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Comparison of horizontal and vertical advective CO_2 fluxes at three forest sites

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ABSTRACT

Extensive field measurements have been performed at three CarboEurope-Integrated Project forest sites with different topography (Renon/Ritten, Italian Alps, Italy; Wetzstein, Thuringia, Germany; Norunda, Uppland, Sweden) to evaluate the relevant terms of the carbon balance by measuring CO_2 concentrations [CO_2] and the wind field in a 3D multi-tower cube setup. The same experimental setup (geometry and instrumentation) and the same methodology were applied to all the three experiments. It is shown that all sites are affected by advection in different ways and strengths. Everywhere, vertical advection (F_{VA}) occurred only at night. During the day, F_{VA} disappeared because of turbulent mixing, leading to a uniform vertical profile of [CO_2]. Mean F_{VA} was nearly zero at the hilly site (Wetzstein) and at the flat site (Norunda). However, large, momentary positive or negative contributions occurred at the flat site, whereas vertical non-turbulent fluxes were generally very small at the hilly site. At the slope site (Renon), F_{VA} was always positive at night because of the permanently negative mean vertical wind component resulting from downslope winds. Horizontal advection also occurred mainly at night. It was positive at the slope site and negative at the flat site in the mean diurnal course. The size of the averaged non-turbulent advective fluxes was of the same order of magnitude as the turbulent flux measured by eddy-covariance technique, but the scatter was very high. This implies that it is not advisable to use directly measured quantities of the non-turbulent advective fluxes for the estimation of net ecosystem exchange (NEE) on e.g. an hourly basis. However, situations with and without advection were closely related to local or synoptic meteorological conditions. Thus, it is possible to separate advection affected NEE estimates from fluxes which

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are representative of the source term. However, the development of a robust correction scheme for advection requires a more detailed site-specific analysis of single events for the identification of the relevant processes. This paper presents mean characteristics of the advective CO_2 fluxes in a first site-to-site comparison and evaluates the main problems for future research.

1. Introduction

Since the formation of tower-based regional flux networks like EuroFlux, AmeriFlux, OzFlux and AsiaFlux (pooled in the global FLUXNET network), there has been a common agreement that measurements using the eddy-covariance (EC) method tend to underestimate carbon fluxes during calm and stable nights (e.g. Wofsy et al., 1993; Goulden et al., 1996; Moncrieff et al., 1996; Baldocchi et al., 2000; Paw U et al., 2000; Massman and Lee, 2002). One indicator of these discrepancies is the disagreement between EC and chamber measurements. The nocturnal carbon efflux is systematically underestimated by the sum of turbulent fluxes and changes in storage, when compared with concurrent chamber measurements of soil and plant respiration (e.g. Goulden et al., 1996). The errors in the EC measurements may result, in part, from: averaging times that are too short to capture low frequency exchange (e.g. Aubinet et al., 2000); missed high frequency (small scale turbulence) exchange (Mahrt and Vickers, 2005); scaling problems during intermittent turbulence (Mahrt, 1999); similarity and stationarity criteria not being fulfilled (Foken and Wichura, 1996); decoupling of flows above and below the canopy, for example by drainage flows (Aubinet et al., 2003), or extended the footprints that result from stable conditions (e.g. Baldocchi, 1997). These and other mechanisms at work in the stable boundary layer affecting EC measurements, and their impact on the carbon balance, have been extensively analyzed by Aubinet (in press). The FLUXNET approach further assumes that the net ecosystem exchange (NEE) is only the sum of the vertical turbulent flux above the canopy and the storage change in the volume below the measurement height of the EC sensors, assumes spatial homogeneity, and ignores all other (advective) terms in the mass conservation equation. The state of the art to overcome nighttime flux underestimation when calculating annual sums for NEE is the u_*-correction as described in Falge et al. (2001), modified by Gu et al. (2005).

During the past few years there have been new attempts to measure advective flows caused by topography and/or heterogeneity in connection with the underestimation of nighttime CO_2 fluxes measured by the EC technique. Direct measurement of the CO_2 balance, including the advective terms, requires an experimental design that allows for the simultaneous measurement of all the mass conservation equation terms (i.e. turbulent flux, storage change, vertical and horizontal advection, and horizontal flux divergence). The design of advection experiments has improved from the first attempts to measure the non-turbulent advective fluxes in a simple single level 2D setup (Aubinet et al., 2003) to multi-level 2D (Marcolla et al., 2005), single level 3D (Staebler and Fitzjarrald, 2004) and multi-level 3D setups (Feigenwinter et al., 2004). Several studies directly addressing advection experiments have been published in the last few years. Some of them found horizontal advection (F_{HA}) and vertical advection (F_{VA}) to be of opposite sign (Aubinet et al., 2003; Feigenwinter et al., 2004), while others reported both to be positive (Marcolla et al., 2005). All papers, including the study of Staebler and Fitzjarrald (2004), concluded that advection increases the nightly source of CO_2. A point common to all these studies is the large scatter of the advection measurements. Drawing more detailed common conclusions from the experiments carried out so far is difficult because experimental setups and, in particular, the different methodologies applied for the spatial integration, varied considerably. Meanwhile, the advection terms have also been investigated using theoretical (e.g. Finnigan, 2007; Belcher et al., in press) and modelling (Katul et al., 2006; Sun et al., 2006) approaches.

The extensive experimental activities of the CarboEurope-Integrated Project (CE-IP) advection group ADVEX took into account the 3D aspect of the problem. ADVEX campaigns were performed from April to September 2005 at the CE-IP site Renon/Ritten (Alto Adige, Italy), from April to June 2006 at the CE-IP site Wetzstein (Thuringia, Germany) and from July to September 2006 at the CE-IP site Norunda (Uppland, Sweden). The standard instrumentation of the flux towers (with EC system and vertical [CO_2] profile measurement) was supplemented with a set of four additional 30 m towers equipped so as to capture vertical profiles of wind velocities, [CO_2] and temperature as well as horizontal transects of [CO_2] and temperature in order to evaluate the exchange processes of CO_2 in the soil–vegetation–atmosphere control volume with a high spatial resolution (see Fig. 1). Each ADVEX site-campaign was performed with the same experimental setup, the same data acquisition system and the measurements were processed with the same methodology, leading to a unique data set for a comprehensive site-to-site intercomparison.

In this study we present mean characteristics of the non-turbulent vertical and horizontal advective CO_2 fluxes and we evaluate the main problems for future research in this field. The paper is organised as follows: The sites and the experimental setup are presented in Sections 2 and 3, respectively. The method for the calculation of the advective fluxes is described in detail in Section 4. The characteristics of the averaged fluxes are presented in the following section and the results are discussed in the context of the respective site properties (topography, flow conditions).

2. Sites

The measurements were made at three sites which are all part of the CE-IP ecosystem observation network. Table 1 lists the