6B.7 EXPERIMENTAL VALIDATION OF THE WEBB CORRECTION FOR CO_2 FLUX WITH AN OPEN-PATH GAS ANALYZER

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1. INTRODUCTION

Turbulent flux by the eddy covariance technique is the only direct measurement over earth surfaces. CO2 and water vapor are the only trace gases that can measure turbulent flux with the open-path gas analyzer. The open-path CO2/H2O gas analyzer does not measure non-dimensional CO2 and water vapor concentrations as mixing ratios but it measures CO2 and water vapor densities. For this reason, the trace gas flux using this analyzer needs to be corrected for the mean vertical flow due to air density fluctuation. Webb et al. (1980) suggested that the flux due to the mean vertical flow cannot be neglected for trace gases such as water vapor and CO2. To evaluate the magnitude of the influence by the mean vertical flow, Webb et al. (1980) assumed that the vertical flux of dry air should be zero for the mass conservation. Practically, sensible and latent heat fluxes evaluated by the eddy covariance technique are used to calculate water vapor and CO2 fluxes by the mean vertical flow (Webb or WPL correction).

The Webb correction is important over sea surface CO2 flux as it is much smaller than the vegetated surface. Ohtaki et al. (1989) suggested that the Webb correction term of CO2 flux is larger than the raw CO2 flux and changes the transport direction of the CO2 flux over the coastal sea surface. And recently, Kondo and Tsukamoto (2007) also confirmed the importance of the Webb correction over the open ocean surface.

The basic Webb correction theory has been discussed well including the recent discussions (e.g. Leuning,2007), but this correction is still poorly understood from actual observed data in various conditions. Therefore, it is important to evaluate the original Webb correction scheme using the experimental data..

For this purpose, we measured the turbulent flux over an asphalt surface (large parking lot), where CO2 and water vapor fluxes were considered almost zero and sensible heat flux was significant.

2. EXPERIMENTAL METHOD

The observation was made in the large parking lot on August 24, 2006. This site is located at a coast in Okayama, Japan. This parking lot extends 110 m x 180 m and provided a uniform and dry asphalt surface. The fine weather continued and the surface was very dry. Sea breeze dominated during this observation period.

Fluctuations of three-dimensional wind velocities and sound virtual temperature were measured using a sonic anemometer–thermometer (KAIJO, DA-600-3TV). The SAT probe was directed against the dominant sea breeze. CO2 and water vapor density fluctuations were measured using an infrared open-path CO2/H2O gas analyzer (LI-COR, LI-7500). Both instruments were mounted on a tripod at a 1.62 m height above the asphalt surface and separated horizontally by 0.25 m. The observation point was located near the northwest edge of the parking lot to ensure the sufficient fetch from the sea breeze. The fetch to the southeast coast was more than 180 m. The analog output signals from these instruments were sampled and digitized at the rate of 10 Hz by a data acquisition system (LabVIEW, National Instruments) on a PC.

3. EDDY FLUX EVALUATION INCLUDING THE WEBB CORRECTION

The sensible heat flux (H) is given by

$$\begin{aligned} H &= C_p \overline{\rho_d}\, \overline{w'T'} \\ &= C_p \overline{\rho_d} (\overline{w'T'_{sv}} - 0.514 \overline{T_{sv}}\, \overline{w'q'}) \end{aligned} \quad (1)$$

$$\overline{T} = \overline{T_{sv}}(1 - 0.514\overline{q}) \quad (2)$$

where,

C_p : specific heat of air at constant pressure (J $kg^{-1}K^{-1}$)
ρ_d : density of dry air (kg m^{-3})
w : vertical wind velocity (m s^{-1})
T : air temperature (K)
T_{sv} : sound virtual temperature (K)
Q : specific humidity (kg kg^{-1}).

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Wind velocities measured by the sonic anemometer were rotated into a coordinate system aligned with the mean wind (McMillen, 1988). The sound virtual temperature by the sonic thermometer included the crosswind correction (Hignett, 1992). Humidity correction was applied to the sound virtual temperature to evaluate the real sensible heat flux (Eq. 1) and air temperature (Eq. 2). In this paper, the specific humidity fluctuation in Eq. 1 was calculated as the ratio of water vapor density fluctuation measured by the infrared open-path CO_2/H_2O gas analyzer to air density. As shown in Fig. 6, the corrected sensible heat flux was almost identical to the raw sensible heat flux, as the humidity correction was negligibly small in the present experiment. Then, the total latent heat (λE) and CO_2 (F_c) fluxes including the Webb correction terms were calculated as follows.

$$\lambda E = \lambda(1+\mu\sigma)\left(\overline{w'\rho'_v} + \frac{\overline{\rho_v}}{\overline{T}}\overline{w'T'}\right) \qquad (3)$$

$$F_c = \overline{w'\rho'_c} + \mu\frac{\overline{\rho_c}}{\overline{\rho_d}}\overline{w'\rho'_v} + (1+\mu\sigma)\frac{\overline{\rho_c}}{\overline{T}}\overline{w'T'} \qquad (4)$$

where,

λ : latent heat of vaporization (J kg^{-1})

μ : ratio of the molecular weights of dry air and water vapor

σ : ratio of water vapor and dry air densities

ρ_v and ρ_c : H_2O and CO_2 densities by the open-path CO_2/H_2O gas analyzer (kg m^{-3}).

The first and second terms of the right parenthesis on the right-hand side in Eq. 3 are the raw water vapor flux and the water vapor Webb correction term due to sensible heat flux. The first, second, and third terms on the right-hand side in Eq. 4 are the raw CO_2 flux and the CO_2 Webb correction terms due to latent and sensible heat fluxes, respectively. Detailed derivations of Eqs. 3 and 4 can be found in Webb *et al.* (1980).

4. RESULTS

4.1 Turbulent fluctuations

Figure 1 shows a typical example of turbulent fluctuations for vertical wind velocity, sound virtual temperature, and water vapor and CO_2 densities measured over the asphalt surface during the daytime. These fluctuations are plotted as 10 Hz raw data as the deviation from the 5 minutes mean value. The sound virtual temperature showed positively skewed fluctuation with an amplitude of 5 K, and was positively correlated with vertical wind velocity. The CO_2 density showed negatively skewed fluctuation with an amplitude of 10 mg m^{-3} (= 6 ppm), and was negatively correlated with vertical wind velocity. Fluctuations of sound virtual temperature and CO_2 density were noted to be distinctly and negatively correlated with each other using an independent instrument. These results showed that the eddy transport of CO_2 was apparently downward from the atmosphere to the asphalt surface with the large upward sensible heat flux. The fluctuation of water vapor density was small and did not show correlation with the fluctuation of sound virtual temperature or CO_2 density. These results showed that there is no cross-sensitivity between H_2O and CO_2 gases by an infrared open-path CO_2/H_2O gas analyzer. In the present study, the total CO_2 flux was determined by the raw CO_2 flux and the CO_2 Webb correction term due to sensible heat flux, because the Webb correction term due to latent heat flux can be negligible in the present data.

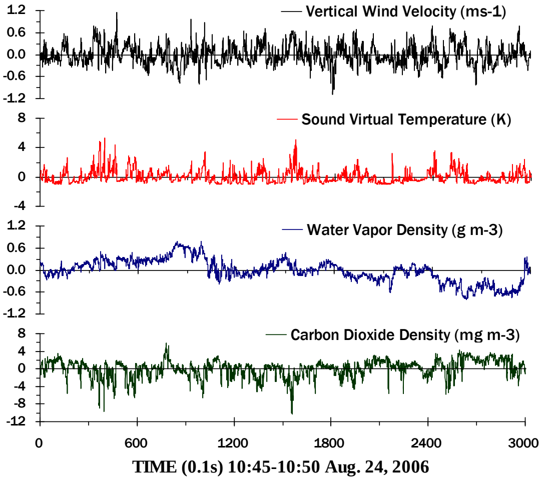

Figure 1 Turbulent fluctuations of vertical wind velocity, sound virtual temperature, and water vapor and CO2 densities

4.2 Power spectra and co-spectra

Figure 2 shows the normalized power spectra of the vertical wind velocity, sound virtual temperature, and water vapor and CO_2 density fluctuations observed by the open-path instruments between 10:45 and 11:00. The normalized power spectral densities $S_{xx}(n)/\sigma^2$, were plotted as functions of nondimensional frequency $f = nz/U$. These power spectra had similar frequency structure, and followed the –5/3 power law in the inertial subrange above 0.11. As shown in Figure 3, the normalized power spectra of CO_2 density fluctuation show similar frequency structures during this observation period.

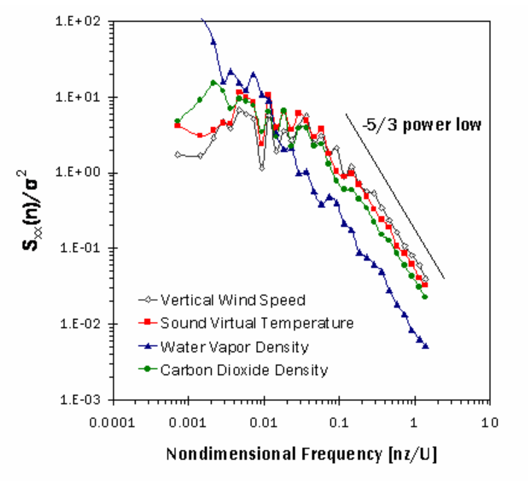

Figure 2 Normalized power spectra of the vertical wind velocity, sound virtual temperature, and water vapor and CO_2 density

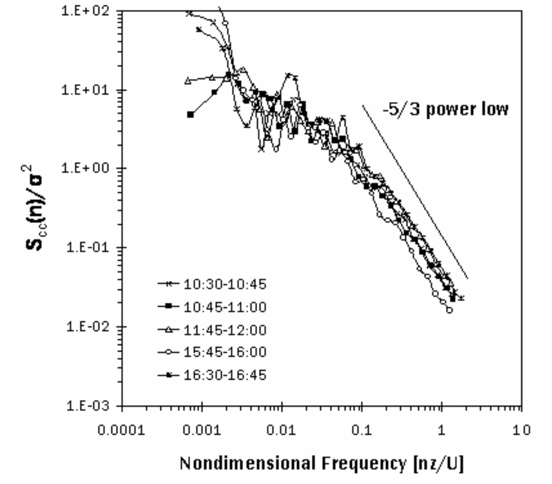

Figure 3 Normalized power spectra of the CO_2 density fluctuations as functions of non-dimensional frequency

Figure 4 shows the cospectra of CO_2 density and vertical wind velocity normalized by raw CO_2 flux as functions of the nondimensional frequency. These were analyzed using the same runs as shown in Fig. 3. These cospectra also had similar frequency structure between each run, and the flux dominant frequency ranges were around 0.05.

Figure 5 compares the ensemble-averaged cospectrum of raw CO_2 flux with those of the Webb CO_2 correction terms due to latent and sensible heat fluxes, and total CO_2 flux. The cospectrum of the CO_2 Webb correction term due to sensible heat flux showed positive for the whole frequency range, and was negatively correlated with that of raw CO_2 flux. In contrast, the cospectrum of the CO_2 Webb correction term due to latent heat flux was negligible for the whole frequency range. The cospectrum of the resulted total CO_2 flux showed a positive value for the whole frequency range.

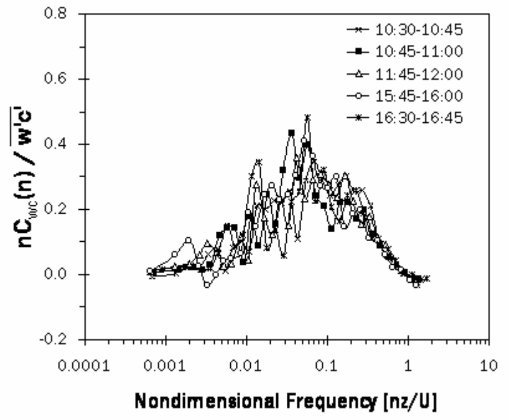

Figure 4 Cospectra of CO_2 density and vertical wind velocity normalized by the raw CO_2 flux as functions of non-dimensional frequency

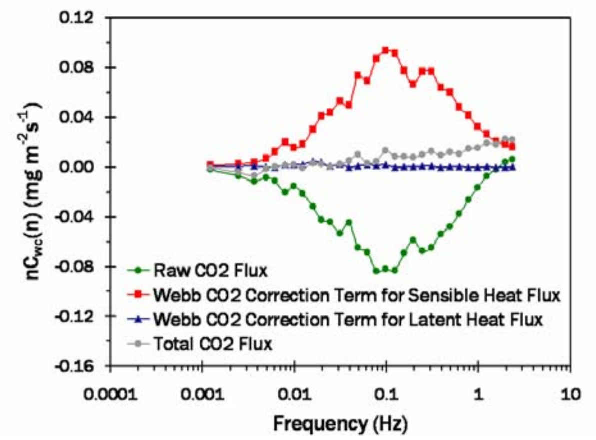

Figure 5 Ensemble-averaged cospectra of the raw CO_2 flux, CO_2 Webb correction terms due to latent and sensible heat fluxes, and total CO_2 flux

4.3 Webb correction on CO_2 flux over the asphalt surface

Figure 6 represents the time series of raw and corrected sensible heat fluxes(Eq.1), and raw and total latent heat fluxes(Eq.3). The raw and corrected sensible heat fluxes are almost identical as the surface was very dry. The latent heat flux represent some positive flux when included the Webb correction as to be discussed later.

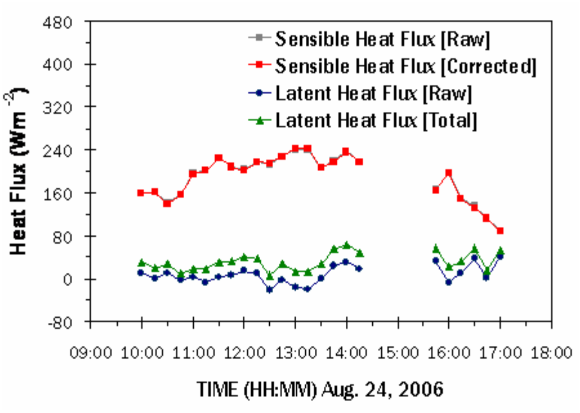

Figure 6 Time-series data of raw and corrected sensible heat fluxes, and raw and total latent heat fluxes. The raw and corrected sensible heat fluxes are almost identical.

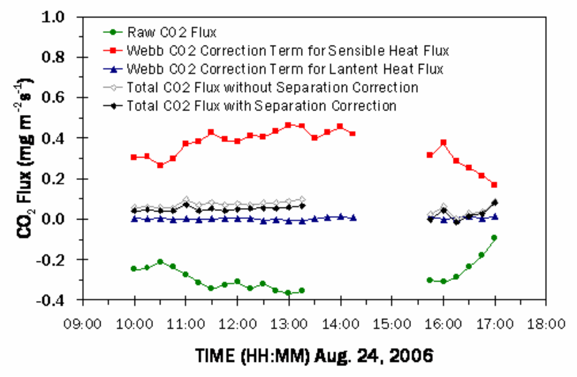

Figure 7 Time-series data of the raw CO_2 flux, Webb CO_2 correction terms for the sensible and latent heat fluxes, and total CO_2 fluxes (uncorrected and corrected the horizontal separation).

Figure 7 shows the time-series data of the raw CO_2 flux, CO_2 Webb correction terms due to sensible and latent heat fluxes, and total CO_2 flux. The raw CO_2 flux showed a diurnal variation, and was always negative (downward from the atmosphere to the asphalt surface) between –0.095 and –0.368 mg m^{-2}s^{-1} (the average was –0.283 mg m^{-2}s^{-1}). The CO_2 Webb correction term due to sensible heat flux also showed a diurnal variation, and was always positive between 0.167 and 0.462 mg m^{-2}s^{-1} (the sensible heat flux was between 87 and 243 Wm^{-2}). The Webb correction term due to latent heat flux was between –0.008 and 0.016 mg m^{-2}s^{-1} (raw latent heat flux was between –21 and 41 Wm^{-2}). Total(corrected) CO_2 flux was always positive between 0.001 and 0.097 mg m^{-2}s^{-1} (the average was 0.064 mg m^{-2}s^{-1}), and did not show a clear diurnal variation, as did raw CO_2 and sensible heat fluxes. Ham and Heilman (2003) performed a similar experiment over an asphalt surface, and reported total CO_2 flux by the eddy covariance technique of 0.02 mg m^{-2}s^{-1} (= 1.8 g m^{-2}day^{-1}) and CO_2 flux by the chamber technique of 0.03 mg m^{-2}s^{-1} (= 2.8 g m^{-2}day^{-1}) over the asphalt surface. The average total CO_2 flux in the present study was about two or three times larger than their result. Although total CO_2 flux measured by the eddy covariance technique as reported by Ham and Heilman (2003) included negative values, total CO_2 flux in the present study retained a significantly positive value.

5. DISCUSSIONS

As shown in Fig. 6, total latent heat flux including the Webb correction term was between 6 and 63 Wm^{-2} (the average was 32 Wm^{-2}), and larger than the result reported by Ham and Heilman (2003), showing systematic diurnal variation. Over the dry asphalt surface latent heat flux is considered almost zero, total latent heat flux resulted in a significantly positive value.

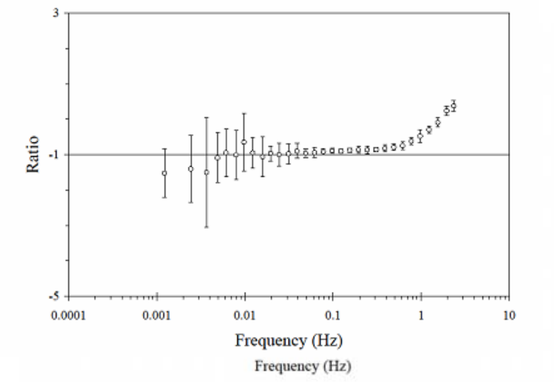

Figure 8 Ratio of cospectrum of the raw CO_2 flux to that of the CO_2 Webb correction term due to sensible heat flux as a function of frequency. The error bars are the standard deviation.

In Fig. 5, the ensemble-averaged cospectrum of total CO_2 flux had dominant frequency ranges around 0.1 Hz, and the range was consistent with those of raw CO_2 flux and the CO_2 Webb correction term due to sensible heat flux. Above 0.62 Hz, the cospectrum of raw CO_2 flux attenuated faster than that of the CO_2 Webb correction term due to sensible heat flux. As a result, the cospectrum of total CO_2 flux kept a positive value in this frequency range. This can be caused by horizontal separation between the sonic anemometer and the open-path CO_2/H_2O gas analyzer. Kristensen *et al*. (1997) showed that the flux causes a loss of 13% at a height of 1 m with a sensor horizontal separation of 0.2 m. To improve the underestimation of raw CO_2 flux by this separation, we have assumed cospectral similarty. Figure 8 shows the ratio of the cospectrum of raw CO_2 flux to CO_2 Webb correction term due to sensible heat flux as a function of frequency. The ratio is almost -1 between 0.04 and 0.62 Hz, suggesting negative cospectral similarity. While above 0.62 Hz the ratio increases from -1, suggesting the dissimilarity. The dissimilarity comes from the sensor separation mentioned above. Assuming that the cospectral similarity is kept in the high frequency above 0.62Hz, the CO2 raw flux was adjusted to keep the ratio as -1. As the result, the raw (negative) CO2 flux increased by 0.021 mg $m^{-2}s^{-1}$ and corrected total (positive) CO_2 flux decreased by 0.021 mg $m^{-2}s^{-1}$ on average as shown in Fig.7. This correction value was about 33% of the separation uncorrected total CO_2 flux (0.064 mg $m^{-2}s^{-1}$) or less than 8% of the raw CO_2 flux (–0.283 mg $m^{-2}s^{-1}$). However, the average total CO_2 flux kept a positive value (0.043 mg $m^{-2}s^{-1}$).

CO_2 flux by the eddy covariance technique using an infrared open-path CO_2/H_2O gas analyzer may include some uncertainties of the Webb correction, cross-sensitivity, energy balance closure, and so on. Our result suggested that the Webb correction may cause an overestimated correction of CO_2 and H_2O fluxes over a dry asphalt surface where there is no cross-sensitivity between H_2O and CO_2 gases by an infrared open-path CO_2/H_2O gas analyzer.

Alternative method of the flux validation can be chamber technique and/or closed-path eddy-covariance. These further studies are required to evaluate the accuracy of the Webb correction by the eddy covariance technique using an open-path CO_2/H_2O gas analyzer.

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