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Carbon dioxide flux in the centre of Łódź, Poland – analysis of a 2-year eddy covariance measurement data set

Włodzimierz Pawlak,* Krzysztof Fortuniak and Mariusz Siedlecki
Department of Meteorology and Climatology, University of Łódź, Łódź, Poland

ABSTRACT: Continuous measurements of carbon dioxide turbulent flux F_{CO_2} carried out with the eddy covariance method have been made in Łódź since F_{CO_2} July 2006. The measurement point (Lipowa Station) is located in the west part of the densely built-up city centre, where artificial surfaces clearly prevail over natural terrain. The measurement system includes a Kipp and Zonen's (Delft, Holland) CNR1 net radiometer, RMYoung (Traverse City, Michigamn, USA) 81000 sonic anemometer and Li-cor (Lincoln, Nebraska, USA) 7500 open path H_2O/CO_2 infrared gas analyser. Sensors are installed on the high tower 20 m above the roof of the building and 37 m above the ground, so the measurement height exceeded the urban canopy layer more than twice. The diurnal and annual variability of carbon dioxide flux for the period July 2006 to August 2008 is analysed in the article. The results show the characteristic features in diurnal and annual courses of F_{CO_2}. Independently from the season, positive (upward) fluxes of the order of 0–15 μmol m^{-2} s^{-1} prevail in the data. During the cold season, an increase in turbulent CO_2 exchange is observed (F_{CO_2} quite often exceeded 30 μmol m^{-2} s^{-1}). This can be attributed to anthropogenic CO_2 emissions, which are particularly strong in winter due to, among other things, mineral fuel combustion during domestic heating. The average monthly fluxes are positive in all seasons, which means that emission of CO_2 in the surroundings of the measurement point prevails over its uptake. Apart from the season, the maximum flux occurred during the day and the minimum during the second part of the night. Wintertime monthly averaged fluxes are much higher than summertime ones. The observed increase in CO_2 exchange during weekdays in comparison with weekends can be caused by the weekly rhythm of traffic in the surroundings of Lipowa Station. Copyright © 2010 Royal Meteorological Society

KEY WORDS carbon dioxide; eddy covariance method; turbulent flux of mass; anthropogenic CO_2 emission

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1. Introduction

CO_2 is one of the components of the atmosphere which, although it comprises a very small fraction (~0.04% of volume), plays an important role in the energy exchange between biosphere, atmosphere, lithosphere and hydrosphere. First of all, CO_2 participates in the photosynthesis process – oxygen leaves the plants and CO_2 is absorbed, which leads to an increment of biomass, but part of the absorbed CO_2 leaves the plants during nocturnal respiration. Second, it is one of the most important greenhouse gases and its concentration influences the radiation balance of the Earth's surface. According to the IPCC reports (IPCC, 2007), a significant increase in CO_2 concentration has been observed over the last 250 years, from 280 ppm in pre-industrial times to 385 ppm in 2009. Such an increase may be the reason for a mean air temperature rise of $0.6 \pm 0.2\,^{\circ}C$ during the last 100 years (IPCC, 2007). Thus, quantitative determination of net CO_2 emissions is very important from the perspective of the global warming problem. One of the factors determining the intensity of CO_2 exchange between the surface and lower troposphere is the type of surface cover. Above natural or agricultural terrain, the vertical exchange of CO_2 is determined mainly by natural biological processes. During the warm season, a strong daily uptake of CO_2 during photosynthesis and nocturnal release of this gas owing to plant respiration is observed (Baldocchi *et al*., 2000; Schmid *et al*., 2000). In the wintertime, when biological processes are very weak, CO_2 exchange is insignificant, especially in the case of snow cover occurrence (Baldocchi *et al*., 2000; Schmid *et al*., 2000; Hirata *et al*., 2007). Above urban terrain, where artificial surfaces dominate over green areas, biological processes proceeding in plants determine CO_2 exchange to a smaller degree. In cities, the most significant source of CO_2 is anthropogenic emission related to mineral fuel combustion, car traffic or heating by the energy industry, which is observed particularly during the cold season (Grimmond *et al*., 2002; Nemitz *et al*., 2002; Moriwaki and Kanda, 2004; Gratani and Varone, 2005; Coutts *et al*., 2007; Vesala *et al*., 2008; Roth and Velasco, 2010). Only during the warm season is anthropogenic emission mitigated to a certain degree by natural CO_2 absorption during photosynthesis (Grimmond *et al*., 2002; Moriwaki and Kanda, 2004; Vesala *et al*., 2008). A qualitative dependence between the degree of urbanization

* Correspondence to: Włodzimierz Pawlak, Department of Meteorology and Climatology, University of Łódź, Narutowicza 88, 90-139 Łódź, Poland. E-mail: wpawlak@uni.lodz.pl

and the amount of CO_2 exchange is well understood (Grimmond *et al.*, 2002), but quantitative determination of net surface CO_2 fluxes in cities are still the subject of intensive study.

During the last years, the number of papers describing the characteristics of CO_2 exchange between active surface and troposphere has increased considerably, but a large majority of them present the results of turbulent net CO_2 flux measurements above natural or agricultural surfaces covered by vegetation (Moncrieff *et al.*, 1997; Baldocchi *et al.*, 2000; Schmid *et al.*, 2000; Hirata *et al.*, 2007). Although urban terrains are significant sources of tropospheric CO_2, long-term data of F_{CO_2} in cities are still relatively rare (Grimmond *et al.*, 2002; Nemitz *et al.*, 2002; Velasco *et al.*, 2005; Vogt *et al.*, 2006; Coutts *et al.*, 2007). The eddy covariance measurements of CO_2 fluxes as a part of the urban surface energy balance programme have continued in Łódź since November 2000 (Offerle *et al.*, 2003, 2005, 2006a, 2006b). Beside two long-term measurement points, a few short-term (a few days to a few weeks) experiments were also carried out in other parts of Łódź; for example, residential, industrial and sub-urban areas (Offerle, 2003; Pawlak *et al.*, 2007). Regular investigations of CO_2 exchange started in July 2006 when the measurement point at Lipowa Street was equipped with a new system including an H_2O/CO_2 gas analyser.

This article presents the results of more than 2 years of continuous measurements of the net turbulent CO_2 flux F_{CO_2} at the Lipowa site. The following section characterizes the area of investigations and the measurement site as well as the instrumentation and data processing methodology. Next, annual variability of F_{CO_2} and the relationship between net turbulent CO_2 monthly exchange and mean monthly air temperature are studied. Further analysis includes the diurnal variability of F_{CO_2} for different months and its differences between weekends and working days. Finally, the role of airflow direction in CO_2 turbulent exchange at the site analysed is discussed. The presented results are the first and only long-term F_{CO_2} measurements from an urban area in Poland and one of a very few Polish F_{CO_2} data sets obtained with the eddy covariance technique.

2. Study area, measurement site location and instrumentation

2.1. Study area and site location

Łódź (51°47′N, 19°28′E) is located in the centre of Poland, on a relatively flat terrain (altitudes range from 180 to 235 m a.s.l.). Because of the lack of water reservoirs, lakes, rivers and orographic barriers in the city surroundings, the modification of the local climate by urbanization can be easily detected. It is the third largest Polish city (after Warsaw and Cracow) with a population of ∼750 000. Until the 19th century, Łódź was a rather small city but after 1800 it grew rapidly and its population rose from less than 1000 in 1820 to 314 000 at the end of the 19th century and then to more than 600 000 before the World War II. This growth was a result of rapid development of the textile industry because of good natural conditions and favourable laws during the 19th century. The city centre, where the Lipowa Street measurement point is located (Figure 1), was built mainly in this period and can be characterized as an extensive, rather homogeneous and compact settlement of great density with buildings reaching mainly 15–20 m in height. Many of these buildings in the whole city centre are heated by individual heaters fired by hard coal or coke. The surroundings of the old city centre are industrial areas, residential areas with one- or two-storey developments and new districts of blocks of flats.

The eddy covariance measurement point of the F_{CO_2} is located at Lipowa Street (Figure 1) in the west part of the dense built-up city centre (51°45′45″N, 19°26′43″E, 204 m a.s.l.). The nearest surroundings of the measurement point (within the diameter of 500 m) are characterized by compact building development. Artificial surfaces (buildings, roads, pavements, etc.) cover ∼50–70% of the surface in this part of the city and ∼30% of all surfaces are roofs (Kłysik, 1998). The surrounding buildings are mainly constructed of concrete or bricks with flat or slightly pitched roofs covered by black tar or, rarely, sheet metal. The roads and pavements are covered by asphalt and concrete, respectively. Vegetation is interspersed with buildings; it consists mainly of many small lawns and covers 38% of all surfaces. Trees are deciduous, 8–15 m tall but generally below building height, covering only 10% of the described area (Kłysik, 1998). Vegetation develops between April and October–November. The Bowen ratio in this period is at its lowest but is not lower than 1. Rapid growth of grass and bushes is observed in spring but leaf area index is the biggest in summer (July and August). Areas placed a little bit further from the measurement point (1000–1500 m) are characterized by asymmetry in building development between the east and the west parts (Figure 1, bottom left). Artificial surfaces cover 80% of the east sector and 55% of the west sector (Kłysik, 1998). There are two parks in the neighbourhood in the southern and western directions within distances of ∼900 m (Poniatowskiego city park) and ∼1.7 km (Zdrowie city park), respectively (Figure 1). Additional vegetation consists of many trees and lawns interspersed with buildings. More details about the study area are provided in Offerle (2003), Fortuniak (2003, 2010) and Offerle *et al.* (2005, 2006a, 2006b).

The average height of the roughness elements in the nearest neighbourhood within a distance of 500 m can be estimated as $z_H \sim 11$ m (Offerle, 2003). The measurement system is installed on a 20-m tower mounted on the roof of a 17-m high building (Figure 3). The height of this building is similar to the highest buildings in the close surroundings, except to the west, where a new 21-m high residential block of flats exceeds the canopy layer by ∼10 m at a distance about 180 m from the measurement point. The displacement height estimated on the basis of a simple rule of thumb, $z_d = f_d \cdot z_H$ (Grimmond and Oke,

Figure 1. West part of Łódź city centre with the location of the measurement point (LS, Lipowa Station) and urban parks (PZ, city park 'Zdrowie'; PP, city park 'Poniatowskiego'). Solid lines surrounding the measurement point indicate source areas at $p = 50$, 75 and 90% calculated for turbulent fluxes measured at 10 : 00 am–2 : 00 pm at LS for unstable stratification (all available data in the period July 2006 to August 2008). The lower pictures show the building development and net of streets in the nearest neighbourhood of LS. Photo source: Municipal Centre of Geodesics and Cartographic Documentation of Łódź.

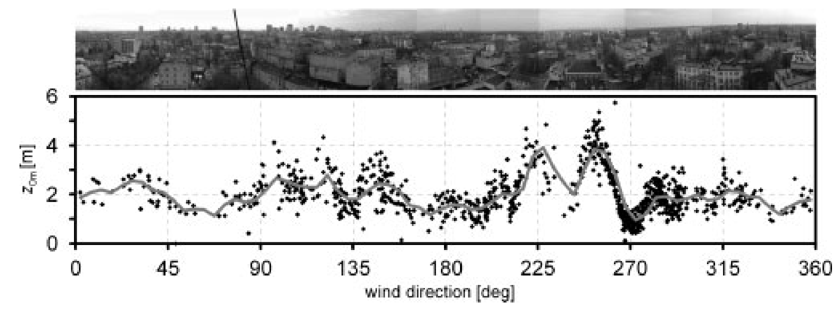

Figure 2. The roughness length for momentum z_{0m} by wind direction at Lipowa Station and panoramic view from the measurement tower.

1999), can be evaluated as $z_d \sim 7.7$ m (for $f_d \sim 0.7$). The measurement height $z_s = 37$ m above ground level exceeds the mean canopy layer more than twice, so it is possible to make the assumption that z_s exceeds the roughness layer height (Grimmond and Oke, 1999). Additional studies of turbulent energy balance components seem to confirm this assumption (Fortuniak *et al.*, 2006; Fortuniak, 2010). The mean value of the roughness length determined for close to neutral stratification from the logarithmic wind profile equation (Grimmond *et al.*, 1998) $z_{0m} = (z_s - z_d) \cdot \exp(-k \cdot U/u_*)$ is close to 2.5 m, but it shows clear angular dependence (Figure 2) with significant increases for the directions between 210° and 270°. Two z_{0m} peaks observed at 220° and 260° can be related to two elements exceeding the surrounding canopy layer. The first is a tall new building situated in this direction within a distance of 180 m (the panorama shown in Figure 2 does not include this building) and the second is a church tower placed at 260° within a distance of 100 m. Decrease of z_{0m} values observed in the direction of 270° is the result of the position of sonic anemometer, because this direction is the azimuth of the tower relative to the sensor (Figure 3) and although the tower diameter is of the order of 0.15 m it can cause a

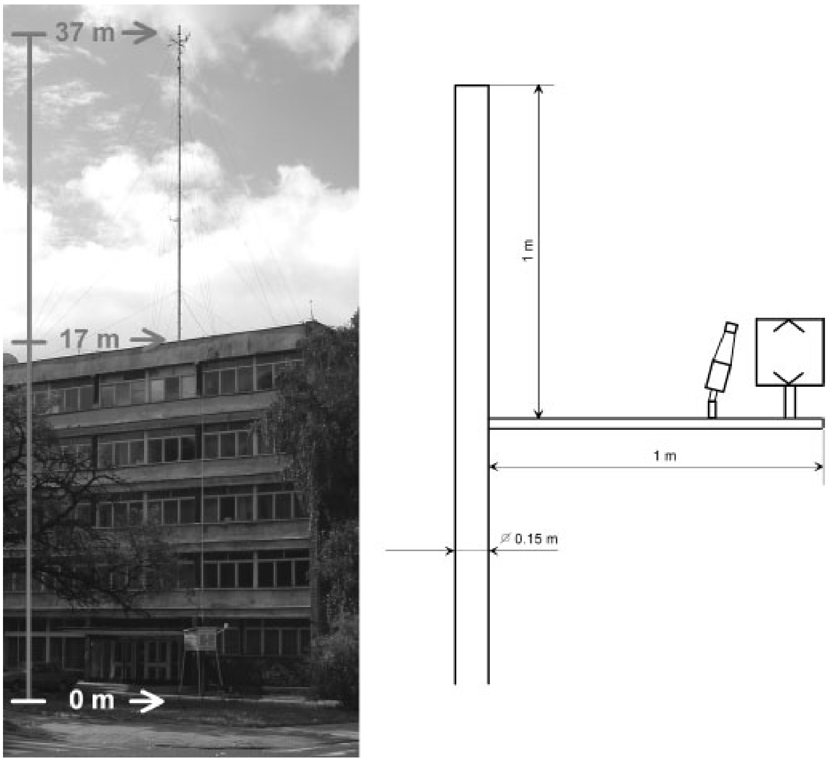

Figure 3. Measurement tower and details of instrument installation at Lipowa Station.

flow distortion owing to the flow interference from the mast. Moreover, between the tower and sonic anemometer the CO_2 gas analyser head is placed (30 cm from the sonic anemometer) and is another potential source of flow distortion. Comparison of wind rises (not presented in the study) calculated for the sonic anemometer data and the wind direction sensor placed at the top of the tower where airflow is not disturbed by the tower are almost identical so there is a possibility that the influence of the tower is relatively small.

High elevation of sensors results in a large source area of turbulent fluxes. Source areas at levels $p = 90$, 75 and 50%, respectively (Figure 1), were evaluated for the analysed period with the aid of an scalar flux-source area model (FSAM) model (Schmid, 1994) surrounding the measurement point with a circular shape up to 1 km in diameter. Calculations were made from all the good data registered during unstable conditions at midday hours (10 : 00 am to 2 : 00 pm). The stability parameter for these data, $(z - z_d)/L$, where L is the Obukhov length, was in the range of −0.05 to −3 with a mean value of −0.35 and the 10th and 90th percentiles equalling −0.77 and −0.074, respectively. For neutral and stable conditions the source areas extend to and can cover parks located to the west and south. The source area of radiation sensors is much smaller and can be evaluated as a circle with a diameter of ∼220 m (for $p = 90\%$).

2.2. Instrumentation and data processing

The eddy covariance sensors are mounted ∼1 m below the top of the tower on its east side about ∼1 m from the tower axis (Figure 3). Fluctuations of vertical wind speed w' and CO_2 density $\rho CO_2{}'$ are measured with a frequency of 10 Hz with an RMYoung 81000 sonic anemometer (RMYoung, Traverse City, Michigan, USA) and a Li-cor 7500 CO_2/H_2O open path infrared gas analyzer (Li-cor, Lincoln, Nebraska, USA). The accuracy of the sonic anemometer is ±−0.05 m s^{-1} for the range of operation 0/30 m s^{-1}. The temperature range operation of Li-cor 7500 is −25 to 50 °C but its accuracy depends on calibration. In this case, the 0 and span of Li-cor 7500 were calibrated once, just before the sensor installation on the tower at the beginning of July 2006. The sensor was not calibrated until the end of the experiment (August 2008), but it was cleaned four times. Cleaning and calibration were not carried out more often because of difficulties with demounting the sensor from the top of the measurement tower. Moreover, according to the manufacturer, Li-cor 7500 emits reference infrared waves, which do not absorb CO_2 and H_2O and are used for correction of waves attenuated by the dirty glasses of the sensor's emitter and receiver. Both sensors are connected to a 21X data-logger (Campbell Scientific, USA). Data are downloaded from the data-logger via serial port RS232 and stored on a PC in files of 15 min. The radiation balance components (incoming and outgoing shortwave, $K\downarrow$, $K\uparrow$, and longwave, $L\downarrow$, $L\uparrow$, radiation) are measured with a CNR1 radiometer (Kipp & Zonen, Delft, Holland), registered with a CR10X data-logger (Campbell Scientific, Logan, Utah, USA) and downloaded via a serial port RS232 to the same PC. The radiation balance Q^* is then calculated as an algebraic sum of measured components. Additional sensors measure air temperature and relative humidity (HMP45C, Vaisala, Helsinki Finland), atmospheric pressure (CS100, Campbell Scientific), wind speed (AR100R, Vector Instruments, Rhyl, Denbighshire, United Kingdom) and direction (W200P, Vector Instruments) with a frequency of 0.1 Hz. F_{CO_2} was calculated as the covariance of fluctuations of vertical wind speed w' and CO_2 density $\rho CO_2{}'$:

$$F_{CO_2} = \overline{w' \cdot \rho CO_2'} \qquad (1)$$

Classical block averaging was used because only this averaging method fulfils the theoretical assumption of turbulent flux calculations (Reynolds averaging) and it is recommended by other groups (Lee *et al.*, 2004). The averaging period was set as 1 h because shorter periods could underestimate fluxes. For example, comparison of fluxes calculated for 1-h block averaging with a mean value of four consecutive fluxes based on 15-min periods shows that fluxes calculated for 15-min periods could be underestimated by about 5% owing to spectral losses. Before the flux calculations, detection of spikes (Vickers and Mahrt, 1997) was carried out. Fluxes were calculated in a rotated coordinate system (natural wind coordinates with double rotation; Kaimal and Finnigan, 1994) and covariance was maximized in the interval ± 2 s (because of the possible influence of separation of sensors). Finally, correction of sonic temperature for humidity (Schotanus *et al.*, 1983) and webb-pearman-leuning (WPL) correction (Webb *et al.*, 1980) were applied. Post-processing data quality verification focused on evaluation of a stationary postulate. We used three stationarity tests: the first was proposed by Foken and Wichura (1996), the second by Mahrt (1998) and the third by Dutaur *et al.* (1999) and Affre *et al.* (2000). Data were excluded from the analysis when all three tests suggested non-stationarity. The total proportion of excluded or missed data in the analysed period is 45.7%, which includes missing data related to the lack of current or computer breakdown (18.0%), data recorded during rainfall and frost deposition, files with <90% good observations (18.5%) and data which failed stationarity tests (9.2%). Missing data is spread throughout the analysis period and equally distributed with the exception of a few cases when there were computer breakdowns and power failure problems (October/November 2006, December 2006 or July 2007; Figure 1).

3. Results and discussion

3.1. Annual variability of carbon dioxide turbulent net flux

Figure 4 shows temporal changes of 1-h averages of basic meteorological elements like radiation balance Q^*, air temperature T and F_{CO_2}. Regardless of the season, a large majority of F_{CO_2} values are positive (upward) and reach values of the order of 0–15 μmol m^{-2} s^{-1}. Negative F_{CO_2} are infrequently observed, with values from 0 to −5 μmol m^{-2} s^{-1}, and exceed −10 μmol m^{-2} s^{-1} in only a few cases. These results show a significant prevalence of CO_2 emission over uptake in the west part of the Łódź city centre, which means that the urban area analysed is a source of CO_2 all year long. Another characteristic feature of F_{CO_2} variability is that in the analysed period it is characterized by an annual course that is the reverse of air temperature or radiation balance courses. F_{CO_2} values observed during the winter season often exceed 30 μmol m^{-2} s^{-1}. Such high F_{CO_2} in wintertime is caused by increased emissions of anthropogenic CO_2 in the cold season from domestic heating sources (Kłysik, 1996; Offerle *et al.*, 2005) and increased traffic densities observed in urban areas especially during the day (Nemitz *et al.*, 2002; Soegaard and Møller-Jensen, 2003; Gratani and Varone, 2005; Vesala *et al.*, 2008). Summertime F_{CO_2} do not exceed values of the order of 15–20 μmol m^{-2} s^{-1}. This can be explained

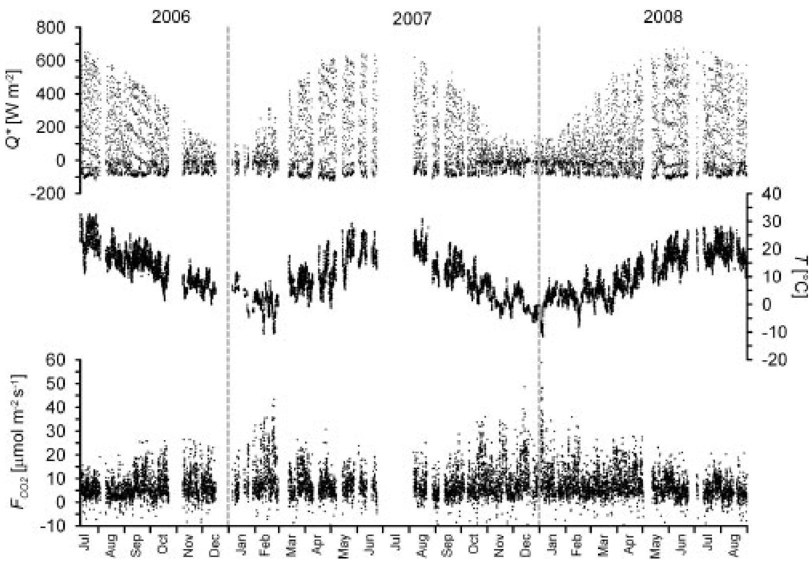

Figure 4. One-hour means of radiation balance Q^*, air temperature T and turbulent flux F_{CO_2}, recorded in the centre of Łódź in the period July 2006 to August 2008.

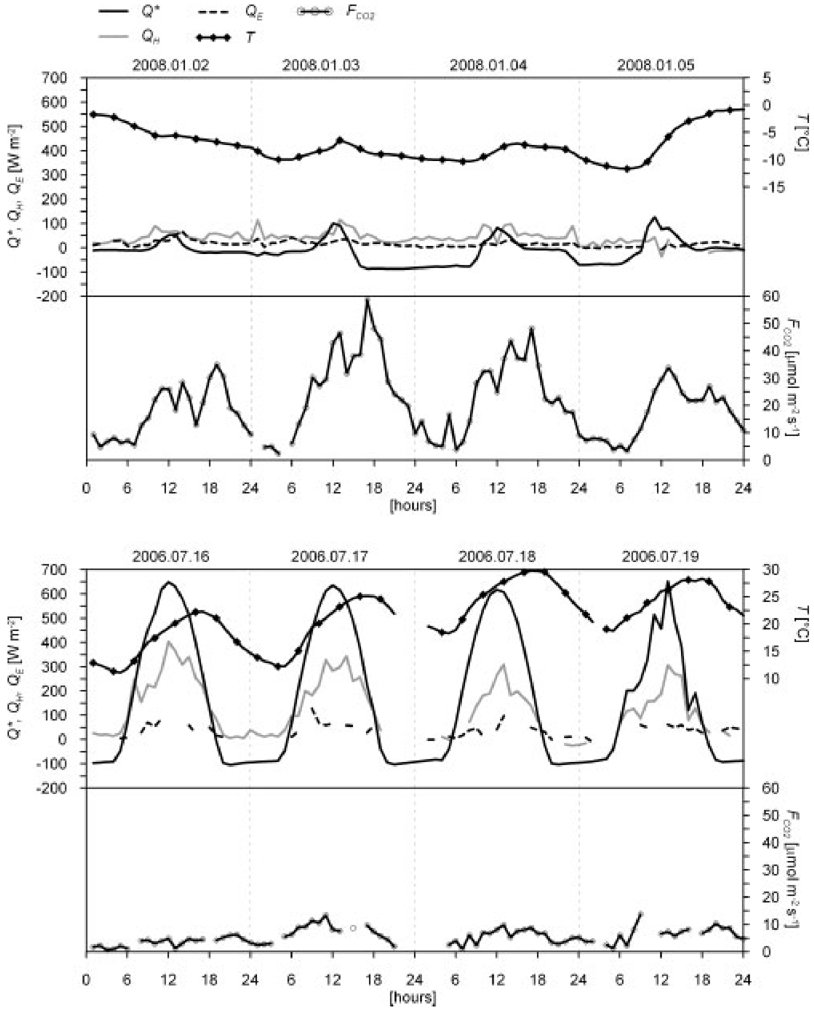

Figure 5. Radiation balance Q^*, sensible heat flux Q_H, latent heat flux Q_E, air temperature T and F_{CO_2} flux variability within selected days in January 2008 and July 2006 (breaks in lines indicate bad or non-stationary data, all values are 1-h averages).

by a decrease in anthropogenic CO_2 emissions (lack of domestic heating and reduced private car traffic) and CO_2 absorption by vegetation. The second reason seems to be much less important. Vegetation accounts for 38% of the surroundings landuse. However, it is predominantly characterized by small lawns interspersed with the street network, and thus the role of absorption of CO_2 during photosynthesis and emission during respiration of plants or soil seems to be rather insignificant. The influence of two green parks in the west and south will be discussed in a later part of this article.

The extremely high F_{CO_2} can be observed only during the winter season. An example of wintertime evolution of fluxes with high values of F_{CO_2} during fine weather characterized by low temperature is presented in the upper graph in Figure 5. Between 2 and 5 January 2008 air temperature decreased at night to $-12\,^{\circ}$C. Sensible heat flux, Q_H, was relatively high, exceeding the radiation balance Q^* even during the day. This is likely to be due to the release of large quantities of anthropogenic heat even during the day (Kłysik, 1996; Offerle *et al.*, 2005). It can also be attributed to a second major anthropogenic source of CO_2, car traffic intensity. During such cold winter days, streets in the centre of Łódź are full of cars moving slowly or standing in long traffic queues. Such a situation occurs particularly in the afternoons and evenings, when people leave the centre and go to the residential quarters. As a result, F_{CO_2} is characterized by a clear diurnal cycle with a maximum in the afternoon or evening hours, when it exceeds 30–40 µmol m^{-2} s^{-1}, reaching 60 µmol m^{-2} s^{-1} on 3 January. The summer season does not favour strong F_{CO_2}, as in the case of a few days in July 2006 (Figure 5, bottom graph). Between 16 and 19 July 2006 the air temperature was higher than $10\,^{\circ}$C all day long and F_{CO_2} reached low values, generally below 15 µmol m^{-2} s^{-1}. The reason is that at this time of year the main anthropogenic sources of CO_2 are very low (car traffic) or do not exist (domestic heating) (Kłysik, 1996; Offerle *et al.*, 2005). Car traffic, especially private car traffic, is reduced because of holidays which start in the last week of June and finish on the last day of August.

3.2. Relationship between net turbulent CO_2 monthly exchange and mean monthly air temperature

As discussed earlier, there are many different sources of anthropogenic CO_2 throughout the year (Kłysik, 1996;

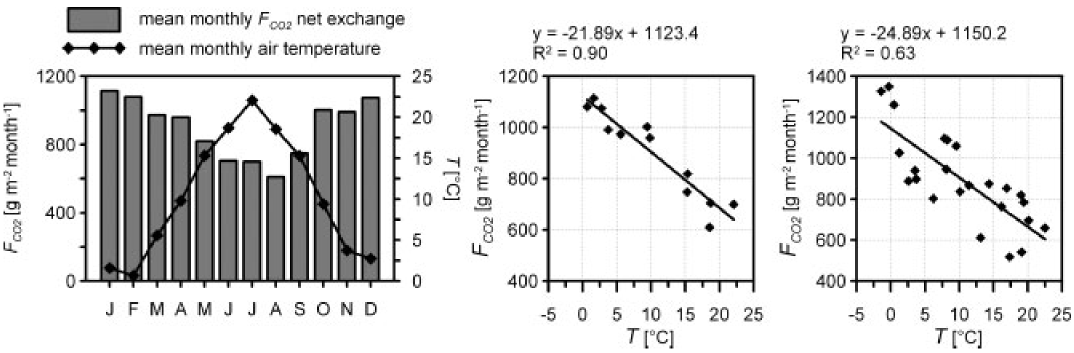

Figure 6. Mean monthly net CO_2 exchange and mean monthly air temperature (left), linear fit between mean monthly air temperature and mean monthly net CO_2 exchange (middle) and monthly net CO_2 exchange (right) in the period July 2006 to August 2008.

Offerle *et al.*, 2005) and the annual course of F_{CO_2} in the part of Łódź analysed is strongly connected with air temperature seasonal variability (Figure 4). A negative correlation can be observed between the mean monthly air temperature and mean monthly F_{CO_2} (Figure 6, left). Monthly totals of F_{CO_2} reach highest values in the order of $\sim$1.1 kg m^{-2} month^{-1} in winter months. The lowest level of mean monthly F_{CO_2} occurs in the summertime, when it decreases to 0.5–0.6 kg m^{-2} month^{-1}. The determination coefficient $R^2 = 0.90$ confirms a tight negative correlation between the mean monthly F_{CO_2} and air temperature (Figure 6, middle). The coefficient calculated for all 26 months (July 2006 to August 2008, Figure 6, right graph) reaches a lower value because of intra-annual variability of mean monthly F_{CO_2} in the period analysed. These results are comparable to those obtained by Pataki *et al.* (2009), who analysed the correlation between heating degree days (HDD) and the proportion of locally-derived CO_2 originating from natural gas combustion. In accordance with these analyses, the higher the value of HDD (lower air temperature), the higher the proportion of anthropogenic CO_2 from fossil fuels combustion. Based on the mean monthly net fluxes, the F_{CO_2} during the whole year has been estimated as $\sim$10.8 kg m^{-2} year^{-1}. This means that the analysed part of the Łódź city centre is a significant source of CO_2 for the troposphere.

3.3. Diurnal variability of carbon dioxide net turbulent exchange

F_{CO_2} variability is characterised by a clear diurnal rhythm (Figure 7). As the factors determining this rhythm change seasonally (anthropogenic emission, vegetation age, length of the day, etc.), the fluxes should be analysed separately for different months. The question of which statistics should be used to describe typical diurnal patterns for individual months must, however, be raised. Many episodes, especially during the cold season, with a very intensive upward CO_2 transport suggest that distribution of the data can be skewed. Distribution of F_{CO_2} frequencies in January and July, as well as mean and median calculated for selected midday (10 : 00 am to 2 : 00 pm) and midnight (10 : 00 pm to 2 : 00 am) hours, confirms this suspicion (Figure 8). Especially for daytime hours in January, the difference between mean and median reaches 3.45 µmol m^{-2} s^{-1}. During daytime periods in the summer and night-time periods in both the winter and summer, differences are much smaller. Nevertheless, both mean and median are used to present diurnal variability of F_{CO_2} for successive months in the period analysed (Figure 7).

Diurnal patterns confirm the annual course of F_{CO_2} and other characteristics described above. Maximal mean values of F_{CO_2} are significantly higher in the cold season, primarily because of the high emission of anthropogenic CO_2 all day long between November and March. In other months, anthropogenic CO_2 fluxes are much lower and exchange is related to the increase in biological processes. In consequence, during the summer months, instead of the F_{CO_2} maximum occurring at noon and in the afternoon, minimum F_{CO_2} occurs at those times. In May, June and August, the minimum starts even before noon. This can be attributed to rapidly increasing photosynthesis, resulting in strong CO_2 uptake which to a high degree offsets the morning peak of car traffic.

Particularly importantly, diurnal patterns of F_{CO_2} in the surroundings of Lipowa Street are positive all day long, regardless of the month. Diurnal F_{CO_2} patterns are irregular but F_{CO_2} maxima in the daytime and minima at the end of the night can be identified in almost all months, especially in the cold season. The minimum F_{CO_2} values occur during the night because of weak turbulence and low values of friction velocity in stable or neutral stratification (Massman and Lee, 2002). As reported from the other measurement sites (Grimmond *et al.*, 2002; Moriwaki and Kanda, 2004; Velasco *et al.*, 2005; Coutts *et al.*, 2007; Vesala *et al.*, 2008), such night-time conditions favour CO_2 storage within the urban canopy layer. After sunrise a rise in F_{CO_2} is observed. It can be attributed to increasing atmospheric instability and developing turbulence which intensifies upward F_{CO_2}, including CO_2 stored within urban canyons during the night. F_{CO_2} increases during forenoon hours, which is also related to rush hours and intensive emission of CO_2 released during fossil fuel combustion by cars. However, the characteristic diurnal pattern of F_{CO_2} of two maxima (one before and one after noon) related to the morning and afternoon rush hours (Vogt *et al.*, 2006; Coutts *et al.*, 2007) is barely recognisable in the centre of Łódź. In the

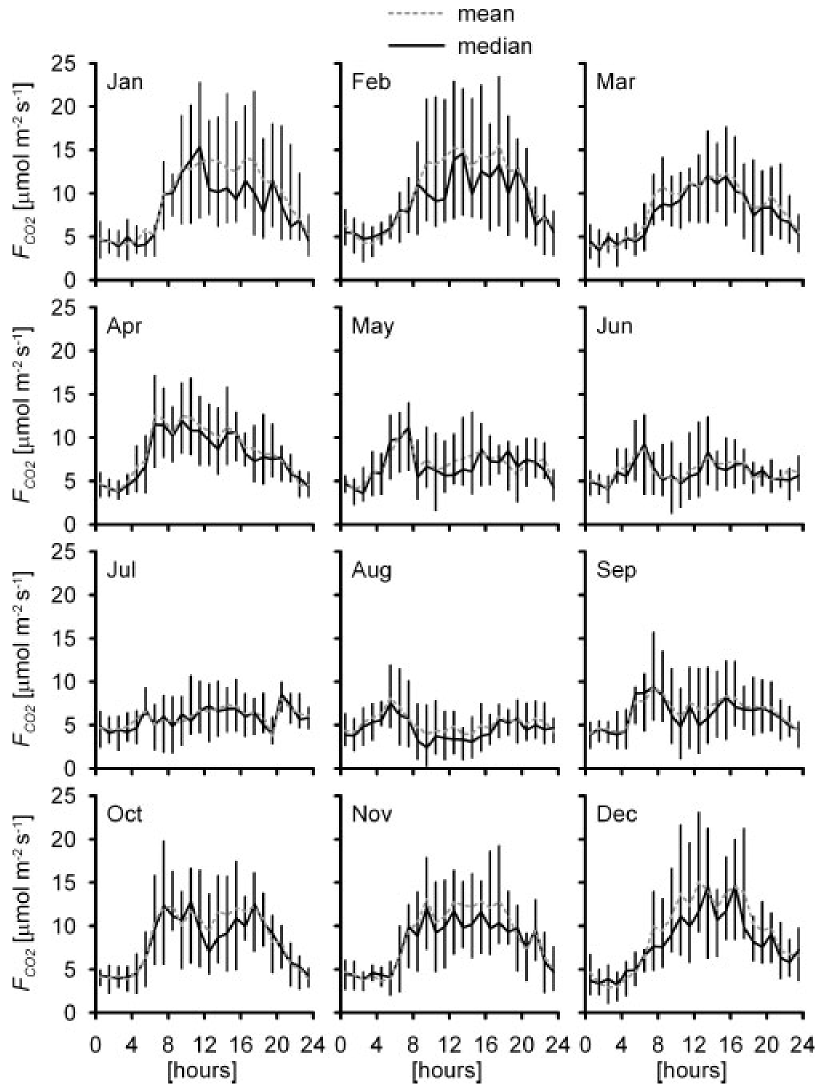

Figure 7. Diurnal courses of median (solid black line) and mean (grey dotted line) values of turbulent flux F_{CO_2} for the months in the period July 2006 to August 2008 based on 1-h data. Vertical black lines indicate values of the first and third quartiles.

case analysed, a broad maximum occurs between 7 : 00 and 8 : 00 am and 6 : 00 and 7 : 00 pm in the majority of months. The magnitude and variability of the F_{CO_2} are smaller during the night compared to the day time period. Typically, the quartile range of the F_{CO_2} is rather small during the night, whereas during the day it is bigger because of stronger turbulence (Figure 7).

The diurnal course of F_{CO_2} calculated for the entire study period is also distinguished by a maximum of the order of 9–10 µmol m^{-2} s^{-1} during the forenoon hours and a minimum before sunrise (Figure 9, left). The highest F_{CO_2} appears at about 4 : 00 to 5 : 00 pm owing to slightly more intensive car traffic in comparison with the morning and forenoon hours. As CO_2 emitted by car traffic is suspected to be a significant anthropogenic source, diurnal courses were recalculated separately for working days (Monday–Friday) and for weekends (Saturday–Sunday; Figure 9). As expected, diurnal courses calculated for different days of the week show similar values of F_{CO_2} at night, but in the midday hours F_{CO_2} is about 1 µmol m^{-2} s^{-1} higher for working days than for the entire week, whereas for the weekends the maximum is lower by about 2–3 µmol m^{-2} s^{-1}. The diurnal courses calculated for all days of the week in the period analysed (Figure 10) confirm this observation: the F_{CO_2} maximum is lower on Saturday and Sunday by about 3 µmol m^{-2} s^{-1}. Moreover, on working days the maximum of F_{CO_2} occurs mainly in afternoon hours. The highest F_{CO_2} appears on Friday owing to intensive car traffic when some people return home from work and others leave town for the weekend. On Sunday afternoons, these people go back to the city and this is the reason for the weak Sunday F_{CO_2} afternoon maximum (Figure 10). The frequencies in all classes are almost equal and differ only by 1 or 2 days. Similar differences between working days and weekends were found in mean daily courses of F_{CO_2} in seasons (Figure 9). The differences in spring and autumn are quite similar to those calculated for the entire study. In summer, regardless of the day of the week, a clear minimum of F_{CO_2} occurs before noon (working days and entire week) or before and after noon (weekends). The F_{CO_2} from Monday to

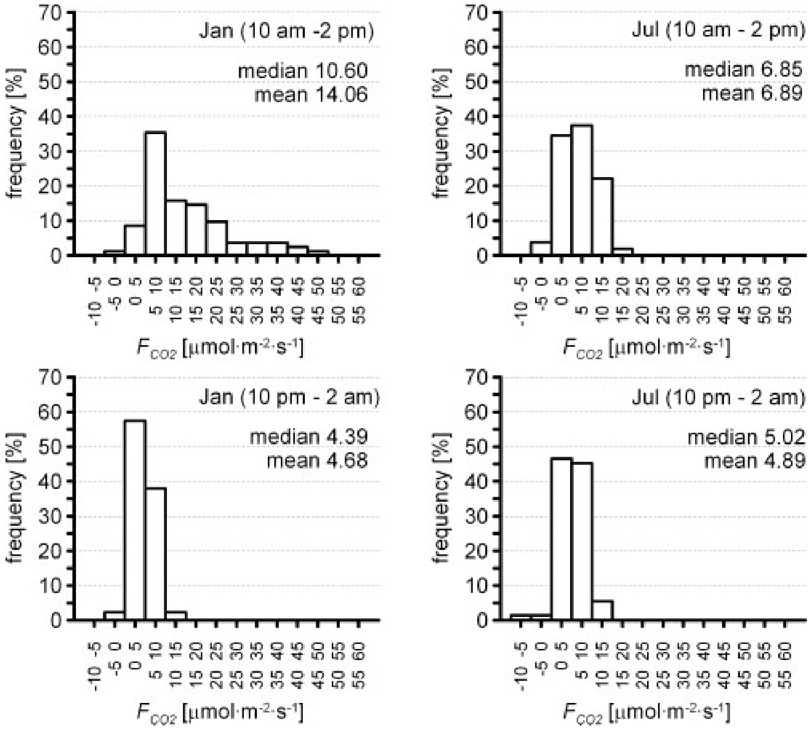

Figure 8. Frequency distribution of 1-h F_{CO_2} flux calculated for midday (10 : 00 am–2 : 00 pm) and midnight (10 : 00 pm–2 : 00 am) hours in January and July.

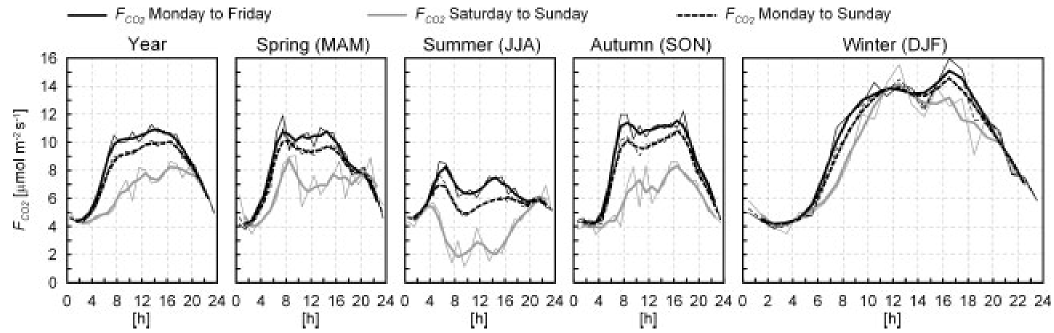

Figure 9. Mean diurnal courses of turbulent flux F_{CO_2} in the period July 2006 to August 2008 calculated for the week (dotted thin black line), working days (solid thin black line) and weekends (solid thin grey line), and smoothed by a three-element running average (thick lines).

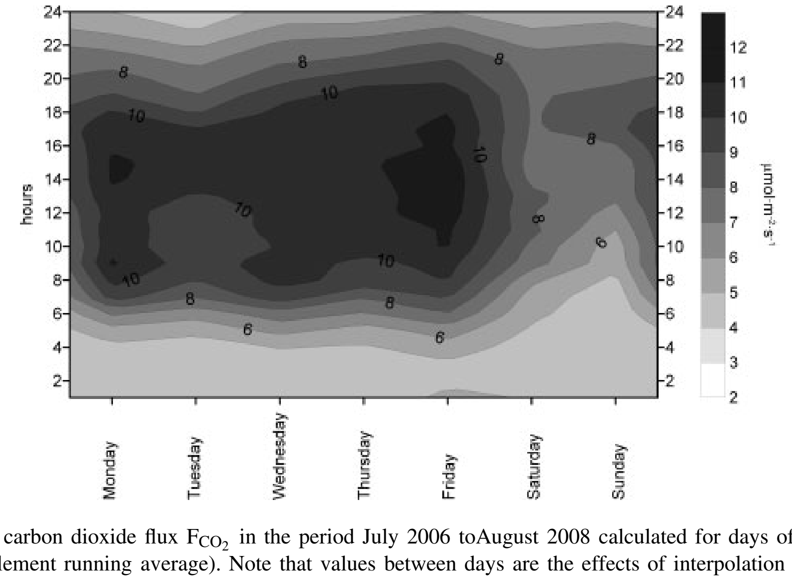

Figure 10. Mean values of carbon dioxide flux F_{CO_2} in the period July 2006 toAugust 2008 calculated for days of week (based on 1-h values and smoothed by a three-element running average). Note that values between days are the effects of interpolation and do not show night-time values of F_{CO_2}.

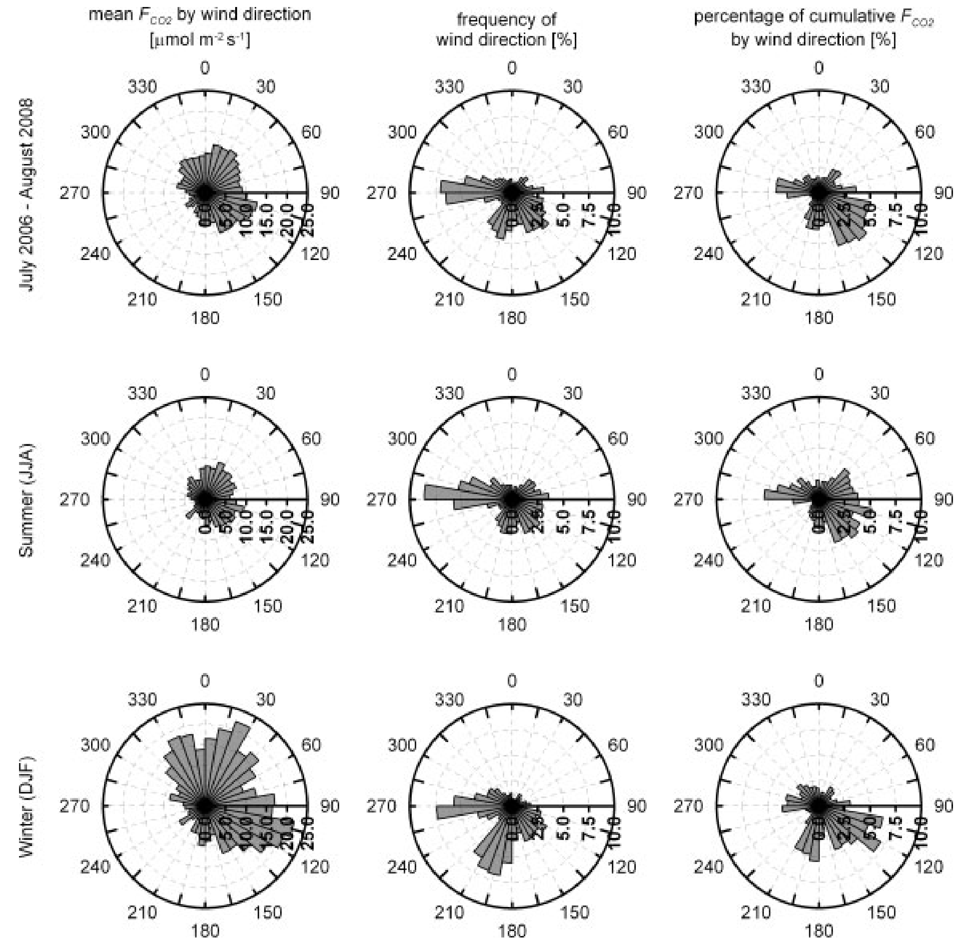

Figure 11. Mean F_{CO_2} flux, wind direction frequency and percentage of total F_{CO_2} by wind direction (10° intervals) calculated for all available data in the period July 2006 to August 2008.

Friday is ~1 μmol m^{-2} s^{-1} greater in comparison with that for the entire week, but for weekends the diurnal F_{CO_2} course has a completely different pattern (Figure 9, middle). First, turbulent emissions are ~4 μmol m^{-2} s^{-1} smaller; second, summer weekends are the only occasion when, on average, an afternoon minimum of F_{CO_2} occurs and third, the afternoon F_{CO_2} peak visible during autumn and spring in summer shifts to the evening hours (8 : 00 to 10 : 00 pm). There are three possible factors contributing to this effect: lower emissions of anthropogenic CO_2 due to minimal anthropogenic heating, less intensive car traffic due to holidays in July and August and a considerable increase in the uptake of CO_2 by urban vegetation. Plant leaves have their largest surface area during this period, so sequestration in the photosynthesis process plays an important role in CO_2 exchange and significantly reduces anthropogenic CO_2 emissions. Moreover, summer F_{CO_2} maximum is observed in the evening hours because the car traffic intensity increases on Sunday evening. The long hours of daylight mean that people go back to the town later than in other seasons. In the winter (Figure 9, right), the mean diurnal weekend course also reaches lower values as a result of less intensive car traffic during weekends. The most important source of CO_2 during wintertime is related to domestic heating, which is on the same level regardless of the day of the week, but differently from other seasons' mean diurnal courses calculated for working days and weekends reach equal values around noon. Analysis of the data reveals that the significant increase in F_{CO_2} observed around noon at weekends is related to a peak in F_{CO_2} observed on Saturdays (the diurnal pattern observed on Sundays is lower than working days throughout the diurnal period). This case is difficult to explain. Such an increase could be related to increase of car traffic (e.g. many people go shopping at that time) but, however, such F_{CO_2} increase is observed on Saturdays in other seasons albeit not so strongly.

3.4. Carbon dioxide turbulent exchange and airflow direction

In the entire analysis period, the dominant wind directions were west and south-west. A similar distribution was observed in summer but during wintertime the western flow dominated (Figure 11). The frequency of airflow from these directions exceeded 5% (Figure 11, middle column), but these airflows were not linked with the highest values of F_{CO_2}. The highest mean F_{CO_2} was observed for airflow from the north-east, east, and south-east sectors – from the city centre (Figure 11, left column). Figure 1 shows the marked differences in land development in different directions around the neighbourhood of Lipowa Station. Although the area immediately surrounding the station and to the north and east can be described as uniform, compact and densely built-up terrain, the western and southern parts of the city centre are not so densely built-up and contain the two green parks described earlier. Thus, the western and southern parts of the city centre on average seem to be a less significant source of CO_2 because during airflow from the west, lower emissions of CO_2 are observed and, especially in summer, CO_2 is additionally absorbed by plants in parks. The maximum F_{CO_2} associated with westerly airflow patterns was $\sim$5 µmol m^{-2} s^{-1}, whereas the F_{CO_2} observed with easterly airflow patterns is at least a few times larger and reaches almost 20 µmol m^{-2} s^{-1} in winter. This is because of much lower vegetation and more intensive car traffic in this direction (city centre). The percentage distribution of total F_{CO_2} (Figure 11, right column) shows that the total amount of emitted CO_2 is related to western and south-eastern airflow.

4. Conclusions

This study has implications for our understanding of the influence of anthropogenic CO_2 emissions on turbulent vertical CO_2 transport between the densely built-up urban surface and the lower troposphere. The analysis of 2 years of eddy covariance measurements of F_{CO_2} in the west part of the centre of Łódź reveals the following results.

First, it shows that strong positive F_{CO_2} dominates throughout the year. This indicates that the centre of Łódź mostly emitted CO_2 and the urban surface analysed is a net source of this gas regardless of the season. These results are in agreement with those obtained in other cities like Chicago (Grimmond *et al*., 2002), Edinburgh (Nemitz *et al*., 2002), Copenhagen (Soegaard and Møller-Jensen, 2003), Tokyo (Moriwaki and Kanda, 2004), Mexico City (Velasco *et al*., 2005), Melbourne (Coutts *et al*., 2007) and Helsinki (Vesala *et al*., 2007). Measurements obtained from Łódź are similar to those obtained for sites established in city centres like Tokyo, Edinburgh and Helsinki (Roth and Velasco, 2010). Our results confirm that one of the factors determining CO_2 exchange intensity is land use. December mean values of measurements obtained in the Łódź site, where $\sim$60% of surfaces are covered by artificial materials, are on average 10 µmol m^{-2} s^{-1} lower than in Tokyo (80% of artificial surfaces). Autumn mean values are on average 25 µmol m^{-2} s^{-1} lower than those obtained in the densely built-up Edinburgh centre, but then are $\sim$5 µmol m^{-2} s^{-1} higher than in Helsinki where vegetation covers an average 46% of all surfaces. Maximum observed values of the order of 60 µmol m^{-2} s^{-1} are lower than in Edinburgh, where emission rates higher than 75 µmol m^{-2} s^{-1} were found.

Second, the F_{CO_2} exhibited an annual pattern that is the reverse of the air temperature course, with maximum values in winter and minimum values in summer. As in the sites specified above, such a rhythm can be attributed to the annual course of anthropogenic CO_2 flux that is strong in wintertime and relatively small and additionally reduced in summer, and warm because of CO_2 uptake by vegetation.

Third, biological processes like photosynthesis and respiration of plants and soil, which lead to uptake or emission of CO_2 and dominate in rural areas, play a meaningful role in urban areas only during the warm season. In the centre of Łódź, there are reduced areas of surfaces covered by vegetation, very small areas with trees or bushes and intensive anthropogenic CO_2 emission. Measurements show that even such a small amount (<40%) of green surfaces (mainly grass) interspersed within the net of streets leads to a clear reduction of F_{CO_2}. On average, F_{CO_2} is 10 µmol m^{-2} s^{-1} lower during the daytime from April to September than in the winter months. What should be emphasized is that such a decrease in CO_2 exchange is also caused by reduced anthropogenic CO_2 sources, especially during the summer season. This is a common effect of these two factors. Moreover, as noted earlier, CO_2 uptake from the atmosphere depends on vegetation cover. Our summertime results describing non-intensive CO_2 exchange are similar to those obtained in the other city centre sites mentioned. Emission rates obtained for the residential site of Preston in Melbourne are 1–2 µmol m^{-2} s^{-1} higher (Coutts *et al*., 2007).

Fourth, significant differences in mean diurnal courses calculated for weekdays and weekends related to the variability of CO_2 emitted by car traffic suggest the existence of a specific weekly variability of vertical turbulent CO_2 transport that does not occur in natural processes. This phenomenon is observed during all seasons with one exception. In the wintertime, at noon hours, the mean weekend F_{CO_2} values are as high as those on working days. We have no explanation for such a phenomenon.

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