Atmos. Chem. Phys. Discuss., 12, 7677–7704, 2012 www.atmos-chem-phys-discuss.net/12/7677/2012/ doi:10.5194/acpd-12-7677-2012 © Author(s) 2012. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Eddy covariance measurements of CO₂ and energy fluxes in the city of Beijing

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Received: 25 November 2011 – Accepted: 6 February 2012 – Published: 16 March 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Long-term measurement of carbon dioxide flux (F_c) was performed using the eddy covariance (EC) method in the Beijing megacity over a 4-yr period in 2006–2009. The EC setup was installed at a height of 47 m on the Beijing 325-m meteorological tower in the northwest part of the city. Latent heat flux dominated the energy exchange 5 between the urban surface and the atmosphere in summer, while sensible heat flux was the main component in the spring. The source area of the measurements of CO₂ is highly heterogeneous, which consists of buildings, parks, and highways. It is valuable for global carbon budget research to study the temporal and spatial variability of F_c in this urban environment of a developing country. Both on a diurnal and monthly 10 scale, the urban surface acted as a net source for CO_2 and downward fluxes were only occasionally observed. The diurnal pattern of F_c showed dependence on automobile traffic and the typical two peak traffic pattern appeared in F_c diurnal cycle. Also, the $F_{\rm c}$ was higher on weekdays than on weekends due to the higher traffic volumes on weekdays. On seasonal scale, F_c was generally higher in winter than during other seasons, likely due to domestic heating during colder months. Total annual average CO_2 emissions were estimated to be 4.90 kg C m⁻² y⁻¹ over the 4-yr period.

1 Introduction

The proportion of the world's population living in urban areas has increased over the past several decades. In China, urbanization has rapidly increased following the reform and opening policy in effect since 1978. At the end of 2009, 46.6% (about 622 million) of China's inhabitants resided in urban environments and this fraction is expected to increase (Pan and Niu, 2010). One of the most important impacts of urbanization on local and regional climates is the emissions of greenhouse gases (primarily CO₂) to the atmosphere and changes in land use (Kalnay and Cai, 2003). Urban areas emit 30–40% of all anthropogenic greenhouse gases, even though they currently cover only





about 4% of the world's dry land surface (Satterthwaite, 2008). CO_2 is one of the most important greenhouse gases, and a significant increase in CO_2 concentrations from 280 ppm in pre-industrial times to 379 ppm in 2005 is the probable cause of the mean air temperature increase of approximately 0.6 °C observed during the last 100 yr (IDCO 4.54, 2007).

- ⁵ (IPCC AR4, 2007). However, knowledge of the magnitude and temporal variability of surface-atmosphere CO₂ exchange in cities has been limited up until the recent years. There is a need to make continuous CO₂ exchange measurements over urban surfaces to provide useful information for CO₂ emission monitoring and to local policy- and decision-makers to make plans to reduce CO₂ emissions from anthropogenic sources.
- Quantification of the urban CO_2 emissions is difficult due to the complex morphological nature of the urban landscape. The most common approaches to quantifying urban CO_2 emission are based on estimates of fossil fuel consumption rather than direct measurements of CO_2 concentration or flux (Grimmond et al., 2002; Vogt et al., 2006). These approaches do not, however, consider the heterogeneity and variability of the
- emission sources (Velasco and Roth, 2010). Advances in instrumentation, notably the eddy covariance (EC) technique, offer a tool to directly measure representative flux data from urban areas. The EC technique has been widely used to measure the net CO₂ exchange of various natural or agricultural ecosystems as part of the global flux network (Baldocchi et al., 2000, 2001), but its application in urban areas remains less
- ²⁰ common. With a few exceptions (Crawford et al., 2011), existing, published long-term (>3 yr) urban flux data sets are rare. Moreover, urban EC studies have mainly focused on cities in developed countries (e.g. Bergeron and Strachan, 2011; Coutts et al., 2007; Grimmond et al., 2002; Matese et al., 2009; Nemitz et al., 2002; Pawlak et al., 2011; Vesala et al., 2008; Vogt et al., 2006). The characteristics of urban CO₂ exchange in
- developing countries, where the degree of industrialization is relatively lower than that in developed countries, are largely unknown, with the only reported measurements from Mexico City (Velasco et al., 2009) and Cairo (Burri et al., 2009).

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Urban CO₂ exchange measured with the EC method represent an integrated response from anthropogenic, biogenic and meteorological factors, and the distribution of their sources and sinks is highly heterogeneous (Vogt et al., 2006). However, urban areas are consistently reported to be a net source for CO₂ on both daily and seasonal timescales, with a strong dependence on the vegetation fraction and human activities (Coutts et al., 2007; Grimmond et al., 2002, 2004; Helfter et al., 2011; Matese et al., 2009; Velasco et al., 2009; Vesala et al., 2008; Vogt et al., 2006). Maximum emis-

sions are typically observed to be consistent with the highest traffic volumes during

- rush hours (Coutts et al., 2007; Vesala et al., 2008). Previous studies have also shown
 large variations of CO₂ flux on seasonal timescales (Bergeron and Strachan, 2011; Crawford et al., 2011; Pawlak et al., 2011; Vesala et al., 2008). Besides traffic, fossil fuel burning for domestic heating can also cause high CO₂ emission levels in winter (Bergeron and Strachan, 2011; Matese et al., 2009; Pawlak et al., 2011). In dense urban areas, CO₂ flux is partly reduced by urban vegetation in summer, but the effect
 is not typically significant enough to offset the emissions from anthropogenic sources
 - (Coutts et al., 2007; Grimmond et al., 2002).

As part of its promise to stage a green Olympics in 2008, Beijing made great efforts to improve its air quality. An odd-even traffic restriction scheme was implemented to reduce traffic congestion on the roads for two months (from July 20 to September

- 20). On days when odd numbered license plates were allowed, vehicles with license plates ending in an even number were prohibited from operating. This regulation was expected to take 45 percent of the city's 3.29 million vehicles off the roads and to reduce vehicle emissions by 63%. In addition, many factories both in and around Beijing were closed for the duration of the Games because they were not expected
- to meet the temporarily increased environmental standards. Song and Wang (2012) analyzed the impact of the reduction of vehicles on CO_2 flux during the Games, and found significant lower flux during this period. However, the analysis was restricted to a year. The differences of CO_2 flux between weekdays and weekends, and the annual variations of CO_2 emission in the long-term are of interest.





This study shows the first long-term urban CO_2 flux (F_c) from Beijing megacity measured with the EC method. This article also contributes to the small number of studies on the net CO_2 exchange in developing countries. The objectives of this study are: (1) to quantify the magnitude of F_c in Beijing; (2) to examine the temporal F_c patterns at diurnal, seasonal, and annual time scales; (3) to examine the spatial variability of F_c in a complex urban environment; and (4) to examine the annual variations of total CO_2 emission.

2 Site description and instrumentation

2.1 The Beijing megacity

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- Beijing, the capital of China, is among the most developed cities in China. It is located in the northern part of the North China Plain and is surrounded by the Yanshan Mountains to the west, north, and east, whereas the small alluvial plain of the Yongding River lies to its southeast. The city has a moderate continental climate with hot, humid summers due to the East Asian monsoon and winters that are generally cold and dry, reflecting the influence of the Siberian anticyclone. The total population in Beijing exceeded 22 million at the end of 2009, making it one of the largest megacities in the world. The municipality's area was estimated to be 16 800 km² and the population density 1309 people per km² in 2009. Caused by rapid urbanization, the increase in vehicle numbers in Beijing has been dramatic: the number of registered vehicles has increased from 2.9
- ²⁰ million in 2006 to 4 million by the end of 2009.

2.2 Site description

The measurements were carried out at a 325-m meteorological tower $(39^{\circ}58' \text{ N}, 116^{\circ}22' \text{ E}, 60 \text{ m} \text{ a.s.l.})$ in the northwest part of Beijing, about 8 km from Tiananmen Square. The tower, built in 1979, has specially been designed for meteorological observation and environmental monitoring. At the time when the tower was built, the





surrounding area was a less built-up area covered by rural croplands and could be classified as suburban. As a result of the rapid urbanization of Beijing since 1980s, the surroundings of the tower have been totally altered to be an urban area and are nowadays clearly more heterogeneous (Fig. 1). The tower adjoins a small park of about 0.3 km² in the west mainly consisting of deciduous trees and lawns. To the east of the

- tower, an expressway (the Beijing-Tibet Expressway) with heavy traffic loads crosses from south to north. Another busy road (Beitucheng West Road) crossing from east to west is located north of the tower. Dense residential buildings are situated in the south and the north, and these areas are characterized by low vegetation cover. The percent-
- age of vegetated area within a circle around the tower corresponding to about 90 % of the footprints, as derived from satellite photographs via color filtering techniques, is approximately 15 %. Within a circle corresponding to 50 % of the footprints, the surrounding area can be divided into four surface cover sectors: the NE sector and the SE sector can be classified as "compact midrise", the SW sector as "compact highrise"
- ¹⁵ and the NW sector as "close-set trees" according to the classification system proposed by Stewart (2009). According to the estimations using the wind profile obsersvations from the tower by Li et al. (2003), the aerodynamic roughness lengths (z_0) in NE, SE, SW, and NW are 2.5 m, 3.0 m, 5.3 m, and 2.8 m, respectively, and the zero-plane displacement heights (d) are 12.3 m, 15.0 m, 26.4 m, and 13.2 m, respectively. The larger z_0 and d in the southwest can be attributed to the tall residential buildings (with the
- mean height of 45.0 m) in this direction. The vegetation fractions for the four sectors are estimated to be 10.7 %, 18.2 %, 12.9 % and 18.6 %, respectively.

2.3 Instrumentation

The EC setup was mounted 47 m above the ground to continuously measure the exchange of CO₂, heat, water, and momentum. The measurement height is almost 3 times the mean displacement height (~16.7 m) in the close surroundings (except in the SW sector), which ensured that measurements were taken in the constant flux layer (Grimmond et al., 2002). The EC setup was mounted on a 2-m horizontal boom



to minimize flow distortions from the tower. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA) was used to directly measure horizontal and vertical wind velocity components and virtual temperature. An openpath infrared gas analyzer (IRGA, LI-7500, Licor Inc., Lincoln, NE, USA) was used to
⁵ measure fluctuations of water vapor and CO₂ concentrations. Both instruments were operated at a sampling frequency of 10 Hz. The IRGA was calibrated at an interval of six months using a dew point generator and standard gases. In addition, air temperature and humidity at the same level were measured using a thermometer and a hygrometer (developed in Institute of Atmospheric Physics). In addition, wind speed and direction were measured at 15 different levels (8 m, 15 m, 32 m, 47 m, 63 m, 80 m, 102 m, 120 m, 140 m, 160 m, 180 m, 200 m, 240 m, 280 m, 320 m) using cup anemometers and vanes (developed in Institute of Atmospheric Physics). The daily and monthly precipitation or air temperature data were obtained from the Caoyang weather station about 10 km southeast of the site.

15 3 Method

In this study we analyzed the EC data over four-year period from 2006 to 2009. Vertical flux F was calculated as a covariance between the vertical velocity w and scalar s of interest according to the eddy covariance technique (Lee et al., 2004):

 $F = \overline{w's'}$

²⁰ Before calculating half-hourly fluxes of CO₂, water, sensible heat and momentum, spike detection and data rejection algorithms were applied using dynamic mean and standard deviation values within a series of moving windows as described by Vickers and Mahrt (1997). Data were rotated into streamwise coordinate system using a double rotation procedure so that the mean vertical velocity was forced to be zero (Kaimal and Finnigan, 1994). The sonic temperature for humidity was corrected following Schotanus et al. (1983). Theoretical spectral corrections (about 2% of the original



(1)



fluxes) were made for high-frequency losses due to sensor separations, path averaging and sensor frequency response (Massman and Lee, 2002). The water vapor and CO_2 fluxes were also corrected for the density fluctuations (Webb et al., 1980). Data quality was assessed using the steady state test and integral turbulence characteristic test

⁵ suggested by Foken et al. (2004). Data not passing the tests were excluded from the analysis. It should be noted that nocturnal fluxes in non-urban ecosystems are known to be underestimated by EC measurements due to the low-turbulence conditions prevailing at night (Aubinet, 2008). However, the u_{*} filtering approach is problematic in urban areas because the urban boundary layer is not always stable at night due to
 ¹⁰ anthropogenic heat emissions, releases of storage heat to the boundary layer, and the heterogeneity of the urban canopy (Crawford et al., 2011). Therefore, no u_{*} filtering was applied in this study.

Data gaps originating from power failures, instrument calibration errors, and sensor malfunctions accounted for 13.2 % during the four-year study period. Out-of-range data

- ¹⁵ removal and spikes detection (outside 3 times of standard deviation from mean value) removed an extra 3.1 % of data. Low-quality data caused by precipitation, dust, or other contamination on the sensor optics, which were indicated by the active gain control (AGC) values of the LI-7500, resulted in 6.9 % of eliminated data. Data that failed the stationary test caused another 6.1 % of the data gaps. Overall, the data coverage
- for the study period was approximately 70 %. Missing data were reconstructed using a gap-filling strategy as follows: (1) small gaps (<2 h) were replaced with linear interpolations; (2) medium gaps (<2 days) were rebuilt based on the mean diurnal variation (MDV) on adjacent days (Falge et al., 2001); and (3) large gaps (>2 days) were rebuilt using a multiple imputation method following Hui et al. (2003). Related meteorologi-
- ²⁵ cal variables such as air temperature, humidity, and wind direction were input in the imputation.





4 Results and discussion

4.1 Environmental conditions

General meteorological conditions during the study period are shown in Fig. 2. The annual total precipitation in Beijing for the four-year period was 473 mm in 2006, 452 mm

- ⁵ in 2007, 619 mm in 2008, and 606 mm in 2009, respectively, with maxima observed during the summer months. The average air temperature over the 4-yr period was 13.3 °C and the extreme air temperatures during the study period ranged from –14.6 °C in February to 37.7 °C in June. The hot and rainy summers are caused by the monsoon winds that bring warm and humid air from the southeast to the Beijing area. Obser-
- ¹⁰ vations of the atmospheric stability defined as $\zeta = (z d)/L$, where *z* is the measurement height and *L* is the Obukhov length, showed that the number of unstable cases ($\zeta < -0.05$) was about 10 % more than the number of stable cases (Fig. 3a). Also 8.6 % of the unstable cases were observed to occur during nighttime (Fig. 3b). The fraction of unstable cases in Beijing is much lower than observed in London where unstable
- cases were three times more common than stable cases (Wood et al., 2010). Also, the number of unstable half hour periods at nighttime was much higher in London than in this study indicating higher nocturnal heat emissions to the atmosphere in their source area. The wind rose measured over the 4-yr period showed prevailing northwesterly and southeasterly winds (Fig. 4). Winds from the 270°–360° sector occurred during 39.5% of the study period, whereas the 90°–180° sector accounted for 33.9% of the study period. It should be noted that high wind speeds were recorded more frequently
- in the northwest sector, whereas the southwest sector experienced low wind speeds due to the tall buildings in this direction.

4.2 Time series of turbulence fluxes

Figure 5 shows the annual behavior of sensible heat flux (*H*), latent heat flux (Le), and carbon dioxide flux (F_c) at 30-min intervals, and the daily precipitation measured





at Caoyang weather station. Also, monthly Bowen ratio calculated as a ratio between the sensible heat and latent heat fluxes is plotted. During the dry seasons, H is the dominant heat flux and reaches its maximum of 250–300 W m⁻² in spring. Le is small (generally less than 100 W m^{-2}) during the dry season due to the lack of precipitation and therefore also evaporation (Fig. 5e). Bowen ratio reaches its maximum 2-2.5 just in the beginning of the dry season when Le is below 100 W m⁻². During the rainv season, Le reaches its maximum of 250-350 W m⁻² in July or August, and the Bowen ratio decreases to less than 0.5 (Fig. 5d). Positive (upward) $F_{\rm c}$ ranging between 0- $3 \text{ mg m}^{-2} \text{ s}^{-1}$ are observed regardless of the season, while negative (downward) F_c are only observed occasionally, with values generally from -1.5 to $0 \text{ mg m}^{-2} \text{ s}^{-1}$ (Fig. 5c). 10 This indicates that CO_2 emissions dominate the CO_2 exchange between the urban surface and the atmosphere. Furthermore, the largest upward fluxes are observed in winter during the colder months when likely more traffic and domestic heating take place. The characteristic features of F_c variability on diurnal, seasonal and annual time scales analyzed below are based on this time series.

4.3 Diurnal variation of energy fluxes

Average course of Le was found to be significantly changed between summer and winter (Fig. 6). Maximum Le at midday was observed to be 137.1 W m^{-2} in JJA, while it was less than 20 W m^{-2} in DJF. The much higher Le in summer was caused by the large amount of precipitation brought by the monsoon. Maximum *H* at midday was observed to be 67.8 W m^{-2} in JJA, while it was 82.1 W m^{-2} in DJF. The difference in the average course of *H* between summer and winter was not significant, with slightly higher maximum values at midday in winter. The results indicate that the climate makes a clear distinction between the wet and dry season in Beijing city. The relationship between energy fluxes and climate in urban areas is beyond the scope of this paper

and will not be discussed here.





4.4 Diurnal variation of F_c

For the diurnal F_c patterns, data were averaged over seasons (winter = DJF, spring) = MAM, summer = JJA and fall = SON) due to similarities in months (Fig. 7). During all seasons the nocturnal fluxes are lower than in daytime when the diurnal variation is characterized by a distinct two peak pattern following the traffic rush hours. In winter, higher F_c is measured over the mean diurnal course, ranging from 15.9 to 31.82 μ mol m⁻² s⁻¹, with an average value of 18.86 μ mol m⁻² s⁻¹. Also, the morning peak is pronounced in winter, likely due to increased emissions from fossil fuel usage during the colder months. Also, the morning peak seemed to have two maxima: the first 26.59 μ mol m⁻² s⁻¹ appeared at 08:00 and is related to intensive traffic flow. 10 The second peak $30.45 \text{ mg m}^{-2} \text{ s}^{-1}$ at 11:00 is likely caused by human activity and the more unstable stratification during daytime (Fig. 3b). On some occasions during the study period, the morning peak reached $68.18 \,\mu$ mol m⁻² s⁻¹. During other seasons. the net CO₂ fluxes are lower due to the increase in biological processes and reduction in anthropogenic emissions. In summer, the mean diurnal course ranged from 8.86 15 to $18.86 \,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$, with an average of $12.73 \,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$. Unlike in winter, the morning peak of F_c has a flat maximum, as human activities began earlier during the warm season and there is an earlier sunrise. In all seasons the evening peak is broad and maxima are observed between 18:00-20:00, indicating emissions from cooking and other household activity after returning from work. In summer, the peak extended 20 longer due to the longer day. The consistently positive values of F_{c} indicate that the

source area is always a net source of CO_2 .

As automobile traffic is a considerable source of CO_2 , the diurnal variations were also analyzed independently for weekdays and weekends (Fig. 7). F_c in weekdays and weekends are very similar through the year, except during the morning rush hours

and weekends are very similar through the year, except during the morning rush hours when higher emissions are observed during the weekdays. This is due to the vehicular traffic caused by the work commuters. It seems that in Beijing the difference between weekday and weekend traffic is not as pronounced as is typically observed in cities





in Western countries. Otherwise, the observed diurnal behavior of F_c follows those measured in other cities where pronounced two peaked pattern has been observed (Coutts et al., 2007; Bergeron and Strachan, 2011; Vesala et al., 2008; Vogt et al., 2006). The mean values of F_c measured at our site (18.86 µmol m⁻² s⁻¹) in winter are lower than those in Montreal, Canada (~20.0 µmol m⁻² s⁻¹) (Bergeron and Strachan, 2011) and Firenze, Italy (~25.68 µmol m⁻² s⁻¹) (Matese et al., 2009). The mean values of F_c measured in the summer at our site were, by contrast, higher than those recorded in Mexico City in Mexico (~9.32 µmol m⁻² s⁻¹) (Velasco et al., 2009), Melbourne in Australia (~10.91 µmol m⁻² s⁻¹) (Coutts et al., 2007), and Basel in Switzer-land (~12.5 µmol m⁻² s⁻¹) (Vogt et al., 2006).

4.5 Spatial variation of F_c

The net CO_2 exchange between the atmosphere and the urban surface is a result of a combination of anthropogenic and biogenic processes. CO_2 sources and sinks are heterogeneous within the flux source area. By analyzing the differences in F_c values based on wind direction, it is possible to investigate the role of local sources in different surface cover areas (Fig. 8).

In winter, the dominant wind direction is northwest with 49% of airflows coming from this direction. The highest F_c values, i.e., about 28.41 µmol m⁻² s⁻¹ during the daytime, are observed from the northeast portion of the study area, which corresponds to ²⁰ the sector with the heaviest traffic loads. During the night, F_c values in the east and northeast are substantially reduced due to the reduction of automobile traffic. On cold winter nights, people usually do not go outside, and automobile traffic volumes are much lower than usual. The highest F_c values were measured when winds blow from the northwest and south, where two dense residential areas are situated.

In summer, the heavy automobile traffic on the expressway and the prevalent southeasterly winds contributed to the highest daytime F_c values (about 22.73 µmol m⁻² s⁻¹). The measured F_c values in the west were much lower due to CO₂ uptake by vegetation





in the park. The photosynthetic processes by urban vegetation, even in such a small park, can play a role in the absorption of CO_2 . At night, F_c generally drops below 9.10 µmol m⁻² s⁻¹, except in the southeast. The higher F_c values in the southeast are due to CO_2 emissions from the expressway in the prevalent wind direction. The results reveal that F_c in urban areas is largely determined by the prevailing surface cover within the flux source area.

4.6 Annual variability of F_{c}

Seasonal and annual variations of F_c were assessed by calculating average monthly F_c from the non-gap-filled half hourly dataset. As already shown by the diurnal behavior of F_c , the average monthly F_c is always positive regardless of the month (Fig. 9). The annual variation of F_c is characterized by an annual time course that varies inversely with air temperature. A negative correlation between the average monthly F_c and average monthly air temperature is observed (Fig. 10), which is the combined effect of fuel combustion and vegetation uptake. With all gaps filled, the urban surface is a net source of carbon dioxide annually, with an average of 4.90 kg C m⁻² y⁻¹ released to the atmosphere. Annual CO₂ emissions for this site are estimated as 4.77 kg C m⁻² y⁻¹ in 2006, 4.80 kg C m⁻² y⁻¹ in 2007, 4.61 kg C m⁻² y⁻¹ in 2008, and 5.40 kg CO₂ m⁻² y⁻¹ in 2009. The higher CO₂ emission in 2009 is possibly due to the reopening of some factories after the Olympic Games and more production made up for the cessation. Our

²⁰ results are within the range of other annual totals reported in the literature (Table 1).

5 Conclusions

This article presents the first result of direct CO_2 flux measurement in the city of Beijing. CO_2 flux was measured for a period of 4 yr in the northwest part of the city to assess the temporal variations from the diurnal to the annual scale. Based on the measurements, the results from this study permit the following conclusions: (1) Diurnal time courses



of CO_2 flux largely depend on automobile traffic. The two peaks in the morning and the evening correspond to the highest traffic volumes of the day. The daytime CO_2 flux is partly moderated by urban vegetation in the warm season. (2) The consistently positive CO_2 flux throughout the year indicates that the analyzed urban surface is a net

- source of CO₂ to the atmosphere. Emissions from domestic heating are a considerable source of CO₂ in the winter. CO₂ sequestration by urban vegetation is not sufficient to offset emissions from local sources. (3) Spatial variation patterns of CO₂ flux are mainly determined by the prevailing surface cover within the flux source area. (4) The integrated annual net CO₂ exchange over the 4-yr period calculated from a gap-filled F_c
- ¹⁰ dataset is 4.90 kg C m⁻² y⁻¹. This study shows an application of the eddy covariance technique to long-term monitoring of CO_2 flux in a densely built urban area. The results presented here can provide valuable information for urban development and help to shape policies for the reduction of greenhouse gases emissions.

Acknowledgements. This research was supported by NSFC projects (41030106, 41021004), and the National Basic Research Program of China (973 Program, 2010CB951801). The authors thank Senior Engineer Li Aiguo (LAPC/IAP, CAS) for maintaining the observation system.

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Table 1. Net annual <mark>carbon dioxide flux</mark> at urban sites around the world

City	Site	Reference	Annual Total (kg m ⁻² y ⁻¹)
Tokyo, Japan	Suburban	Moriwaki and Kanda (2004)	3.52
Cub Hill, Baltimore, USA	Suburban	Crawford et al. (2011)	0.36
Melbourne, Australia	Urban	Coutts et al. (2007)	2.32
London, UK	Urban	Helfter et al. (2010)	9.67
Mexico City, Mexico	Urban	Velasco et al. (2009)	3.49
Essen, Germany	Urban	Kordowski and Kuttler (2010)	1.64
Montreal, Canada	Urban	Bergeron and Strachan (2011)	5.45
Łódź, Poland	Urban	Pawlak et al. (2011)	2.95
Beijing, China	Urban	this study	<mark>4.90</mark>







Fig. 1. Satellite photograph of the area around the measurement site taken from Google Earth. Source areas were calculated using the footprint model by Korman and Meixner (2001) from all half-hour data in 2006–2009. White contours represent the percentage of the accumulated flux within the contour. The 50 % contour is marked by a dotted line. The black dot indicates the location of the tower.







Fig. 2. Monthly precipitation for each study year separately and monthly air temperature for the whole measurement period measured at Caoyang weather station.











































Fig. 8. Wind direction frequency, mean F_c by wind direction during daytime (06:00 a.m.–10:00 p.m.) and nighttime (10:00 p.m.–06:00 a.m.) calculated at 10° intervals from all available data during the study period.



Discussion Paper

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Fig. 10. The relationship between monthly average F_c and air temperature (T_a).



