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Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower

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Abstract. In most studies of the net ecosystem-atmosphere exchange of CO_2 (NEE) using tower-based eddy covariance (EC) systems it has been assumed that advection is negligible. In this study we use a scalar conservation budget method to estimate the contribution of advection to NEE measurements from a very tall tower in northern Wisconsin. We examine data for June–August 1997. Measured NEE_0, calculated as the sum of the EC flux plus the rate of change of storage below the EC measurement level, is expected to be constant with measurement height, and we take the differences between levels as a measure of advection. We find that the average difference in total advection ΔF_{Cadtot} between 30 and 122 m is as large as 6 μmol m^{-2} s^{-1} during the morning transition from stable to convective conditions and the average difference ΔF_{Cadtot} between 122 and 396 m is as large as 4 μmol m^{-2} s^{-1} during daytime. For the month of July, advection between 30 and 122 m is 27% of the diurnally integrated NEE_0 at 122 m, and advection between 122 and 396 m accounts for 5% of the NEE_0 observed at 396 m. The observed differences of advection often have significant correlation with the vertical integral of wind speed within the same layer. This indicates that the horizontal advection contribution to NEE could be significant. Direct observations of the vertical gradient in CO_2 show that ΔF_{Cadtot} cannot be explained by vertical advection alone. It is hypothesized that differing flux footprints and pooling of CO_2 in the heterogeneous landscape causes the advection contribution. The magnitudes of the total advection component F_{Cadtot} of NEE at the 30 m level are roughly estimated by a linear extrapolation. A peak in F_{Cadtot} at 30 m of ~3 μmol m^{-2} s^{-1} during the morning transition is predicted for all three months. The July integrated F_{Cadtot} is estimated to be 10% of the diurnally integrated NEE_0 at 30 m.

1. Introduction

Several lines of evidence indicate that terrestrial ecosystems of the Northern Hemisphere constitute a large sink for atmospheric CO_2 [*Tans et al.*, 1990; *Conway et al.*, 1994; *Ciais et al.*, 1995; *Denning et al.*, 1995; *Keeling et al.*, 1996; *Myneni et al.*, 1997]. *Fan et al.* [1998] suggest that terrestrial ecosystems in North America are a carbon sink as large as 1.7 ± 0.5 Pg C yr^{-1}. This magnitude could completely balance the fossil fuel emissions of 1.6 Pg C yr^{-1} from the continent. The report of *Fan et al.* [1998] has aroused active debate about where and how much carbon could be accumulating in the Northern Hemisphere biosphere [*Kaiser*, 1998; *Holland et al.*, 1999]. Several groups have reported that North America is a much smaller carbon sink of 0.1–0.2 Pg C yr^{-1} [*Cao and Woodward*, 1998; *Oliver et al.*, 1998; *Brown and Schroeder*, 1999]. These estimates of the terrestrial carbon sink, obtained by different approaches and disparate in both their magnitudes and spatial distributions, imply that it is very difficult to get a credible understanding of the CO_2 balance without long-term direct measurements of terrestrial carbon flux.

Eddy covariance (EC) measurements can provide a direct measure of terrestrial carbon exchange [*Wofsy et al.*, 1993; *Grace et al.*, 1995; *Goulden et al.*, 1996a; *Black et al.*, 1996; *Davis et al.*, 1997; *Baldocchi et al.*, 1988; *Baldocchi and Meyers*, 1998]. A network of tower-based EC measurements has been established in North America (AmeriFlux), and Europe (EUROFlux), and is growing globally (FLUXnet). Long-term micrometeorological flux measurements at these sites will significantly improve our understanding of the size and causes of the terrestrial carbon sink from landscape to global scales [*Holland et al.*, 1999].

The net ecosystem-atmosphere exchange of CO_2 (NEE) has usually been calculated as the sum of a turbulent flux and a storage flux measured from the EC towers. However, it is evident that this approach, which is based on the assumption of horizontal homogeneity, can lead to systematic errors in NEE measurements due to neglect of advection or other factors [*Lee and Black*, 1993a, b; *Goulden et al.*, 1996b; *Grace et al.*, 1996; *Jarvis et al.*, 1997; *Baldocchi*, 1997; *Mahrt*, 1998; *Lindroth et al.*, 1998]. When atmospheric mixing is weak (typically at night), the measurements often appear to underestimate the magnitude of NEE [e.g., *Goulden et al.*, 1997; *Lindroth et al.*, 1998; *Black et al.*, 1996]. The most likely reason for this is horizontal and/or vertical advection rather than instrumental error [*Vick-*

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ers and Mahrt, 1997; *Grelle and Lindroth*, 1996; *Dabberdt et al.*, 1993] because most tower sites do not strictly meet the measurement criteria of horizontal homogeneity [*Baldocchi et al.*, 1988].

Lee [1998] analyzed this problem and proposed a vertical advection correction to measured NEE based on the scalar conservation budget in a one-dimensional framework. He neglected horizontal advection with the assumption that the scalar source distributions are horizontally homogeneous within the fetch area. *Finnigan* [1999] used a thought experiment and a linear model [*Raupach et al.*, 1992] to analyze the condition of Lee's vertical advection correction. He pointed out that Lee's correction is only valid under very particular conditions. In heterogeneous terrain, vertical and horizontal advection are closely related and may have similar magnitudes [*Finnigan*, 1999; *Sun et al.*, 1998, 1997; *Mahrt et al.*, 1994; *Raupach et al.*, 1992]. It is very important for the tower flux measurement community to know the total advection contribution to NEE. However, direct measurement of horizontal or vertical advection from a single tower is very difficult.

We examine the question of advection using measurements from three heights on a very tall tower in northern Wisconsin. The tall tower allows us to look at differences of the sum of turbulent flux and storage flux between different levels above the vegetation. If there is no advection and the horizontal "control volume" [*Finnigan*, 1999] represented by these data is homogenous, the difference in NEE among levels will be zero. Nonzero differences must be balanced by the sum of horizontal and vertical advection because there is no source or sink of CO_2 above the vegetation. This balance method permits us to estimate the magnitude of the contribution of total advection to NEE. In other words, we estimate the magnitude of total advection by computing the difference between NEE measurements at different heights above the canopy. We cannot conclusively distinguish vertical from horizontal advection, but we can draw some useful inferences.

2. Study Site and Measurements

The study site is located in the Chequamegon National Forest in northern Wisconsin. The region is in a heavily forested zone of low relief. A grassy clearing of ~180 m radius surrounds the tower. The site, instrumentation, and flux calculation methodology have been described by *Bakwin et al.* [1998] and B. W. Berger et al. (Long-term carbon dioxide fluxes from a very tall tower in a northern forest: Flux measurement methodology, submitted to *Journal of Oceanic and Atmospheric Technology*, 1999) (hereinafter referred to as Berger et al., submitted manuscript, 1999). The tower is a 447 m tall television transmitter. Three-axis sonic anemometers (Applied Technologies Inc., Boulder, Colorado, Model SAT-11/3K, or Campbell Scientific Inc., Logan, Utah, Model CSAT3, depending on date) are deployed at 30, 122, and 396 m above the ground to measure turbulent winds and virtual potential temperature. Air from each level is drawn down long tubes to the base of the tower where three infrared gas analyzers (IRGAs) (LiCor Inc., Lincoln, Nebraska, Model LI-6262) are used to determine CO_2 and water vapor mixing ratios at 5 Hz for EC flux calculations. Two minute mean CO_2 mixing ratios are also sampled at six levels (11, 30, 76, 122, 244, and 396 m) by two IRGAs (LiCor Model Li-6251) [*Bakwin et al.*, 1998] to give CO_2 profiles. Observations of net radiation, photosynthetically active radiation, and rainfall provide supporting meteorological data. Profile observations were initiated in October of 1994, and flux observations began in May of 1995. We examine data from June through August 1997, encompassing the majority of the growing season of 1997.

3. Method

The conservation equation for a scalar quantity c is

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + w\frac{\partial c}{\partial z} = \nu_c\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial z^2}\right) + s_c, \tag{1}$$

where x is aligned with the horizontal mean wind direction, z is perpendicular to the long-term average streamlines at the tower (nearly perpendicular to the local terrain surface), u and w are the respective components of velocity in the x and z direction, ν_c is the molecular diffusivity, and s_c is a source term which for CO_2 is negligible above the forest canopy. Reynolds decomposition and averaging in combination with the turbulent continuity equation leads to

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{w}\frac{\partial \bar{c}}{\partial z} + \frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \overline{w'c'}}{\partial z} = \nu_c\left\{\frac{\partial^2 \bar{c}}{\partial x^2} + \frac{\partial^2 \bar{c}}{\partial z^2}\right\} + \bar{s}_c. \tag{2}$$

Here an overbar denotes Reynolds averaging, and $\overline{u'c'}$ and $\overline{w'c'}$ are the turbulent horizontal and vertical fluxes of the scalar. The first term on the right-hand side of (2) is molecular diffusion. Observations indicate that this term is several order of magnitudes smaller than the other terms and can be neglected [*Stull*, 1988]. In convective conditions the horizontal turbulent flux divergence on the left side of (2) is expected to be much smaller than the vertical turbulent flux divergence as long as the spatial scale of the horizontal flux divergence is much larger than the convective boundary layer (CBL) height [*Davis*, 1992]. This can be demonstrated via the following inequality:

$$\frac{\partial \overline{u'c'}}{\partial x} \le \frac{\partial \sqrt{\overline{u'^2}\,\overline{c'^2}}}{\partial x} \ll \frac{\partial \overline{w'c'}}{\partial z}. \tag{3}$$

The first inequality in (3) is based on the cross-correlation inequality described by *Bendat and Piersol* [1986]. The second one can be shown by a scaling analysis as follows. Observations show that a typical horizontal wind velocity variance for the CBL is $0.3w_*^2$ and a typical scalar mixing ratio variance is $10(\overline{w'c'_0}/w_*)^2$ [*Lenschow et al.*, 1980], where w_* and $\overline{w'c'_0}$ are the convective velocity scale and surface turbulent flux in the CBL, respectively. Thus we can define the nondimensional variables (denoted by a superscript asterisk) as follows:

$$\overline{u'^2}^* \equiv \overline{u'^2}/(0.3w_*^2), \qquad \overline{c'^2}^* \equiv \overline{c'^2}\Big/10\left(\frac{\overline{w'c'_0}}{w_*}\right)^2,$$
$$x^* \equiv x/L, \qquad z^* \equiv z/z_i, \qquad \overline{w'c'}^* \equiv \overline{w'c'}/\overline{w'c'_0}, \tag{4a}$$

where L is the horizontal scale over which we compute the turbulent flux terms and z_i is the height of the CBL. If we use Taylor's hypothesis, L is equal to the product of the averaging time for the fluxes with the mean wind speed. With the scaling expression (4a) we have

$$\frac{(0.3\times 10)^{1/2}\overline{w'c'_0}}{L}\frac{\partial \overline{u'c'}^*}{\partial x^*} \ll \frac{\overline{w'c'_0}}{z_i}\frac{\partial \overline{w'c'}^*}{\partial z^*}, \tag{4b}$$

provided $L \gg z_t$ [*Davis*, 1992]. For turbulence over a homogeneous surface this simply requires that the Reynolds averaging length L is much larger than the depth over which flux divergence occurs. This condition is easily satisfied. Heterogeneous surface fluxes, however, could create persistent spatial gradients in the horizontal turbulent flux at the scale of the surface heterogeneity, redefining L as the scale of the heterogeneity. This is most significant if the surface heterogeneity occurs at a spatial scale that is similar to the flux footprint. At smaller scales the surface heterogeneity will be washed out by larger-scale turbulent eddies. The size of the patches of wetland and upland around the tower is a few hundred meters. Except for the 30 m level this is substantially smaller than the flux footprint in unstable conditions. In stable conditions the primary difference will be a smaller vertical scale and a larger flux footprint; hence this approximation should be more robust. Thus (2) becomes

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\,\frac{\partial \bar{c}}{\partial x} + \bar{w}\,\frac{\partial \bar{c}}{\partial z} + \frac{\partial \overline{w'c'}}{\partial z} = \bar{s}_c. \tag{5}$$

In order to get NEE we integrate (5) over a control volume chosen such that its horizontal scale is close to the tower footprint and its height is equal to the measurement height [*Finnigan*, 1999]. We obtain

$$\mathrm{NEE} \equiv \int_0^{Zr} \bar{s}_c\, dz + (\overline{w'c'})_{z=0} \tag{6a}$$

$$\mathrm{NEE} = \int_0^{Zr} \frac{\partial \bar{c}}{\partial t}\, dz + (\overline{w'c'})_{Zr} + \int_0^{Zr} \left\{ \bar{u}\,\frac{\partial \bar{c}}{\partial x} + \bar{w}\,\frac{\partial \bar{c}}{\partial z} \right\} dz \tag{6b}$$

$$\mathrm{NEE} = F_{Cst} + F_{Ctb} + F_{Cadtot}. \tag{6c}$$

The quantities on the right-hand side of (6a), (6b), and (6c) are horizontally averaged values within the control volume. The first term on the right-hand side of (6b) is the CO_2 storage flux F_{Cst}, which is calculated from the CO_2 profiles measured from the tower. The second term is the turbulent flux F_{Ctb}, which is a direct EC flux measurement. These two components can be readily measured from a tower, and their sum

$$\mathrm{NEE}_0 = F_{Cst} + F_{Ctb} \tag{7}$$

has been widely used as an approximation to NEE with the assumption that the total advection flux F_{Cadtot} is negligible. With the approximation [*Lee*, 1998; *Finnigan*, 1999]

$$\frac{\partial \bar{w}}{\partial z} \approx \frac{\bar{w}_r}{Z_r}, \tag{8}$$

where the subscript r refers to values at the EC measurement level, the total advection flux can be expressed as the sum of horizontal, F_{Cadh}, and vertical, F_{Cadv}, components

$$F_{Cadtot} = \int_0^{Zr} \bar{u}\,\frac{\partial \bar{c}}{\partial x}\, dz + \bar{w}_r(\bar{c}_r - \langle \bar{c} \rangle_r)$$
$$= F_{Cadh} + F_{Cadv}, \tag{9}$$

where

$$\langle \bar{c} \rangle_r = \frac{1}{Z_r} \int_0^{Zr} \bar{c}\, dz$$

is the mean CO_2 mixing ratio over the control volume. The horizontal gradient of CO_2, which is needed to estimate F_{Cadh}, is difficult to measure from a single tower. However, the CO_2 mixing ratio difference $(c_r - \langle c \rangle_r)$ needed to estimate F_{Cadv} is measured with high precision from the tower [*Bakwin et al.*, 1998], but it is not easy to measure the mean vertical velocity because its typical value is small compared to the errors caused by the tilt and absolute accuracy of the sonic anemometers. Therefore we focus on quantifying the total advection flux F_{Cadtot} instead of the individual components. Future analyses of mean vertical velocity may allow these components to be distinguished.

According to (6a)–(6c) and (7), the difference of NEE between two levels (Z_1 and Z_2) above the canopy can be derived as

$$\Delta\mathrm{NEE} = \Delta\mathrm{NEE}_0 + \Delta F_{Cadtot}$$
$$= \int_{Z_1}^{Z_2} \bar{s}_c\, dz = 0, \tag{10}$$

where Δ denotes the difference in a quantity between two observational levels above the canopy. The ΔNEE vanishes because there is no source or sink of CO_2 above the canopy. Therefore we have

$$\Delta F_{Cadtot} = \int_{Z_1}^{Z_2} \left\{ \bar{u}\,\frac{\partial \bar{c}}{\partial x} + \bar{w}\,\frac{\partial \bar{c}}{\partial z} \right\} dz$$
$$= -\Delta\mathrm{NEE}_0 = -(\Delta F_{Cst} + \Delta F_{Ctb}). \tag{11}$$

Equation (11) indicates that the difference in NEE_0 between two levels must be balanced by the total advection integrated between these levels (ΔF_{Cadtot}). The quantities on the right-hand side of (11) can be directly measured from the very tall tower using any two of the three EC flux measurement levels. Therefore we can directly estimate ΔF_{Cadtot}.

The ultimate cause of any differences in NEE_0 ($\Delta\mathrm{NEE}_0$) is rooted in source/sink heterogeneity. Either differing turbulent flux footprints lead to differences in the turbulent flux term ΔF_{Ctb}, or spatial gradients in CO_2 mixing ratios are advected, altering the observed difference in storage ΔF_{Cst} from the ideal one-dimensional case. Differing flux footprints contribute to $\Delta\mathrm{NEE}_0$ because the fetch area at one level differs from the fetch at another level [*Baldocchi et al.*, 1988] and the underlying surface is heterogeneous along the fetch direction. This heterogeneity would appear as a systematic difference in the turbulent flux F_{Ctb} among levels in addition to the vertical flux divergence typical of the boundary layer over a homogeneous surface. Similarly, spatial gradients in CO_2 mixing ratios that lead to advection are ultimately rooted in flux differences across the landscape, though the fetch which influences F_{Cst} is different from that of F_{Ctb}.

An apparent $\Delta\mathrm{NEE}_0$ may also result from measurement errors, such as differences in calibration of the sonic anemometers or CO_2 sensors at the different tower levels. Measurement precision is discussed in detail by Berger et al. (submitted manuscript, 1999) and *Bakwin et al.* [1998]. We will show that instrumental error is not a likely explanation for the results we present.

4. Results and Discussion

We focus on the monthly averaged diurnal cycle of the terms in (6a)–(6c). Without doubt a single hourly or half-hourly observation of NEE could be greatly influenced by advection. However, we wish to investigate persistent advective tendencies that can significantly influence (bias) the sum of eddy flux plus storage in terms of the mean diurnal and seasonal cycles. Advection may be insignificant as a long-term average but can influence the mean diurnal cycle of NEE_0 and hence may lead to erroneous interpretation of relationships between NEE_0 and environmental variables such as light and temperature. Alternatively, persistent advection could influence the long-term integral of NEE_0 [*Lee*, 1998].

4.1. Diurnal Cycle

The monthly averaged diurnal pattern of CO_2 mixing ratio at six levels (11, 30, 76, 122, 244, and 396 m) for July 1997 is shown in Figure 1a. At night a stable boundary layer forms near the ground, and respiration adds CO_2 to this shallow layer. The vertical CO_2 gradient decreases dramatically with height and becomes very small above 200 m. During the daytime the boundary layer is convectively mixed, and the CO_2 mixing ratio is nearly uniform in the vertical. This mixed layer typically reaches a depth of 1–2 km in the afternoon and is depleted of CO_2 by photosynthesis in excess of respiration. There is also entrainment of CO_2 into the mixed layer from above. In the afternoon, CO_2 mixing ratios at 396 m exceed those at 30 m by 1–2 ppm [*Bakwin et al.*, 1998]. The morning transition from a stable boundary layer to an unstable mixed layer can be identified by the dramatic decrease of CO_2 mixing ratios near the ground with time due to mixing, photosynthesis, and entrainment. During the evening transition an inversion typically forms close to the ground and increases in height with time. Above the inversion an approximately neutral residual layer is evident from the CO_2 profiles. The departures of CO_2 mixing ratios from their control volume mean values are shown in Figure 1b. These departures are considerable during nighttime as a result of the stratified stable boundary layer and near zero during daytime because of turbulent mixing. Therefore according to (9) a significant mean vertical motion during nighttime will cause a substantial F_{Cadv}, but F_{Cadv} will be negligible during the daytime. The diurnal pattern of horizontal wind speed is shown in Figure 1c. At 30 m the maximum wind speed is reached in early afternoon, and the minimum is reached at night. At 122 and 396 m the maximum occurs at night because these levels are usually decoupled from the ground and the influence of surface friction.

The most striking feature of the diurnal pattern of F_{Cst}, as shown in Figure 2a, is a pronounced minimum during morning transition reflecting the export of CO_2 stored within the nocturnal stable layer. The minima at higher levels lag those at lower levels, and the magnitudes at these levels are similar to the magnitudes of F_{Ctb} around noon shown in Figure 2b. The F_{Ctb} at the three levels are similar during the daytime (Figure 2b). During nighttime, F_{Ctb} at 122 and 396 m are near zero as these levels are often above the nocturnal boundary layer, but there is turbulent flux F_{Ctb} caused by shear at 30 m. The values of NEE_0 at three levels shown in Figure 2c are generally similar, but there still are persistent differences between them

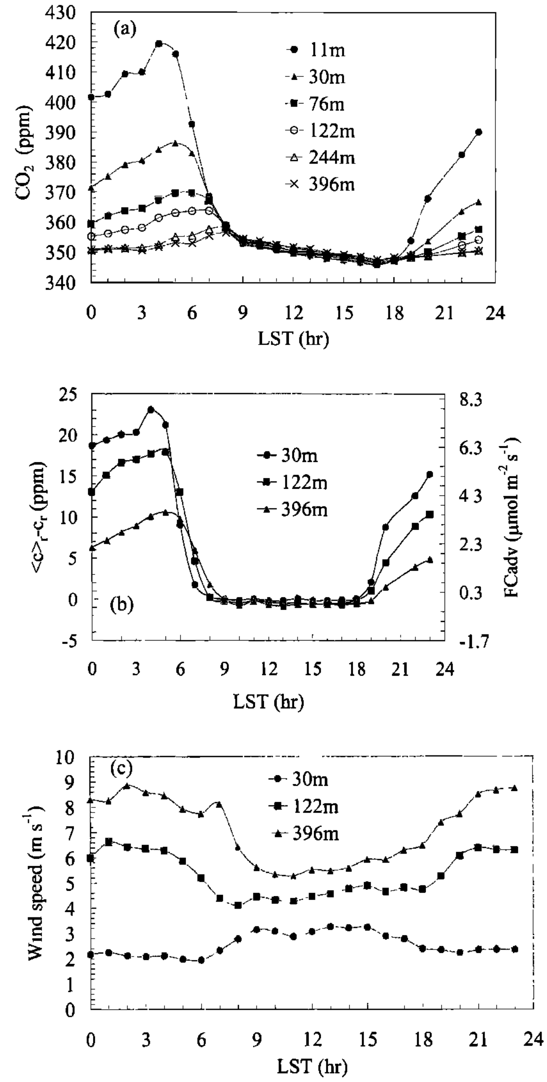

Figure 1. Diurnal cycles of (a) CO_2 mixing ratio, (b) the difference of CO_2 mixing ratio and the control volume average, and (c) wind speed for each measurement level on the Wisconsin tower for July of 1997. Here, c_r is CO_2 mixing ratio at the measurement level, and $\langle c \rangle_r$ is the control volume average of CO_2 mixing ratio. The right vertical axis in Figure 1b is vertical advection F_{Cadv} calculated from equation (14) by assuming mean vertical velocity to be -0.01 (m s^{-1}). LST, local standard time.

during the morning transition and daytime. These differences will be discussed in detail in section 4.2.

4.2. Total Advection (ΔF_{Cadtot})

Figure 3a shows the differences ΔNEE_0 ($= -\Delta F_{Cadtot}$, solid line) between 30 and 122 m in July of 1997. The greatest magnitude of ΔF_{Cadtot}, ~6 μmol m^{-2} s^{-1}, was observed during the morning transition in all three months of our study. These marked differences indicate that the contribution of F_{Cadtot} to NEE at 122 m was much larger than at 30 m during the morning transition. The advection component may be horizontal or vertical (or both). A possible explanation for vertical advection is significant mean vertical motion occurring during the morning transition, which could occur as the wind at 122 m is slowing down and the wind at 30 m speeds up (Figure 1c).

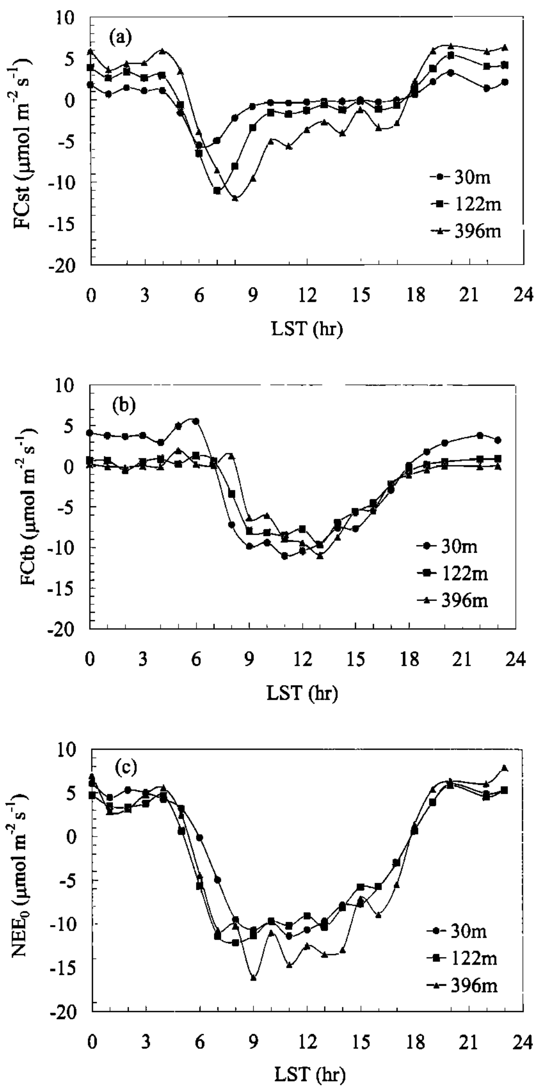

Figure 2. Average diurnal CO_2 (a) storage flux F_{Cst}, (b) turbulent flux F_{Ctb}, and (c) NEE_0 for July of 1997. NEE_0 is the sum of a storage flux and a turbulent flux.

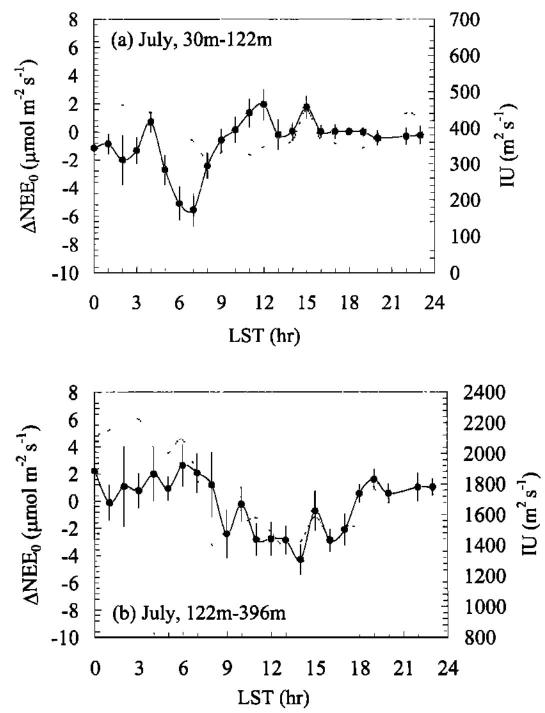

Figure 3. The average diurnal difference of NEE_0 (solid lines) (a) between 30 and 122 m ($(NEE_0)_{122\,m} - (NEE_0)_{30\,m}$) and the integral of wind speed IU (dashed line) between 30 and 122 m and (b) between 122 and 396 m ($(NEE_0)_{396\,m} - (NEE_0)_{122\,m}$) and the integral of wind speed IU (dashed line) between 122 and 396 m for July of 1997. June and July also have these persistent patterns. The difference of total advection is the same in magnitude and opposite in sign as ΔNEE_0. The vertical bars indicate standard deviation of the mean.

This diurnal pattern in the wind coexists with large vertical gradients in the CO_2 mixing ratio and the onset of convective vertical motions. A vertical velocity of -0.05 m s^{-1} and a vertical difference in CO_2 mixing ratios of 2–3 ppm between 30 and 122 m, for example, would result in vertical advection F_{Cadv} as large as the observed maximum in ΔF_{Cadtot}. The difference in mixing ratio among levels at this time of day is on this order of magnitude (Figure 1). Horizontal advection could arise from pooling of CO_2 at various locations in the landscape at night followed by systematic horizontal mixing of these pools during the early morning turbulence transition. For most of the morning transition period there is little turbulent flux at the 122 m level as it is above the nocturnal boundary layer.

Systematic measurement errors (e.g., instrument calibration) could also cause a difference in NEE_0 to be observed, but it would be difficult to account for the diurnal patterns observed here. For the same reason it seems unlikely that the features shown in Figure 3b (122–396 m differences) are caused by measurement errors. Following *Anthoni et al.* [1999], morning data were segregated according to nighttime wind speed, and it was found that the morning ΔNEE_0 was largest after calm nights, consistent with the fact that most of the flux at this hour stems from the storage term. This is consistent with the results of *Anthoni et al.* [1999] and suggests that this pattern is not unique to our site. We expect that this difference in NEE_0 is accentuated at sites with complex terrain and that we are able to detect this phenomenon because the magnitude of the storage term increases as the altitude of the flux measurement increases. It is possible that the imbalance during the morning transition could be resolved using an alternative decomposition of the basic equation (1). Reynolds averaging may not be the best choice during this nonstationary period.

The diurnal integral of ΔF_{Cadtot} between 30 and 122 m is found to be 27% of the daily integral of NEE_0 at 122 m for the month of July. Advection, therefore, may play a large role in the NEE_0 observed at 122 m. Note that in turbulent conditions, when flux footprints are relatively small, we expect the grassy clearing around the tower (approximately 180 m radius) to have a substantial impact on the flux measurements at 30 m. It is not surprising, therefore, that NEE_0 from the two levels differ substantially. NEE_0 at 30 m is less negative (less CO_2 storage in the landscape) than that observed at 122 m. We cannot prove that either of the two measurements of NEE_0 is unrepresentative of NEE since the advective contribution from 0 to 30 m is unknown (see equations (6a)–(6c) and (7)).

In all three months, ΔF_{Cadtot} between 122 and 396 m reaches a maximum during the daytime, as shown with July 1997 data by the solid line in Figure 3b. Vertical advection F_{Cadv} is expected to be negligible during the day because the vertical

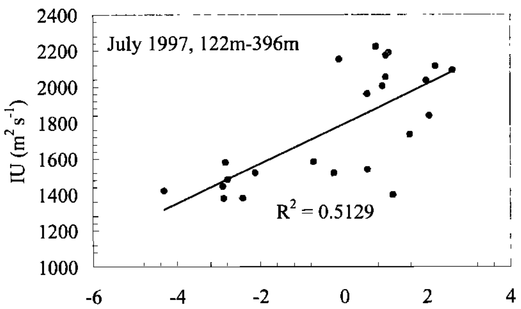

Figure 4. Correlation between $\Delta NEE_0 = -\Delta F_{Cadtot}$ and the integral of wind speed IU shown in Figure 3b.

CO_2 gradient is negligible (Figure 1). Our results therefore imply significant systematic differences in horizontal advection ΔF_{Cadh} between 122 and 396 m levels.

The diurnal integral of ΔF_{Cadtot} between 122 and 396 m is only 5% of the daily integral of NEE_0 at 396 m for the month of July. At upper levels, therefore, a one-dimensional scalar budget measurement appears to be more robust. The diurnal integral of NEE_0 at 122 m is slightly less negative (less CO_2 storage in the landscape) than the 396 m observation. However, advection significantly influences the diurnal cycle of measured NEE_0.

4.3. Horizontal Advection

In order to examine further how much of the differences of total advection are linked with horizontal advection, we define an integral of horizontal wind speed from level Z_1 to Z_2 as

$$\mathrm{IU} = \int_{Z_1}^{Z_2} \bar{u}\, dz. \tag{12}$$

If we assume that the CO_2 horizontal gradient is a constant between two observational levels, then

$$\Delta F_{Cadh} = \int_{Z_1}^{Z_2} \bar{u} \frac{\partial \bar{c}}{\partial x} dz \approx \frac{\partial \bar{c}}{\partial x} \int_{Z_1}^{Z_2} \bar{u}\, dz \propto \mathrm{IU}. \tag{13}$$

The ΔF_{Cadtot} (solid line) has much better correlation with IU (dotted line) for the upper layer (122–396 m, Figure 3b) than for the lower layer (30–122 m, Figure 3a). A formal regression analysis shows that R^2 is equal to 0.5129 for the upper layer (Figure 4) and 0.0056 for the lower layer. During the daytime, convection typically homogenizes CO_2 mixing ratios in the vertical, but significant horizontal gradients can persist. The correlation between IU and ΔF_{Cadtot} indicates that horizontal rather than vertical advection dominates at this time of day. For the lower layer the correlation of ΔF_{Cadtot} with IU is relatively poor (Figure 3a) compared to the upper layer. This suggests that during the morning transition, horizontal advection F_{Cadh} may not account for as much of the observed ΔF_{Cadtot}. As noted in section 4.2, vertical advection is likely during this period.

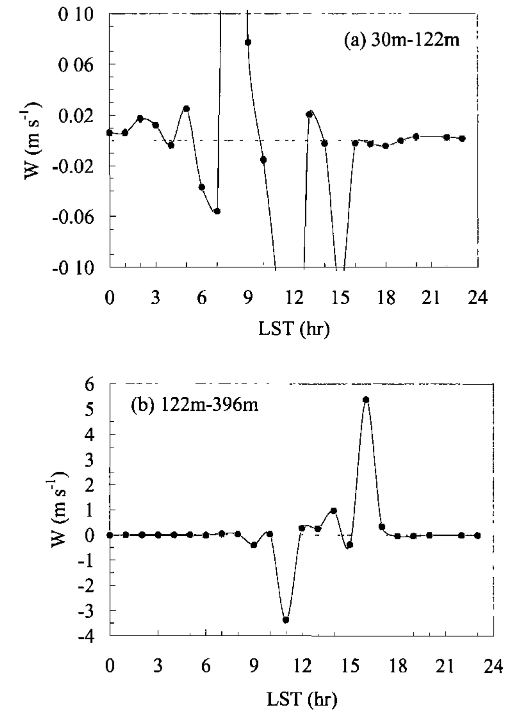

Figure 5. The derivation of the mean vertical velocity for (a) lower layer and (b) upper layer, by assuming that vertical advection F_{Cadv} could explain the total advection F_{Cadtot} based on the observed CO_2 concentration gradient (Figure 1b) and equation (14).

4.4. Vertical Advection

Vertical advection can be written as

$$F_{Cadv} = \bar{w}(\bar{c}_r - \langle \bar{c} \rangle_r). \tag{14}$$

Measurement of the mean vertical velocity is very difficult. We do know that the mean vertical velocity is rarely greater in magnitude than several centimeters per second for any one hour and most likely smaller than this for a monthly diurnal average. By using the observed concentration gradients from our tower and (14) we illustrate when it is feasible that vertical advection could account for the ΔF_{Cadtot} observed in Figures 3a and 3b.

Figures 5a and 5b show the mean vertical velocities that would be necessary, given the monthly mean CO_2 gradients shown in Figure 1b, to explain the ΔF_{Cadtot} observed in Figures 3a and 3b, respectively. The mean vertical velocity required to account for the large ΔF_{Cadtot} values for the 30–122 m layer during the morning transition (around 0600 and 0700 local standard time (LST), when the depth of CBL has not approached 122 m (Figure 1a), is approximately -0.05 m s^{-1} (Figure 5a). It is plausible during this time that these modest vertical motions could result from when the wind at 122 m is slowing down and at 30 m speeds up (Figure 1c). However, when the depth of the CBL is greater than 122 m (after 0730 LST, Figure 1a), the required mean vertical velocity becomes unreasonably large (Figure 5a). We expect that vertical advection of CO_2 is very important during the morning transition but that the daytime ΔF_{Cadtot} under well-mixed conditions is driven by horizontal advection, possibly stemming from differing turbulent flux footprints.

In order to show how F_{Cadv} and F_{Cadh} are related to one

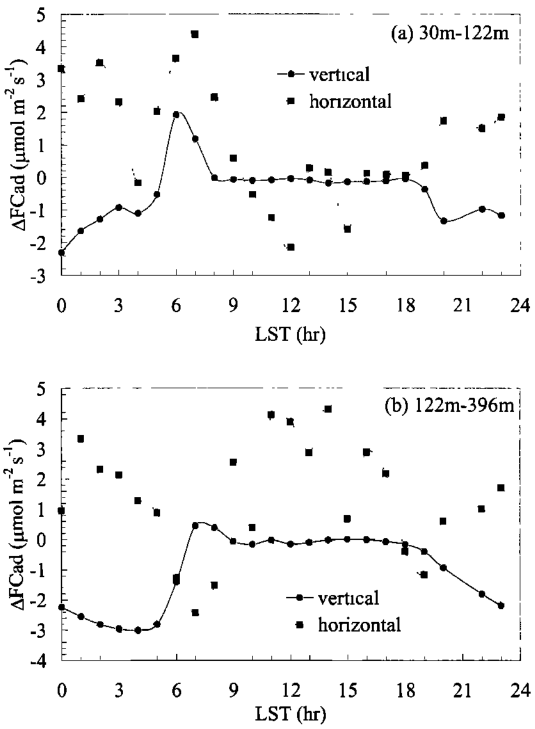

Figure 6. (a) Average diurnal differences of CO_2 fluxes from horizontal and vertical advection between 30 and 122 m based on Figure 1b and Figure 3a. (b) The same as Figure 6a but for the layer between 122 and 396 m.

another qualitatively, we take the mean vertical velocity to be constant with a value of -0.01 m s^{-1}, characteristic of synoptic-scale subsidence. The vertical advection F_{Cadv} can be estimated from the observed concentration gradients and (14). Figure 1b shows the contributions of F_{Cadv} to NEE from three levels under the condition of a constant mean vertical velocity of -0.01 m s^{-1} for July of 1997. The most striking feature is that these contributions are larger during nighttime and near zero during daytime. The pattern of F_{Cadv} in Figure 1b is probably not realistic because the mean vertical velocity is likely to be larger at 396 m than at lower levels. During daytime the mean vertical velocity could be large and variable because of convection, but this would not cause much F_{Cadv} because CO_2 vertical gradients are small (Figure 1). Mean vertical velocity could also be large during the morning transition.

The difference of horizontal advection between two levels above the canopy can be estimated as

$$\Delta F_{Cadh} = \Delta F_{Cadtot} - \Delta F_{Cadv}. \tag{15}$$

The differences of vertical and horizontal components for the two layers are shown in Figures 6a and 6b. Because there is no significant contribution from vertical advection during daytime, the horizontal contribution could account for the total advection. The interesting feature shown during nighttime is that the horizontal advection has similar order of magnitude to the vertical advection. This qualitative pattern implies that CO_2 transport from horizontal advection and vertical advection should both be important when there is no convection or turbulence is not strong. *Finnigan* [1999] supports this hypothesis from a theoretical basis.

4.5. Extrapolation to an Above-Canopy Tower

The growing global network of eddy covariance–based measurements of long-term biosphere-atmosphere CO_2 exchange (e.g., FLUXNET, see Oak Ridge National Laboratory Distributed Active Archive Center web site at http://daacl.esd.ornl.gov/FLUXNET/) makes it imperative that we understand the contribution of horizontal and vertical advection terms in computing the net ecosystem-atmosphere exchange of CO_2. We propose that it is more proper to refer to such tower-based NEE measurements as surface layer budget measurements rather than eddy covariance flux measurements, since the turbulence flux is only one term in the full equation for NEE. While the results presented here may be driven by local topography or heterogeneous surface vegetation cover and hence not easily generalized to other sites, it is worthwhile to understand how advection might influence NEE_0 measurements collected from a standard above-canopy (e.g., 30 m) flux tower at this site.

To estimate the absolute magnitude of F_{Cadtot} at the 30 m level, we assume that

$$\bar{u}\,\frac{\partial \bar{c}}{\partial x} + \bar{w}\,\frac{\partial \bar{c}}{\partial z} = \alpha = \text{const} \tag{16}$$

within a layer, and therefore it can be taken out of the integral in (11). Although α might not be a constant within the layer, in this case it may be taken out of the integral based on the mean value theorem as long as α is continuous. We assign to α its value at the middle of a layer (i.e., at level $(Z_1 + Z_2)/2$). Then α can be determined by

$$\alpha = \frac{\Delta F_{Cadtot}}{\Delta z} = -\frac{\Delta \mathrm{NEE}_0}{\Delta z}, \tag{17}$$

where $\Delta z = Z_2 - Z_1$. Finally, α at 30 m can be estimated by linear extrapolation from the α within the upper layer at 259 m and the α within the lower layer at 76 m. Thus the total advection at 30 m can be estimated as

$$F_{Cadtot} = \int_0^{30} \left\{ \bar{u}\,\frac{\partial \bar{c}}{\partial x} + \bar{w}\,\frac{\partial \bar{c}}{\partial z} \right\} dz \approx 30\alpha. \tag{18}$$

These approximations are very crude but are used only to get an estimate of the magnitude of F_{Cadtot}. Figure 7 shows that for our imaginary 30 m tower there would be a peaks in F_{Cadtot} of $\sim$3 μmol m^{-2} s^{-1} during the morning transition, which is most likely caused by vertical advection as discussed in section 4.2. The integral of this rough estimate of F_{Cadtot} over the diurnal cycle is $\sim$10% of the NEE_0 observed at 30 m.

5. Conclusions

A method to estimate the effects of total advection on NEE from a very tall tower measurement is developed based on the scalar conservation budget. In the typical case where the horizontal scale of the flow field is much larger than the depth of CBL, the horizontal turbulent flux divergence can be neglected compared to the vertical turbulent flux divergence. Thus measured NEE consists of four components: storage flux F_{Cst}, turbulent flux F_{Ctb}, horizontal advection flux F_{Cadh}, and vertical advection flux F_{Cadv}. The sum, NEE_0 ($= F_{Cst} + F_{Ctb}$), is considered a good approximation to NEE if CO_2 sources/sinks

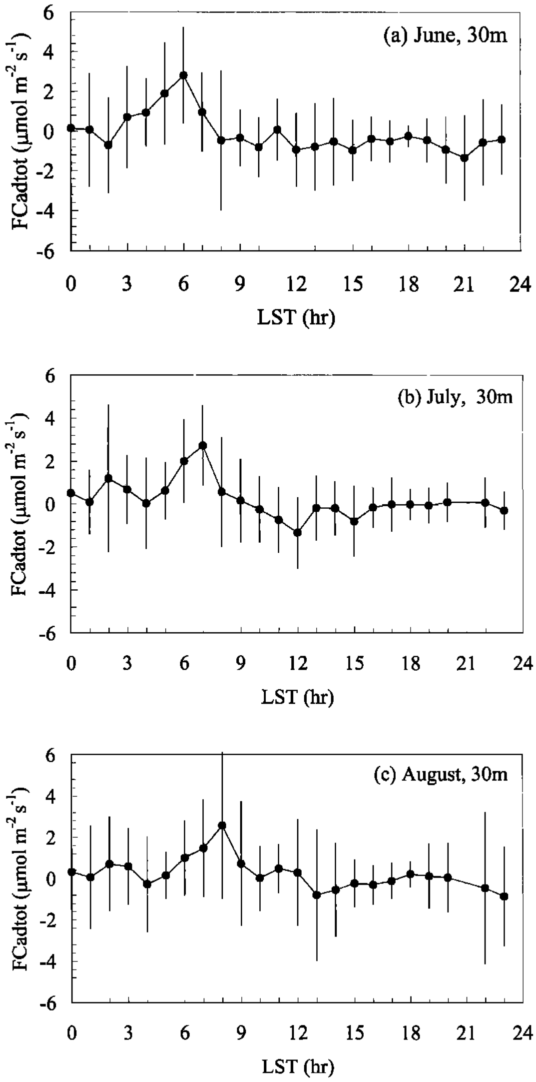

Figure 7. Average diurnal CO_2 flux from total advection estimated at 30 m for (a) June, (b) July, and (c) August. The vertical bars show the standard deviation of the mean.

are homogeneous and the terrain is flat. Few tower sites meet these conditions at all times, and hence an advection correction to NEE_0 is necessary in many cases. The multialtitude measurements from a very tall tower can provide measurements of the differences of NEE_0 between two different levels above the canopy, and these differences are equal in magnitude to the differences of total advection (but opposite in sign).

It is observed that the contribution of total advection to NEE from measurements at 122 m is larger by ~6 μmol m^{-2} s^{-1} than from measurements at 30 m during the morning transition. Vertical advection could account for a significant portion of these differences because the transition may be characterized by nonzero mean vertical velocity and large vertical gradients of CO_2.

Total advection below 396 m was, on average, 4 μmol m^{-2} s^{-1} larger than below 122 m during daytime (Figure 3b). During daytime, vertical advection could not account for these differences because CO_2 mixing ratios were nearly uniform in the vertical. Significant horizontal transport of CO_2 could result from spatial gradients in CO_2 driven by regional land cover patterns. A high degree of correlation with horizontal winds supports the hypothesis that horizontal advection is important at upper levels. During nighttime the observed total advection of CO_2 is small at upper levels. However, the possibility of subsidence/convergence leading to a significant vertical transport of CO_2 cannot be ruled out because vertical CO_2 gradients are very large near the surface (Figures 1a and 1b). This vertical transport would need to be balanced by horizontal advection.

The diurnal integral of total advection between 30 and 122 m (ΔF_{Cadtot}) is a significant portion of NEE_0 at 122 m. The diurnal integral of total advection between 122 and 396 m is less significant compared to NEE_0 at 396 m. We cannot say for certain that these integrals quantify the diurnally averaged error due to advection in the NEE_0 measurements from the tall tower because we do not directly measure the advection between ground and the lowest measurement level.

The order of magnitude of total advection F_{Cadtot} at 30 m is estimated to be ~3 μmol m^{-2} s^{-1} during morning transition (Figure 7). The diurnal integral of F_{Cadtot} is estimated to be 10% of the diurnal integral of NEE_0 at 30 m. This provides an estimate of the importance of advection for a typical above-canopy tower. It should be noted that this estimate is crude and that the results are somewhat specific to the landscape around the Wisconsin tower.

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