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Short Contribution

Analysis of the different faces of a nocturnal urban heat island

GÜNTER GROSS*

Institut für Meteorologie und Klimatologie, Universität Hannover, Germany

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Abstract

The measurements of an urban-rural observation network in Hannover obtained over almost four years were used to analyse a canopy layer urban heat island (UHI_{UCL}). Especially during the summer months, the UHI_{UCL} was pronounced on numerous nights with maximum values of more than 6 K. We have demonstrated that the choice of rural reference station is important to describe a UHI_{UCL} in detail. The time evolution of UHI_{UCL} differed greatly from night to night and four main types could be identified with comparable frequencies of occurrence. The difference between these types was the appearance of the maximum urban heat island intensity during very different times of the night. The main drivers for the development of a specific type were the rural winds and rural temperature changes caused by turbulent mixing within the near-surface inversion.

Keywords: urban climate, urban rural measurements, urban heat island types, rural wind speeds

1 Introduction

A distinct feature of larger urban areas is the urban heat island (UHI) effect which causes nocturnal near surface air temperatures to be higher inside a city than in the surrounding rural environment. Following the classification of OKE et al. (2017), the focus of interest here was a canopy layer urban heat island (UHI_{UCL}). Mainly caused by modifications in the surface energy balance (ARNFIELD, 2003; OKE et al., 2017), the urban atmosphere will be warmer than the atmosphere in the areas surrounding a city. Especially during calm and cloudless nights during the summer, a UHI_{UCL} will be well developed and urban-rural temperature differences of up to 8–10 K for larger cities will be observed (KUTTLER et al., 2015; TZAVALI et al., 2015; VAN HOVE et al., 2015; HENNINGER and WEBER, 2020).

However, the magnitude of UHI_{UCL} intensity strongly depends on the individual selection of the observation sites as well as on the statistical measures used (MARTIN-VIDE et al., 2015). All sites, urban and rural, are located in complex and unique environments and measurements will therefore be affected in a more or less specific way. Alternatively, the concept of Local Climate Zones (STEWART and OKE, 2012) can be used to identify sites with many advantages in order to obtain representative observations.

Observations for urban and rural sites provide a sufficient basis to further investigate nocturnal UHI_{UCL}. However, the UHI intensity depends strongly on the evaluation measure, e.g., the maximum temperature difference at a specific hour during the night and the nocturnal average for both land uses.

To describe a UHI properly, assumptions and conditions have to be defined. Without such detailed specifications, numerical values for UHI intensities will be difficult to compare with findings from different studies.

2 Observations

Observations from a monitoring system of the German Meteorological Service (DWD) in the Hannover area were used to study the UHI_{UCL} (DWD, 2022). The locations of the stations are given in Fig. 1. The temperature (T) at a 2 m height and wind (U) at a 2.5 m height were recorded at the Weidendamm (WD) urban station which is now used as a routine urban climate station of the DWD. Weidendamm is a compact midrise area with only few trees, mostly paved and bricks and concrete are used as construction material of the surrounding buildings. In addition, observations were available from the Kattenbrookpark (K) rural station (T at 2 m, U at 2.5 m) in the south of Hannover as well as the synoptic weather station at Hannover airport (T at 2 m, U at 10 m) to the north. Both areas are characterized by natural grassland with only few bushes and trees. The distance of these rural stations to WD was approximately 8 km. All data used in this study are 10-minute mean values for the period from June 2017 to November 2020.

The annual and diurnal variations of the urban-rural difference (WD-K) of air temperature are presented in Fig. 2. For the whole period, the UHI_{UCL} was well developed especially during the summer months but restricted to the night-time hours. During daytime, however, the temperature differences were smaller than 1 K or even negative, with values of up to 6 K observed during the night. This picture of the Hannover UHI_{UCL} is very consistent with other observations (KUTTLER et al., 2015; ZHOU et al., 2013).

*Corresponding author: Günter Gross, Institut für Meteorologie und Klimatologie, Universität Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany, e-mail: gross@muk.uni-hannover.de

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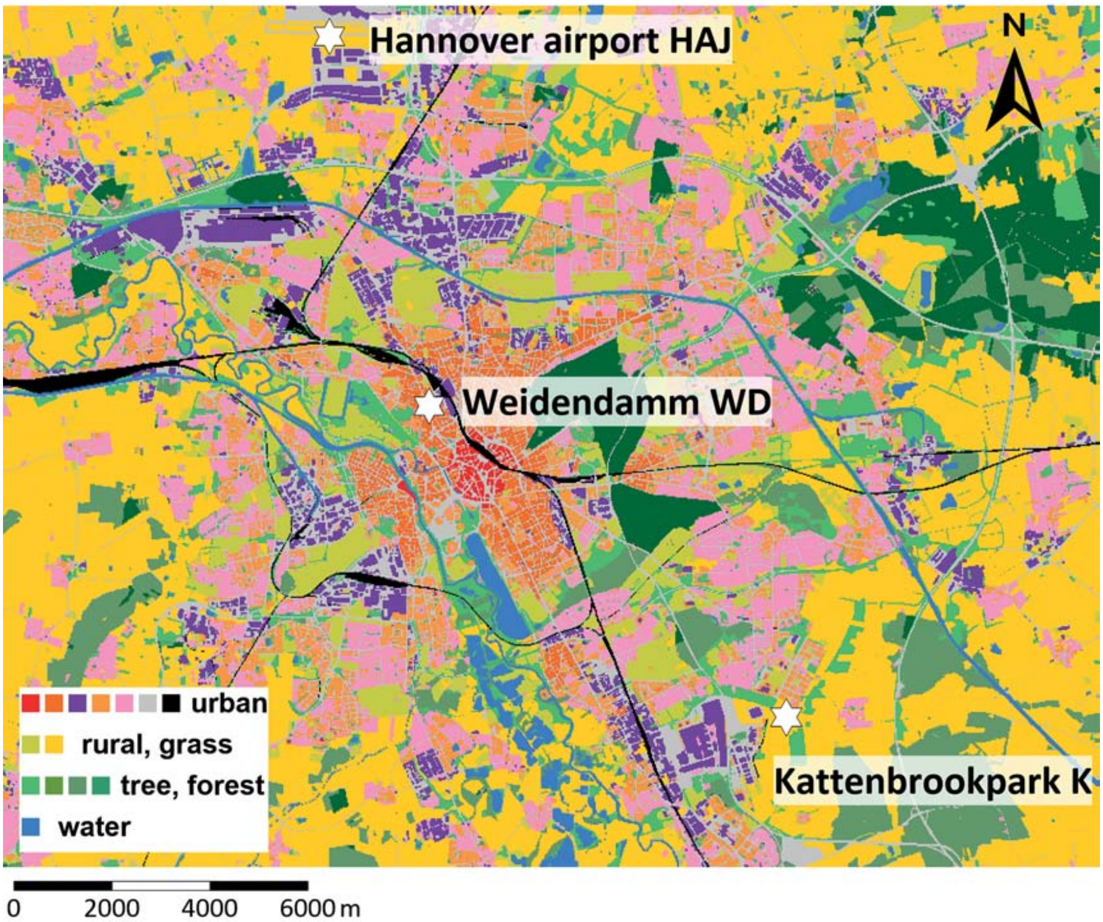

Figure 1: Land use in the Hannover area and locations of the observation stations.

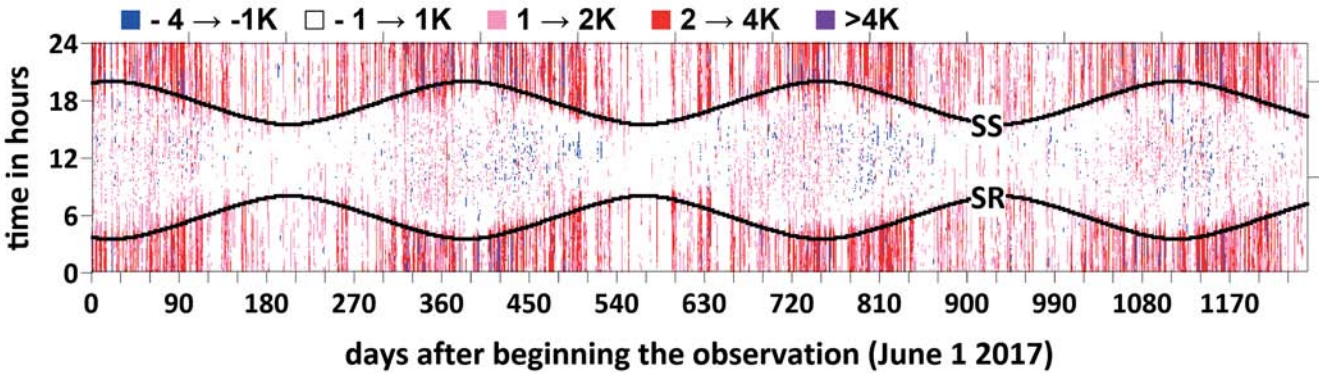

Figure 2: Annual and diurnal variations of urban-rural differences in temperature (WD-K). The solid lines indicate hours of sunrise (SR) and sunset (SS). Data base: 10 min-mean values.

3 Analysis of the UHI_{UCL}

As a representative example, the temperatures and UHI_{UCL} for a four-day period are shown in Fig. 3. A nearly unhindered solar insolation (Q_S) caused large diurnal temperature amplitudes with an increased day-by-day warming. While the urban and rural temperatures were very similar around noon, evening and nighttime cooling in the surrounding rural areas were much stronger than in the city resulting in a pronounced UHI_{UCL} effect. However, the observations of the two rural reference stations K and HAJ showed that the temperature contrast with the urban station WD was quite significant. Maximum values for UHI_{UCL} as well as the time evolution were comparable only to a limited extent.

The UHI_{UCL} intensity was estimated from the 10-min mean values as the maximum temperature difference at any time during the night as well as for the difference of the urban and rural temperature means, calculated from sunset to sunrise. A comparison of the results using the two different rural stations is provided in Fig. 4 and shows the relatively large scatter for both measures with

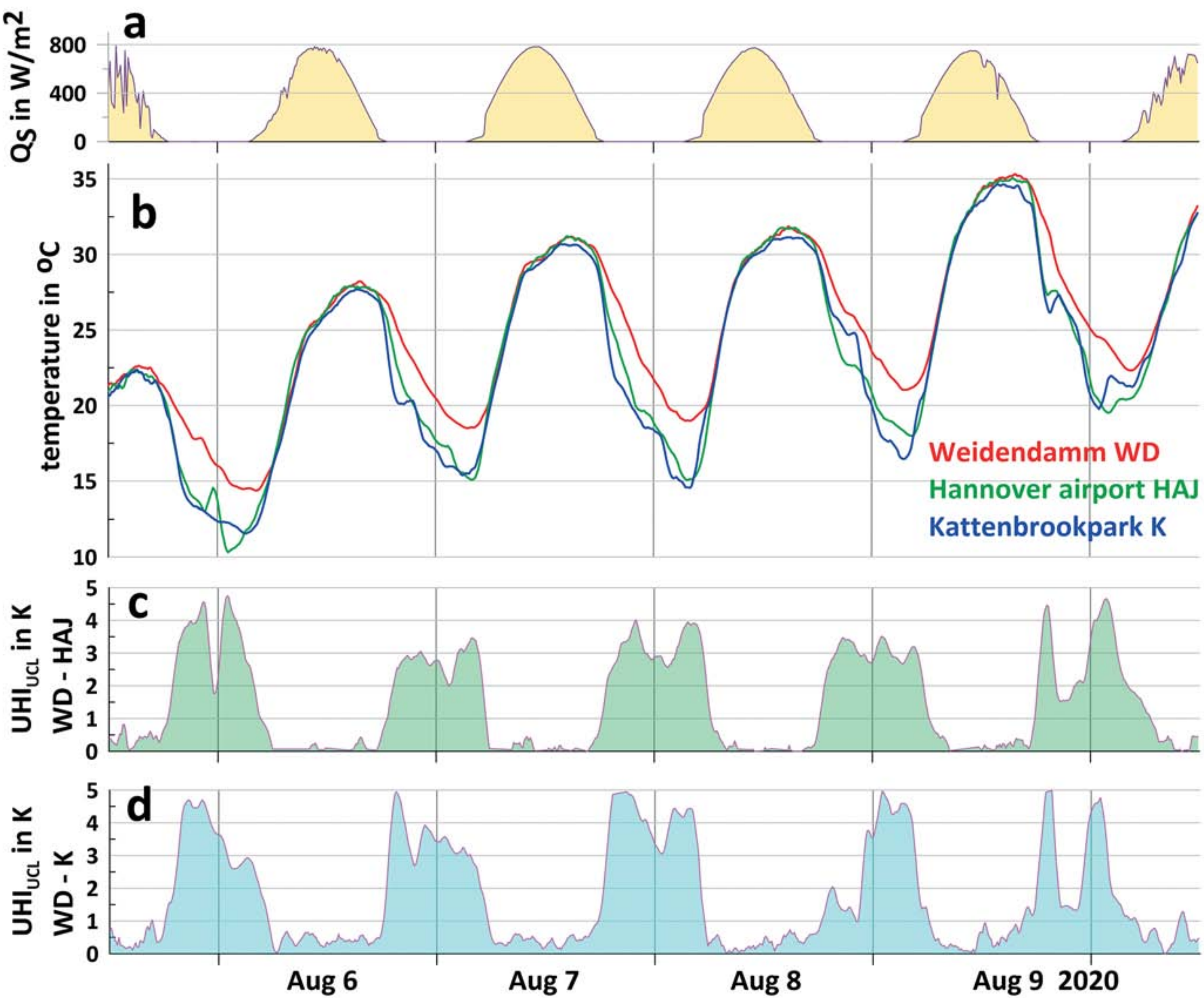

Figure 3: Observations for a selected four-day period at the urban and the rural sites, a. solar radiation Q_S, b. temperature at a 2-m height, c. UHI$_{UCL}$ WD-HAJ, d. UHI$_{UCL}$ WD-K. Data base: 10 min-mean values.

a correlation coefficient of $r = 0,76$ for $\max(T_{urb} - T_{rur})$. Although the UHI$_{UCL}$intensities were very different on individual nights according to the observations of the two rural references, a statistical analysis for the whole period yielded a remarkably similar picture (Table 1). Especially for the maximum UHI during the night, the exceedance of different threshold values was nearly the same. In the period from June 2017 to November 2020, covering a total of 1280 nights, the UHI$_{UCL}$ intensity was larger than 2 K on around 600 nights and larger than 5 K on over 60 nights. Using the measure based on the temperature means ($\bar{T}_{urb} - \bar{T}_{rur}$), the exceedances of specific thresholds were smaller and the match of both statistics was poorer.

The UHI$_{UCL}$is a night-time phenomenon which is caused by different near surface cooling rates. After sunset (SS), rural cooling is much greater than in urban areas, resulting in the rapid development of strong temperature contrasts. For an idealized situation, the peak of the UHI$_{UCL}$ would occur close to midnight (MN) and

Table 1: Frequency (in number of days) of UHI$_{UCL}$ magnitudes using different rural reference stations and different analysis methods, WD = Weidendamm, K = Kattenbrookpark, HAJ = synoptic station Hannover airport (period 6/2017–11/2020).

	UHI$_{UCL}$ (WD-K)		UHI$_{UCL}$ (WD-HAJ)	
	$\max(T_{urb} - T_{rur})$	$\bar{T}_{urb} - \bar{T}_{rur}$	$\max(T_{urb} - T_{rur})$	$\bar{T}_{urb} - \bar{T}_{rur}$
> 1 K	893	566	951	588
> 2 K	584	249	620	313
> 3 K	384	79	410	107
> 4 K	215	14	200	10
> 5 K	61	1	62	
> 6 K	11		4	

be followed by a sharp decrease until sunrise (SR) (Oke et al., 2017; Stewart et al., 2021; Núnez-Peiro et al., 2021). However, an analysis of the available observations indicate that this idealized picture was not the standard case. Indeed, the time series for temperature for a

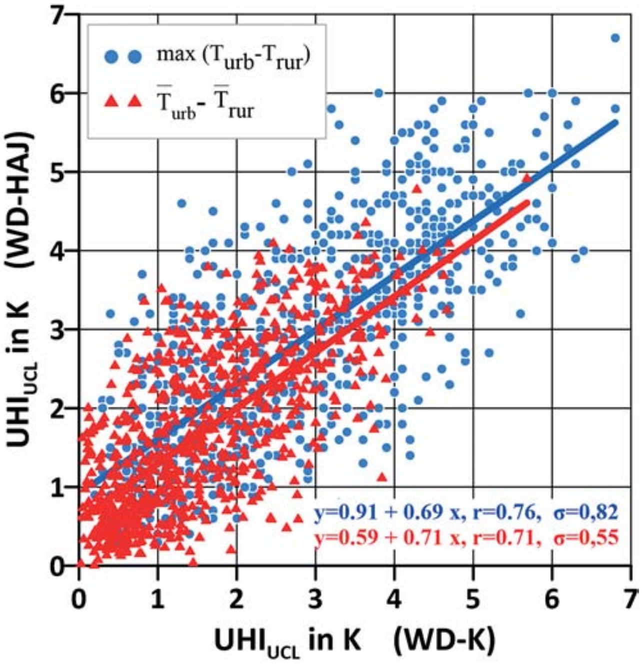

Figure 4: Comparison of a canopy layer urban heat island (UHI_{UCL}) calculated with 10 min mean temperatures from different rural stations for two different measures. Statistics are included at the bottom.

calm and cloudless weather situation depicted in Fig. 3 revealed a very different scenario. The time behaviour of the urban-rural temperature difference during the night, hereinafter referred to as UHI_{UCL}, was dominated by significant peaks and local minima.

According to the evaluation of the UHI_{UCL} for the complete period of 1280 nights from the 10-min mean values for temperature, four basic UHI types could be identified which are shown in Fig. 5 together with real world examples.

- Type 1 is characterized by a strong UHI_{UCL} during the first half of the night followed by a continuous decrease until SR the next day.
- For type 2, the situation is reversed with a weak UHI_{UCL} in the first half of the night followed by an increase and a maximum before SR.
- Pronounced double peak during each half of the night are typical of a Type 3 UHI_{UCL}.
- The time evolution of a Type 4 UHI_{UCL} follows the idealized concept with a strong increase around SS, a maximum around midnight, and a decrease around SR.

Several of these types of UHI_{UCL} are shown in Fig. 3. However, this figure clearly illustrates that the intensity of a UHI_{UCL}, as well as its type, will depend on the specific choice of observations made at the rural reference station.

The type of UHI was determined for the 600 nights with $UHI_{UCL} > 2$ K. For a Type 3 UHI, the minimum

Table 2: Frequency in % of the different UHI_{UCL} types for the period from June 2017 to November 2020.

	UHI_{UCL} (WD-K) > 2 K	UHI_{UCL} (WD-HAJ) > 2 K
Type 1	20.5	11.3
Type 2	18.8	19.8
Type 3	29.7	31.3
Type 4	31.0	37.6

had to be at least half of this threshold (= 1 K) lower than the values of the two maxima before and after midnight. A mean nocturnal evolution was calculated for each type in order to define the overall picture. However, since the time from SS to SR was different for all days, time was normalized according to the length of the night. In Fig. 6, sunset was normalized at time 0, SR at 1.0, and midnight at 0.5. The magnitude of the heat island was also normalized with the maximum of the UHI_{UCL} value for the individual nights. A clear distinction between the four types could be made. While Type 1 and 2 are very close to the idealized structure given in Fig. 5, this is less apparent for Type 3 although for individual nights, the minimum characterizing this type is very well developed (see Fig. 3). However, the time of occurrence of this minimum is broadly distributed over the night time hours and by averaging the nocturnal evolution of the UHI_{UCL} the idealized picture from Fig. 5 is smoothed. Considering all nights without a type differentiation (= mean in Fig. 6), this curve remarkably followed that of the idealized situation as described by Oke et al. (2017). The frequency of occurrence was 20–30 % for all four types and no type was particularly predominant (Table 2). The observations used in this study show that the idealized picture of the night-time UHI_{UCL} was the result of a superposition of very different UHI types.

In a high-pressure system with calm winds and a cloudless sky, the nocturnal UHI_{UCL} was well pronounced, and the time evolution followed the "Oke 2017" or "mean" curve presented in Fig. 6. However, as a dominant factor for UHI_{UCL} intensity, the winds disturbed this picture even for small changes in wind speed. The strong influence of rural winds on UHI_{UCL}, which follows approximately an inverse square root function, could be confirmed by analysing the available observations at the rural station K (Fig. 7). However, the use of the wind data obtained at the urban station for such an investigation demonstrated that the development of a well pronounced UHI_{UCL} was independent of wind speeds up to 2 m/s but with a sharp decrease for wind speeds larger than 2 m/s. It was demonstrated by Gross (2019) that especially during well developed UHI situations the inner city wind speed is higher than the rural one. This is caused by an increased downward flux of momentum from air flow passing over the city in a warmer urban atmosphere of reduced thermal stability.

The UHI_{UCL} intensity was calculated as an urban-rural temperature difference. Night-time rural temper-

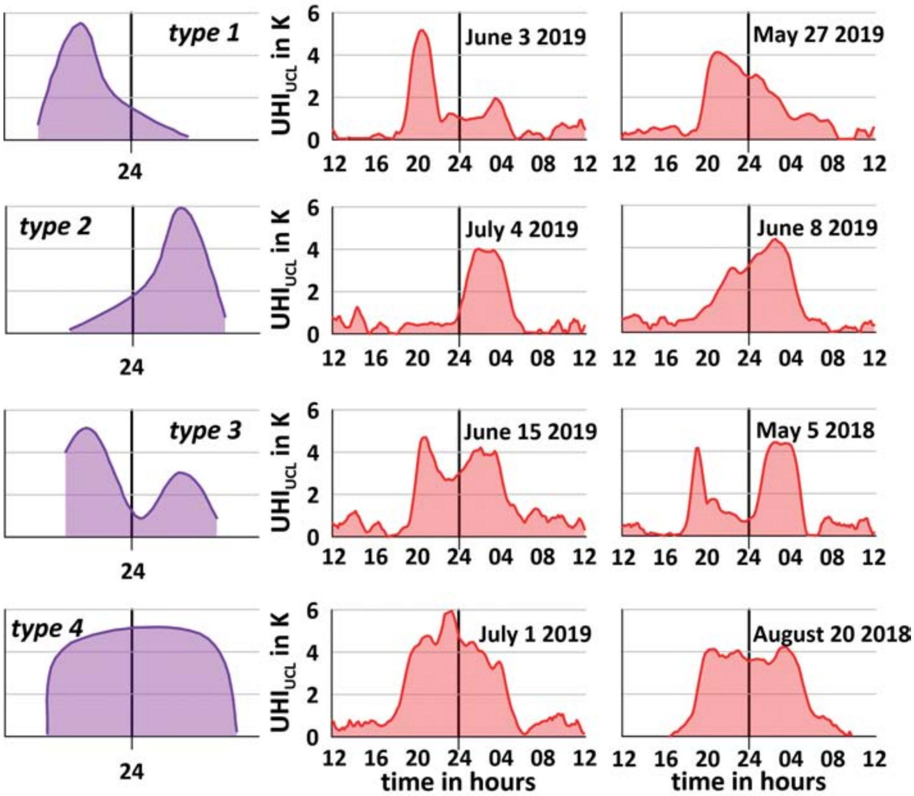

Figure 5: Schematic view of different canopy layer urban heat island (UHI_{UCL}) types (left) and observations as examples (right).

atures depend strongly on surface winds and small changes may result in noticeable temperature effects. The causes and reasons for small wind changes may include the development of weak nocturnal circulations which can be notoriously variable in space and time. The strong correlation between rural winds and temperatures is presented in Fig. 8. A temporary increase of the rural airflow resulted in a nocturnal temperature increase with a significant impact on the UHI_{UCL}(times marked by double arrows). On the other hand, a similar modification of the urban wind speed would likely have had almost no effect at all on the urban temperatures. Changes in wind speeds are generally associated with a modification of turbulence and enhanced turbulent mixing would link the near surface situation with the atmosphere above. At the rural site with a nocturnal inversion, relatively warm air will be transported from above while the night-time temperatures in the UCL inside a city will already be well mixed (Gross, 2019).

According to this knowledge one can conclude that the UHI_{UCL} intensity and UHI_{UCL} type will be primarily determined by the time evolution of rural temperatures. This finding underlines that the proper choice of rural reference station is of great importance.

4 Conclusions

Observations of an urban-rural monitoring system in Hannover, operated by the DWD, were used to study a UHI. The UHI_{UCL}, defined as the temperature difference between an urban and a rural site, is a very common feature in Hannover which occurs on numerous cloudless nights of the year especially during the summer months and for weak wind conditions. In general, urban temperatures were higher than in the rural surroundings and the magnitude of the UHI_{UCL} was controlled by the specific arrangement and characteristics of the adjacent buildings. For a given urban temperature, the UHI_{UCL} intensity would depend on a comparative value observed at a rural reference site. It was found that for individual nights, the maximum UHI temperatures differed by up to 3–4 K from those recorded at various locations in the countryside.

The general trend of the evolution of a nocturnal UHI_{UCL} was defined by a strong increase of the temperature contrast after SS, a maximum around midnight, followed by a decrease until SR. Although this pattern could be noted in the observations for specific nights, it was an exception rather than the rule. An analysis of the night-time temperatures of the nearly four-year period clearly showed the existence of four main types of UHI_{UCL}, each with a frequency of occurrence of 20–30 %. Besides the types of UHI described in this study, situations with a distinct maximum either before or after midnight or a double peak with a pronounced minimum in between could also be observed.

Night-time temperatures in urban areas are generally higher than in their rural surroundings due to modified energy exchange processes. At the same time, thermal

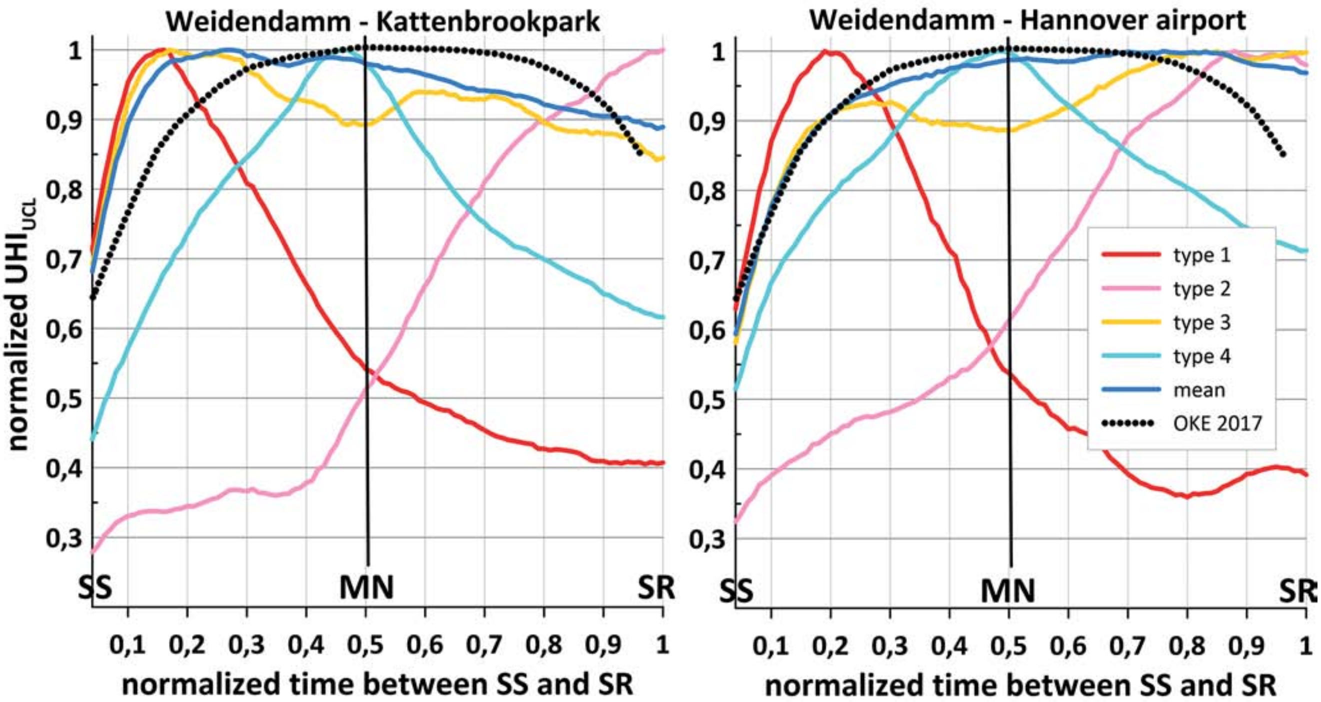

Figure 6: Normalized nocturnal evolution of canopy layer urban heat island (UHI$_{UCL}$) types for the difference in rural-urban air temperatures (WD-K) (left) and WD-HAJ (right). The dotted line represents the idealized expectation according to Oke et al. (2017).

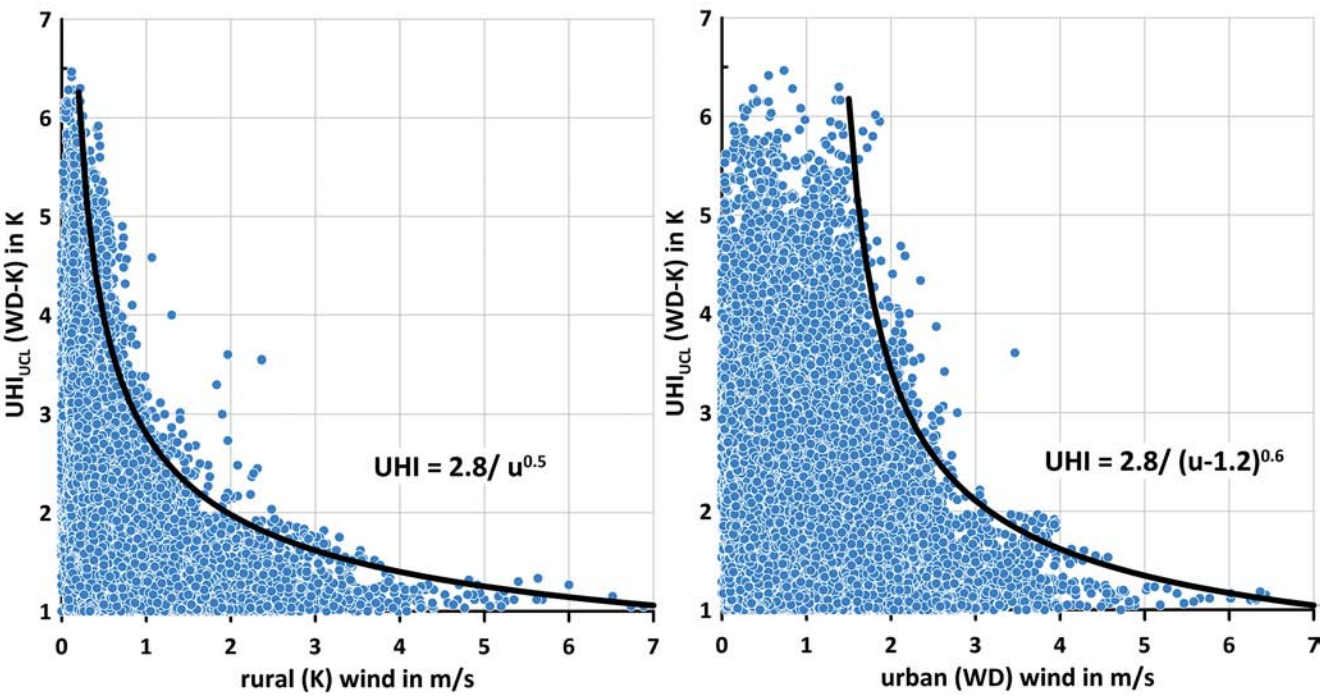

Figure 7: Scatter diagram of urban heat islands (WD-K) and wind speeds at the rural site (left) and the urban site (right). Data base: night time 10 min-mean values for UHI$_{UCL}$ > 1 K. Black curves are the approximated boundary lines of the data points.

stratification in cities is less stable and urban air is well mixed vertically. The type of UHI$_{UCL}$ as well as its intensity would depend on the nocturnal wind situation especially at the rural sites. Even small modifications of the air flow may cause enhanced turbulence and a transport of warm air from above the inversion layer. While the temperatures were seen to decrease continuously during the night at the urban site, the time evolution of rural temperatures was characterized by short-term changes which finally determined the UHI$_{UCL}$ type.

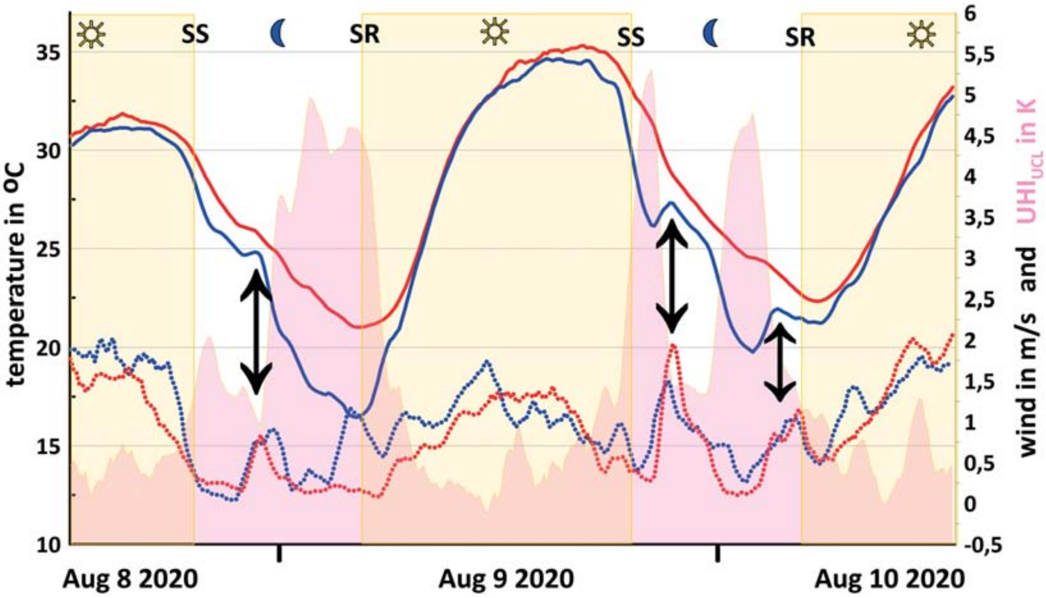

Figure 8: Diurnal variations of winds and temperatures at the rural site K (blue) and the urban site WD (red) and UHI_{UCL} WD-K (pink).

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