**12.5** ANNUAL FLUXES OF ENERGY AND $CO_2$ OVER A RESIDENTIAL AREA IN TOKYO

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## 1. INTRODUCTION

FLUXNET have increased our knowledge of surface energy balance and carbon dioxide ($CO_2$) fluxes (Baldocchi et al. 2001). However, urban areas are one of the few remaining surfaces where the energy and $CO_2$ exchanges are still not well understood. Although a number of short campaigns over urban areas have reported water and energy exchange (e.g., Oke 1988; Grimmond and Oke 1999; Kanda et al. 2002), the current understanding of energy budgets in these environments have been mainly focused on the variation of the fluxes that occur over several days in summer season. Urban observations of carbon dioxide ($CO_2$) flux are more limited (e.g., Grimmond et al. 2002; Nemitz et al. 2002). A long-term monitoring of fluxes of radiation, heat, and $CO_2$ in an urban area is required for further understanding of the seasonal variability of energy and $CO_2$ exchange.

The purpose of this study is to gain an understanding of the diurnal, seasonal, and annual fluxes of the energy and $CO_2$ for a suburban surface. We also investigate the contributions of various sources such as garden trees, artificial materials, traffic, human activities, and human exhalations, to the meteorologically measured latent heat and $CO_2$ fluxes.

## 2. FIELD EXPERIMENTS

The measurements were made from May 2001 to April 2002 in a low-storied residential area in Kugahara, Tokyo, Japan (35º34'N, 139º41'E) (Figure 1). The instruments were attached to a 29-m tower installed in a backyard to one of the homes (Figure 2). The residential area mainly consists of densely built-up houses, paved roads, and small playgrounds. According to Moriwaki and Kanda (2004), the percentage of ground area covered by buildings was 32.6%, the total green cover ratio was about 20.6%, and the mean building height is 7.3 m (Table 1). A sonic anemometer (USA1, Metek GmbH) and an infrared $CO_2/H_2O$ open-path analyzer (LI-7500, LI-COR, Lincoln, NE, USA) were installed at a height of 29 m. The fluctuations of three-dimensional wind velocities, air temperature, and the concentrations of vapor and $CO_2$ were measured at 8 Hz. These data were logged to a data logger (CR10X, Campbell Sci., Inc., Logan, UT, USA) and stored on a computer.

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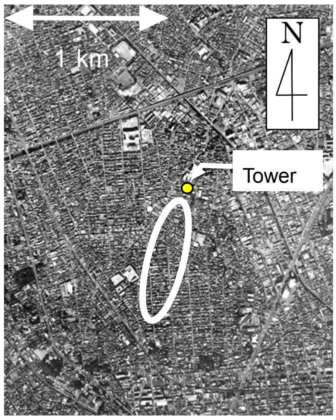


Fig. 1 Aerial photo of the study area.
The white oval show a typical flux source area that was determined using the flux source area model (FSAM) of Schmid (1994).

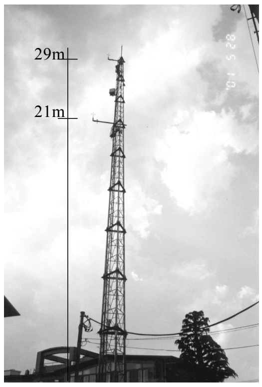


Fig. 2 Tower for the measurements

Table 1 Building height and surface cover at the study site.

| | | |
|---|---|---|
| Building height | $z_H$ | 7.3 m (Std. 1.3 m) |
| Areal fraction covered by buildings | $\lambda_p$ | 32.6% |
| Areal fraction covered by vegetation | $\lambda_V$ | 20.6% |
| Areal fraction of impervious space (paved road + concrete) | $\lambda_I$ | 38.3% (26.2% + 12.1%) |
| Areal fraction of pervious space (playground except for vegetation) | $\lambda_G$ | 8.5% |

Upward and downward shortwave and longwave radiation intensities were measured separately using two sets of pyranometers (MS-42, 62, Eko Instruments) and pyrgeometers (MS-201, 202) at a height of 25 m. The precipitation was recorded using a tipping-bucket rain gauge (MW-10, Eko Instruments).

Heat, water vapor, and $CO_2$ fluxes were estimated using the eddy-covariance method every 60 min. Coordinate axes were rotated so that the mean vertical velocity was zero (McMillen 1988). The water vapor and $CO_2$ fluxes were corrected for density effects (WPL correction; Webb et al. 1980). The storage heat flux (G) is determined as the energy balance residual from direct observation of net all-wave radiation (Rn), sensible heat (H), and latent heat (LE) fluxes.

$$Rn-(G-A)=H+LE+Q \quad (1)$$

Here, the anthropogenic heat A was derived from a database in Tokyo. Heat storage in the air between the surface and the measurement height Q was determined from the volumetric heat capacity of air and the measured change of air temperature between the hours.

For the evaluation of seasonal and diurnal courses in sunny days, we used data only from fair-weather days, that is, days with a percentage of sunshine exceeding 80%. Such days were determined using data from a weather station of the Japan Meteorological Agency 12.5-km away. We then obtained average diurnal sequences for the sunny days by taking hourly averages. In the following sections, the data from July and December are used to represent typical data in summer and winter, respectively. As for the annual totals of the energy and $CO_2$ fluxes, we integrated the $CO_2$ and energy fluxes (LE and H) only for the available datasets (71% of a full year dataset) and then filled in missing data using the following method. Missing data due to precipitation (10% of the full year dataset) were replaced with data from fully cloudy-weather days within the 2-week period. In the case of the sensor malfunction (19% of the full year dataset), missing data were estimated from hourly data on days that have similar weather conditions.

## 3. RESULTS AND DISCUSSION

### 3.1 *Energy Balance*

The energy fluxes change seasonally corresponding to the variation of Rn (Fig. 3). At midday in July, the peak values of Rn, H, and LE were about 700, 300, and 180 W $m^{-2}$, respectively, which are more than twice the December values (Fig. 4). However, G in the daytime is about the same for summer and winter. The daytime flux ratio G/Rn in December is 0.62 and larger than those in July (0.26). In an urban setting, the abundance of vertical walls can efficiently reserve the energy from radiation in winter even though the solar azimuth angle is relatively low. This result contrasts with earlier models

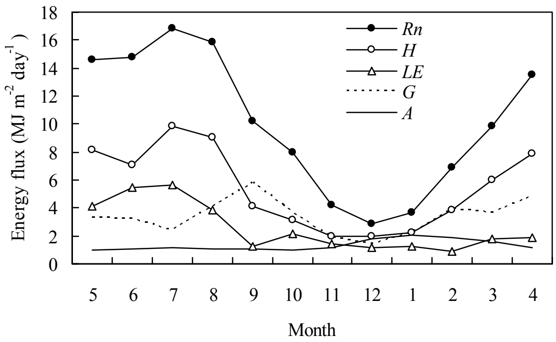


Fig. 3 Monthly daily-accumulated surface energy fluxes for sunny days.

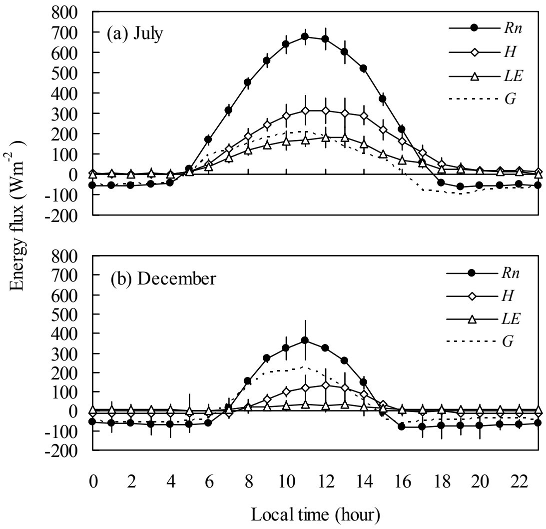


Fig. 4 Mean hourly surface energy fluxes for sunny days in July (a) and December (b).

of storage heat flux for urban canopies (e.g., Oke and Cleugh 1987; Grimmond et al. 1991), where it was assumed that the G is modeled as a function of Rn and the surface properties of the site.

In the summer daytime, LE is relatively larger than expected. The most plausible sources of vapor may be attributed to the urban vegetation such as trees, shrubs, and bare soil, which altogether amount to about 29% of the area. There are no other large sources of vapor (Moriwaki and Kanda, 2004). If we assume that this evaporation is only due to natural coverage (garden trees and bare soil), the latent heat flux per unit natural coverage should be 631 W $m^{-2}$. This value exceeds the available energy Rn–G+A of 320 W $m^{-2}$ and thus is much larger than the value usually expected over homogeneous vegetation canopy. The relatively high amount of evaporation is consistent with the oasis effect; that is, in non-homogeneous terrain, the advection of hotter and/or drier air from upwind areas causes increased evaporation via leading-edge effects (Oke 1978). In this area, each tree and patch of soil is isolated. Thus, isolated urban vegetation and bare soil has a higher potential for evaporation than a much more horizontally extended and homogeneous region of vegetation or soil.

### 3.2 *$CO_2$ Flux*

The $CO_2$ flux is positive throughout the year because the urban surface is a $CO_2$ source. The most significant trend is the $CO_2$ flux being more than twice as large in winter as it is in summer (Fig. 5). Moreover, the flux is also positive at all times of the day in summer and winter (Fig. 6). These positive fluxes are in agreement with other urban $CO_2$ studies (e.g., Grimmond et al. 2002; Nemitz et al. 2002; Vogt et al. 2003). In this study, the flux values range from 0.2 to 0.5 mg $m^{-2}s^{-1}$ in July and from 0.2 to 1.1 mg $m^{-2}s^{-1}$ in December. The range in July roughly equals that reported by Grimmond et al. (2002) in Chicago for the summer, but the range in December roughly equals that reported by Vogt et al. (2003) in Basel for the summer. The measurements seem to depend not only on land use information but also on location in a city; for example, measurements in Edinburgh (Nemitz et al., 2002) were in the center of the city and had the highest measured values of all the studies. The $CO_2$ flux was relatively constant throughout the day in July, but had a sharp peak in the morning and a broad peak during the night in December (Fig. 6). The main sources of $CO_2$ were the consumption of fossil fuels, from both vehicles and home heating, and the exhalations of humans. The larger magnitude of the $CO_2$ flux in winter was primarily due to the uptake of $CO_2$ by vegetation in summer and the larger fuel consumption in winter (Moriwaki and Kanda, 2004).

Table 2 Annual total fluxes from May 2001 to April 2002. '% flux data coverage' is the percent of hours which contain measured values for all components of the energy balance. Values for a temperate deciduous forest are from Wilson and Baldocchi (2000) for energy fluxes and Baldocchi and Wilson (2001) for $CO_2$ flux.

| Variable | Suburban (this study) | Temperate deciduous forest |
|---|---|---|
| Precipitation (mm) | 1722 | 1454 |
| Air temperature (ºC) | 16.0 at 29 m | 14.9 |
| % flux data coverage | 71% | 78% |
| Solar radiation $S_{down}$ (GJ $m^{-2}$) | 4.69 | 5.43 |
| Net radiation $Rn$ (GJ $m^{-2}$) | 2.36 | 3.04 |
| Latent energy flux $LE$ (GJ $m^{-2}$) | 0.90 | 1.39 |
| Sensible heat flux $H$ (GJ $m^{-2}$) | 1.35 | 1.05 |
| Evaporation (mm) | 369.5 | 567.2 |
| $CO_2$ flux (gC $m^{-2}$) | 3352 | -460 to -620 |

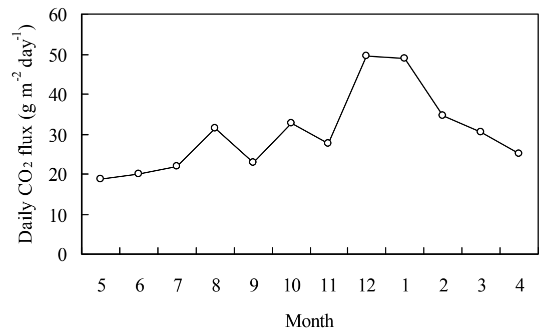


Fig. 5 Monthly averages of net CO2 flux per day. Positive sign of the flux indicates transfer from the surface to the atmosphere.

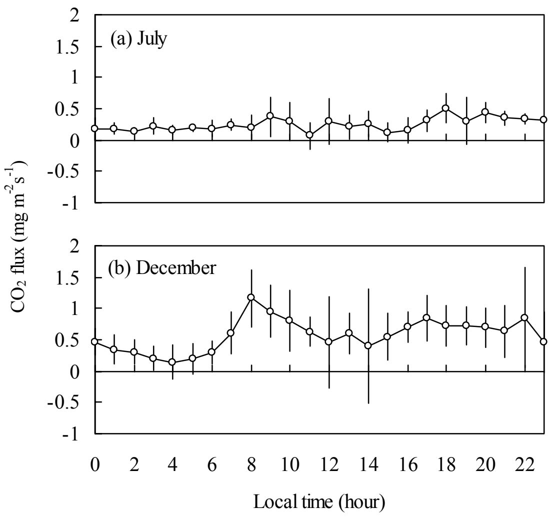


Fig. 6 Mean diurnal changes of CO2 flux for sunny days for July (a) and December (b).

### 3.3 *Annual energy, water, and $CO_2$ budgets*

The annual totals of energy and $CO_2$ fluxes are listed in Table 2 with those from a natural ecosystem. The natural ecosystem is a temperate deciduous forest in Oak Ridge in the USA that is nearly at the same latitude (35º57'N) as this study site (35º34'N). The data on this ecosystem are Wilson and Baldocchi (2000) for energy fluxes and Baldocchi and Wilson (2001) for $CO_2$ flux.

The total of Rn was 2.36 GJ $m^{-2}$ and the ratio of net radiation to solar radiation (Rn/S) was 0.50. Thus, about a half of the amount of input solar radiation is available for the surface energy exchange. This value is slightly smaller than the forest value of 0.56. Although a definitive comparison of urban-natural net radiation is not simple (e.g., Oke 1988), the smaller Rn value in our case is probably because the urban surface is warmer than that of the forest canopy and gives off more radiative energy via longwave emission. The energy partitioning rates to sensible heat (H/Rn) is 0.57 and that for latent heat (LE/Rn) is 0.38.

The annual total evaporation and precipitation (P) are 228 mm and 1362 mm, respectively. Thus, the ratio of evaporation to precipitation E/P is 0.21, which is much smaller than the forest value of 0.39. The radiative dryness index (RDI) proposed by Budyko (1974), which equals Rn/LP, is a useful measure of the potential wetness of a region because and RDI <1 indicates sufficient precipitation to keep the surface wet. Here, RDI equals 0.56; nevertheless, the actual evaporation is relatively low (E/P=0.21) because 80% of the precipitation is not trapped but runs off. Such a low E/P is a distinctive feature of the water balance in urban areas because urban areas have sewer systems and the surface is covered with impervious materials (buildings and paved roads).

The annual total $CO_2$ emission at this site was 3352 gC $m^{-2}$ $yr^{-1}$, while the annual total $CO_2$ absorption in a deciduous forest is -450 to -620 gC $m^{-2}$ $yr^{-1}$ (Baldocchi and Wilson 2001). These values indicate that one would need about six times more areal forest to remove all the $CO_2$ emitted from this site.

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