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CO_2 Exchange in Kwangneung Broadleaf Deciduous Forest in a Hilly Terrain in the Summer of 2002

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2002년 여름철 경사진 광릉 낙엽 활엽수림에서의 이산화탄소 교환

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ABSTRACT

We report the first direct measurement of CO_2 flux over Kwangneung broadleaf deciduous forest, one of the tower flux sites in KoFlux network. Eddy covariance system was installed on a 30 m tower along with other meteorological instruments from June to August in 2002. Although the study site was non-ideal (with valley-like terrain), turbulence characteristics from limited wind directions (i.e., 90±45°) was not significantly different from those obtained at simple, homogeneous terrains with an ideal fetch. Despite very low rate of data retrieval, preliminary results from our analysis are encouraging and worthy of further investigation. Ignoring the role of advection terms, the averaged net ecosystem exchange (NEE) of CO_2 ranged from -1.2 to 0.7 mg $m^{-2}s^{-1}$ from June to August in 2002. The effect of weak turbulence on nocturnal NEE was examined in terms of friction velocity (u_*) along with the estimation of storage term. The effect of low u_* on NEE was obvious with a threshold value of about 0.2 m s^{-1}. The contribution of storage term to nocturnal NEE was insignificant; suggesting that the CO_2 stored within the forest canopy at night was probably removed by the drainage flow along the hilly terrain. This could be also an artifact of uncertainty in calculations of storage term based on a single-level concentration. The hyperbolic light response curves explained >80% of variations in the observed NEE, indicating that CO_2 exchange at the site was notably light-dependent. Such a relationship can be used effectively in filling up the missing gaps in NEE data through the season. Finally, a simple scaling analysis based on a linear flow model suggested that advection might play a significant role in NEE evaluation at this site.

Key words **: Net ecosystem exchange, CO_2 flux, Forest, Eddy covariance, Hilly terrain, KoFlux**

I. INTRODUCTION

Forests play a critical role because they consist of almost 90% of all biomass carbon. Consequently, small changes in net uptake or release of carbon by forests can have a great influence on atmospheric CO_2 concentration. To better understand these processes, information on ecosystem fluxes of carbon, water, and energy and how these fluxes interact with the physical climate and ecosystem function and structure must be quantified. KoFlux is a Korean regional network of long-term micrometeorological flux measurement sites that focus on ecosystems in Asia and provides several reference sites to a regional, continental, and global network such as AsiaFlux, CEOP/GEWEX, and FLUXNET (e.g., Baldocchi *et al.*, 2001; Kim *et al.*,

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2002).

The broadleaf deciduous site at Kwangneung research forest (assigned as 'DK' site) was selected as one of KoFlux sites because 1) it is one of the key forest ecosystems in temperate Asia and 2) long term ecological studies have been conducted over the last 10 years (Lim *et al.*, 2003). While direct eddy covariance measurement of energy and water flux has been continued since April 2000 (Park, 2001), CO_2 flux (hereafter, Fco_2) measurement has not started until September 2001. On the other hand, CO_2 budget has been indirectly estimated based on ecophysiological measurements at the same site for several years (Lim *et al.*, 2003). Despite the potential mismatch of space and time scales of two approaches, the resultant databases are complementary in advancing our understanding of CO_2 exchange mechanism in this key ecosystem.

DK site is located in a valley-like terrain with a slope of ~10%, resulting in limited fetch of about 2 km only for east wind. Therefore, the measurement and interpretation of vertical turbulent fluxes of momentum and scalar at this site could be problematic. Finnigan *et al.* (2003) state that averaging time and analysis techniques that have proved adequate to measure surface exchange over short canopies need to be revisited for application to forests. Yet, Beljaars *et al.* (1983) reported that, for non-uniform fetch conditions, the shear stress increased with height, but heat and moisture fluxes did not necessarily change with upstream obstacles. Panofsky *et al.* (1982) showed that vertical velocity spectra adjusted more rapidly to local terrain than horizontal spectra. These prior studies suggest that scalar fluxes are less sensitive to terrain effects than momentum flux.

The analysis of mean flows using the data from 2000 to 2002 indicated that mountain-valley wind was dominant with upwind flow (from east) during daytime and downwind flow (from west) during nighttime due to topographic characteristics. Since DK site had very limited fetch conditions, availability and quality of the flux data were further limited by more frequent downwind flow and the likely occurrence of drainage flow at night. In short, it is a challenge to quantify net ecosystem exchange (NEE) and to determine whether DK site is a sink or source of atmospheric CO_2. The objectives of this study were (1) to document current progresses in CO_2 flux measurement at DK site, (2) to examine diurnal variations of CO_2 fluxes and concentrations, (3) to assess the light response of canopy CO_2 exchange and (4) to evaluate the relative roles of storage and advection terms on NEE computation.

II. METHODS AND MATERIALS

2.1. Theoretical background

2.1.1 Eddy covariance method

Basically, the conservation equation provides the framework for using the eddy covariance method for the direct measurement of vertical flux of energy and matter (e.g., CO_2) (e.g., Aubinet *et al.*, 2000):

$$\underset{(I)}{\int_0^{z_r} S\,dz} = \underset{(II)}{\overline{w'\rho_c'}} + \underset{(III)}{\int_0^{z_r} \frac{\partial \overline{\rho_c}}{\partial t}dz} + \underset{(IV)}{\int_0^{z_r} \bar{u}\frac{\partial \overline{\rho_c}}{\partial x}dz} + \underset{(V)}{\int_0^{z_r} \bar{w}\frac{\partial \overline{\rho_c}}{\partial z}dz} \quad (1)$$

where term (I) represents the scalar source/sink which corresponds to the NEE; term (II) is the vertical eddy flux at the reference measurement height, z_r, where w is vertical wind speed and ρ_c is CO_2 density; term (III) represents the storage below z_r; term (IV) is the horizontal advection, where $\bar{u}$ is the mean horizontal wind speed; and term (V) is the vertical advection. The overbar means time averages and the primes fluctuations around the average. While terms (II), (III) and (V) can be measured at a single tower, term (IV) may be evaluated by using spatially distributed multiple towers and/or by modeling approach. In general, term (II) alone can be used to represent NEE over homogeneous short vegetation. However, in forest, other terms could be significant in representing NEE (e.g., Paw U, 2000). The evaluation of advection terms is beyond the scope of our paper and will be addressed elsewhere except some qualitative consideration (in Section 3). In this paper, we tentatively assumed that the uncertainty associated with these advection terms were about 20% of NEE when the wind direction was favorable (i.e., 90±45°) for flux measurements.

2.1.2. Computation of the CO_2 storage

Over a tall forest, the CO_2 flux (Fco_2) measured by eddy covariance system does not always equal to NEE. A systematic error can occur when CO_2 is stored in or withdrawn from the layer of air below the eddy covariance system. Storage is significant during the night when the atmosphere is stably stratified and winds are weak. A withdrawal of previously stored CO_2 occurs with daybreak, when convective turbulence resumes and CO_2 is rapidly vented from the canopy into overlying atmosphere. Furthermore, the CO_2 stored within the canopy could be removed by drainage flow in a hilly site at night, resulting in significant underestimation of nocturnal NEE (e.g., Lee, 1998).

The CO_2 storage equals the integration, with respect to height, of the time rate of change of the CO_2 concentration profile:

$$F_{storage} = \int_0^{z_r} \frac{\partial \rho_c(z)}{\partial t} \partial z. \qquad (2\text{-}1)$$

During this study, we did not measure the CO_2 concentration profile above and within the forest. Accordingly, we approximated this storage term using a discrete representation (e.g., Hollinger *et al.*, 1994; Greco and Baldocchi, 1996):

$$F_{storage} = \frac{\Delta \rho_c(h) z_r}{\Delta t} \qquad (2\text{-}2)$$

where $\Delta\ \rho_c(h)$ (i.e., present concentration - previous concentration) over Δt (i.e., 1800 s in this study) refers to the temporal change in CO_2 concentration measured over a 30 minutes period at the reference measurement height. A detailed analysis by Hollinger *et al.* (1994) and by Greco and Baldocchi (1996) indicates that use of equation (2-2) is justified over a tall forest when vertical mixing is strong. However, due to the complexity of the site topography and the relatively low wind speeds, Eq. (2-2) may not hold in our site. Accurate quantification of storage term must be made based on a direct measurement of within canopy profile of CO_2 concentration at DK site.

2.1.3. Response of NEE to photosynthetically active radiation

NEE during daytime can be related to photosynthetically active radiation (PAR) since it is mainly due to leaf assimilation in the absence of water stress. For this, a hyperbolic light response curve was used as (Michaelis and Menten, 1913):

$$NEE = a_1 - \frac{a_2 PAR}{a_3 + PAR}. \qquad (3)$$

In principle, the equation is based on the form of *leaf-level* kinetics of photosynthetic light response, where a_1 is a dark respiration, a_2 is the maximum rate of photosynthesis, a_3 is the Michaelis-Menten constant (e.g., Lee *et al.*, 1999). However, the curve has been shown to be a useful measure to evaluate CO_2 exchange at ecosystem level like Penman-Montieth equation. (e.g., Lee *et al.*, 1999; Hollinger *et al.*, 1999; Schimid *et al.*, 2000; Pilegaard *et al.*, 2001). Therefore, if the curve is applied to ecosystem level, a_1 corresponds to ecosystem respiration and a_2 to the maximum rate of canopy photosynthesis. The parameters in Eq. (3) may be significantly changed depending on the growth stage of the vegetation (i.e., LAI) together with changes in environment (e.g., Hollinger *et al.*, 1999; Valentini *et al.*, 1996; Gu *et al.*, 1999; Law *et al.*, 2002). In the long term measurement of NEE, data missing is inevitable due to instrument failure, calibration, and precipitation, for instance. For gap-filling of these missing data, Eq (3) could be used effectively by judiciously selecting the parameters with changing environmental and ecophysiological conditions (e.g., Falge *et al.*, 2001).

2.2. Study site

The measurement site is located in Kwangneung research forest near Seoul, Korea (37° 45' 25.37" N, 127° 9' 11.62" S: elevation 340 m). The terrain around the tower site has a valley-like topography with ~10% slope along the east-west direction. Adequate fetch (of about 2 km) was limited to east wind (i.e., 90±45°). The forest has not been disturbed and the tree age ranged from 60 to 400 years. Main species were *Quercus serrata* and *Carpinus laxiflora* and the mean canopy height was 18 m. Leaf area index (LAI) was on average 3.76 during the growing season. More detailed description on canopy architecture, species composition and soil properties are given in Lim *et al.* (2003).

2.3. Field measurement

Fluxes of CO_2, water vapor and sensible heat were measured above the forest by eddy covariance system installed on a 30-m walk-up tower. The system consisted of a fast response infrared gas analyzer (LI7500, LI-COR Inc.) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.). Calibration was made for the infrared gas analyzer on a monthly basis. For span calibration of CO_2, standard CO_2 gases of 500~600 ppm were used whereas a dew point generator (LI-610, LI-COR Inc.) was used for H_2O. Three components of wind velocity, concentrations of CO_2 and H_2O, and temperature were measured with a sampling rate of 20 Hz (from June to early July) and 10 Hz (during other periods) and stored on a memory card in the data logger (CR5000, Campbell Scientific Inc.) for post-processing. In addition, half-hourly averaged fluxes and turbulence statistics were calculated on a real time basis and stored in the same data logger.

Four radiation components were measured above the canopy at the height of 30 m with a radiometer (CNR-1, Kipp & Zonen). To measure PAR, a quantum sensor (LI-190SA, LI-COR Inc.) was installed near the radiometer. Soil heat flux was measured at two depths (0.01 and 0.1 m) at two locations with soil heat transducers (HFT, Campbell Scientific Inc.). Profiles of air temperature and relative humidity were measured with temperature/humidity probes (HMP-45C, Campbell Scientific Inc.) at six levels (29, 19, 14, 9, 4 and 0.3 m). Cup anemometers were also placed at the same heights (except 0.3 m) together with a wind vane at 29 m. Several soil temperature probes (TCAV, Campbell Scientific Inc.) were buried in the layer of 0.1 m and water content reflectometers (CS-615, Campbell Scientific Inc.) were also buried in the layers of 0.0~0.1, 0.0~0.3 and 0.3 - 0.6 m, respectively. These meteorological data were sampled every 30 seconds except for soil water content, which was sampled every 30 minutes. All the data were averaged for 5 and 30 minutes and stored on a series of CR23X data loggers. For power supply, 220 V AC was supplied which was converted into 12 V DC for instruments and data acquisition systems. More detailed information for instrumentation can be found in Kim *et al.* (2002).

2.4. Flux corrections

Considering that NEE is determined from the small difference in the balance between uptake (photosynthesis) and release (respiration) of CO_2, various corrections on flux computation must be carefully made. Finniagn *et al.* (2003) state that the component of vertical flux divergence approximates the total divergence as closely as possible. The frame discrepancy may result from terrain slope, instrument tilt (to axis normal to mean streamline), offsets in instrument, and other non-zero mean vertical velocity due to mesoscale motion and/or aerodynamic interference by tower and/or anemometer frame. For measurement over simple and flat terrain (e.g., rice paddy), natural coordinate determined by measurement is rotated such that mean lateral and vertical wind speeds become zero over averaging time (i.e., "double rotation") (e.g., Wesely, 1970; Massman and Lee, 2002). For measurement over forest in a complex terrain (e.g., DK site), however, double rotation based on half-hourly averages may be inadequate since vertical axis normal to mean streamline changes with height and/or non-zero mean vertical velocity may still exist. Streamline coordinate system based on longer averaging time is more appropriate for this case. Turbulence statistics measured by sonic anemometer (i.e., at sonic anemometer's coordinate) can be transferred to those at streamline coordinate by "planar fit method" (Wilczak *et al.*, 2001; Hong and Kim, 2002). Our preliminary analysis indicated that the differences in CO_2 fluxes corrected with these two different rotations were ~1% under unstable conditions and ~5% under stable conditions.

Following Webb *et al.* (1980), corrections for density variation due to simultaneous transfer of heat and water vapor were applied to CO_2 and water vapor fluxes. Due to large latent heat flux during this measurement period, Fco_2 was reduced typically by 20~40% during daytime.

2.5. Quality check

To ensure the quality of the measured fluxes, we examined, among other things, the stationary and the integral turbulence characteristics of the data. (e.g., Aubinet *et al.*, 2000). Equation (1) is based on the assumption of stationarity that the statistical properties of the flow do not change with given averaging time (e.g., half hour) (Kaimal and Finnigan, 1994). In nature, this condition cannot be realized due to longer-term variability in the atmosphere such as diurnal trends, mesoscale motions and passage of clouds. The degree of non-stationarity was assessed, following Mahrt (1998). In this analysis, the data with computed values of non-stationararity ratio (NR) of ≤ 2 were considered to satisfy the stationarity assumption. NR was calculated for each half hour period after removing bad signals (e.g., CO_2 concentrations below 400 or over 800 mgm^{-3}) during the post-processing.

Fig. 1 shows the diurnal variation of the computed NR averaged for the whole measurement period. Overall, NR was less than 2, indicating that Fco_2 data were stationary over half-hour averaging period. NR tended to be greater during the transition periods (e.g., sunrise, sunset) and gradually decreased during the day. Its variability was larger at night.

Focken and Wichura (1996) proposed to use the Monin-Obukhov similarity to check the quality of eddy covariance data by testing whether or not the turbulence was well developed according to the similarity theory of turbulence fluctuations. This test allows finding out whether there is significant additional mechanical

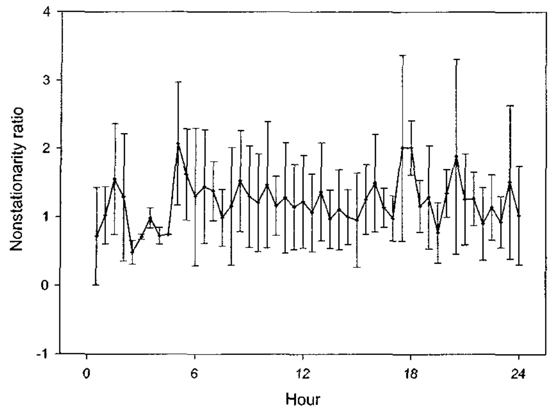

Fig. 1. Diurnal variation of nonstationarity ratio.

turbulence caused by obstacle or generated by the measuring device itself or not. For example, integral turbulence characteristics of vertical wind can be written as (e.g., Kaimal and Finnigan, 1994).

$$\sigma_w / u_* = a_1 [a_2 + a_3 (z_r - d/L)]^{a_4} \quad (4)$$

where σ_w is the standard deviation of vertical wind velocity; u_* is the friction velocity; z_r is the measurement height; d is zero-plane displacement; L is the Obukhov length; and a_1, a_2, a_3 and a_4 are empirical coefficients. While raw data were required to calculate NR, half-hourly averaged statistics was used to evaluate ITC.

To evaluate the relationship between σ_w/u_* and $(z_r - d)/L$, σ_w, u_* and L in streamline coordinate were selected for the following conditions: (1) wind direction between 45 and 135°, (2) mean horizontal wind speed of >2 m s^{-1}, and (3) positive vertical wind velocity, corresponding to wind direction (i.e., upslope). Following De Bruin and Verhoef (1996), the zero plane displacement was estimated to be 14.0 m at the site. In Fig. 2, the measured σ_w/u_* was plotted against z/L in absolute magnitude. For a comparison purpose, the functions given in Kaimal and Finnigan (1994) were also presented. Measured σ_w/u_* agreed reasonably well with the function, $1.25(1-3(z_r-d)/L)^{1/3}$ under unstable conditions and $1.25(1+0.2(z_r-d)/L)$ under stable conditions. This result suggests that the turbulence measured at the DK tower was developed according to the Monin-Obukhov similarity under all stability for the selected conditions of wind speed and direction. De Bruin (1991) found that the measured values of ITC were significantly higher than the predicted for the terrains with inhomogeneous distribution of surface temperature and moisture, but not with inhomogeneous surface roughness. Although the test results of ITC at DK site are encouraging, investigations on homogeneity of temperature, moisture and roughness must be made based on satellite image analysis to ensure the quality of NEE evaluation. To use ITC of w as a practical basis of quality control, only the data with the difference between measured and predicted ITC of w of <30%

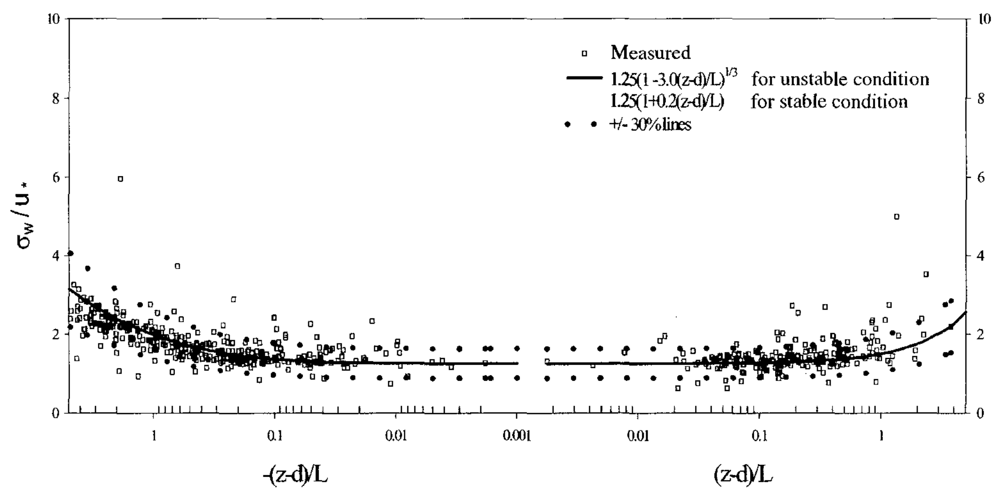

Fig. 2. Integral turbulence characteristics of vertical wind velocity under unstable (left-hand side) and stable (right-hand side) conditions: measured σ_w/u_* (Squares); the functions in Kaimal and Finnigan (1994) (solid line); and ±30% deviation from the solid line (dotted lines).

were selected and the corresponding Fco_2 data were used for NEE evaluation and analysis.

Additional quality checks included the examination of measured CO_2 and H_2O concentrations. During the long-term field operation, gas analyzers may fail to produce correct signals due to precipitation, snow, fog or dew formation on the window of IRGA. Similar problems can be imposed on the transducers of sonic anemometer. Quality of the eddy flux data were scrutinized based on the precipitation records and field run log on environmental conditions. Also, CO_2 and H_2O concentration data from IRGA were checked based on the limits of their concentrations and standard deviations corresponding to the measurement periods and the comparison against values from slow response instruments. The typical criteria used in our quality control for CO_2 and H_2O were respectively 340~400 ppm and 5~20 gm^{-3} for concentration; and 0~6 ppm and 0~1 gm^{-3} for standard deviation during the summer.

III. RESULTS AND DISCUSSION

3.1. Meteorological variables

Fig. 3 shows frequency distribution of wind direction (left-hand side) and mean wind speed (right-hand side) for 15° sector during the growing season in 2002. At DK site, east (i.e., upwind flow) and west wind (i.e., downwind flow) were dominant, with the former occupying ~40% of the data. Wind speed was also highest for upwind flow likely due to speed-up of wind speed along the upslope and the maximum mountain-valley wind in the afternoon (Taylor *et al.*, 1987; Whiteman, 2000). Stronger horizontal wind produces more effective vertical mixing, making eddy covariance measurement with east wind being less error prone. However, only about 10% of east wind was of >2 m s^{-1}, which was the criteria for quality control.

3.2. Net ecosystem CO_2 exchange

Fig. 4 shows the diurnal variation of Fco_2 averaged from June to August. Negative CO_2 flux (i.e., net uptake of CO_2) continued from 0700 hours to 1800 hours. Around noon, CO_2 flux ranged from -1.2 to -0.5 mg $m^{-2}s^{-1}$. At night, positive Fco_2 (i.e., net CO_2 release by canopy/soil respiration) fluctuated from 0.3 to 0.7 mg $m^{-2}s^{-1}$. Storage term also showed diurnal variation but its magnitude was an order of magnitude smaller than Fco_2 from eddy covariance. Overall, its sign was negative during daytime and positive during nighttime. CO_2 concentration averaged over these three months ranged from 350 to 370 ppm. As expected, it was largest around sunrise due to accumulation of nighttime respiration from both plants and soil and smallest in mid afternoon due to vigorous draw-down of CO_2 by photosynthetic activity.

3.3. Correction of nighttime CO_2 flux

If advection can be neglected in the conservation equation, the sum of Fco_2 and $F_{storage}$ represents NEE. However, during nighttime when vertical turbulent mixing is weak, their sum underestimates true NEE

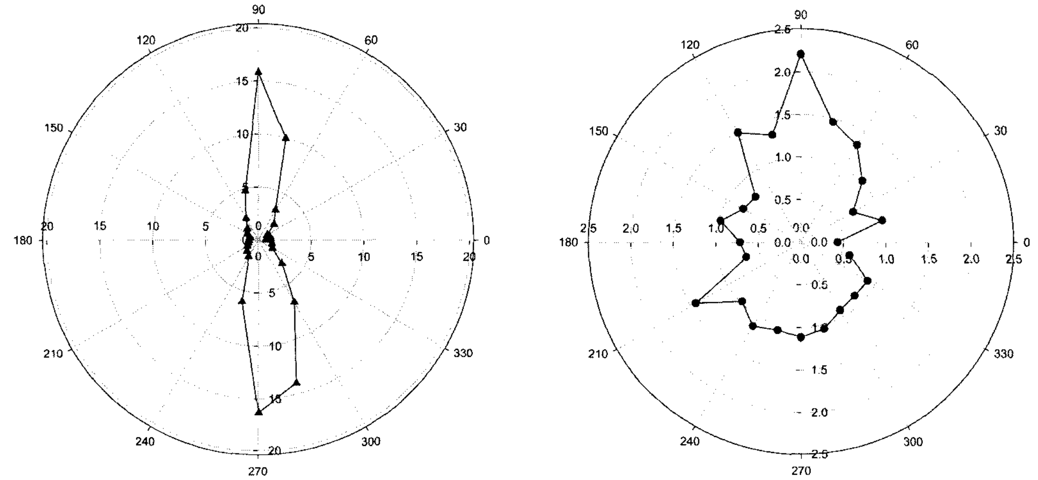

Fig. 3. Frequency distribution of wind direction and mean wind speed for each 15° sector during the growing season in 2002.

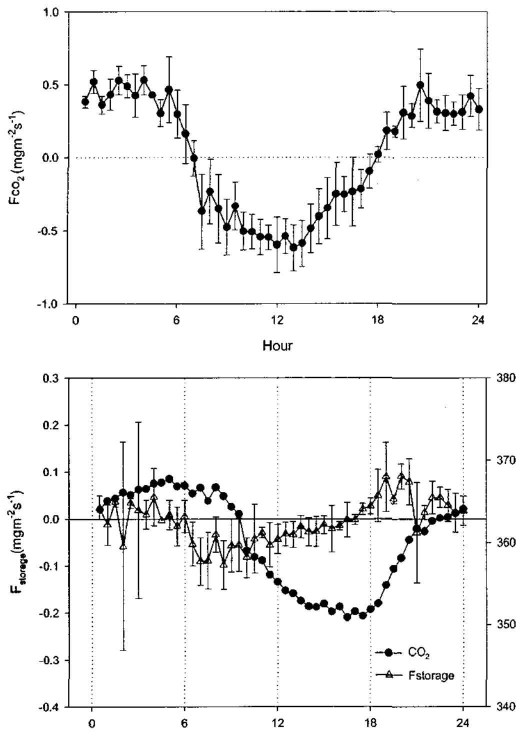

Fig. 4. Averaged diurnal variation of Fco_2, $F_{storage}$ term and CO_2 concentration during June-August in 2002. (Error bars are standard deviations).

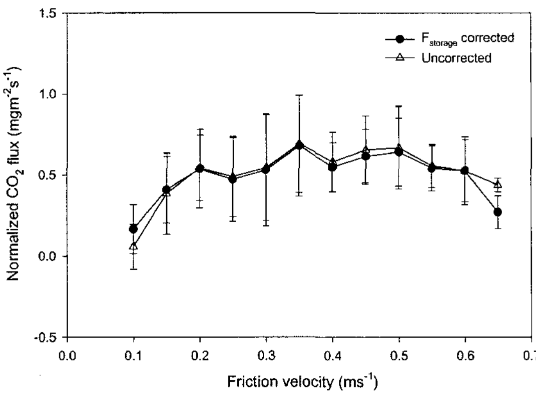

Fig. 5. Nighttime CO_2 flux (normalized by the saturation value). Uncorrected represents Fco_2 only and $F_{storage}$ corrected represents NEE ($=Fco_2+F_{storage}$).

(e.g., Goulden *et al.*, 1996; Aubinet *et al.*, 2002). This could be due to drainage flow (i.e., advection) as well as systematic error in eddy covariance measurement. Since such underestimation is a selective systematic error (e.g., Moncrieff *et al.*, 1996), it could result in significant bias for DK site to be stronger CO_2 sink when NEE is accumulated over a long period (e.g., Aubinet *et al.*, 2002). The remedy for such systematic error is to replace the measured NEE under weak mixing conditions by the simulated efflux estimated from a temperature function derived under well mixing conditions (e.g., Chae *et al.*, 2003).

The criteria of weak mixing conditions were determined by plotting friction velocity with Fco_2 and NEE (i.e., the sum of Fco_2 and $F_{storage}$). This was based on the assumption that Fco_2 (without considering $F_{storage}$) represents NEE when vertical turbulent mixing was sufficient (e.g., large friction velocity). Data were selected from 2100 to 0400 hours. To minimize the scatter, Fco_2 and NEE data were sorted by u_* with the interval of 0.05 m s^{-1}. Because representative temperature functions were not available, Fco_2 data were restrained to a narrow range of soil temperature (i.e., 1.5°C) and the saturation value of Fco_2 was determined for each temperature range (at the high friction velocity). To eliminate correlation between u_* and temperature, Fco_2 were normalized by each saturation value (e.g., Goulden *et al.*, 1996; Aubinet *et al.*, 2000). Fig. 5 shows the variations of normalized Fco_2 and NEE with friction velocity. The effect of low u_* on NEE was obvious with a threshold value of about 0.2 m s^{-1}. Also noted was the insignificance of storage corrections, suggesting at least two possible explanations. One is that the stored CO_2 within the canopy at night must have been removed from the forest (e.g., by drainage flow) and therefore was not included in the tower flux measurement. The other possibility would be the uncertainties in our approximate estimation of $F_{storage}$ using a single-level CO_2 concentration high above the canopy. Obviously, more detailed within canopy measurements (e.g., profile system) and further analysis are needed to better quantify and understand nighttime CO_2 exchange at DK site.

3.4. Response of daytime NEE to PAR

To examine the light response of NEE, half-hourly NEE was plotted with PAR in Fig. 6. To minimize the effect of different stage of plant growth (e.g., LAI), data were separated into individual month. Then, the light response curve (Eq. (3)) was fit to the observed data to estimate the coefficients. The Michaelis-Menten equation explained on average >80% of the observed variance, which was greater than those (50-65%) reported for a temperate deciduous forest in Canada (e.g., Lee *et al.*,

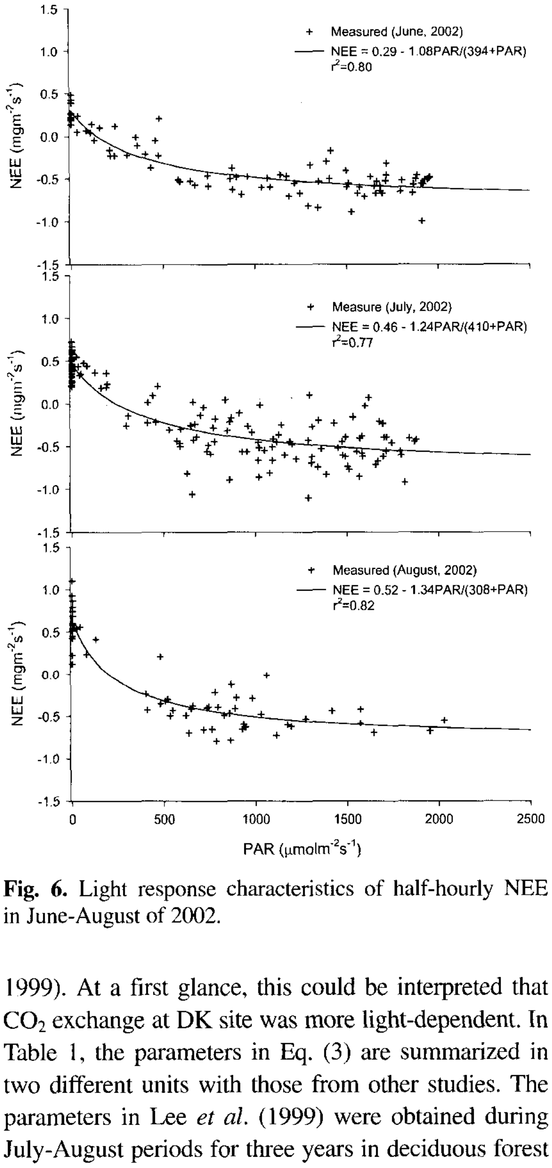

Fig. 6. Light response characteristics of half-hourly NEE in June-August of 2002.

1999). At a first glance, this could be interpreted that CO_2 exchange at DK site was more light-dependent. In Table 1, the parameters in Eq. (3) are summarized in two different units with those from other studies. The parameters in Lee *et al.* (1999) were obtained during July-August periods for three years in deciduous forest (with LAI of <4.1 and age of ~100 years) in Canada whereas those in Granier *et al.* (2003) were from four beach forests in June in Europe (with LAI of >5 and age of <100 years). In comparison with those forests, trees in DK site were much older and had smaller LAI.

In Table 1, two parameters are particularly worth noting. The parameter a_1 now represents canopy and soil respiration, and a_2 maximum rate of canopy photosynthesis. Table 1 shows that DK site had the highest value of a_1 (i.e., higher respiration rate) while values of a_2 were lowest (i.e., lower rate of canopy photosynthesis). This difference may not be attributed solely to relatively older age of forest in DK site. Buchmann and Schulze (1999) compared the maximum values of net ecosystem surface assimilation using the data from 139 ecosystem studies and showed that maximum net ecosystem surface assimilation of old forest (>160 yrs) was similar to those of younger forest (30-80 yrs) and always higher than those of regenerating stand. In a concurrent study at DK site, the magnitudes of soil CO_2 efflux from the forest floor were similar to those reported in other studies under comparable conditions (Chae *et al.*, 2003). Therefore, higher rate of ecosystem respiration at DK site could be more related to tree physiology than soil related processes. To better understand the related processes, more systematic analyses must be made by minimizing the confounding effect of vapor pressure deficit, soil moisture, or air temperature on the relationships presented in Fig. 6. It is quite encouraging and worth noting that there were statistically significant, specific relationships between PAR and NEE for each month with systematic changes in parameters. Considering the fact that data retrieval rate at DK site was very low, such strong relationships can be used effectively as one of the main tools in filling up the missing gaps in the data set through the

Table 1. Light response characteristics of the half-hourly NEE at DK site and other deciduous forests

Study Site (in $mgm^{-2}s^{-1}$)	a_1	a_2	a_3	Study Site (in $\mu molm^{-2}s^{-1}$)	a_1	a_2	a_3
Lee *et al.* (Year 1995)	0.33	1.70	793	Granier *et al.* (Collengo)	3.0	38.2	859
1996	0.28	1.52	595	Soroe	4.9	38.2	955
1997	0.27	1.79	721	Vielsalm	3.3	24.7	465
DK				***DK***			
June	0.29	1.08	394	***June***	6.5	24.4	394
July	0.46	1.24	411	***July***	10.5	28.3	411
August	0.52	1.34	308	***August***	12.0	30.1	308

season.

3.5. Qualitative remarks on advection

In this paper, we have ignored advection term in the estimation of NEE. Since the flux measurement at DK site was not designed to measure advection (using multiple towers, for instance), a simple theoretical consideration was attempted here. Based on a linear analytic scalar flow and transport model, a scaling analysis can be made for each term in the conservation equation (i.e., Eq. (1)). Strictly speaking, this analysis should be applied to flows over low hills (i.e., $H/D << 1$, where H is the height of hilltop and D is the characteristic length, defined as the distance from the hilltop to the upstream point where the elevation is half its maximum) (Jackson and Hunt, 1975). However, linear analytic model has shown good results on the hilltop and upstream with $H/D \leq 0.4$ (e.g., Taylor, *et al.*, 1987). At DK site, H/D is approximately 0.38 and thus a scaling analysis may be applied here. Following Finnigan (personal communication), the order of magnitude of horizontal and vertical advection terms seemed comparable and their relative magnitudes to the vertical eddy covariance term depended on H/D. As a crude approximation, the magnitude of advection was of the order of 40% (or less, depending on the signs of the two advection terms) of that of vertical eddy flux. Hence, advection would play an important role in NEE estimation and deserve further investigation as a priority.

IV. SUMMARY AND CONCLUSION

Eddy covariance measurement of CO_2 flux has been attempted at a non-ideal site on a hilly terrain, located in Kwangneung broadleaf deciduous forest, Korea. To evaluate the validity of flux measurement and the data quality at such site, we selected the study period from June to August in 2002 when the forest growth and soil processes were most vigorous with maximum rates of CO_2 exchange. Due to the topographic and meteorological characteristics at the site, data retrieval rate from the flux tower turned out to be on the order of 10%. After quality controls and corrections, this limited amount of flux data was then examined in the context of the conservation equation. Our preliminary analyses with first order approximations indicated that the contribution from both storage and advection terms could be significant in NEE estimation. Nevertheless, in terms of their magnitudes, temporal patterns and light-response characteristics, the observed NEE data showed potential for gap filling, scaling and parameterization of the processes. To minimize the uncertainty in the measured NEE, further investigations (e.g., CO_2 profile measurement, theoretical scaling analysis) are currently in progress.

적 요

본 연구에서는 KoFlux 네트워크 타워 관측소의 하나인 광릉 낙엽 활엽수림에서 최초로 직접 관측된 이산화탄소 플럭스를 보고한다. 2002년 6월부터 8월까지 에디 공분산 시스템을 다른 기상 관측 기기들과 함께 30 m 타워에 설치하였다. 관측 장소가 계곡과 같은 경사지에 위치해 있음에도 불구하고 관측된 난류 특성이, 제한된 풍향(즉, 90±45°)의 경우, 평평하고 균질한 이상적인 장소에서 관측된 것들과 크게 다르지 않았다. 관측 자료 회수율은 비록 낮았으나, 분석된 예비 결과는 고무적이고, 연구해야 할 가치가 있는 것으로 나타났다. 이류 항을 무시하면, 생태계의 순 CO_2 교환(NEE)은 6월에서 8월까지 약 -1.2에서 0.7 mg $m^{-2}s^{-1}$의 범위를 보였다. 약한 난류가 야간 NEE에 미치는 효과를 마찰 속도(u_*) 및 저류 항의 산출과 관련하여 살펴보았다. 낮은 u_*가 NEE에 미치는 영향은 약 0.2 m s^{-1}의 문턱 값을 기점으로 뚜렷하게 나타났다. 야간 NEE에 미치는 저류 항의 역할은 거의 나타나지 않았는데, 이는 밤 동안 산림 내에 축적된 CO_2가 경사면을 따라 배수류로 빠져나갔기 때문인 것으로 사료된다. 이는 또한 저류 항을 한 높이에서만 관측된 농도 자료를 사용함으로 생긴 오차로 인한 인위적인 결과일 수도 있다. 쌍곡선 광 반응식을 적용한 결과, 관측된 NEE 변화의 80% 이상이 설명되어, 이 산림 지역의 CO_2 교환이 주로 빛에 의해 조절됨을 보여주었다. 이러한 관계식은 계절에 걸쳐 빠진 자료를 채워 넣는 자료 처리 과정에 효과적으로 사용될 수 있다. 마지막으로, 선형류 모형에 근거한 간단한 규모 분석에 의하면, 이류항의 효과가 NEE 산출에 큰 영향을 미칠 수 있는 것으로 나타났다.

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