Turbulent CO_2 flux measurements by lidar: length scales, results and comparison with in-situ sensors

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1. Introduction

A mechanistic understanding of the global carbon cycle requires quantification of terrestrial ecosystem CO_2 fluxes over regional scales. Different attempts, i.e. “top-down” or “bottom-up” methods, to infer CO_2 fluxes from the small (0.1 – 1 km) to larger scales (10 – 1000 km) need experimental verification and instrumentation to do so. Range resolved CO_2 flux measurements will help significantly our understanding of the vertical transport of CO_2 at, firstly, the ABL – free troposphere interface. Indeed the entrainment zone is usually not reached by the tall towers and such data are inexistent. Particular interest is in the morning and evening transition, but also night time vertical transport. Secondly, the biosphere – ABL interface can be studied. While the results here are from a ground-based experiment, an airborne lidar would be powerful instrument to address the issue of CO_2 surface flux variability at different scales linked to the stratification of the atmosphere and the spatial heterogeneity of the surface (structure of the canopy).

Lidar has the ability to make direct range resolved flux measurements using an eddy-covariance method. Previous measurements of the flux of a scalar in the atmospheric boundary layer (ABL) have already been reported with latent flux using a combination of ground-based [1] or airborne [2] Doppler and DIAL lidars.

Two micrometer Differential Absorption Lidar (DIAL) systems for CO_2 mixing ratio measurements have already been developed at the NASA Langley Research Center and at the Institut Pierre Simon Laplace, Laboratoire de Météorologie Dynamique. [3-5] They demonstrated a good precision of ~ 1 % with rather large time (~ 30 min) and space resolution (~ 1 km) though. These former Doppler lidars use heterodyne detection which also provides radial velocity measurements. Using this double ability, i.e. concentration and velocity measurements, we present here a preliminary study of CO_2 flux measurements by lidar using the eddy-covariance method. Rather than a geophysical study of CO_2 flux in the ABL, the goal of this paper is to present the requirements for the design of a dedicated future ground-based or airborne Doppler DIAL system for accurate CO_2 flux measurements. Section 2 describes the experimental site in Wisconsin, the NASA Doppler DIAL and *in-situ* sensors. Section 3 shows details of lidar CO_2 flux calculations. Taking advantage of a useful synergy between *in-situ* and lidar instruments, section 4 presents the characteristics of night and daytime turbulent CO_2 and velocity fluctuations in the whole ABL. Section 5 shows a preliminary comparison of CO_2 fluxes calculated using the eddy-covariance method and *in-situ* and lidar data.

2. Study site and instrumentation

The field experiment took place in June 23, 2007 at the WLEF tall tower site in the Chequamegon National Forest in northern Wisconsin (45.95°N, 90.27°W, 472 m above sea level) (Fig. 1). The region is a heavily forested zone of low relief. The tower is a 447 m tall television transmitter. Two minute mean CO_2 mixing ratios are sampled at six levels (11, 30, 76, 122, 244, and 396 m) by two infrared gas analyzers (IRGA) (LiCor Model Li-6251) to give CO_2 profiles. Turbulent winds, virtual potential temperature and H_2O mixing ratio are also measured by three sonic anemometers and other IRGAs at 30, 122 and 396 m above the ground. A ground based meteorological station provides also others observations such as net radiation and surface pressure, temperature and moisture.

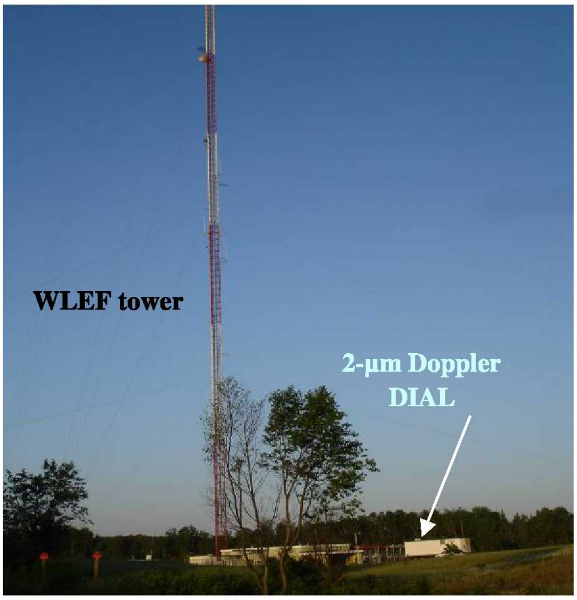

Fig.1: WLEF tower experimental site, Park Falls, Wisconsin, USA.

The NASA Langley 2-µm Doppler DIAL was positioned underneath the tower, approximately 40-m away from the tower's centreline. The 2-µm lidar transmitter is a 90-mJ, 140-ns, 5-Hz pulsed Ho,Tm:YLF oscillator injection seeded by continuous-wave (CW) lasers. The pulsed laser has been described in detail in other publications; [3, 6] its relevant parameters are summarized in Table 1.

Tab.1.Experimental set up

Pulse energy	90 mJ
Pulse repetition rate for a wavelength pair On-Off	2.5 Hz
Pulse width/ Line width	140 ns/ 3 MHz
Off-line/ On-line	2053.410/ 2053.242 nm
Spectral locking (On-line)	±1.9 MHz
Telescope aperture	100 mm
Detection heterodyne	Dual balanced InGaAs photodiodes
Signal digitization	8 bits/ 500 MHz
Signal processing Estimators	- Squarer (power) - Levin-like (power, velocity)

3. Turbulent CO_2 flux measurements by lidar

To infer a CO_2 flux estimate using the eddy-covariance method we need (as for in-situ data) high frequency measurements of CO_2 and velocities. We are looking for a correlation between the fluctuations of CO_2 mixing ratio and vertical velocities due to turbulence only. The CO_2 EC flux is given by:

$$F_{CO_2} = \overline{\langle w' \rangle . \overline{\langle \rho_{CO_2}{}' \rangle}} \quad (1)$$

where $\langle \ \rangle$ and are respectively for the vertical and time resolution of lidar CO_2 and velocities measurements.

Signal averaging can be used to decrease the instrumental error on flux measurements as long as the final time and space resolution of the lidar fits within the time and space integral scale of CO_2 turbulent flux. Otherwise, biases on lidar flux measurements may occur.

4. Space and time integral scales of turbulence

In this section, we investigate the turbulence characteristics of *in-situ* and lidar observations using covariance techniques. The autocovariance (ACV) is used to separate signal variance due to space correlated atmospheric processes from uncorrelated instrumental noise. For the atmospheric variable $c(x)$:

$$ACV_c(X) = \overline{c(x)' c(x+X)'}, \quad (2)$$

where $c(x) = \bar{c} + c'(x)$ with $c'(x)$ is for the space-dependant fluctuation and X the space lag represents the mean in the range gate used to calculate the autocovariance.

For lidar measurements, Eq. (2) becomes: $ACV_c(X) = \overline{\langle c(x) \rangle' \langle c(x+X) \rangle'}$ where $\langle \ \rangle$ is for both time and space lidar averaging. As we used a ground-based instrument, the horizontal ACV is a function of time. Knowing that $ACV_c(0) = \sigma_c^2 = \sigma_{c,inst}^2 + \sigma_{c,atm}^2$ and using a Fourier transform to determine $\sigma_{c,inst}^2$ we can measure $\sigma_{c,atm}^2$. Then, we can define the autocorrelation function (ACR) by: $ACR_c(X) = ACV_c(X) / \sigma_{c,atm}^2$. The integral of this function is called the integral scale (IS). The first maximum of this integral is usually chosen to be the IS. [1,7,8] The IS is related to the dominant eddy size and enables us to determine the space and time scales of turbulence.

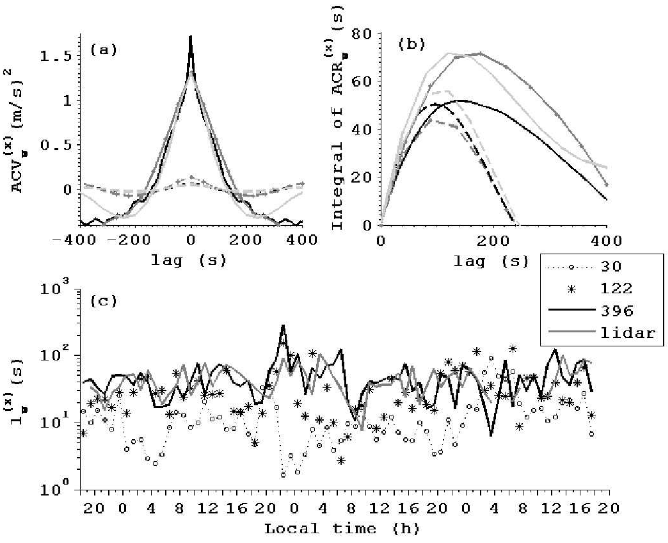

Fig. 2: (a) Horizontal autocovariance (ACV) and (b) integral of autocorrelation (ACR) of hourly vertical velocity from the sonic anemometer at 396 m at 10 Hz (black lines) and the Doppler lidar at 375 m (grey lines) during the 06/14 night (0-1 h = dashed lines) and day (12h30-13h30 = solid lines). The light grey lines are for sonic anemometer data interpolated to lidar time resolution of 40 s (c) Horizontal hourly integral scale of vertical velocity ($l_w^{(x)}$) for WLEF sonic anemometers at 30, 122 and 396 m and for the lidar at 375 m. $l_w^{(x)}$ is the maximum in the integrals of $ACR_w^{(x)}$. Lidar $l_w^{(x)}$ are corrected from bias due to lidar time averaging.

Figure 2 shows a horizontal daytime integral scale of about 50 s whereas during the night, the integral scale varies over a wide range from 10 s to more than 1 min, depending on the occurrence of dynamic perturbations such as nocturnal jets or subsidence. A similar study has been made in the vertical direction. We find a vertical integral scale of ~ 150 m in the convective boundary layer and lower than 100 m during the quiet nights.

5. Results and validation with in-situ sensors

Figure 3 displays a synoptic view of the three days of measurements June 14-16, 2007. Lidar measurements (first range gate at 150 m) concern the residual layer during the night and the convective boundary layer (CBL) during the day. 06/14 and 06/16 days are characterized by weak wind speed conditions with V < 5 m.s^{-1} whereas June 15 is particularly windy with V ~ 10 m.s^{-1}. The three CBLs are characterized by cumulus clouds and large entrainment zones (especially for June 14 and 15). The June 15 night is disturbed by a strong nocturnal jet with V > 10 m.s^{-1}.

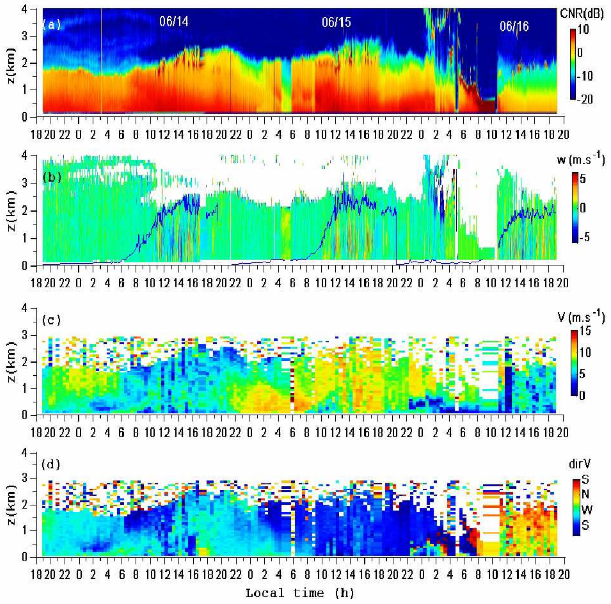

Fig. 3: (a) Off-line Carrier to Noise Ratio (CNR) (b) Vertical velocity (w) and horizontal wind (c) speed (V) and (d) direction (dirV) as a function of the local time.

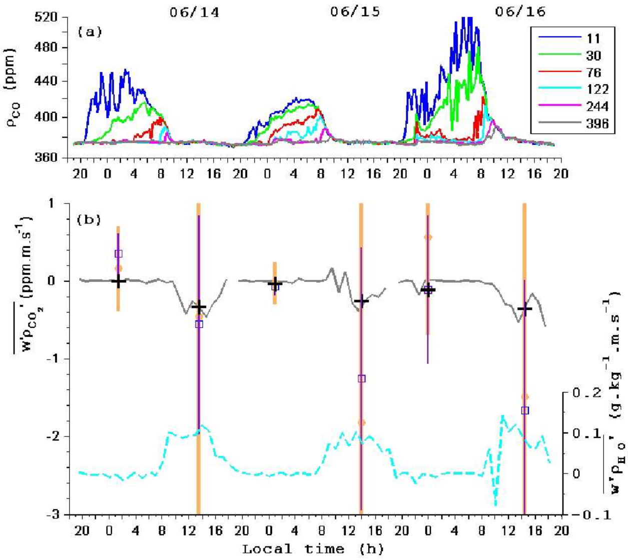

Fig. 4: (a) In-situ CO$_2$ mixing ratio measurements at 11, 30, 76, 122, 244 and 396 m. (b) In-situ eddy-covariance CO$_2$ flux at 396 m (grey line) and 1.5-km-ABL-mean lidar CO$_2$ flux estimates using the eddy-covariance technique on 150-m-80-s (orange dot) and 300-m-160-s (purple square) rolling averaged lidar CO$_2$ mixing ratio and vertical velocity measurements. The error bars represent the standard deviation of range-resolved fluxes in the 1.5 km vertical range gate (0.3 – 1.5 km) divided by the square root of the number of samples. The blue dashed line is for the in-situ water vapor eddy-covariance flux at 396 m used to correct H$_2$O bias on CO$_2$ flux measurements.

Downward slanting structures in the aerosol profile lead us to suspect additional significant subsidence motion during June 14 night. During June 16 night, a thunderstorm gave some rain around 3 h.

Figure 4b shows CO_2 eddy-covariance flux measurements inferred from the *in-situ* sensors at 396 m and the 2-µm Doppler DIAL. The mean flux lidar measurements are estimated in a temporal and vertical range gate of ~ 6 h and 1500 m (from 300 m to 1800 m), respectively. The lidar flux results displayed in Figure 14b are calculated from different time and space resolution of CO_2 mixing ratio and vertical velocity estimates, 150 m – 80 s (dots) and 300 m – 160 s (squares) in order to reduce as much as possible the statistical error on CO_2 mixing ratio measurements. The flux measurements are corrected from the bias due to parasitic H_2O absorption. During the daytime, although large statistical errors exist, lidar CO_2 flux estimates are negative like the *in-situ* measurements. A CO_2 uptake by the vegetation creates a sink in the surface layer, corresponding to a negative CO_2 flux at the bottom of the CBL. In addition, NOAA airborne measurements around the WLEF site (46.00±0.05°N, 90.17±0.03°W) report a free troposphere CO_2 mixing ratio of 384.5 ± 0.4 ppm from 2200 m up to 3900 m on June, 11, 2007. Therefore, the free troposphere represents a source of CO_2 for the ABL and we expect a negative flux of CO_2 at the top of the CBL. A mean ABL negative eddy-covariance CO_2 flux during the daytime is thus expected and verified with the measurements. During the night time, lidar flux measurements are in agreement with the *in-situ* measurements within the error bars. The increase of CO_2 for the different levels below 244 m shows the build-up of CO_2 in the nocturnal layer due to a positive CO_2 surface flux linked to the vegetation respiration. At the top of the residual layer, because of larger free tropospheric CO_2 mixing ratio than in the residual layer, entrainment flux is expected to be negative. These considerations explain the *in-situ* negative CO_2 flux measured during 06/15 and 06/16 nights, both due to intrusion of free tropospheric air in the residual layer.

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