

## Research note

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# Nocturnal CO<sub>2</sub> exchange over a tall forest canopy associated with intermittent low-level jet activity

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With 2 Figures

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## Summary

Nocturnal eddy-covariance carbon dioxide fluxes have uncertainties arising from non-stationary atmospheric processes. Low-level jets (LLJ) are one of the prominent nocturnal boundary-layer phenomena observed over non-mountainous terrain, and are capable of generating shear and turbulence close to the ground. The influence of intermittent LLJ activity on nocturnal carbon dioxide exchange measurements is investigated using wind profile observations and eddy-covariance flux measurements over a tall forest canopy. Results suggest that the buildup and venting of CO<sub>2</sub> are closely associated with LLJ activity during the night. Of significance in quantifying nocturnal fluxes, this paper demonstrates how low-level jet activity introduces sporadic coupling between the canopy and the atmosphere.

## 1. Introduction

Since nighttime CO<sub>2</sub> respiration is a major component of the carbon balance, and an accurate estimation of the nocturnal flux of CO<sub>2</sub> is crucial to understand the role of forest ecosystems in sequestering carbon. Proper quantification of nocturnal respiration is challenging, as nights are

often characterized by non-stationary atmospheric conditions, periods of intermittent vertical mixing, flow decoupling, presence of low-level jets (LLJ), and canopy or gravity waves. Several studies have reported that nighttime eddy-covariance CO<sub>2</sub> fluxes are often underestimated due to these complexities and may lead to systematic errors in long-term carbon budgets (e.g. Goulden et al., 1996; Black et al., 2000; Falge et al., 2001; Baldocchi, 2002; Massman and Lee, 2002; Aubinet et al., 2003). The magnitude of the errors is site-dependent with reported values varying between 5 and 50% (Schmid et al., 2000; Aubinet et al., 2002).

Filtering and correction procedures accounts for nighttime fluxes in weak mixing conditions are the subject of active investigation. Ongoing discussions are centered on the determination of a correct friction velocity ( $u_*$ ) threshold and on the methodology of corrections, i.e. whether all fluxes measured below a  $u_*$  threshold are replaced with fluxes obtained during well-mixed conditions, or corrected before or after accounting for the storage term (Falge et al., 2001; Aubinet

et al., 2002; Carrara et al., 2003; Saleska et al., 2003; Hollinger et al., 2004; Gu et al., 2005). A consensus is yet to be reached on this subject. In this regard, it is important to understand site-specific atmospheric processes responsible for observed turbulence and fluxes as this information is invaluable to correct and interpret net ecosystem exchange (NEE) measurements.

Site characteristics and mesoscale processes play a crucial role in the observed turbulence and flow features in the lower boundary-layer, especially in nocturnal periods. Low-level maxima in the wind speed profile, known as LLJs, are important nocturnal boundary-layer phenomena over flat terrain. Blackadar (1957) suggested that the LLJs, are associated with flow decoupling resulting from surface cooling leading to an acceleration of the flow above that layer. Stull (1988, p. 521) has listed several other processes known to cause LLJs. Several studies have indicated that LLJs are capable of generating and modifying both shear and turbulence, and thus influencing both the mixing and transport of gases (Smedman et al., 1988; Corsmeier et al., 1997; Banta et al., 1998; Mahrt, 1999; Banta et al., 2002; Mahrt and Vickers, 2002). In the application of the nocturnal boundary-layer budget technique, Mathieu et al. (2005) noticed that the presence of a low-level jet leads to confinement of gases within the nocturnal boundary-layer (NBL) thus providing the sine qua non conditions required to calculate the nocturnal fluxes using the NBL budget technique.

Regardless of the known potential of LLJs in controlling surface-atmosphere exchange at night, the association between observed CO<sub>2</sub> fluxes and LLJs has not yet been examined systematically. This may be mainly due to the fact that, at most flux sites, observations are limited to tower measurements a few meters above the canopy top, whereas LLJ observations often require measurements up to several hundred meters. The present study is based on the analysis of sodar and eddy-covariance measurements performed over a tall forest canopy at the Florida AmeriFlux site. Features of a night with sporadic LLJ activity are discussed. The study addresses the buildup and flushing out of CO<sub>2</sub> in the canopy volume in the presence of intermittent jet activity and its effect on eddy-covariance CO<sub>2</sub> fluxes.

## 2. Experiment and data analysis

The data used for the study was collected at the Florida AmeriFlux site (29° 45' N, 82° 10' W) located 10 km northeast of Gainesville, Florida, as a part of a micrometeorological experiment conducted during April–June, 2004. The terrain at the site is flat. The measurements were carried out at a managed slash pine (*Pinus elliottii* Engelm. var. *elliottii*) plantation with an average tree height (h) of 13.5 m. Additional site details can be found in Clark et al. (2004). A 30 m tall walkup tower was instrumented with three-dimensional sonic anemometers at fifteen levels (seven model CSAT3 ultrasonic anemometers, Campbell Scientific Inc., Logan, UT, USA and eight model 81000 ultrasonic anemometers, RM Young Inc., Michigan, USA), Krypton hygrometers (KH20, Campbell Scientific Inc., Logan, UT, USA) and CO<sub>2</sub>/H<sub>2</sub>O open-path analyzers (Li-7500, LI-COR Inc., Lincoln, NE, USA) at four levels. The data were sampled at 10 Hz using a data acquisition system involving CR5000/CR9000 dataloggers (Campbell Scientific Inc., Logan, UT, USA), wireless communication system and a personal computer. Supporting measurements of net radiation (Model NR LITE, Kipp and Zonen USA Inc., Bohemia, NY, USA), wind speed and direction (Model 034B, Met One Instruments Inc., Oregon, USA), air temperature and relative humidity (Model HMP45C, Campbell Scient. Inc., Logan, UT) were conducted above the canopy at 1.4 h and half-hourly mean values were stored on a datalogger (CR10X, Campbell Scientific Inc., Logan, UT, USA).

A boundary-layer sodar (Model PA2, Remtech Inc., France) was deployed approximately 500 m away on the west side of the flux tower in a clear area surrounded by 3 m tall pine trees. The sodar was operated continuously throughout the measurement period. 30 min profiles of average wind speed, direction, and standard deviations of three-dimensional velocity components up to 1000 m with 10 m resolution were saved on a laptop computer dedicated to control sodar operations and data collection.

The night of June 25–26, 2004 is characterized by an intermittent LLJ and was chosen for analysis. The planar-fit method (Wilczak et al., 2001) is applied for tilt correction using coefficients estimated from the three-measured velocity

components  $u$ ,  $v$  and  $w$  during the three-month (April–June, 2004) period. Eddy-covariance fluxes are estimated following spike removal (Vickers and Mahrt, 1997), linear de-trending (Rannik and Vesala, 1999) of the data, and density corrections (CO<sub>2</sub> fluxes) based on Webb et al. (1980). To minimize the effect of non-stationarity associated with intermittent turbulence, shorter averaging periods of 15-min duration are used instead of 30-min for processing data obtained during turbulent periods immediately after calm periods.

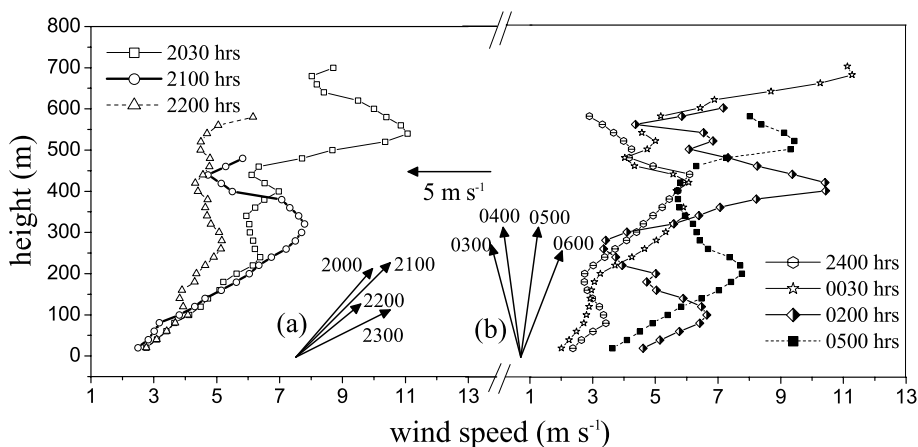
### 3. Results and discussion

Jets of varying strength, duration, and heights are noticed in sodar observations on several nights during the three-month period of the campaign. Many of the nights examined exhibit strong and mostly uniform jet activity throughout, whereas, on some other nights, the jets are of moderate or weak strength and are intermittent. Double windspeed maxima are often noticed in this category with the first maximum within 80 to 200 m above the surface and the second above 400 m. The night of 25–26 June analyzed here belongs to the second category. Alternating periods of calm and turbulent conditions are observed within and above the canopy, coupled with the sporadic jet activity.

Hodographs of the observed wind at the jet core during two episodes (Fig. 1, marked as ‘a’ and ‘b’) show clockwise turning of the wind vector with time, indicating inertial oscillation coupled with static stability and frictional decoupling (Blackadar, 1957; Corsmeier et al., 1997) as plausible mechanism for the formation of

LLJ on this night. Periods between these two episodes (2230–0030) characterize weakening of the jet and intermittent activity. Selected periods of sodar wind profiles during this night are presented in Fig. 1. Important features of the jet activity are summarized in Table 1. Atmospheric stability values characterized by the stability parameter  $((z - d)/L)$ , with  $d$  as the displacement height,  $L$  the Obukhov length calculated from sonic anemometer measurements at  $z = 1.4$  h are also presented in Table 1. As seen in the Table, stability is closely coupled to the intermittency of the jet. The wind shear at the lower levels also exhibited considerable variation throughout the night. Turbulence and CO<sub>2</sub> measurements within and above the forest canopy suggest that this night is characterized by periods of intermittent turbulence and mixing.

Time series of  $w$  together with  $u_*$  at 1.4 h and CO<sub>2</sub> concentrations at 1 h, 1.4 h and 2.1 h are shown in Fig. 2a and b. Early evening hours are characterized by mixing attributed to near-neutral to lightly stable atmospheric conditions above the canopy. This period is followed by sporadic jet activity of varying strength and duration. It is reflected in changes in  $w$ ,  $u_*$  and CO<sub>2</sub> concentrations. Friction velocities are small in general and drop below  $0.2 \text{ m s}^{-1}$  after 2030 hrs and remain low throughout the night, except during periods with jet activity. Three spells of enhanced turbulence and mixing following periods of calm conditions are observed in the time series and are denoted as I, II and III in the Fig. 2. From these observations, the influence of jets is evident at the canopy level nearly thirty percent of the night. It is also noticed that the increased shear initially enhances the turbulence close to



**Fig. 1.** Sodar observations of wind profiles on selected periods, 25–26 June. (a) and (b) are the hodograph of the observed wind at the jet heights corresponding to two jet episodes during evening and early morning hours

**Table 1.** Jet height, wind speed at the jet height and mean shear below 100 m inferred from sodar measurements on 25–26 June, 2004. Stability  $(z - d)/L$  is estimated from the sonic anemometer measurements at 1.4 h

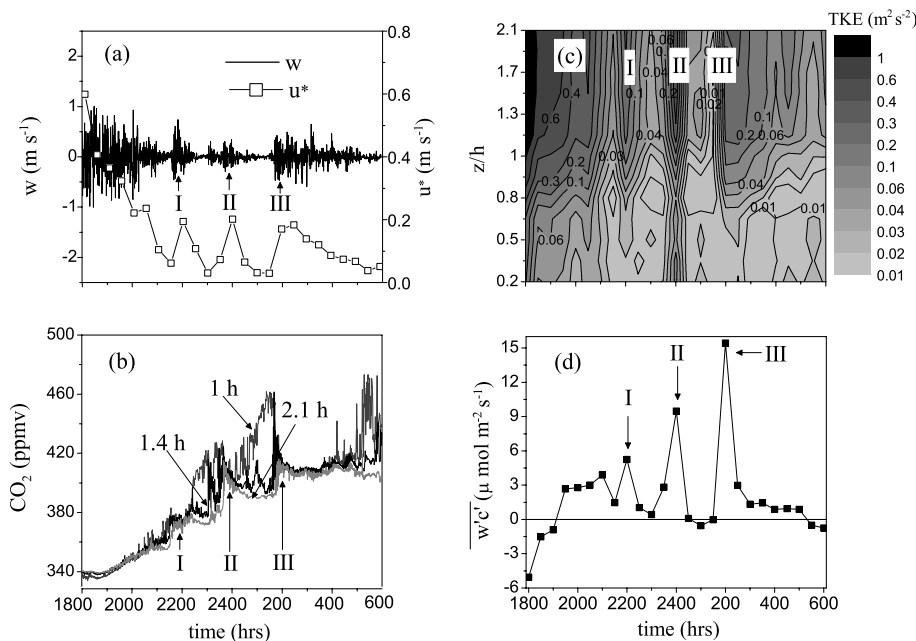
Periods (hrs)	Jet height (m)	Wind speed at the jet height ( $\text{m s}^{-1}$ )	Mean wind shear in the 20–100 m layer ( $\text{s}^{-1}$ )	Stability $(z - d)/L$
2030	240	6.4	0.017	0.10
2100	320	7.8	0.015	0.50
2200	280	5.2	0.017	0.15
2330	220	5.6	0.008	1.5
2400	80	3.5	0.020	0.1
0030	340	6.0	0.011	0.4
0200	100	6.7	0.030	0.2
0500	200	7.8	0.022	1.3

the canopy, which enacts to gradually reduce the strength of the jet.

During 2030–2130, calm conditions ( $u_* < 0.1 \text{ m s}^{-1}$ ) prevail at the lower levels though a jet peak existed above 300 m. The observed shear is also very low during this period (Table 1). Close to 2200, the wind speed at the lower levels increase slightly along with a downward shift in jet height (Fig. 1) and a slight increase in shear. This period (marked as I in Fig. 2) exhibits moderate mixing, which again weakens after a short duration. After 2230, calm conditions exist at the lower levels for about 45 min. During this period, the canopy-top concentration increases by about

40 ppmv, whereas the two higher-level concentrations remain nearly the same due to negligible vertical mixing. This is followed by a period characterized by a weak wind maximum close to 80 m (Fig. 1) and a corresponding turbulent period before 2400, as evident in Fig. 2a and b (marked as II). The mixing introduced during this period causes the canopy top  $\text{CO}_2$  concentration to drop and the two upper level concentrations to rise. Very calm conditions exist shortly after 2400 until about 0130 and the canopy top concentration increases up to 460 ppmv, maintaining a large gradient with the 1.4 h and 2.1 h levels.

This calm period is followed by a well-mixed period attributed to the development of the jet activity during 0130–0200, with the core of the jet around 100 m (Fig. 1). At the beginning of this period (marked as III in Fig. 2), the  $\text{CO}_2$  concentration at the canopy top drops sharply by about 60 ppmv and higher-level concentrations increase slightly as a result of vertical mixing, eliminating large gradients between levels. During subsequent hours, the jet nose moves up gradually, resulting in a reduction in the wind speeds at the lower levels. This is reflected in the  $w$  and  $\text{CO}_2$  time series showing a gradual weakening of turbulence and mixing during the early morning hours (0300–0600). These features are evidence that when jets introduce turbulence and mixing following calm conditions,



**Fig. 2.** Time series of **a)** vertical velocity ( $w$ ) and estimated friction velocity at 1.4 h, **b)**  $\text{CO}_2$  concentration at 1 h, 1.4 h and 2.1 h, **c)** turbulent kinetic energy estimated using sonic anemometer measurements at thirteen levels within and above the canopy and **d)**  $\text{CO}_2$  flux at 1.4 h on June 25–26.  $w$  and  $\text{CO}_2$  time series are re-sampled to 0.05 Hz to reduce cluttering. Periods marked as I, II and III correspond to the jet activity following calm conditions

the accumulated CO<sub>2</sub> within the canopy volume mixes with the air above and significantly reduces the concentration gradient. This is an example of LLJ-induced flushing out of stored CO<sub>2</sub>. Without the LLJ, such flushing might not occur until the morning hours immediately after sunrise.

The turbulent kinetic energy ( $TKE = 0.5(u'^2 + v'^2 + w'^2)$ ) estimated from sonic anemometer observations at thirteen levels within and above the canopy is depicted in Fig. 2c. TKE is derived from the variances of the velocity components for each averaging period. As depicted in the figure, the large TKE values ( $>0.6 \text{ m}^{-2} \text{ s}^{-2}$ ) observed during the early evening hours diminish to very small values ( $<0.05 \text{ m}^{-2} \text{ s}^{-2}$ ) by 2100. Corresponding to the jet activity at 2200, 2400 and 0200 and coinciding with the periods marked as I, II and III, increased TKE ( $>0.2 \text{ m}^{-2} \text{ s}^{-2}$ ) are noticed, which otherwise remain very small during the rest of the night. At 2400, the higher values of TKE even penetrate down to the lower canopy bottom, an observation attributed to the wind maximum developed close to the surface (Fig. 1). These results substantiate that low-level jets generate turbulence and enhance TKE.

Characteristics of the eddy-covariance CO<sub>2</sub> fluxes at 1.4 h depicted in Fig. 2d at 1.4 h suggest that the behavior of eddy-covariance CO<sub>2</sub> fluxes is closely coupled to the jet properties exhibit matching behavior with the intermittent jet activity and turbulence characteristics discussed previously. Fluxes are very small during calm periods following early evening hours and large fluxes are observed corresponding to the periods I, II and III. The flux is more than  $9 \mu\text{mol m}^{-2} \text{ s}^{-1}$  at 2400 and  $15 \mu\text{mol m}^{-2} \text{ s}^{-1}$  at 0200, though the  $u_*$  values increased only just above  $0.2 \text{ m s}^{-1}$ . This is an indication that during intermittent turbulent periods associated with features such as sporadic jets, high fluxes are possible from the large fluctuations in the accumulated CO<sub>2</sub>, in phase with moderate vertical velocity fluctuations. Anomalously high nocturnal CO<sub>2</sub> fluxes are also observed at the Howland AmeriFlux site when  $u_*$  during the preceding half-hour is less than  $0.2 \text{ m s}^{-1}$  (Hollinger et al., 2004). This has consequences in filtering and gap filling the CO<sub>2</sub> flux data based on critical  $u_*$  values, as fluxes measured during periods exhibiting turbulence

immediately after calm periods are greater than and partially compensate for low fluxes measured during calm periods.

#### 4. Conclusions

LLJs are important nocturnal boundary-layer phenomena capable of influencing surface-atmosphere exchange. Flux sites located over flat terrain are highly susceptible to the occurrence of LLJs. In an attempt to understand the role of LLJs on eddy-covariance CO<sub>2</sub> fluxes, eddy-covariance data are analyzed together with wind profile observations at the Florida AmeriFlux forest site.

Flux data analyzed for a night with discontinuous LLJs suggest that variations in the atmospheric stability, friction velocity and turbulent kinetic energy are closely linked to LLJ activity at the site. Friction velocities on this night are generally very small, except during active jet periods. Nearly thirty percent of this night is influenced from the LLJ activity, contributing to enhanced turbulence and mixing. It is seen that, during re-activation of the jet following a calm period, even moderate  $u_*$  values (slightly higher than  $0.2 \text{ m s}^{-1}$ ) are associated with high CO<sub>2</sub> fluxes. High fluxes result from large fluctuations in CO<sub>2</sub> concentrations associated with flushing out of the accumulated CO<sub>2</sub> within the canopy volume, induced by the jet activity. These observations demand careful analysis of nighttime cases while accounting for fluxes corresponding to low  $u_*$  conditions. The presence of nocturnal phenomena, such as LLJs, further underlines the need for both site-specific and night-specific analysis. Corrections to reduce uncertainties and errors associated with nighttime flux measurements should be examined in the light of these results.

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