The turbulence characteristics of the atmospheric surface layer on a rice paddy and an urban flux tower
(水稻田及都會區之大氣紊流特性量測研究)

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Abstract

In this study, we measured urban surface radiation at a rice paddy (120°41'E, 24°01'N, Fig 1), at different land type sites and turbulent heat fluxes on a tower standing on the roof of a 7-floor building (24°12' N, 120°67' E, Fig 2) by using Eddy covariance system (ECS) in Taichung, Taiwan. The results show that the aerodynamic roughness estimated from EC data is determined to be 0.02-0.03 m and the Bowen Ratio was about 0.16 during the daytime on a rice paddy. The urban experimental results show that the average urban albedo is determined to be 0.2 estimated within the radius of 1.4 km from the tower site. Furthermore, corrections, including coordinate system rotation, Webb, urban albedo, advected term, and long-wave radiational cooling term correction, are incorporated. As a result, the energy closure gap between turbulent heat flux and available surface heat flux on the urban tower is reduced to 4%-5% after using 2-D and 3-D coordinate rotation correction, and the gap is around 6% on a rice paddy.

While measuring the turbulent heat fluxes at different height, it is found that the turbulent heat flux (the sum of the latent heat flux and sensible heat flux) at 33 m agl (above ground level) was 21% lower than the available surface heat flux. In contrast, at 50 m agl the turbulent heat flux was only 4% lower than the available flux. The main reason to this difference is due to that observation at 50 m agl was within the atmospheric surface layer, while the observation at 33 m agl was not.

1. Introduction

In the past, these characteristics have been difficult to measure. They are usually derived from the measurements of wind speed, temperature and humidity at many levels within the atmospheric surface layer (ASL) (e.g., Brutsaert and Kustas 1987; Sugita and Brutsaert 1990; Brutsaert and Parlange 1992; Parlange and Brutsaert 1993; Sugita et al. 1997). Recently, due to the advance of the EC technique, they can now be measured continuously at a single level, at a much lower price. The use of EC flux towers to monitor these fluxes and trace gases between the land surface and the atmosphere has proliferated, such as Euroflux (Valentini et al., 2000), AmeriFlux (Baldocchi et al., 2001), through global networks such as Fluxnet (Baldocchi et al.,2001).

According to a formulation for the first law of thermodynamics, the energy flux should obey the energy balance principle; however, it is found that the surface energy budget is not balanced at many flux tower sites (Aubinet et al., 2000; Baldocchi et al., 2001; Wilson et al., 2002a; 2002b). In this study, we measured the urban surface radiation different land type sites and used the ECS to understand the turbulent heat flux in the different land types and tried to find out the possible methods to correct the energy closure gaps.

2. Methodology

2.1 Surface energy closure

Surface energy budget is based on the fundamental principle of conservation of energy. It can be showed that the sum of surface latent heat and sensible heat flux should be equivalent to all other energy sinks and sources (e. g. Wilson et al., 2002) as:

$$\begin{aligned} V &\equiv R_n - G - C - S - A - \Delta R_{ln} - Q \\ &= LE_c + H_c \end{aligned} \qquad (1)$$

where V is the available heat flux for turbulent heat fluxes. R_n is net radiation; G is the soil heat flux measured by the heat flux plate; C is the canopy heat storag between the land surface and the height of the eddy covariance system; S is the soil heat storage between the soil surface and the depth of the heat flux plate sensors; ΔR_{ln} is the net long-wave radiation cooling between the land surface and the height of the heat flux plate sensors; A is the local advected heat flux; Q is the sum of all additional energy sources and sinks; LE_c is the latent heat flux at the canopy height; H_c is the sensible heat flux at the canopy height.

2.2 Examination of energy balance closure gaps

Two methods are used to examine energy balance closure in this study:

(1) The first method is to derive regression coefficients from the ordinary least squares (OLS) relationship between the hourly sums of the turbulence heat fluxes (LE + H) against the available heat flux (V) (Wilson et al., 2002).

$$(LE+H) = a\,(Rn - G - C - S - A - \Delta R_{ln}) + b \quad (2)$$

(2) The second method is to evaluate the energy balance ratio (EBR) (Wilson et al., 2002) between the sum of the turbulence heat fluxes (LEc + Hc) and the available heat flux (V) over a specific time period, i.e.,

$$EBR \equiv \frac{\sum(LE_c + H_c)}{\sum(V)} \quad (3)$$

2.3 Coordinate correction and Webb correction

The latent heat flux and the sensible heat flux observed from the EC system can be hindered due to the tilt of the instrument and the slope of the terrain. Under the assumption of the mean vertical velocity being zero, 2-axis coordinate rotation is applied to all EC estimates to correct the non-zero vertical velocity according to Wilczak et al. (2001).

Webb et al. (1980) showed that the eddy flux of heat should be corrected for density fluctuations in calculating the fluxes of water vapor and CO_2. Therefore, the corrections for the effects of density fluctuations, owing to transfer of sensible heat on the water vapor and CO_2 fluxes were carried out.

3. Experiment

3.1 Site description

The study sites are located on a rice paddy (Wufeng, Taichung County, 24 to 29 May 2005, Figure 1) and a 7-floor building (Taichung, 11 February to 1 June, 2006, Figure 2). Because the ratio of fetch to the highest measurement height of a fingerprint is about 28:1 (Horst, 1999; Tsai and Tsuang, 2005), the heat flux on a rice paddy can represent the area within 140 m upwind from the EC site and that measured at the urban tower can represent the area within radius of 1.4 km.

3.2 Instrumentation

The instrument used in this study is EC system. High response subsystem consists of a three-dimensional sonic anemometer (CSAT3) to measure the means and standard deviations of wind velocity components and virtual temperature, a fine-wire thermocouple (FW05) to measure the mean and standard deviation of air temperature, and an open path H_2O fast response infrared gas analyzer (LI7500, LICOR) to measure fluctuations in water vapor density. Low response system consists of a Solar Infrared Radiation Station (SIRS) system to measure each component of the radiations, two soil heat flux plate sensors (REBS' HFT-3) to measured ground heat flux and TCAV to measured the soil temperature.

4. Result and discussion

4.1 Albedo and Bowen ratio

The aerodynamic roughness estimated from EC data is determined to be 0.02-0.03 m, the albedo is around 0.1, and the Bowen Ratio is about 0.16 during the daytime on a rice paddy. The urban experimental results show that the average urban albedo is determined to be 0.2 estimated within the radius of 1.4 km from the tower site.

4.2 Energy closure gaps

The data measured were used to calculate the metropolitan turbulent flux, and the energy closure gaps were discussed as the follows.

(1) Observed turbulent flux

The observed turbulent flux (LE+H) results show that the main flux was sensible flux, which the highest value is about 200 W/m^2 (Figure 3). The regression coefficient between the turbulent flux and surface land energy flux (Rn-G) is 0.842. The EBR on a rice paddy in the daytime and in all day are 0.76 and 0.86. The energy closure gaps and EBR at the urban tower in the daytime and in all day are 23.3 W/m^2, 0.72 and 94.7 W/m^2, 0.61.

(2) Coordinate rotation and correction

After using Webb, urban albedo, advected term, and long-wave radiational cooling term correction on the rice paddy, the energy closure gaps are 5.9% for daytime and 19% for full day (Table 1). For the urban tower, the EBR decreased to 4.1% for 2-D coordinate rotation and 5.7% for 3-D rotation (Table 2). And the gaps on the urban tower occur after noon and reach the maximum near evening. The OLS results show that the regression coefficient between turbulent flux and available heat flux are 0.90 for the rice paddy and 0.86 for the urban tower.

(3) Energy closure at various heights

That vertical wind velocity, w, at the height of 50 m is almost zero shows that the wind field is more stable than that at the height of 33 m. The energy closure gaps at 50 m are smaller than that at 33 m (Figure 4). The main reason to cause these results may be that the observation at 55 m is in the atmospheric surface layer but that at 33 m high is not.

5. Conclusion

The observed surface energy budget was imbalanced and the turbulent heat flux was 24% (rice paddy) and 28% (urban tower) lower than the available surface heat flux during the study period. Thus, 2-D and 3-D coordinate rotation with Webb, urban albedo, advected term correction, and long-wave radiative cooling term correction were used to reduce the energy closure gaps. Therefore, the gaps are decreased to 5.9% for the rice paddy and 5% for the urban tower. In addition, the observed height of flux tower is suggested to set up in the atmospheric surface layer (40-70m) to avoid the building wakes.

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a) b)

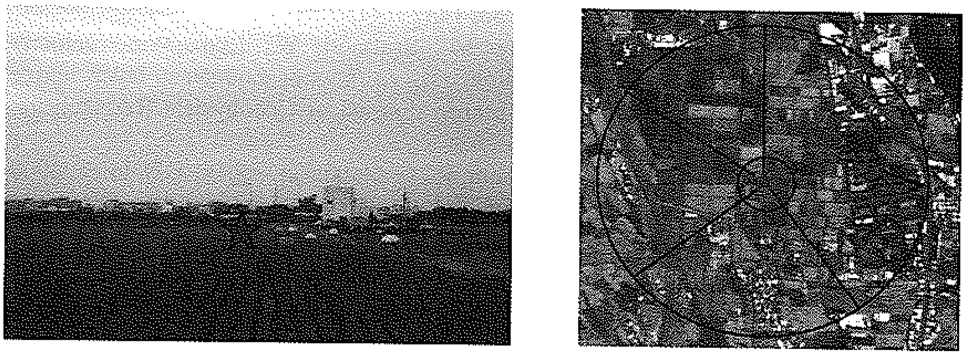

Figure 1. a) Photograph taken facing north, from 80 m south of the study site (star) in Wufeng, Taichung County, Taiwan on 1 May 2005; b) Satellite image of the studied area, where the star denotes the instrument site. The radius of the outer circle is 1000 m and that of the inner circle is 150 m.

a) b) c)

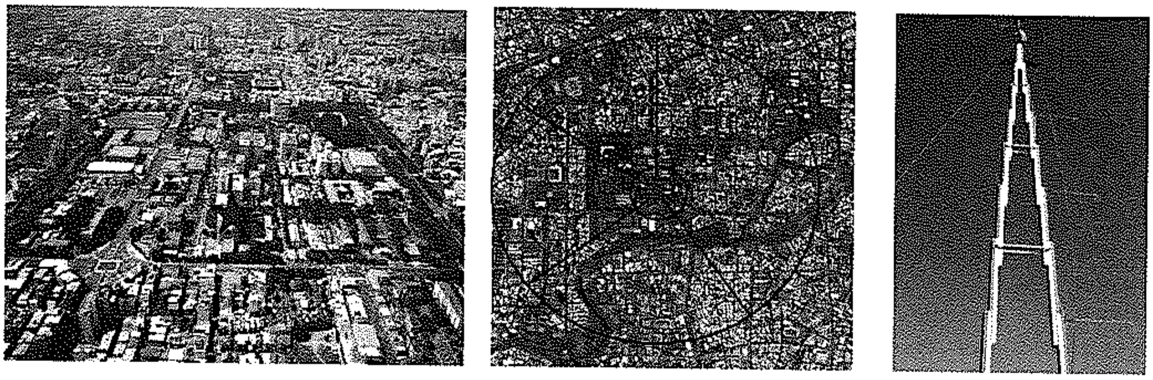

Figure 2. a) the oblique photographs taken from the east of the study site to the west; b) the satellite image of the study site (star), the radius of black circle is 1.4 km; c) the flux tower image after raising and the height of the top is 50 m agl.

(a) (b)

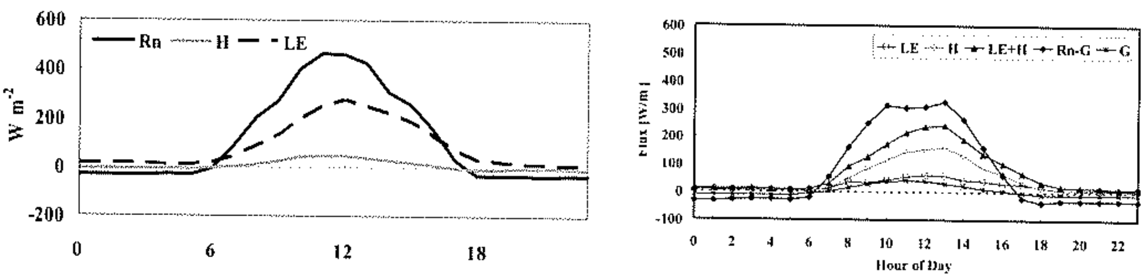

Figure 3. a) the diurnal turbulent flux (LE, H) observed on a rice paddy; b) the diurnal observed turbulent flux (LE, H) observed at urban flux tower.

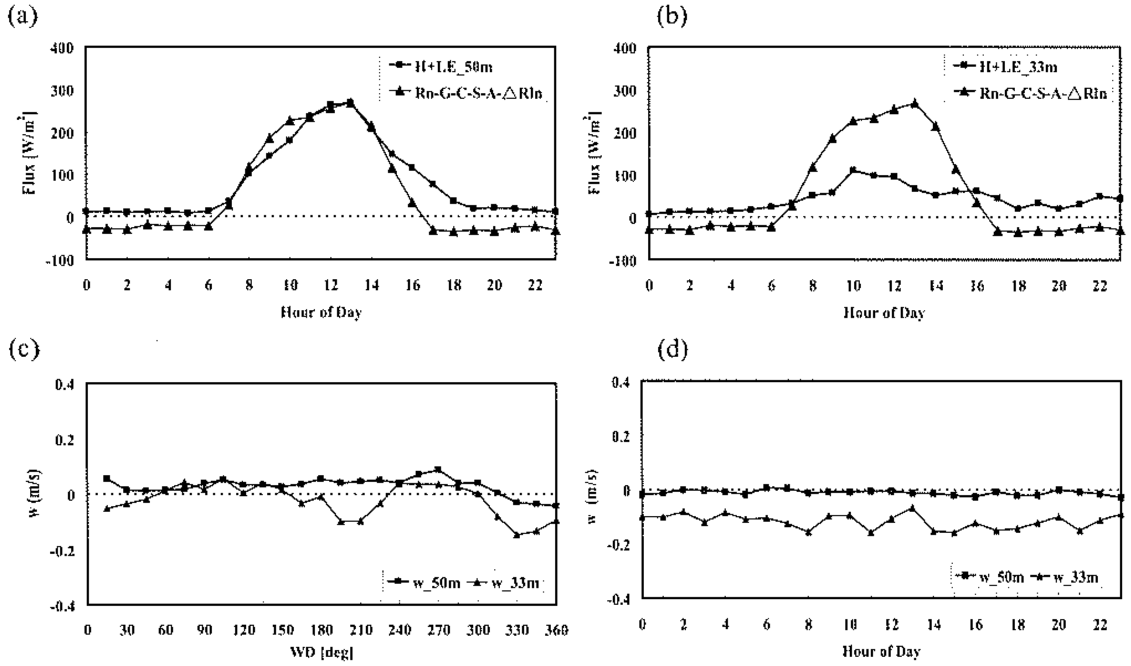

Figure 4. (a) the vertical wind velocity at every wind direction; (b) the diurnal vertical wind velocity; (c) the diurnal flux after correction observed at the height of 50 m; (d) the diurnal flux after correction observed at the height of 33 m.

Table 1. Energy balance ratio (EBR) and the regression coefficients from the ordinary least squared (OLS) relationship between the hourly sums of the turbulence heat fluxes (LE + H) against the available heat flux (V) on a rice paddy.

Step	Variable	EBR		OLS	
		full day	daytime	slope	r
I	Raw LE, H	0.755	0.855	0.721	0.903
II	I+Coordinate rotation	0.786	0.904	0.794	0.95
III	II+Webb et al. (1980) correction	0.803	0.921	0.836	0.90
IV	III+C correction	0.791	0.930	0.845	0.901
V	III+A correction	0.798	0.922	0.838	0.899
VI	III+F correction	0.801	0.931	0.848	0.895
VII	III+C+A+F correction (final)	0.810	0.941	0.861	0.90

Table 2. Energy balance ratio (EBR) and the regression coefficients from the ordinary least squared (OLS) relationship between the hourly sums of the turbulence heat fluxes (LE + H) against the available heat flux (V) on a flux tower.

Step	Variable	EBR	OLS	
		full day	slope	r
I	LE+H / Rn-G	0.719	0.43	0.842
II	LE+H (2D & Webb) / Rn-G-C-S	0.832	0.53	0.869
III	LE+H (3D & Webb) / Rn-G-C-S	0.818	0.51	0.855
IV	II+ albedo correction	0.942	0.63	0.874
V	III+ albedo correction	0.927	0.61	0.861
VI	IV+ (A+ΔR_{ln}) correction	0.959	0.63	0.874
VII	V+(A+ΔR_{ln}) correction	0.943	0.61	0.860