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Research Paper

Impact of CO_2 storage flux sampling uncertainty on net ecosystem exchange measured by eddy covariance

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A R T I C L E I N F O

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A B S T R A C T

Complying with several assumption and simplifications, most of the carbon budget studies based on eddy covariance (EC) measurements quantify the net ecosystem exchange (NEE) by summing the flux obtained by EC (*FC*) and the storage flux (*SC*). *SC* is the rate of change of a scalar, CO_2 molar fraction in this case, within the control volume underneath the EC measurement level. It is given by the difference in the quasi-instantaneous profiles of concentration at the beginning and end of the EC averaging period, divided by the averaging period. The approaches used to estimate *SC* largely vary, from measurements based on a single sampling point usually located at the EC measurement height, to measurements based on profile sampling. Generally a single profile is used, although multiple profiles can be positioned within the control volume. Measurement accuracy reasonably increases with the spatial sampling intensity, however limited resources often prevent more elaborated measurement systems. In this study we use the experimental dataset collected during the ADVEX campaign in which turbulent and non-turbulent fluxes were measured in three forest sites by the simultaneous use of five towers/profiles. Our main objectives are to evaluate both the uncertainty of *SC* that derives from an insufficient sampling of CO_2 variability, and its impact on concurrent NEE estimates.Results show that different measurement methods may produce substantially different SC flux estimates which in some cases involve a significant underestimation of the actual SC at a half-hourly time scales. A proper measuring system, that uses a single vertical profile of which the CO_2 sampled at 3 points (the two closest to the ground and the one at the lower fringe of the canopy layer) is averaged with CO_2 sampled at a certain distance and at the same height, improves the horizontal representativeness and reduces this (proportional) bias to 2–10% in such ecosystems. While the effect of this error is minor on long term NEE estimates, it can produce significant uncertainty on half-hourly NEE fluxes.

1. Introduction

The estimation of the net ecosystem exchange (NEE) by the eddy covariance (EC) technique is based on simplifications of the mass balance equation, and on its integration over a control volume that extends horizontally on a representative surface and vertically from the soil level to the measurement height (Finnigan et al., 2003; Foken et al., 2012). After Reynolds averaging, integrating over the control volume, ignoring horizontal turbulent flux divergence and the horizontal variation of the vertical flux, the source/sink strength of a scalar c integrated over the height z of the control volume is given by (Aubinet et al., 2005; Feigenwinter et al., 2010a, 2008):

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$$NEE = \frac{1}{V_m}\overline{w'c'}\bigg|_z + \int_0^z \frac{1}{V_m}\frac{\partial\overline{c}(z)}{\partial t}dz + \int_0^z \frac{1}{V_m}\overline{w}(z)\frac{\partial\overline{c}(z)}{\partial z}dz + \int_0^z \frac{1}{V_m}\left(\overline{u}(z)\frac{\partial\overline{c}(z)}{\partial x} + \overline{v}(z)\frac{\partial\overline{c}(z)}{\partial y}\right) dz \quad (1)$$

where NEE denotes the biological source/sink of CO_2, V_m is the molar volume of dry air ($m^3\ mol^{-1}$), c the CO_2 molar fraction ($\mu mol\ mol^{-1}$), t the time (s), u, v, w ($m\ s^{-1}$) are the wind velocity components in x, y and z directions respectively. Overbars refer to the Reynolds averaging operator. The first term on the right hand side (RHS) of Eq. (1) is the turbulent vertical flux (FC, $\mu mol\ m^2\ s^{-1}$) measured by the EC system at the reference height z (m). The second term on the RHS refers to the rate of change in storage of CO_2 (SC, $\mu mol\ m^2\ s^{-1}$), usually estimated from vertical profile measurements. The third and fourth terms denote the non-turbulent vertical and horizontal advection fluxes, respectively. In the prevalence of carbon budget studies, also those involved in continental and global monitoring networks like ICOS, Ameriflux or FLUXNET, the advection terms are rarely quantified directly either because of their assumed minor importance or because of the critical difficulties in measuring them with the required accuracy (Aubinet et al., 2010; Heinesch et al., 2007; Moderow et al., 2011; Vickers et al., 2012). More often their contribution is partially, and indirectly, taken into account by applying specific corrections (e.g. the friction velocity filter, McHugh et al., 2017). Especially in tall vegetation ecosystems, the storage term represents an important part of the mass balance equation. Although both terms (storage change and advection) are related and involved in the so called night-flux problem (Aubinet et al., 2010), advection will not be considered in this paper, referring the readers to specific literature (e.g. Feigenwinter et al., 2008; Kang et al., 2017; Montagnani et al., 2009; Yi et al., 2000 and aforementioned references). Here, the focus is on the storage term because it commonly represents the only non-turbulent term quantified and used to estimate the NEE. Thus, after this simplification Eq. (1) reduces to

$$NEE = FC + SC \quad (2)$$

The storage term SC reflects the temporal dynamics of CO_2 in the air volume below the FC measurement height, not influenced by turbulence. Positive SC values are due to an accumulation of CO_2 within the control volume while negative values mean a depletion. In practice, SC is the rate of change of CO_2 given by the difference in the instantaneous profiles of concentration at the beginning and end of the EC averaging period, divided by the averaging period itself (Finnigan, 2006). While cumulating over daily to yearly periods leads to a nullification of SC, it can be significant at short time intervals such as half-hours or hours, especially around sunrise and sunset. During night, when atmospheric stratification is stable and turbulence is suppressed, SC becomes important, equalling or even exceeding FC. It follows that, for a closer quantification of the true NEE, SC cannot be ignored (Papale et al., 2006).

The typical approach to compute SC is based on a single tower concentration profile assuming horizontal homogeneity (one-dimensional integration), although ideally, it should be derived from concentrations averaged in the whole volume (three-dimensional integration). Under non-ideal conditions, as in cases of heterogeneity in the source/sink distribution or of tall canopies forests, the error caused by this assumption can be large (Pattey et al., 2002; van Gorsel et al., 2009). Despite this evidence, it is not unusual that SC computation is further simplified based solely on the temporal changes of the concentrations measured at the tower top and assuming a constant CO_2 concentration in the air column underneath (also known as one-point, tower-top or discrete approach). The error associated with this additional assumption is proportional to the degree of decoupling between the CO_2 measurement height (generally the EC system height) and the below canopy air space. Some studies attested the comparability between profile and one-point SC estimates (Greco and Baldocchi, 1996; Knohl et al., 2003; Lee et al., 1999; Priante-Filho et al., 2004) while others reported general underestimates (Gu et al., 2012; Iwata et al., 2005). The choice of one sampling design over another is essentially due to technical (and cost-related) aspects. By reducing the sampling intensity, the accuracy of SC is also reduced, according to the spatial variability of the source/sink distribution. On the other hand, an overly complex setup could be expensive, difficult to implement and manage, and possibly not needed. A functional distribution of sampling points (SPs) is thus crucial in order to avoid errors in the estimates. Some studies assayed the effect of profile vertical configuration on SC and NEE estimates (Bjorkegren et al., 2015; Gu et al., 2012; Wang et al., 2016; Yang et al., 2007, 1999) based on a single vertical profile analysis. For example Gu et al. (2012) found that the CO_2 storage based on the tower-top measurement was underestimated by up to 34% with respect to the one based on their 8 level profile. Yang et al. (2007) reported that a profile system with 4 sampling levels or fewer, even if optimally distributed, is not adequate for CO_2 storage measurements in a forest with a complex vertical structure because its mean error is on the same order of magnitude as the nighttime NEE (1.0–$5.8\ \mu mol\ m^{-2}\ s^{-1}$).

In this paper we extend the analysis to a three-dimensional space with the objective to 1) quantify the error in SC measurements due to an insufficient sampling of the spatial variability of CO_2 concentration, 2) identify and evaluate an efficient measurement set-up, and 3) quantify the impact of SC sampling error on consequent NEE estimate.

The data used in this study are a part of the dataset of ADVEX, the CarboEurope-Integrated Project (CE-IP) advection campaigns (Feigenwinter et al., 2008). It is worth to note that we focused on the spatial sampling error only. Other main sources of error in SC measurements, as the temporal sampling error (Finnigan, 2006), are not considered (details on this can be found in e.g. Cescatti et al., 2016; Marcolla et al., 2014; Siebicke et al., 2011; Wang et al., 2016; Yang et al., 2007).

2. Materials and methods

2.1. The dataset: ADVEX

The ADVEX project aimed at providing a possible methodology to accurately quantify advective fluxes in EC measurements. Three analogous experiments were performed at three different forest sites across Europe in 2005 and 2006. The sites were part of the CE-IP and are characterized by different orography (Fig. 1): Norunda (NO in the following) in Sweden is on a basically flat surface, Renon (RE) in Italy, is located on a notable alpine slope (11°), Wetzstein (WS) in Germany is located on a hill ridge (Feigenwinter et al., 2008). Their mean altitude is 45 m, 1735 m and 782 m respectively, however the average temperature was comparable at the three sites. Also the species composition was similar and dominated by spruce (*Picea abies* L. Karst.), in association with *Pinus sylvestris* L. at NO and with *Pinus cembra* L. at RE. The average leaf area index was 4.5 at NO (Lagergren et al., 2005), 5.1 at RE (Marcolla et al., 2005), 7.0 at WS (Rebmann et al., 2010). The mean canopy height was about 25 m at NO and RE and 22 m at WS. NEE was rather different as in the ADVEX experiment year NO was on average a net source of CO_2 ($52\ g\ C\ m^{-2}\ y^{-1}$), RE was a strong sink ($-721\ g\ C\ m^{-2}\ y^{-1}$) and WS was a moderate sink ($-96\ g\ C\ m^{-2}\ y^{-1}$, Rebmann et al., 2010).

The experimental set-ups were similar, composed by one main tower (M) surrounded by four shorter towers (A–D, named satellites from now on) forming a quadrangle (Fig. 1). The main instrumentation on each tower is summarized in Table 1.

A comprehensive description of sites' characteristics, data collection, instruments and setup used during ADVEX can be found in the related bibliography (Aubinet et al., 2010; Feigenwinter et al., 2010a, 2010b, 2008; Moderow et al., 2011; Montagnani et al., 2010) and in the supplementary material of this article.

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