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Determining the contribution of vertical advection to the net ecosystem exchange at Hyytiälä forest, Finland

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ABSTRACT

In nighttime the importance of advection processes to full carbon balance estimated by micrometeorological methods is pronounced. The vertical advection needs the determination of mean vertical velocity which can be obtained from planar fitting, which is the determination of mean local streamline coordinates based on the statistics of the wind field measured over long periods. We tested the utilization of planar-fitting based vertical advection using long-term eddy covariance and CO_2 concentration gradient data at SMEAR II field station (Hyytiälä, Southern Finland). The vertical-advection corrected carbon balance, without any friction velocity filtering, agrees very well with those obtained by filtering and gap-filling procedure, and those by chambers and ecosystem model. Although no direct measurements for horizontal advection is available, the results indicate minor significance of horizontal advection in the studied cases.

1. Introduction

The most direct and presently most common technique to measure trace gas fluxes is the eddy covariance (EC) technique. Since the 1990s, direct flux measurements sites are getting more and more numerous. The commercial availability of the fast-response gas analysers for various atmospheric compounds has significantly improved. The EC technique facilitates direct turbulent flux measurements without affecting the natural gas transfer between the surface and the air (Baldocchi, 2003). In the traditional usage of the EC approach the surface exchange is estimated from the measurements of turbulent fluctuations together with measurements of temporal changes of vertical concentration profile, on which the storage flux is calculated. However, the full mass balance equation for the net ecosystem exchange (NEE) includes also advection terms, which are difficult to assess on routine basis. The estimate of NEE through a horizontal plane at height z_r is usually written as:

$$\mathrm{NEE} = \int_0^{z_r} \frac{\partial c(z)}{\partial t}\,\mathrm{d}z + (\overline{w'c'})_{z_r} + \int_0^{z_r} \overline{w}(z)\frac{\partial \overline{c}(z)}{\partial z}\,\mathrm{d}z + \int_0^{z_r}\left[\overline{u}(z)\frac{\partial \overline{c}(z)}{\partial x} + \overline{v}(z)\frac{\partial \overline{c}(z)}{\partial y}\right]\mathrm{d}z, \tag{1}$$

where on the right-hand side, the first term is the storage change, the second is the EC flux, the third and the fourth terms are the vertical and horizontal advective flux, respectively (Feigenwinter et al., 2004 and many others). Here z_r denotes the measurement height above the canopy. In eq. (1), we have neglected the horizontal turbulent flux divergence terms and the horizontal variation of vertical flux, expected to have very small contribution at spatially homogeneous forest sites with respect to the other terms (Staebler and Fitzjarrald, 2004). Whereas the turbulent transport and the storage change are routinely measured, the advective terms are typically not known, because of the larger uncertainty on the estimation of the mean vertical velocity and the horizontal CO_2 gradient. However, recently remarkable theoretical and experimental efforts have been made in order to estimate these terms in many micrometeorological sites (Aubinet et al., 2005).

The importance of the advective fluxes becomes critical mainly during the stable night conditions, when the CO_2 exchange, based on EC and storage change fluxes, is underestimated. Besides the instrumental errors, meteorological limitations (as gravity waves, advection, large footprints), induced by topography and flow/sources heterogeneities have a strong influence on NEE estimation (Massman and Lee, 2002). Measurements of vertical and horizontal advection differ drastically since in its simplicity the vertical advection can be estimated by a single tower whereas the horizontal one requires measurements at several horizontal locations. However, the vertical velocities associated with the vertical bulk transport are very small and prone to significant measurements biases. The attempts to assess the vertical advection have utilized indirect methods to estimate the vertical velocity, like tilt correction methods (Lee, 1998; Paw U et al., 2000; Wilczak et al., 2001) and an approach based on

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the continuity equation. In the latter one, several vertical profiles of horizontal velocities are measured. In spite of an evident robustness (being more representative than a single point estimation of $\overline{w}$), this approach presents several technical problems concerning the difficulty to have long-term spatially distributed profile measurements. At present only one recent study (Vickers and Mahrt, 2006) has applied this method to estimate the mean vertical velocity. The main conclusion was that there is a statistically significant difference between the $\overline{w}$ estimates based on the mass continuity approach and those based on tilt correction methods. The high degree of complexity of the site of Vickers and Mahrt (2006), characterized by an abrupt surface roughness change, may be the main reason of this disagreement.

Lee (1998) was the first one to use the tilt correction for the vertical advection problem. He presented the measured mean vertical velocity as a function of the true mean vertical velocity, the measured horizontal velocity and wind direction dependent coefficients. The tilt correction technique let us to estimate the mean vertical velocity, and then, together with a concentration profile, the vertical advective flux of CO_2. However, the method does not successfully correct nocturnal mass balance if the horizontal advection is ignored (Aubinet et al., 2003; Heinesch et al., 2007), although, in theory, in the case of the positive vertical advection (which regularly occurs in the night) and for a horizontally homogeneous site the horizontal advection should be very small (M. Aubinet, 2006, personal communication). We hypothesize that this is the case in Hyytiälä flux tower site and study it here.

We applied the planar fitting method (Wilczak et al., 2001) for estimation of the vertical velocity and to further calculate the vertical advection. We estimated NEE independently from chamber measurements and an up-scaling model. The aim was to estimate the horizontal advection as a residual between the imbalance of two NEE estimates: one based on chamber measurements and model; the other based on EC, storage change and vertical advection terms. The obtained estimates were used for testing the hypothesis.

Finally, the annual carbon balance is estimated by two ways. The first is a standard procedure, where low friction velocity periods are filtered and gap-filled by regressions. In the second we included the vertical advection without any filtering. The two annual estimates are compared.

2. Site description

For this study the experimental data collected at the Station for Measuring Forest Ecosystem-Atmosphere Relations (SMEAR II) field measurement station (Hyytiälä, southern Finland) have been used. The micrometeorological measurement tower (72 m high) is located within extended forested areas of roughly the same aerodynamic properties. Around the tower there is a 44-year-old Scots pine (*Pinus sylvestris* L.) stand, which is homogeneous about 200 m in all directions, and extending to the north

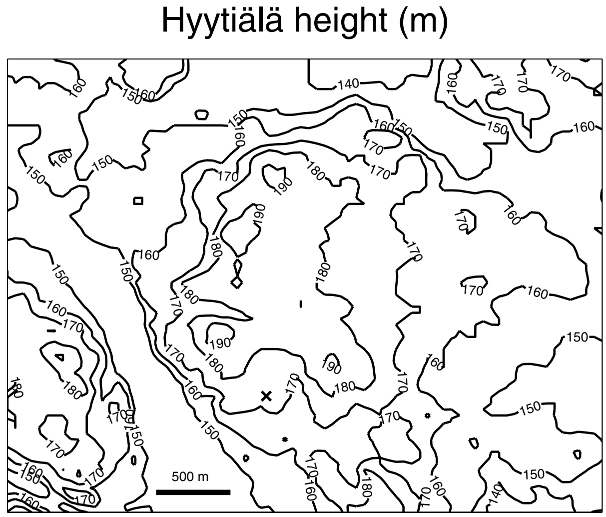

Fig. 1. Topography map of the site. The cross indicates the location of the micrometeorological tower.

about 1 km. For longer distances other stand types, different in age/composition, are also present. The average height of the trees is about 14 m and the mean all-sided leaf area index is 6. The forest floor vegetation consists of dwarf shrubs (*Vaccinium vitis-idaea* L., *V. myrtillus* L.) and mosses (*Pleurozium*, *Dicranum*).

The micrometeorological tower is located on the southern part of a very low spur ridge (at 179 m a.s.l.), which extends for about 1 km along the north-south direction (Fig. 1). It degrades to west/southwest direction, where at a distance of about 700 m there is an oblong lake, situated at 150 m above sea level. The slope becomes more gentle in east/southeast direction, where the elevation difference is up to 10–15 m over a distance of 1.5 km. Finally, on the northern side of the measuring tower, the terrain is almost flat reaching the ridge top (193 m a.s.l.) over a distance of 500 m.

A detailed description of the site in micrometeorological context can be found in Rannik (1998) and Vesala et al. (2005).

3. Measurements

In this study field data collected during the all year 2004 have been analysed.

3.1. EC flux measurements

The micrometeorological fluxes of momentum, heat, CO_2 and H_2O were measured using the eddy covariance technique. The system, located at 23.3 m above the ground, includes an ultrasonic anemometer (Solent Research 1012R2) to measure three wind speed components and sonic temperature, and a closed-path infrared gas analyser (LI-6262, Licor, USA) that measures CO_2

and H_2O concentrations. The data were sampled at 21 Hz; planar fit method for tilt correction of sonic anemometer data (Wilczak et al., 2001) and filtering to eliminate spikes were performed.

3.2. *Profile measurements*

Concentration profiles measurements of CO_2 were performed via six sample lines of equal length from levels of 4.2, 8.4, 16.8, 33.6, 50.4 and 67.2 m on the measurement tower. At the sampling levels in the tower air sample flows were taken through PTFE teflon inlets installed directly on the side of the tower. The inlets were designated to minimize in-flow of liquid water into the sample lines.

The measurement of CO_2 concentration was based on absorption of infrared radiation (analyser URAS 4, Hartmann and Braun, Frankfurt am Main, Germany). All the gas concentrations were measured successively at 60 s intervals from the six levels. The full cycle of measurements of concentration profile was performed in 6 min. For more information about the monthly calibration of the analyser, the correction and treatment of raw data and other technical details, the reader can refer to Rannik et al. (2004).

Moreover the air temperatures were measured at the same six levels with platinum resistance thermometer Pt-100. Temperature sensors were shielded from solar radiation and ventilated.

At three heights (8.4, 16.8 and 50.4 m) wind direction was registered by wind vanes.

3.3. *Chamber measurements*

We calculated an independent chamber-based estimate for night-time NEE. The chamber-based NEE included forest floor CO_2 efflux, respiration of woody parts of the trees, and respiration of foliage. The fluxes were measured with an automatic chamber system. Forest floor CO_2 efflux, including dark respiration of the ground vegetation, was measured approximately hourly with three chambers (Pumpanen et al., 2001), wood respiration hourly with two steady-state flow-through chambers attached on the bark, and foliage CO_2 exchange at 15–20 min intervals with three shoot chambers (Altimir et al., 2002), each enclosing a Scots pine shoot. The spatial representativeness of the fluxes measured with the automatic soil chambers was confirmed by conducting monthly campaigns with a manual chamber system (Kolari et al., 2004) at permanently installed collars in the vicinity of the eddy-covariance mast. The upscaling method of the measurements follows in Section 4.3.

4. Methods

4.1. *Sonic tilt correction and EC flux calculation*

The eddy covariance fluxes were calculated as 30 min average covariances between the scalars (or horizontal wind speed) and vertical wind velocity according to commonly accepted procedures (Aubinet et al., 2000). Except for momentum, upward fluxes were defined to be positive. The fluxes were corrected for high- and low-frequency losses by empirical transfer functions and cospectral transfer characteristics (Rannik et al., 2004).

Before the fluxes were calculated, a tilt correction was applied to 3-D sonic anemometer wind measurements in order to remove the effect of misalignment of the sonic anemometer and of irregularities of topography. The tilt correction approach differs from the standard rotation method (Kaimal and Finnigan, 1994), which imposes the mean vertical velocity $\overline{w}$ to be zero for each half-hour run. Recently, many studies (Lee, 1998; Finnigan, 1999; Paw U et al., 2000) questioned this assumption identifying the importance of non-zero $\overline{w}$ for calculating the advective components of the total flux. Instead the tilt correction approach assumes that the long-term mean vertical velocity $\overline{w}$ averaged over weeks to months has to be zero. The residuals in the half-hour $\overline{w}$ that remain after removing the long-term vertical velocity represent in principle the real vertical motions. Several tilt correction methods have been proposed in literature (Lee, 1998; Paw U et al., 2000; Wilczak et al., 2001). In this study the planar fit method (Wilczak et al., 2001) has been used. In this method, the measured velocities $\overline{w}_m$, for a given anemometer orientation, are fitted by using a multiple linear regression against the horizontal ($\overline{u}_m$) and cross-wind velocities ($\overline{v}_m$):

$$\overline{w}_m = b_0 + b_1\overline{u}_m + b_2\overline{v}_m \tag{2}$$

in order to find the best tilted plane parallel to the mean flow. Then from the regression coefficients b_0, b_1 and b_2, it is possible to determine the rotation angles around the v-axis and u-axis.

In particular, our raw data have been processed in the following way: (1) regression of monthly dataset of measured velocities (averaged over half-hour periods); (2) different regression planes for different wind direction sectors (20° bin); (3) half-hour runs with extreme wind speed (>5 m s^{-1}) have been discarded (5%) and (4) spikes have been removed.

4.2. *Storage change and vertical advection*

The storage change term was estimated according to

$$Sc = \int_0^{z_r} \frac{\partial c(z)}{\partial t}\,\mathrm{d}z \tag{3}$$

which was numerically integrated using the trapezoidal rule between the surface and $z_r = 23.3$ m.

The CO_2 concentration at $z = 0$ was estimated taking twice the value of the slope between the 4.2 and 8.4 m measurements. Although this assumption has no theoretical or empirical background, it may describe better the real concentration value at $z = 0$ than a simple linear extrapolation of the 4.2 and 8.4 m measurements. However, the use of different extrapolation functions does not influence significantly our results. The profiles of CO_2 concentration and the estimation of the mean vertical velocities let us to evaluate the CO_2 vertical advection flux, which can contributes significantly to the NEE mainly during the night-time, when the intensity of turbulent mixing is very low. The vertical advection was estimated according to (Lee, 1998)

$$\int_0^{z_r} \overline{w}(z) \frac{\partial \overline{c}(z)}{\partial z} \, \mathrm{d}z = \overline{w}_{z_r}(\overline{c}_{z_r} - \langle \overline{c} \rangle), \tag{4}$$

where

$$\langle \overline{c} \rangle = z_r^{-1} \int_0^{z_r} \overline{c}(z) \, \mathrm{d}z \tag{5}$$

and $\overline{c}_{z_r}$ and $\overline{w}_{z_r}$ are the mean concentration and the mean vertical velocity at the EC system height above the canopy, in our case 23.3 m.

4.3. The respiration estimate

For the summer 2004 we calculated an independent chamber-based estimate of night-time NEE. The measured chamber fluxes were not used directly due to varying measuring intervals and occasional spikes and other anomalies in the chamber data. Instead, we modelled each flux component separately and used the chamber data to parametrize the models. Respiration (R) was modelled as a function of temperature with an exponential equation

$$R = R_{\mathrm{ref}} Q_{10}^{(T - T_{\mathrm{ref}})/10}, \tag{6}$$

where R_{ref}(μmol m^{-2} s^{-1}) is CO_2 flux at reference temperature $T_{\mathrm{ref}} = 15^\circ$ C, Q_{10} the temperature sensitivity and T the temperature (Lloyd and Taylor, 1994).

As the majority of forest floor CO_2 efflux in Hyytiälä stand originates in the uppermost 10 cm of the ground (Pumpanen et al., 2003), the mean of temperatures measured in the organic layer and in the mineral soil surface (A horizon) was used as the explanatory factor in the model of forest floor CO_2 efflux. Bole temperature was used as the driving factor for wood respiration (Zha et al., 2005) and air temperature at 8 m height for foliage respiration (Mäkelä et al., 2006).

For each flux component, the temperature sensitivity parameter Q_{10}, that is, the slope of the temperature response, was first determined by fitting the corresponding component model to chamber measurements pooled over the whole summer. The absolute level of respiration also varies during the summer due to variation in the proportions of maintenance and growth respiration, substrate availability for microbial decomposition in the soil, and soil moisture. To take into account this variation, not directly related to temperature, the response functions were rescaled daily by estimating R_{ref} in a moving time window of 3 d while keeping the temperature sensitivity Q_{10} constant.

Foliage respiration was upscaled over the whole forest stand by multiplying the respiration rate per unit needle area by the total needle area of the canopy, and stem respiration by multiplying the respiration rate per stem surface area by the total stem surface area (0.5 m^2 m^{-2} ground) in the stand. Soil chambers directly give the CO_2 efflux per unit ground area. The mean fluxes measured with three automatic chambers were within the estimated standard error (7%) of the manual chamber fluxes (measured in previous campaigns); so there was no need to correct for spatial representativeness.

The average upscaled R_{ref} over the summer 2004 was 1.29 μmol m^{-2} s^{-1} for the tree foliage, 0.60 μmol m^{-2} s^{-1} for the stems and branches and 4.20 μmol m^{-2} s^{-1} for the forest floor. The estimated values of Q_{10} were 2.0, 2.2 and 1.9, respectively.

5. Results and discussion

In this section, we present the results obtained using the data collected during the summer 2004 (Julian day 162–231).

5.1. EC planar fitting flux and vertical velocity

Figure 2 shows a comparison between EC fluxes during summer season calculated by planar fit technique and standard rotation method (2-D rotation). Although there was a small run-to-run variation of the fluxes, the slopes of the regressions were not statically different from unity, as also found by Wilczak et al. (2001) and Turnipseed et al. (2003).

The planar fit technique let us to estimate the mean vertical velocity $\overline{w}$, and then, together with CO_2 concentration profiles, the vertical advective flux of CO_2. Figure 3 shows the mean diurnal variation of $\overline{w}$. In addition, of planar fit technique, we estimated the mean vertical velocity also using the tilt angle approach (Paw U et al., 2000) and the linear regression method proposed by Lee (1998). For our site the mean vertical motion is not sensitive to the choice of tilt correction method. As also observed by other studies (Lee, 1998; Aubinet et al., 2003; Feigenwinter et al., 2004), the mean vertical velocity is skewed toward negative values in nighttime, and is mainly positive during the day, indicating the presence of rising motions. According to Lee (1998), the night-time negative values suggest horizontal flow divergence beneath the tower.

5.2. Diurnal CO_2 concentration profiles and CO_2 fluxes

Figure 4 shows the mean diurnal variation of CO_2 concentration difference $\overline{c}_{z_r} - \langle \overline{c} \rangle$. The CO_2 values exhibited the typical diurnal pattern. During the day the CO_2 concentration field was vertically well mixed, while during the night, the vertical gradient was negative. In absence of turbulent mixing, in fact, the CO_2 emitted from the soil and vegetation was accumulated in the subcanopy layer.

The mean diurnal variation of right-hand side terms (except the horizontal advection) of eq. (1) is shown in Fig. 5. Small positive values of the storage change is observed during the night and negative storage change in the morning. Afternoon this flux

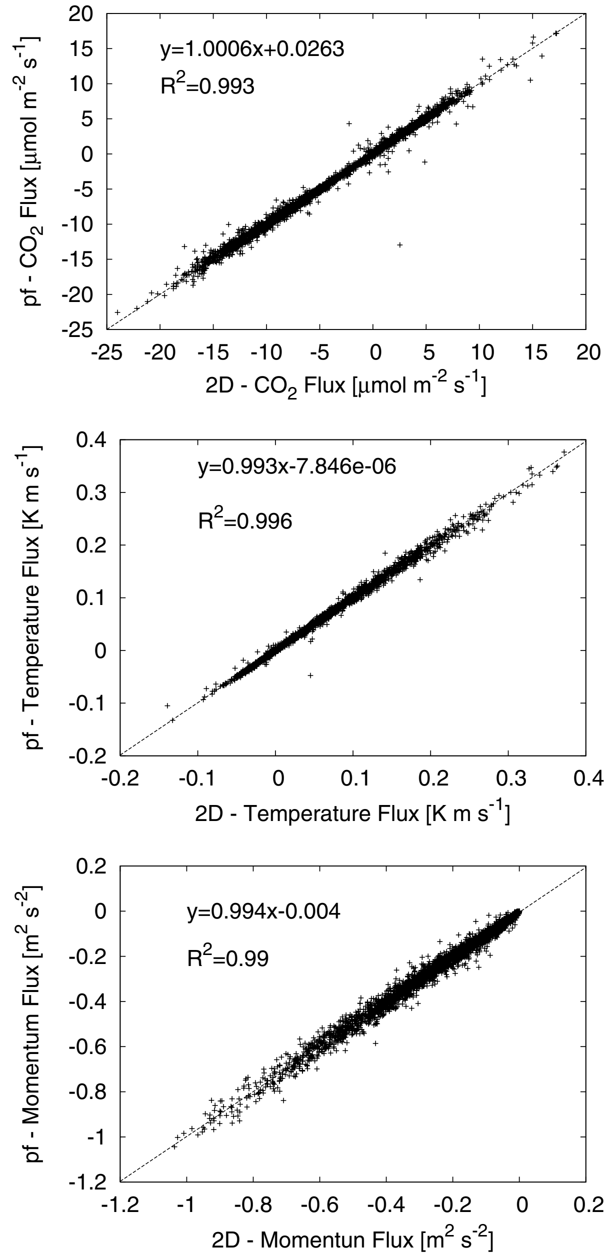

Fig. 2. Comparison of EC fluxes calculated by planar fit method (pf) and classical 2-D rotation (2-D).

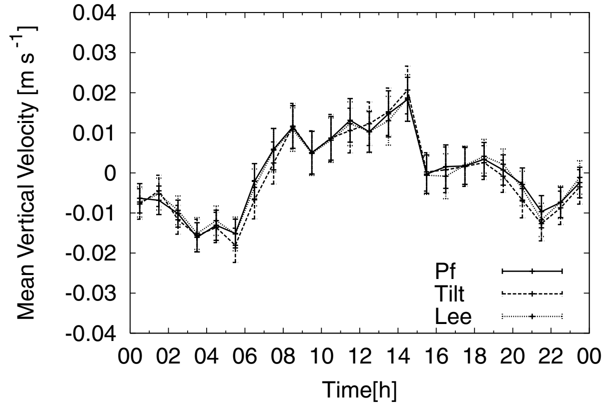

Fig. 3. Mean diurnal course of mean vertical velocity for the summer 2004, estimated by planar fit method (solid line), tilt angle method (dashed line) and Lee's method (dotted line). Bars are standard error.

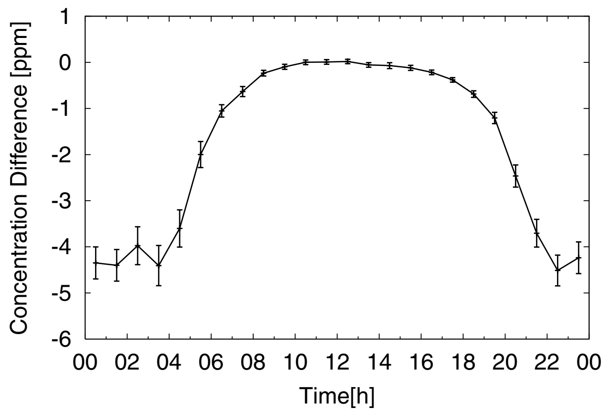

Fig. 4. Mean diurnal course of CO_2 concentration difference $\overline{c}_{z_r} - \langle\overline{c}\rangle$. Bars are standard error.

contribution becomes negligible. The daily pattern of storage change is in agreement with that in other sites (Feigenwinter et al., 2004; Aubinet et al., 2005).

As observed in previous experimental studies (Feigenwinter et al., 2004; Aubinet et al., 2005), the vertical advection is positive during the night due to mainly negative vertical velocities and negative concentration gradients, and indicating a removal of CO_2 from the control volume, due to the mass flow divergence (Lee, 1998). Values up to 2 μmol m^{-2} s^{-1} with large standard errors are observed during the transition periods (early morning and evening), while daytime values are close to zero and do not show any temporal variation.

The eddy-covariance flux exhibits the well-known daily pattern, showing CO_2 uptake in daytime and CO_2 release during the night.

Including the vertical advective fluxes in the NEE budget, the night-time respiration increases by 20–30%, while the contribution of this term to the daily NEE is negligible (Fig. 6).

5.3. Dependence of night-time fluxes on flow conditions

It is well known that during nighttime the eddy-covariance measurements are frequently underestimating NEE under stable stratification and weak turbulent mixing (Aubinet et al., 2000). In such condition, beside the systematic and random errors of EC flux measurements (e.g. low-frequency loss), other mechanisms can be responsible for carbon dioxide depletion during nighttime (Aubinet et al., 2005).

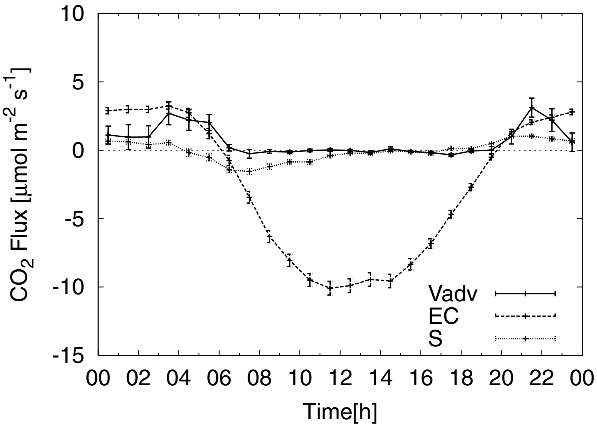

Fig. 5. Mean diurnal course of CO_2 fluxes with standard error bars for the summer 2004. Symbols: vertical advective flux (solid line), EC flux (dashed line) and storage change (dotted line).

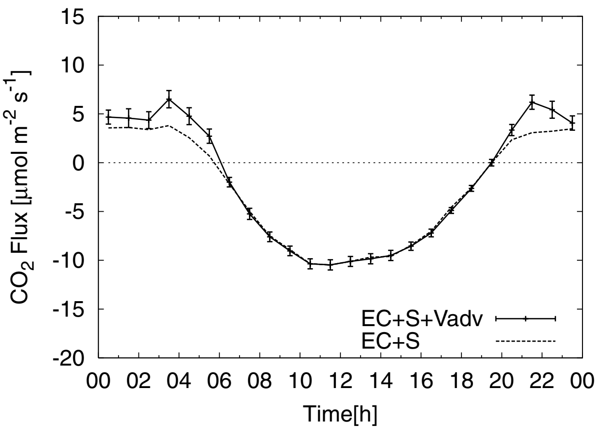

Fig. 6. Mean diurnal course of CO_2 fluxes with standard error bars for the summer 2004. Symbols: EC flux + storage change + vertical advection (solid line) and EC flux + storage change (dashed line).

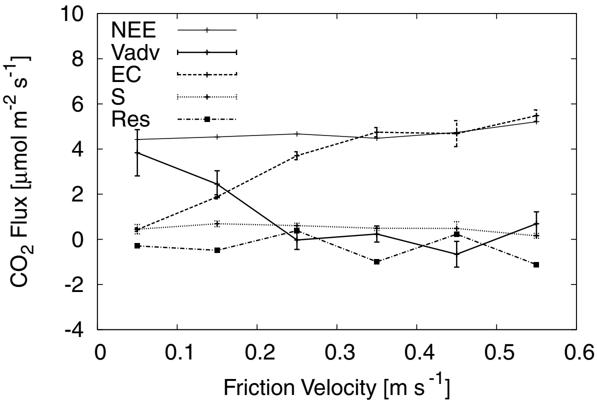

Fig. 7. The bin-average CO_2 night-time fluxes with standard error bars against the friction velocity. Symbols: vertical advection (solid line), EC flux (dashed line), storage change (dotted line), NEE (thin solid line), horizontal advection calculated as residual (dot–dashed line).

Table 1. Average, standard deviation (in brackets) and number of runs (N, half-hour values) for night-time CO_2 flux for different friction velocity classes

u_*	Vadv	S	EC	Vadv+S+EC	N
<0.1	3.83 (12.88)	0.45 (2.61)	0.43 (1.02)	4.71 (13.18)	159
0.1–0.2	2.44 (9.64)	0.69 (2.09)	1.88 (1.46)	5.01 (9.96)	265
0.2–0.3	−0.02 (5.78)	0.61 (1.50)	3.70 (2.44)	4.28 (6.75)	192
0.3–0.4	0.23 (3.62)	0.49 (0.97)	4.74 (2.09)	5.47 (4.07)	104
0.4–0.5	−0.66 (3.78)	0.48 (1.99)	4.68 (3.82)	4.58 (4.21)	44
0.5–0.6	0.69 (3.36)	0.15 (0.67)	5.47 (1.62)	6.32 (3.69)	41

With clear sky and strong radiative cooling inducing stable thermal stratification, the nocturnal turbulence is suppressed and other non-turbulent large-scale processes (entrainment, drainage flow, waves) may contribute considerably to the NEE. It is recognized that, especially in presence of complex topography and/or surface heterogeneity, these mechanisms advect the respirated CO_2 in vertical or horizontal direction. In the following subsections, we employed bin-averaging to test for relationships between CO_2 fluxes and some turbulent parameters.

5.3.1. Friction velocity dependence. A turbulent parameter frequently used as indicator of reliability of night-time CO_2 flux measurements is the friction velocity u_* (Aubinet et al., 2000). The u_* filtering approach is commonly used to estimate the long-term NEE in most of the micrometeorological sites (Goulden et al., 1996; Falge et al., 2001). According to this method, the EC flux records with low values of u_* are rejected and replaced by NEE values, modelled as a function of soil temperature. The threshold value is derived plotting the storage corrected EC flux as a function of u_*. Below the threshold value, an apparent increase of EC flux with increasing u_* is commonly observed. Above the threshold value, the EC flux becomes independent of u_*.

For the Hyytiälä site a threshold value between 0.2 and 0.3 m s^{-1} has been normally used in several studies (Rannik et al., 2001; Kolari et al., 2004). However this value is not universal and it varies between sites. It depends on the canopy structure, which influences the subcanopy thermal stratification and then the degree of decoupling between the surface and the measurement height above the forest.

The dependence of night-time CO_2 fluxes on friction velocity is shown in Fig. 7 and Table 1. Eddy covariance flux increases at increasing u_* as is usually observed. The storage change term is slightly positive for low values of friction velocity, and about zero at increasing u_*.

The vertical advection has a positive contribution to NEE (removing CO_2 from the control volume) for $u_* < 0.25\,\mathrm{m\,s^{-1}}$, and a negligible contribution for higher values.

Without any measurements of the horizontal CO_2 gradient, we cannot have a direct estimation of the horizontal advective flux. As an exercise, we calculated this flux as a residual from eq. (1).

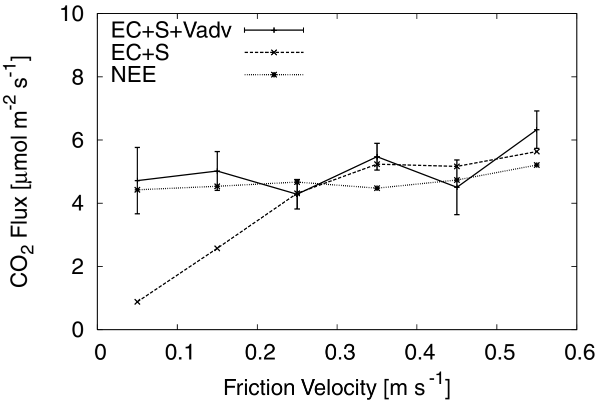

Fig. 8. The bin-average CO_2 night-time composite fluxes with standard error bars. Symbols: EC flux + storage change + vertical advection (solid line), EC flux + storage change (dashed line) and NEE (dotted line).

The respiration term (left-hand side term of eq. 1) was derived from chamber measurements, as discussed in Section 4.3.

The residual (horizontal advective term) show negative and very small values for low values of friction velocity and it gives a bit higher contribution at higher u_*.

On average, the total flux (with vertical advection included) does not show any clear dependence on u_* (Fig. 8), as expected, since CO_2 exchange should not depend on the efficiency of turbulent transport, but only on source/sink intensity.

The result shows that, at least for the analysed period, the vertical advection term can account for significant fraction of total transport of CO_2 under stable stratification, as was also the case in the study by Lee (1998).

Apparently this contradicts other theoretical and experimental studies (Finnigan, 1999; Aubinet et al., 2003; Feigenwinter et al., 2004; Aubinet et al., 2005), which show that the horizontal and vertical advection are normally of opposite sign and of the same order of magnitude, then cancelling out each other in the long-term carbon balance.

However, we must consider several points to interpret our result:

(1) The horizontal advection was not directly measured.

(2) The respiration estimate (NEE), used to calculate the residual, is totally independent of the other fluxes.

(3) At large-scale the area is dominated by conifer forest. Then we could assume that the horizontal distribution of sources and sinks are rather homogeneous.

(4) The evaluation of the horizontal advection term is in practical very difficult, because of the large uncertainty on the estimation of horizontal CO_2 gradients.

(5) Using the theoretical framework proposed by Finnigan (1999), we can speculate about the magnitude and the sign of the two advection terms in our site. The linearized theory shows that over an hill the perturbation of the concentration and velocity fields depends on four components: streamline convergence/divergence, changes in turbulent stresses, changes in surface shear stress and changes in surface scalar fluxes. Each of these components have a different contribution if we consider the inner region close the surface, where the momentum and scalar fields are strongly affected by the perturbations to the turbulent fluxes or the above outer region, where the flow is inviscid and the changes to the scalar field are due to the advection along the distorted mean flow streamlines.

Hence following the Finnigan's conclusion, in the outer region the horizontal and vertical advection terms have the opposite sign and about the same magnitude.

In the inner layer, where likely our measurements are made, the two advection terms may be of different magnitude and of the same or different sign. In general it depends on the relative contributions of the mechanisms earlier mentioned.

Unfortunately, from our measurements we cannot estimate the contribution of the different forcing.

5.3.2. Stability dependence. Also other parameters than u_* can be useful to assess the reliability of night-time CO_2 EC flux, as well as the role of non-turbulent motion under very stable stratification. Staebler and Fitzjarrald (2004) observed that for their site the negative buoyant forcing, responsible of drainage flows occurrence near the ground, was a better predictor of nocturnal cases with respiration deficit, than the commonly used u_* criteria.

For our forest site, we defined a canopy Richardson number, written as

$$R_B = \frac{g\Delta\overline{\theta}z}{\overline{\theta}(\overline{u})^2}, \tag{7}$$

where g is the acceleration due to the gravity, $\overline{\theta}$ is the potential temperature just above the canopy top (16 m), $\Delta\overline{\theta}$ is the temperature difference between above canopy (16 m) and subcanopy levels (8 m) and $\overline{u}$ is the above canopy mean velocity.

Figure 9a shows the relationship between the negative temperature flux and R_B. As found by Mahrt et al. (1998), we can distinguish in our data three stable boundary-layer regimes: (1) weakly stable regime ($0 < R_B < 0.05$), where the absolute values of flux increase from zero neutral value; (2) transition stability regime ($0.05 < R_B < 0.6$), where the flux decreases rapidly due to decreasing amplitude of the vertical velocity fluctuations and (3) very stable regime ($R_B > 0.6$), where the flux is very small.

Within these regimes, in spite of a possible self-correlation between the respiration and the subcanopy temperature, the CO_2 fluxes show different behaviours. The EC flux plus the storage change is approximately constant under near-neutral/weakly stable condition (small values of R_B), then for $R_B > 0.05$ it decreases and becomes negligible under very stable condition (Fig. 9d). In a symmetric way, the vertical advection is about zero for $R_B < 0.05$, and it increases as the stability increases

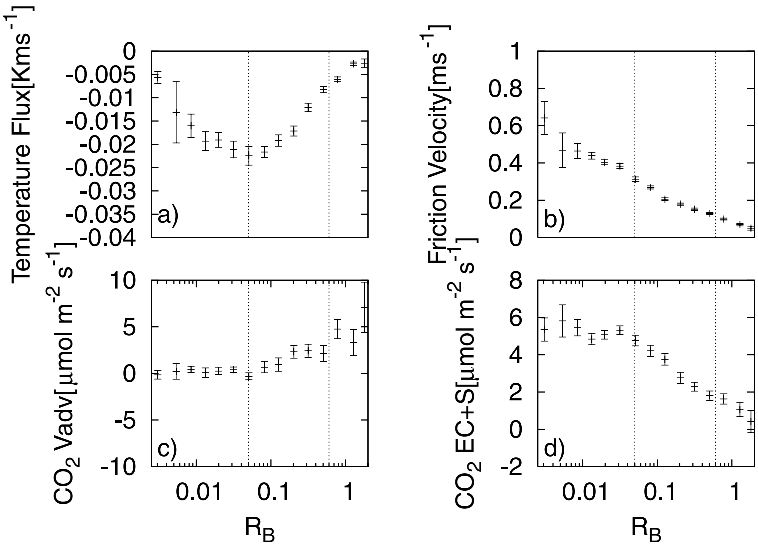

Fig. 9. The bin-average of (a) temperature flux, (b) friction velocity, (c) CO_2 vertical advection and (d) CO_2 EC + Storage flux against the canopy Richardson number.

(Fig. 9c). This result is in agreement with the flux pattern found using the friction velocity as a significant parameter for reliability of night-time CO_2 flux measurements. This is not surprising due to the strong correlation between u_* and R_B (Fig. 9b).

However this result suggests that within the regimes (2) and (3), we can expect that the non-turbulent motions becomes more and more important. In fact, when we move in the descending part of the curve in Fig. 9a (e.g. $R_B > 0.05$), the thermal decoupling between the boundary layer and the canopy become more and more probable, because the turbulent heat flux cannot oppose the radiative cooling (net long-wave radiation), leading to larger temperature difference ($\Delta\overline{\theta}$) and then larger values of R_B.

Under these regimes the subcanopy flow was partially or completely decoupled from the flow above the canopy. During some nights the subcanopy wind was mainly downslope with a nearly northern direction, while the wind above the canopy was from every direction (Fig. 10). This suggested the presence of drainage flow which in some case can develop in the subcanopy layer.

At last we must say that the regime limit values can be sensitive to the definition of the Richardson number. For instance we plotted the fluxes against a subcanopy Richardson number, defined with temperature measurements at two subcanopy levels (not shown here), obtaining different limit values. However, the fluxes shown the same patterns.

5.4. *Impact of advection correction on long-term carbon budget*

This analysis highlighted that for SMEAR II the short-term carbon balance is improved using the vertical advection approach proposed by Lee (1998). The CO_2 vertical advection accounts for significant fraction of CO_2 transport under low mixing conditions during nighttime.

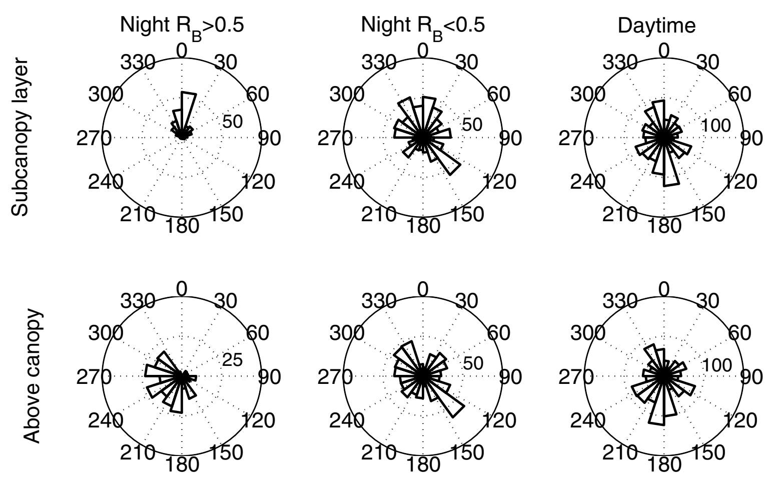

Fig. 10. Distribution of wind direction above the canopy (bottom) and in the subcanopy layer (top).

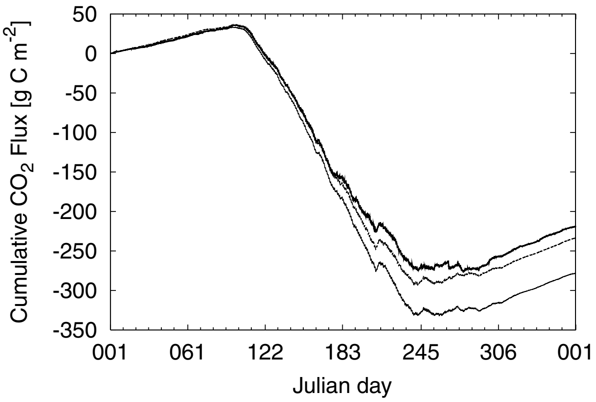

Fig. 11. The annual cumulative curves of CO_2 flux, calculated as EC + Storage flux with vertical advection correction (thick solid line), with u_* filtering approach (dashed line) and without any correction (thin solid line).

At present, to the best of the author's knowledge, only few studies (Baldocchi et al., 2000) discussed the impact of advection correction on long-term carbon budget.

Figure 11 shows the annual cumulative curves for the year 2004 calculated using different approaches. The annual sum of NEE (in terms of grams of carbon per square metre) calculated with advection correction (thick solid line) gives a value (−220) which is very close to that calculated with the standard u_* filtering procedure (−233, dashed line). The cumulative NEE curve calculated without any correction (EC + Storage change) is also displayed (−278, thin solid line). About 10% of data record was gap-filled during periods of malfunctioning of the sensors.

Besides the total uncertainty of long-term EC measurements, estimated to be about $50\,\mathrm{g\,C\,m^{-2}}$ for measurements at nearly ideal sites (Baldocchi, 2003), this result highlights that in Hyytiälä forest site, taking into account the random uncertainties of the estimation of vertical motions, the inclusion of the CO_2 vertical advection provides a reliable estimation of NEE also on the long-term period.

Vickers and Mahrt (2006) also estimated NEE using a u_* filter and deduced the horizontal advection term as a residual. In their case the term was significant, but our result indicates that for more homogeneous site the vertical advection alone can remove the apparent friction velocity dependence of the measured flux estimate.

6. Conclusions

This analysis highlights that the Hyytiälä site may be characterized by some local subcanopy circulation in very stable conditions, when the strong radiative cooling determines surface layer decoupling situations. In general, however, there is no evidence of systematic down-slope and up-slope circulations, as expected, since the site is slightly complex and subject to moderate height variation. The vertical advection term dominates in night-time conditions (clear sky and low wind speed). Then including this flux in the NEE of CO_2, the night-time respiration is increased and the apparent dependence on turbulent mixing is removed. We were able to show that there exist cases when the horizontal advection is marginal, as has been also theoretically envisaged.

Furthermore, the results show that the vertical velocities estimated from a tilt correction can carry physical meaning and are reliable for estimating the vertical advection. We stress the importance of estimating NEE by different independent ways in flux tower sites. In the context of direct meteorological flux measurements, advection processes have been studied mainly for carbon dioxide, but similar considerations and attempts to measure advection terms should be extended to measurements of other trace gases. Versatile approaches would give valuable information on nocturnal micrometeorological processes and reliability of flux measurement methods.

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