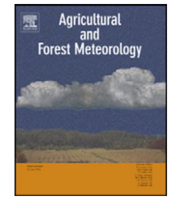
Agricultural and Forest Meteorology 150 (2010) 655–664

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Direct advection measurements do not help to solve the night-time CO_2 closure problem: Evidence from three different forests

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ARTICLE INFO

Article history:
Received 14 November 2008
Received in revised form 25 October 2009
Accepted 25 January 2010

Keywords:
Advection
Forests
CO_2 fluxes
Eddy covariance

ABSTRACT

The ADVEX project involved conducting extensive advection measurements at three sites, each with a different topography. One goal of the project was to measure the [CO_2] balance under night-time conditions, in an attempt to improve NEE estimates.

Four towers were arranged in a square around a main tower, with the sides of the square about 100 m long. Equipped with 16 sonic anemometers and [CO_2] sampling points, the towers were installed to measure vertical and horizontal advection of [CO_2]. Vertical turbulent fluxes were measured by an eddy covariance system at the top of the main tower.

The results showed that horizontal advection varied greatly from site to site and from one wind sector to another, the highest values being reached when there were large friction velocities and fairly unstable conditions. There was less variation in vertical advection, the highest values being reached when there were low friction velocities and stable conditions.

The night-time NEE estimates deduced from the mass balance were found to be incompatible with biologically driven fluxes because (i) they varied strongly from one wind sector to another and this variation could not be explained in terms of a response of the biologic flux to climate, (ii) their order of magnitude was not realistic and (iii) they still showed a trend vs. friction velocity.

From a critical analysis of the measurement and data treatment we concluded that the causes of the problem are related to the representativeness of the measurement (control volume size, sampling resolution) or the hypotheses underlying the derivation of the [CO_2] mass balance (ignoring the horizontal turbulent flux divergence). This suggests that the improvement of eddy flux measurements by developing an advection completed [CO_2] mass balance at night would be practically difficult.
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1. Introduction

The eddy covariance technique is the most frequently used method for estimating [CO_2] fluxes exchanged between the land surface and the atmosphere. Despite its success, however, it is known to generally underestimate the fluxes at night, during periods of low air mixing. This problem was first detected by Goulden et al. (1996) and was confirmed in many subsequent studies (Aubinet et al., 2000; Gu et al., 2005).

Two methods may be applied to overcome this problem. The filtering approach involves removing from the time series measurements obtained when net ecosystem exchange (NEE) is poorly represented by eddy flux measurements. When needed, the data gaps created in this way can be filled using parameterisations, look-up tables, modelling or neural networks (Falge et al., 2001; Papale et al., 2006). A problem with this approach is that both the filtering criteria and the data gap filling procedures are based on empirical approaches and suffer from a great degree of uncertainty (Moffat et al., 2007; Richardson et al., 2006).

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0168-1923/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2010.01.016

An alternative approach is based on the mass conservation equation of carbon dioxide and involves directly measuring the advection terms. In this paper we refer to this approach as the ‘advection completed mass balance’ (ACMB).

The CO_2 mass balance equation is derived from the instantaneous mass conservation equation that states that the CO_2 produced or absorbed by the biological source/sink is either stored in the air or removed by flux divergence (Aubinet et al., 2000). After applying Reynolds decomposition, integration over a control volume of height h, and sides $2L$, ignoring the horizontal turbulent flux divergence and the horizontal variation of the vertical flux, and applying the continuity equation, the mass conservation equation reads (Finnigan, 1999; Feigenwinter et al., 2004):

$$NEE = \int_0^h \frac{1}{V_m}\left[\frac{\partial \overline{c}}{\partial t}\right]dz + \frac{1}{V_m}(\overline{w'c'})_h + \int_0^h \frac{1}{V_m}\overline{w}(z)\frac{\partial \overline{c}}{\partial z}dz + \frac{1}{4L^2}\int_{-L}^{+L}\int_{-L}^{+L}\int_0^h \frac{1}{V_m}\left(\overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{v}\frac{\partial \overline{c}}{\partial y}\right)dzdxdy. \quad (1)$$

where NEE represents the net ecosystem exchange; c is the molar mixing ratio of CO_2 to dry air; V_m is the molar volume of dry air; u, v and w represent the wind velocity components in the horizontal (x, y) and vertical (z) directions, respectively. The overbars represent time averages and prime departures from those averages. This equation in itself is a simplification in that it assumes horizontal homogeneity of the three first RHS terms and ignores horizontal turbulent fluxes. A more general equation was put forward by Finnigan *et al.* (2003). In Equation (1) the NEE should be representative of the biological source/sink strength term, which we refer to in this paper as the ‘biotic flux’. The ACMB approach therefore involves estimating the biotic flux as the sum of the four RHS terms in Equation 1. The four terms are: F_S, the storage of CO_2 in the air of the control volume; F_C, the vertical turbulent transport; F_{VA}, the vertical advection; and F_{HA}, the horizontal advection.

Lee (1998) was the first to estimate NEE by adding vertical advection to the CO_2 balance. He proposed computing vertical advection as:

$$F_{v\Delta} = \bar{w}(\bar{c}_h - \langle c \rangle) \quad (2)$$

Where, $\bar{c}_h$ represents [CO_2] at the top of the control volume and $\langle c \rangle$ a [CO_2] averaged between this height and the soil. This approach remained incomplete, however, as horizontal advection was not included in the budget (Finnigan, 1999). Estimates based on the ACMB approach were first proposed by Aubinet et al. (2003), followed by Feigenwinter et al. (2004), Staebler and Fitzjarrald (2004, 2005), Marcolla et al. (2005), Aubinet et al. (2005), Sun et al. (2007), Heinesch et al. (2008), Yi et al. (2008), Leuning et al. (2008) and Tota et al. (2008).

In 2005, the ADVEX project was launched to provide more complete advection estimates in order to improve ACMB flux estimates. This involved arranging four 30 m-high towers in a square, around a main tower, with each side of the square about 100 m long; the towers were fully equipped with wind velocity, temperature and [CO_2] profile measurements (16 sampling points of each), and were installed at sites already equipped with an eddy covariance system. The set-up was rotated among three European forest sites, each of them characterized by a specific topography: an Alpine slope (Renon/Ritten, Italy), a hill-crest (Wetzstein, Germany) and a flat site (Norunda, Sweden). In addition to using the same set-up, similar data collection and computation procedures were used at the three sites. At each site the project was implemented for 2–4 months. A complete description of the set-up and the first results were presented by Feigenwinter et al. (2008).

The main goal of this paper is to assess the ability of the ACMB approach to provide realistic estimates of the biotic CO_2 fluxes in night-time conditions. In the absence of independent NEE estimates, one possibility is to evaluate the robustness of ACMB estimates by testing their independence of meteorological factors that should not affect NEE. As at night, NEE results from ecosystem respiration, it should depend only on temperature and, to a lesser degree, soil humidity. Night-time ACMB estimates should thus remain independent of other variables as long as they do not co-vary with temperature. In particular, our work tested how independent the night-time ACMB estimates were of friction velocity and wind direction. The first approach is not new: the dependence of night flux estimates on u^* has been often used to question the validity of eddy flux measurements in night-time conditions (Goulden et al., 1996) and the ability of ACMB to offset this dependence has been used as a quality test, in particular by Marcolla et al. (2005) and Mammarella et al. (2007). The analysis of the dependence of ACMB estimates on wind direction has been studied, so far as we know, only by Heinesch et al. (2008).

After presenting and discussing the relation between F_{VA}, F_{HA} and friction velocity and stability at each site and for different wind sectors, the ACMB flux estimate independence of wind direction and friction velocity will be tested. As this independence will not be established, an error analysis will be developed in order to assess the causes of the mismatch. Finally, a bibliographical review will be provided in order to evaluate the generality of these results.

2. Material and methods

The measurement set-up, data collection and advection computation procedures we used are common to many papers in this special issue and were described in detail by Feigenwinter et al. (2008). We outline the main features here.

2.1. Site description

The Renon/Ritten site (RE) is situated at 1735m a.s.l. in the Italian Alps, 12 km NNE of Bolzano in Alto Adige, Italy. Its topography is characterized by an alpine slope with a mean slope of about 11° in a N–S direction. The site is covered mainly by unevenly aged Norway spruce varying between 20 m and 30 m high. About 60 m upslope to the north of the main tower there is a pasture that breaks the wind fetch in the predominant night-time wind direction. The undergrowth varies widely from sparse to dense. The climate is characterized by low temperatures, high precipitation and, often, high wind speeds (average annual temperature 4.1 °C, annual precipitation 1010 mm). The meteorological conditions during the measurement period were dominated by a very persistent local slope wind system with upslope S–SW winds during the day and downslope NNW winds during the night. This situation covered about 75% of the measurement period. The rest of the period was synoptically dominated either by the “Tramontana”, a cold and strong wind, which blows consistently for a few days from the north also during daytime and penetrating into the canopy, or by persistent moderate warm winds from S to SW, also blowing during the night.

The Wetzstein site (WS) is situated at 782 m a.s.l., almost on the crest of an SSW–NNE aligned ridge in the Thuringian forest in Germany, with steep slopes to the ESE and WNW. The site is covered by 50-year-old Norway spruce that provides a homogeneous canopy at a height of about 22 m. The fetch exceeds 500 m in all directions. The undergrowth is very sparse, with well-defined trunk spaces reaching a height of about 10 m. The climate is temperate humid (average annual temperature 5.9 °C, annual precipitation 840 mm). During the measurement period, due to its location on the top of a ridge, the site was very wind exposed and

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