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Plot-scale vertical and horizontal transport of CO_2 modified by a persistent slope wind system in and above an alpine forest

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ABSTRACT

Data from the flux tower site Renon/Ritten, Italy, located at 1735 m. a.s.l. on a south exposed steep (11°) forested alpine slope, is analyzed. In spite of the complex terrain, a persistent slope wind system prevailed at the site during most of the ADVEX campaign from April to September 2005. We describe in detail how CO_2 is transported parallel to the slope and how this transport affects net ecosystem exchange (NEE) in the diurnal course. The local slope wind system may be strongly modified by two different large scale synoptic situations. The "Tramontana", a persistent strong wind from the north, amplified the drainage flow during nighttime and suppressed the upslope flow above the forest canopy during daytime. Vice versa, we observed periods with continuing flow from the south, which supported the local daytime upslope flow and partly suppressed the nighttime downslope flow. This led to periods of several hours with opposite flow directions in and above the canopy. Depending on the prevailing situation, the trunk space is coupled and/or decoupled with/from the roughness sublayer above the forest canopy. In particular, vertical and horizontal mixing of CO_2 was strongly dependent on the dominating wind field with essential impact on the horizontal advective flux of CO_2. The most common "Local" situation, dominated by the slope wind system, showed positive horizontal and vertical advection (with typical values around 7 and 3 μmol m^{-2} s^{-1}, respectively) together with downslope winds at night and slightly negative horizontal advection (typical values around -2 μmol m^{-2} s^{-1}) together with upslope winds during the day. This pattern was amplified at night when the wind was consistently (day and night) blowing downslope (the "Tramontana" situation) and, vice versa, attenuated during the night, when the wind was blowing permanently upslope (the "Southerlies" situation). Taking into account these advective fluxes would significantly reduce the reported annual CO_2 uptake of this forest. Related effects are expected to occur at flux tower sites with similar topography and vegetation.

1. Introduction

Forests play an important role in the continental, regional and local carbon budget, and they are considered as an important terrestrial sink for CO_2 (Grace, 2005). Within the global FLUXNET flux tower network, the eddy covariance technique has become the most important method for measuring the CO_2-exchange between forests and the atmosphere (Baldocchi et al., 2001). However, many of these flux towers are situated in complex terrain and mountainous regions, and are therefore subject to significant errors (Massman and Lee, 2002). Amongst other phenomena, terrain-induced flows, e.g., nocturnal drainage flows, were found to be an important source of error (Aubinet, 2008). Such flows result from multi-scale interactions between land surface and the overlaying atmosphere (Mahrt et al., 2001) and directly affect the land-atmosphere exchange of momentum, heat and scalars. The dominating effect of the topography is extremely important in mountainous regions, where wind flows are generated and modified by overlapping influences of different scales. Depending on location, such flows as (i) large scale synoptic flows (ii) meso-scale mountain-valley and slope wind systems and (iii) micro-scale drainage flows are involved to form the resultant wind field. This

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resulting flow field has complex diurnal variations because the contributing components can be large and are not necessarily in phase (Whiteman, 2000). Advection is often linked to drainage flows (Aubinet et al., 2003; Yi et al., 2005; Sun et al., 2007; De Araújo et al., 2008) and may behave differently for different synoptic situations (Heinesch et al., 2008; Hurwitz et al., 2004). Experimental investigation of the non-turbulent advective fluxes of CO_2 started in the late nineties after the publication of Lee (1998). During the last decade, several research teams tried to measure advection in the near surroundings of flux tower sites. Because of the complexity of the subject, the 3D nature of the problem and the considerable expenses in infrastructure and manpower, the studies vary from comparatively basic 2D configurations (e.g., Aubinet et al., 2003; Paw et al., 2004; Marcolla et al., 2005) to more sophisticated 3D experimental designs (e.g., Feigenwinter et al., 2004; Feigenwinter et al., 2008; Leuning et al., 2008; Yi et al., 2008). As a consequence, the methods for calculating the advective fluxes vary widely, because they are strongly adapted to the respective available measurements. This makes a quantitative and qualitative comparison between the studies difficult and there is certainly need for a comprehensive review of advection papers. Nevertheless, there are some points common to all advection studies, namely: (i) advection is highly site specific; (ii) advection is difficult to measure; (iii) advective fluxes show a high day to day variability.

In this study, data from the ADVEX field campaign (Feigenwinter et al., 2008, henceforward referred to as FE08) at the CarboEurope site Renon/Ritten in the Italian Alps is analyzed with respect to the dominating local and synoptic conditions. Three clearly distinguishable situations show distinct and consistent patterns when analyzed with respect to the horizontal and vertical forest-atmosphere CO_2-exchange. The horizontal and vertical advection terms are analyzed and their impact on net ecosystem exchange (NEE) for these situations is discussed.

2. Site and experimental setup

The Renon/Ritten site is situated some 12 km north of Bolzano at 1735 m a.s.l. on a south exposed steep (11°) forested slope in the Italian Alps. The main species of the uneven-aged forest is Norway Spruce (*Picea abies* (L.) Karst)) with tree heights between 20 and 30 m, and a LAI of 5.5. There are some small clearings between groups of older and younger trees and the ground vegetation varies widely from sparse to dense. Branches of the younger trees reach down to the forest soil, but also in the older stands there is no distinct open trunk space. The fetch in south (downslope) direction is sufficiently homogeneous, while a pasture located about 60 m north (upslope) of the main tower disturbs the fetch for the dominating nighttime wind direction. More details about the site and its vegetation structure can be found in Cescatti and Marcolla (2004), Marcolla et al. (2005) and in FE08.

Extensive measurements of the 3D wind vector and temperature with a high temporal and spatial resolution were made from 5 May to 15 September 2005 in the frame of the CarboEurope-IP advection experiment ADVEX. Four additional towers of 30 m height were installed in about 60 m diagonal distance of the central flux tower to form a 3D cube control volume. Wind components *u, v, w*, and temperature *T* were measured at four levels (1.5, 6, 12 and 30 m) at each tower by ultrasonic anemometers at 10 Hz. In addition, CO_2 and H_2O concentrations were measured at the same locations every 160 s by two multi valve systems (MVS) each connected to a Li-6262 Infrared Gas Analyzer (IRGA). Fig. 1 shows the topography and the location of the towers. For further details about the experimental setup, instrumentation and data acquisition refer to FE08.

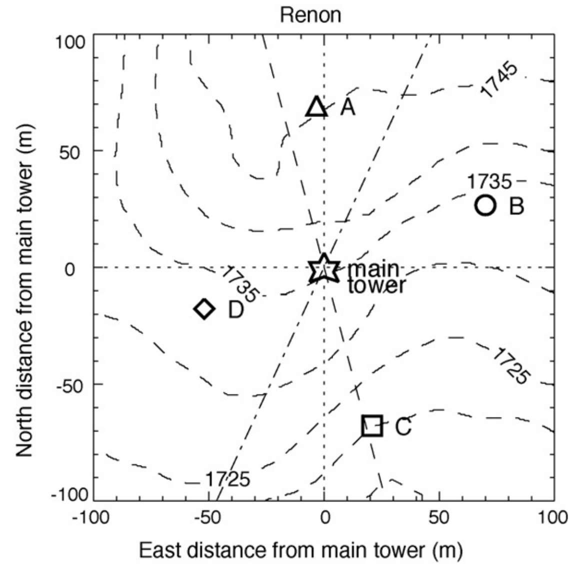

Fig. 1. Tower locations and topography. ADVEX towers A, B, C and D are located around the main tower in the center. Thick dashed and dashed-dotted lines refer to slices in Figs. 4 and 6.

3. Spatial integration of measurements

A modified linear interpolation scheme was used to derive vertical profiles from the measured CO_2 concentrations (henceforward $[CO_2]$) and the horizontal wind components at the four levels of each tower. For more details about profile construction refer to FE08. Each level of these vertical profiles was bi-linearly interpolated in a 10 m × 10 m grid between the four towers to obtain a "data cube" with $[CO_2]$ and horizontal wind components *u* and *v* (corresponding to *east (x)* and *north (y)* directions) for each grid point. From this data set storage change (F_S), vertical (F_{VA}) and horizontal (F_{HA}) advection were calculated according to

$$F_s = \frac{1}{V_m}\frac{z_r}{T}\frac{1}{4}\sum_i \left(\left\langle \overline{c_i}^T\left(\tfrac{T}{2}\right)\right\rangle - \left\langle \overline{c_i}^T\left(-\tfrac{T}{2}\right)\right\rangle\right) \tag{1a}$$

$$F_{VA} = \frac{1}{V_m}\frac{1}{4}\sum_i \overline{w_i}(z_r)\left(\overline{c}_i(z_r) - \langle\overline{c_i}\rangle\right) \tag{1b}$$

$$F_{HA} = \frac{1}{V_m}\frac{\Delta z}{N}\sum_{nx,ny,nz}\left(\overline{u}\frac{\Delta\overline{c}}{\Delta x}(x_j,y_k,z_l) + \overline{v}\frac{\Delta\overline{c}}{\Delta y}(x_j,y_k,z_l)\right), \tag{1c}$$

where V_m is the molar volume of dry air, $\langle c\rangle$ denotes the mean $[CO_2]$ in the control volume under consideration, *T* refers to the time of one averaging period (1 h in this study), and $\overline{w}(z_r)$ represents the mean vertical wind component at the reference height z_r, computed by the planar fit tilt correction algorithm after Wilczak et al. (2001). Index *i* refers to the four ADVEX towers, indices *j, k, l* refer to the *x, y, z* coordinates of the grid points, *N* is the number of grid points in the *x–y* plane, $\Delta c/\Delta x$ and $\Delta c/\Delta y$ are the $[CO_2]$ gradients in *x* and *y* direction at the respective grid point, and Δz is the vertical thickness of a layer as defined by the resolution of the vertical interpolation scheme. According to Eq. (1a)–(1c), the total storage F_S and the total F_{VA} are the respective average of the fluxes at the four ADVEX towers, and total F_{HA} is the average of the vertically integrated F_{HA} at every grid point in the *x–y* plane. For more details of flux computation refer to FE08.

If these fluxes are considered to be representative for the control volume, net ecosystem exchange NEE may be computed as

$$\mathrm{NEE} = F_S + F_C + F_{VA} + F_{HA}, \tag{2}$$