Turbulence characteristics and energy balance on urbanized area - Łódź case study

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1. Eddy covariance sites in Łódź
2. Data verification
3. Standard deviations for wind components and for scalars
4. Energy balance and its parameterisation
5. Scintillometry
Energy balance (EB) measurement points in Łódź

**EB 1 Lipowa**
Grimmond and Offerle
(since July 2006)

Łódź, Poland, 51°47’N, 19°28’E
population 750,000

**EB 2 Narutowicza**
(since June 2005)
Eddy covariance towers in Łódź

**EB 1**
- Measurement height (above ground): 37m
- Building height: 17m
- Mean building height: 11m

**EB 2**
- Measurement height (above ground): 42m
- Building height: 16m
- Mean building height: 17m
Łódź city centre with location of measurement sites and views of measurement towers. Solid lines surrounding the measurement point indicates source areas at $p = 50$, 75 and 90% calculated for turbulent fluxes measured in unstable stratification.
Three stationarity tests used in post-processing data quality control:

- $R_{NW}$ – the statistic proposed by Foken and Wichura (1996) with critical value 0.3;
- $NR$ – the non-stationarity ratio given by Mahrt (1998) with critical value $NR=2$;
- $RCS$ – the relative covariance stationarity criterion, introduced by Dutaur et al. (1999) and modified by Nemitz et al. (2002) with critical value $RCS=0.5$. 
Quality control – flow direction selection

Wind rose for Narutowicza is typical for central Poland. At Lipowa strong influence of tunnelling by street canyon is observed.

- Data excluded from further analysis
- Strong inhomogeneity in surface cover
- Wind tunnelling by the street canyon
- Flow distortion by the mast

![Wind rose diagram](image-url)
Normalised standard deviations of wind components

- Lipowa
- Narutowicza

- Foken and Wichura (1996)
- Roth (2000)
- Panofsky and Dutton (1984)
- Wood et al. (2010)
- Pahlow et al. (2001)
- Al-Jiboori et al. (2002)
Normalised standard deviations of temperature

- Narutowicza

\[ \frac{-\sigma_T}{T_*} \]

- Lipowa

\[ \frac{\sigma_T}{T_*} \]

- Raw data
- Block averaged data
- **Fit:** \(-\sigma_T/T_* = 1.6(-\zeta)^{-1/3}\)
- Wood et al. (2000)
- Roth (2000)
- Al-Jiboori et al. (2002)
- **Fit:** \(\sigma_T/T_* = 3.9 + 0.135\zeta^{-0.71}\)
- Quan and Hu (2009)
- Pahlow et al. (2001)
Normalised standard deviations of humidity

- $\frac{b}{b_*}$ vs. $-z'/\Lambda$
- $\frac{\sigma_q}{q_*}$ vs. $z'/\Lambda$

**Narutowicza**
- Raw data
- Block averaged data
- Fit: $-\frac{\sigma_q}{q_*} = 2.1(-\zeta)^{-1/3}$
- Lohou et al. (2010)
- Quan and Hu (2009)

**Lipowa**
- Raw data
- Block averaged data
- Fit: $-\frac{\sigma_q}{q_*} = 8.06(1 - 41.9\zeta)^{-1/3}$
- Moreas et al. (2005)
Normalised standard deviations of CO$_2$
Average diurnal course of energy balance components in seasons.
Average diurnal course of energy balance components in seasons

[Diagrams showing energy balance components for different seasons (SON and DJF) at Lipowa and Narutowicza locations, with graphs depicting Q*, Q_H, and Q_E over time in CET hours.]
Modelled and measured turbulent fluxes

$Q_H$ and $Q_E$ measured at Narutowicza in the period 3-13 May 2006 (dashed lines), modelled with the aid of M-O similarity (black) and as regression versus $Q^*$ (green)
Diurnal course of the stability parameter, $\zeta = z'/\Lambda$, at Lipowa and Narutowicza sites for the entire study periods. Lines from the bottom to the top indicate 5th, 10th, 25th, 50th (median – bold line), 75th, 90th, and 95th percentiles.
Histograms of night-time (mean for all night hours) $Q_H$ and $Q_E$.
Scintillometry – BLS900

Lipowa
- $z_s=37m$
- Mean building height $z_i=11m$
- $z_o=7.7m$

Narutowicza
- $z_s=42m$
- Mean building height $z_i=16m$
- $z_o=11.2m$

Path = 3140m

500m
Scintillometry – BLS900

\[ Q_H = b \cdot \rho \cdot c_p \cdot k \cdot z_{eff} \cdot \left( \frac{g}{T} \right)^{1/2} \cdot \left( C_T^2 \right)^{3/4} \]  - free convection assumption

\[ z_{eff} = \int_{0}^{1} (z_{path} - d) \cdot W(u) \, du = 25m \]

Scintillometer path height (dashed line) above topography of the ground (thick line) and topography of the built canopy (dotted line).
Mean daily course of $Q_H$ measured by scintillometer (free convection assumption) and at two eddy covariance towers in a period 2010.06.11 – 2010.11.05 (148 days).
$Q_H$ measured by scintillometer (free convection assumption) and at two eddy covariance towers in a period 2010.06.11 – 2010.11.05 (148 days). All data – blue dots, data for $z/L<-0.05$ – black dots.
Summary

1. Results from two eddy covariance points in Łódź give information on energy balance for the area of the diameter about 1 km – results are representative for central part of mid-European towns.

2. Analysis of normalised variances of wind components and scalars shows that local scaling is suitable for describing urban data with the framework of Monin-Obukhov similarity theory. Normalised standard deviations of wind components and scalars undergo power law with exponent equal $\pm 1/3$ in free convection limit.

3. Energy balance in central parts of Łódź is characterised by domination of sensible heat flux in noon hours (similar to other cities) and large frequency of stable stratification during the night (unlike to other cities).

4. Average sensible heat flux measured by scintillometer is very similar to the fluxes measured at two eddy-covariance points.
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