SCINTILLOMETER MEASUREMENTS OF THE SENSIBLE HEAT FLUX IN ŁÓDŹ, CENTRAL POLAND

Zieliński M.1, Fortuniak K.1, Pawlak W.1, Siedlecki M.1

1 Department of Meteorology and Climatology, University of Łódź, Łódź, Poland

mariusz.r.zielinski@gmail.com

Summary

The energy balance components play an important role in Urban Climate studies measurements. The most common method of flux measurements – eddy covariance – allows to obtain the representative fluxes for relatively small areas, while scintillometry has an ability to measure the fluxes along the path even up to few kilometers long. Therefore, such measurements could be used i.e. for verification of the numerical weather prediction models. This method has been proved reliable in natural areas while only few studies have been conducted in urban ones. In Łódź scintillometer (Scientec BLS900) was deployed in August 2009 and operated until October 2012. The measurements path is nearly 3.2 km long and traverses over the city centre. As in cities the visibility is often, especially in winter, significantly reduced the amount of reliable data is reduced as well. Moreover, in case of considered measurements the technical problems has contribute to gap occurrence. Therefore the statistical model based on the additional measurements of energy balance components have been used to fulfill the mentioned gaps. This study presents the results of three-year measurements of the sensible heat flux. Its diurnal and annual course is discussed as well as intercomparison with eddy covariance measurements. As urban areas are heterogeneous the variability of the surface beneath the optical path is considered as well.

Keywords: scintillometer, sensible heat flux, urban climate

INTRODUCTION

The singularities of the urban climate are well known and one the most essential is the modification of the energy balance. Due to the heterogeneity of the surface in urban areas the point measurements such as eddy covariance could be representative for relatively small areas. The scintillation method has the advantage of delivering the area-averaged values of the surface fluxes of sensible and latent heat. Many studies has prooved the reliability of this method in the heat fluxes estimation (e.g. De Bruin et al 1995, Meijninger et al. 2006). However, there are only few studies considering the application of scintillometer in the urban areas. One of the first such experiments was performed in Tokyo (Kanda et al., 2002), the next measurements were conducted during the BUBBLE and ESCOMPTE campaigns in Bassel and Marseille respectively (Roth et al., 2006; Lagouarde et al., 2006). More recently the scintillometer were deployed in i.a. London, Swindon, Helsinki.

This study presents some of the results of nearly 3-year measurements of the sensible heat flux ($Q_H$) by means of scintillation method. The previous studies revealed quite good agreement of scintillometer measurements with the
eddy covariance (Zieliński et al., 2012). Consideration are given to the estimation of the footprint area, moreover the modeled $Q_H$ is discussed as well.

**MEASUREMENTS SITES, DATA AND METHODS**

Łódź (51°47’N, 19°28’E) is a city located in Central Poland. Considering the population it is the third biggest city in abovementioned country. The relatively flat surface and the lack of rivers and large water reservoirs contributed development of distinctly visible singularities of urban climate in Łódź. The urban flux measurements are conducted in the city centre, that is occupied with 15-20 m height buildings, built mainly in the end of 19th century. The relatively uniform height and similar roof coverage (mainly tarred roofs are present here) makes this part of the city rather a homogeneous surface. Outward the city centre the surface is more complex as some parks with high vegetation could be found as well as industrial areas.

The Scintec BLS 900 scintillometer (hereinafter BLS) was used in that study. The BLS transmitter was mounted at a height of 31 m above ground level on the mast 20 m in height standing on the roof of the 17 m height building at 81 Lipowa Str. (51°45’45”N, 19°26’43”E, 204 m a.s.l.) (Fig. 1). The mean height of the surrounding buildings ($z_H$) is about 16 m. That site is located in the city centre about 1.5 km to the south-west from most densely built-up areas in Łódź. The BLS receiver was deployed on the roof of the building at 12 Matejki Str. (51°46’24”N, 19°28’52”E, 221 m a.s.l.) that is 36 m in height. The optical path of the BLS is 3142 m long and traverses over the city centre. Since the BLS path height above the ground is not uniform the effective measurements height ($z_{eff}$) had to be estimated (Hartogensis et. al 2003, Kleissl et al, 2008).

*Figure 1:* The location of scintillometer (BLS) measurements in Łódź. 1 - transmitter of the BLS, 2 – receiver of the BLS, eddy covariance system, radiation balance measurements, 3 - eddy covariance system, radiation balance measurements. Aerial photograph source: www.geoportal.gov.pl

In case of considered measurements the $z_{eff}$ for unstable conditions is 22.14 m (with standard deviation equal 0.06 m) while for stable 22.22 m. The weighted average (with BLS path-weighting function) displacement height ($d$) estimated as a $d=0.7z_H$ (GRIMMOND AND OKE, 1999) is 11.54 m while roughness length ($z_0$) is 1.65 m ($z_0=0.1z_H$). The ratio of $z/z_H$ is 2.14 so the measurements were conducted close to the blending height.
The BLS measurements started in Łódź in August 2009 and were conducted until November 2012. Nevertheless this study considers only the data set from September 2009 to May 2012. As the extensive construction works have started in the beginning of 2012 in the central part of analyzed area, their influence on the measured values still have to be studied. In urban areas BLS operation is frequently prevented by unfavorable weather conditions including the low visibility and increased amount of aerosols in the air. Thus the amount of available data was significantly reduced. Another reason for this were the technical problems that occurred mainly in the winter. Data have undergone the quality control i.e. 1-hour intervals with insufficient amount of data or stored with BLS errors were rejected, as well as time periods when precipitation occurred or EC data did not passed stationarity tests.

For the estimation of the sensible heat flux from the BLS measurements some additional data are necessary. In addition to the BLS two eddy covariance (EC) systems operates in Łódź (Fig. 1). The first is mounted at the same mast as BLS transmitter, however, 6 m higher. Here as well as at the second site (EC on Fig. 1) the radiation balance components are measured. The second EC is mounted at height of 42 m (17 m height building and mast 25 m in height) at 88 Narutowicza Str. (51°46′24″N, 19°28′52″E, 221 m a.s.l.).

The mean temperature and mean atmospheric pressure from both sites were used for computation of the temperature structure parameter \( C_T^2 \) from the BLS measurements (15-minute intervals). The \( C_T^2 \) values were corrected according to Bowen-correction (Wesely, 1976) for which the mean Bowen ratio from both EC measurements was used.

\[
C_T^2 \approx \alpha \cdot \frac{p^2}{T^4} \cdot C_T^2 \left( 1 + \frac{0.03}{\beta} \right)^2
\]

where: \( \alpha \) is a constant depending on scintillometer type, \( T \) is the absolute temperature [K], \( p \) is the atmospheric pressure [hPa] and \( \beta \) is the Bowen ratio.

The sensible heat flux \( (Q_{H}) \) from the BLS was computed iteratively with the application of Monin-Obukhov Similarity Theory (MOST) and then averaged in 1-hour intervals. The universal function presented by Andreas (1988) was applied in the set of equation 2-5. In addition mean wind speed from both EC sites was used for the friction velocity computation in consecutive steps of iterative procedure.

\[
\frac{C_T^2(z_{\text{eff}})}{\theta^2} = f_{TT} \left( \frac{z_{\text{eff}}}{L_{OB}} \right)
\]

\[
L_{OB} = \frac{u_s^2 T}{g k \theta}
\]

\[
u(z) = \frac{u_s}{k} \left[ \ln \left( \frac{z}{z_0} \right) - \Psi_m(\zeta) + \Psi_m \left( \frac{z_0}{L_{OB}} \right) \right]
\]

\[
Q_H = -\rho \cdot c_p \cdot u_s \cdot \theta_s
\]

where: \( \theta_s \) is the turbulent temperature scale, \( f_{TT} \) is the universal MOST function, \( L_{OB} \) is the Obukhov length, \( u \) is the wind speed, \( u_s \) is the friction velocity, \( z \) is the measurements height, \( z_0 \) is the surface roughness, \( \zeta \) is the stability parameter \((z/L_{OB})\) and \( \Psi_m \) is a well-known Businger-Dyer equation.
SCINTILLOMETER SOURCE AREA

To evaluate the source area (SA) of the BLS the analytical footprint model FSAM by Schmid (1994, 1997) was applied. As the FSAM model was developed for single point measurements to determine the source area of the BLS the superposition of multiple model runs along the optical path were computed. As the BLS measurements are the most sensitive to the turbulence in the centre of optical path, all of computed footprints were normalized with path-weighting function. To provide the ultimate BLS source area all acquired footprints for points along the path were averaged. Similar approach was applied by Göckede et al. (2005).

For the unstable conditions (fig. 2) the BLS source area at p=90% covers the area about 3.5 km² (for near-neutral conditions the SA is nearly twice as big – 6.1 km² – not shown in fig. 2), however, for specific case the SA could be significantly decreased. It highly depends on the wind direction. When wind direction is perpendicular to the BLS path the SA is the largest, on the other hand while the wind direction is parallel to the measurement path, the footprint covers considerably smaller area. In considered case the 25% of measured QH developed over the 0.4 km² area situated in the centre of the BLS path. In general the SA is covered with the artificial surfaces, however, close to the centre of the considered area a few parks could be found. The areas covered with vegetation occupies 0.16 km² what is 4.6% of the SA at p=90%. Even though the amount of vegetation cover is not significant, the BLS SA could not be assumed as homogeneous. It is distinctly shown by the Land Surface Temperature (LST) pattern. The most uniform is the surface in the north-western and western sector of the BLS SA. On the other hand the greatest spatial variability could be found in the eastern part of considered area.

The measurement height along the BLS path is not uniform, therefore it affects the estimated footprint. Above the city centre (western part of SA) measurements are conducted a few meters lower than in the rest of the considered area, thus the SA do not reach so large distance as for instance in the eastern part of BLS path.

Figure 2: The scintillometer source area. Solid lines point indicates source areas at $p = 25, 50, 75$ and 90% calculated for turbulent fluxes measured in unstable stratification. In the footprint area the Land Surface Temperature (LST) pattern obtained from the LANDSAT 5TM image acquired on 6th July 2011 is shown. Aerial photograph source: www.geoportal.gov.pl

SENSIBLE HEAT FLUX PARAMETRIZATIONS

In this study two model were used for modeling of the $Q_H$ from the BLS measurements. The first model (CT2) was based on the relation between the temperature structure parameter measured by the BLS and $C_{T2}$ obtained from EC on the basis of equation 2. The $C_{T2}$ from the EC were next inferred in the iterative procedure. Therefore, model CT2 allowed to obtain not only the $Q_H$ values but also the rest of the parameters estimated in the iterative process (i.e. $u_*, z_{eff}$).
The second model (MR) was based on the additional measurements of radiation balance, temperature and wind speed. For the unstable conditions, the multiple regression based on all abovementioned variables was applied, while for stable condition model was based only on the wind speed.

In figure 3 the observed diurnal and annual course of $Q_H$ is presented as well as the difference between the observed and modeled data. Both models present quite good agreement with the observed values (table 1), however, there are some significant differences. The first of considered models (CT2) seems to overestimate the observed $Q_H$, especially during the winter and spring (fig. 3c). The another interesting pattern could be found in July, when model underestimates $Q_H$. The second model (MR) is better fitted to observed data what is confirmed by relatively small errors (table 1.).

### Table 1. Mean Bias Error (MBE), Mean Square Error (MSE) and its root (RMSE), Mean Absolute Error (MAE) and index of agreement (d) computed between observed and modeled $Q_H$. All errors $[\text{Wm}^{-2}]$, d – dimensionless.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>MBE</th>
<th>MSE</th>
<th>RMSE</th>
<th>MAE</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT2</td>
<td>14.55</td>
<td>1100.19</td>
<td>33.17</td>
<td>21.08</td>
<td>0.98</td>
</tr>
<tr>
<td>MR</td>
<td>-1.57</td>
<td>602.306</td>
<td>24.54</td>
<td>16.91</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**Figure 3:** Observed values of sensible heat flux $Q_H$ (a), difference between modeled data with model CT2 and MR (b), difference between observed and modeled data for model CT2 (c), MR (d). Only data after quality control are presented here.
The modeled course of the $Q_H$ in the period from September 2009 to May 2012 (fig. 4) indicates that the highest values of $Q_H$ could be found in May and June. Nevertheless, one must be aware that in considered period the July and August were relatively cold and wet in Poland, what in turn could contribute to lower $Q_H$. This phenomena is distinctly highlighted by the model CT2 (fig. 4a), however, model MR also indicates the summer decrease of $Q_H$. Both models agree that in January and February the heat flux is positive almost during the whole day. During the rest of the year the course of $Q_H$ is similar in case of both considered models, and the greatest discrepancies occurs during the nights and winter time – the periods when stable conditions prevail.

**SUMMARY**

This study presented some aspects of the scintillometer measurements of the sensible heat flux ($Q_H$) conducted in Łódź. Consideration was given to the source area (SA) estimation and the modelling of the $Q_H$ on the basis of the additional measurements.

The applied approach of SA estimation (average superposition of source area for point measurements) allowed to determine the areas that contributed most to the measured values of $Q_H$. The extent of the BLS SA is greater than in case of point measurement technique such as eddy covariance, therefore obtained fluxes are representative for relatively vast areas (up to a few square kilometres). However, the size of SA depends on the optical path length and the wind direction.

Models applied in this study could give the opportunity to fulfil the gaps found in the $Q_H$ time series. This might be the most helpful in winter when the amount of valid data was significantly reduced. From two considered models the MR model based on radiation balance, air temperature and wind speed data performed better than the CT2 model based on the temperature structure parameter (obtained from eddy covariance with Monin-Obukhov Similarity Theory). Nevertheless, some more consideration should be given to $Q_H$ modelling with CT2 model, as it is promising since it could deliver more parameters, such as path-averaged friction velocity or Obukhov length, than the second of the considered models.

**ACKNOWLEDGMENTS**

Present work was funded by Polish National Science Centre under grant DEC-2011/01/N/ST10/07529 in years 2011-2014 and by Polish Ministry of Science and Higher Education (State Committee for Scientific Research) under grant N N306 276935 in years 2008-2011.
REFERENCES


