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Surface layer CO_2 budget and advective contributions to measurements of net ecosystem–atmosphere exchange of CO_2

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Abstract

The aim of this case study is to examine the surface layer CO_2 budget and possible impacts of advection on the 20 km scale on estimates of net ecosystem–atmosphere exchange (NEE) of CO_2 under windy conditions. The advection terms in the CO_2 mixing ratio conservation equation are computed using data from two flux towers 20 km apart in a forested area in Wisconsin, USA. The data are analyzed when the winds blow continuously from the southeast (SE) or from the northwest (NW) under windy conditions for 5 h or longer during the months of May through September of 1999 and 2000. Compared to the vertical turbulent flux, the contribution of horizontal flux divergence is negligible on the scale of 20 km at all times. The contributions of both horizontal and vertical advection terms to NEE estimates are negligible in the day. The mean nocturnal vertical and horizontal components of the advective fluxes have opposite signs and are of the same order of magnitude. Considering only one of the two advection terms in NEE calculation would be inappropriate. On the spatial scale specified, the contribution of horizontal advection is negative and can be 10% of NEE at night under sustained SE winds. The contribution of vertical advection is positive and is about 20% of NEE for the same wind direction. The contribution of nocturnal advection is negligible for most cases with sustained NW winds. The evaluation of the advective effects is still incomplete only from this dataset and significant contribution of advection on the scales smaller than 20 km is not ruled out because the 20-km scale may not be the primary scale of the heterogeneous distributions of land cover and soils. Nevertheless, the analyses suggest that significant errors due to the neglect of the impacts of the land cover and soil heterogeneity at larger scales (than local) are possible in one-dimensional eddy-covariance NEE measurements under windy conditions; these measurements are usually selected to describe nighttime NEE at this site and, therefore, the likely errors may deserve attention. The analyses also suggest that impacts of both advection terms within the surface layer on NEE estimates from the atmospheric boundary budget method could be negligible in the day but significant at night. More comprehensive experiments are needed to completely assess the advection issue.

Keywords: Advection; Atmospheric surface layer; Carbon dioxide budget; Net ecosystem–atmosphere exchange; Atmospheric boundary layer budget

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1. Introduction

Tower-based eddy-covariance (EC) measurements of the net ecosystem–atmosphere exchange (NEE) of carbon dioxide (CO_2) (hereafter NEE refers to NEE of CO_2) are typically calculated based on the surface layer budget of CO_2 as the sum of a turbulent flux at some height above the vegetation canopy and a storage flux in the underlying air (e.g., Baldocchi et al., 2001; Goulden et al., 1996; Valentini et al., 1996). Heterogeneous surfaces and atmospheric flows, however, can lead to advection and horizontal flux divergences that should be included in a complete measurement of NEE (e.g., Yi et al., 2000). The contribution of horizontal flux divergence to the surface layer budget of a scalar is typically assumed to be negligible because while vertical and horizontal turbulent fluxes can be similar in magnitude, the horizontal scales of flux divergence are usually much larger than the vertical scales except under extreme conditions (Stull, 1988). Vertical and horizontal advection, however, are not always negligible. The inability to conclusively account for advective contributions to NEE measurements remains a significant source of uncertainty for the EC method. This is the case for the one-dimensional atmospheric boundary layer (ABL) budget method that is also usually used to infer NEE (e.g., Denmead et al., 1996; Raupach et al., 1992). Many papers have re-evaluated the advection issue in recent years (Aubinet et al., 2005; Aubinet et al., 2003; Baldocchi et al., 2000; Feigenwinter et al., 2004; Finnigan, 1999; Finnigan et al., 2003; Lee, 1998; Paw U et al., 2000; Staebler and Fitzjarrald, 2004; Yi et al., 2000) either by theory, inference, or direct measurements. In the literature, vertical advection is often estimated by multiplying the mean vertical velocity measured with a sonic anemometer and the difference in CO_2 mixing ratios in the vertical direction (e.g., Aubinet et al., 2003; Baldocchi et al., 2000; Lee, 1998; Paw U et al., 2000) despite debate over whether or not the mean vertical velocity can be measured accurately with standard instruments (e.g., Sun and Mahrt, 1994). On large scales, researchers used atmospheric reanalysis data to estimate the mean vertical velocity and the vertical advection term and successfully interpreted their results (Bakwin et al., 2004; Helliker et al., 2004). It is rather difficult to measure the contribution of horizontal advection to the surface layer budget because horizontal advection of CO_2 is a strong function of spatial scale and surface horizontal heterogeneity usually exists on a variety of scales. Although extensive discussion of the advection issue exists in the literature, direct and comprehensive observations of the contributions of advection and horizontal flux divergence to NEE measurements on various scales are rare. Available datasets or experiments are restricted to address the advective issue only on a particular range of scale or wind direction.

Recently, much attention has been paid to investigating the impacts of advection due to the small-scale drainage flow on NEE measurements under very stable, light wind conditions at night (e.g., Aubinet et al., 2005; Aubinet et al., 2003; Feigenwinter et al., 2004; Staebler and Fitzjarrald, 2004; Yi et al., 2005). In those studies, measurements were designed to capture the local-terrain-induced winds and gradients of CO_2 mixing ratio. The impacts of larger-scale (e.g., 10–10^2 km) land-cover heterogeneity and atmospheric circulations on NEE estimates, however, have not been extensively examined. Under windy conditions, this portion of the advective contribution can be significant while the impacts of small-scale advection can be reduced. Because NEE measurements under turbulent and windy conditions are usually selected to describe nighttime NEE in the literature (e.g., Cook et al., 2004; Davis et al., 2003; Falge et al., 2001; Goulden et al., 1996), it is important to examine the impacts of larger-scale advection (e.g., due to land cover heterogeneity) on one-dimensional NEE estimates. Partially assessing such impacts is the goal of this case study. To achieve the assessment, we quantified the CO_2 budget and assessed likely advective contributions to NEE estimates by using well-calibrated data collected at two towers 20 km apart in a forested area in northern Wisconsin. The influence of small-scale advection (e.g., terrain-induced local drainage flow) particularly on EC NEE estimates cannot be examined using this dataset, but we can demonstrate directly the contribution of advection to the NEE estimates on the scale of 20 km (mainly due to land cover and soil heterogeneities at this site) along the line connecting the two towers. In addition, the data can be used to assess the impacts of surface layer advection on the ABL-budget-based NEE estimates. While limited by the scale of the data and the geography of this particular site, this work represents progress towards a more comprehensive accounting of all terms of the surface layer budget that contribute to the budget-based meteorological observations of carbon fluxes.

2. Experimental site

The study site, located in north-central Wisconsin (http://cheas.psu.edu), contains continuous eddy-covariance flux measurements at the WLEF tower

(45.94587°N, 90.2723°W) situated within a flat but heterogeneous forest landscape. The forest around the WLEF tower includes upland areas occupied by broadleaf deciduous and coniferous tree species (e.g., *Acer saccharum*, *Betula papyrifera*, *Populus tremuloides*, *Populus grandidentata*, *Pinus rubra*, *Abies balsamea*), and lowlands areas occupied by tree species (e.g., *Thuja occidentalis*, *Picea mariana*, *Larix laricina*), shrubs (e.g., *Alnus regosa*, *Salix spp.*), and a variety of grass and sedges species. More details about the vegetation cover can be found in the literature (Burrows et al., 2002; Cook et al., 2004; Davis et al., 2003; Mackay et al., 2002). About 20 km southeast of the tower, mature second-growth northern hardwood forests and aspen of various ages are more common and denser than at the WLEF site. To measure the NEE of CO_2 over this upland forest area, flux measurements at the Willow Creek (WC) tower (45.8087°N, 90.0787°W) were set up in a hardwood stand primarily consisting of 60–80-year-old *Acer saccharum*, *Tilia americana*, and *Fraxinus pennsylvanica* species. The forest understory is sparser at the WC site than at the WLEF site. Most of the soils in the region are composed of similar parent materials (glacial deposits), and the mineral soils in the region are mostly coarse texture sandy loams or loamy sands (Cook et al., 2004). The nighttime fluxes suggest that the soil respiration rates are most likely different at the WLEF and WC sites (Cook et al., 2004; Davis et al., 2003). Fig. 1 presents the locations of the towers and vegetation distribution. Using the observations at the two towers, we can assess advective contributions to the one-dimensional NEE measurements at one of the towers.

At WLEF, vertical flux data are collected at 30, 122, 396 m 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 30 m above the ground and CO_2 mixing ratio data are measured at 0.6, 1.5, 3.0, 7.6, 13.7, 21.3, and 29.6 m above the soil surface. Winds and virtual air temperatures are measured using sonic anemometers (Applied Technologies Inc., Boulder, Colorado, model SATI/3K or Campbell Scientific Inc., Logan, Utah, model CSAT3). CO_2 and water vapor mixing ratios are measured using infrared gas analyzers (IRGA, Li-Cor Inc., Lincoln, Nebraska, model LI-6262). The CO_2 mixing ratio profile at WLEF is measured using two LI-6251s. For this analysis, we use data collected during May through October of 1999 and 2000.

To compare the mixing ratios of CO_2 at the two towers as accurately as possible, the same calibration methodology and data processing techniques are applied at the two towers, based on the work of Bakwin et al. (1998). We used CO_2 standard gases prepared by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL, Boulder, CO, USA), or working standards calibrated using the NOAA/CMDL standards.

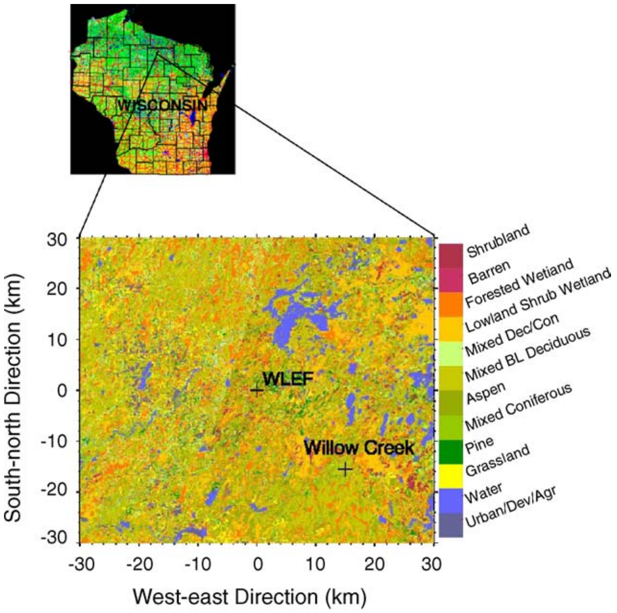

Fig. 1. Locations of the WLEF tower and the Willow Creek tower (plus signs) and land cover (WiDNR, 1998). The distance between the two towers is about 20 km.

Continuous calibration of the IRGA was performed every 30 min with the reference or ‘‘zero gas’’, and approximately every 3 h with a range of three to four standards. The standards were replaced infrequently in the 2 years, reducing the biggest source of systematic errors. Detailed descriptions of the instrumentation, site, and flux calculation methodology of the WLEF tower and the WC tower were presented by Berger et al. (2001) and Cook et al. (2004), respectively.

3. Equations and methods

An expression of NEE in the mean wind direction coordinate can be written:

$$\begin{aligned}\mathrm{NEE} &= F_0 + \int_0^{z_r} \bar{S}\,\mathrm{d}z \\ &= (\overline{w'c'})_{z=z_r} \\ &\quad + \int_0^{z_r}\left[\frac{\partial\bar{c}}{\partial t} + \bar{u}\frac{\partial\bar{c}}{\partial x} + \bar{w}\frac{\partial\bar{c}}{\partial z} + \frac{\partial(\overline{u'c'})}{\partial x} + \frac{\partial(\overline{v'c'})}{\partial y}\right]\mathrm{d}z,\end{aligned} \tag{1}$$

where $\bar{u}$ and $\bar{w}$ are the mean velocity components in the horizontal (x, mean wind direction) and vertical (z) directions, respectively. The mean velocity in the cross-wind direction ($\bar{v}$) is assumed to be zero; F_0 denotes the flux cross the soil–air interface; $\bar{S}$ is a source term; $\bar{c}$ is the mean mixing ratio of CO$_2$; $\overline{u'c'}$, $\overline{v'c'}$, and $\overline{w'c'}$ are the horizontal along-wind turbulent flux, horizontal cross-wind turbulent flux, and vertical turbulent flux of the mixing ratio of CO$_2$, respectively, and z_r is the height of the flux observation. The first term on the far right-hand side of Eq. (1) 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. The integral of the time rate of change is also called the storage flux term. Under the assumption of horizontal homogeneity and no mean wind in the vertical, the expression returns to the one-dimensional format usually seen in the literature (Baldocchi et al., 1996; Cook et al., 2004; Davis et al., 2003; Goulden et al., 1996; Valentini et al., 1996). With z_r being above the boundary layer top, the expression of NEE usually used in the ABL budget method can be derived from Eq. (1) (see Denmead et al., 1996; Raupach et al., 1992). Errors in NEE estimates are introduced by the use of single-point measurements over a heterogeneous surface where the assumption of horizontal homogeneity is violated. Since no natural surface is truly homogeneous, it is important to quantify the magnitude of the error introduced by this simplification on any scales.

The horizontal advection of $\bar{c}$, denoted by H_{adv}, at a height of z is:

$$H_{\mathrm{adv}} = \bar{u}(z)\frac{\partial\bar{c}(z)}{\partial x}. \tag{2}$$

In practice, finite differences are used to approximate the spatial derivative in Eq. (2), e.g.:

$$H_{\mathrm{adv}} \approx \bar{u}_m(z)\frac{\delta_c(z)}{L}, \tag{3}$$

where $\bar{u}_m(z)$ is the mean wind speed of the two measurement points located a distance L apart in the x direction at height z above the surface; $\delta_c(z)$ is the difference between the mixing ratios of CO$_2$ measured at the two points. The finite-difference approximation Eq. (3) serves as a low-pass filter that selectively removes spatial features in the advection field on scales in the x direction much smaller than L and passes spatial features on scales larger than L (e.g., Wyngaard, 2003). From another perspective, the approximation Eq. (3) is roughly equivalent to the spatial average of the horizontal advection over L. For instance, with the mean-value theorem, the spatial average of the horizontal advection over L can be written as:

$$\frac{1}{L}\int_{-L/2}^{L/2}\bar{u}(z)\frac{\partial\bar{c}(z)}{\partial x}\mathrm{d}x = \frac{1}{L}\bar{u}(x_m)\delta_c(z), \tag{4}$$

where x_m lies between the two measurement points assumed to be located at $-L/2$ and $L/2$. As a first approximation, $\bar{u}(x_m)$ can be replaced by $\bar{u}_m$. Therefore, Eqs. (3) and (4) are approximately equivalent (the difference between them is second order).

The same filtering applies to the along-wind horizontal flux divergence term (div) when it is approximated by the difference of the horizontal fluxes measured at the two points, i.e.:

$$\mathrm{div} = -\frac{\partial\overline{u'c'}}{\partial x} \approx -\frac{\delta_{uc}(z)}{L}, \tag{5}$$

where $\delta_{uc}(z)$ is the difference of along-wind horizontal turbulent fluxes measured at the two points. This finite difference approximation exactly represents the spatial averaging of the flux divergence over L because,

$$\frac{1}{L}\int_{-L/2}^{L/2}\frac{\partial\overline{u'c'}(z)}{\partial x}\,\mathrm{d}x=\frac{1}{L}\delta_{uc}(z). \tag{6}$$

The cross-wind flux divergence is not discussed since the cross-wind flux is shown to be much smaller than the along-wind flux (see below).

The vertical advection, denoted by V_{adv}, at height z (Stull, 1988) is:

$$V_{\mathrm{adv}}=\bar{w}(z)\frac{\partial\bar{c}(z)}{\partial z}. \tag{7}$$

It is not easy to estimate this term in practice because the mean vertical velocity is usually small compared to fluctuations of atmospheric vertical motions, and hence it is difficult to measure accurately. Moreover, the vertical velocity measured with a sonic anemometer at the tower might not represent the average over the 20-km scale because the measurement is most likely affected by local topography. Considering these difficulties, the direct measurements of the vertical velocity from the sonic anemometer are not adopted. Alternatively, we use the mean vertical velocity estimated from the hourly Rapid Updated Cycle (RUC) analysis data (Benjamin et al., 2004). The analysis process assimilates many types of observations from (but not limited to) aircrafts, wind profilers, rawinsondes, surface stations, and satellites, providing meteorological fields with the spatial resolution of as high as 20 km and maybe higher in the future (Benjamin et al., 2004). RUC data and other reanalysis data have been successfully used in CO_2 budget studies (Bakwin et al., 2004; Helliker et al., 2004; Wang et al., 2005). In earlier studies, the mean vertical velocity was also estimated to a first approximation only from the along-wind divergence component via the continuity equation or vice versa, and the results were reasonably interpreted (e.g., Baldocchi et al., 2000; Klipp and Mahrt, 2003; Lee, 1998; Mahrt and Vickers, 2005). To examine this approximation at this site, we compare the along-wind divergence component from the two-tower measurements with the total horizontal divergence from the RUC data. The vertical mixing ratio gradient is estimated from the tower measurements. To make the evaluation with more confidence, the vertical advection term is also estimated as a residual of the budget equation of CO_2 mixing ratio using multi-level measurements (CO_2 turbulent fluxes and mixing ratios) at the WLEF tower when the winds blow from the WC tower to the WLEF tower. In this method, the source term is zero above the canopy. This is similar to Yi et al. (2000) except that we use the horizontal advection and flux divergence calculations described above to isolate vertical advection as a residual, rather than solving for all three terms combined.

To estimate the vertical integrals of the advection and flux divergence terms from the surface to z_r in Eq. (1), multilevel measurements at each point are needed below z_r. Considering the complexities and difficulties of field experiments in reality, we use one-level measurements to approximate the integrals in the following evaluation. This approximation approach has been used in similar studies (e.g., Aubinet et al., 2003; Staebler and Fitzjarrald, 2004; Sun and Mahrt, 1994).

4. Data analyses and results

The impacts of vegetation heterogeneity on NEE measurements are more significant in the in-leaf season (approximately from May to September in this region) than in the leafless season of the year. In the leafless season, the difference in CO_2 mixing ratio between the two sites is observed to be almost zero. Therefore, data were selected from the two in-leaf seasons in 1999 and 2000.

4.1. Data selection and meteorological conditions

To estimate the gradients of CO_2 mixing ratios along the connecting line between the two towers, the data were selected when the winds were either from the southeast (SE, wind direction is $135^\circ \pm 22.5^\circ$) or from the northwest (NW, wind direction is $315^\circ \pm 22.5^\circ$). The yearly frequencies of SE and NW winds were about 11.5% and 12.5%, respectively. The corresponding hourly mean wind speeds at 30 m above the grounds were about 3.6 and 3.7 m/s. The wind roses for the two towers were almost the same.

The numbers of day when SE and NW winds blew were 146 and 153, respectively, in the in-leaf seasons during the 2 years. Table 1 shows the number of the periods when a sustained SE or NW wind blew. This analysis was based on hourly averaged winds, and therefore the minimum period for a sustained mean SE

Table 1
Number of periods when SE or NW wind blows for continuous hours, h

Wind direction	$1 \le h \le 2$	$3 \le h \le 4$	$5 \le h \le 12$	$h > 12$
NW	158	56	62	9
SE	168	46	55	7

Note that the minimum period is 1 h.

Table 2
The means for meteorological variables measured at 30 m above the ground at the WLEF tower in the selected period of this study

Wind direction	U (m/s)		T (K)		u_* (m/s)		H (W/m^2)		RH (%)		
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	#
SE	3.94 (0.10)	3.69 (0.11)	289 (0.5)	284 (0.6)	0.49 (0.02)	0.32 (0.02)	71 (6.1)	−22 (2.4)	75 (2)	90 (1)	35
NW	3.96 (0.10)	3.56 (0.16)	288 (0.4)	282 (0.8)	0.53 (0.02)	0.33 (0.03)	43 (7.2)	−13 (1.6)	72 (2)	92 (2)	45

Notes: # denotes the percentage of hours when air is saturated at night. Night is between 22:00 and 5:00 local time (LT). Day is between 6:00 and 21:00 LT. U, T, u_*, H, and RH represent wind speed, air temperature, friction velocity, sensible heat flux, and relative humidity, respectively. The numbers in the parentheses are the standard deviations of the corresponding variables. The number of samples for each wind direction is approximately 60 for nighttime, and 180 for daytime.

or NW wind was 1 h. Note that, because multiple periods of sustained SE or NW winds may occur during the same day, the total number of SE or NW wind periods in the table exceeds that of the days.

To ensure that the two towers measure the same fields of wind and CO_2 mixing ratios, we selected periods during which SE or NW winds were sustained for 5 h or longer (note that longer duration is better, but less data are available). Weather map analyses indicated that most of the selected periods were associated with large-scale synoptic systems, and hence the sustained winds blew across large spatial scales. For example, a low pressure system located southwest of the sites was slowly moving eastward during 3–5 May 1999, resulting in a sustained SE wind on the spatial scale of more than 1000 km for 24 h. In this case, the towers 20 km apart measured the same meteorological fields and wind directions at the two towers did not vary much. Further, the periods of sustained winds eliminated the periods when winds were calm (wind speed at 30 m < 2 m/s) or the atmosphere was very stable (u_* measured at 30 m < 0.1 m/s). With the duration of 5 h and longer under windy conditions, the towers sampled the same flow and CO_2 at one site can be transported to another site. Local drainage flows or other microscale phenomena, not captured by our two towers separated by 20 km, were most likely to be important contributors to the surface layer CO_2 budget during very calm conditions.

Table 2 summarizes the mean values of some meteorological variables for the NW and SE wind directions measured at the 30 m level of the WLEF tower. On average, the weather was warmer and drier when the winds come from SE than from NW.

4.2. 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 400 m of the atmosphere over the forest (Fig. 2), indicating that the ABL is well mixed. The diurnal variation in the difference of CO_2 mixing ratio between 30 and 11 m at the WLEF tower is similar to that between 29.6 and 13.7 m at the WC tower. 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 (Fig. 2), implying 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.

In the in-leaf season, horizontal gradients of the mean mixing ratios of CO_2 exist, depending on time of day and wind direction (Fig. 3). For the SE wind direction, the difference in the mean mixing ratio of CO_2 is generally larger at night than in the day (Fig. 3a). The difference suggests that the contribution of horizontal advection might be significant in estimating the NEE. For the NW wind direction, the horizontal difference in mixing ratio is smaller. The dependence of the gradients on wind direction is probably caused in part by the weather accompanying the winds and local spatial patterns in NEE. Since the weather accompanying NW winds is on average cloudier, more humid,

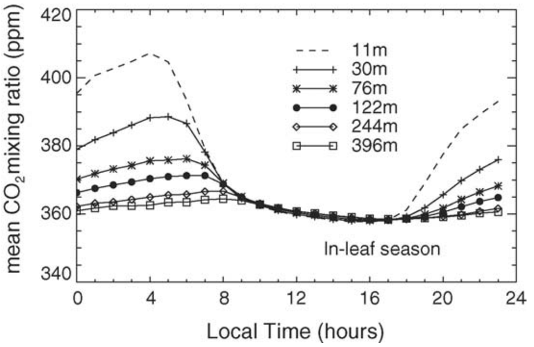

Fig. 2. Distributions of diurnal CO_2 mean mixing ratio at 11, 30, 76, 122, 244, and 396 m above the ground at the WLEF tower during May through October 1999 and 2000.

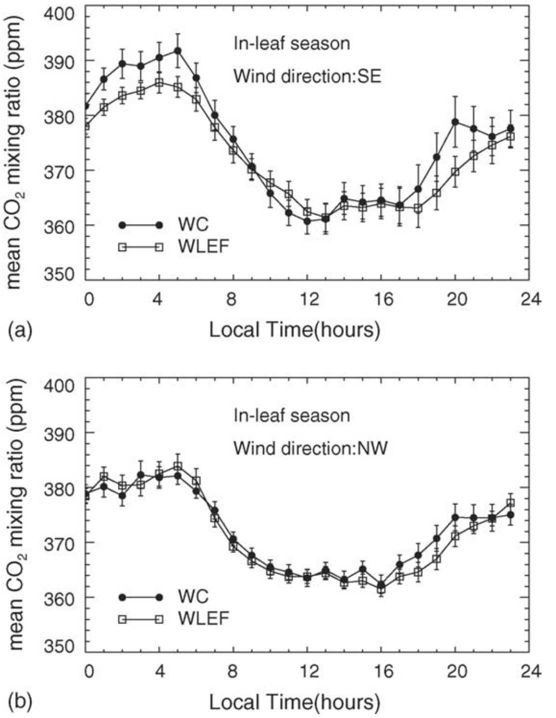

Fig. 3. Comparisons of the diurnal patterns of mean CO_2 mixing ratio at 30 m above the ground from the WLEF tower (open squares) and WC tower (filled circles) with SE (a) and NW (b) winds occurring in the in-leaf season. The vertical bars denote the standard errors.

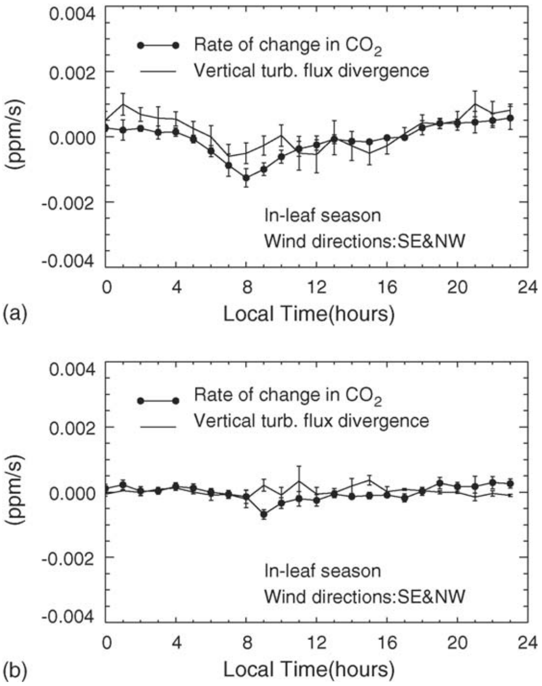

Fig. 4. Comparisons of the diurnal pattern of the time rate of change in CO_2 mixing ratio (filled circles) and the vertical turbulent flux divergence (solid line) in the air layer between 30 and 122 m (a), 122 and 396 m (b) from the WLEF tower when sustained SE or NW winds blow. The vertical bars denote the standard errors.

cooler, and less stable (Table 2), for instance, it is likely that the magnitude of the surface flux heterogeneity across the region was suppressed. Another possible reason to explain the direction-dependence is that the distribution of surface sources is a function of direction; this cannot be addressed further since relevant data are unavailable.

Instrumental offset in the CO_2 mixing ratio measurements is ruled out as a likely cause of the observed patterns in Figs. 2 and 3 since the vertical gradient measurements are made, in fact, with a single IRGA that samples air from multiple inlets using an automated switching mechanism (Bakwin et al., 1998). The two towers use different IRGAs and calibration gases, thus offsets between towers are likely. But data analyses suggest that such offsets are not significant because an offset of this sort would not depend upon wind direction. Further, the two tower CO_2 measurements were compared during winter months when spatial gradients, both vertical and horizontal, are very small. The mean of 4 months of data showed a mean mixing ratio difference of -0.34 ± 0.27 ppm where the error bound represents the standard error of 620 hourly data points.

4.3. One-dimensional CO_2 mixing ratio budget

The assumption of horizontal homogeneity 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 the mean mixing ratio of CO_2 $(\partial\bar{c}/\partial t)$ should be balanced by vertical turbulence flux divergence $(-\partial\overline{w'c'}/\partial z)$. Fig. 4 examines this assumption using data from the WLEF tower. In the air layer between 30 and 122 m, the two terms are closer in the day than at night (Fig. 4a), suggesting that (total) advection and horizontal flux divergence are smaller in the day than at night. The two terms are better balanced in the layer of 122–396 m (Fig. 4b), implying that the impact of surface heterogeneity on the scalar budget is less significant at higher altitudes.

4.4. Horizontal flux divergence

The NEE equation (Eq. (1)) includes a cross-wind $(-\partial\overline{v'c'}/\partial y)$ and an along-wind horizontal flux divergence term $(-\partial\overline{u'c'}/\partial x)$. Fig. 5 shows that the magnitude of $\overline{u'c'}$, about 1 ppm m/s, is one order

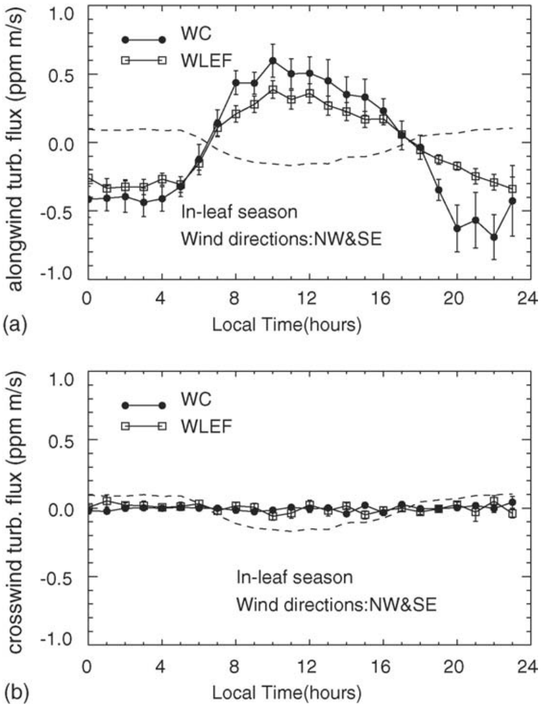

Fig. 5. Diurnal patterns of $\overline{u'c'}$ (a) and $\overline{v'c'}$ (b) at 30 m above the ground from the WLEF tower (open squares) and the WC tower (filled circles) with sustained SE or NW winds occurring in the in-leaf season. As a comparison, $\overline{w'c'}$ (dashed line) at the WLEF tower is shown.

greater than that of $\overline{v'c'}$ (about 0.1 ppm m/s) and approximately three to five times greater than the vertical turbulent flux, $\overline{w'c'}$ (0.1–0.3 ppm m/s). 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. 5). Due to the small magnitude of $\overline{v'c'}$, the crosswind horizontal flux divergence is most likely smaller than the along-wind horizontal flux divergence. Therefore, we estimate only the magnitude of the latter.

It is somewhat difficult to calculate the contribution of the vertically integrated horizontal flux divergence terms to the NEE estimates in Eq. (1) because we do not have flux measurements at all heights from the surface to height z_r. The contribution of those terms, however, can be estimated by using a scaling argument. In Eq. (1), the order of the integrated horizontal flux divergence terms on the scale of L can be estimated as,

$$\int_0^{z_r} (\mathrm{div})\,\mathrm{d}z = \int_0^{z_r}\left[\frac{\delta_{uc}(z)}{L}\right]\mathrm{d}z = z_r\left\langle \frac{\delta_{uc}(z)}{L}\right\rangle < \frac{z_r \mathrm{O}(\overline{u'c'})}{L}, \qquad (8)$$

where the angle bracket denotes the vertical average from the surface to the sensor level (also called layer-average), and $\mathrm{O}(\overline{u'c'})$ is the order of $\overline{u'c'}$. As a first approximation, the horizontal turbulent fluxes measured at 30 m from the two towers are used to estimate (8). For the data used here, L is the distance between the two towers, z_r is 30 m. $\mathrm{O}(\overline{u'c'})$ is 1 ppm m/s (Fig. 5). Therefore, the order of the contribution of horizontal flux divergence term is estimated to be about 1.5×10^{-3} ppm m/s, much smaller than the order of the vertical turbulent flux term, 0.1–0.3 ppm m/s (Fig. 5), indicating that the contribution of the horizontal flux divergence to NEE measurements can be neglected for the horizontal length scale of 20 km.

The contribution of horizontal flux divergence, however, may not always be negligible, depending on both the scale of surface heterogeneity and the spatial scale of interest. For example, experiments indicated that the horizontal variation of turbulent fluxes could reach about 30% of the magnitude of the fluxes over a horizontal distance of about 100 m in a forested area (e.g., Smith et al., 1985). In this case, if the scale of interest is of the order of 100 m, the contribution of the flux divergence might be significant. Staebler and Fitzjarrald (2004) also conducted a similar evaluation. Practically, the contribution of horizontal flux divergence can be negligible if the measurement height is small compared to the dominant scale of surface heterogeneity or the horizontal scale of interest (e.g., $z_r/L \ll 1$, see Eq. (8) and note that the scale analysis probably overestimates the divergence term since the horizontal turbulent flux normally contains a large horizontally invariant part).

4.5. Horizontal advection

The contribution of the horizontal advection, also called the horizontal advective flux hereafter, on the scale of L is:

$$\int_0^{z_r} \bar{u}\frac{\partial \bar{c}}{\partial x}\mathrm{d}z = z_r\left\langle \bar{u}(z)\frac{\partial \bar{c}(z)}{\partial x}\right\rangle = z_r\left\langle \bar{u}(z)\frac{\delta_c(z)}{L}\right\rangle. \qquad (9)$$

Because only the data at 30 m above the surface are available to calculate the horizontal advection term (Eq. (3)), the vertically averaged horizontal advection has to be estimated using the one-level measurements as usually done in the literature (Aubinet et al., 2003; Staebler and Fitzjarrald, 2004; Sun and Mahrt, 1994). Sun and Mahrt (1994) estimated the layer-averaged horizontal advection as 60% of the advection term computed at their aircraft level (33 m) 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. Aubinet et al. (2003) also used measurements at one level to estimate the advective flux by introducing a scaling height. Staebler and Fitzjarrald (2004) introduced a similarity hypothesis and calculated a shape factor from the single-location vertical profile measurements. Considering the limits of the data used, we estimate the advective flux as follows:

$$\int_0^{z_\mathrm{r}} \bar{u}\frac{\partial \bar{c}}{\partial x}\mathrm{d}z = z_\mathrm{r}\left\langle \bar{u}(z)\frac{\delta_c(z)}{L}\right\rangle = \bar{u}(z_\mathrm{r})\frac{\delta_c(z_\mathrm{r})}{L} z_\mathrm{r} f_\mathrm{h}, \qquad (10)$$

where f_h is a shape factor defined as:

$$f_\mathrm{h} = \frac{\int_d^{z_\mathrm{r}} \bar{u}(z)\bar{c}(z)\mathrm{d}z}{z_\mathrm{r}\bar{u}(z_\mathrm{r})\bar{c}(z_\mathrm{r})} + \frac{\int_0^{d} \bar{u}(z)\bar{c}(z)\mathrm{d}z}{z_\mathrm{r}\bar{u}(z_\mathrm{r})\bar{c}(z_\mathrm{r})}, \qquad (11)$$

where d is the zero-plane displacement height (15 m) that is used to characterize the overall effects of the canopies (Stull, 1988). The above-d component of the factor f_h (i.e., the first term on the right-hand side) is estimated by the vertical profiles of $\bar{u}$ and $\bar{c}$ in the layer between the displacement height and z_r based on the flux–profile relationship as a first approximation. The variables used in the calculation such as the momentum flux, CO_2 vertical turbulent flux, heat flux, air temperature, wind speed, and the mixing ratio of CO_2 are directly measured at 30 m above the ground. We did not use the similarity hypothesis introduced by Staebler and Fitzjarrald (2004) because the canopy structures such as the forest types and densities at the two tower sites are different. Since the wind speed below d is not really zero and the CO_2 mixing ratio may be large near the ground, we evaluated the near-ground component of f_h to a first approximation using the CO_2 and wind speed profile measurements below d at the WC tower. With the near-ground component of f_h that is about 0.08 being considered, the shape factor ranges from 0.28 to 0.53, depending largely on atmospheric stability.

Fig. 6 shows the diurnal patterns of the horizontal advective flux when sustained SE and NW winds blow, respectively. When the SE winds blow (i.e., from the WC tower to the WLEF tower), the contribution of the horizontal advection to NEE measurements at the WLEF site can be estimated. In this case, the horizontal advective flux is larger at night than in the day. The typical magnitudes of the horizontal advective flux are about 0.002 and 0.01 ppm m/s in the day and at night, respectively (Fig. 6a). A typical magnitude of the nighttime vertical turbulent flux of CO_2 mixing ratio at 30 m at the WLEF site is observed to be about 0.1 ppm m/s (Fig. 5). 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 measurements at night is approximately −0.01 ppm m/s, implying that the true NEE (respiration rate) is overestimated by about 10% due to the neglect of the horizontal advection term. In the day, the contribution of the horizontal advective flux (about 0.002 ppm m/s) is negligible compared to the vertical turbulent flux term (about −0.15 ppm m/s, Fig. 5). When the winds blow from NW (i.e., from the WLEF tower to the WC tower), the magnitudes of horizontal advective fluxes (Fig. 6b) are overall smaller than those when the winds are from SE due to smaller horizontal gradients (Fig. 3b). The horizontal advective fluxes have the same magnitude, about 0.002 ppm m/s, both at night and in the day. The magnitudes of the vertical turbulent fluxes at the WC site are about 0.3 and 0.2 ppm m/s in the day and at night, respectively. Therefore, the contribution of the horizontal advection to NEE measurements at the WC site is not significant on the scale of 20 km when airflows come from NW. Despite this, we do not rule out the possibility that the advective

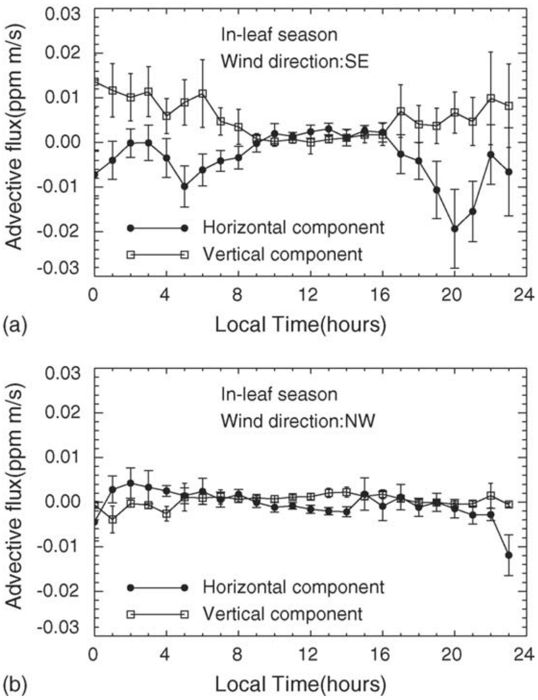

Fig. 6. The diurnal patterns of the horizontal (filled circles) and vertical (open squares) advective fluxes (see the text) in the in-leaf season when sustained SE (a) or NW (b) winds blow. The vertical bars denote the standard errors.

fluxes could be significant on the scales smaller than 20 km since the horizontal advection term is strongly dependent on spatial scales.

4.6. Vertical advection

As a comparison, we evaluate the vertical component of the advective flux on the similar scale. The vertical advective flux is estimated based on the vertical gradient of the CO_2 mixing ratio measured at one level due to the same difficulty mentioned in the previous section. The vertical advective flux can be written as:

$$\int_0^{z_r} \bar{w}\frac{\partial \bar{c}}{\partial z}\mathrm{d}z = z_r\left\langle \bar{w}\frac{\partial \bar{c}}{\partial z}\right\rangle = f_v z_r\left(\bar{w}(z_r)\frac{\Delta\bar{c}(z_r)}{\Delta z}\right), \tag{12}$$

where $\Delta\bar{c}$ represents the difference of $\bar{c}$ over the distance Δz in the vertical direction; f_v is similar to f_h in Eq. (10), i.e., the ratio of the layer-averaged vertical advection to the vertical advection at height z_r, determined by the vertical profiles of $\bar{w}$ and $\bar{c}$ between the surface and z_r. Due to the lack of the profile data, the values of f_v are approximated by those of f_h calculated in Section 4.5.

The diurnal patterns of the vertical advective fluxes are also shown in Fig. 6 for comparison. In the calculation of the vertical advection term at height z_r, the mean vertical velocity is estimated from the RUC reanalysis data as described in Section 3, and the average of the vertical gradients of the mixing ratio of CO_2 measured at the two towers is used for each hour. When SE winds blow, the magnitude of the vertical advective flux is larger at night than in the day, as a result of the larger vertical gradient of the mixing ratio of CO_2 in the nighttime ABL (Fig. 2). The contribution of vertical advection is negligible compared to the vertical turbulent flux in the day, similar to that of horizontal advection. At night, the advective flux is of order of 0.01 ppm m/s, approximately 10% of NEE. When NW winds blow, the magnitude of the vertical advective flux is generally smaller than that when SE winds blow. This is mostly due to the fact that the vertical gradients of the mixing ratio of CO_2 are observed to be smaller when NW winds blow than when SE winds blow. In this case, the vertical advective flux is small compared to the vertical turbulent flux.

In addition, we find in Fig. 6 that the vertical and horizontal advective fluxes generally have opposite signs, suggesting that their impacts on NEE measurements partly compensate (Aubinet et al., 2005; Aubinet et al., 2003; Feigenwinter et al., 2004). Theoretically, the relationship between the vertical and horizontal components of the advective flux depends on the spatial patterns of the airflow and CO_2 mixing ratio distribution fields that can vary with sites. The RUC data suggest that persistent horizontal divergence and convergence exist near the surface when the winds are from SE and NW, respectively, during the selected period in this study. We also calculate the along-wind divergence component using the horizontal wind speeds at 30 m of the two towers when SE or NW winds blow, and find that the along-wind divergence component accounts approximately for 80% of the total horizontal divergence (from the RUC data) during the selected period. At this site, the mean pattern of the airflow could be due in part to a horizontal gradient of surface roughness, for instance. The upland forests near the WC tower are likely characterized by greater roughness length than the lower-stature mixed forests and wetland near the WLEF tower, possibly resulting in divergence and convergence in the tower area when wind directions are SE and NW, respectively. The vertical and horizontal patterns of the mean CO_2 mixing ratio distribution field are shown in Figs. 2 and 3, respectively. The patterns of mean airflow and mixing ratio fields lead to the opposite impacts of the two components of the advective flux to NEE estimates in the study site, implying that both components need to be taken into account when the budget is assessed.

The magnitude of the vertical advection term from the residual method (see Section 3) is of the same order as the above result, but the former is generally about two to three times as large as the latter. Both of them are in reasonable agreement, but we cannot tell which one is more reliable because each method has its limitations. For example, in the residual method, the residual term aggregates all of the errors in the other terms, possibly resulting in large uncertainties in the estimate. The mean vertical velocity from the RUC data represents an average over the grid area. Therefore, we average the results from the two methods as an estimate of the vertical advection term at z_r as a compromise. With Eq. (12), the vertical advective flux at night is overall about 20% of nighttime NEE when the SE winds blow.

4.7. Implications

The impacts of horizontal advection on NEE estimates occur on a variety of scales, making it difficult to conduct measurements in the field. Under light wind and very stable conditions, the small-scale advection such as the local drainage flow dominates. The advective impacts can be as large as, or even larger than the magnitude of NEE according to earlier studies in the literature (e.g., Aubinet et al., 2005; Aubinet et al., 2003; Feigenwinter et al., 2004). As a result, one-dimensional EC measurements are usually screened out under the very stable conditions to avoid possible significant bias estimates of NEE. Instead, nighttime NEE is described and modeled by one-dimensional EC measurements under turbulent and windy conditions (e.g., Cook et al., 2004; Davis et al., 2003; Falge et al., 2001; Goulden et al., 1996). In this case, the impacts of the larger-scale horizontal advection may increase even at relatively flat sites due to the heterogeneous distribution of vegetation and soil types. Our evaluations suggest that the horizontal advective contribution to NEE measurements can be as large as 10% of the magnitude of NEE at night on the 20 km scale at this site. In other words, an error of about 10% of the magnitude of NEE is possible due to the neglect of the effects of horizontal advection; this may deserve attention when nighttime EC NEE measurements are interpreted. More assessments on other scales are needed.

In addition, the analyses provide direct evidence of advective impacts on NEE estimates using the ABL budget method since the method is usually applied on the similar spatial scale to this study. Our calculations suggest that contributions of both advection terms within the surface layer can be negligible in the day on the 20-km scale at this site; this is usually assumed in the ABL budget method. This assumption is supported by this study. In contrast, when the ABL budget method is applied at night, both the horizontal and vertical advection terms are significant even only within the surface layer, making the budget method difficult to apply in the nocturnal boundary layer, particularly for short time scales.

5. Discussion and conclusions

We examined the CO_2 budget of the surface layer on the scale of 20 km in a forested area of northern Wisconsin as a case study. The data measured at two towers are selected when the sustained SE or NW winds, i.e., along the axis connecting the two towers, blew continuously for five or more hours during the in-leaf seasons in 1999 and 2000. On the scale of 20 km, the horizontal flux divergence term is negligible compared to the vertical turbulent flux term. The horizontal and vertical advection terms are negligible in the day. They can, however, be significant at night. The diurnal patterns of the advective fluxes depend on wind direction. The budget analyses also suggest that the vertical and horizontal components of advection generally have opposite signs at this site when sustained SE or NW winds blow. Therefore, the effects of the two components partly compensate, implying that only including one of them could lead to additional uncertainties in the budget calculation at this site. The neglect of the contribution of the nighttime horizontal advection can overestimate nighttime NEE by as large as 10% on the 20 km scale when the sustained SE winds blow. However, the neglect of the contribution of the nighttime vertical advection might result in an underestimate of the NEE by about 20% for the same wind direction, although this estimate has a large uncertainty. The contribution of advection is negligible when the winds are from NW.

Due to limits of the data used, the budget calculations in this study are made only on the specified scale under two specific wind directions. It should be noted that the advective impacts might not dominate on the scale of 20 km under windy conditions at this site since the measurements are not designed specifically for the study of advection. The evaluation of the advective impacts is still incomplete. We are uncertain about whether the advective fluxes are significant or not on the scales smaller than 20 km from this dataset and we cannot estimate them in other wind directions. In addition, there are deficiencies in our estimates of the advection terms. For example, errors in the CO_2 mixing ratio, wind speed, and mean vertical velocity are sources of uncertainty in our estimates. Approximations are made to estimate the integrals from the surface to the measurement level, resulting in additional errors. Nevertheless, our analyses from the limited data do imply that the neglect of the impact of advection may also lead to errors in one-dimensional EC NEE measurements even at relatively flat sites due to the heterogeneous distribution of land cover, or soil, or both; this issue has not been much studied yet in the literature and might deserve further investigation. The analyses also provide direct evidence that the advective contributions within the surface layer can be negligible when the ABL budget method is applied to inferring NEE (on the scales of about tens of km) in the day. However, this is not the case at night.

The nighttime advective issue is still challenging the carbon research community. More comprehensive evaluations of the advective effects require measurements with a higher spatial resolution, theoretical research, and model developments. In order to more completely address advective influences on long-term NEE measurements and their dependences on spatial scales and atmospheric variables, two- or threedimensional measurement systems are probably required, in particular over complex terrain. Examples include the experiments in Aubinet et al. (2005), Feigenwinter et al. (2004), and Staebler and Fitzjarrald (2004). Alternatively, nighttime NEE or advective effects can be constrained by a combination of approaches on multiple scales such as ecophysiological measurements, micrometeorological measurements, and coupled ecosystem–atmosphere mesoscale modeling (Baldocchi, 2003). Successful assessment of NEE over heterogeneous surface or complex terrain will require a particularly rigorous approach of intensive measurements and modeling.

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