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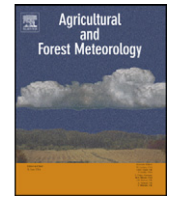

Spatiotemporal evolution of CO_2 concentration, temperature, and wind field during stable nights at the Norunda forest site

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ABSTRACT

Unusually high CO_2 concentrations were frequently observed during stable nights in late summer 2006 at the CarboEurope-Integrated Project (CEIP) forest site in Norunda, Sweden. Mean CO_2 concentrations in the layer below the height of the eddy-covariance measurement system at 30 m reached up to 500 μmol mol^{-1} and large vertical and horizontal gradients occurred, leading to very large advective fluxes with a high variability in size and direction. CO_2 accumulation was found to build up in the second part of the night, when the stratification in the canopy sub-layer turned from stable to neutral. Largest vertical gradients of temperature and CO_2 were shifted from close to the ground early in the night to the crown space of the forest late at night, decoupling the canopy sub-layer from the surface roughness layer. At the top of the canopy at 25 m CO_2 concentrations up to 480 μmol mol^{-1} were observed at all four tower locations of the 3D cube setup and concentrations were still high (>400 μmol mol^{-1}) at the 100 m level of the Central tower. The vertical profiles of horizontal advective fluxes during the nights under investigation were similar and showed largest negative horizontal advection (equivalent to an additional CO_2-sink) to occur in the crown space of the forest, and not, as usually expected, close to the ground. The magnitude of these fluxes was sometimes larger than −50 μmol m^{-2} s^{-1} and they were caused by the large horizontal CO_2 concentration gradients with maximum values of up to 1 μmol mol^{-1} m^{-1}. As a result of these high within canopy CO_2 concentrations, the vertical advection also became large with frequent changes of direction according to the sign of the mean vertical wind component, which showed very small values scattering around zero. Inaccuracy of the sonic anemometer at such low wind velocities is the reason for uncertainty in vertical advection, whereas for horizontal advection, instrument errors were small compared to the fluxes. The advective fluxes during these nights were unusually high and it is not clear what they represent in relation to the biotic fluxes. Advection is most likely a scale overlapping process. With a control volume of about 100 m × 100 m × 30 m and the applied spatial resolution of the sensors, we obviously miss relevant information from processes in the mesoscale as well as in the turbulent scale.

1. Introduction

The Eddy Correlation (EC) technique is one of the most established techniques to measure the fluxes of water, energy and CO_2 between the biosphere and the atmosphere. In the frame of FLUXNET, a global flux tower network including hundreds of sites covering different climate conditions and land cover, the EC-approach is used to measure net ecosystem CO_2 exchange (*NEE*) and water balance of forests from daily to annual time scales (Baldocchi et al., 2001; http://www.fluxnet.ornl.gov/fluxnet/index.cfm; Baldocchi, 2008). Though widely used, the EC-method is subject to some substantial shortcomings when applied in complex (non-flat) topography and over heterogeneous vegetation. Numerous studies address these problems (e.g. Goulden et al., 1996; Aubinet et al., 2000; Massman and Lee, 2002; Loescher et al., 2006). In particular, CO_2-fluxes measured by the EC-method during calm and stable nights with low turbulence and limited air mixing are in disagreement with total ecosystem respiration measured by alternative methods such as soil chambers and leaf cuvettes. Since this nighttime flux anomaly only occurs when the ecosystem is a net source of CO_2, it is thought to lead to an overestimation of the total carbon sequestration (Moncrieff et al.,

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1996). In practice the problem is by-passed for the estimation of annual carbon balances by the application of the friction velocity (u^*)-filtering approach. With this method, data corresponding to periods with insufficient mixing, determined by a site specific threshold for friction velocity, are replaced by fluxes derived from turbulent nights according to their response to the climate (Falge et al., 2001; Papale and Valentini, 2003; Gu et al., 2005; Reichstein et al., 2005). Though widely used and currently considered as the best method to overcome the problem, the u^*-filter approach itself is subject to considerable concerns and must be applied with caution (Papale et al., 2006).

Several studies (e.g. Lee, 1998; Finnigan, 1999; Baldocchi et al., 2000; Paw et al., 2000) suggest that advection of CO_2 may be one of the main reasons for the ''missing'' CO_2 at night. As a consequence, an increasing number of groups tried to explicitly measure the advective fluxes in field experiments during the last decade (Aubinet et al., 2003, 2005; Staebler and Fitzjarrald, 2004; Feigenwinter et al., 2004; Marcolla et al., 2005; Wang et al., 2005; Sun et al., 2007; Heinesch et al., 2008; Leuning et al., 2008; Tóta et al., 2008; Yi et al., 2008). However, the experimental setup and the methodology of these experiments vary largely, which makes a comparison of the results very difficult.

The ADVEX campaigns, a series of three identical field experiments in mid European forests with the aim to explicitly measure the non-turbulent advective fluxes (Feigenwinter et al., 2008, referred to as FE08 in the following), were the first to provide data collected at three different sites with the same experimental setup and processed with the same methodology. The forest site Norunda was actually chosen to be the ''non-advective reference site'' for the ADVEX experiments because of its presumed ideal location in a homogeneous forest with good fetch conditions in a flat topography. In addition, Norunda is one of the very few forest sites which are reported to be a source of CO_2 (Lindroth et al., 1998; Valentini et al., 2000; Lagergren et al., 2008). However it turned out from the ADVEX site comparison in FE08, that Norunda showed (i) the largest variability in all CO_2-fluxes (turbulent flux F_C, storage change F_S, advective fluxes F_{VA} (vertical) and F_{HA} (horizontal)), and (ii) the largest magnitudes of F_S, F_{VA} and F_{HA}. Another characteristic of the results was the negative sign of F_{HA}. According to these results the Norunda site would act as a CO_2 sink even during nighttime, which does not make sense at all. However, this fact reflects many of the problems and limitations confronted with when trying to measure advective fluxes in a field experiment.

In this paper we analyse a particular series of nights with extremely large CO_2 concentrations and large advective fluxes F_{VA} and F_{HA}, which are representative (about 30% of the investigated period of 73 days) for several similar periods with a duration of 2–5 days. The analysis will demonstrate the facts that lead to these large fluxes. We will show that F_{HA} derived from horizontal CO_2 concentration gradients and horizontal wind velocities are real and not due to measurement errors. The vertical profiles and horizontal distribution of CO_2 and the wind field are analyzed with respect to their contributions to F_{HA} and F_{VA}. In the last section we discuss the meaning of measured advective fluxes and how they are related to the biotic fluxes.

2. Site and measurements

We analyse data from the ADVEX campaign carried out from 7 July to 18 September (DOY 188-261) in 2006 in Norunda, Uppland, Sweden. For an overview on the ADVEX campaigns and the general experimental setup see FE08. More detailed information about the site may be found in Lindroth et al. (1998), Lundin et al. (1999), Mölder et al. (1999), Widén (2002) and Lagergren et al. (2005) amongst others. In the following we recall the most relevant information for this particular study.

The Norunda flux tower is situated in central Sweden (60°5′N, 17°29′E, 45 m a.s.l.) in a coniferous forest dominated by Scots pine (65%, *Pinus sylvestris* L.) and Norway spruce (33%, *Picea abies* (L.) Karst.) with a small fraction of deciduous tree and heights of 24–28 m. The topography is flat with the forest spreading at least 1 km in each direction. Leaf area index (LAI) varies between 4 and 5 with the higher values for stands dominated by spruce. The stands in the control volume are about 100 years old but differ in soil properties and species composition in both the tree and forest floor vegetation. The soil is a sandy glacial till with moderate to high occurrence of large boulders and is covered with mosses and stands of dwarf shrubs. A detailed description of the vegetation and soil properties can be found in Lagergren et al. (2005). Generally, compared to other FLUXNET forest sites, conditions at the Norunda site are fairly good for EC-measurements.

The analyzed dataset is a combination of permanent standard measurements and measurements taken during the ADVEX campaign. Standard measurements at the main tower include an EC-system at 33.5 m with an open-path infrared gas analyzer (LI-7500, LI-COR Inc., Nebraska, U.S.) and an ultrasonic anemometer (USA-1, METEK GmbH, Germany) operated at 10 Hz, a CO_2/H_2O vertical profile (LI-6262 multi-valve system (see Mölder et al., 2000)) with measurement points at 8.5, 13.5, 19, 24.5, 28, 31.7, 36.9, 43.8, 58.5, 73, 87.5 and 100.6 m height (sampling time is 12 s per line at a flow rate of $3\,l\,min^{-1}$). A temperature profile was measured at the same heights using radiation-shielded and ventilated thermocouples. The 3D wind vector was measured also at 100 m with another ultrasonic anemometer of type USA-1. For the period under consideration, the main tower was additionally equipped with wind vector measurements (Model 81000V ultrasonic anemometer, R.M. Young, Michigan, U.S.) at 1.5 and 6 m height.

The ADVEX setup consisted of four 30 m tall towers located at about 60 m distance from the main tower enclosing a cube of about $100\,m \times 100\,m \times 30\,m$ as shown in Fig. 1. Each tower was equipped for measurements of CO_2/H_2O (sampling time 20 s per line, LI-6262 multi valve system) and wind vector (sampling rate 10 Hz, Model 81000V ultrasonic anemometer) at heights 1.5, 6, 12 and 30 m. Towers B and C were additionally equipped with open path EC-systems (LI-7500; Gill R3 ultrasonic anemometer, Gill Instruments Ltd., U.K.) at 33.5 m height. At tower B, an independent 12-level vertical profile of CO_2/H_2O (LI-7000 multi-valve system) was measured at heights 0.4, 0.9, 1.5, 3.0, 6.0, 9.0, 12.0, 15.5, 19.0, 22.5, 26.5 and 30.5 m. This high-resolution profile (from hereon referred to as ''the LUND profile'') provided an excellent opportunity to evaluate the differences with the 4-level ADVEX profiles.

Recalling the ADVEX results for Norunda, we showed that occasionally extremely large negative horizontal advection was observed when winds were blowing from SSW and, less frequently, from WNW (Fig. 8 in FE08). Since the magnitude of these fluxes bears no relation to the biotic fluxes, we will take a closer look to the facts that lead to these results.

3. Methods and observations

In general, most advection studies use the following equation as a base for the calculation of net ecosystem exchange (*NEE*) including the vertical and horizontal advection terms. It is given by

$$NEE = F_S + F_C + F_{VA} + F_{HA}, \tag{1}$$

where F_S is the storage change, F_C is the vertical turbulent flux, F_{VA} and F_{HA} denote the vertical and horizontal advection, respectively.