SINGULARITIES OF TURBULENT URBAN HEAT FLUXES IN ŁÓDŹ

CECHY CHARAKTERYSTYCZNE TURBULENCYJNYCH STRUMIENI CIEPŁA W MIEŚCIE NA PRZYKŁADZIE ŁÓDZI

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Energy balance components measured at two points near the centre of the city of Łódź, central Poland, are analysed. Both points were located in comparable environment dominated by 3–5 stories in height buildings. Eddy-covariance systems were mounted at high masts about 25 m above roof level. Turbulent fluxes were calculated for two non-overlapping periods: 2000.11.05 – 2003.09.02 at Lipowa point and 2005.06.14 – 2008.01.31 at Narutowicza point. The monthly ensemble diurnal cycles of the turbulent fluxes at two points are similar for months with similar mean weather conditions. The latent heat flux (QE) accounts approximately 50% of sensible heat flux (QH) in noon hours. During the night QH can be both positive and negative within the range –60 ÷ +60 W·m⁻² whereas QE rarely drops below zero. Turbulent fluxes vary in annual course with winter minimum and summer maximum. Transient weather situations can significantly modify typical pattern of energy partitioning. In extreme case related with warm advection a negative QH can be observed all over 24 hours. In opposite case QH can be even larger than net radiation in noon hours.

INTRODUCTION

Knowledge about turbulent fluxes is fundamental to advances in understanding energy exchange of urban surfaces. Due to high costs of sensors and methodological problems experimental activities in the field on flux measurements in cities were relatively sparse up to the year 2000. Most of the early studies investigated the surface energy balance over suburban residential areas in relatively short periods (Oke 1978; Cleugh, Oke 1986; Roth, Oke 1993; Grimmond, Oke 1995, 1999; Oke et al. 1999). After the
year 2000 number of measurements of turbulent fluxes in the cities grew significantly and many of them have been ongoing over more extended periods (Fortuniak et al. 2001; Grimmond et al. 2002; Rotach 2002; Nemitz et al. 2002; Vogt et al. 2006; Al-Jiboori et al. 2002; Soegaard, Møller-Jensen 2003; Moriwaki, Kanda 2004; Offerle et al. 2006a, 2006b). Contrary to the early experiments which focused on the energy partitioning under favourable weather conditions (“golden days”), long term measurements provide more comprehensive information about ensemble diurnal patterns and about seasonal changes in energy balance components. Large campaign-style urban climate experiments allowed also studying intra-urban differences of surface energy fluxes and their vertical profiles. In spite of these studies knowledge on turbulent fluxes variability, their extremes and respond to the weather conditions is still very little. The objectives of this paper are to present both typical patterns of turbulent fluxes evolution and their untypical course under specific weather situations. Data from two urban locations in Łódź, Central Poland, are used to meet this goal.

STUDY AREA AND SIDES CHARACTERISTIC

Łódź is the second largest city in Poland with population about 800 000. It is situated in central Poland (19°27′E, 51°56′N) in relatively flat area slightly inclined south-easterly (altitudes from 180 m to 235 m). Lack of significant geographical peculiarities like lakes, rivers, valleys, mountains, or sea allows analysis a clear urban effect. Rapid urban development in the second half of 19th century is a reason for the regular arrangement in the old centre where adjoined buildings, 3–5 stories in height, create real urban canyons. Apart from a few high-rise buildings roof-level and zero-plane displacement can be easily defined in the old centre. Because of all these features Łódź is a good place for urban climate studies.

Measurements of energy balance components with eddy-covariance method started in Łódź in November 2000. First, an urban energy balance system has been developed at Indiana University and installed at Lipowa 81 (Fortuniak et al. 2001; Offerle 2006a) by Prof. Sue Grimmond and Dr Brian Offerle (Fig. 1). This site worked continuously up to the end of August 2003. Second, a very similar system, has worked at Narutowicza 88 since May 2005 (Fortuniak et al. 2006). Both measurement points are located in the core of old centre in separated by 2.8 km. Surface cover characteristics of the surrounding neighbourhoods are very similar, with comparable proportions of roofs, roads, pavements, lawns and trees.
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Fig. 1. Map of Łódź with location of measurement sites:
1 – Lipowa 81, 2 – Narutowicza 88

Rys. 1. Mapa Łodzi z zaznaczoną lokalizacją punktów pomiarowych:
1 – ul. Lipowa 81, 2 – ul. Narutowicza 88

Eddy-covariance and radiation sensors are mounted near the top of high masts (20 m – Lipowa, 25 m – Narutowicza) placed on the flat roofs of buildings (17 m – Lipowa, 16 m – Narutowicza). Average roof level can be estimated as ~11 m at first site and as ~16 m at second, which according to rule-of-thumb (Grimmond, Oke 1999), gives the zero-plane displacements as $z_d = 7.7$ m and $z_d = 11.2$ m respectively. Roughness lengths for momentum calculated in close to neutral stratification ($-0.05 < \zeta < 0.01$) are $z_{0m} = 2.0$ m and $z_{0m} = 1.9$ m.

METHODOLOGY AND DATA USED

At each site eddy-covariance system consists of three-dimensional sonic anemometer-thermometer (SWS–211/3K ATI – Lipowa, R.M. Young 81000 – Narutowicza) and krypton hygrometer (KH20 Campbell Sci.) connected to data-logger. Data sampled at 10 Hz were used to calculate fluxes with simple
box-averaging for 1 hour periods. For each averaging period vertical wind velocity was nullified with double rotation (Kaimal, Finnigan 1994). Fluctuations of sonic temperature were converted into actual temperature. Humidity fluxes were corrected for oxygen cross-sensitivity of krypton hygrometer. Fluxes were also corrected for density fluctuation (WPL-correction; Webb et al. 1980) and for spatial separation of sensors. Additionally, all components of radiation balance were measured independently by Kipp & Zonen CNR1 net radiometer.

In the present study data from Lipowa for the period 2000.11.05 – 2003.09.02 and from Narutowicza for the period 2005.06.14 – 2008.01.31 are used to study singularities of turbulent urban heat fluxes.

RESULTS

Conventionally, a typical diurnal pattern of any meteorological parameter can be obtained by averaging available data over the selected period of observation or by analysing selected days. Examples of ensemble diurnal pattern in fluxes for July are presented at Fig. 2. It shows high consistency of fluxes at both measurement sites. This consistency is a consequence of the locations in comparable environments and similar weather conditions for the Julys during the periods of observation. Depending on prevailing weather conditions for other months the average diurnal fluxes evolution vary between the sites or are
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similar. Nevertheless, high consistency of fluxes on both stations, located in these similar environments, gives a hope that sensors are located above roughness sub-layer, and fluxes are representative of the constant flux layer. As is typical for urban areas, in noon hours the turbulent sensible heat flux \( \dot{Q}_H \) is larger than the latent heat flux \( \dot{Q}_E \) with Bowen ratio close to 2 at both stations. In the majority of summer days \( \dot{Q}_H \) is in the range of 150–250 W·m\(^{-2}\) at both sites with generally higher values at Lipowa than at Narutowicza (Fig. 3). However, as net radiation \( (Q^*) \) is a main forcing controlling the sensible heat flux, \( \dot{Q}_H \) can rise in hot summer days above 300 W·m\(^{-2}\). The largest \( \dot{Q}_H \) recorded in a 1 h averaging period reached 445 W·m\(^{-2}\) on May 25th, 2001 (Lipowa). Whereas, during cloudy weather there are very small turbulent fluxes (even below 50 W·m\(^{-2}\)). A second consequence of the steering role of radiation in sensible heat flux evolution is the annual course of \( \dot{Q}_H \) gradually increasing from winter minimum to summer maximum.

Fig. 3. Monthly box-and-whiskers plots for sensible \( (\dot{Q}_H) \) and latent \( (\dot{Q}_E) \) turbulent heat fluxes calculated for midday hours (10–14 h) for days possessing valid observations for \( \dot{Q}_H \) and \( \dot{Q}_E \). The tops and bottoms of each “box” are the 25th and 75th percentiles of the samples, respectively. The line in the middle of each box is the sample median. Dots mark outlier (values that are more than 1.5 times the interquartile range away from the top or bottom of the box).
More factors determine the latent heat flux. Besides radiation and precipitation, vegetation plays an important role in latent heat flux intensity as it pumps water from deep soil to the atmosphere. Even if vegetation is reduced in urban areas, it rapidly develops in May, resulting in a jump of $Q_e$ from low winter values to (typically in range $0–50$ W·m$^{-2}$ from October to April) to summer ones (Fig. 3). Typical summer values of $Q_e$ are in a range $70–120$ W·m$^{-2}$. Latent heat flux extremes are difficult to estimate due to limitations of measurement technique because during wet weather or immediately following, when one can expect the highest water vapour flux from the ground, raindrops deposit on the sensor windows which leads to spurious results. Only a few episodes of high $Q_e$ are observed. These are situations when the krypton hygrometer dried quickly after rain which could be recorded. Still, it is unlikely that they represent real maxima.

The example diurnal patterns (Fig. 2) illustrate another feature of urban climate, that of the sensible heat flux is close to zero through the night indicating a near-neutral surface layer at the measurement height. However, distributions of all nocturnal fluxes (Fig. 4) suggest that this is a mean value rather that an every night occurrence. Standard deviations ($\sigma$), 10%, and 90% quantiles ($q_{10\%}, q_{90\%}$) additionally show high diversity of night-time $Q_h$. Their values at Lipowa are: $\sigma = 17$ W·m$^{-2}$, $q_{10\%} = -19$ W·m$^{-2}$, $q_{90\%} = 20$ W·m$^{-2}$ and at Narutowicza: $\sigma = 15$ W·m$^{-2}$, $q_{10\%} = -29$ W·m$^{-2}$, $q_{90\%} = 9$ W·m$^{-2}$. Additionally, negative $Q_h$ characterise more than 50% of night at both stations – 64% at Lipowa and 75% at Narutowicza. Latent heat flux is positive on the majority of nights (88% at Lipowa and 92% at Narutowicza) and it never drops below $-15$ W·m$^{-2}$. Larger values of $Q_h$ are mainly associated with post-rain situations which create the right tail of the distributions.

![Fig. 4. Probability density functions of night-time (for all night hours) values of sensible ($Q_h$) and latent ($Q_e$) turbulent fluxes at two measurements sites in Łódź](image)

Rys. 4. Funkcje gęstości prawdopodobieństwa średnich nocnych wartości (dla każdej nocyśrednica po wszystkich godzinach nocnych) turbulencyjnego strumienia ciepła jawnego ($Q_h$) i ciepła utajonego ($Q_e$) na dwóch punktach pomiarowych w Łodzi
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Figure 5 presents a typical evolution of $Q^*$, $Q_H$ and $Q_E$ in five days of fine weather in July 2006. As in mean diurnal variation case (Fig. 2), the sensible heat flux dominates over a latent heat. Because of increased heat capacity of urban structures $Q_H$ remains positive late in evening, when $Q^*$ drops below zero. However, large radiative cooling leads to a negative $Q_H$ in the analysed nights. Latent heat flux is positive in the analysed case varying from about $100\, \text{W}\cdot\text{m}^{-2}$ at midday to a few $\text{W}\cdot\text{m}^{-2}$ at night. This classical pattern can dramatically change under specific weather conditions, especially during winter when radiative forcing is relatively weak. Warm advection after a period of cold weather decreases the sensible heat flux. An extreme case (Fig. 6), was the two days 15–16 November 2002 when $Q_H$ was negative not only at night but also in the middle of the day. During this period the air temperature rose to 10–12°C whereas just a few days earlier it had remained close to 0°C for more than a week. However under cold advection (Fig. 7), as occurred during the period 16–17 January 2001 the air temperature dropped from about 0°C to about –6°C. The sensible heat flux during this period was positive throughout 24 hours per day and even greater than the net all wave radiation during the daytime.

![Figure 5. Energy balance components evolution under fine weather conditions](image)

Fig. 5. Energy balance components evolution under fine weather conditions
– days with one of the greatest $Q_H$ at Narutowicza

Rys. 5. Przebieg składników bilansu cieplnego w kilkudniowym okresie ładnej pogody
– dni z jednymi z największych wartościami $Q_H$ na posterunku przy ul. Narutowicza
**CONCLUSIONS**

Long term measurements of turbulent fluxes in Łódź allow analysis of the urban energy partitioning beyond the “golden days” to transient weather situations. The individual diurnal pattern of turbulent fluxes can differ significantly from the mean evolution. Day-time turbulent fluxes vary in a wide range for each month depending not only on the present but also on the past weather conditions. The high heat capacity of a town can amplify sensible heat fluxes due to heat accumulation or reduce this flux due to large surface cooling. This must be considered in numerical model evaluations.
REFERENCES


STRESZCZENIE

W pracy przeanalizowano wyniki pomiarów składników bilansu cieplnego na dwóch punktach pomiarowych położonych w centralnych dzielnicach Łodzi – punkt przy ul. Lipowej 81 i punkt przy ul. Narutowicza 88. Oba punkty zlokalizowane były w miejscach o podobnym typie zabudowy zdominowanym przez 3–5 piętrowe budynki. Pomiary strumieni turbulencyjnych wykonano z zastosowaniem metody kowariancji wirów. Czujniki zamontowane były na wysokościach, ok. 25 m nad średnim poziomem dachów. Turbulencyjne strumienie ciepła jawnego \( Q_H \) i ciepła utajonego \( Q_E \) oraz składniki bilansu radiacyjnego mierzono na posterunku przy ul. Lipowej w okresie 2000.11.05 – 2003.09.02, a na posterunku przy ul. Narutowicza w okresie 2005.06.14 – 2008.01.31. Średnie dobowe przebiegi składników bilansu cieplnego w poszczególnych miesiącach cechuje duże podobieństwo dla obu punktów pomiarowych (rys. 2). W godzinach południowych strumień ciepła utajonego stanowi ok. 50% strumienia ciepła jawnego. W ciągu nocy (rys. 4) \( Q_H \) może być zarówno dodatnie jak i ujemne zmieniając się w granicach \(-60 \div +60 \text{ W} \cdot \text{m}^{-2}\), z wartością średnią zbliżoną do 0 W·m\(^{-2}\). Natomiast nocny strumień ciepła utajonego jedynie w wyjątkowych wypadkach spada poniżej zera. Turbulencyjne strumienie ciepła charakteryzuje wyraźna zmienność sezonowa z maksimum w lecie i minimum w zimie (rys. 3). Typowa dobowa zmienność składowych bilansu cieplnego pojawiająca się w radiacyjnym typie pogody (rys. 5) może ulec znacznemu zaburzeniu podczas pogody adwekcyjnej. W wyjątkowych przypadkach adwekcji ciepła strumień ciepła jawnego może być mniejszy od zera przez całą dobę (rys. 6). W okresie zimowym, podczas napływu mroźnego powietrza nad miasto, \( Q_H \) może być nie tylko dodatnie przez całą dobę, lecz nawet w południe przyjmować wartości większe od salda promieniowania (rys. 7).