
Tatsuki Hirano

Carbon dioxide flux measurement in the central area of Tokyo

Tatsuki Hirano[1], Hirofumi Sugawara[1], Shohei Murayama[2], and Hiroaki Kondo[2]

[1] *National Defense Academy of Japan, Hashirimizu 1-10-20 Yokosuka-shi, Kanagawa, Japan, ed15004@nda.ac.jp*

[2] *National Institute of Advanced Industrial Science and Technology, Onogawa 16-1 Tsukuba-shi, Ibaraki, Japan*

1. Abstract

From November 2012 to October 2013, we measured the eddy covariance flux of carbon dioxide (CO_2) in the middle of Tokyo, Japan. The study area is characterized to low-vegetated mid-rise residence with some arterial roads. The study area was net source of CO_2 whose annual total was +4300 gC m^{-2} yr^{-1}. The resulting diurnal CO_2 flux has one peak in the morning and one in late evening. This diurnal amplitude is larger in winter and also larger on weekday. The significant difference in the morning flux between weekday and holiday should be attributed to the anthropogenic emission.

2. Introduction

The Earth's carbon cycle is an urgent climate research topic, particularly the surface emission of carbon dioxide (CO_2). Large contributions of global emissions should be from cities. However, cities present a particularly complex system consisting wide variety of land-cover and human activities, so it is difficult to estimate the emissions there. A promising method of inversion-analysis for estimating the surface sources/sinks uses concentration measurements and an atmospheric transport model, and has been used to estimate the emission distribution over the building scale (Cambaliza al., 2013) as well as the global scale (e.g., Maksyutov et al., 2013).

However, results of such an inversion-analysis method, as well as its inputs from the emission inventory must be validated using direct measurements of CO_2 flux on the ground. In such tests, the point-measured flux should be scale-matched to the larger spatial and temporal scale in the inversion analysis, and such matching requires knowledge of the spatial distribution and diurnal variation of CO_2 flux. Complexity of urban system makes it difficult to inquire the diurnal-variation of the CO_2 flux, as well as its daily/annual totals. Velasco and Roth (2010) reviewed the studies of this topic, and concluded that the diurnal pattern of urban CO_2 flux varies in each observation sites. Anthropogenic emission should vary among each city, and another possible reason for the discrepancies is that the emissions from fossil-fuel use are offset by CO_2 absorption of urban vegetation. For example Coutts et al. (2007) argued that the very different diurnal variations of CO_2 flux in two urban areas could be attributed to the areas' different area-ratio of vegetation. Thus, it is necessary to clarify relative contribution of the factors controlling the diurnal variation of urban CO_2 flux.

Since the spatial distribution of land use and human activities in urban cities are heterogeneous, it is difficult to estimate the representative emission amount in urban area. MK04, previous findings in Tokyo, measured the CO_2 flux in residential area using eddy covariance method. Around their measurement site the total green cover ratio was 20.6% so that vegetation was probably one of the controlling factors for the measured flux. Moreover, the flux source area does not include any arterial roads. Here we measured CO_2 flux in a residence area in Tokyo which includes very small fraction of vegetation and two arterial roads. Our study, together with MK04, would contribute to inquire the representative emission in Tokyo.

The purposes of this study are to clarify the diurnal variation of the CO_2 fluxes year-round in Tokyo, Japan.

3. Observation

The study area is a compact, mid-rise residential area in Yoyogi, Tokyo, Japan (35.66°N, 139.68°E) (Fig. 1). The instruments were installed on a roof-top tower (52-m above ground, 25-m above roof). See Fig. 2 for the sensor setup. In this area, the mean height of the buildings is 9-m, and therefore the instruments are located above the roughness sublayer in the building canopy (Roth, 2000). The sonic anemometer (WindMasterPro II, Gill) and an open-path infra-red gas analyzer (LI-7500A, LI-COR) measures the turbulence and turbulent fluctuation of both CO_2 and water vapor at 10 Hz. These instruments are 1.4-m horizontally apart from the mast (17-cm diameter) on the northeastward horizontal boom. A test of the momentum flux found that the flow distortion by the mast does not significantly influence the turbulence data except at a wind direction of southwest, where the mast partly obstructs the wind.

Figure 1 is overlaid with the typical flux footprints in winter and summer, those are calculated by the model of Schmid (1994) in neutral stratification. In summer (June to August), prevailing wind is from SW sector. The source region of flux in this direction includes residence, a large park, and university campus with vegetation (mainly deciduous broadleaf). According to analysis of RGB counts in a 1-m resolution aerial photo, the area ratio of vegetation in the southwest sector (180° – 270°) is 9%. In winter (December to February), prevailing wind is from NW sector (71%). The main land-cover in this direction is residence. The typical footprint shown includes an arterial road and a busy shopping area near its far-end. The density of population in this area is 16600 persons km^{-2}. The vegetation in the northwest sector (270° – 360°) is mainly the private gardens and occupies only 2% in this sector.

As part of the data processing, we do the following. (i) Fluxes are processed as block-averaged half-hourly values. (ii) Wind vectors are aligned in the physical streamline coordinate system using a double rotation procedure (Wilczak et al., 2001). (iii) Corrections are applied for water-vapor density fluctuation (Webb et al., 1980). Lower quality data were removed in two cases: 1) During a period of precipitation, and 2) when a spike exceeding 2.0 mg m^{-2} s^{-1} appeared in the CO_2 flux. Measurements began in November 2012, running for one year through October 2013, with a data availability of 79.6%.

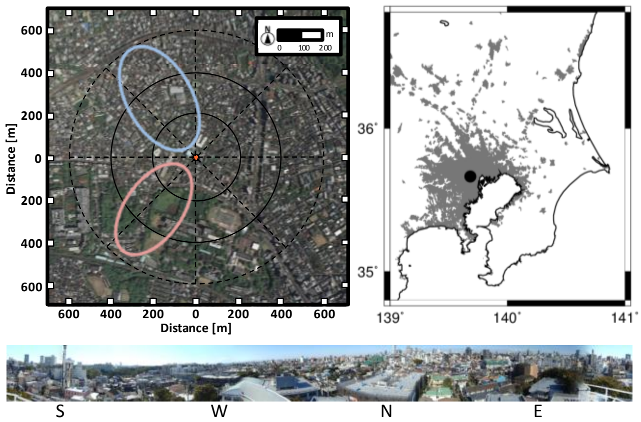

Fig. 1. The study area (left panel, aerial photo from the Geospatial Information Authority of Japan). The ovals show typical flux footprint in winter (blue: December to February) and summer (red: June to August). At right panel, the filled circle is the location of the measurement area and the hatched area indicates a densely inhabited district. The bottom image shows the measured area seen from the tower.

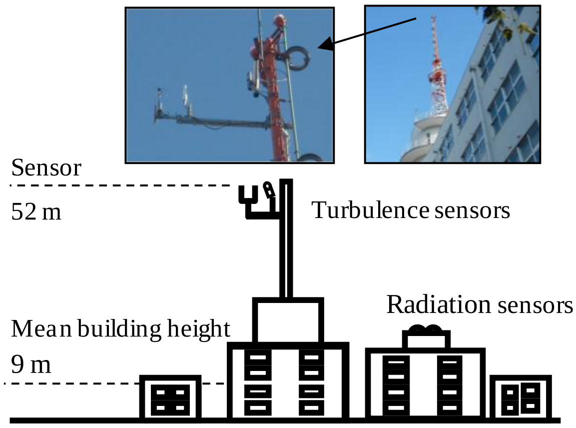

Fig. 2. The The measurement tower.

4. Seasonal variation of observed CO_2 flux

Figure 3 shows the seasonal change of measured flux in Yoyogi, together with that in Kugahara in MK04. The annual total CO_2 flux at the study area is found to be +4300 gC m^{-2} yr^{-1}, the positive sign indicating net emission into the atmosphere. Any data gaps, owing to either instrument malfunction or low-quality measurement due to precipitation, were filled in by the monthly mean flux. The annual emission is 1.3 times larger than that in a low-storied residential area in Kugahara, Tokyo (+3352 gC m^{-2} yr^{-1}). Note that measurement periods are different between two sites; 2012 to 2013 in Yoyogi, and 2001 to 2002 in Kugahara. Over the two measurement periods, the annual carbon emission over all of Tokyo slightly decreased 2% (MEIT, 2015), thus the 1.3 times larger value in Yoyogi should be mainly due to the land-cover difference. The Yoyogi area includes two arterial roads and less vegetation than that of Kugahara area. Synthesis comparison of urban sites in world-wide (Nordbo et al., 2012; Ward et al., 2015) showed that the annual total CO_2 flux increases as the vegetation cover decreases. In 8 months denoted with shade in Fig. 3, monthly average fluxes in Yoyogi were found to be greater than those in Kugahara (statistically significant in Z-test with 5% significance level).

A clear seasonal variation occurs (Fig. 3), with winter maximum and summer minimum being statistically significant (Z-test: 5% significance level). Although the summer flux should be influenced by the uptake of CO_2 by the vegetation located south-west from the site, the measured flux is nevertheless positive throughout the year. The pattern is consistent with previous studies that show a winter maximum in the CO_2 flux; for example, in Kugahara, Tokyo (MK04), in London, UK (Kotthaus and Grimmond, 2012), and in Montreal, Canada (Bergeron and Strachan, 2011).

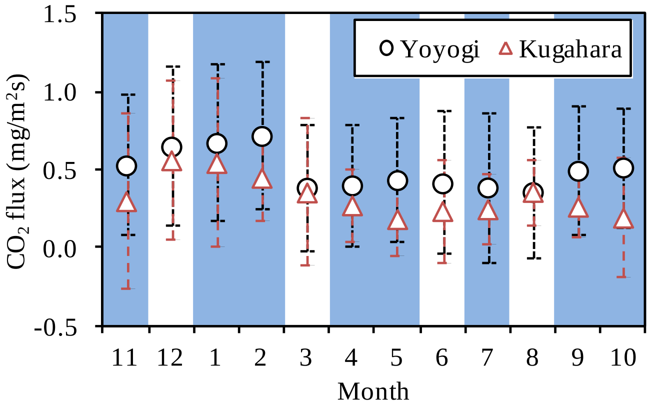

Fig. 3. Monthly averages of measured CO_2 flux. Results from Kugahara are also shown (MK04). Error bars are the standard deviations in time averaging. The shade indicates the period when the Yoyogi—Kugahara difference is statistically significant (Z-test, 5% significance level). The number of measurement runs of Yoyogi is 3782 for winter (December to February) and 3050 for summer (June to August).

5. Diurnal variation of observed CO_2 flux

Here, the data gaps are not filled in this analysis, although they were filled in the previous section. In autumn and winter, the CO_2 flux has two peaks, one in the morning (8–10 LST) and one at evening (18–23 LST) (Fig. 4). Having two peaks is consistent with several findings, e.g. in Melbourne, Australia (Coutts et al., 2007), Firenze, Italy (Matese et al., 2009), Swindon, UK (Ward et al., 2015), Lodz, Poland (Pawlak et al., 2015) although the peaks are small, but contrasts with the single, small daytime peak found in London, UK (Helfter et al., 2011, Ward et al., 2015). Here, winter has the largest amplitude diurnal variation, summer the least. This seasonal distinction, especially the relatively flat pattern in summer daytime may be due to 1) variation of emission 2) the greater uptake by vegetation in summer daytime, particularly as the flux footprint in summer includes a large green space just south of the site, although their relative contributions are hard to be clarified in this study.

In winter, one also sees a difference in diurnal CO_2 flux between weekday and holiday (Fig. 5). The weekday/holiday contrast is consistent with the results in London and Swindon, UK (Ward et al., 2015), and in Lodz, Poland (Pawlak et al., 2015) although the contrast in Lodz is not evident in winter likely due to similar use of domestic heating regardless the day of week. The diurnal pattern and weekday/holiday difference, which differs site to site, should the attributed to those of human activities in the flux footprint. In Yoyogi, the weekday flux exceeds that of holidays in the morning (T-test, 5% significance level), but little difference occurs the rest of the day. The morning difference suggests an influence from anthropogenic emissions.

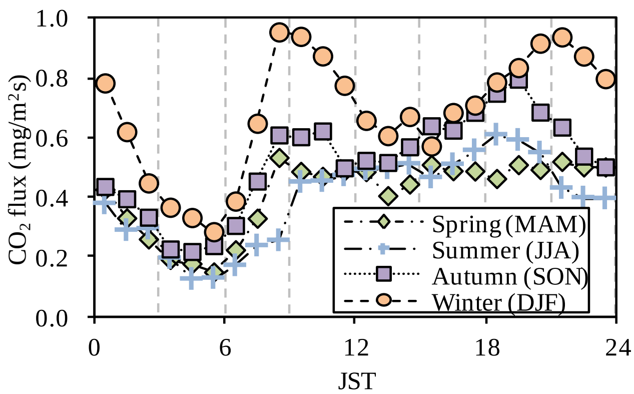

Fig. 4. Mean diurnal change of CO_2 flux.

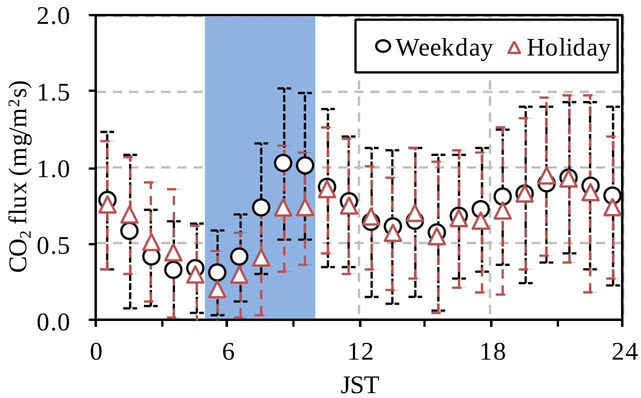

Fig. 5. Measured flux on weekdays (N=2677) and holidays (N=1105) from December to February. Error bars are the standard deviations in ensemble average. The shade indicates the period when the weekday—weekend difference is statistically significant (T-test, 5% significance level). The holidays do not include national holidays.

8. Conclusion

The turbulent flux of CO_2 was measured diurnally and seasonally in a compact mid-rise residential area in Yoyogi, Tokyo, Japan. The annual total CO_2 flux was +4300 gC m^{-2} yr^{-1}, which is 1.3 times larger than other residential area in Kugahara, Tokyo (MK04). The larger flux in Yoyogi should be attributed to some arterial roads and less vegetation in Yoyogi. The comparison revealed that the spatial variation of CO_2 flux can reach 30% even in the same category of land-use. The diurnal variation of CO_2 flux had one peak in the morning and one at evening. This diurnal pattern was most distinct in winter and autumn, and least in summer. The peak flux in the morning was larger on weekdays than holidays, by an amount that was statistically significant.

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