# Influences of Advection and Horizontal Flux Divergence on Net Ecosystem-atmosphere Exchange of $CO_2$ as Observed from Two Towers

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**Abstract**

The influences of horizontal advection, vertical advection, and horizontal flux divergence on measurements of net ecosystem-atmosphere exchange of $CO_2$ (NEE) have been investigated using the data from two towers separated by about 20km in a forested region of Northern America: a multilevel flux observation tower (WLEF) and a one-level flux tower (Willow Creek). Significant horizontal advection of $CO_2$ is inferred from the measurements at night in the growing season. Analyses indicate that ignoring the contribution of horizontal advection and vertical advection to NEE measurements can lead to an overestimate and underestimate of nighttime NEE by about 15% and 23%, respectively. The influences of horizontal and vertical advection on the measurements are usually negligible in the day. The estimated contribution of horizontal flux divergence between the two towers is negligible. Errors in measurements of the mean vertical velocity and $CO_2$ mixing ratio are also discussed. Combination of those errors results in a rather large relative error in the calculation of the vertical advection term by multiplying the measured mean vertical velocity and the vertical gradient of $CO_2$ mixing ratio. The results show that it is inappropriate, at least for short time scales, to use the measured mean vertical velocity to assess the contribution of vertical advection to NEE measurements.

*Key words:* Advection; Atmospheric boundary layer; Carbon budget; Error analysis

## 1. Introduction

Net ecosystem-atmosphere exchange (NEE) is the flux of a scalar or energy across the boundary between the atmosphere and the soil and vegetation. Two methods are often used to measure NEE. One is the chamber technique (e.g., Edwards and Sollins, 1973, Keller et al. 1986). The other is the eddy-covariance (EC) method. The latter has been used widely in recent years (Goulden et al., 1996, Black, et al., 1996) because it is in situ, does not disturb the environment around plant canopies, and allows continuous measurements (Baldocchi et al., 1988). A global network of tower-based, long-term EC flux measurement sites, FLUXNET, is operating in Europe (EuroFlux, Valentini et al. 1996), North America (AmeriFlux, Hollinger and Wofsy, 1997), and elsewhere in order to understand the processes that control the NEE of $CO_2$ in various terrestrial ecosystems. Tower-based calculation of NEE of a scalar constituent (e.g., $CO_2$) is typically calculated as the sum of a turbulent flux and a storage flux in the underlying air. The contribution of advection and horizontal divergence and horizontal variations in mean vertical fluxes measured at a height above the ground over a representative surface patch of an area are usually assumed to be negligible (Finnigan et al., 2003). This implicit assumption in the conventional one-dimensional measurement of NEE is described in section 3 and probably accounts for some errors in the NEE observations documented at many Fluxnet sites, e.g., the lack of energy balance closure and the systematic underestimate of nighttime NEE of $CO_2$ (Baldocchi et al., 2000; Lee, 1998; Goulden et al., 1996; Jarvis et al., 1997). Research already indicates that instrumentation is not likely to be the cause of these systematic errors (Vickers and Mahrt, 1997; Grelle and Lindroth, 1996). Many flux sites are within forests and other complex terrain, most of the long-term flux measurement sites do not meet standard micrometeorological criteria, e.g., a relatively open, flat terrain and uniform underlying surface, which ensures that the above assumption is valid. Therefore, the conventional one-dimensional EC method may lead to errors in NEE estimates.

Existing literature does not provide clear guidelines on the eddy covariance method over a tall canopy and complex terrain. It is relatively straightforward to measure NEE using the EC method above open, flat, canopy-free and uniform surfaces. Under such situations, the heterogeneous zone (the so-called roughness sublayer) near the surface is usually thin and hence the contribution of advection and flux divergence can be ignored compared to vertical fluxes measured at some height near the ground (Businger, 1986; Kanemasu, 1979). The heterogeneous zone (e.g., Fig. 1 in Mahrt, 2000) over a forest area with a tall canopy, however, is much thicker than that over a flat, canopy-free surface and is usually a function of the mixing ability of the atmosphere (Mahrt, 2000; Raupach et al., 1980). Instruments are sometimes within this zone, depending on the depth of the zone. Therefore, the contribution of advection, flux divergence or both to NEE could be significant under some conditions.

Horizontal heterogeneity necessarily leads to advection and horizontal flux divergence. Some authors have discussed this issue in the past. Lee (1998) proposed a method to estimate the effect of a non-zero mean vertical velocity on the atmospheric exchange over forests with the assumptions of horizontal homogeneity of the mixing ratio of a scalar and negligible horizontal flux divergence. Finnigan (1999) discussed Lee's scheme and pointed out that vertical advection cannot be used to provide a bound on the magnitude of total advection and hence a two- or three-dimensional analysis framework for the scalar conservation budget in an advective flow or heterogeneous flow is unavoidable. Baldocchi et al.(2000) applied Lee's approach over a temperate broadleaved forest growing in undulating terrain and compared their results to a process-based model. They concluded that the inclusion of a one-dimensional, vertical advection term in the NEE equation is still not sufficient for evaluating $CO_2$ exchange over tall forests in complex terrain, indicating that the horizontal advection term is non-zero. Yi et al. (2000) used EC data from three levels on a 400m tall tower to assess NEE of $CO_2$ and found that the total advection does come from not only vertical advection but also horizontal advection. Paw U et al. (2000) discussed two types of horizontal homogeneity assumptions and pointed out that even with horizontal source homogeneity, significant horizontal scalar gradients also could occur resulting in non-zero horizontal advection. In general, they showed that advection plays an important role in NEE measurements, but they did not provide a quantitative comparison among the contributions of horizontal, vertical advection, and horizontal flux divergence to NEE measurements.

We examine the terms, including vertical advection, horizontal advection and horizontal flux divergence, in the conservation equation for NEE of a scalar (e.g., $CO_2$ mixing ratio) using long-term (2 years) NEE measurements from two towers in a forest region in northern Wisconsin, USA. The contribution of the advection and horizontal flux divergence terms to measured NEE of $CO_2$ are estimated. We find that inclusion of vertical advection in the NEE calculation (Lee, 1998, Baldocchi, et al., 2000) results in additional uncertainty due to uncertainty in the measurement of mean vertical velocity. Usually the mean vertical motion is too small to be measured accurately with standard instrumentation (e.g., Sun and Mahrt, 1994). Particularly at night, the vertical gradient of

$CO_2$ mixing ratio near the surface is large so that an error in the mean vertical velocity is amplified in the vertical advection estimate. This issue is also addressed in this paper.

## 2. Experimental sites

The study sites, WLEF (45.95°N, 90.27°W) and Willow Creek (WC) (45.75°N, 90.1°W), are located in the Park Falls Ranger District of the Chequamegon National Forest, Wisconsin, USA. Fig. 1 shows locations of the two towers and the local land cover. The WC tower is about 20 km southeast of the WLEF tower. The forest around the WLEF tower is less dense and includes areas of wetland and conifers. Mature second-growth northern hardwood forests and aspen of various ages are more common around the WC tower. Topography in the experimental area is flat to gently sloping. Detailed descriptions of the instrumentation, site, and flux calculation methodology of the WLEF tower and the WC tower are presented by Berger et al. (2001) and Cook et al. (2002), respectively. The same measurement methodology and data processing techniques are applied at the two towers.

The height of the WLEF tower and multiple levels of flux instrumentation are unique among current AmeriFlux sites. At WLEF, flux data are collected at 30, 122, 396m above the ground and $CO_2$ mixing ratio data are collected at 11, 30, 76, 122, 244, 396 m. At WC, flux data are collected at 30m above the ground and $CO_2$ mixing ratio data are collected within and above the canopy, which is about 20m tall. Winds and temperatures are measured using sonic anemometers (Applied Technologies Inc., Boulder, Colorado, model SAT-11/3K or Campbell Scientific, Inc., Logan, Utah, model CSAT3). $CO_2$ and water vapor mixing ratios are measured using infrared gas analyzers (Li-Cor, Incorporated, Lincoln, Nebraska, model LI-6262). For this analysis, we use data collected during 1999-2000.

## 3. Methods and equations

We begin with the conservation equation for a scalar, $\tilde{c}$ ,

$$\frac{\partial \tilde{c}}{\partial t} + \frac{\partial(\tilde{u}\tilde{c})}{\partial x} + \frac{\partial(\tilde{v}\tilde{c})}{\partial y} + \frac{\partial(\tilde{w}\tilde{c})}{\partial z} = S , \tag{1}$$

where $\tilde{u}, \tilde{v}, \tilde{w}$ denote the velocity components in the x-, y- (horizontal) and z-(vertical) directions, respectively, $S$ is a source term, and we have ignored molecular viscosity. After Reynolds decomposition and averaging, equation (1) can be rewritten as,

$$\frac{\partial \overline{c}}{\partial t} + \frac{\partial(\overline{u}\,\overline{c})}{\partial x} + \frac{\partial(\overline{v}\,\overline{c})}{\partial y} + \frac{\partial(\overline{w}\,\overline{c})}{\partial z} + \frac{\partial(\overline{u'c'})}{\partial x} + \frac{\partial(\overline{v'c'})}{\partial y} + \frac{\partial(\overline{w'c'})}{\partial z} = \overline{S} , \tag{2}$$

where overbars denote ensemble mean quantities and primes denote departures from the means (e.g., $\tilde{c} = \overline{c} + c'$ ). Aligning the coordinate system along the mean wind (hence zero cross-wind advection, $\overline{v} = 0$ ) and using the mean continuity equation ( $\partial \overline{u}_i / \partial x_i = 0$ ), equation (2) becomes,

$$\frac{\partial \overline{c}}{\partial t} + \overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{w}\frac{\partial \overline{c}}{\partial z} + \frac{\partial(\overline{u'c'})}{\partial x} + \frac{\partial(\overline{v'c'})}{\partial y} + \frac{\partial(\overline{w'c'})}{\partial z} = \overline{S} \ . \tag{3}$$

The integration of equation (3) with respect to $z$ yields an expression of NEE for the scalar.

$$\text{NEE} = (\overline{w'c'})_{z=0} + \int_0^{z_r} \overline{S} dz = (\overline{w'c'})_{z=z_r} + \int_0^{z_r} [\frac{\partial \overline{c}}{\partial t} + \overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{w}\frac{\partial \overline{c}}{\partial z} + \frac{\partial (\overline{u'c'})}{\partial x} + \frac{\partial (\overline{v'c'})}{\partial y}] dz \,, \quad (4)$$

where $z_r$ is the height of the flux observation. The first term on the far right-hand side (RHS) of equation (4) is the vertical turbulent flux measured at height $z_r$ above the ground. The remaining terms represent the contribution due to the time rate of change, horizontal advection, vertical advection, horizontal along-wind flux divergence, and horizontal cross-wind flux divergence of the scalar, respectively, in the underlying air from the ground to the height $z_r$.

Equation (4) strictly refers to the NEE over an infinitesimal control area (e.g., d$A$), while in practice we wish to measure the NEE from a representative surface patch of area $A$. As detailed in Finnigan et al.(2003), we integrate equation (4) horizontally over area $A$ and then divide by the area, yielding an expression of area-averaged NEE for the scalar, $\overline{\text{NEE}}$, i.e.,

$$\begin{aligned}
\overline{\text{NEE}} &= \frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L} (\text{NEE}) dxdy = \frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L} (\overline{w'c'})_{z=0}\, dxdy + \int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L} \overline{S} dxdy\right] dz \\
&= \frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L} (\overline{w'c'})_{z=z_r}\, dxdy + \int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L} \frac{\partial \overline{c}}{\partial t} dxdy\right] dz \\
&+ \int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(\overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{w}\frac{\partial \overline{c}}{\partial z}\right) dxdy\right] dz + \int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(\frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \overline{v'c'}}{\partial y}\right) dxdy\right] dz, \quad (5)
\end{aligned}$$

where for convenience area $A$ is taken as a square of area $4L^2$ and centered at origin of coordinates, (0,0). In writing this equation, we have assumed that mean wind direction is not changed over a distance of $2L$ in the y-direction so that terms containing $\overline{v}$ still disappear.

In reality, it is not easy to measure the horizontal area-averaged terms in the equation. Usually we are restricted to measurements on a single tower and use them to approximate those area-averaged terms, unavoidably resulting in errors in the estimate of $\overline{\mathrm{NEE}}$ (Finnigan et al., 2003). When an observational site meets the micrometeorological criteria as described in section 1, i.e., the site is horizontally quasi-homogeneous and canopy-free, where the roughness sublayer (i.e., the heterogeneous zone) is thin, equation (5) can be simply written as,

$$\overline{\mathrm{NEE}} = \frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}(\overline{w'c'})_{z=0}\,dxdy + \int_{0}^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\overline{S}dxdy\right]dz \approx (\overline{w'c'})_{z=z_r} + \int_{0}^{z_r}\frac{\partial\overline{c}}{\partial t}dz\,, \qquad (6)$$

under the assumption of local horizontal homogeneity or negligible contribution of advection and horizontal flux divergence. In this case, if the measurement height, $z_r$, is low, the second term in the far RHS of equation (6) (also called the storage flux term) is usually small compared to the vertical flux measured at $z_r$ and hence the surface vertical flux is equal to the vertical flux at the measurement level (the term containing $\overline{S}$ is also assumed to be negligible), which is the so-called constant flux layer assumption.

For a heterogeneous area, errors are unavoidable when measurements on a single tower are used to estimate area-averaged NEE. In order to reduce the errors, turbulent fluxes need to be measured at a height (e.g., $z_r$) which should be, on one hand, high enough to ensure that the covariance $\overline{w'c'}$ measured at a single point, e.g., (0, 0, $z_r$), can approximately represent the area-averaged covariance (i.e., the first term on the far RHS of equation (5)). This is because the effects of surface heterogeneity at small spatial scales on flux measurements generally decay with height more rapidly than those at large spatial scales (Wang and Davis, 2002). In other words, horizontal variations in measured mean vertical fluxes are reduced with measurement height. If a blending height (Mason, 1988; Mahrt, 2000) can be defined and $z_r$ is greater than this height, horizontal variations in measured vertical fluxes are negligible. On the other hand, the height $z_r$ has to be low enough to ensure that the effects of advection and horizontal flux divergence (the last two terms on the far RHS of equation (5)) are negligible. Usually these two integral terms increase with $z_r$ (Yi et al., 2000). The storage flux term measured at a single-point might not be representative of the area-averaged storage flux term (the second term on the far RHS of (5)). Because it is usually small compared to turbulent fluxes in the day, using single-point measurements cannot lead to large error in NEE calculation. The storage flux is, however, comparable to the vertical turbulent flux at night, indicating that ignoring horizontal variations in the storage term can lead to significant errors. Finnigan et al. (2003) give a good discussion about effects of those terms on NEE calculations.

Therefore, for NEE measurements over heterogeneous areas, e.g., complex terrain with a high forest canopy and heterogeneous vegetation and soils, some terms in equation (5) usually ignored may be non-negligible, depending on atmospheric conditions and surface heterogeneity. Many EC flux towers are sited within forested terrain. To make us confident on our NEE measurements in the forested areas, it is necessary to assess the terms in equation (5) for area-averaged NEE.

The area around the WLEF and WC towers is relatively flat with a canopy height that varies from a few meters to 20 meters. To calculate NEE, one might need to consider the effects of advection or horizontal flux divergence, or both because the vegetation around the two towers is heterogeneous. In order to assess the effects of advection and horizontal flux divergence on calculated NEE of $CO_2$ at the WLEF tower, the data when wind directions are from the southeast (SE) are selected, i.e., the wind blows from the WC tower to the WLEF tower. Advective effects and horizontal flux divergence in equation

(5) are inferred in the mean wind direction coordinate using data measured at 30m above the ground from the two towers.

## 4. Data analysis and results

In this section, characteristics of $CO_2$ mixing ratios observed at the two towers are compared and then the magnitudes of advection and horizontal flux divergence terms are estimated and discussed.

### *4.1 Diurnal characteristics of $CO_2$ mean mixing ratios observed from the two towers*

During the daytime mean $CO_2$ mixing ratios vary little with height in the lowest 400m of the atmosphere over the forest (Fig. 2), indicating that the atmospheric boundary layer (ABL) is mixed well. Because the WC tower is near the WLEF tower, similar vertical distributions of mean $CO_2$ mixing ratios can be expected at the WC site in the daytime ABL. The vertical gradients of $CO_2$ mixing ratios are large at night especially in the growing season (Fig. 2a). The gradients are small in the dormant season (Fig. 2b) because of little biological activity. The large vertical gradients in the growing season imply that the effect of vertical advection on the calculation of NEE of $CO_2$ could be significant if a non-zero mean vertical velocity exists (Eqs. 4 and 5). This issue is discussed in detail in Yi et al. (2000).

In the growing season large mean horizontal gradients of the mean mixing ratios of $CO_2$ exist, depending on time of day (Fig. 3a). Those existing gradients indicate that horizontal advection could be important in the NEE calculation. The difference in the mean mixing ratio of $CO_2$ is generally larger at night than in the day (Fig. 3a). This phenomenon is consistent with the fact that the daytime boundary layer eddies mix $CO_2$ well not only in the vertical but also in the horizontal to some degree. At night, the mean mixing ratio of $CO_2$ increases locally and rapidly because of respiration into a shallow, stable ABL, leading to large differences in $CO_2$ mean mixing ratio between the two sites as shown in Fig. 3a. In the dormant season, the mean mixing ratios of $CO_2$ at 30m at the two sites (Fig. 3b) are almost the same because of little photosynthesis or respiration.

In the growing season, the magnitudes of the vertical turbulent fluxes of $CO_2$ are greater at the WC tower than at the WLEF tower (Fig. 4a), resulting from local differences in vegetation. Fluxes are close to zero at both sites in the dormant season (Fig. 4b).

The results in Figures 2 through 4 indicate that the differences in $CO_2$ mean mixing ratio between the two sites can potentially result in advection and horizontal flux divergence. Because only small differences in $CO_2$ mean mixing ratio between the two sites exist in the dormant season, we analyze only the data from the growing season in the following sections.

### *4.2 One-dimensional budget of the conservation equation of $CO_2$ mixing ratio*

The assumption of horizontal homogeneity at all heights or negligible contribution of advection and horizontal flux divergence is typically used to compute the NEE of $CO_2$.

Under this assumption, the time rate of change in mean mixing ratio of $CO_2$ ($\frac{\partial \overline{c}}{\partial t}$) should be balanced approximately by vertical turbulence flux divergence ($-\frac{\partial \overline{w'c'}}{\partial z}$). Fig. 5 examines this assumption using data from the WLEF tower. In the air layer between 30 and 122m, the two terms are closer in the day than at night (Fig. 5a), indicating that advection and horizontal flux divergence are smaller in the day than at night. In contrast, the two terms are better balanced in the layer of 122-396m (Fig. 5b) than in the lower layer, indicating that the effect of surface heterogeneity on the scalar budget is more significant at low altitudes than at high altitudes. Similar results are also reported in Yi et al. (2000).

*4.3 Single-point measured and area-averaged turbulent fluxes*

In the tower-based NEE calculation, vertical turbulent fluxes measured at a single point are usually used to approximate the area-averaged turbulent fluxes (i.e., the first term in the far RHS of (5)),

$$\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}(\overline{w'c'})_{z=z_r}\,dxdy \approx \overline{w'c'}\,(\text{at a tower})\,. \tag{7}$$

Horizontal variations in the vertical turbulent fluxes can lead to error in the above approximation. Fig. 4 shows that horizontal variations in $\overline{w'c'}$ can reach 0.2-0.3 ppm m/s (about 50% of magnitude of NEE) over the distance between the two towers (20km), indicating that the measurements from the WLEF or WC tower cannot represent the area-averaged NEE of $CO_2$ on a horizontal length scale of 20km in this forested area.

However, the approximation of equation (7) can be valid over smaller areas. Scaling arguments and numerical simulations indicate that the influence of small-scale surface heterogeneity decays more rapidly with height than that of large-scale surface heterogeneity (Wang and Davis, 2002). In other words, horizontal variations in vertical turbulent fluxes on small length scales can be reduced more rapidly with height than on large length scales. Therefore, equation (7) may be a reasonable approximation over areas of some length scales less than a critical value which depends on surface heterogeneity, atmospheric stability, and acceptable level of error. So far, we do not have sufficient data to quantitatively address this issue.

### *4.4 Horizontal flux divergence*

The NEE expression includes a cross-wind horizontal flux divergence term ($-\frac{\partial \overline{v'c'}}{\partial y}$) and an along-wind horizontal flux divergence term ($-\frac{\partial \overline{u'c'}}{\partial x}$) of the mixing ratio of $CO_2$. Figure 6 shows that the magnitude of $\overline{u'c'}$, about 1 ppm m/s, is one order greater than that of $\overline{v'c'}$ (about 0.1 ppm m/s) and approximately 3-5 times greater than the vertical turbulent flux, $\overline{w'c'}$ (0.1- 0.3 ppm m/s). The magnitude of $\overline{v'c'}$ is smaller than that of $\overline{w'c'}$. The spatial variation of $\overline{u'c'}$ between the two towers is of the order of 1 ppm m/s, the same order as that of $\overline{u'c'}$ (Fig. 6).

It is somewhat difficult to calculate the contribution of the integrated horizontal flux divergence terms to the area-averaged NEE estimates in Equation (5) because we do not have flux measurements at all heights from the surface to the sensor level. The contribution of those terms, however, can be estimated using a scaling argument. In Equation (5), the order of the integrated horizontal flux divergence terms can be estimated as,

$$\int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(\frac{\partial\overline{u'c'}}{\partial x}+\frac{\partial\overline{v'c'}}{\partial y}\right)dxdy\right]dz=\int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\delta_x(\overline{u'c'})dy+\frac{1}{4L^2}\int_{-L}^{L}\delta_y(\overline{v'c'})dx\right]dz$$
$$\sim\int_0^{z_r}\left[\frac{\delta_x(\overline{u'c'})}{2L}+\frac{\delta_y(\overline{v'c'})}{2L}\right]dz\sim z_r\times\left\langle\frac{\delta_x(\overline{u'c'})}{2L}\right\rangle+z_r\times\left\langle\frac{\delta_y(\overline{v'c'})}{2L}\right\rangle$$
$$\sim\frac{z_r O(\overline{u'c'})}{2L}+\frac{z_r O(\overline{v'c'})}{2L}, \qquad (8)$$

where

$$\delta_x(\overline{u'c'})=(\overline{u'c'})_{x=L}-(\overline{u'c'})_{x=-L},$$
$$\delta_y(\overline{v'c'})=(\overline{v'c'})_{y=L}-(\overline{v'c'})_{y=-L},$$

and angle brackets denote the vertical average from the surface to the sensor level (also called layer-average), 2$L$ is the horizontal length scale of interest, and $O(\overline{u'c'})$ and $O(\overline{v'c'})$ are the orders of $\overline{u'c'}$ and $\overline{v'c'}$, respectively. As a first approximation, the horizontal turbulent fluxes measured at 30m from the two towers are used to estimate the contribution of horizontal flux divergence to NEE calculation. For the data used here, the horizontal length scale of interest, 2$L$ is about 20km (the distance between the two towers and here the WLEF and WC towers are assumed to be located at $x=L$ and $x=-L$, respectively), $z_r$ is 30m. $O(\overline{u'c'})$ and $O(\overline{v'c'})$ are 1 ppm m/s and 0.1 ppm m/s (Fig. 6), respectively. Therefore, the order of the horizontal divergence terms is estimated to be about $1.5\times10^{-3}$ ppm m/s, much smaller than the order of the vertical turbulent flux term, 0.1-0.3 ppm m/s, indicating that the integrated horizontal flux divergence terms can be neglected for the horizontal length scale of 20km.

From equation (7), we can find that the magnitude of the integrated horizontal divergence term increases with increasing horizontal variation in $\overline{u'c'}$ and decreasing horizontal length scale of interest. The critical horizontal length scale ($L_x$) where the magnitude of the integrated horizontal divergence term is comparable to that of 10% of vertical turbulent flux term can be estimated as,

$$L_x \sim \frac{z_r \delta_x (\overline{u'c'})}{10\% \times O(\overline{w'c'})}, \tag{9}$$

where $O(\overline{w'c'})$ denotes the order of $\overline{w'c'}$. Our data show that $\delta_x(\overline{u'c'})$ is of order of $O(\overline{u'c'})$ over the distance of 20km. In some cases, one might expect that the magnitude of $\delta_x(\overline{u'c'})$ would decrease with decreasing the horizontal length scale. It is possible, but some experiments indicate that the horizontal variation of vertical turbulent fluxes still can reach about 30% of magnitude of fluxes over a horizontal distance of ~100m in a forested area with tall canopy (Smith et al., 1985). Therefore, we can use $O(\overline{u'c'})$ to approximate $\delta_x(\overline{u'c'})$ in our forested area and hence $L_x$ is of the order of $\frac{z_r O(\overline{u'c'})}{0.1 \times O(\overline{w'c'})}$, approximately equal to 50 times the sensor height.  For a typical sensor height (e.g., 30m), $L_x$ is about $10^3$ m in the forested area. In other words, if the horizontal length scale of interest is greater than 50 times the sensor height, the contribution of horizontal divergence can be ignored compared to the vertical turbulent flux term in the NEE calculation over a forested area. If the length scale is smaller than the critical length scale, ignoring the horizontal divergence terms might lead to a relative error of 10% or more in the NEE calculation depending on surface heterogeneity.

*4.5 Horizontal advection*

Horizontal advection ($-\overline{u}\dfrac{\partial \overline{c}}{\partial x}$) at 30m above the surface is of the same order as the time rate of change in the mean mixing ratio of $CO_2$ (Fig. 7). As expected, the effect of horizontal advection is smaller in the day than at night because horizontal $CO_2$ gradients are smaller.

Following the scaling argument used in section 4.4, the integrated horizontal advection term in Equation (5) is estimated as,

$$\int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(-\overline{u}\frac{\partial \overline{c}}{\partial x}\right)dxdy\right]dz \sim z_r \times \left\langle -\overline{u}\frac{\delta_x(\overline{c})}{2L}\right\rangle, \tag{10}$$

where $\delta_x(\overline{c}) = \overline{c}_{x=L} - \overline{c}_{x=-L}$ can be estimated as the difference of $CO_2$ mean mixing ratio measured at the two towers. The term within the angle brackets can be regarded as the area-averaged horizontal advection. However, it is difficult to estimate the vertically averaged horizontal advection because we do not have measurements at all heights below $z_r$. It has to be estimated using the advection at the sensor level. Usually the averaged horizontal advection between the surface and the sensor level is less than that at the sensor level because the wind speed rapidly decreases as height decreases in the surface layer. Sun and Mahrt (1994) estimated the layer-averaged horizontal advection as 0.6 of that computed at their aircraft level (33m), because the reduction factor of 0.6 maximizes the correlation between the surface fluxes and the NDVI (normalized difference of vegetation index) in their study. As a first order approximation, the factor of 0.6 is also used in this paper. Therefore, equation (10) can be written as,

$$\int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(-\overline{u}\frac{\partial\overline{c}}{\partial x}\right)dxdy\right]dz \sim -0.6\cdot\overline{u}\,\frac{z_r\delta_x(\overline{c})}{2L}. \tag{11}$$

Typically, the magnitudes of the horizontal advection term at 30m are 0.001 ppm m/s at night and 0.0001 ppm m/s during the day (Fig. 7). Therefore, the corresponding values of the integrated horizontal advection term are roughly 0.018 ppm m/s and 0.0018 ppm m/s.

A typical magnitude of the nighttime vertical turbulent flux of $CO_2$ mixing ratio at 30m at the WLEF site is observed to be about 0.1 ppm m/s. The nighttime storage flux of $CO_2$ mixing ratio is typically about 0.02 ppm m/s. Thus, a typical value of nighttime NEE of $CO_2$ is about 0.12 ppm m/s. The contribution of horizontal advection to the NEE estimate at night is approximately -0.018 ppm m/s, reducing the NEE estimate by about 15%. In the day, the integrated horizontal advection term is negligible compared to the vertical turbulent flux term. It should, however, be noted that those estimates are not the net effect of advection on the NEE estimate since horizontal advection is usually compensated partly or totally by vertical advection because of mass conservation (Finnigan, 1999). Vertical advection is discussed in the next section.

*4.6 Vertical advection*

Following subsections discuss the vertical advection term calculated using two methods and errors in the direct calculation of the vertical advection term.

*4.6.1 Vertical advection estimated from the budget equation*

The vertical advection term in the budget equation (3) can be calculated if all other terms in the equation are known. In this section, the source term is assumed to be zero above the canopy and the horizontal crosswind flux ($\overline{v'c'}$) divergence term is assumed to be negligible. All other terms in equation (3) are estimated from the measurements, giving vertical advection as a residual. Fig. 7 (filled circles) shows the diurnal pattern of the calculated vertical advection term ($-\overline{w}\frac{\partial \overline{c}}{\partial z}$) at 30m above the ground at the WLEF tower. It can be seen, as predicted in section 4.1, that the vertical advection term is more significant at night than in the day. Negative vertical advection at night implies that the mean vertical velocity is negative because the nighttime vertical gradient of $CO_2$ mean mixing ratio is usually negative. The negative mean vertical velocity is probably due to a horizontal gradient of surface roughness. The upland forests near the WC tower are likely characterized by greater roughness than the lower-stature mixed forests and wetland near the WLEF tower, possibly resulting in divergence near the WLEF tower when wind direction is SE. The smaller daytime vertical advection is due to the small vertical gradient of $CO_2$ mixing ratio in the daytime ABL. The vertical and horizontal advection terms generally have opposite signs (Fig. 7), indicating that their effects partly compensate, consistent with the analysis of Finnigan (1999). Therefore, only including the vertical advection term on the NEE estimate could overestimate the total influence of advection, as indicated by Yi et al. (2000) and Baldocchi et al. (2000).

Since we use difference schemes instead of the differential terms to calculate the vertical advection, the result should represent an average of vertical advection over the distance between the two towers (20km) and a time scale of one hour. Therefore, the integrated vertical advection term in equation (5) can be estimated as,

$$\int_0^{z_r}\left[\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\left(-\overline{w}\frac{\partial \overline{c}}{\partial z}\right)dxdy\right]dz \sim z_r \times \left\langle -\overline{w}\frac{\partial \overline{c}}{\partial z}\right\rangle. \qquad (12)$$

Similar to section 4.5, the factor of 0.6 suggested by Sun and Mahrt (1994) is again used here to estimate the layer-averaged vertical advection. The contribution of vertical advection to the estimate of NEE of $CO_2$ is roughly 0.027ppm m/s at night (a typical nighttime value of the vertical advection term is -0.0015 ppm/s), increasing the nighttime NEE estimate by about 23%. Again, the increased relative importance of the effect of advection at night is due not only to the larger nighttime vertical advection, but also to the smaller observed vertical flux at night. The overall effect of horizontal and vertical advection on the nighttime NEE estimate is about a 10% underestimate. In the day, a typical magnitude of the vertical advection term is about 0.0005 ppm/s. Thus the integrated vertical advection term is about 0.009 ppm m/s, two orders of magnitude smaller than the daytime vertical turbulent flux.

*4.6.2 Direct calculation of the vertical advection term*

The method of computing the vertical advection term used in section 4.6.1 is not readily implemented in practice because measurements are usually made at a single tower and hence the terms of horizontal advection and flux divergence of $CO_2$ are unknown in the budget equation. Another approach to estimate the vertical advection term is to use the measured mean vertical velocity and vertical mixing ratio gradient of $CO_2$. Although the mean vertical velocity is thought to be too small to measure accurately with standard instruments, some authors (Lee, 1998; Baldocchi et al., 2000) have still used it to estimate the effect of vertical advection on the NEE measurements. Fig. 8 presents the vertical advection term calculated by multiplying the measured mean vertical velocity (Berger et al., 2001; Lee, 1998) and the vertical gradient of the mean mixing ratio of $CO_2$

at the two towers. Although the estimates show that the vertical advection is much smaller in the day than at night, similar to the result from the budget equation (Fig. 7), some significant differences (e.g., signs and magnitudes) exist, particularly at night. One possible reason is that the vertical advection term estimated from the conservation equation represents an average over the distance between the two towers, while the direct calculations of the vertical advection term probably represent only local influences of topography and vegetation near the two towers. Another reason for differences in the two estimates is measurement errors in the mean vertical velocity, which are likely to be large because the magnitude of the hourly averaged vertical velocity is much smaller than that of the wind speed fluctuation in the low-level atmosphere. In order to assess our ability to estimate the effect of vertical advection on measurements of NEE using single-tower data, we must quantify the uncertainty in the direct calculation.

*4.6.3 Uncertainty in the direct calculation of the vertical advection term*

Uncertainty in the direct calculation of the vertical advection term arises from random and systematic errors in the mean vertical velocity and $CO_2$ mean mixing ratio measurements.

Random error sources include random instrumental noise (e.g., Lenschow and Kristensen, 1985), data processing, and sampling (Wyngaard, 1973; Lenschow, et al., 1994; Vickers and Mahrt, 1997). Sources for systematic errors in the measurements include instrument alignment, methods of data processing, and sampling. An example of the systematic error due to sampling is failure to capture all transporting scales of the atmosphere (Vickers and Mahrt, 1997). Sometimes the systematic and random errors due to sampling are not separated and called the sampling error. Sampling errors are usually large compared to instrumental errors (Lenschow, et al., 1994; Lenschow and Kristensen, 1985). Therefore, we discuss here only the uncertainty due to the sampling error in the calculation of the vertical advection term.

In practice, the time average of a variable is usually used to approximate its ensemble average. The difference between the two averages results in the sampling error. According to Lumley and Panofsky (1964) and Wyngaard (1973), an estimate of the sampling error is,

$$\sigma_s = \left( \frac{2\sigma_a^2 \tau}{T} \right)^{1/2}, \tag{13}$$

where $\sigma_s$, the sampling error, is the standard deviation of the time-averaged value of a variable about the ensemble mean; $\sigma_a$, $\tau$, and $T$ are the atmospheric standard deviation of the variable, the atmospheric turbulent integral time scale, and the averaging time, respectively. The integral time scale may be estimated as $10(z-d)/\overline{u}$ (Businger, 1986; Kaimal et al., 1972), where $z$ is the measurement height, and $d$ is the zero-plane displacement distance (about 5m for the WLEF tower area). We use data from the WLEF tower for the growing season in 1999 and 2000 to estimate $\sigma_s$. Table 1 summarizes some typical values of turbulent variables. For the measurements at the WLEF tower, $T$ is equal to one hour. The mean horizontal wind speed ($\overline{u}$) over the growing season at 30m is about 3.46 m/s during the day and 2.67 m/s at night. Therefore, the magnitude of the sampling error in the mean vertical velocity is calculated to be about 0.1-0.2m/s (Table 1), large compared to instrumental errors for a sonic anemometer which are less than 0.01m/s (Kaimal et al., 1990). In addition, because the hourly-mean vertical velocity is of order of 0.01-0.1m/s (Yi et al., 2001), the relative error of its measurements is large. In contrast, the relative error of $CO_2$ mean mixing ratio is small because the atmospheric $CO_2$ mean mixing ratio is of order of 370 ppm and the sampling error of $CO_2$ mixing ratio is just about 0.4-0.6ppm (Table 1).

Errors in measurements of the mean vertical velocity and $CO_2$ mixing ratio are combined to calculate the error in the vertical advection term,

$$\sigma_f^2 = \left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2, \tag{14}$$

(Barlow, 1989), where *f* is a function of independent variables, *x* and *y*; $\sigma_x$ and $\sigma_y$ are errors in *x* and *y*, respectively; $\sigma_f$ the combined error on *f*. Therefore, an error ($\sigma_{adv}$) in the vertical advection term can be estimated to be,

$$\sigma_{adv}^2 = \left(\frac{\partial \overline{c}}{\partial z}\right)^2 \sigma_{sw}^2 + \overline{w}^2 \sigma_g^2, \tag{15}$$

where $\sigma_{sw}$ is the sampling error in the mean vertical velocity; $\sigma_g$ is the sampling error in the vertical gradient of $CO_2$ mean mixing ratio. $\sigma_g$ can be estimated to be, as a first order approximation,

$$\sigma_g^2 = \sigma_{\partial \overline{c}/\partial z}^2 \approx \frac{1}{(z_1 - z_2)^2}\left(\sigma_{sc_1}^2 + \sigma_{sc_2}^2\right) \approx \frac{2\sigma_{sc}^2}{(z_1 - z_2)^2}, \tag{16}$$

where $\sigma_c$ is the sampling error in $CO_2$ mixing ratio; $\sigma_{sc_1}$ and $\sigma_{sc_2}$ are the sampling errors in $CO_2$ mixing ratios at heights $z_1$ and $z_2$, respectively. In this case, $z_1$ and $z_2$ are 30 and 11m, respectively. Thus, using the results shown in Table 1, $\sigma_g$ is about 0.17 ppm/m in the day and 0.20 ppm/m at night. The measurements show that the magnitudes of mean vertical gradients of $CO_2$ mixing ratio are about 0.001 ppm/m during the day and 0.35

ppm/m at night in the growing season. In the day, the vertical gradient is statistically zero since its standard deviation is large. In contrast, the vertical gradient is large at night as shown in previous sections. Assuming the mean vertical velocity is of order of 0.01m/s and substituting $\sigma_g$, $\sigma_{sw}$, and $\frac{\partial \overline{c}}{\partial z}$ into (15), we can estimate the errors in the vertical advection term to be 0.002 ppm/s and 0.035 ppm/s, respectively, in the day and at night. Those errors are much larger than the corresponding magnitudes of the vertical advection term, namely, 0.0005 ppm/s and 0.0015 ppm/s, implying rather large relative errors. Therefore, we conclude that it is inappropriate to use the direct calculation method to estimate hourly-averaged vertical advection.

When errors are random, errors in estimated means can diminish with increasing size of data set, but many more data points are needed to reduce a random error in the estimated mean to an acceptable level for the vertical advection term than for other terms such as the vertical turbulent flux. Nevertheless, increasing data set size cannot reduce systematic errors. A small systematic bias in the mean vertical velocity still can lead to a large error in nighttime NEE estimates.

## 5. Conclusions

We investigated the influences of vertical and horizontal advection and horizontal flux divergence on measurements of NEE of $CO_2$ using data from two towers in a forested region of northern Wisconsin. The results indicate that the effects of advection on NEE measurements are more significant at night than in the day in the growing season and are negligible in the dormant season. The contributions of nighttime horizontal and vertical advection of $CO_2$ mixing ratio are about 15% and 23% of nighttime NEE. The horizontal advection and vertical advection terms usually have opposite signs and hence partly compensate for each other, and the net effect of advection increases nighttime NEE estimate by about 8%. Whether the influence of horizontal flux divergence is negligible or not depends on the length scale of a representative surface patch of interest, characteristics of roughness sublayer, or both. A size of the surface area patch that NEE measurements at a single tower can represent depends on scale-dependent horizontal variations in turbulent fluxes, horizontal flux divergence, advection, and acceptable level of error.

The study also analyzes uncertainty in the calculation of the vertical advection term using the vertical velocity from direct measurements with a sonic anemometer. Considerable errors in the direct calculation at night are caused by large nighttime vertical gradients of $CO_2$ mixing ratio and errors in measurements of the mean vertical velocity, significantly affecting NEE measurements. The daytime relative errors in the direct calculation are also large but are negligible for the NEE estimates because the magnitudes of both the vertical advection term and its error are small compared with the turbulent flux. Therefore, the measured mean vertical velocity should not be used to estimate influences of vertical advection on NEE measurements, particularly for short time scales. For long time scales, the uncertainty might be reduced with increasing the size of the dataset, but systematic errors can then become more important.

This paper analyzes the influence of advection and horizontal flux divergence on NEE measurements only for conditions when the mean wind direction was aligned with our two towers. In order to more completely address advective influences on long-term NEE measurements, one needs to set up more towers, and analyze the data with a high resolution ecophysiological model coupled to an atmospheric transport model (e.g., Denning et al., 2002) . Successful assessment of NEE in complex terrain will require a particularly rigorous approach of intensive measurements and modeling.

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Table 1. Atmospheric standard deviations averaged over the growing season ($\sigma_a$) and the sampling errors ($\sigma_s$) of the vertical velocity and $CO_2$ mixing ratio at 30m above the ground (see the text).

| | Day | | Night | |
|---|---|---|---|---|
| | $\sigma_a$ | $\sigma_s$ | $\sigma_a$ | $\sigma_s$ |
| Vertical velocity ($\overline{w}$, m/s) | 0.79 | 0.16 | 0.44 | 0.10 |
| $CO_2$ mixing ratio ($\overline{c}$, ppm) | 2.28 | 0.45 | 2.71 | 0.61 |

## **Figure Captions**:

Fig. 1. Locations of the WLEF tower and the Willow Creek tower (filled circles) and land cover. The distance between the two towers is about 20 km. (source: http://www.dnr.state.wi.us/org/at/et/geo/data/wlc.htm# )

Fig. 2. Distributions of diurnal $CO_2$ mean mixing ratio at 11, 30, 76, 122, 244, and 396m above the ground at the WLEF tower in the growing season (A) and the dormant season (B).

Fig. 3. Comparisons of the diurnal patterns of mean $CO_2$ mixing ratio at 30m above the ground from the WLEF tower (open squares) and WC tower (filled circles) in the growing season (A) and the dormant season (B). The vertical bars denote the standard errors.

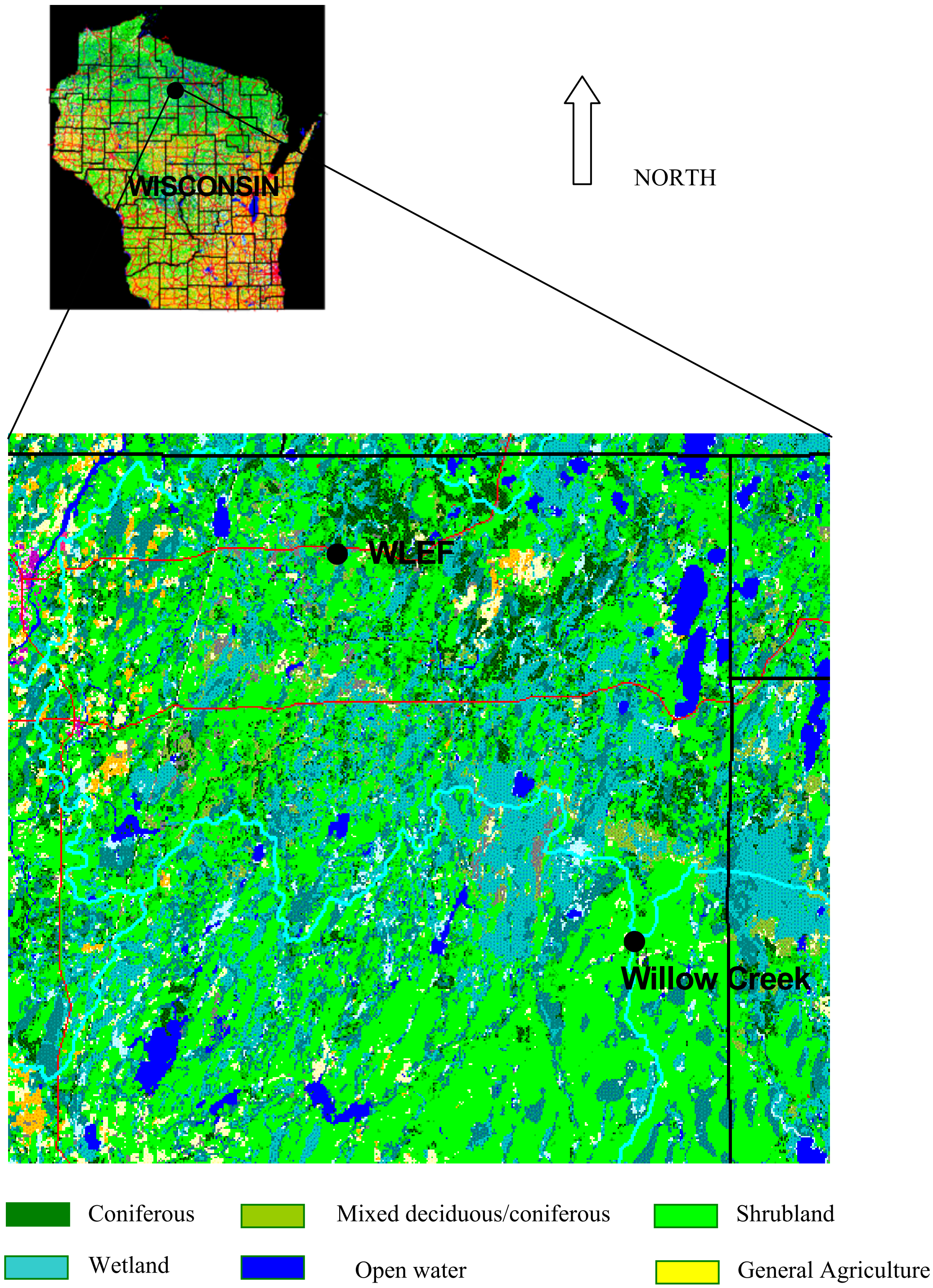
Fig. 4. Comparisons of the diurnal patterns of mean vertical turbulent flux of $CO_2$ at 30m above the ground observed from the WLEF tower (open squares) and WC tower (filled circles) in the growing season (A) and the dormant season (B). The vertical bars denote the standard errors.

Fig. 5. Comparisons of the diurnal pattern of the time rate of change in $CO_2$ mixing ratio (filled circles) and the vertical turbulent flux divergence (solid line) in the air layer between 30 and 122m (A), 122 and 396m (B) from the WLEF tower. The vertical bars denote the standard errors.

Fig. 6. Diurnal patterns of $\overline{u'c'}$ (A) and $\overline{v'c'}$ (B) at 30m above the ground from the WLEF tower (open squares) and the WC tower (filled circles) in the growing season. As a comparison, $\overline{w'c'}$ (dotted line) at the WLEF tower is shown.

Fig. 7. The diurnal patterns of the horizontal advection ($-\overline{u}\frac{\partial \overline{c}}{\partial x}$, broken line), vertical advection ($-\overline{w}\frac{\partial \overline{c}}{\partial z}$, filled circles) terms, and time rate of change ($\frac{\partial \overline{c}}{\partial t}$, solid line) in $CO_2$ mean mixing ratio at the height of 30m. The vertical bars denote the standard errors

Fig. 8. The diurnal pattern of the vertical advection term ($-\overline{w}\frac{\partial \overline{c}}{\partial z}$) of $CO_2$ mixing ratio calculated by multiplying the measured mean vertical velocity and the vertical gradient of the mean mixing ratio of $CO_2$. The vertical bars denote the standard errors.

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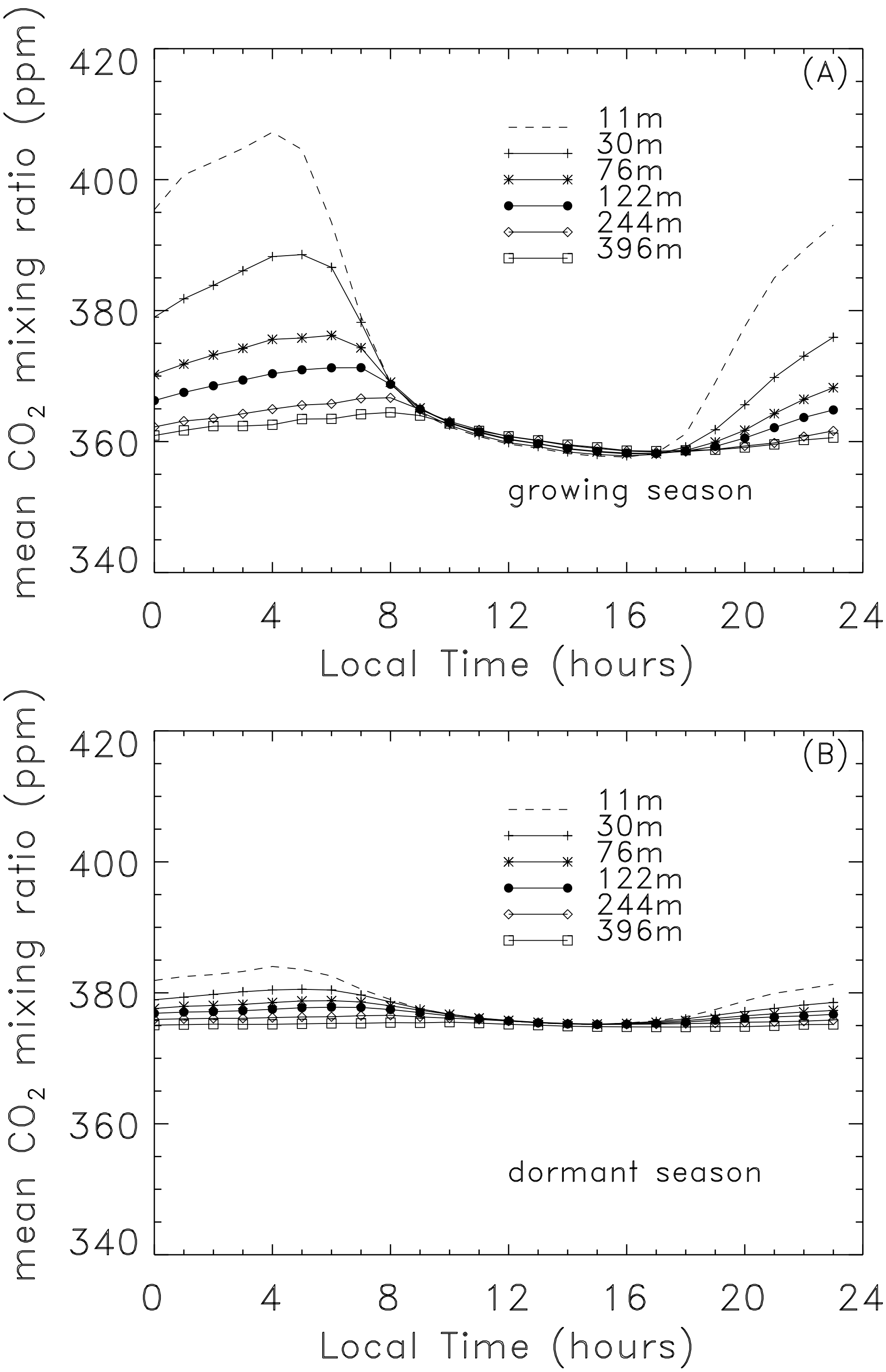


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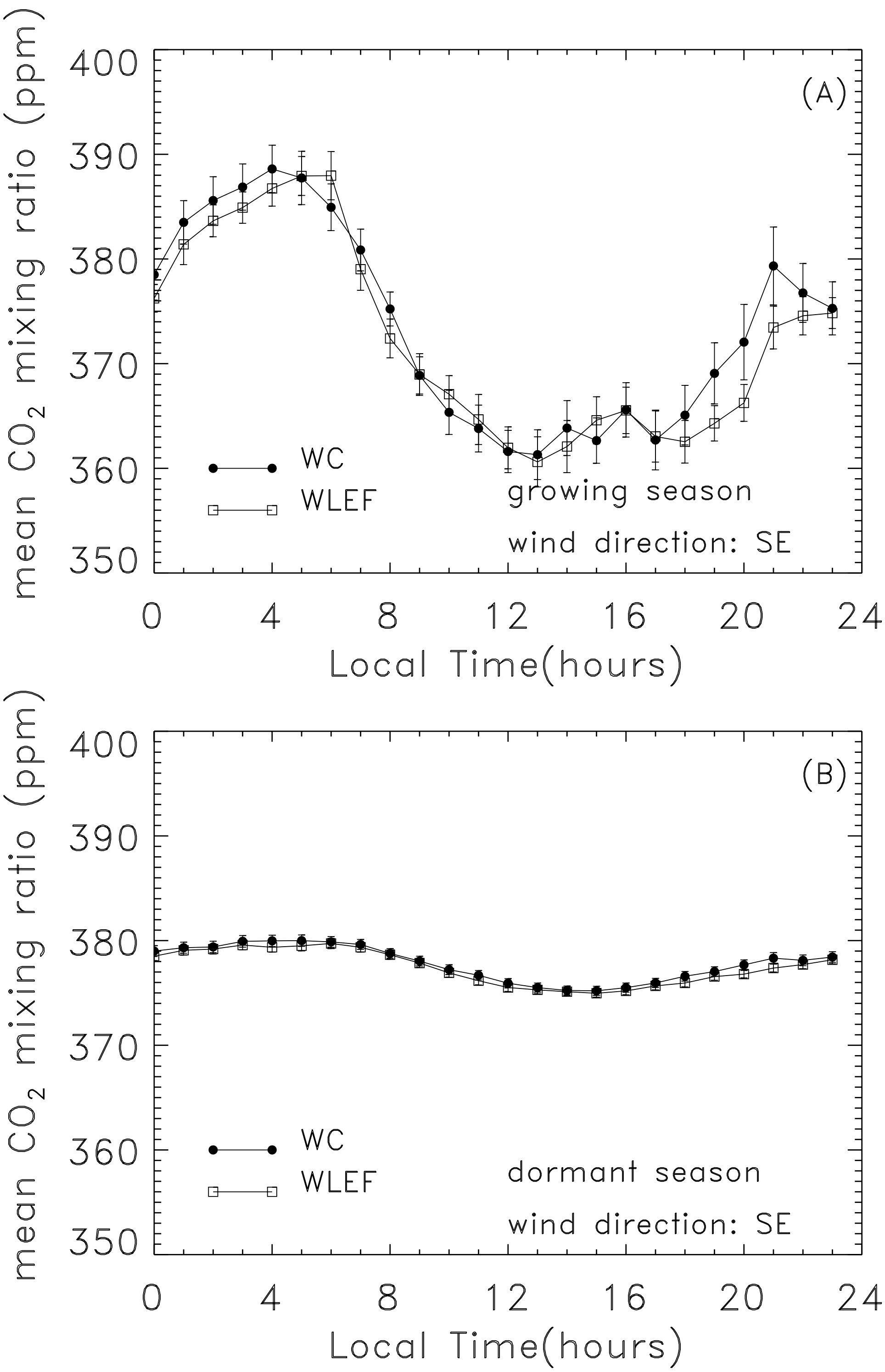


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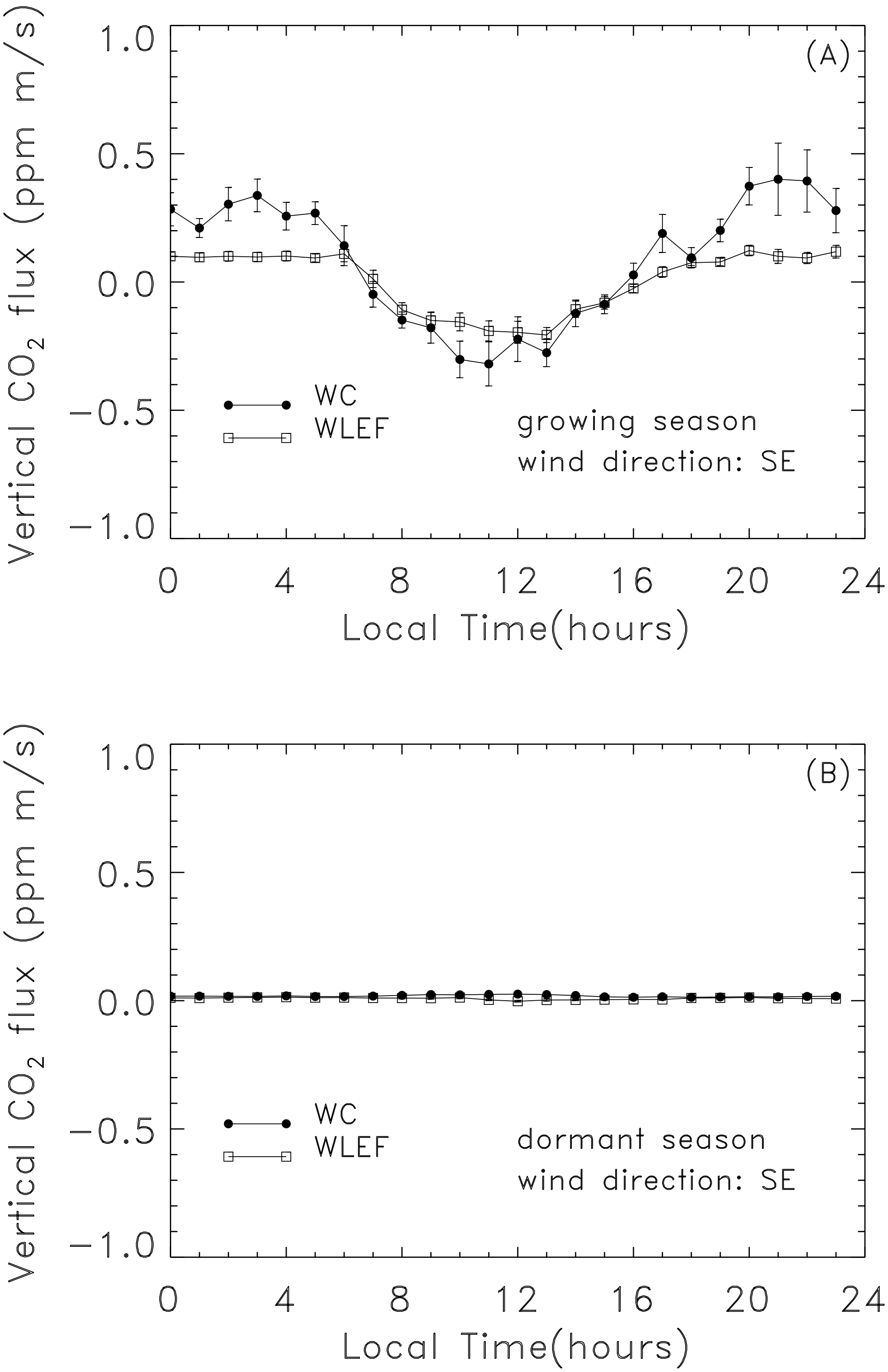


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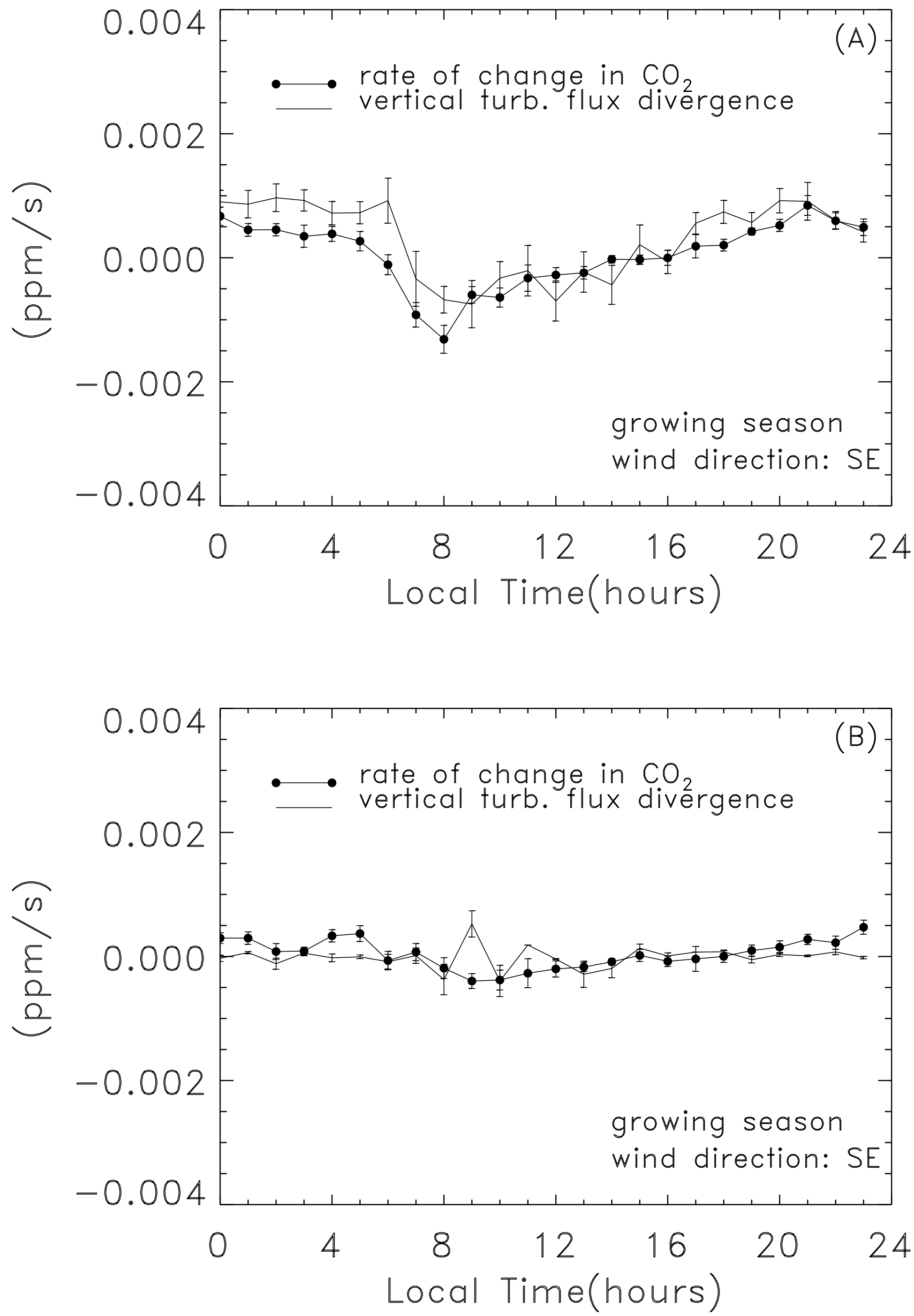


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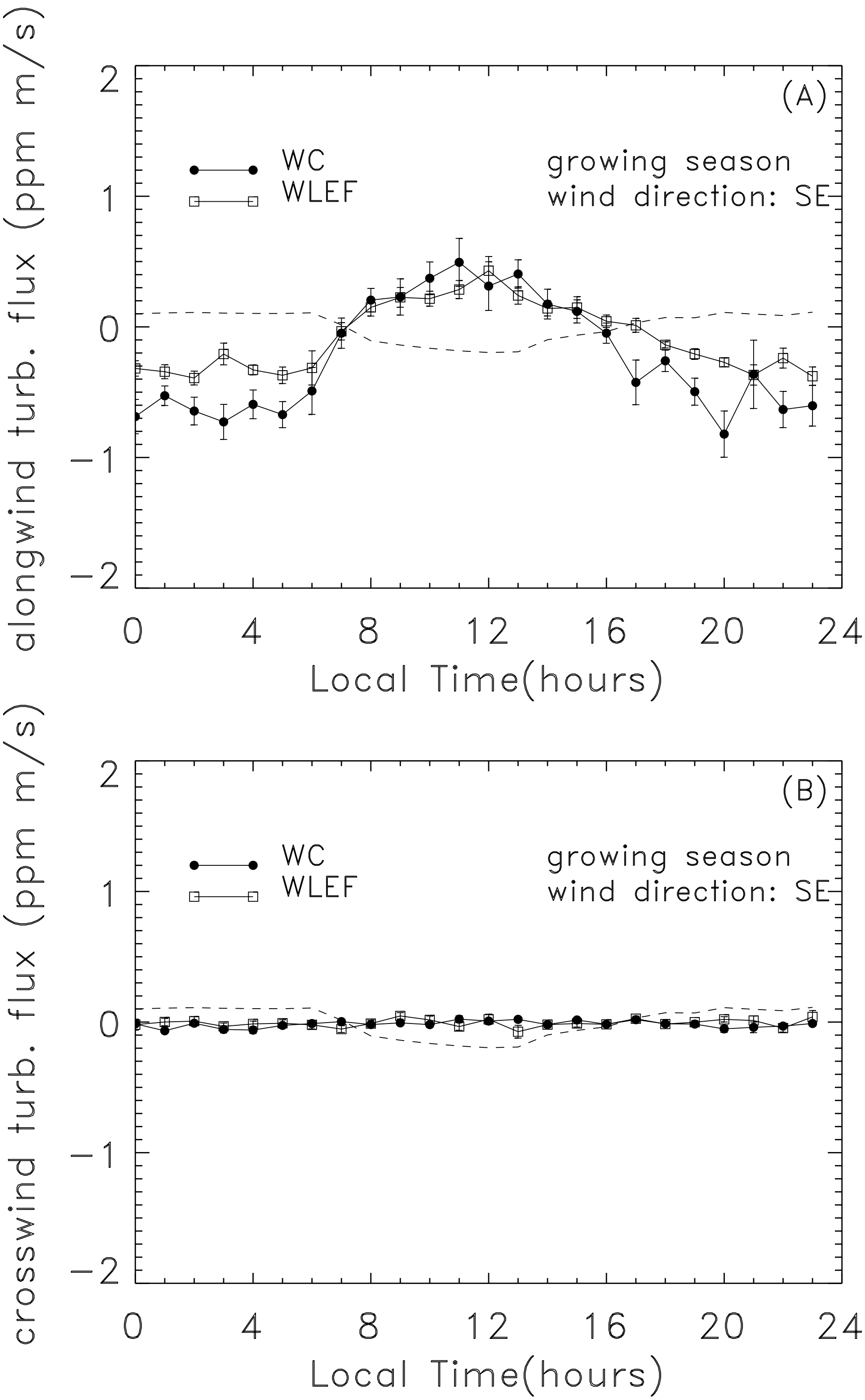


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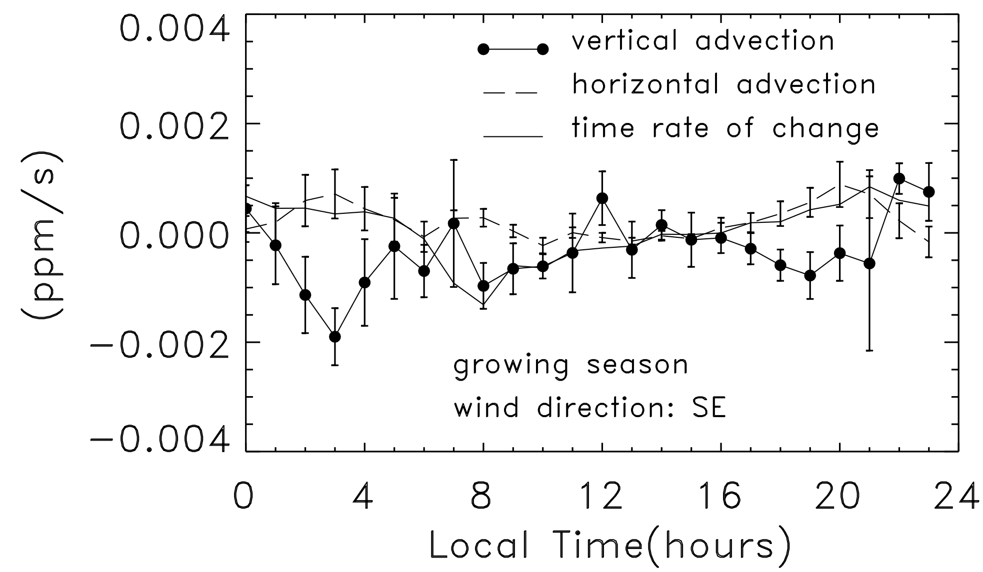


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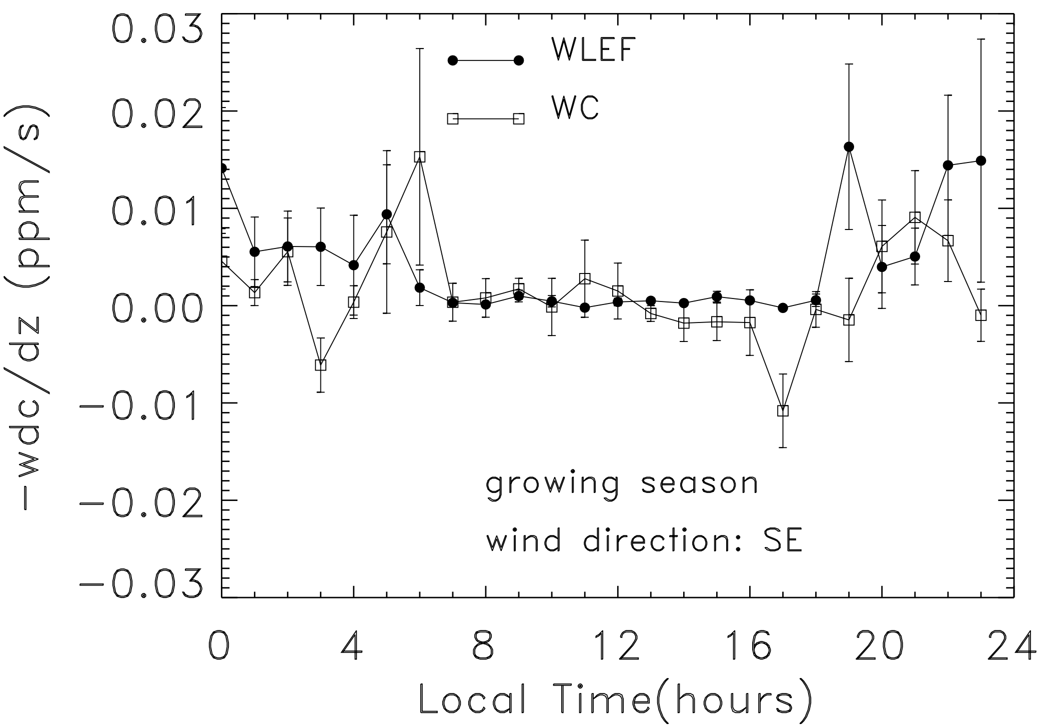


Fig. 8. The diurnal pattern of the vertical advection term ($-\overline{w}\frac{\partial \overline{c}}{\partial z}$) of $CO_2$ mixing ratio calculated by multiplying the measured mean vertical velocity and the vertical gradient of the mean mixing ratio of $CO_2$. The vertical bars denote the standard errors.