Abstract

From September 2006 to September 2007 the inter-site variability of turbulence characteristics and turbulent heat fluxes was analysed at two urban stations in Essen, Germany. One site was installed within an urban residential setting while the other was located at the border of an urban park and suburban/urban residential housing. Therefore the surroundings at both sites contributing to surface-atmosphere exchange differed in terms of surface cover and surface morphology.

The structure of turbulent flow turned out to be rather comparable at both sites, e.g. only 6 % difference on average in momentum flux between sites occurred. Turbulence characteristics, i.e. normalised standard deviations of wind components, were in agreement to empirical fits from other urban observations. Small deviations in inter-site comparison were attributed to differences in roughness and surface cover around the sites. During the one-year measurement period 20 % of data was characterised by stable atmospheric stratification. Generally, observations of urban turbulence characteristics in stable stratification are scarce so far.

Comparison of turbulent heat fluxes indicated typical urban features in the site located in the urban setting with increased surface heating and higher surface heat fluxes by about 30 %. Also the temporal evolution of heat fluxes on the diurnal course was affected.

Key words: turbulence, urban surface, stability

1. INTRODUCTION

The turbulent atmosphere-surface exchange in urban areas is significantly modified from the non-built surrounding (Oke 1988; Roth 2000). This is due to the degree of urban complexity, e.g. various artificial and natural surface covers, large number of roughness elements and emission of anthropogenic heat and pollutants. Those parameters significantly affect urban microclimates and the dispersion of pollutants in the urban boundary and canopy layers (Weber et al. 2006; Weber and Weber 2008).

At present, more than 50 % of the world’s population live in urban agglomerations with more than 70 % to be reached in the course of the 21st century. To better manage air and environmental quality in cities, an increased understanding of the exchange of heat, mass and momentum between the atmosphere and the urban surface is necessary.

The motivation of this study is to compare conditions of atmospheric stability, turbulence characteristics and turbulent fluxes of heat and momentum from two measuring sites within one city.

2. STUDY AREA

A one-year turbulence data set was collected at two sites in Essen, Germany, in the time period from September 15, 2006 to September 15, 2007. Essen (585 000 inhabitants) is situated in the western part of Germany and covers a surface area of about 210 km².

The first site was installed in an urban surrounding (URB) in the northern part of the city. A sonic anemometer was placed on a building at a height of z = 35 m above ground level (agl) attached to a circular 10 m mast erected at roof top. The building itself has a height of 25 m agl and is one of the largest in this area. The flat surrounding comprises of residential buildings of 3 to 5 floors. By means of aerial laser scan measurements a mean building height of about \( z_H = 17 \) m was estimated for this area of the city.

The second site (SUP) was installed in the south-western part of Essen at the border of an urban park south-west of the station and suburban/urban residential areas to the north and east with buildings of 2 to 4 floors. The horizontal distance to URB is about 5.5 km. A solid concrete tower - basically a visitor attraction and observation tower of the park - hosted the measurements. From a platform at a height of 26 m agl a horizontal boom hosting the sonic was extending about 3.5 m from the tower to the south-east facing approximately 150°. The urban park located in the south-west of the measurement site covers a surface area of about 70 ha. The terrain negligibly slopes by about 10 m to the south-west, however, generally the site can be characterised as flat.

3. MATERIAL AND METHODS

3.1 Instrumentation

Both sites were equipped with sonic anemometer-thermometers (USA-1, Metek, Germany) sampling horizontal and vertical wind vectors \( u, v, w \) and acoustic temperature (\( T_s \)) at a rate of 10 Hz. Five min block averages of \( u, v, w, T_s \) and covariances were calculated from raw data for subsequent analysis. The 5 min block averages were
subjected to tests for implausible data, afterwards 30 min averages were aggregated. For flux, calculation data were rotated into streamwise coordinates by a double rotation procedure according to Kaimal and Finnigan (1994).

Due to interference and flow distortion by the tower at SUP, data from a direction sector $260^\circ < \text{dir} < 360^\circ$ was rejected from data analysis.

To study effects of atmospheric stratification, the surface layer stability parameter $z/L = (z-d)/L$, with $d$ the displacement height in m and $L$ the Obukhov length in m, was calculated. Displacement height was assumed as $d = 0.66 z_0$ (e.g. Grimmond and Oke 1999). With the estimated displacement height the aerodynamic roughness length, $z_0$ was evaluated anemometrically from measured data using the log-law of the vertical wind profile. Data in the range $-0.05 < z/L < 0.05$ was defined as neutral atmospheric stratification.

3.2 Surface characteristics around the measurement sites
To support interpretation of turbulent fluxes and turbulence characteristics from both measurement sites, differences in surface characteristics and surface morphology around both stations were assessed.

On average, the fraction of surface cover is not significantly different, plan area density at URB and SUP is about the same order. Main differences are found in the percentages of open/non-built spaces and park areas. The percentage of unsealed, vegetated surface at SUP with about 30 % is roughly twice the amount in comparison to URB. However, when focusing on certain wind direction sectors, significant differences become evident. The south-west-sector at SUP is mainly influenced by the urban park. The south-west is characterised by a park fraction of 58 % (14 % buildings) at SUP and a 50 % building fraction (13 % parks) at URB. With a relative frequency of 59 % at SUP (48 % at URB) the SW also turned out to be the main wind direction sector during the study period.

4. RESULTS AND DISCUSSION

4.1 Atmospheric stability
Conditions of atmospheric stability have important implications for the dispersion of atmospheric pollutants. Similar to observations at other urban sites (e.g. Grimmond and Oke 2000; Christen 2005), the maximum of the frequency distribution of stability at both sites lies within the neutral range with about 47 % of data at URB and 60 % at SUP (data not shown here). The higher fraction of unstable situations at URB = 33 % (SUP = 20 %) is due to enhanced surface heating of artificial surface and roof materials in the vicinity of URB. This fact also becomes apparent in the average diurnal course of $z/L$ indicating stronger instability at URB during daytime (Fig. 1). Note that for characterisation of diurnal courses of $z/L$ the median value is plotted. Especially due to small nocturnal values of thermal ($T'$) and mechanical ($u^*$) turbulence the resulting Obukhov length becomes large and biases the arithmetic mean of $z/L$ (e.g. Mahrt et al. 1998). The median value therefore is a more robust estimate.

The majority of situations, about 80 % at both sites, characterises non-stable atmospheric stratifications, i.e. $z/L < 0.05$. However, with the remaining $\approx 20 \%$ of data a significant amount of stable stratification was measured. The diurnal course of $z/L$ for the one-year study period indicates nocturnal periods at both sites to be characterised by neutral situations mainly. However, a distinct fraction of data lies beyond the neutral stability criteria indicating stable situations at both sites starting from around 2100 Central European time (CET). The surface has sufficiently cooled by that time so that a change of sign in turbulent heat fluxes results in small but negative (downward) heat fluxes at night.
4.2 Turbulence characteristics

To describe and compare the structure of turbulence above different surfaces a number of observations on turbulence characteristics have been published during recent years. Turbulence characteristics or normalised standard deviations of velocity are defined by the ratio of the standard deviations of wind vectors divided by friction velocity \( u^* \). Within the framework of the Monin Obukhov similarity theory (MOS) surface layer turbulence characteristics were shown to be a function of atmospheric stability (e.g. Kaimal and Finnigan 1994). However, due to the limited number of urban observations under stable stratification the behaviour in these situations is still under debate.

Turbulence characteristics for both measurement sites in Essen have been calculated for different atmospheric stratification (Fig. 2). In the unstable range, data follows empirical fits to urban data well and shows the general increase with increasing instability (Roth 2000). Generally, slight departure from the Roth (2000) data under neutral to slight unstable stratification, i.e. \( z/L > -0.4 \), is visible. However, normalised standard deviations of velocity have been observed to vary in magnitude with observational site (Zhang et al. 2001). With stronger instability, data is very much in agreement with the reference data. There is a tendency for larger ratios in urban areas in comparison to flat and homogeneous terrain (e.g. Al-Jiboori et al. 2001).

**Fig. 2:** Means of turbulence characteristics \( \sigma_i/u^* \) (i = u, v, w) vs. stability binned into 0.05-z/L classes for unstable (–z/L, left panel) and stable (z/L, right panel) atmospheric stratification. Error bars indicate standard deviation. For reasons of clarity of the plots only positive or negative standard deviations are indicated. Empirical fits are based on the data from URB and on literature data from Panofsky et al. (1977), Roth (2000) and Al-Jiboori et al. (2002).

In the stable range (z/L > 0) observations from homogeneous terrain reported the standard deviation to be relatively constant with increasing z/L (e.g. Al-Jiboori et al. 2002). While a rather constant behaviour of \( \sigma_w/u^* \) is observable at URB the SUP ratio shows a slight increase with increasing stability.

4.3 Turbulent heat fluxes

The diurnal courses of heat and momentum fluxes at URB and SUP are relatively similar in their temporal evolution but they differ in magnitude (not shown here). With a maximum yearly average heat flux at noon of 0.085 K m s\(^{-1}\) at URB \( (Q_H = 102 \text{ W m}^{-2}) \) it is about 0.03 K m s\(^{-1}\) \( (= 36 \text{ W m}^{-2}) \) higher in comparison to SUP. Based on one-year data of heat fluxes, URB is characterised by 30 % higher fluxes. The larger kinematic heat fluxes are driven by stronger absorption of shortwave downward solar radiation and higher temperatures of the artificial surface cover at URB. The atmosphere reacts to stronger surface heating at the urban site with positive (upward directed) heat fluxes starting at around 0700 CET on average. At SUP positive heat fluxes can be observed with a one hour delay in comparison to URB. After sunset heat fluxes at URB remain positive for about 1.5 h after fluxes changed sign at SUP due to onset of surface cooling in the urban park. Negative surface heat fluxes during night time are generally small at both sites with nocturnal minima of about –15 W m\(^{-2}\) (SUP) and –10 W m\(^{-2}\) (URB), respectively. However, the difference between both sites indicates SUP to experience stronger near-surface...
cooling during night-time. Therefore surface warming takes longer at SUP after sunrise. The inter-site difference might be strengthened by some additional release of stored heat from the urban fabric at URB.

The general behaviour of heat flux differences between both sites is preserved throughout the year (Fig. 3). Maximum seasonal averages at noon are reached during MAM with 173 W m\(^{-2}\) at URB and 126 W m\(^{-2}\) at SUP. Higher fluxes during MAM in comparison to JJA are due to the persistence of a high-pressure system in April 2007. However, the magnitude of fluxes is in accordance with flux estimates from other sites, e.g. Offerle et al. (2006) report maximum monthly averages of about 180 - 220 W m\(^{-2}\) for May and June from an urban site in Lodz, Poland. As stated before, the difference of noon heat fluxes at our sites can be estimated with about 30 %.

Heat fluxes during winter are generally small at both sites reaching noon maxima of around 24 W m\(^{-2}\) at SUP and 42 W m\(^{-2}\) at URB. A fraction of this 18 W m\(^{-2}\) inter-site difference might be related to an effect of increased anthropogenic heating in the vicinity of URB. Generally inter-site differences are larger in winter, e.g. the daytime average ratio of URB/SUP for Q\(_H\) is about a factor 2 during winter and 1.5 during the summer season. Offerle et al. (2005) found that the wintertime anthropogenic heat flux during noon reaches a magnitude of about 40 % of Q\(_H\) on average. This estimate roughly corresponds to the inter-site difference found in this study.

Fig. 3: Seasonally averaged diurnal courses of sensible heat fluxes during the one-year study period. Error bars indicate standard deviations. For reasons of clarity of the plots only positive or negative standard deviations are indicated.

**References**


