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Air-Sea CO_2 Flux by Eddy Covariance Technique in the Equatorial Indian Ocean

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Direct measurements of the air-sea CO_2 flux by the eddy covariance technique were carried out in the equatorial Indian Ocean. The turbulent flux observation system was installed at the top of the foremast of the R/V MIRAI, thus minimizing dynamical and thermal effects of the ship body. During the turbulent flux runs around the two stations, the vessel was steered into the wind at constant speed. The power spectra of the temperature or water vapor density fluctuations followed the Kolmogorov –5/3 power law, although that of the CO_2 density fluctuation showed white noise in the high frequency range. However, the cospectrum of the vertical wind velocity and CO_2 density was well matched with those of the vertical velocity and temperature or water vapor density in this frequency range, and the CO_2 white noise did not influence the CO_2 flux. The raw CO_2 fluxes due to the turbulent transport showed a sink from the air to the ocean, and had almost the same value as the source CO_2 fluxes due to the mean vertical flow, corrected by the sensible and latent heat fluxes (called the Webb correction). The total CO_2 fluxes including the Webb correction terms showed a source from the ocean to the air, and were larger than the bulk CO_2 fluxes estimated using the gas transfer velocity by mass balance techniques.

Keywords:
· Eddy covariance technique,
· eddy correlation technique,
· CO_2 flux,
· air-sea interaction,
· Webb correction,
· spectral analysis.

1. Introduction

The ocean is one of the main sinks of anthropogenic CO_2. Precise measurements of the CO_2 gas transfer across the air-sea interface provide a better understanding of the global carbon cycle. However, many of the mechanisms that control the air-sea gas transfer are not well understood.

The eddy covariance (correlation) technique is the only direct measurement of the momentum, heat, and trace gas (e.g. water vapor, CO_2, and DMS) fluxes across the air-sea interface. This technique can evaluate the trace gas flux on a shorter time scale (e.g. several minutes or hours) than mass balance techniques using the tracers of the natural and bomb-produced ^{14}C, $^{222}Rn/^{226}Ra$, and $SF_6/^3He$.

Jones and Smith (1977) reported the first measurement of CO_2 fluxes by the eddy covariance technique using an open-path CO_2 gas analyzer over the coastal sea. Their result shows an order of magnitude larger CO_2 fluxes than the bulk CO_2 fluxes estimated using the gas transfer velocity by mass balance techniques. Subsequent observations over coastal seas in a variety of environments are not consistent with the bulk CO_2 fluxes (Wesely *et al*., 1982; Smith and Jones, 1985; Ohtaki *et al*., 1989; Jacobs *et al*., 1999). McGillis *et al*. (2001) reported the measurement of CO_2 fluxes evaluated by the eddy covariance technique over the open ocean using a closed-path CO_2/H_2O gas analyzer. Their result shows almost the same values as the bulk CO_2 fluxes estimated using the gas transfer velocity, which was simultaneously evaluated in situ by the mass balance technique using $SF_6/^3He$ dual tracers.

One important problem is the question of what physical and chemical processes influence the gas transfer across the air-sea interface, such as bubble enhancement, surfactant, surface film, wave, wind speed, and atmospheric stability. However, the present parameterization of the gas transfer velocity indicates that this velocity is a function of the wind speed only. Wanninkhof and McGillis (1999) suggested that this relationship depends on the time scale of the evaluated CO_2 fluxes. The eddy covariance technique can evaluate the trace gas flux on a shorter time scale than mass balance techniques, and also includes the uncertain processes (e.g. bubble enhance-

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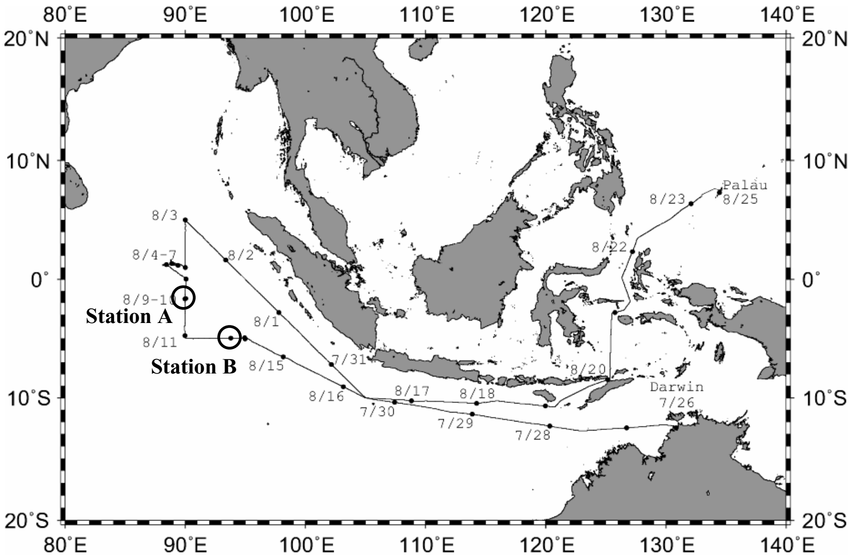

Fig. 1. Cruise track of the R/V MIRAI during MR05-03 leg 2. The two circles represent station A (90°E, 1.5°S) and B (95°E, 5°S) at which special observations of the turbulent flux were performed.

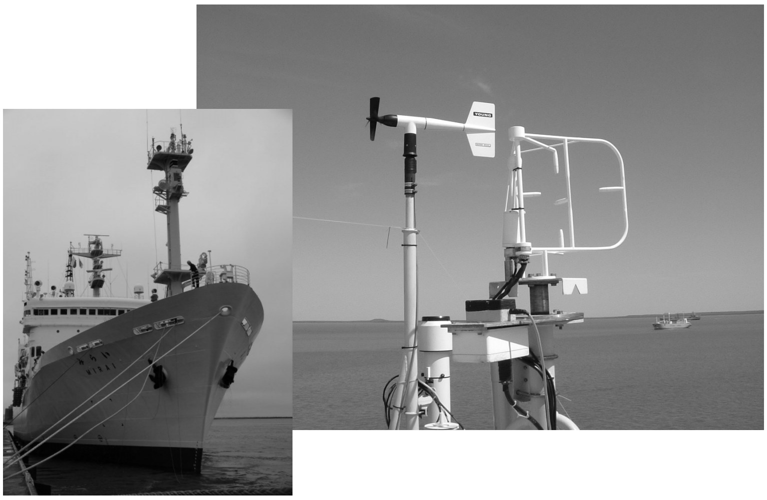

Fig. 2. Systems for turbulent flux observation and ship motion correlation on the top of the foremast of the R/V MIRAI, JAMSTEC.

ment, surfactant, surface film, wave, and atmospheric stability) that the parameterization does not consider.

This paper focuses on the direct measurement of CO_2 fluxes evaluated by the eddy covariance technique over the open ocean, and compares these fluxes with the bulk CO_2 fluxes estimated using the gas transfer velocity by mass balance techniques.

2. Methods and Observation Procedures

2.1 Study site

The measurement was conducted aboard the R/V MIRAI of JAMSTEC (Japan Agency for Marine-Earth Science and Technology) in the equatorial Indian Ocean. The cruise track is shown in Fig. 1. The general meteorological data (air temperature, humidity, short- and long-wave radiation, wind speed and direction, and air pressure) were measured at about 24 m height above the sea surface. The properties of the bulk seawater temperature and salinity were measured at about 4.5 m depth below the sea surface. The fugacities of CO_2 in bulk seawater and air were also measured at the same height or depth (Murata and Takizawa, 2003).

During this cruise, special observations of the turbulent flux were performed at the two stations. The first run at station A (90°E, 1.5°S) was performed from 9 (15:00) to 10 (3:00) August 2005; the second run at station B (95°E, 5°S) was performed from 12 (16:30) to 13 (4:30) August 2005. During both runs, the vessel was steered into the wind at a constant speed of 8 knots for about an hour, and then returned to keep the same position. This leg was repeated for 12 hours at the two stations.

2.2 Turbulent flux measurement system

We installed the turbulent flux system and ship motion correction system on the top of the foremast (about 24 m above the mean sea surface) of the R/V MIRAI (Fig. 2). The turbulent flux system consisted of a sonic anemometer-thermometer (KAIJO, DA-600-3TV) and an infrared open-path CO_2/H_2O gas analyzer (LI-COR, LI-7500). We cleaned the LI-7500 optical windows to avoid contamination by salt particles and raindrops before special observations, and checked the AGC value ("clean window" baseline value) before and after these observations. The ship motion correction system consisted of a two-axis inclinometer (Applied Geomechanics, MD-900-T), a three-axis accelerometer (Applied Signals, QA-700-020), and a three-axis rate gyro (Systron Donner, QRS11-0050-100). Analog output signals from these fast response instruments were sampled and digitized at the rate of 10 Hz by a data acquisition system (National Instruments, LabVIEW). The digitized signals were averaged to 2.5 Hz during the data processing.

2.3 Ship motion correction

One of the greatest difficulties in measuring turbulent flux by the eddy covariance technique over the open ocean is the apparent wind velocity caused by the ship motion. Fujitani (1985) suggested that the true wind velocity (V_{true}) can be expressed as follows:

$$V_{\text{true}} = TV_{\text{observed}} + \Omega T(R - r) + V_{\text{ship}}, \tag{1}$$

where V_{observed} is the raw wind velocity measured by the sonic anemometer, T is the coordinate transformation matrix, Ω is the angular velocity vector of the ship around the reference coordinate, R is the position vector of the sonic anemometer with respect to the ship coordinate, r is the position vector of the motion sensor, and V_{ship} is the velocity vector of the ship.

We adopted the simplified system proposed by Takahashi *et al.* (2005). This system was installed in the ship motion correction system at the same position as the sonic anemometer (i.e. $R = r$). The above equation can therefore be simplified as follows:

$$V_{\text{true}} = TV_{\text{observed}} + V_{\text{anemo}}. \tag{2}$$

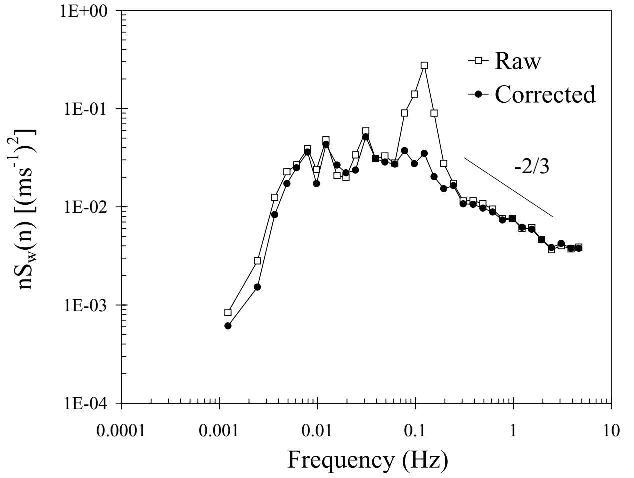

Fig. 3. Power spectra of the raw and corrected vertical wind velocity fluctuations. Raw data are open squares (□) and corrected data are closed circles (●).

The yaw, pitch, and roll angles measured by the inclinometer and rate gyro lead to the coordinate transformation matrix. V_{anemo} is obtained as the time integration of the three-axis accelerations. Figure 3 shows the power spectra of the raw and corrected vertical wind velocity fluctuations. The power spectrum of the raw vertical wind velocity fluctuation shows a false peak around 0.1 Hz. This frequency is the same as the cycles caused by the ship motion. On the other hand, the power spectrum of the corrected vertical wind velocity fluctuation does not show the false peak.

2.4 Turbulent CO_2 flux by the eddy covariance technique

The air-sea turbulent CO_2 flux by the eddy covariance technique is given by:

$$Fc(eddy) = \overline{w\rho_c} = \overline{w'\rho_c'} + \overline{w}\,\overline{\rho_c}, \tag{3}$$

where w is the vertical wind velocity and ρ_c is the CO_2 density. The prime indicates the fluctuation as deviations from the mean value (overbar) over a sampling period. The CO_2 flux was calculated as fifteen minute statistics. The first term on the right hand side of Eq. (3) is the raw CO_2 flux measured by the turbulent flux system. The second term on the right hand side is the CO_2 flux due to the mean vertical flow. 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 CO_2. To evaluate the magnitude of the influence of the mean vertical flow, Webb *et al.* (1980) assumed that the vertical flux due to the density fluctuation of the dry air (ρ_a) should be zero:

$$\overline{w\rho_a} = \overline{w}\,\overline{\rho_a} + \overline{w'\rho_a'} = 0. \tag{4}$$

Using the ideal gas equation, the final expression for the mean vertical flow is as follows:

$$\overline{w} = \frac{\mu}{\overline{\rho_a}}\overline{w'\rho_v'} + (1+\mu\sigma)\frac{\overline{w'T'}}{\overline{T}}. \quad (5)$$

For the total CO_2 flux, it is as follows:

$$Fc(eddy) = \overline{w'\rho_c'} + \mu\frac{\overline{\rho_c}}{\overline{\rho_a}}\overline{w'\rho_v'} + (1+\mu\sigma)\frac{\overline{\rho_c}}{\overline{T}}\overline{w'T'}, \quad (6)$$

where μ is the ratio of the molecular weights of dry air and water vapor, σ is the ratio of water vapor and dry air densities, ρ_v is the water vapor density, and T is the absolute temperature. Practically speaking, the sensible ($\overline{w'T'}$) and latent ($\overline{w'\rho_v'}$) heat fluxes evaluated by the eddy covariance technique are used to calculate CO_2 fluxes due to the mean vertical flow (Webb correction terms). The actual values of these terms are discussed in Subsection 3.2. A detailed derivation of Eq. (4) can be found in Webb *et al*. (1980).

2.5 *Air-sea bulk CO_2 flux*

The air-sea bulk CO_2 flux is given by (Liss and Merlivat, 1986):

$$Fc(bulk) = k_{CO2}\, S_{CO2}\, \Delta fCO_2, \quad (7)$$

where k_{CO2} is the gas transfer velocity of CO_2 modified by the Schmidt Number, S_{CO2} is the solubility of CO_2, and ΔfCO_2 is the difference between the fugacities of CO_2 in bulk seawater and air. We adopted the gas transfer velocity proposed by Wanninkhof (1992), which was estimated by mass balance techniques using tracers of the natural and bomb-produced ^{14}C, $^{222}Rn/^{226}Ra$, and $SF_6/^3He$. The time scale of this mass balance-based gas transfer velocity ranged from several days to years. We estimated the bulk CO_2 flux at each station using the mean wind speed and ΔfCO_2 for a period of 12 hours, during which the flux observation runs were performed.

3. Results

Figure 4 shows the time-series data of the difference between the fugacities of CO_2 in bulk seawater and air ($\Delta fCO_2 = fCO_2sea - fCO_2air$), and the wind speed including special observation periods of the turbulent flux.

The ΔfCO_2 was positive and almost constant during both station runs. The mean ΔfCO_2 was $+27.2 \pm 0.5$ μatm at station A, and $+16.6 \pm 2.5$ μatm at station B. The wind speed was light (<7 ms^{-1}) during both runs, varying from 1.4 to 5.9 ms^{-1} at station A and 1.6 to 6.6 ms^{-1} at station B.

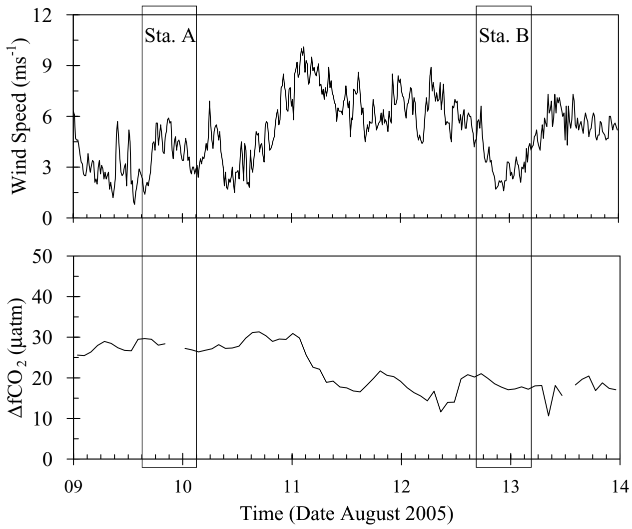

Fig. 4. Time-series data of the air-sea CO_2 fugacity difference ($\Delta fCO_2 = fCO_2sea - fCO_2air$, lower) and wind speed at 24 m above the sea surface (upper).

3.1 *Spectrum and cospectrum*

Figure 5 shows an example of the power spectra of the temperature (△), water vapor density (■), and CO_2 density (○) fluctuations observed by the turbulent flux measurement system, 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 wind speed [ms^{-1}] at the measurement height z [m].

The shapes of the power spectra of the temperature, water vapor density, and CO_2 density fluctuations were basically similar. The power spectra of the temperature and water vapor density fluctuations followed the Kolmogorov –5/3 power law over a wide frequency range above 0.04. On the other hand, the power spectrum of CO_2 density fluctuation followed the –5/3 power law in the frequency range 0.04–1.6, while white noise appeared above the nondimensional frequency range 1.6.

This CO_2 white noise is due to the inadequate sensitivity of the gas analyzer to the small CO_2 density fluctuation. The CO_2 density fluctuations over the ocean are an order of magnitude smaller than those over the vegetation on land.

Figure 6 shows an example of the cospectra of the parameters mentioned above and the vertical wind velocity as functions of the nondimensional frequency. Each flux is equivalent to a frequency integral of the cospectrum of each parameter. The shapes of the cospectra of the temperature, water vapor, and CO_2 fluxes were also basically similar, giving the same result as the power spectra. The cospectrum of the CO_2 flux showed a negative flux (rep-

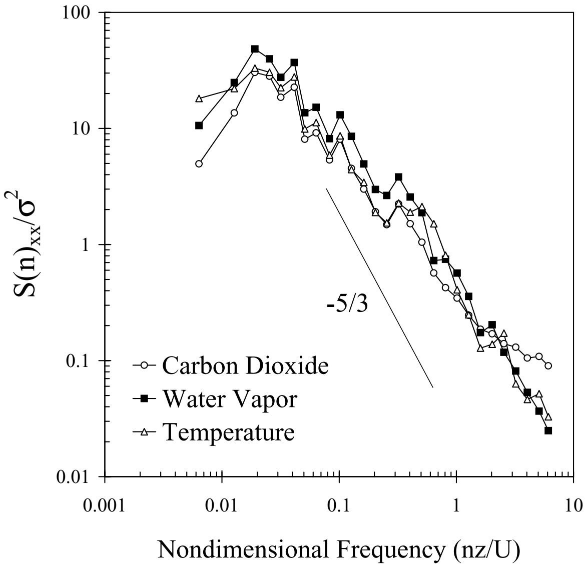

Fig. 5. Power spectra of carbon dioxide density (○), water vapor density (■), and temperature (△) fluctuations normalized by the variance during 12 (16:45–17:00) August 2005.

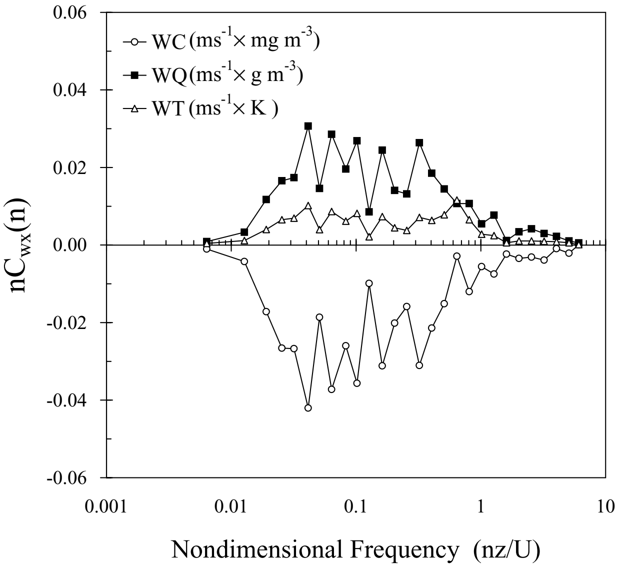

Fig. 6. Cospectra of vertical wind velocity fluctuation and carbon dioxide density (WC, ○), water vapor density (WQ, ■), and temperature (WT, Δ) fluctuations during 12 (16:45–17:00) August 2005.

resenting a CO_2 sink) over the entire frequency range, while those of the temperature and water vapor fluxes were positive fluxes (representing energy sources).

The cospectrum of the CO_2 flux does not show the influence of white noise, which was observed in the high frequency range of the power spectrum in Fig. 5. This is because the instrumental white noise of CO_2 density fluctuation does not correlate with the vertical wind velocity fluctuation. This cospectrum was mainly limited to the frequency range 0.006–1.6, and the most dominant frequency range was centered at 0.04, as were the cospectra of the temperature and water vapor fluxes. The CO_2 flux in the frequency range 1.6–6.1 showing white noise represented only about 2 percent of the entire CO_2 flux. As this cospectrum does not show any influence from the ship motion, the turbulent flux (integrated value as the covariance) evaluated directly by the eddy covariance technique is considered to be reasonable.

3.2 CO_2 flux

Figure 7 shows the time-series data of the raw and total CO_2 fluxes evaluated directly by the eddy covariance technique, and those of the CO_2 fluxes due to the mean vertical flow corrected by the sensible and latent heat fluxes (Webb correction terms) at the two stations. The open circle (○), solid circle (●), open triangle (△), and solid square (■) represent the raw and total CO_2 fluxes, and the Webb correction terms for the sensible and latent heat fluxes, respectively. The Webb correction terms for the sensible and latent heat fluxes were evaluated directly by the eddy covariance technique, and calculated as the second and third terms of Eq. (6).

The raw CO_2 fluxes were negative, and the mean value was –0.052 mg $m^{-2}s^{-1}$ at station A and –0.063 mg $m^{-2}s^{-1}$ at station B. The Webb correction terms were positive, and the mean values were +0.023 mg $m^{-2}s^{-1}$ (Webb correction term for the sensible heat flux) and +0.039 mg $m^{-2}s^{-1}$ (Webb correction term for the latent heat flux) at station A, and +0.017 mg $m^{-2}s^{-1}$ and +0.047 mg $m^{-2}s^{-1}$ at station B, respectively. The Webb correction term for the latent heat flux was larger than the Webb correction term for the sensible heat flux. The sum of Webb correction terms for the sensible and latent heat fluxes was almost the same as or rather larger than the raw CO_2 flux. As a result, the total CO_2 fluxes were positive, the mean value being +9.6 × 10^{-3} mg $m^{-2}s^{-1}$ at station A and +0.9 × 10^{-3} mg $m^{-2}s^{-1}$ at station B.

Table 1. Mean values and standard deviations of the wind speed and the air-sea CO_2 fugacity difference (ΔfCO_2), and the estimated bulk CO_2 fluxes at the two stations.

	Wind speed [ms^{-1}]	ΔfCO_2 [μatm]	Bulk CO_2 flux [10^{-3} mg $m^{-2}s^{-1}$]
Station A	3.4 ± 1.0	+27.2 ± 0.5	+0.51
Station B	4.7 ± 1.6	+16.6 ± 2.5	+0.59

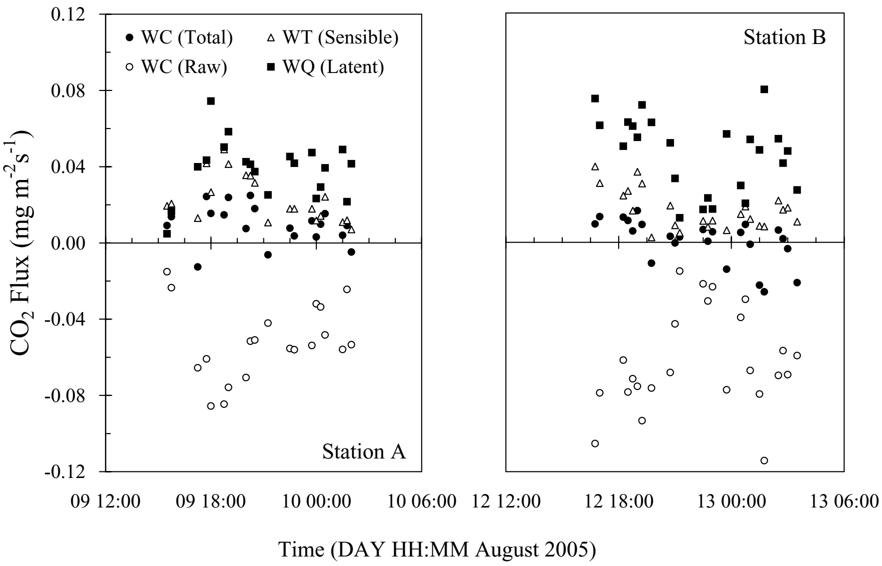

Fig. 7. Time-series data of total (●) and raw (○) CO_2 fluxes, and mean vertical flow CO_2 fluxes corrected by sensible (△) and latent (■) heat fluxes at station A (left) and station B (right).

Table 2. Mean values (upper) and ranges (lower) of the CO_2 fluxes evaluated directly by the eddy covariance technique, and mean values of the estimated bulk CO_2 flux at the two stations. The sensible and latent heat fluxes evaluated by the eddy covariance technique are used to calculate of the mean vertical flow CO_2 fluxes (Webb correction terms). Units are 10^{-3} mg $m^{-2}s^{-1}$.

	CO_2 flux by eddy covariance technique				Bulk CO_2 flux
	Raw CO_2 flux	Webb correction term for the sensible heat flux	Webb correction term for the latent heat flux	Total CO_2 flux	
Station A	−51.95	+22.94	+38.62	+9.62	+0.51
	−85.54~−15.11	+7.11~+49.05	+4.81~+74.38	−12.57~+24.93	
Station B	−62.66	+17.05	+46.50	+0.90	+0.59
	−114.21~−15.06	+2.58~+39.69	+12.84~+80.06	−25.88~+16.55	

On the other hand, the bulk CO_2 fluxes estimated using the gas transfer velocity proposed by Wanninkhof (1992) were $+0.51 \times 10^{-3}$ mg $m^{-2}s^{-1}$ at station A and $+0.59 \times 10^{-3}$ mg $m^{-2}s^{-1}$ at station B (Table 1). As a result, the total CO_2 flux evaluated by the eddy covariance technique was an order of magnitude larger than the estimated bulk CO_2 flux at station A. However, the total CO_2 flux evaluated by the eddy covariance technique was similar to the estimated bulk CO_2 flux at station B.

4. Discussion

Direct measurements of the air-sea CO_2 flux by the eddy covariance technique were performed over the open ocean with careful quality control. The ΔfCO_2 was positive and almost constant at both stations. The wind speeds were light, varying over a rather narrow range 1.4–6.6 ms^{-1} during special observations of the turbulent flux. The shapes of the normalized power spectra of the temperature, water vapor density, and CO_2 density fluctuations were basically similar. The total CO_2 fluxes were positive and the mean vertical flow CO_2 fluxes by the Webb correction were almost the same as or rather larger than the raw CO_2 fluxes.

Table 2 shows the mean values and ranges of the CO_2 fluxes evaluated by the eddy covariance technique, and the mean values of the estimated bulk CO_2 flux at the two stations. The sensible and latent heat fluxes evaluated by the eddy covariance technique are used for the calculation of the mean vertical flow CO_2 fluxes (Webb correction terms). The total CO_2 flux by the eddy covariance technique and the bulk CO_2 flux disagree at station A, but become similar at station B. However, the

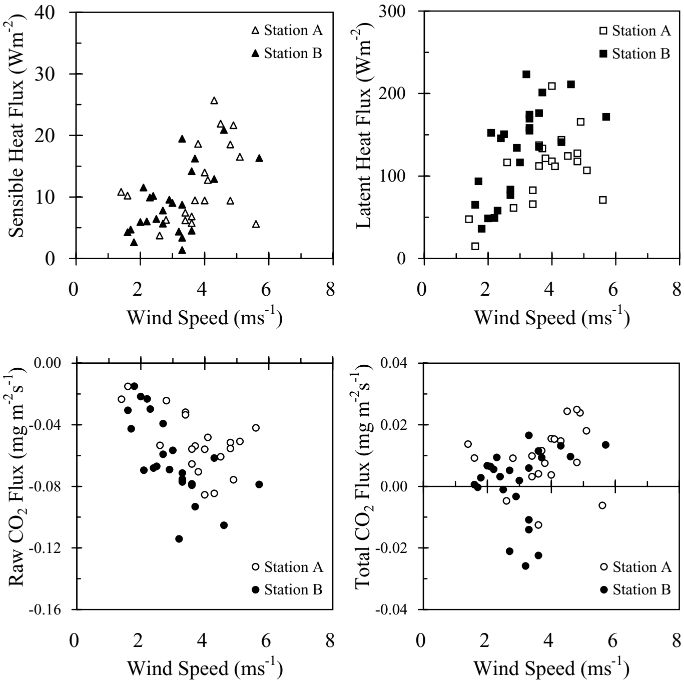

Fig. 8. Sensible heat, latent heat, raw CO_2, and total CO_2 fluxes as a function of wind speed using data from both stations.

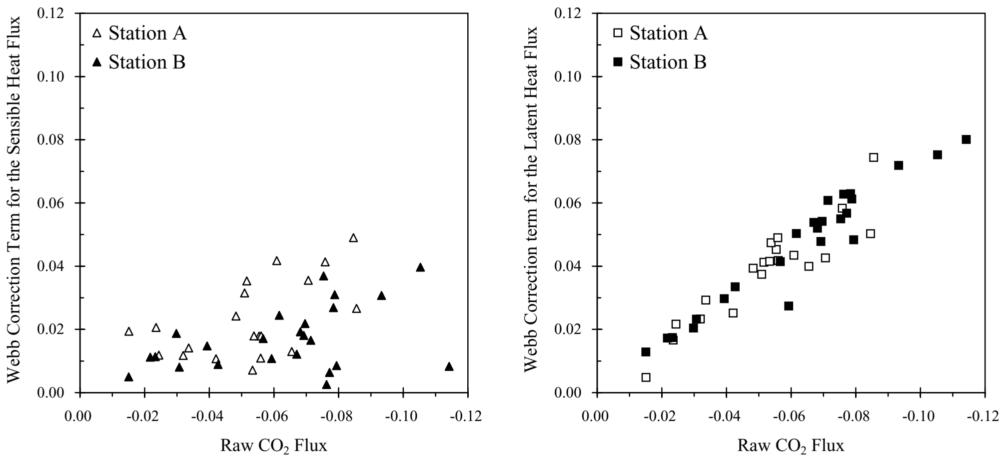

Fig. 9. Webb correction terms for sensible and latent heat fluxes as a function of raw CO_2 flux using data at both stations.

ranges of the total CO_2 flux by the eddy covariance technique at both stations are almost the same.

Figure 8 shows the sensible heat, latent heat, raw CO_2, and total CO_2 fluxes as a function of the wind speed using the data at both stations. Although there is some scatter, the sensible heat, latent heat, raw CO_2 fluxes increase with increasing wind speed, due to the increasing turbulent intensity. On the other hand, the total CO_2 flux depends roughly on the wind velocity as well as the sensible heat, latent heat, and raw CO_2 fluxes at both stations. However, the total CO_2 fluxes at station B include large negative values, even after the Webb correction is applied.

Figure 9 shows the Webb correction terms for the sensible and latent heat fluxes as a function of the raw CO_2 flux using the data at both stations. The Webb correction term for the latent heat flux correlates closely with the raw CO_2 flux at both stations, although there is a poorer correlation between the Webb correction term for the sensible heat flux and the raw CO_2 flux. The large negative total CO_2 fluxes at station B may be due to small sensible heat fluxes, even given the large raw CO_2 fluxes. However, the cospectra of sensible heat fluxes are basically similar to those of latent heat and raw CO_2 fluxes.

McGillis *et al.* (2001) suggested that CO_2 flux measurements by the eddy covariance technique should be performed under large ΔfCO_2 and high wind speed environments to be successful. However, we need to know what certain parameters to control the CO_2 fluxes over the various oceans. In fact, there are very few large ΔfCO_2 areas over the ocean (Takahashi *et al.*, 2002). In this study, we observed the CO_2 fluxes by the eddy covariance technique in areas of small ΔfCO_2 and low wind speed over the ocean. The CO_2 density fluctuation shows white noise in the high frequency range, which has no influence on the CO_2 fluxes.

Our goal is the precise evaluation of the ocean uptake of anthropogenic CO_2. The eddy covariance technique is the only direct air-sea flux measurement that allows us to understand the process controlling the air-sea CO_2 fluxes over short time and space scales. To reach our goal, the following issues remain for future studies:

(1) Flux evaluation by observations at fixed points and for a long term (days and weeks) over the open ocean;

(2) Development of a turbulent flux measurement system without the need for the Webb correction;

(3) Confirmation of the transport direction measuring the vertical CO_2 concentration profile in air.

The time scale needed to estimate the gas transfer velocity by mass balance techniques is generally long, from days ($^{222}Rn/^{226}Ra$ and $SF_6/^3He$) to years (natural and bomb-produced ^{14}C). On the other hand, the eddy covariance technique can evaluate the trace gas flux on the time scale of minutes or hours. In this study, we have attempted to evaluate the CO_2 fluxes by the eddy covariance technique on a time scale of 12 hours at the same position over the open ocean. The present results did not always correspond to the bulk CO_2 fluxes estimated using the gas transfer velocity by mass balance techniques.

This study found that the upward mean vertical flow CO_2 fluxes by the Webb correction are of the same order as the downward raw CO_2 fluxes, leading to the upward total CO_2 fluxes. This is the same situation as the coastal sea results reported by Ohtaki *et al.* (1989). The total CO_2 fluxes are order of magnitude larger than the bulk CO_2 fluxes. We need to attempt flux observations using turbulent flux measurement system without the need for the Webb correction, and to measure the vertical CO_2 concentration profile in air.

Further work is now in progress in an attempt to measure CO_2 flux more precisely by the eddy covariance technique.

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References

Fujitani, T. (1985): Method of turbulent flux measurement on a ship by using a stable platform system. *Pap. Met. Geophys.*, **36**, 157–170.

Jacobs, C. M. J., W. Kohsiek and W. A. Oost (1999): Air-sea fluxes and transfer velocity of CO_2 over the North Sea: results from ASGAMAGE. *Tellus*, **51B**, 629–641.

Jones, E. P. and S. D. Smith (1977): A first measurement of sea-air CO_2 flux by eddy correlation. *J. Geophys. Res.*, **82**, 5990–5992.

Liss, P. S. and L. Merlivat (1986): Air-sea gas exchange rates: Introduction and synthesis. p. 113–127. In *The Role of Air-Sea Exchange in Geochemical Cycles*, ed. by P. Buat-Manard and D. Reidel, Norwell, MA.

McGillis, W. R., J. B. Edson, J. E. Hare and C. W. Fairall (2001): Direct covariance air-sea CO_2 fluxes. *J. Geophys. Res.*, **106C**, 16729–16745.

Murata, A. and T. Takizawa (2003): Summertime CO_2 sinks in shelf and slope waters of the western Arctic Ocean. *Cont. Shelf Res.*, **23**, 753–776.

Ohtaki, E., O. Tsukamoto, Y. Iwatani and Y. Mitsuta (1989): Measurements of the carbon dioxide flux over the ocean. *J. Meteorol. Soc. Japan*, **67**, 541–554.

Smith, S. D. and E. P. Jones (1985): Evidence for wind-pumping of air-sea gas exchange based on direct measurements of CO_2 fluxes. *J. Geophys. Res.*, **90C**, 869–875.

Takahashi, S., F. Kondo, O. Tsukamoto, Y. Ito, S. Hirayama and H. Ishida (2005): On-board automated eddy flux measurement system over open ocean. *SOLA*, **1**, 37–40.

Takahashi, T., S. C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninlkhof, R. A. Feely, C. Sabine, J. Olafsson and Y. Nojiri (2002): Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Res.*, **49**, 1601–1622.

Wanninkhof, R. (1992): Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.*, **97C**, 7373–7382.

Wanninkhof, R. and W. R. McGillis (1999): A cubic relationship between air-sea CO_2 exchange and wind speed. *Geophys. Res. Lett.*, **26**, 1889–1892.

Webb, E. K., G. I. Pearman and R. Leuning (1980): Correlation of flux measurement for density effects due to heat and water vapour transfer. *Q. J. R. Meteoro. Soc.*, **106**, 85–100.

Wesely, M. L., D. R. Cook, R. L. Hart and R. M. Williams (1982): Air-sea exchange CO_2 and evidence for enhanced upward fluxes. *J. Geophys. Res.*, **87C**, 8827–8832.