Evaluation of Webb Correction on CO₂ Flux by Eddy Covariance Technique Using Open-Path Gas Analyzer over Asphalt Surface

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Abstract

Webb correction is indispensable when evaluating trace gas flux by the eddy covariance technique using an open-path gas analyzer. In the present study, direct measurements of CO₂ flux by the eddy covariance technique using an open-path CO₂/H₂O gas analyzer were carried out over an asphalt surface where CO₂ and latent heat fluxes were considered almost zero. The power spectrum of CO₂ density fluctuation had similar frequency structure to those of vertical wind velocity, sound virtual temperature, and water vapor density fluctuations. The cospectrum of raw CO₂ flux was negatively correlated with that of sensible heat flux. The cospectrum of latent heat flux was almost zero and poorly correlated with that of raw CO₂ or sensible heat fluxes. Raw CO₂ flux was apparently downward from the atmosphere to the asphalt surface during this observation period. The Webb CO₂ correction term for sensible heat flux was upward and larger than the raw CO₂ flux, although the Webb CO₂ correction term for latent heat flux was almost zero. Total latent heat and CO₂ fluxes were evaluated as significant upward fluxes. This result shows that Webb correction may cause an overestimated correction to CO₂ flux by the eddy covariance technique using an open-path CO₂/H₂O gas analyzer over surfaces, especially where small CO₂ flux by soil respiration or air-sea exchange process is observed.

Key words: CO₂ flux, eddy covariance technique, open-path gas analyzer, trace gas flux, Webb correction

1. Introduction

The evaluation of the momentum, sensible heat, latent heat, and trace gas (e.g., CO₂) fluxes between various surfaces and the atmosphere is one of the most basic process studies. Turbulent flux by the eddy covariance technique using open-path instruments is the only direct measurement over surfaces. CO₂ and water vapor are the only trace gases that can measure turbulent flux using the open-path gas analyzer. The open-path CO₂/H₂O gas analyzer does not measure nondimensional 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 correct 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. 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).

Ohtaki *et al.* (1989) suggested that the Webb CO₂ flux due to air density fluctuation is larger than the raw CO₂ flux and changes the transport direction of the total CO₂ flux over the coastal sea surface. Kondo and Tsukamoto (2007) also confirmed these results over the open ocean surface.

Recently, Liu (2005) presented an alternative equation to correct effects of density fluctuations due to sensible and latent heat fluxes that does not require the original Webb correction assumption that dry air is conserved and the use of mean vertical velocity, and concluded that the original Webb correction is incomplete. However, Kowalski (2006) and Massman and Tuovinen (2006) argued that Liu's theory is mistaken. Leuning (2007) revised the correction theory

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presented by Webb *et al.* (1980) on the assumption that there is no source or sink of dry air at the ground or in the layer below the height of measurement. The basic Webb correction theory has been discussed well, but this correction is still poorly understood from actual observed data in various conditions. Therefore, it is important to evaluate the original Webb correction by applying it to data measured over various surfaces.

This paper experimentally evaluates the accuracy of the original Webb correction due to the air density fluctuation from water vapor and CO₂ flux measurements by the eddy covariance technique using an open-path CO₂/H₂O gas analyzer. 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. Methods and Observation procedures

2.1 Study site and instruments

The observation was made in the parking lot of the KOJIMA motorboat racetrack on August 24, 2006 (Fig. 1). This site is located at 34°26' N, 133°48' E in Okayama. This parking lot extends 110 m×180 m and provided a uniform and dry asphalt surface. The weather had been fine since a few days earlier, and the sea breeze dominated during this observation period.

Fluctuations of three-dimensional wind velocities and sound virtual temperature were measured using a sonic anemometer-thermometer (KAJIO, DA-600-3TV). The SAT probe was directed against the dominant sea

Fig. 1. Parking lot of the KOJIMA motorboat racetrack. This parking lot covers an area of 2×10^4 m², and provided a uniform and dry surface during this observation period. The SAT probe was directed against the dominated sea breeze.

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. Air temperature and humidity were also measured using humidity and temperature probes (VAISALA, HMP45A) placed at the same height as the turbulent instruments mentioned above. The analog output signals from these instruments were sampled and digitized at the rate of 10 Hz by a data acquisition system (National Instruments, LabVIEW) on a PC.

2.2 Flux calculation algorithm by the eddy covariance technique

The sensible heat flux (H) is given by

$$H = C_p \bar{\rho}_d \overline{w'T'} \\ = C_p \bar{\rho}_d (\overline{w'T'_{sv}} - 0.514 \bar{T}_{sv} \overline{w'q'}) \quad (1)$$

$$\bar{T} = \bar{T}_{sv} (1 - 0.514 \bar{q}) \quad (2)$$

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 measured by the sonic thermometer (K)

q : specific humidity (kg kg⁻¹).

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 performed on the sound virtual temperature measured by the sonic thermometer 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 CO₂/H₂O gas analyzer to air density. As shown in Fig. 3, the corrected sensible heat flux was almost identical to the raw sensible heat flux, as the humidity correction was negligibly small. Then, the total latent heat (λE) and CO₂ (F_c) fluxes including the Webb correction

terms were calculated as follows.

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

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

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 : H₂O and CO₂ densities by the open-path CO₂/H₂O 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 latent heat flux and the Webb latent heat correction term for the sensible heat flux. The first, second, and third terms on the right-hand side in Eq. 4 are the raw CO₂ flux and the Webb CO₂ correction terms for latent and sensible heat fluxes, respectively. A detailed derivation of Eqs. 3 and 4 can be found in Webb *et al.* (1980).

3. Results

3.1 Meteorological condition

Figure 2 shows the time-series data of the wind speed, air temperature, water vapor density, and carbon dioxide density. The sea breeze dominated and the mean wind speed was almost constant between 2.3 and 3.2 ms⁻¹ during the period between 9:30 and 14:15. Between 14:15 and 15:45, the wind direction shifted from onshore with the lower wind speed,

Fig. 2. Time-series data of wind speed, air temperature, water vapor density, and carbon dioxide density.

Fig. 3. 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.

and all flux data were rejected because of the flow distortion from the turbulent instrumental probes. From 15:45, the wind direction recovered and wind speed gradually decreased. After 17:15, all flux data were rejected because the momentum flux was calculated as negative. The wind attack angle was less than 3.6° during this observation period. The air temperature gradually increased and reached about 33°C from 14:30 to 15:30. Water vapor density measured by the open-path gas analyzer gradually increased during this observation period, and corresponded to that

calculated from the humidity and temperature probes. CO_2 density measured by the open-path gas analyzer was almost constant, but suddenly increased from 13:30 to 14:45. The standard deviation of the CO_2 density also increased during this period, although those of the air temperature and water vapor density did not. During this period, only CO_2 flux data were rejected.

3.2 Turbulent fluctuations

Figure 4 shows a typical example of atmospheric turbulent fluctuations for vertical wind velocity, sound virtual temperature, and water vapor and CO_2 densities

Fig. 4. Atmospheric turbulent fluctuations of vertical wind velocity, sound virtual temperature, and water vapor and CO_2 densities measured over the asphalt surface during 10:45-10:50.

Fig. 5. 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 during 10:45-11:00.

Fig. 6. Normalized power spectra of the CO_2 density fluctuations as functions of the nondimensional frequency during this observation period.

measured over the asphalt surface during the daytime. These fluctuations are plotted at 10 Hz raw data as the deviation from the 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 CO₂ 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 CO₂ density were noted to be distinctly and negatively correlated with each other using an independent instrument. These results showed that the eddy transport of CO₂ 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 CO₂ density. These results showed that there is no cross-sensitivity between H₂O and CO₂ gases by an infrared open-path CO₂/H₂O gas analyzer. In the present study, the total CO₂ flux was determined by the raw CO₂ flux and the Webb CO₂ correction term for the sensible heat flux, because the Webb correction term for the latent heat flux can be negligible.

3.3 Power spectra and cospectra

Figure 5 shows the normalized power spectra of the

Fig. 7. Cospectra of CO₂ density and vertical wind velocity normalized by the raw CO₂ flux as functions of the nondimensional frequency.

Fig. 8. Ensemble-averaged cospectra of the raw CO₂ flux, Webb CO₂ correction terms for the latent and sensible heat fluxes, and total CO₂ flux.

Fig. 9. Time-series data of the raw CO₂ flux, Webb CO₂ correction terms for the sensible and latent heat fluxes, and total CO₂ fluxes (uncorrected and corrected the horizontal separation).

Fig. 10. Ratio of cospectrum of the raw CO₂ flux to that of the Webb CO₂ correction term for the sensible heat flux as a function of frequency. The error bars are the standard deviation.

vertical wind velocity, sound virtual temperature, and water vapor and CO₂ density fluctuations observed by the open-path instruments between 10:45 and 11:00. The ordinate is the power spectral density $S_{xx}(n)/\sigma^2$, normalized by the variance of each parameter. The abscissa is the nondimensional frequency $f=nz/U$ on a logarithmic scale. Here, n is the frequency (Hz), and U is the mean wind speed (ms⁻¹) at the measurement height z (m). These power spectra had similar frequency structure, and followed the $-5/3$ power law in the wide frequency ranges (the inertial subrange) above 0.11. The normalized power spectra of CO₂ density fluctuation were of similar shapes during this observation period (Fig. 6).

Figure 7 shows the cospectra of CO₂ density and vertical wind velocity normalized by raw CO₂ flux as functions of the nondimensional frequency. These were analyzed using the same runs as shown in Fig. 6. These cospectra also had similar frequency structure between each run, and the dominant frequency ranges were around 0.05. Figure 8 compares the ensemble-averaged cospectrum of raw CO₂ flux with those of the Webb CO₂ correction terms for the latent and sensible heat fluxes, and total CO₂ flux. The abscissa is frequency (Hz). The cospectrum of the Webb CO₂ correction term for sensible heat flux showed positive for the whole frequency range, and was negatively correlated with that of raw CO₂ flux. In contrast, the cospectrum of the Webb CO₂ correction term for latent heat flux was a negligible value for the whole frequency range. The cospectrum of the resulted total CO₂ flux showed a positive value for the whole frequency range.

3.4 Webb correction on CO₂ flux over the asphalt surface

Figure 9 shows the time-series data of the raw CO₂ flux, Webb CO₂ correction terms for sensible and latent heat fluxes, and total CO₂ flux. The raw CO₂ 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⁻²s⁻¹ (the average was -0.283 mg m⁻²s⁻¹). The Webb CO₂ correction term for sensible heat flux also showed a diurnal variation, and was always positive between 0.167 and 0.462 mg m⁻²s⁻¹ (the sensible heat flux was between 87 and 243 Wm⁻²). The Webb correction term for latent heat flux was between -0.008 and 0.016 mg m⁻²s⁻¹ (raw latent heat flux was between -21 and 41 Wm⁻²), and was not influenced by the Webb correction. Total CO₂ flux was always positive between 0.001 and 0.097 mg m⁻²s⁻¹ (the average was 0.064 mg m⁻²s⁻¹), and did not show a clear diurnal variation, as did raw CO₂ and sensible heat fluxes. Ham and Heilman (2003) performed a similar experiment over an asphalt surface, and reported total CO₂ flux by the eddy covariance technique of 0.02 mg m⁻²s⁻¹ ($=1.8$ g m⁻²day⁻¹) and CO₂ flux by the chamber technique of 0.03 mg m⁻²s⁻¹ ($=2.8$ g m⁻²day⁻¹) over the asphalt surface. The average total CO₂ flux in the present study was about two to three times larger than in their result. Although total CO₂ flux measured by the eddy covariance technique as reported by Ham and Heilman (2003) included negative values, total CO₂ flux in the present study retained a significantly positive value.

4. Discussion

The eddy covariance technique is the most promising flux evaluation technique. This technique is the only direct measurement of momentum, heat, and trace gas fluxes, and can evaluate trace gas flux on a short time scale (e.g., several tens of minutes to hours) over various surfaces. However, when we evaluate trace gas flux using an open-path gas analyzer, the correction due to the air density fluctuation is indispensable. Although the original Webb correction reported by Webb *et al.* (1980) is believed to be the most promising correction, we should confirm this correction experimentally and need to understand the degree of its accuracy.

As shown in Fig. 3, 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 considered almost zero in comparison with CO₂ flux, total latent heat flux was also a significantly positive flux.

In Fig. 8, the ensemble-averaged cospectrum of total CO₂ flux had dominant frequency ranges around 0.1 Hz, and the range was consistent with those of raw CO₂ flux and the Webb CO₂ correction term for sensible heat flux. Figure 10 shows the ratio of each frequency of cospectrum of raw CO₂ flux to Webb CO₂ correction term for sensible heat flux. Above 0.62 Hz, the cospectrum of raw CO₂ flux attenuated faster than that of the Webb CO₂ correction term for sensible heat flux. As a result, the cospectrum of total CO₂ flux kept a positive value in this frequency range. This can be caused by horizontal separation between the sonic anemometer-thermometer and the open-path CO₂/H₂O 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 CO₂ flux by this separation, we have assumed that the ratio of each frequency of cospectrum of raw CO₂ flux to Webb CO₂ correction term for sensible heat flux above 0.62 Hz has the same value between 0.04 and 0.62 Hz. As shown in Fig. 9, total CO₂ flux increased by 0.021 mg m⁻²s⁻¹ on average. This value was about 33% of the total CO₂ flux (0.064 mg m⁻²s⁻¹) or less than 8% of the raw CO₂ flux (-0.283 mg m⁻²s⁻¹). However, the average total CO₂ flux kept a positive value (0.043 mg m⁻²s⁻¹).

CO₂ flux by the eddy covariance technique using

an infrared open-path CO₂/H₂O gas analyzer may include some uncertainties of the Webb correction, cross-sensitivity, energy balance closure, and so on. Liu *et al.* (2006) suggested that incomplete energy balance closure does not necessarily lead to an underestimation of CO₂ flux. Our result suggested that the Webb correction may cause an overestimated correction of CO₂ and H₂O fluxes over a dry asphalt surface where there is no cross-sensitivity between H₂O and CO₂ gases by an infrared open-path CO₂/H₂O gas analyzer.

This study did not use the chamber technique performed by Ham and Heilman (2003), which can be helpful in verifying CO₂ flux over the asphalt surface in the present study site as an alternative technique. The closed-path CO₂/H₂O gas analyzer measures the nondimensional CO₂ and water vapor concentrations as the mixing ratios. The eddy covariance technique using the closed-path analyzer can evaluate CO₂ flux without the Webb correction. These further studies are required to evaluate the accuracy of the Webb correction by the eddy covariance technique using an open-path CO₂/H₂O gas analyzer.

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