macroclimate is characterized by mild winters with little snowfall and temperate summer temperatures (long-term values; yearly average air temperature: 10 °C; annual precipitation sum: 760 mm; Koeppen climate: *Cf* b (MURL, 1989)).

The data for analysis of urban/rural water vapour pressure differences in this study is based on a pair of climate stations which was extracted from a network of eight stations in total. Those were in operation from November 2001 to October 2002 to study the urban climate of Krefeld.

The comparability of our study period with long-term data was verified by the distribution of circulation regimes in the period 1881–1997 (Gerstengarbe and Werner, 1999). The circulation regimes are classified and published monthly by the German weather service. Comparison to the long-term data indicated that cyclonic and anticyclonic circulation regimes (59 and 41% resp.) were comparable to the long-term distribution so that the study period can be defined as covering an 'average year'.

The station pair chosen for the present analysis was best suited to characterize urban/rural microclimatic differences. While the urban station is situated in an area with a high percentage of sealed surfaces and average building height (mean building height <25 m, sky view factor (SVF) = 0.5; Blankenstein and Kuttler, 2004), the rural station is situated above an agricultural surface (SVF = 1) at a distance of 5 km to the south of the urban station. For this station pair the highest maximum urban heat island intensity on an hourly basis of all climate stations in the network was estimated with $\mathrm{UHI}_{\max} = 2.5$ K (for location see Figure 1). However, the relatively low absolute value of UHI intensity in comparison to other cities (e.g. Matzarakis, 2001) with similar number of inhabitants is attributed to a high degree of unsealed and green surfaces within the city of Krefeld ('garden city').

MATERIAL AND METHODS

During the study period air temperature (T_a) and relative humidity (rH) were measured at 2 m above ground level (agl). Air temperature was measured by Pt 100 thermometers, relative humidity by hair-hygrometers (Thies Clima, Göttingen, Germany). Both quantities were sampled every 15 s and stored to dataloggers (Thies Clima) as 3 min averages. The measurement accuracy was $T_a = \pm 0.1$ K and $\mathrm{rH} = \pm 2\%$. To analyse humidity differences between the urban and the rural station water vapour pressure (e) was calculated. Water vapour pressure was

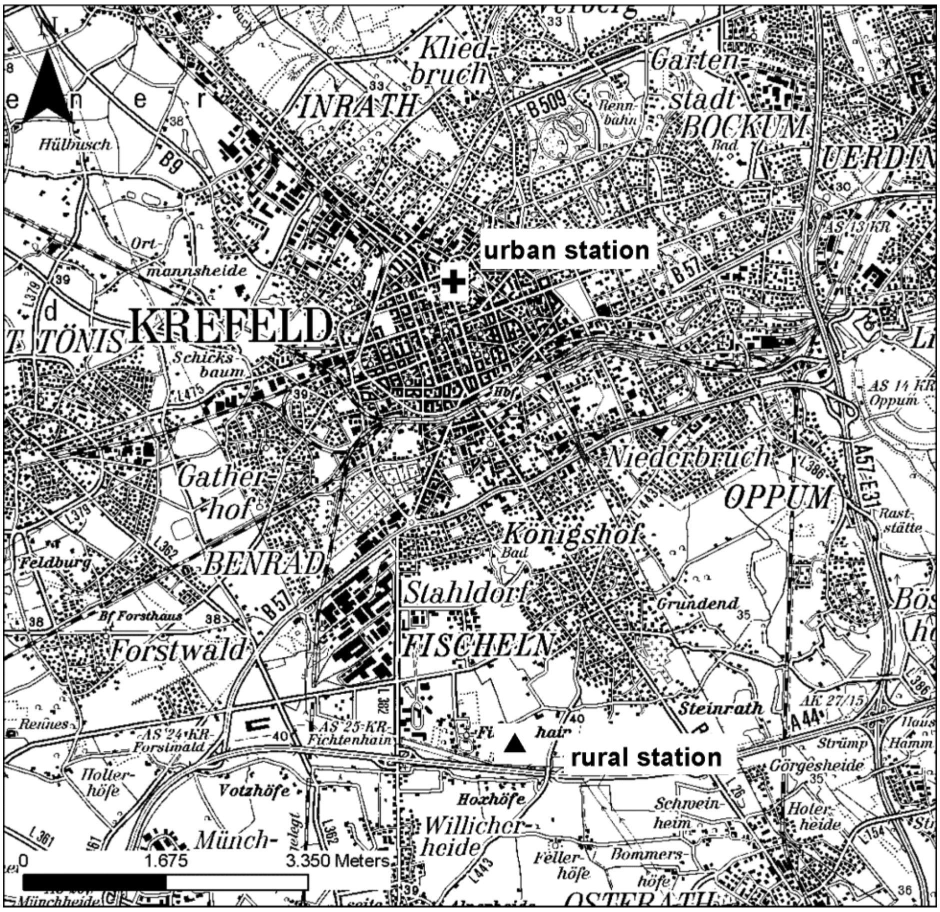

Figure 1. Overview of the city of Krefeld, Germany and the urban und rural measurement sites (Map base: Topographical map 1 : 100.000 (TK100), North–Rhine Westphalia).

used as direct humidity estimate since it shows no dependence on temperature as e.g. relative humidity. However, water vapour pressure has shortcomings, too, since air humidity differences at low temperatures become small and measurement inaccuracy increases. Both humidity/temperature sensors were intercalibrated prior to the measurement campaign. However, systematic differences between the hair-hygrometers cannot be ruled out especially in situations of a near saturated atmosphere. We checked the water vapour pressure values during time period where differences between urban and rural values can assumed to be small (windy and cyclonic conditions, winter months). Thereby a tendency of enhanced humidity values at the rural site became obvious. Expressed as water vapour pressure this resulted in a correction factor of 0.31 hPa for the rural site. The rural data was subsequently recalculated using this correction factor. The magnitude is in comparison to differences found by others (e.g. Holmer and Eliasson, 1999).

Wind direction (ϕ) and speed (u) were gathered at both sites at 4 m agl by wind vane and cup anemometers (Thies Clima) and logged as 3 min averages.

Due to storage failure some of the measured data had to be rejected. The present data set for analysis of vapour pressure differences and UME comprises 7353 hourly averages (= 84% of year hours). The 16% of non-available data is seasonally distributed to spring (0.9%), summer (4.6%), fall (7.4%) and winter (3.1%). On the diurnal course non-available data is almost equally distributed between day (7.5%) and night hours (8.5%).

Definition of UME

Besides the analysis of urban/rural water vapour pressure and vapour pressure differences emphasis will be put on the study of urban moisture excess. UME events are defined as those cases when the urban vapour pressure e_u is larger compared to the rural vapour pressure e_r, e.g. $\Delta e_{u-r} > 0$ hPa. Supplementing this definition of UME we further classify UME according to the strength of the positive vapour pressure difference between the urban and rural site. We define weak UME events when $0 \text{ hPa} < \Delta e_{u-r} \leq 0.5$ hPa and intense UME when $\Delta e_{u-r} > 0.5$ hPa. With this definition we make sure that the data quality is not limited by possible measurement inaccuracies but that the data sample for intense UME is large enough ($n = 340$) to calculate statistics.

RESULTS

This section will be divided into different parts: First, we will focus on the frequency distribution and temporal behaviour of absolute values of water vapour pressure at the urban and rural station. Afterwards urban/rural differences in water vapour pressure and their dependences on meteorological quantities will be analysed. The final part deals with the statistical analysis of UME.

Water vapour pressure at the urban/rural station pair

The mean absolute vapour pressure during the study period was $e_u = 9.9$ hPa ($\sigma = 4.0$ hPa) at the urban station and $e_r = 10.1$ hPa ($\sigma = 4.2$ hPa) at the rural station with a range of $R_u = 21.8$ hPa and $R_r = 23.1$ hPa, respectively.

In general, both the mean annual and daily courses exhibit higher values at the rural station in comparison to the urban site. On the annual course maxima are reached during the summer months (August: $e_u = 16.5$ hPa, $e_r = 17.0$ hPa) while minimum values occur during winter (December: $e_u = 6.3$ hPa, $e_r = 6.4$ hPa; Figure 2). Differences in absolute mean monthly values between both sites are smaller in winter than in summer.

On the average daily course (Figure 3) both sites show highest vapour pressures in the early morning at 9 Central European Time (CET) while lowest values are reached in the afternoon at 16–17 CET. The daily course of vapour pressure at the rural site is characterized by the well-known double wave (Geiger, 1966) with two distinct

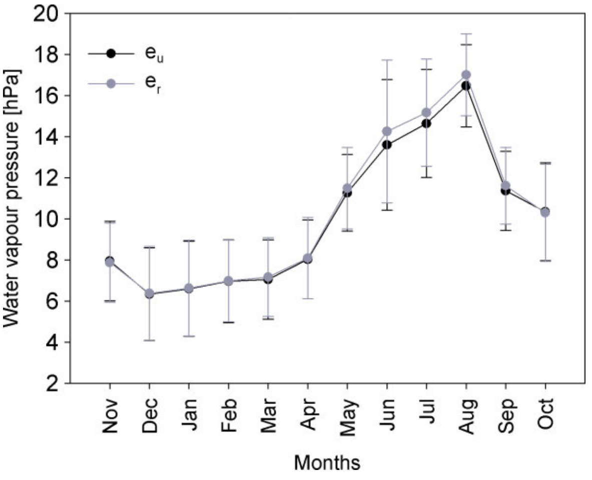

Figure 2. Annual course of urban/rural water vapour pressure in Krefeld (11/2001–10/2002, based on hourly averages). Standard deviations are indicated by vertical error bars. This figure is available in colour online at www.interscience.wiley.com/ijoc

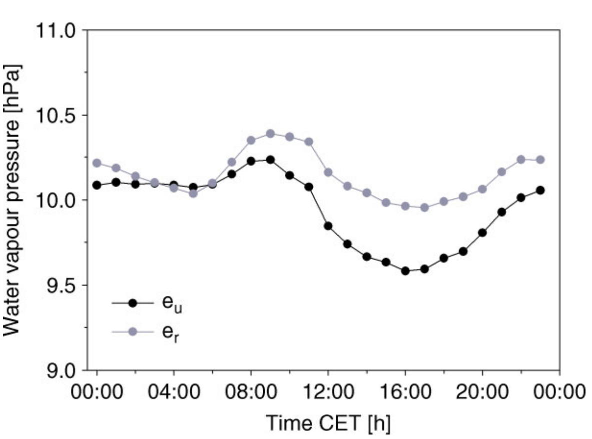

Figure 3. Daily course of urban/rural water vapour pressure in Krefeld (11/2001–10/2002, based on hourly averages). This figure is available in colour online at www.interscience.wiley.com/ijoc

peaks, the main peak during the morning period (around 9 CET), the second peak around midnight. The maximum periods are separated by minimum values of vapour pressure at around 5 and 16 CET.

At the urban site the maximum vapour pressure occurs at around 9 CET but is short-lived in comparison to the rural counterpart. It is separated by a distinct minimum at 16 CET from the increasing values in the early evening. The main difference between urban and rural vapour pressures is that urban values remain at a constant level during the second half of the night (23–5 CET) while rural values are reduced significantly resulting in a decreasing difference of urban-rural water vapour pressure difference.

Frequency analysis of urban/rural water vapour pressure differences

To analyse urban/rural differences we calculated $\Delta e_{\mathrm{u-r}}$ for the entire data set of 7353 hourly averages. As indicated in Table II a relative wide range of $\Delta e_{\mathrm{u-r}}$ occurs while the average and median values are negative. This means, that the rural canopy layer (RCL) is more humid on average, however variability is high indicated by a large standard deviation.

In winter urban/rural vapour pressure differences show only little fluctuation with maximum differences of −2.0 hPa (RCL more moist) and +1.0 hPa (UCL more moist). However, summer differences of up to −4.3 hPa and +2.9 hPa are twice as high compared to the winter period (data not shown here).

The frequency distribution of $\Delta e_{\mathrm{u-r}}$ is right-skewed and unimodal (Figure 4). Large negative and positive values are relatively seldom, whereas absolute vapour pressure values are higher at the rural site (−4.3 hPa) than at the urban site (+2.9 hPa, data not shown here).

Altogether it indicates that the UCL is less moister than the RCL. In around 64% of the cases the RCL is moister than the UCL.

To analyse differences in the daily course of $\Delta e_{\mathrm{u-r}}$ a winter (December) and summer month (August) are selected from the data set (Figure 5). During winter $\Delta e_{\mathrm{u-r}}$ differences are hardly to be seen. The summer data are characterized by a distinct diurnal course with small $\Delta e_{\mathrm{u-r}}$ values during the night-time ($\Delta e_{\mathrm{u-r}}$ approximately −0.2 hPa) but large differences during late afternoon ($\Delta e_{\mathrm{u-r}}$ approximately −1.1 hPa and enhanced σ-values). Especially during the second half of the night (0–6 CET) nearly no differences between summer and winter values can be observed. Although we measured an increase in vapour pressure difference between morning and late afternoon we have to conclude that this happens during the period where the absolute vapour pressures are low at both sites. The large negative difference between the sites is forced by the larger decrease of e_u (stronger convection) in comparison to e_r (evaporation of dew during the morning). Further on, the negative difference increases throughout the course of the day.

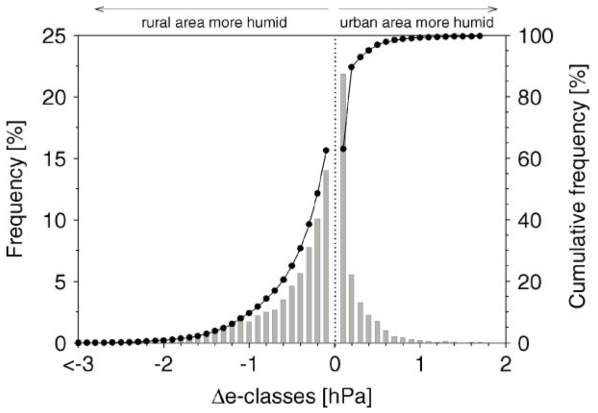

Figure 4. Frequency (grey bars) and cumulative frequency (circles) distribution of urban/rural water vapour pressure differences ($\Delta e_{\mathrm{u-r}}$) in Krefeld (11/2001–10/2002, based on hourly averages). This figure is available in colour online at www.interscience.wiley.com/ijoc

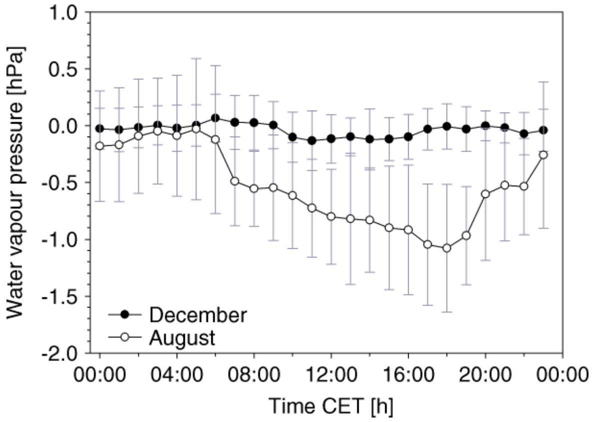

Figure 5. Daily course of $\Delta e_{\mathrm{u-r}}$ during a winter (December) and summer (August) month (11/2001–10/2002 in Krefeld, based on hourly averages for $\Delta e_{\mathrm{u-r}} > 0$ hPa). This figure is available in colour online at www.interscience.wiley.com/ijoc

Dependence of $\Delta e_{\mathrm{u-r}}$ on meteorological quantities

Wind speed and direction. A correlation analysis revealed no significant dependence of $\Delta e_{\mathrm{u-r}}$ on either wind speed or wind direction. There is some indication that

Table II. Statistical values for weak and intense UME events during the study period in Krefeld (11/2001–10/2002).

Statistics	$\Delta e_{\mathrm{u-r}}$	$\Delta e_{\mathrm{u-r}} > 0$ hPa	0 hPa $< \Delta e_{\mathrm{u-r}} \leq 0.5$ hPa	$\Delta e_{\mathrm{u-r}} > 0.5$ hPa
Frequency	7353 (100%)	2647 (36%)	2307 (31.4%)	340 (4.6%)
Mean	−0.2	0.25	0.17	0.80
Standard dev.	0.53	0.27	0.13	0.37
Median	−0.09	0.16	0.14	0.65

variability in Δe_{u-r} becomes smaller with higher wind speeds. The correlation analysis for wind direction did also indicate positive Δe_{u-r} values primarily during easterly flow at the rural site while smaller differences were attributed to northwesterly flow. Since easterly flow coincides with weaker wind speeds, conditions prevail during which the microclimate is mainly controlled by local factors resulting in urban heat island effects and higher dew point temperatures. This results in a stronger influence on the humidity field than during periods of higher wind speeds.

UHI intensity. A statistically significant relationship between urban and rural water vapour pressure differences and UHI could not be established. However, significant relationships to UHI were only observed for vapour pressure differences $\Delta e_{u-r} > 0$ hPa. This will be discussed in more detail in section 'Temporal coherence of UHI and UME'.

Urban moisture excess (UME)

The statistical analysis of UME events was performed for the following groups of data:

(i) $\Delta e_{u-r} > 0$ hPa (frequency related to population = 36.0%),
(ii) 0 hPa $< \Delta e_{u-r} \leq 0.5$ hPa (weak UME = 31.4%) and
(iii) $\Delta e_{u-r} > 0.5$ hPa (intense UME = 4.6%; Table II).

The average of all UME events ($\Delta e_{u-r} > 0$ hPa) was 0.25 hPa. If only intense UME events are considered it results in an average of 0.8 hPa.

Intense and weak UME events were analysed according to a dependency on large-scale weather conditions (Figure 6). This was done by means of large-scale circulation regimes as classified by Gerstengarbe and Werner (1999). These are based on the so-called 'Grosswetterlagen' invented by Hess and Brezowsky (1977). They used the geographical setting of predominant pressure systems and frontal zones to describe the large-scale weather conditions over central Europe.

It is evident that both UME modes are related to certain circulation regimes. Most intense UME events are attributed to the high Central Europe (HM) and ridge of high pressure, Central Europe (BM). HM is characterized by intense high pressure above central Europe that goes along with a weak pressure gradient, weak winds and during summer high values of solar radiation. BM is marked by a ridge between two high pressure systems being situated in the subtropical region and above Eastern Europe. During these situations the western parts of Europe are characterized by bright and dry conditions. Both regimes set good preconditions for the development of optimal microclimatic differences between urban and rural sites. The weak UME events are predominantly attributed to cyclonic weather conditions (e.g. WZ, NWZ) as well as to BM and HM circulation regimes.

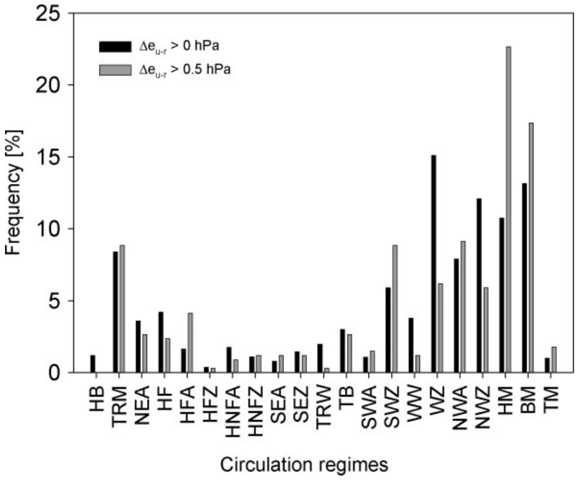

Figure 6. Correlation of UME data *versus* European 'Grosswetterlagen' as classified by Gerstengarbe and Werner (1999). **Zonal circulation patterns:** westerly type, cyclonic (WZ); angular westerly type (WW) **Mixed circulation patterns:** southwesterly type, anticyclonic (SWA); southwesterly type, cyclonic (SWZ); northwesterly type, anticyclonic (NWA); northwesterly type, cyclonic (NWZ); high, Central Europe (HM); ridge of high pressure, Central Europe (BM); low, Central Europe (TM) **Meridional circulation patterns:** high, British Islands (HB); trough, Central Europe (TRM); northeasterly type, anticyclonal (NEA); hight, Fennoscandia, anticyclonic (HFA); hight, Fennoscandia, cyclonic (HFZ); high, Arctic Ocean–Fennoscandia, anticyclonic (HNFA); high, Arctic Ocean–Fennoscandia, cyclonic (HNFZ); southeasterly type, anticyclonic (SEA); southeasterly type, cyclonic (SEZ); Low, British Islands (TB); trough, Western Europe (TRW).

Annual and diurnal course of UME

Annual course. Weak UME events (0 hPa $< \Delta e_{u-r} \leq$ 0.5 hPa) appear in every month of the year (mean frequency 8.2%, Figure 7). Fewest UME events were measured in August (3%), most in November (14%). We observed differences between the summer and winter half-year (6 and 10% resp.). Intense UME events ($\Delta e_{u-r} > 0.5$ hPa) were generally more seldom but did also occur in every month of the year with highest frequencies in November and May (15%) and lowest in February, March and December (3%).

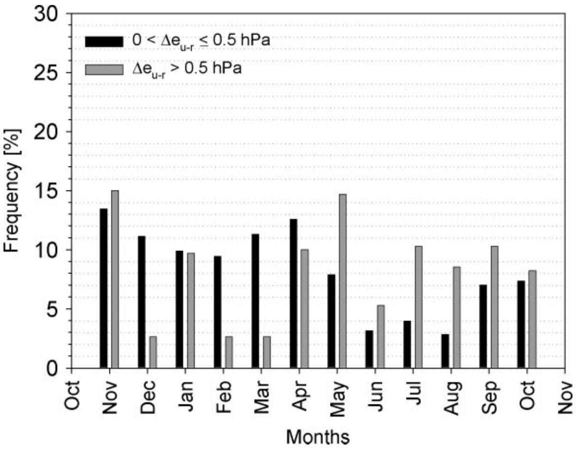

Figure 7. Frequency distribution of UME per month in Krefeld ($0 < \Delta e_{u-r} \leq 0.5$ hPa, $\Delta e_{u-r} > 0.5$ hPa) for the study period from 11/2001 to 10/2002 based on hourly averages.

Diurnal course. On the diurnal course, weak and intense UME events are prevailing during the second half of the night (33% and 51% resp.) while the frequency in both cases is less during daytime (Figure 8).

Concerning weak UME events, second most events occurred during the first half of the night (23% of all cases) and then during first half of the day (22%). 23% of intense UME events were observed during the first half of the day while 13% occurred during the first half of the night. The remaining UME were attributed to the second half of the day. Maxima of intense UME events are evident during the second half of the night between 04 and 07 CET from July to September (Figures 7 and 8).

Duration of UME events

The data set was analysed with regard to the duration (in hours) of continuous periods of weak and intense UME events (Table III). Intense and weak UME events occurred for a maximum duration of up to 12 and 14 h respectively. One-hour events occurred most frequently (41% weak UME, 50% intense UME). UME durations of 2 and 3 h were observed in 29% (weak) and 31% (intense) of the cases, respectively. The remaining data was attributed to durations between 4 and 14 h.

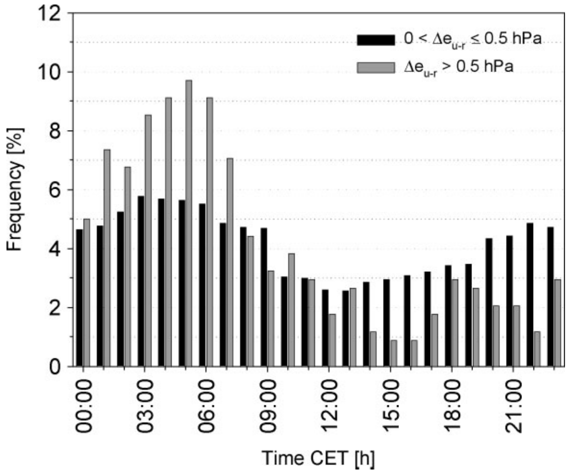

Figure 8. Diurnal course of the frequency distribution of UME in Krefeld ($0 < \Delta e_{u-r} \leq 0.5$ hPa, $\Delta e_{u-r} > 0.5$ hPa) for the study period from 11/2001 to 10/2002 based on hourly averages.

For both types of UME it is evident that not only most events took place during the second half of night but also most of the longest duration prevailed during that episode (except the maximum of 12 h).

Temporal coherence of UHI and UME

To check for temporal coherence between the occurrence of maximum UME and UHI we extracted those events from the data set where UME and UHI occurred simultaneously and contiguously for at least 5 h in the night-time (18–6 CET). With that criterion 124 nights with weak and 54 nights with intense UME were extracted from the data (Table IV).

It is shown, that in 37% (weak) and 35% (intense) of the cases UME and UHI appeared simultaneously, in 40% (44%) the UHI preceded the UME up to 7 h while during 24% (20%) of the cases the UHI lagged UME up to 4 h.

Dependency of UME on meteorological quantities

Weak and intense UME data was analysed for any correlation with wind speed, wind direction and UHI intensity. Both, intense and weak UME did not exhibit a significant correlation with wind speed or direction. However, with increasing UME some slight but statistically insignificant relationship with low wind speeds from NNE to SSE was found.

A correlation between UME and UHI intensity can be established if data is grouped (0.2 hPa classes).

Table III. Duration of UME in Krefeld based on hourly averages of $0 < \Delta e_{u-r} \leq 0.5$ hPa and $\Delta e_{u-r} > 0.5$ hPa (in brackets) during the study period 11/2001–10/2002. The determining factor for classifying the events to the different 6 h-periods of the day was the frequency of events belonging to that period.

Length of contiguous period (h)	1. Half of night 18 to 24 h	2. Half of night 1 to 6 h	1. Half of day 7 to 12 h	2. Half of day 13 to 18 h	Total
1	60 (14)	47 (25)	81 (18)	66 (5)	254 (62)
2	28 (3)	28 (10)	38 (7)	32 (2)	126 (22)
3	10 (4)	13 (8)	13 (3)	17 (1)	53 (16)
4	13	19 (4)	8 (2)	6 (2)	46 (8)
5	5	16 (2)	4 (1)	4	29 (13)
6	9	5 (3)	7	3	24 (3)
7	1 (1)	7 (3)	1	1	10 (4)
8	6	13 (3)	4 (1)	–	23 (4)
9	1	15	4	3	23 (0)
10	2	3	1	–	6 (0)
11	–	4 (1)	–	1	5 (1)
12	1	7	(1)	1	9 (1)
13	1	3	–	–	4 (0)
14	–	3	–	2	5 (0)
Total	137 (22)	183 (59)	161 (33)	136 (10)	617 (124)

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Table IV. Timing of weak (0 hPa $< \Delta e_{u-r} \leq 0.5$ hPa) and intense ($\Delta e > 0.5$ hPa) UME events in Krefeld (11/2001–10/2002). Number of intense events is given in brackets.

Timing in hours	Number		Comment
−4	2	(0)	UME precedes UHI
−3	4	(1)	
−2	8	(2)	
−1	15	(8)	
0	46	(19)	UME and UHI appear simultaneously
1	13	(7)	UHI precedes UME
2	7	(3)	
3	9	(3)	
4	6	(3)	
5	4	(2)	
6	6	(3)	
7	4	(3)	
Total	124	(54)	
Sum of events <0	29	(11)	
Sum of events = 0	46	(19)	
Sum of events >0	49	(24)	

About 2647 hourly averages were selected for which the criterion of $\Delta e_{u-r} > 0$ hPa was valid (Figure 9). It clearly shows that UME increases with increasing UHI intensity. Another interesting point is the behaviour of the range of both groups. While weak UME occur during both strong and weak UHI, the range of UHI values decreases with increasing UME. This indicates a dominating influence of UHI during intense UME events, while the influence of UHI seems to be less important during weak UME events.

Relation between UME and dew point temperatures

To analyse whether UME is dependent on rural dew point difference ($T_a - T_d$) the $\Delta e_{u-r} > 0$ hPa values were correlated to grouped rural dew point differences (Figure 10). It is evident that UME events mainly appear during nocturnal periods of saturated conditions (dew point difference 0–2 K). This group covers 51% of the data set and goes along with the highest UME values (not shown here). Therefore the dominant effect of rural dewfall in comparison to absent or delayed urban dewfall for the formation of UME is apparent. This phenomenon will again be taken up in the context of the analysis of intense UME in the following section.

Meteorological boundary conditions during intense UME

For the analysis of the influence of meteorological boundary conditions on UME only intense events were selected (Table V). Averages were calculated for each hour in the period from 0 to 23 CET. These values are not evenly distributed throughout the course of day, most UME events occur during the second half of the night (Table V, row 0, *n* values).

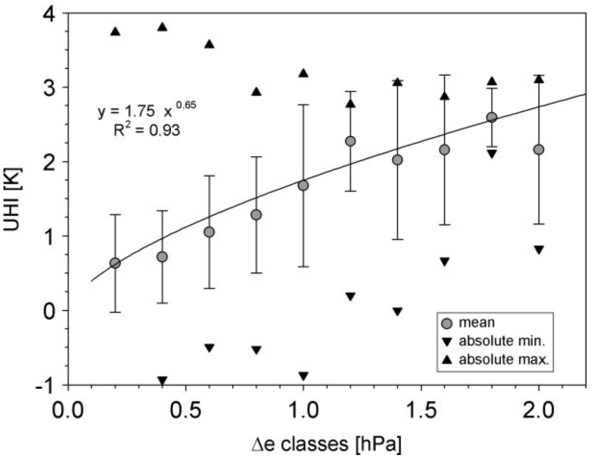

Figure 9. Relation between UME ($\Delta e_{u-r} > 0$ hPa) and UHI in Krefeld on the basis of hourly averages (11/2001–10/2002; $n = 2647$). Vertical error bars indicate the standard deviation.

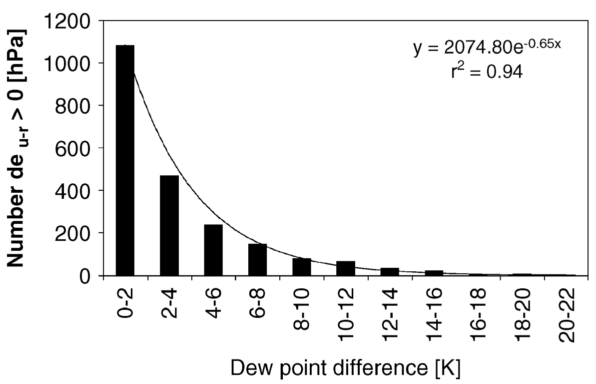

Figure 10. Dependence of UME from rural dew point differences ($T_a - T_d$, $n = 2142$) for the study period from 11/2001 to 10/2002 in Krefeld.

Table V. Mean diurnal courses for different quantities during intense UME events ($n = 340$) based on hourly averages during the study period 11/2001–10/2002 in Krefeld. (n: number of cases; T_a: air temperature in°C; rH: relative Humidity in %; T_d: dew point temperature in °C; $T_{a}–T_d$: dew point difference in K; e: water vapour pressure in hPa; Δe_{u-r}: UME in hPa).

ID	Quantity	Site	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	n		17	25	23	29	31	33	31	24	15	11	13	10	6	9	4	3	3	6	10	9	7	7	4	10
1	T_a	u	13.4	10.9	12.1	10.1	10.1	9.5	8.5	6.8	6.2	6.5	11.4	9.3	9.6	13.6	11.7	13.3	18.4	9.9	11.4	8.8	12.1	8.8	5.8	14.4
2		r	11.6	9.2	10.0	8.3	8.3	7.7	6.9	5.5	5.4	5.8	10.9	8.6	9.3	13.3	11.1	12.7	18.0	9.2	10.8	8.2	11.3	8.0	5.0	13.3
3	UHI	u − r	1.8	1.7	2.1	1.8	1.8	1.8	1.6	1.3	0.8	0.7	0.5	0.7	0.2	0.4	0.6	0.6	0.4	0.7	0.6	0.7	0.8	0.8	0.8	1.1
4	rH	u	85.1	88.8	88.8	90.0	88.4	90.6	91.4	91.3	91.6	87.2	73.8	79.1	77.6	65.3	72.1	59.3	58.5	80.4	78.4	87.3	75.9	84.3	90.9	80.0
5		r	93.1	95.3	96.5	96.3	94.2	96.6	96.4	94.7	92.4	87.5	73.5	79.8	75.9	64.3	72.9	59.1	58.0	81.1	78.0	88.5	77.0	86.2	92.8	82.9
6	T_d	u	11.1	9.3	10.5	8.8	8.5	8.2	7.4	5.7	5.0	4.4	6.4	5.3	5.3	6.2	5.9	4.1	9.7	6.4	7.5	6.7	7.2	6.0	4.5	10.9
7		r	10.6	8.7	9.7	8.0	7.6	7.4	6.6	4.9	4.2	3.8	5.7	4.7	4.6	5.5	5.3	3.4	9.2	5.8	6.8	6.3	6.7	5.6	4.0	10.4
8	$T_{d\ u-r}$	u − r	0.4	0.6	0.7	0.8	0.9	0.8	0.8	0.7	0.8	0.7	0.6	0.6	0.6	0.7	0.6	0.7	0.4	0.6	0.7	0.4	0.5	0.4	0.5	0.5
9	$T_a - T_d$	u	2.3	1.6	1.6	1.4	1.6	1.3	1.1	1.1	1.2	2.1	5.0	4.0	4.3	7.4	5.7	9.2	8.7	3.5	3.9	2.1	4.9	2.8	1.3	3.5
10		r	0.9	0.5	0.3	0.3	0.7	0.3	0.3	0.6	1.2	2.0	5.1	3.9	4.7	7.8	5.7	9.3	8.7	3.4	4.0	1.9	4.6	2.4	1.0	2.9
11	e	u	13.4	12.0	13.0	11.7	11.4	11.1	10.5	9.3	8.8	8.5	9.7	9.0	8.8	9.4	9.3	8.1	12.5	10.0	10.7	10.1	10.5	9.4	8.5	13.6
12		r	12.8	11.2	12.1	10.8	10.5	10.2	9.7	8.5	8.1	7.8	9.0	8.3	8.1	8.7	8.6	7.5	11.9	9.3	9.9	9.5	9.8	8.9	7.9	12.8
13	Δe_{u-r}	u − r	0.6	0.8	0.9	0.9	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.8	0.6	0.7	0.6	0.6	0.8

Air temperatures at the urban and rural site (*cf.* rows 1 and 2) barely show any differences during the day. During nocturnal periods, especially in the second half of the night, the air temperature at the urban station is larger by more than 1.5 K. That is the typical UHI situation which is characteristic for clear and calm nights (*cf.* row 3). Diurnal courses of relative humidity are comparable at both sites with lower values during the day (*cf.* rows 4 and 5). In particular during the second half of the night relative humidity differs by more than 5% points, whereas the urban values are lower than the rural values which are near saturation (>95%).

Looking at the urban and rural dew point temperatures (T_d, rows 6 and 7) it is evident, that the rural T_d-values are lower at each hour of the day with up to 0.8 K (row 8). The dew point differences ($T_a - T_d$, rows 9 and 10) show that only during the second half of the night saturation is evident at the rural site (row 10) while the urban station is characterized by dew point differences of >1 K (row 9). This situation is the dominating effect on UME formation as described in section 'Relation between UME and dew point temperatures'. The water vapour pressure data (rows 11 and 12) reflects the fact that the urban location is more humid especially in the second half of the night (row 13).

DISCUSSION

The analysis of urban/rural humidity differences in Krefeld, Germany, based on hourly averages in the time period 11/2001–10/2002, shows increased vapour pressure at the rural site in comparison to the urban site as is characteristic for urban/rural station pairs (e.g. Landsberg, 1981).

On the annual course not only the highest absolute values at both sites occur in summer, but also higher differences between them. On the diurnal course the rural humidity levels are higher than the urban, above that the double wave of water pressure (Geiger, 1966) at the rural site is missing in the urban data.

The mean urban/rural differences can be attributed to the facts, that there are less evaporating surfaces in the urban area due to a high degree of sealed surfaces, rapid run-off after precipitation events and little amounts of dewfall during clear and calm nights, especially in summer (Kuttler, 2006). The light building geometry, the relatively high frequency of green surface types in Krefeld ('garden city') as well as the largely absence of industry should lead to lesser urban climate effects in comparison to dense built and highly sealed cities. This might be implied by the relatively little UHI intensity of 2.5 K which is smaller than could be assumed for a city with the population of Krefeld (Matzarakis, 2001; Kuttler, 2004a,b). The results presented here might therefore be larger in cities with less green and a higher degree of sealed surfaces.

Meanwhile studies on air humidity and UME were performed in a couple of cities (Table I). The maximum

UME values in Krefeld (*cf.* Table II) correspond to the ones measured in Gothenburg, Sweden (Holmer and Eliasson, 1999), where the mean maximum UME events at comparable sites were 3.2 hPa. However, this data is based on only 34 clear and calm nights during a dry summer period in 1994. For similar nights during 'normal' summers between 1988 and 1990 mean UME maxima of only 1 hPa were measured. Larger UME maxima (up to 5 hPa) were observed in Lodz, Poland, during a 6-year campaign (Fortuniak *et al.*, 2006). In comparison to the studies in Gothenburg and Krefeld similar UME events of up to 1.8 hPa were gathered during clear and calm August nights in Leicester, UK (Chandler, 1967). Those, as well as the data from Munich, Germany (Bründl *et al.*, 1986) and Christchurch, NZ (Tapper, 1990) were based on mobile measurements (car traverses). In both cities mean maxima of around 2.5 hPa were estimated. With 0.9 hPa essentially smaller mean maxima were reported from 10-year data gathered at an urban and a rural airport (Lee, 1991). However, these values are based only on monthly averages for August and September.

Likewise based on station measurements Jauregui and Tejeda (1997) estimated maximum UME for Mexico City from an urban/rural pair with 1.25 hPa during a dry July. Mayer *et al.* (2003) observed maximum UME during August in Munich, which differed from 1.2 hPa to 2.2 hPa between sites. These results demonstrate a satisfactory comparability of literature values to the ones measured in this study despite the shortcomings in data comparability due to different methods and study periods (see discussion above).

The annual course of UME shows events occurring during all months of the year (Figure 7). The distribution of UME events on the diurnal course indicates that weak and intense events occur during each hour of the day. Both groups however are characterized by a distinct maximum during the second half of the night (>33% and 51% of the weak and intense cases respectively; Figure 8). These results are in agreement with Holmer and Eliasson (1999) in Gothenburg, where highest UME values likewise occurred 3–5 h after sunset in summer.

Analysis of the duration of UME clearly indicates that most weak and intense events prevail only temporary (1 h, 41% and 50% resp.). UME events lasting for two and three hours can be observed for 29% (weak) and 31% (intense) of the cases. The maximum of 14 h duration was measured for some weak but not for intense events (Table III). Unfortunately, comparisons from literature do not exist.

The analysis of correlation between UME ($\Delta e_{\mathrm{u-r}} > 0$ hPa) and different meteorological quantities did only show a significant correlation to UHI (Figure 9). While weak UME occurred during a wide range of UHI events, intense UME were coupled to large UHI with little range. These results correspond to findings by others (Lee, 1991; Holmer and Eliasson, 1999; Unkaševic *et al.*, 2001). Linear regression of UME and UHI indicates (e.g. Mayer *et al.*, 2003) that both variables, despite some variability, are positively correlated. This means, common meteorological causes might be important for the onset of intense UME and UHI events that are given during clear and calm summer nights with strong nocturnal cooling, temperatures below the dew point temperature and near-surface dew point inversions in the rural atmosphere (Ackerman, 1987). This is also indicated by the analysis of temporal coherence between maximum UHI and intense UME, whereby in the majority of cases (37% and 35% resp.) a simultaneous occurrence was observed (Table IV). The UHI preceded UME up to seven hours in 40% (weak) and 44% (intense) of the cases, while UHI lagged UME up to for hours during 24% (weak) and 20% (intense) of the cases. This partly corresponds to the studies conducted in Munich and Gothenburg. In Munich the mean UME maximum preceded the mean UHI maximum by 3–5 h during the months August and January (Mayer *et al.*, 2003). Holmer and Eliasson (1999) instead found that UME lagged the UHI maximum in Gothenburg by 2–5 h. They argue the UHI to be essential for the formation of UME what is comparable to most of our results.

When addressing the question which causes are relevant for the onset of UME, the analysis of intense events shows that during nocturnal periods rural dewfall starts earlier and lasts longer in comparison to the urban site (Table V). In more than 40% of the cases UME develops if the nocturnal rural dew point difference is <2 K (cf. Figure 10). While dewfall leads to a drier nocturnal rural canopy layer, strong evaporation from the rural surfaces can start after sunrise and leads to increasing humidity levels in the rural atmosphere in comparison to the urban atmosphere. Similar observations are reported by Hage (1975) and Ackerman (1987). Richards (2005) follows this interpretation but also points to continuing evapotranspiration and absent dewfall in cities.

Chandler (1967) found rare events of UME without dewfall in the rural environment. These situations were believed to be due to ongoing evapotranspiration in the city as well as to anthropogenic input of water which in the summer might be mainly related to traffic. However, the extra input of water by traffic should be negligible in influencing urban humidity as was shown by Holmer and Eliasson (1999) for Gothenburg.

CONCLUDING REMARKS

Studies on the temporal behaviour of humidity differences in the urban/rural canopy layer were conducted in Krefeld, Germany, on the basis of 1 year of hourly averages. Focus was put upon the analysis of UME. It was shown to be a phenomenon that

- is mainly coupled to clear and calm weather all around the year,
- has its maximum during the second half of the night,
- is short-lived
- occurs relatively seldom (intense UME) and
- has little intensity.

A literature survey revealed a number of studies from other cities; however, comparability is limited due to the differences in methodology. Future research should therefore aim for standardized methods to be able to compare and better understand the spatio-temporal behaviour of UME.

REFERENCES

Ackerman B. 1971. Moisture content of city and country air. *Preprints Conference on Air Pollution Meteorology*. American Meteorological Society: Raleigh, NC; 154–158.

Ackerman B. 1987. Climatology of Chicago area urban-rural differences in humidity. *Journal of Climate and Applied Meteorology* **26**: 427–430.

Adebayo YR. 1991. Day-time effects of urbanization on relative humidity and vapour pressure in a tropical city. *Theoretical and Applied Climatology* **43**: 17–30.

Blankenstein S, Kuttler W. 2004. Impact of street geometry on downward longwave radiation and air temperature in an urban environment. *Meteorologische Zeitschrift* **13**(5): 373–379.

Bornstein RD, Lorenzen A, Johnson D. 1972. Recent observations of urban effects on wind and temperatures in and around New York city. *Prepr. Conf. Urb. Environm. and Second Conf. Biomet.*. American Meteorological Society: Philadelphia, PA; 28–33.

Brazel J, Balling RC. 1986. Temporal analysis of long term atmospheric moisture levels in Phoenix, Arizona. *Journal of Climate and Applied Meteorology* **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 Material 43*; Bayrisches Staatsministerium für Landesentwicklung und Umweltfragen: Munich.

Brys T, Caputa Z, Wibig J, Brys K, Fortuniak K. 2003. Humidity gradients in urban environments on the example of Wroclaw, Sosnowiec and Lodz. In *5th International Conference on Urban Climate*, Lodz, Poland; 41–45.

Chandler TJ. 1965. *The Climate of London*. Hutchinson: London.

Chandler TJ. 1967. Absolute and relative humidities in Towns. *Bulletin of the American Meteorological Society* **48**: 394–399.

Charciarek T. 2003. Daily course of vapour pressure and relative humidity differences between urban and rural site in Lodz. In *5th International Conference on Urban Climate*, Lodz, Poland, 1; 51–54.

Chow SD, Chang C. 1984. Shanghai urban influence on humidity and precipitation distribution. *Geo-Journal* **8**(3): 201–204.

Deosthali V. 2000. Impact of rapid urban growth on heat and moisture islands in Pune City, India. *Atmospheric Environment* **34**: 2745–2754.

Fortuniak K, Klysik K, Wibig J. 2006. Urban-rural contrasts of meteorological parameters in Lodz. *Theoretical and Applied Climatology* **84**: 91–101.

Geiger R. 1966. *The Climate Near the Ground*. Harvard University Press: Cambridge, MA.

Gerstengarbe FW, Werner PC. 1999. *Katalog der Großwetterlagen Europas (1881–1997)*, 5th edn; Deutscher Wetterdienst (German Weather Service): Potsdam.

Goldreich Y. 1974. Observations on the urban humidity island in Johannesburg. *Israel Journal of Earth Sciences* **23**: 39–46.

Grimmond CSB, Oke TR. 1999. Rates of evaporation in urban areas. Impacts of Urban growth on surface and ground waters. *International Association of Hydrological Sciences Publication* **259**: 235–243.

Hage KD. 1975. Urban – rural humidity differences. *Journal of Applied Meteorology* **14**: 1277–1283.

Henry JA. 1981. Spatial and temporal distributions of atmospheric moisture in a small midwestern city. *Physical Geography* **2**: 146–159.

Hess P, Brezowsky H. 1977. *Katalog der Großwetterlagen Europas*. Deutscher Wetterdienst: Offenbach a. M.

Hilberg SD. 1978. Diurnal temperature and moisture cycles. Summary of METROMEX, Vol. 2: causes of precipitation anomalies. *Illinois State Water Survey Bulletin* **63**: 25–42.

Holmer B, Eliasson I. 1999. Urban-rural vapour pressure differences and their role in the development of urban heat islands. *International Journal of Climatology* **19**: 989–1009.

Jauregui E, Tejeda A. 1997. Urban-rural humidity contrasts in Mexico-City. *International Journal of Climatology* **17**: 187–196.

Kawamura T. 1985. Urban-rural humidity differences in Japan. *Geographical Review of Japan* **58**: 83–94.

Kopec RJ. 1973. Daily spatial and secular variations of atmospheric humidity in a small city. *Journal of Applied Meteorology* **12**: 639–648.

Kratzer PA. 1956. *The Urban Climate (Das Stadtklima, in German), Die Wissenschaft 90*; Friedri Vieweg and Sohn: Braunschweig.

Kuttler W. 2004a. Stadtklima, Teil 1: Grundzüge und Ursachen Urban Climate, Part 1: Basics and Causes (in German). *UWSF – Zeitschrift für Umweltchemie und Ökotoxikologie* **16**(3): 187–199.

Kuttler W. 2004b. Stadtklima, Teil 2: Phänomene und Wirkungen (Urban Climate, Part II: Phenomena and Impacts (in German). *UWSF – Zeitschrift für Umweltchemie und Ökotoxikologie* **16**(4): 263–274.

Kuttler W. 2006. Stadtklima. In *Witterung und Klima. Eine Einführung in die Meteorologie und Klimatologie (Weather and Climate. An introduction to Meteorology and Climatology (in German)*, 12th edn, Hupfer P, Kuttler W (eds). BG Teubner Verlag: Wiesbaden; 371–432.

Landsberg HE. 1981. *The Urban Climate*, *International Geophysical Series 28*. Academic Press: New York and London.

Lee DO. 1991. Urban-rural humidity differences in London. *International Journal of Climatology* **11**: 577–582.

Matzarakis A. 2001. Die thermische Komponente des Stadtklimas. *The Thermal Component of the Urban Climate (in German)*. Berichte des Meteorologischen Institutes der Universität Freiburg 6: Freiburg.

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

Mayer H, Matzarakis A, Iziomon MG. 2003. Spatio-temporal variability of moisture conditions within the urban canopy layer. *Theoretical and Applied Climatology* **76**: 165–179.

MURL (Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen). 1989. *Klima-Atlas von Nordrhein-Westfalen*. Düsseldorf.

Mulawa PA, Cadle SH, Lipari F, Ang CC, Vandervennet RT. 1986. Urban dew: its composition and influence on dry deposition rates. *Atmospheric Environment* **20**(7): 1389–1396.

Nunez M, Oke TR. 1977. The energy balances of an urban canyon. *Journal of Applied Meteorology* **16**: 11–19.

Richards K. 2005. Urban and rural dewfall, surface moisture, and associated canopy-level air temperature and humidity measurements for Vancouver, Canada. *Boundary-Layer Meteorology* **114**: 143–163.

Robaa SM. 2003. Urban-suburban/rural differences over Greater Cairo, Egypt. *Atmosfera* **16**(3): 157–171.

Rubio MA, Lissi E, Villena G. 2002. Nitrite in rain and dew in Santiago city, Chile. Its possible impact on the early morning start of the photochemical smog. *Atmospheric Environment* **36**: 293–299.

Sachweh M, Koepke P. 1995. Radiation fog and urban climate. *Geophysical Research Letters* **22**(9): 1073–1076.

Shreffler H. 1978. Detection of centripetal heat-island circulation from tower data in St. Louis. *Boundary-Layer Meteorology* **15**: 229–242.

Sisterson DL, Dirks RA. 1978. Structure of the daytime urban moisture field. *Atmospheric Environment* **12**: 1947–1949.

Tapper NJ. 1990. Urban influences on boundary layer temperature and humidity: results from Christchurch, New Zealand. *Atmospheric Environment* **24**: 19–27.

Unger J. 1999. Urban-rural air humidity differences in Szeged, Hungary. *International Journal of Climatology* **19**: 1509–1515.

Unkaševic M, Jovanovi O, Popovi T. 2001. Urban-suburban/rural vapour pressure and relative humidity differences at fixed hours over the area of Belgrade City. *Theoretical and Applied Climatology* **68**: 67–73.

Weber S, Kuttler W. 2005. Surface energy-balance characteristics of a heterogeneous urban ballast facet. *Climate Research* **28**: 257–266.

Yaalon DH, Ganor E. 1968. Chemical composition of dew and dry fallout in Jerusalem, Israel. *Nature* **217**: 1139–1140.

Yamazoe Y. 2003. Recent change of temperature-humidity index in Tokyo. *Preprints of 5th International Conference on Urban Climate*, Lodz, Poland; 111–114.