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

Christian Feigenwinter [a,c,*], Meelis Mölder [b], Anders Lindroth [b], Marc Aubinet [a]

[a] Gembloux Agricultural University, Physique des Biosystèmes, Av. de la Faculté 8, B-5030 Gembloux, Belgium
[b] Lund University, GeoBiosphere Science Centre, Physical Geography and Ecosystems Analysis, Lund, Sweden
[c] University of Basel, Institute of Meteorology, Climatology and Remote Sensing, Basel, Switzerland

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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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* Corresponding author at: University of Basel, Institute of Meteorology, Climatology and Remote Sensing, Klingelbergstr., 27, CH-4056 Basel, Switzerland. Tel.: +41 61 267 0754; fax: +41 61 267 0689.
E-mail address: feigenwinter@metinform.ch (C. Feigenwinter).

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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 $3\,\mathrm{l\,min^{-1}}$). 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 × 100 m × 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.

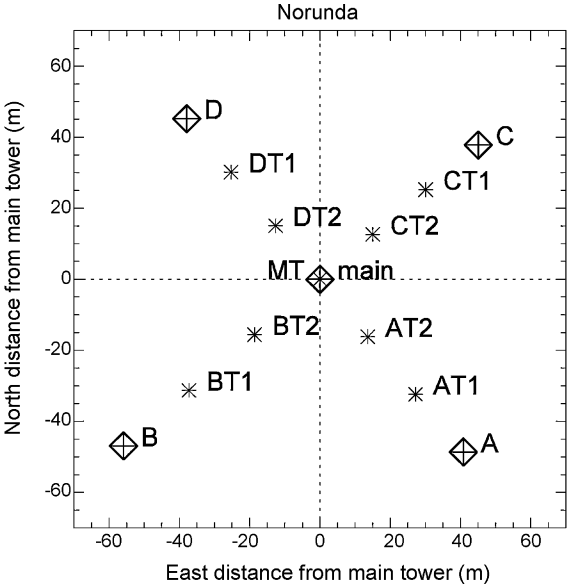

Fig. 1. Location of ADVEX towers A, B, C, D, the Central tower and transect measurement points (AT1, AT2, ...).

The single terms in Eq. (1) are defined as follows:

$$F_S = \int_0^{z_r} \frac{1}{V_m} \frac{\overline{\partial c(z)}}{\partial t} dz \tag{2a}$$

$$F_C = \frac{1}{V_m} \overline{w'c'}(z_r) \tag{2b}$$

$$F_{VA} = \int_0^{z_r} \frac{1}{V_m} \overline{w}(z) \frac{\partial \overline{c}(z)}{\partial z} dz \tag{2c}$$

$$F_{HA} = \frac{1}{4L^2} \int_{-L}^{+L} \int_{-L}^{+L} \int_0^h \frac{1}{V_m} \left(\overline{u}(z) \frac{\partial \overline{c}(z)}{\partial x} + \overline{v}(z) \frac{\partial \overline{c}(z)}{\partial y} \right) dxdydz \tag{2d}$$

where V_m is the molar volume of dry air (mol m^{-3}), L is half the lateral extend of the control volume, c is the CO_2 molar fraction (μmol mol^{-1}), t is the time, u, v, w are the wind velocity components in the x, y and z directions, respectively. Overbars refer to the Reynolds averaging operator and primes to departures of the instantaneous values from the mean. F_S is usually estimated from vertical profile measurements. F_C may be expressed by the measured EC flux at the reference height z_r. The usual sign convention is adopted here according to Lee (1998): a negative flux value indicates CO_2 removal by the forest, and vice versa, a positive value indicates CO_2 release by the forest.

The practical application of these equations differs enormously in the available advection studies, depending on the experimental setup and the available data for the calculation of F_{VA} and F_{HA}. The simpler the setup, the more assumptions must be made for the calculations. The ADVEX experimental setup was designed to measure the advection terms in Eq. (1) with the best possible accuracy to avoid any uncertainties that arise from insufficient resolution of the vertical profiles of CO_2 and wind speed. Other advection studies tried to overcome missing information, e.g. by introducing a “scaling height” (Aubinet et al., 2003) or a “scale factor” (Staebler and Fitzjarrald, 2004; Tóta et al., 2008), assuming similarity of vertical concentration profiles. As shown later in Section 3.2, similarity of profile shape was far from being attained at the Norunda site.

3.1. Meteorological conditions

Fig. 2 gives an overview of the meteorological conditions during the analyzed period. The strong, consistently negative net radiation at night implies clear nights. Temperatures in the sub-canopy were always colder than above the canopy indicating stable conditions in the canopy during the whole period. Wind velocities at the top of the 100 m high Central tower reached up to 8 m s^{-1} and showed generally higher wind speeds at night than during the day. Close above the top of the canopy, wind velocities scattered around 2 m s^{-1} with higher values during daytime and lower values during nighttime. In the canopy at 1.5 m height wind speed was generally below 0.5 m s^{-1}. Wind directions above and below the canopy at 1.5 m did not differ significantly during nighttime, except for a short period in the early morning of DOY 244.

3.2. CO_2 profiles

In particular, CO_2 concentrations (henceforward referred to as [CO_2]) at the same height at all four ADVEX towers were measured with the same IRGA to avoid offset corrections due to different instruments. As a compromise, the vertical profiles at the towers were composed from measurements of two different multi-valve systems and their corresponding IRGAs (heights 30 and 6 m and heights 12 and 1.5 m, respectively). The transect measurements were made by a third IRGA. To correct for the unavoidable offset in absolute concentration between the different IRGAs, all three instruments measured [CO_2] at the same location (common point) at the beginning of each half hour. The difference of this measurement was used to adjust the measurements. We arbitrarily chose one multi-valve system (heights 30 and 6 m) as our reference system and therefore all absolute [CO_2] refer to this system. Note that the choice of the reference system has no impact on the results because all calculations are based on concentration differences rather than absolute values.

The two independent profiles measured at tower B turned out to match nearly perfectly at the same heights after correcting for instrument offset. The comparison shows that the 4-level profile misses some information in the crown space, which could be of relevance during certain periods for the calculation of F_S, F_{VA} and F_{HA}. In between the towers additional CO_2/H_2O measurements were taken, indicated by the cross symbols in Fig. 1. The excellent match of the ADVEX profile when compared with the independent high-resolution LUND profile at tower B provides a high degree of confidence in this method and in our [CO_2] measurements.

The shape of the CO_2 profiles in Norunda was occasionally very different when compared to profiles published in other studies and to profiles at the ADVEX sites in Renon and Wetzstein in particular, where it was possible to fit a log-square (Feigenwinter et al., 2004) or exponential (Leuning et al., 2008) function to the measurements. We frequently observed profiles in the form as shown in Fig. 3a. Sometimes the maximum [CO_2] was even observed at the 12 m level or above. We therefore chose to use a simple interpolation scheme for the vertical profiles as described in FE08. Fig. 3a and b clearly show the deficits of the ADVEX standard profile with 4 levels when compared to the 12-level high-resolution LUND profile at tower B and the permanent profile at the Central tower. During certain situations the mismatch in the layer between the 12 and the 30 m level is large and may probably affect all towers. The mismatch results in over- or underestimation of the [CO_2] in certain layers. In Fig. 3a, [CO_2] at tower B is underestimated by the ADVEX profile in the layer between 6 and 12 m, and overestimated in the layer between 12 and 30 m by the linear interpolation scheme when compared to the LUND profile. On the other hand, [CO_2] is significantly underestimated by the

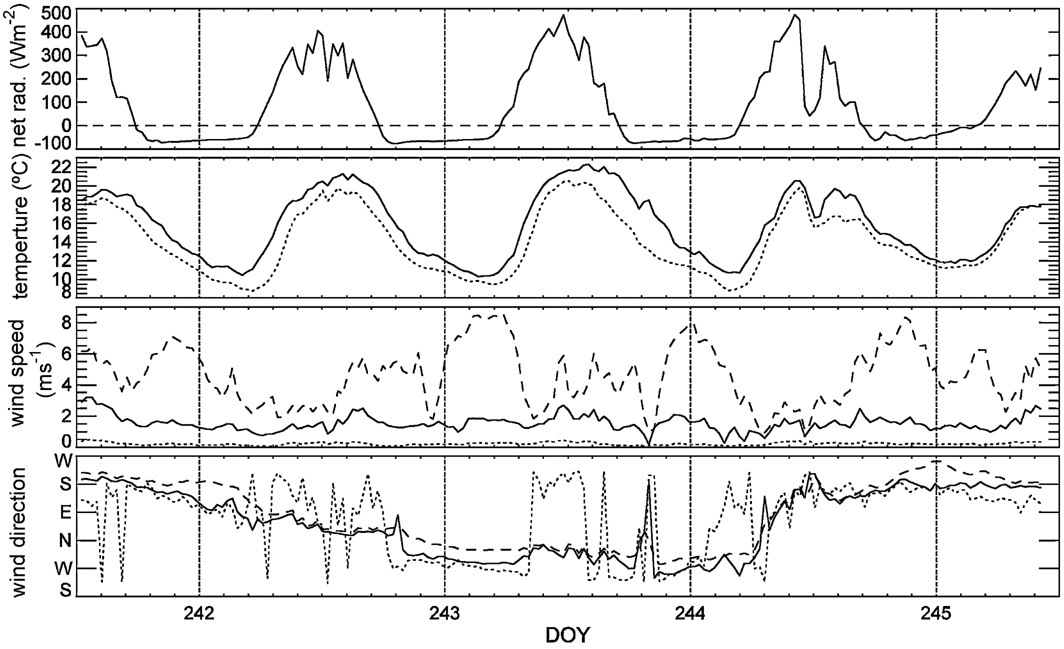

Fig. 2. Meteorological conditions during the period of investigation. From top to bottom: net radiation, average temperature in and above the canopy, average wind speed and average wind direction in and above the canopy. Dashed lines refer to 100 m level at the Central tower, solid lines to 30 m level and dotted lines to the 1.5 m level, respectively. Averages refer to the average of the four ADVEX towers (30 and 1.5 m level).

ADVEX profile at tower B in the crown space in Fig. 3b. The consequences of this imprecision is not clear, since we do not know the exact shape of the profile in this layer at towers A, C and D. The profiles generally coincide close above the canopy top at the 30 m level. Fig. 3a and b additionally shows some typical features which will help to understand the analysis of the advective fluxes in Sections 3.3 and 3.4.

The largest horizontal concentration differences are frequently observed at the 12 m level and not close to the forest floor as observed at the ADVEX sites in Wetzstein and Renon and as reported in other advection studies. As a consequence, this layer contributes most of all to F_{HA}.

The horizontal [CO_2] gradients in the crown space may reach values of up to 1 μmol mol^{-1} m^{-1} or about 40 μmol m^{-4} if expressed in molar density (e.g. the difference at the 12 m level between towers B and A in Fig. 3a). Even assuming a very weak horizontal wind component of 0.1 m s^{-1} along this gradient results in a horizontal advective flux of 4 μmol mol^{-1} m^{-2} s^{-1} for a layer of 1 m thickness according to the definition of F_{HA} in Eq. (2d). Such large fluxes bear no relation to the biotic fluxes (typical value for soil efflux is around 10 μmol m^{-2} s^{-1} (Widén, 2002; Lagergren et al., 2008)).

Crossing profiles between two measurement heights in Fig. 3a let one conclude that the horizontal gradient changes its direction

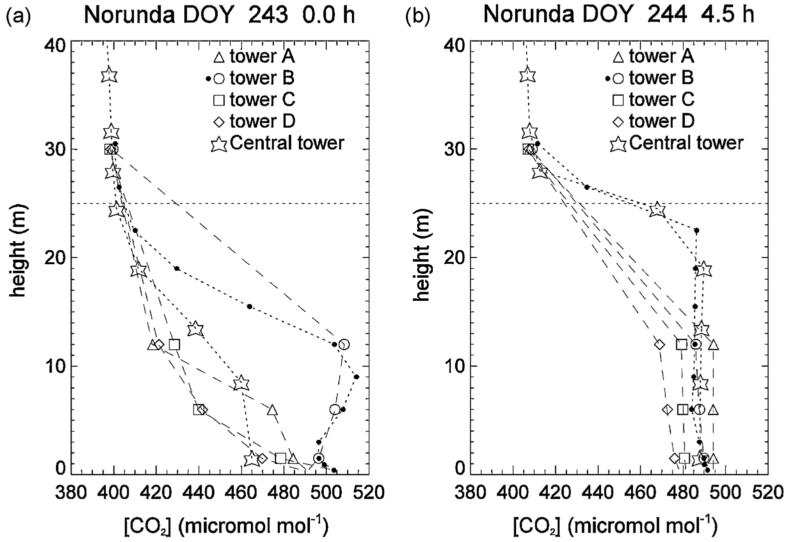

Fig. 3. Profiles of [CO_2] showing the mismatch between the high-resolution profiles at tower B (black circles, dotted line) and at the Central tower (stars, dotted line) and the standard 4 level ADVEX profiles (towers A, B, C and D, dashed lines). (a) Relative [CO_2] overestimation of the ADVEX profile compared to the 12-level high-resolution profile in the crown space (12–25 m) by linear interpolation at tower B. (b) Relative underestimation of [CO_2] in the crown space. The dotted horizontal line indicates the mean canopy height (25 m).

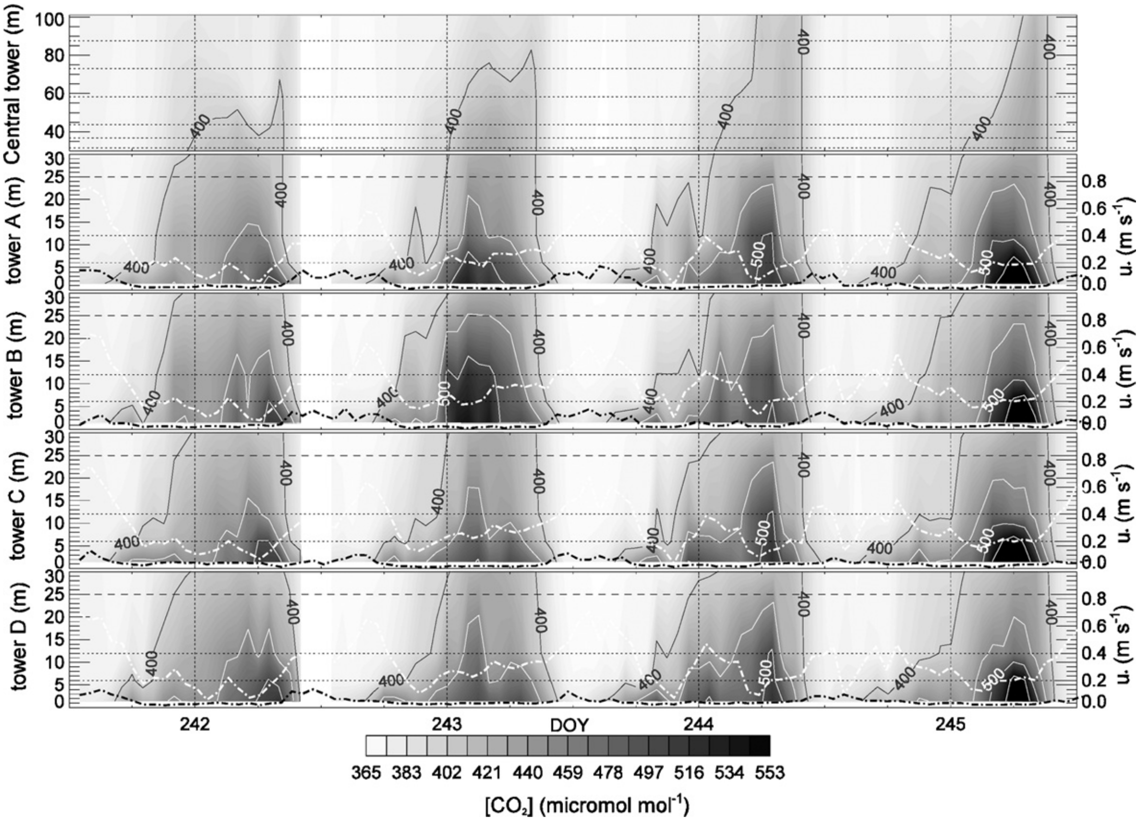

Fig. 4. The evolution of $[CO_2]$ with time and height from DOY 241.5 to 245.5. From top to bottom: Central tower section 30–100 m, ADVEX towers A, B, C and D. Thick solid white and black lines refer to friction velocity u^* at the respective tower in 30 and 1.5 m height, respectively. The scale for u^* is on the right side of the plot. The dashed lines refer to the mean canopy height; the dotted lines refer to heights of the CO_2 measurements. Vertical dotted lines refer to the beginning of the respective DOY (i.e. midnight) on the *x*-axis.

with height. Depending on the wind direction this may result in a change of the magnitude and in some cases even in a change of the sign of F_{HA} with height.

Fig. 3b is representative for a very typical late nighttime situation at the Norunda site. Profiles are practically uniform until high up in the canopy and then quickly collapse close above the canopy. Note that horizontal gradients are still remarkably large at the 12 m level. It seems that lakes of CO_2 are building up during a certain period of time and then they are partly dissipated leading to profile-shapes as shown in Fig. 3a.

CO_2 concentrations above the canopy are still notably high compared to other forests. We frequently observed $[CO_2] > 400\ \mu\text{mol mol}^{-1}$ in 100 m height at the Central tower as shown in Fig. 4. Such high concentrations are only rarely reported in literature at these heights (e.g. Bakwin et al., 1998; Yi et al., 2001; Hurwitz et al., 2004).

Fig. 4 shows the evolution of CO_2 concentrations during the period under investigation at the four ADVEX towers and the upper part of the Central tower. Note that these nights were not totally calm, though there were some calm periods as shown in Fig. 2. u^* at the 30 m level was higher than $0.2\ \text{m s}^{-1}$ for most of the time.

Although $[CO_2]$ differences between towers can be large for a short period of time (e.g. the period 4–6 h on DOY 243), all four nights show a consistent general pattern in the evolution of the $[CO_2]$ distribution: CO_2 starts to accumulate early in the evening, when net radiation is most negative, in a strongly stable layer close to the forest floor. With ongoing night the stratification in the trunk space becomes less stable or even neutral and allows CO_2 to accumulate in this layer with a nearly uniform vertical distribution up to the 12 m level and higher. In the second part of the night the largest vertical gradients of $[CO_2]$ and temperature are observed in the crown space (Figs. 5 and 6). With the onset of turbulence at sunrise, the profiles collapse quickly first in the crown space and then in the trunk space. A stable layer holds permanently close to the forest floor also during the day. Comparing Fig. 5a,c with b,d shows again the failure of the ADVEX setup in properly resolving the crown space layer between 12 and 30 m. Note that we did not observe such behaviour during the previous ADVEX campaigns in Wetzstein and Renon (FE08). Fig. 4 also suggests that the storage change term F_S is occasionally large and may frequently change its sign during such nights.

3.3. Vertical advection

Lee's (1998) method was used for the calculation of F_{VA} applying the sectorwise (18 sectors) planar-fit tilt-correction algorithm according to Wilczak et al. (2001) for the calculation of the mean vertical wind component. See FE08 for more details.

The mean vertical wind component $\bar{w}$ is the crucial variable for vertical advection when computed according to Eq. (2c). Its sign defines the direction of F_{VA} because the mean vertical $[CO_2]$ gradient between the forest floor and the reference height above the canopy is always negative during nighttime. However, $\bar{w}$ is small and close to the measurement accuracy of sonic anemometers ($0.05\ \text{m s}^{-1}$). Additionally, the application of different tilt correction algorithms may even result in different signs of $\bar{w}$ for the same situation (Vickers and Mahrt, 2006), especially when vertical motions are weak (e.g. during calm nights). Together with the large vertical $[CO_2]$ gradients observed at the Norunda site, this results in large fluxes of F_{VA} in either direction, frequently changing sign from 1 h to the other during the night. Fig. 7 shows F_{VA} and its components for the four ADVEX towers for the period under

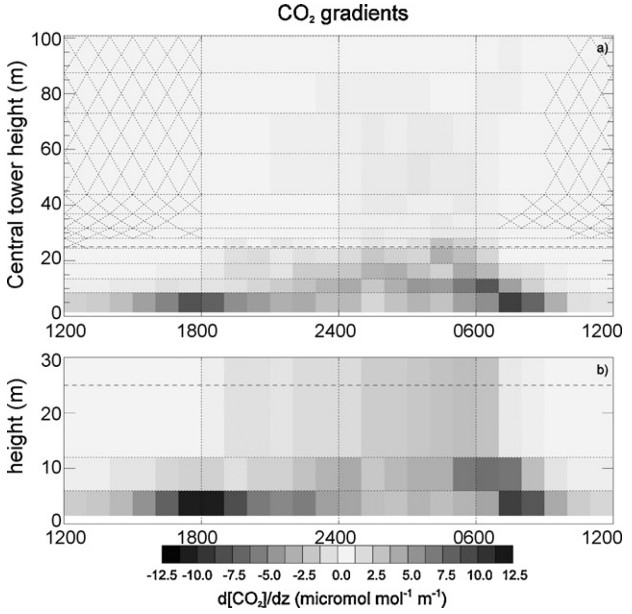

Fig. 5. Mean diurnal distribution of vertical $[CO_2]$ gradients for the period from DOY 241.5 to 245.5. (a) $[CO_2]$ gradient at Central tower and (b) mean $[CO_2]$ gradient at ADVEX towers (average of all four ADVEX towers. Dashed lines refer to mean canopy height, dotted horizontal lines refer to measurement heights, cross hatched regions refer to positive gradients according to gray scales.

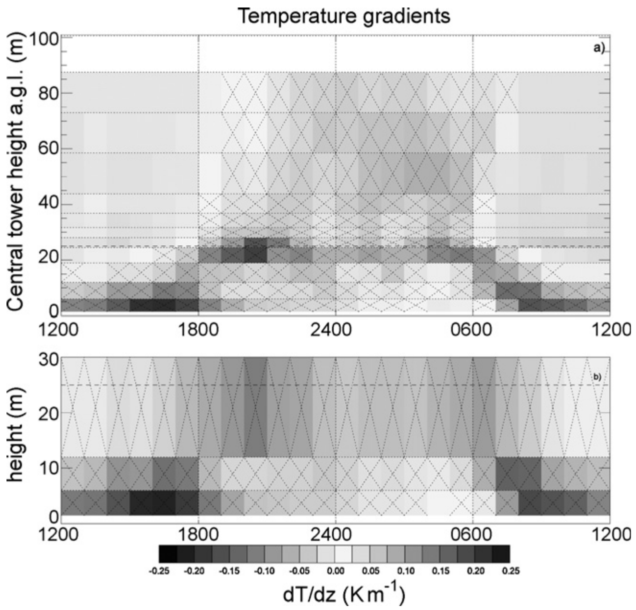

Fig. 6. As Fig. 5 but for potential temperature gradients. (a) Temperature gradient at Central tower and (b) temperature gradient at ADVEX towers (average of all four ADVEX towers). Dashed lines refer to mean canopy height, dotted horizontal lines refer to measurement heights, cross hatched regions refer to positive gradients according to gray scales.

investigation. $\bar{w}$ is very low and no persistent diurnal pattern and no clear correlation between the different towers is recognizable. This is in contrary to the Wetzstein and the Renon site, where all towers show similar patterns of $\bar{w}$ and thus also for F_{VA} (FE08). It rather seems that $\bar{w}$ scatters more or less arbitrarily around the zero line and so does the respective flux in Fig. 7c. At times, single tower F_{VA} reaches values exceeding ±50 μmol m^{-2} s^{-1}. In contrast, the evolution of the vertical gradient in Fig. 7b, expressed by the difference between $[CO_2]$ at the reference level and the mean concentration in the volume below according to Lee (1998), shows a consistent pattern of increasing CO_2 storage in the trunk space during each night. Although Fig. 7b represents mainly the vertical $[CO_2]$ gradient at the different towers, it also provides relevant information about the mean horizontal concentration distribution. In the extreme case (the night from DOY 242 to 243) differences in *mean* $[CO_2]$ may be as large as 50 μmol mol^{-1} between towers. Not surprisingly F_{HA} is unusually high, as discussed in the next section.

The large absolute values of F_{VA} clearly have its origin in the large vertical $[CO_2]$ gradients, while its large scatter and its uncertainty has two reasons: (a) measurement accuracy of the mean vertical wind component and (b) tilt correction algorithm. The combination of both decides if the flux is positive or negative. Since the terrain in Norunda is totally flat, the choice of a certain tilt correction algorithm is not that crucial as in complex terrain, because it mainly corrects for the tilt of the instrument and only to a lesser part for influences of topography and/or vegetation heterogeneities. We therefore conclude that it is the error in the measurement of the vertical wind component that is the main reason for the uncertainty of F_{VA}. Theoretically, the approach using the continuity condition to estimate the mean vertical wind component is certainly the best one, as proposed by Vickers and Mahrt (2006) and Heinesch et al. (2007). However, in practice, its success will also depend on the experimental setup and especially the spatial resolution and the accuracy of the measurements. In fact, an experimental approach to estimate the *true* meteorological vertical wind component based on the continuity condition probably requires even higher instrument accuracy than any tilt correction algorithm.

3.4. Horizontal advection

In contrary to F_{VA}, insufficient instrument accuracy can be excluded as a main source of error in evaluating F_{HA} at the Norunda site. Though horizontal wind velocities were small in the sub-canopy layer during the investigated nights, they are at least 2–4 times larger than sonic instrument specifications. The estimation of the horizontal $[CO_2]$ gradient could be another crucial point for the calculation of F_{HA} as addressed by Heinesch et al. (2007). This may be true for small horizontal $[CO_2]$ differences in the control volume together with high wind speeds, which could result in high F_{HA}. Such conditions were observed, e.g. during the ADVEX campaign in Renon during synoptically dominated strong wind conditions (Feigenwinter et al., 2010; Aubinet et al., 2010; Canepa et al., 2010). However, in Norunda, the situation is different: Horizontal $[CO_2]$ differences are much larger than the specification of the Li-6262, which is around ±1 μmol mol^{-1}. In addition, the precision of the measurements was further increased by using the same analyzer for the measurements at the same height and tubes of the same length. The precision was also confirmed by comparison with the independent LUND profile at tower B. Though we are aware that the accuracy of $[CO_2]$ not only depends on instrument specification, but also on the analyser's stability (e.g. during a 30 min period), the air transporting and valve switching system and the number of measurements (11 in our case) during one half hour, we exclude instrument accuracy as a relevant source of error for F_{HA}, because in this case, horizontal $[CO_2]$ differences are in the order of tens of μmol mol^{-1}.

As addressed in the discussion of the $[CO_2]$ profiles in Section 3.2, the missing information in the crown space between 12 and 30 m results in an underestimation or overestimation of $[CO_2]$ and we do not know about the behaviour of the horizontal gradient in this obviously very "active" layer. Nevertheless the measurements at the 1.5, 6, and 12 m levels already show the characteristics of the wind field and the CO_2 distribution which

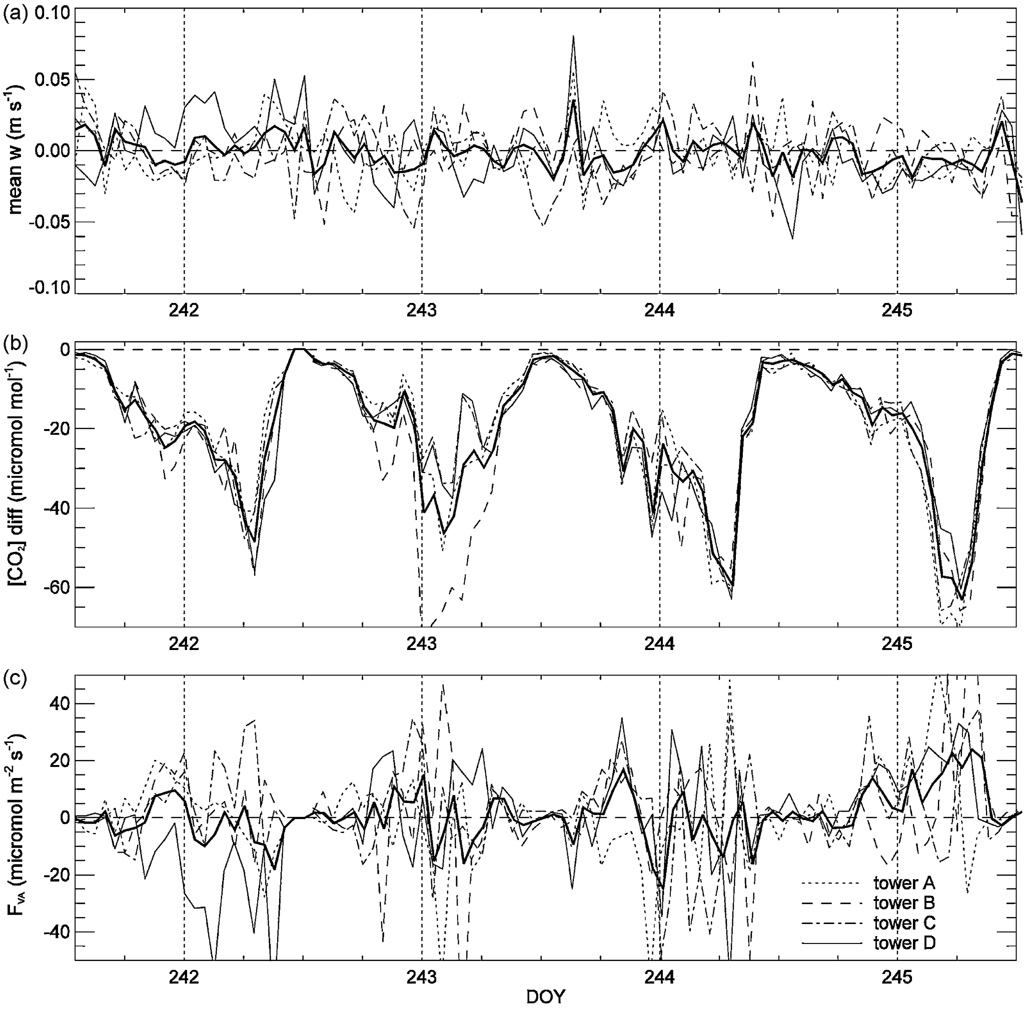

Fig. 7. F_{VA} and its components (a) mean vertical velocity component and (b) [CO_2] differences between the reference height above the canopy and the mean concentration in the volume below. Thin lines refer to ADVEX towers A, B, C and D. The thick black line represents the average of the four ADVEX towers.

determine the size and the direction of F_{HA} during these nights. Fig. 8 shows the particular situation from Fig. 3a in the spatial context. It demonstrates the facts that lead to confusing values of F_{HA}.

Largest horizontal [CO_2] gradients do not necessarily occur close to the forest floor. Indeed we observe the largest gradients at the 12 m level in Fig. 8c.

Horizontal [CO_2] gradients may change direction with height. In the example from DOY 243 at midnight in Fig. 8, highest [CO_2] are

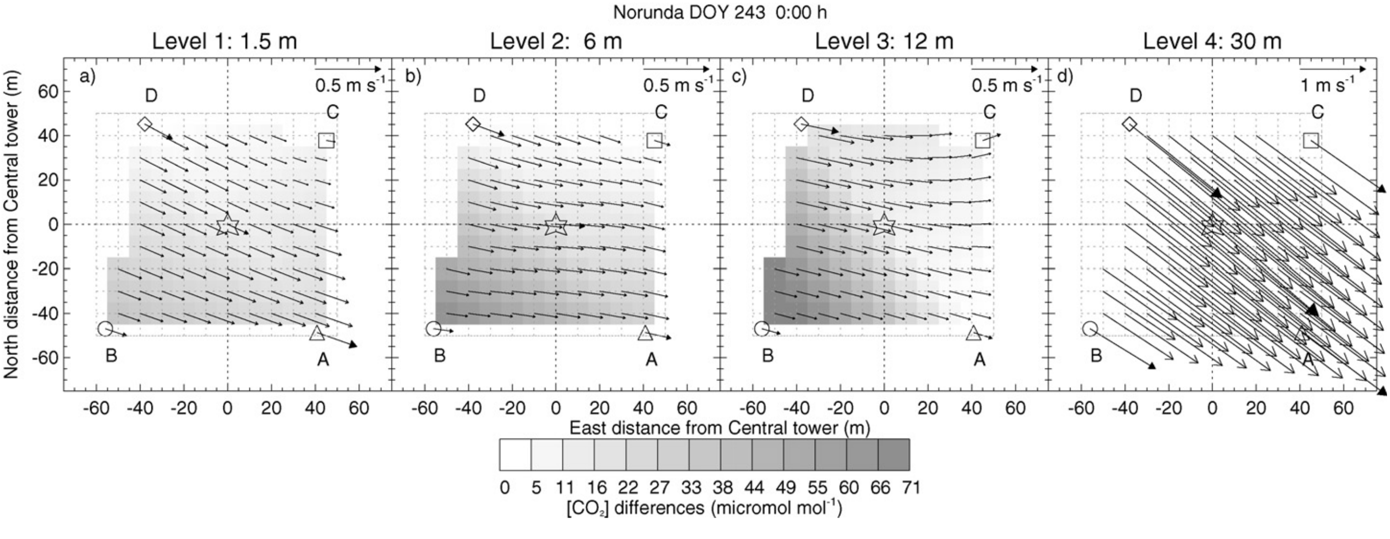

Fig. 8. Wind field and [CO_2] differences on DOY 243 0:00 h at levels 1–4 (left to right). Thick arrow heads refer to measurements at towers, thin arrow heads are derived by bi-linear interpolation between towers. Gray scales refer to [CO_2] differences relative to the point with the lowest [CO_2].

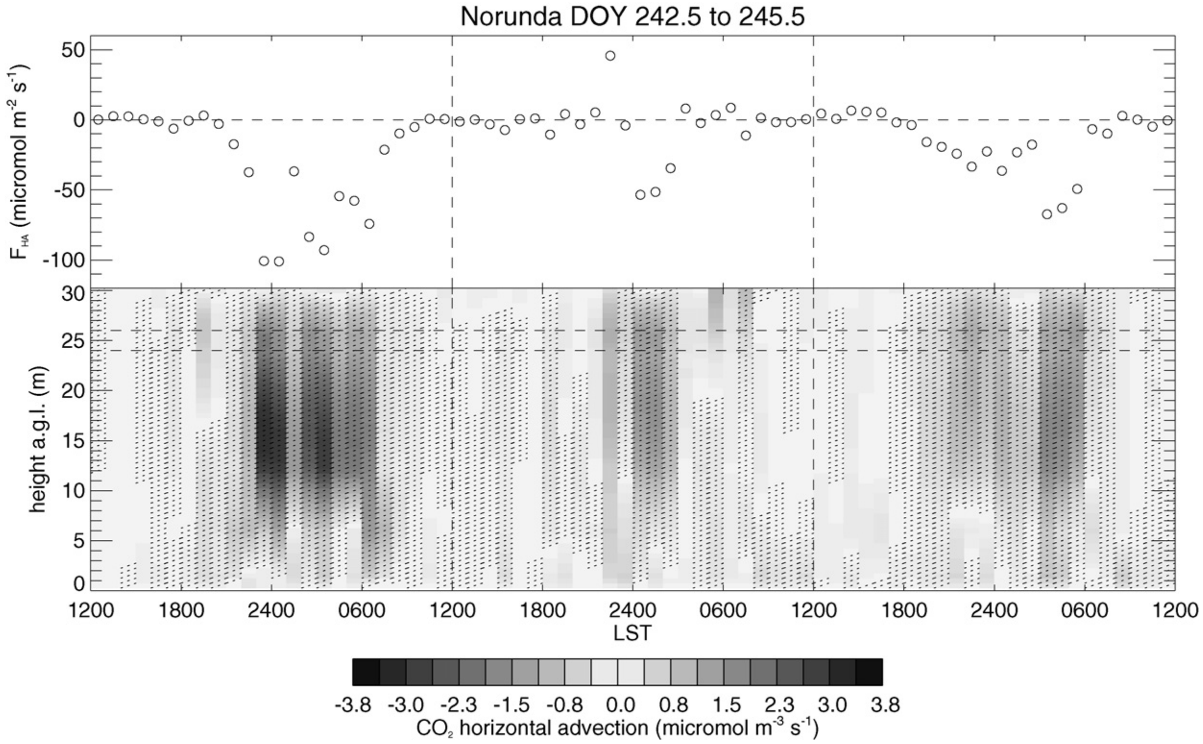

Fig. 9. Vertical distribution (bottom) and total (top) F_{HA} for the period from DOY 242.5 to 245.5. Hatched regions refer to negative values of F_{HA} according to gray scales.

observed near tower B at all levels, but the location of lowest [CO$_2$] moves from somewhere between towers C, D and Central tower at level 1.5 m in Fig. 8a to tower C at level 6 m in Fig. 8b and to tower A at level 12 m in Fig. 8c.

Horizontal wind vectors, though in general similar, show differences in magnitude and direction with height which are relevant for the computation of F_{HA}.

Due to (ii) and (iii), F_{HA} may be positive and negative at the same time at different locations (grid points) in the control volume. Assuming constant wind velocity and a constant [CO$_2$] gradient, absolute values of F_{HA} are largest when the wind is blowing parallel to the gradient (in either direction) and zero when blowing perpendicular to the gradient. As shown in Fig. 8 this can result in a quite heterogeneous distribution of F_{HA} in the same horizontal layer, though in general the wind blows from regions of higher [CO$_2$] to regions with lower [CO$_2$] and thus results in negative total F_{HA}.

The horizontal [CO$_2$] gradient completely disappears above the canopy at the 30 m level in Fig. 8d and so does F_{HA}.

The vertical distribution of F_{HA} during the analyzed nights in Fig. 9 shows that maximum horizontal advective fluxes concentrate in the crown space and in the second part of the night, i.e. after midnight. If positive values occur during nighttime, they are small and often observed in the trunk space. Vertical integration then results in very high negative fluxes, as shown in the upper panel of Fig. 9. Knowing that these fluxes are not a result of erroneous measurements, but are nearly one order of magnitude larger than the biotic fluxes during nighttime (i.e. total ecosystem respiration), the question arises, what do they represent?

4. Discussion and conclusions

Maximum horizontal and vertical [CO$_2$] gradients in Norunda were frequently observed in the crown space during nighttime. Similar vertical [CO$_2$] profiles as presented in Fig. 3b were observed in tropical forests by Goulden et al. (2006), de Araújo et al. (2008) and Tóta et al. (2008), showing a nearly uniform vertical CO$_2$ profile throughout the lower and middle canopy and a sharp gradient in the upper part of the canopy. But, to our knowledge, none of the previous advection studies reported such large horizontal gradients (and coinciding horizontal advection) in the upper part of the canopy as we observed in Norunda. Similar phenomenon is likely to occur also at other flux tower sites. However, standard flux tower equipment is not able to detect horizontal gradients and the resolution of the vertical [CO$_2$] profiles is often densest close to the ground and may therefore miss the special features of the presented vertical profiles.

In fact, when reviewing advection studies published until to date, the way of calculating the advective fluxes, and F_{HA} in particular, is far from being standardized and often quite visionary. The fact that horizontal gradients may change direction with height, which will have an impact on the size and sign of F_{HA}, is often ignored by the introduction of generalized profile shapes for [CO$_2$] and wind velocities. All studies mention the large scatter and the large uncertainty, however, extreme values and their origin are seldom quantified nor presented. Though being aware that small errors in wind velocities, wind directions and horizontal [CO$_2$] gradients can produce large errors in F_{HA}, we showed that such errors are not the reason for the large fluxes presented in this study. While uncertainty in F_{VA} is clearly related to the problem of measurement accuracy of the vertical wind component and incomplete tilt correction algorithms in connection with large vertical [CO$_2$] gradients, we can exclude measurement errors as a source for the large F_{HA}, even if they would be in the range of several μmol m^{-2} s^{-1}. One may also question how bi-linear interpolation maps the real conditions in the control volume between towers. However, more detailed spatial information about canopy structure, source strength, flow properties and [CO$_2$] distribution in the control volume would be necessary to develop a more sophisticated methodology. Needless to mention that even then, we will probably end up with the same problems.

The good correlation between vertical temperature gradients and CO_2 gradients in the second part of the night at crown space height, as shown in Figs. 5 and 6, suggests a strong decoupling of the canopy sub-layer from the surface roughness layer above. Yi (2008) hypothesized about a "super stable layer" developing during the night in sloping terrain at the Niwot Ridge AmeriFlux site and confirmed their findings by a SF_6 tracer experiment. According to this assumption, the main environmental characteristics leading to the formation of the "super stable layer" are: slow mean air-flow, minimum vertical exchange, maximum density of drag elements, maximum $[CO_2]$ gradient (or other scalar). They concluded that horizontal advection occurs only below this layer, where no mean vertical movement of air exists (longitudinal exchange zone). Above this layer, on the other hand, only the mean (and turbulent) vertical exchange is important (vertical exchange zone). Though not directly comparable, similar conditions characterize the stratification in the second part of the investigated Norunda nights and it remains to be tested, if the supposition of a "super stable layer" is applicable. The impact of a separation into a "longitudinal" and "vertical" exchange layer and calculating the advective fluxes according to this hypothesis would significantly reduce the absolute values of these fluxes.

In this study we presented some extreme nights, but FE08 showed, that F_{HA} was consistently negative at night in Norunda during the complete measurement campaign. Moreover, it turned out that F_{HA} of CO_2 and sensible heat are negatively correlated at all three ADVEX sites (not shown). For Norunda this means that positive horizontal advection of sensible heat was observed. The role of the massive Central tower acting as a thermal conductor should be further investigated in this context.

It remains to be clarified what the measured advective fluxes are representing.

Though there are still a lot of open questions, the present analysis provides new insights into the mechanisms at work in forest (sub-)canopies during stable and calm nights. On the other hand it also shows the limitations of our experimental approach. The spatial (horizontal and vertical) resolution of the measurement points (as dense as possible) and the size of the control volume (big enough!) are two crucial points which limit each other when designing the experimental setup. Advection is most likely a scale-overlapping process from the microscale (up to 100 m) to the mesoscale (up to 10 km). With the probed volume of about $100\ \text{m} \times 100\ \text{m} \times 30\ \text{m}$ we were not able to adequately sample mesoscale motions, which may play an important role at the Norunda site. Additional complications are that wind velocities (horizontal and vertical) in the canopy during nearly calm and stable nights are very low and the wind directions are changing frequently within one half hour. Half hourly averages of wind components may therefore not correctly represent these features and the analysis has also to be extended to the turbulence scale.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Adv. Ecol. Res. 30, 113–175.

Aubinet, M., Heinesch, B., Yernaux, M., 2003. Horizontal and vertical CO_2 advection in a sloping forest. Bound. Layer Meteorol. 108, 397–417.

Aubinet, M., Berbigier, P., Bernhofer, C.H., Cescatti, A., Feigenwinter, C., Granier, A., Grünwald, T.H., Havrankova, K., Heinesch, B., Longdoz, B., Marcolla, B., Montagnani, L., Sedlak, P., 2005. Comparing CO_2 storage and advection conditions at night at different CarboEuro sites. Bound. Layer Meteorol. 116, 63–94.

Aubinet, M., Feigenwinter, C., Bernhofer, C., Canepa, E., Lindroth, A., Montagnani, L., Rebmann, C., Sedlak, P., Van Gorsel, E., 2010. Advection is not the solution to the nighttime CO_2 closure problem—evidence from three inherently different forests. Agric. Forest Meteorol. 150, 655–664.

Bakwin, P.S., Tans, P.P., Hurst, D.F., Zhao, C., 1998. Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. Tellus 50B, 401–415.

Baldocchi, D.D., 2008. "Breathing" of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. Aust. J. Bot. 56, 1–26.

Baldocchi, D.D., Finnigan, J.J., Wilson, K.W., Paw, U.K.T., Falge, E., 2000. On measuring net ecosystem carbon exchange in complex terrain over tall vegetation. Bound. Layer Meteorol. 96, 257–291.

Baldocchi, D.D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, D., Anthoni, P.M., Bernhofer, C., Davis, K.J., Evans, R., Fuentes, J.D., Goldstein, A.H., Katul, G.G., Law, B.E., Lee, Z., Malhi, Y., Meyers, T.P., Munger, W., Oechel, W., Paw, U.K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S.B., Vesala, T., Wilson, K.B., Wofsy, S.C., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Met. Soc. 82 (11), 2415–2434.

Canepa, E., Feigenwinter, C., Georgieva, E., Manca, G., Montagnani, L., 2010. Application of a mass consistent flow model to study the CO_2 mass balance of forests. Agric. Forest Meteorol. 150, 712–723.

De Araújo, A., Kruijt, B., Nobre, A.S., Dolman, A.J., Waterloo, M.J., Moors, E.J., de Souza, J.S., 2008. Nocturnal accumulation of CO_2 underneath a tropical forest canopy along a topographical gradient. Ecol. Appl. 18, 1406–1419.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Ta Lai, C., Law, B., Meyers, T., Moncrieff, J., Moors, E.J., Munger, J.W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. Forest Meteorol. 107, 43–69.

Feigenwinter, C., Bernhofer, C., Vogt, R., 2004. The influence of advection on the short term CO_2-budget in and above a forest canopy. Bound. Layer Meteorol. 113, 201–204.

Feigenwinter, C., Bernhofer, C., Eichelmann, U., Heinesch, B., Hertel, M., Janous, D., Kolle, O., Lagergren, F., Lindroth, A., Minerbi, S., Moderow, U., Mölder, M., Montagnani, L., Queck, R., Rebmann, C., Vestin, P., Yernaux, M., Zeri, M., Ziegler, W., Aubinet, M., 2008. Comparison of horizontal and vertical advective CO_2 fluxes at three forest sites. Agric. Forest Meteorol. 148, 12–24.

Feigenwinter, C., Montagnani, L., Aubinet, M., 2010. Plot-scale vertical and horizontal transport of CO_2 modified by a persistent slope wind system in and above an alpine forest. Agric. Forest Meteorol. 150, 665–673.

Finnigan, J.J., 1999. A comment on the paper by Lee (1998): on micrometeorological observations of surface-air exchange over tall vegetation. Agric. Forest Meteorol. 97, 55–64.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biol. 2, 169–182.

Goulden, M.L., Miller, S.D., da Rocha, H.R., 2006. Nocturnal cold air drainage and pooling in a tropical forest. J. Geophys. Res.-Atmos. 111, D08S04, doi:10.1029/2005JD006037.

Gu, L., Falge, E., Boden, T., Baldocchi, D.D., Black, T.A., Saleska, S.R., Suni, T., Vesala, T., Wofsy, S., Xu, L., 2005. Observing threshold determination for nighttime eddy flux filtering. Agric. Forest Meteorol. 128, 179–197.

Heinesch, B., Yernaux, M., Aubinet, M., 2007. Some methodological questions concerning advection measurements: a case study. Bound. Layer Meteorol. 122, 457–478.

Heinesch, B., Yernaux, M., Aubinet, M., 2008. Dependence of CO_2 advection patterns on wind direction on a gentle forested slope. Biogeosciences 5, 657–668.

Hurwitz, M.D., Ricciuto, D.M., Bakwin, P.S., Davis, K.J., Wang, W., Yi, C., Butler, M.P., 2004. Transport of carbon dioxide in the presence of storm systems over a northern Wisconsin forest. J. Atmos. Sci. 61, 607–618.

Lagergren, F., Eklundh, L., Lundblad, M., Grelle, A., Mölder, M., Lankreijer, H., Lindroth, A., 2005. Net primary production and light use efficiency in a mixed coniferous forest in Sweden. Plant Cell Environ. 28, 412–423.

Lagergren, F., Lindroth, A., Dellwick, E., Ibrom, A., Lankreijer, H., Launiainen, S., Mölder, M., Kolari, P., Pilegaard, K., Vesala, T., 2008. Biophysical controls on CO_2 fluxes of three Northern forests based on long-term eddy covariance data. Tellus 60B, 143–152.

Lee, X.H., 1998. On micrometeorological observations of surface-air exchange over tall vegetation. Agric. Forest Meteorol. 91, 39–49.

Leuning, R., Zegelin, S.J., Jones, K., Keith, H., Hughes, D., 2008. Measurement of horizontal and vertical advection of CO_2 within a forest canopy. Agric. Forest Meteorol. 148, 1777–1797.

Lindroth, A., Grelle, A., Morén, A.-S., 1998. Long-term measurements of boreal forest carbon balance reveals large temperature sensitivity. Global Change Biol. 4, 443–450.

Loescher, H.W., Law, B.E., Mahrt, L., Hollinger, D.Y., Campbell, J., Wofsy, S.C., 2006. Uncertainties in, and interpretation of, carbon flux estimates using the eddy covariance technique. J. Geophys. Res.-Atmos. 111, D21S90, doi:10.1029/2005JD006932.

Lundin, L.-C., Halldin, S., Lindroth, A., Cienciala, E., Grelle, A., Hjelm, P., Kellner, E., Lundberg, A., Mölder, M., Morén, A.-S., Nord, T., Seibert, J., Stähli, M., 1999. Continuous longterm measurements of soil-plant-atmosphere variables at a forest site. Agric. Forest Meteorol. 98–99, 53–73.

Marcolla, B., Cescatti, A., Montagnani, L., Manca, G., Kerschbaumer, G., Minerbi, S., 2005. Importance of advection in the atmospheric CO_2 exchanges of an alpine forest. Agric. Forest Meteorol. 130, 193–206.

Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agric. Forest Meteorol. 113, 121–144.

Mölder, M., Grelle, A., Lindroth, A., Halldin, S., 1999. Flux–profile relationships over a boreal forest—roughness sublayer corrections. Agric. Forest Meteorol. 98–99, 645–658.

Mölder, M., Lindroth, A., Halldin, S., 2000. Water vapor, CO_2, and temperature profiles in and above a forest—accuracy assessment of an unattended measurement system. J. Atmos. Ocean. Technol. 417–425.

Moncrieff, J.B., Malhi, Y., Leuning, R., 1996. The propagation of errors in long-term measurements of land atmosphere fluxes of carbon and water. Global Change Biol. 2, 231–240.

Papale, D., Valentini, R., 2003. A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatialization. Global Change Biol. 9, 525–535.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofere, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., Yakir, D., 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation. Biogeosciences 3, 571–583.

Paw, U.K.T., Baldocchi, D.D., Meyers, T.P., Wilson, K.B., 2000. Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. Bound. Layer Meteorol. 97, 487–511.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biol. 11, 1424–1439.

Staebler, R.M., Fitzjarrald, D.R., 2004. Observing subcanopy CO_2 advection. Agric. Forest Meteorol. 122, 139–156.

Sun, J., Burns, S.P., Delany, A.C., Oncley, S.P., Turnipseed, A.A., Stephens, B.B., Lenschow, D.H., LeMone, M.A., Monson, R.K., Anderson, D.E., 2007. CO_2 transport over complex terrain. Agric. Forest Meteorol. 145, 1–21.

Tóta, J., Fitzjarrald, D.R., Staebler, R.M., Sakai, R.K., Moraes, O.M.M., Acevedo, O.C., Wofsy, S.C., Manzi, A.O., 2008. Amazon rain forest subcanopy flow and the carbon budget: Santarém LBA-ECO site. J. Geophys. Res. 113 , doi:10.1029/2007JG00597 G00B02.

Valentini, R., Matteucci, G., Dolman, H., Schultze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalsky, A.S., Vesala, T., Rannik, U., Berbigier, P., Lousteau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Vickers, D., Mahrt, L., 2006. Contrasting mean vertical motion from tilt correction methods and mass continuity. Agric. Forest Meteorol. 138, 93–103.

Wang, W., Davis, K.J., Cook, B.D., Bakwin, P., Yi, C., Ricciuto, D., Butler, M., 2005. Surface layer CO_2 budget and advective contributions to measurements of net ecosystem atmosphere exchange of CO_2. Agric. Forest Meteorol. 135, 202–214.

Widén, B., 2002. Seasonal variation in forest-floor CO_2 exchange in a Swedish coniferous forest. Agric. Forest Meteorol. 111, 283–297.

Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithm. Bound. Layer Meteorol. 99, 127–150.

Yi, C., 2008. Momentum transfer within canopies. J. Appl. Meteorol. Clim. 47, 262–275.

Yi, C., Davis, K.J., Berger, B.W., Bakwin, P.S., 2001. Long-term observations of the dynamics of the continental planetary boundary layer. J. Atmos. Sci. 58, 1288–1299.

Yi, C., Anderson, D., Turnipseed, A., Burns, S., Sparks, J., Stannard, D., Monson, R., 2008. The contribution of advective fluxes to net ecosystem exchange in a high-elevation, subalpine forest. Ecol. Appl. 18 (6), 1379–1390.