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Short Contribution

On the self-ventilation of an urban heat island

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Abstract

Measurements of a new German Meteorological Service urban observation network in Hannover were used to analyse the urban heat island (UHI) and the dynamics of urban wind. The UHI was well pronounced on many nights of the year and had a maximum intensity during the observation period of more than 6 K. A strong correlation between the UHI intensity and wind speed difference between the urban and the rural station was found. During the night, wind speed inside the city was significantly higher than in the surrounding rural area for an increasing air temperature contrast. This effect was attributed to the weaker thermal stability inside the city when there was a well-developed heat island, which enhanced the turbulent momentum flux from above.

Keywords: urban rural measurements, urban heat island, urban wind speed

1 Introduction

Meteorological variables like air temperature, wind, and air composition are modified in a characteristic way in urban areas. The resulting urban heat island (UHI) and air pollution adversely affect the quality of life and comfort of city dwellers. An effective measure to improve the urban thermal environment and air quality is enhanced ventilation, which leads to a reduction of diurnal air temperature extremes and effective dispersion of pollutants. Physical mechanisms to bring wind into the city include superimposed synoptic flow, orographically induced wind systems in hilly terrain (MVI, 2012), the thermally induced country breeze (Kuttler et al., 1998), and intra-city currents caused by air temperature differences of different land use areas. Several planning and design measures can be that allow wind penetration into built-up areas. Potential strategies range from reducing ground coverage and the frontage area of buildings to increase the permeability, to a sustainable urban planning in order to preserve and create effective breezeways and air paths from rural surroundings deeper into the city (Hidalgo et al., 2008; Wong et al., 2012; You et al., 2017).

Besides urban field experiments (e.g., Scherer et al., 2019), long-term measurements are necessary to assemble the basic knowledge and gain insights into the complex interactions between urban areas and the surrounding countryside. The German Meteorological Service (DWD) is focusing on this topic (DWD, 2018) by operating a number of paired stations in up to 10 larger German cities. In this study, observations from this monitoring system are used to analyse the well-developed UHI of Hannover, and in particular, the related differences in wind speed between the urban and the rural station an aspect, that has previously attracted little attention.

2 Urban monitoring system

The new DWD monitoring system contains three additional sites in Hannover and is supplemented by long-term observations at the synoptic weather stations at the Hannover airport and the Hannover university (IMuK, 2018). However, long-term records are not representative of an urban area and the new site inside the city opens a completely new perspective on the urban climate of Hannover. Instruments are arranged on a small mast to measure air temperature, relative humidity, and global radiation at 2 m height, while wind speed is observed at 2.5 m height. All data are processed and stored as mean values for a 10-minute period.

The rural station is located to the southeast of Hannover in the vicinity of the fairground within a park with short grass. This wider area is dominated by open agricultural land that is occasionally interspersed by bushes and low trees. The urban station is located at the northern edge of the city centre inside a built-up area with a high degree of sealing and ground coverage. The site is surrounded to the south by multistorey apartment blocks while an industrial area extends to the north. Only some green spots with individual trees interrupt the overall urban appearance.

The observations of an 18-month period from June 2017 to November 2018 are available for further investigations.

3 Observations and results

Especially during night and under calm synoptic wind conditions air temperature in urban areas are significantly higher than in surrounding rural areas. This phenomenon is known as the urban heat island (UHI) and

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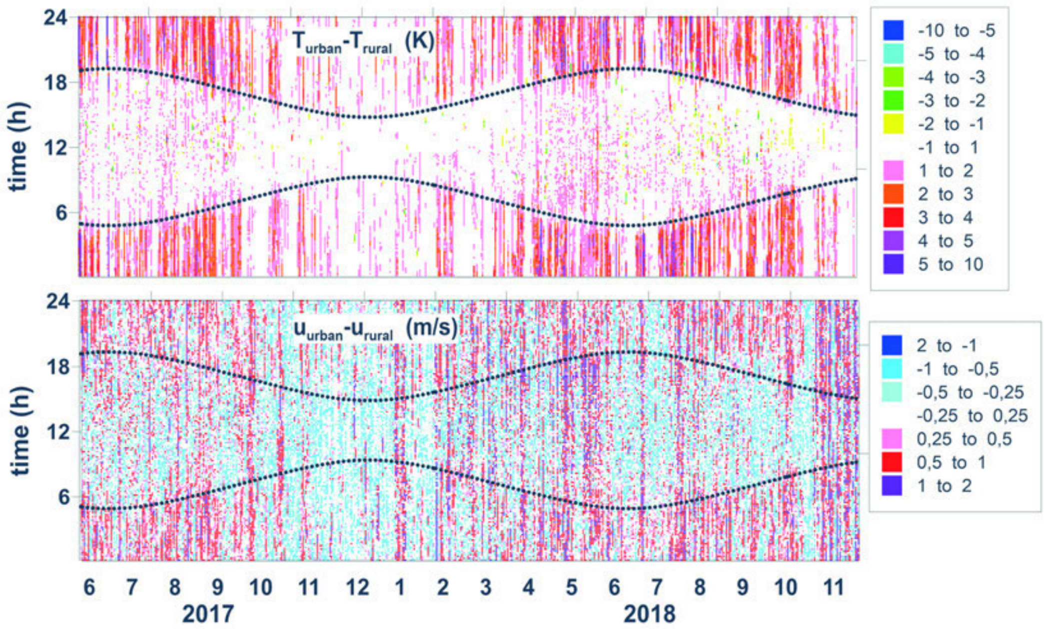

Figure 1: Annual and diurnal variations of urban-rural differences of air temperature (above) and wind speed (below). Dotted lines indicate sunrise + 1 hour and sunset – 1 hour.

has been observed in many settlements around the world (Kuttler et al., 2015; Zhou et al., 2013). To quantify the UHI, the air temperature difference ΔT_a between the urban and the rural observations are used as a measure. Although ΔT_a depends on a multitude of parameters, such as e.g. city size and population density or climate and weather conditions, nearly all observations show very similar features with the most pronounced UHI detected during the summer season and night-time hours.

In this respect, the DWD urban climate observations in Hannover present a very consistent picture (Fig. 1). The largest air temperature differences are observed during the summer months and strongest UHI-intensities with ΔT_a of more than up to 5 K are restricted to the nighttime hours. During the day, air temperature in the rural area and in the city are nearly the same. Although wind observations inside a built-up area are strongly affected by the surrounding morphology and representative measurements are difficult to obtain, wind speed differences between the urban and rural site (Δu) show a very similar pattern and structure to ΔT_a. Especially in the summer season, urban wind speed appear consistently higher during night and lower during the day relative to rural observations (Fig. 1).

The strong correlation between diurnal cycles of wind speed and air temperature are exemplarily illustrated in Fig. 2 for a 5-day period in August 2018. During this fine weather period with strong incoming solar radiation, a well pronounced UHI was observed over several consecutive nights that were followed by daytime hours with no significant air temperature differences. In parallel, observed wind speeds show the typical diurnal pattern (Fajber et al., 2014) with higher near surface wind speed during unstable daytime conditions and much lower values during night in a more stably stratified atmosphere. However, especially during periods with strong UHI conditions on specific nights, nocturnal urban winds were conspicuously higher than rural wind. This pattern was also observed at other locations (Kuttler et al., 2015).

The strong correlation between UHI intensity and urban–rural wind speed differences was found in the complete set of 10-minute means over the 18-month period. Air temperature difference could be large (up to 7 K) when rural winds were weak, but these conditions were nearly always associated with higher wind speed inside the urban area (Fig. 3). When wind speeds were stronger in the countryside, the UHI effect was significantly lower, and rural wind speed, in general, was much higher than in the city.

A statistical evaluation of wind speed and air temperature during different UHI intensities demonstrates the general pattern of higher nocturnal wind speed inside the city. Maximum air temperature differences during the nighttime hours of each day were used as a classification for calculating mean diurnal profiles of wind speed and air temperature. For 340 of the total 547 day period, an UHI intensity in excess of 2 K was observed. Simultaneously, nocturnal urban wind speed was 0.2 m s^{-1} higher than in the surrounding rural area during these situations. During 34 nights, the UHI was larger than 5 K and was associated with a mean urban wind speed in excess of 0.4 m s^{-1} (Fig. 4). Especially for the extreme UHI situations with UHI greater than 6 K, inner city nighttime wind speed at 2.5 m height was up to 1 m s^{-1} higher than the rural observation (Fig. 5). The highest values of Δu occured in the late afternoon hours before sunset and

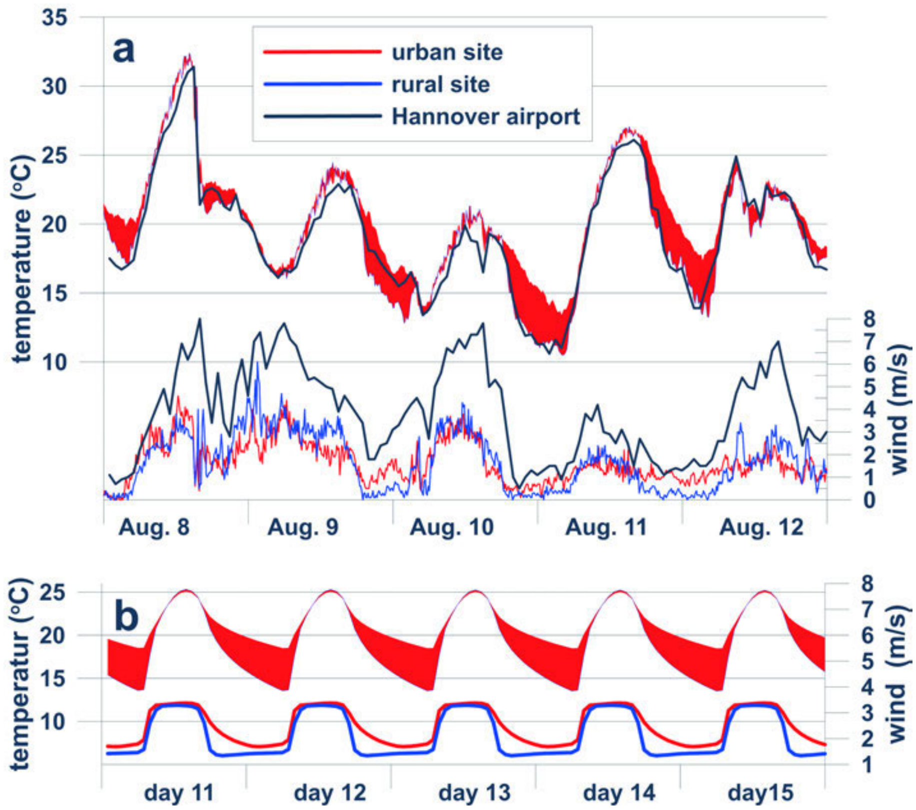

Figure 2: a. Observations of wind speed and air temperature for a selected 5-day period at the new urban and the rural site. Black line indicates DWD observations of 2 m temperature and 10 m wind speed at Hannover airport.
b. Simulated diurnal variation of wind speed and temperature at 2 m height with input parameter for an urban and a rural location.

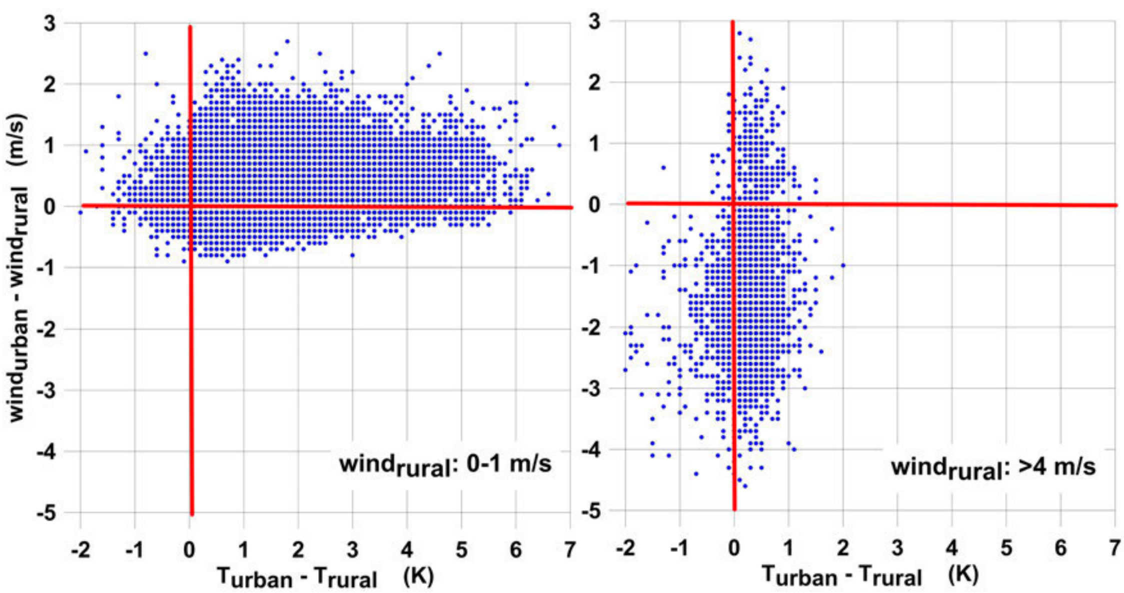

Figure 3: Observed urban-rural wind speed difference for different UHI intensities for weak (left) and for high (right) larger-scale rural wind conditions.

were followed by lower, but relatively constant, values during the night.

To explain the greater Δu observed under strong UHI conditions, a one-dimensional planetary boundary layer model was used (Gross, 2012a, b) to simulate diurnal variation for an idealized urban and rural situation. The simple model consists of prognostic equations for horizontal wind components, temperature, humidity and turbulence kinetic energy. Temperature at the ground is calculated by a surface energy budget. Using different values for roughness length z_o ($z_o^{\mathrm{urban}} = 0.05\,\mathrm{m}$ and $z_o^{\mathrm{rural}} = 0.01\,\mathrm{m}$), thermal conductivity of the soil λ

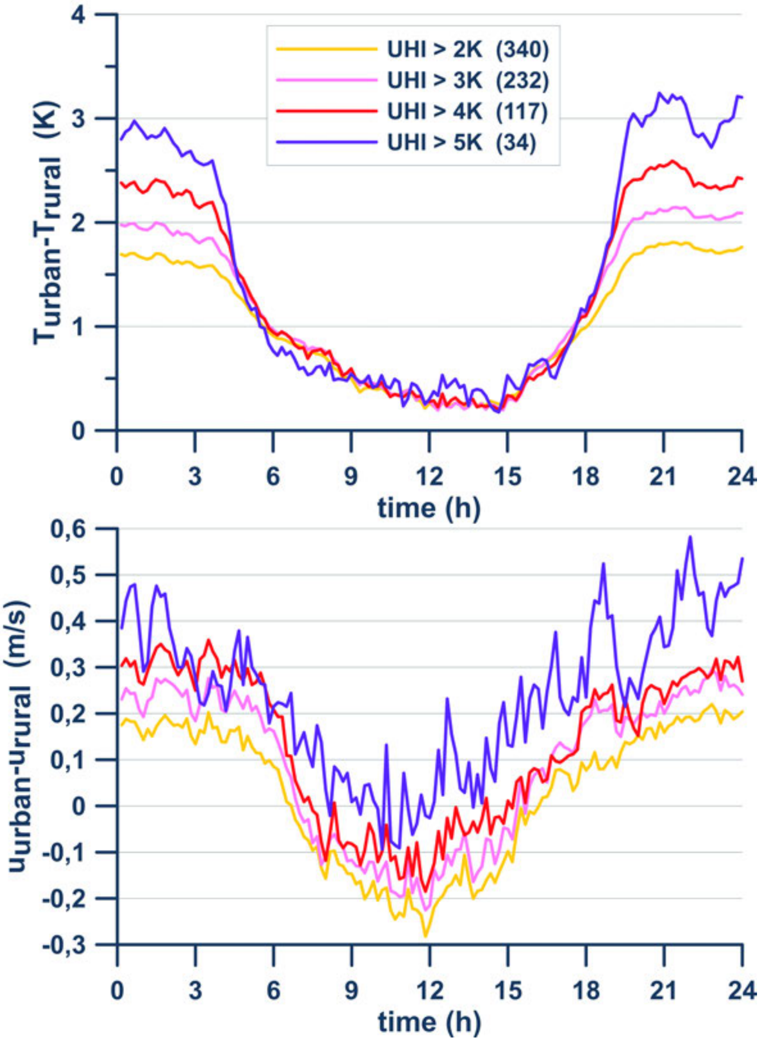

Figure 4: Diurnal variation of mean urban-rural differences for air temperature (above) and wind speed (below) for different maximum UHI intensities (number of days are given in the legend).

($\lambda^{\text{urban}} = 1.6\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$ and $\lambda^{\text{rural}} = 0.8\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$), and albedo a ($a^{\text{urban}} = 0.15$ and $a^{\text{rural}} = 0.20$), a 15 day simulation with constant forcing was carried out in order to obtain a nearly periodic diurnal cycle. With the specified set of parameters, a maximum nighttime 2 m-temperature difference around 5 K was simulated and the diurnal variation was comparable to the observed UHI intensities (Fig. 2b). More interesting here was the variation of the simulated 2 m urban wind speed, which was greater than the rural value during nighttime and exhibited maximum difference in the late afternoon. These urban–rural differences, ΔT_a and Δu, were included in Fig. 5 and the general features match reasonably well to the exemplarily selected observations for UHI intensities in excess of 6 K. Based on the results of the numerical simulation, the mechanism explaining why observed wind speed in the urban area was larger during the nocturnal period than in the rural surrounding becomes clear. As assumed and formulated by Bornstein and Johnson (1977), thermal stratification in the afternoon hours and during the entire night is less stable inside the city, which causes enhanced turbulent momentum transport from above where slightly higher wind speed are present (10 m-wind speed at Hannover airport are also shown in Fig. 2). Using turbulence kinetic energy as a measure for turbulent mixing, higher values emerged for the urban simulation during the entire night and a pronounced maximum difference before sunset.

4 Conclusions

Observations of an urban–rural monitoring system in Hannover, operated by the German Meteorological Service, were used to study the urban heat island and the resulting differences in wind speed. The UHI was a very common feature in Hannover where it occurred on many nights of the year, especially those during the summer months and when prevailing wind conditions were weak. When rural wind speed were higher, that is, more than $4\,\text{m}\,\text{s}^{-1}$ at 2.5 m height, the UHI effect almost totally disappeared. However, on more than 25 % of the nights of the period considered here, the UHI was very

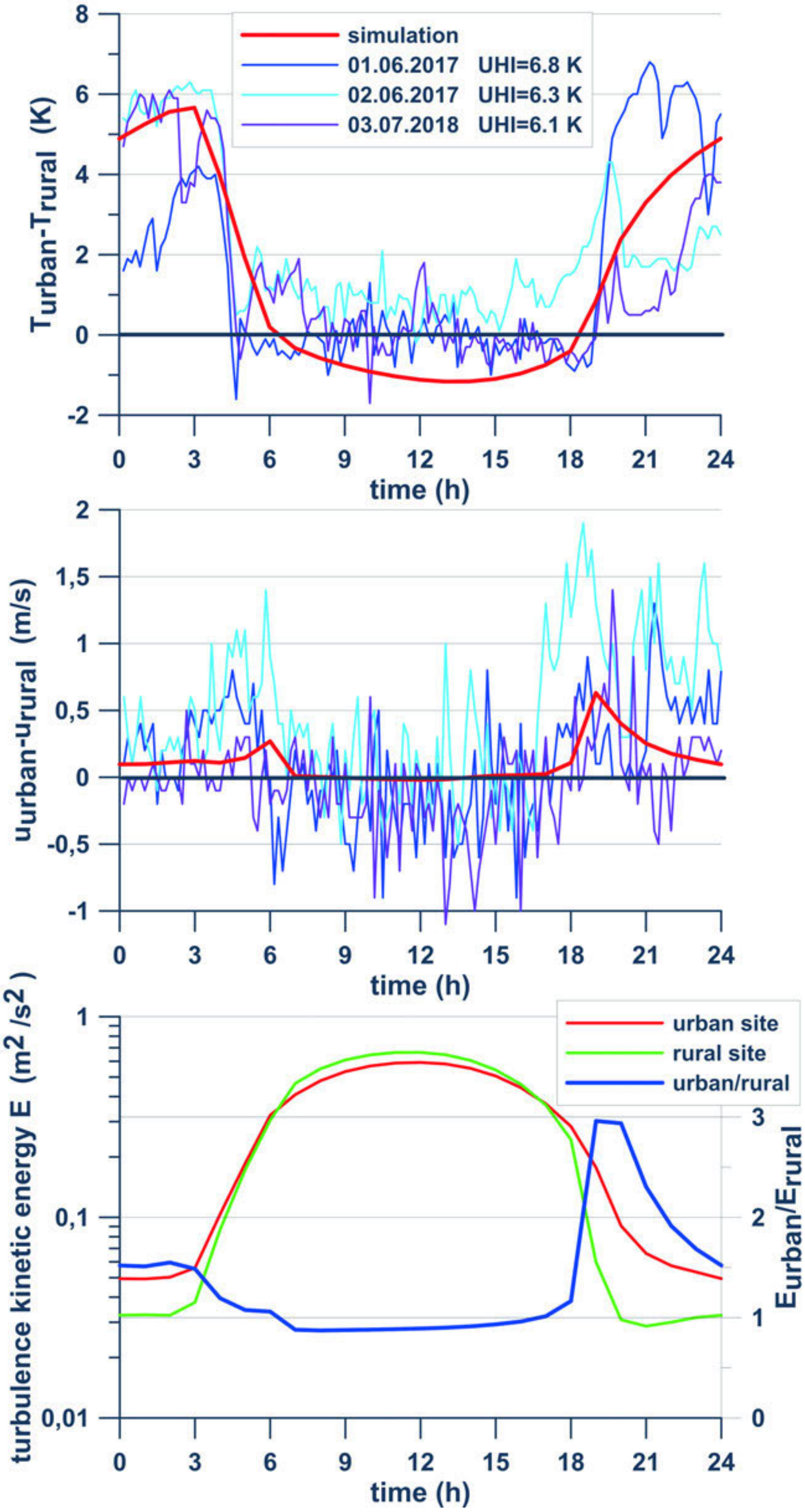

Figure 5: Diurnal variation of urban-rural difference for air temperature (above) and wind speed (middle) for UHI intensities >6 K. Red lines indicate model results. Simulated turbulence kinetic energy with input parameter for an urban and a rural location (below).

pronounced with ΔT_a larger than 4 K. Since such a large surplus in air temperature is unfavourable for a sufficient human physical recovery, different opportunities to reduce those impacts require further analyses. The most promising approach to reduce UHI is to bring wind into the city, for example, by planning breezeways or by opening spaces for country breezes.

Further, observations from the urban and the rural sites in Hannover clearly demonstrate an additional mechanism for ventilation that is triggered by the UHI itself. Reduced thermal stability in the warmer urban atmosphere during night causes an increased downward flux of momentum from airflow passing over the city that enhances intra-city near surface wind speed. This additional ventilation effect is most pronounced when there was stronger UHI and when wind speed difference with the rural site was in the order of 0.5–1 m s^{-1}.

Up to now, a standardized recommendation about location and requirements of urban meteorological sites does not exist. Therefore it should be mentioned here, that the magnitude of UHI and wind speed difference between the urban and the rural site given in the text depend on the specific site conditions.

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