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Contribution of advection to the carbon budget measured by eddy covariance at a steep mountain slope forest in Switzerland

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Abstract

We calculated the contribution of advection to the C budget measured by the eddy covariance (EC) technique for a steep and forested mountain site (CarboEurope site CH-Lae, Laegeren, Switzerland) during the growing season 2007 (May to August). Thereby we followed two approaches: (1) the physical correction of the EC data for directly measured advection terms and (2) the u_* filter approach that replaces periods with u_* below a site-specific threshold with empirically modelled fluxes. We found good agreement between the two approaches in terms of daily (linear regression slope: 0.77±0.04, intercept: 1.23±0.27 µmol m^{-2} s^{-1}, adj. R^2=0.80) and seasonal sums of gross fluxes (difference ≤12%), when using a u_* threshold of 0.3 m s^{-1} and correcting EC for horizontal advection only. Incorporating also vertical advection into the mass balance equation resulted in unrealistic and highly erratic fluxes. However, on a daily basis vertical advection cancelled out to nearly zero. The u_* filter seems to account primarily for respiration fluxes, which are mainly affected by horizontal advection. We could confirm our corrections by a cross-validation with independent approaches, such as soil respiration chamber measurements, light curves and energy budget closure. Our results show that flux measurements on steep sites with complex topography are possible. Actually, sloping sites seem to have the advantage over flat sites that advection measurements can be reduced to a simplified two-dimensional measurement approach due to the two-dimensional characteristics of the wind field at those sites.

1 Introduction

The eddy covariance (EC) method has become an important tool to study long-term gas exchange processes between the atmosphere and the biosphere, since it is the only method that allows direct measurements of gas exchange at the ecosystem level. However, several requirements have to be fulfilled to obtain reliable and spatially representative estimates of the CO_2 exchange rates. According to (Baldocchi, 2003), EC

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measurements are most accurate when atmospheric conditions are steady, underlying vegetation is homogeneous, and instruments are set up over flat terrain of sufficiently spatial extension. Under stable conditions, largest uncertainties and errors in EC measurements are introduced by intermittent turbulence and advection. On sloping terrain, the occurrence of advection is assumed to be the largest problem (Aubinet, 2008). Additionally, as homogeneity tends to decrease with increasing roughness length, forests create more difficult preconditions for EC measurements than short-statured vegetation types. Thus, forests on sloping terrain are regarded as most difficult sites for flux measurements (Baldocchi et al., 2000). Due to these non-ideal conditions, EC studies in mountainous ecosystems are rare. However, mountains cover 25% of the world's area (UNEP, 2008) and mountainous ecosystems are supposed to be heavily affected by anthropogenic and climatic impacts (Huber et al., 2005; FAO, 2008; Metzger et al., 2008). Furthermore, forest ecosystems act as an important sink within the global carbon cycle (e.g., Janssens et al., 2003; Luyssaert et al., 2008). Thus, regions with complex topography are among the most important regions for determining local and global carbon and water budgets (Schimel et al., 2002). Therefore it is necessary to extend the application of the EC technique to mountain ecosystems, such as mountain forests, to understand ongoing processes and be able to include these ecosystems into global calculations and models.

Contrary to the persistent hypothesis that EC measurements are most precise on flat and homogeneous terrain, large advection fluxes were observed also on very flat areas (Feigenwinter et al., 2008). Due to their openness and lack of orography, wind is not channeled over such areas and shows no systematic pattern like wind systems in mountainous areas. This makes the measurement of advective fluxes on flat areas extremely challenging and requires substantial technical and thus financial efforts. In contrast, wind patterns in mountains are dominated by local wind systems, such as diurnal slope or valley winds (Whiteman, 2000), leading to a two-dimensional wind pattern, which makes the assessment of advective fluxes much easier. However, deviations from this general rule are found during synoptic-scale weather events. Of-

ten, these events are associated with adverse weather conditions (e.g., rain, snowfall), where EC measurements become more uncertain or even fail, irrespective of locality or topographical conditions. This is also the case at our study site. Being a mixed forest located on a relatively steep slope of the Jura mountain range and featuring a highly complex small-scale topography, this site poses apparently challenging preconditions for applying the EC technique. But just because of this steep slope and the pronounced ridge, winds above the canopy and inside the canopy are strongly channeled, which offers the possibility to assess advection in a simplified two-dimensional approach.

Integration of the advection term directly into the CO_2 mass balance for calculation of net ecosystem exchange (NEE) is still an important topic in the current scientific discussion. Measured advection fluxes presently show large scatter and errors that are in the same order of magnitude as measured exchange fluxes (Heinesch et al., 2007). Usage of hourly advection values is therefore regarded as difficult (Feigenwinter et al., 2008) and physical correction allows not always an improvement of night-time fluxes (Aubinet, 2008). Correction of EC measurements is usually done by excluding periods with stable stratification and subsequent data gap-filling based on validation periods with turbulent conditions (Moffat et al., 2007). Generally, the friction velocity u_* is used as a filter criterion, as below a certain empirical u_* threshold insufficient stationarity and high temporal variability of turbulence as well as the occurrence of advection are assumed (Aubinet et al., 2003; Gu et al., 2005). However, the weakness of this approach was addressed in several studies (Moureaux et al., 2006; Papale et al., 2006; Ruppert et al., 2006; Kutsch et al., 2009) and alternative correction methods have been developed (Staebler and Fitzjarrald, 2004; Van Gorsel et al., 2008; Acevedo et al., 2009). Nevertheless, Aubinet (2008) recently recommended rather to filter EC measurements by a u_* threshold than to correct them physically for advection. However, the contribution of advection to measured turbulent fluxes is essential when we strive to get reliable estimates of the gross fluxes of ecosystems, i.e., gross primary production (GPP) and ecosystem respiration (Reco), as used in global models and estimates of source and sink strength of ecosystems. In our study we calculated the contribution

of advection to the C budget, with special reference to the respiration flux, since this flux is known to be generally underestimated by the EC method on longer time scales (Goulden et al., 1996). Hence, we focus in this paper on daily and monthly fluxes during the vegetation period. The objectives of our study were (1) to quantify advection with a relatively simple and cost efficient approach, (2) to calculate the contribution of advection to the gross ecosystem fluxes by applying two approaches for calculation: the u_* filter approach and the physical correction by direct advection measurements, and (3) to validate our correction approaches with independently derived data.

2 Methods

2.1 Study site

The Lägeren research site (47°28′42″ N, 8°21′52″ E , 682 m a.s.l. (base of flux tower) is located on the relatively steep (in average 24°, maximum 45°), south-facing slope of the Lägeren mountain, north-west of Zurich, Switzerland. The Lägeren mountain is the easternmost outcrop of the Jura mountain range of about 11 km length and 1.5 km width. The site is part of the Swiss air quality monitoring network (NABEL) since 1986. Routine CO_2 and H_2O flux measurements by the eddy covariance (EC) method are running since 2004 as a contribution to the CarboEuropeIP and FLUXNET network (Eugster et al., 2007).

The linear topography of the Lägeren mountain leads to a strongly channeled atmospheric flow along the ridge with two distinct lobes of the flux footprint towards the West and the East (Fig. 1). Vegetation cover is a productive mixed forest dominated by beech (*Fagus sylvatica*), with a high diversity concerning tree species, age and diameter distributions. Mean leaf area index (LAI) during the vegetation period ranges from 1.7 to 5.5 $m^2\,m^{-2}$. Mean tree height is 30.6 m, and the aerodynamic displacement height was estimated at 18 m (Eugster et al., 2007). The surrounding of the Lägeren is dominated by agricultural land-use. The nearest small industrial towns Baden and

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Wettingen are located 3 km west of the flux tower. Mean annual temperature is 8.6 °C (2007: 9.1 °C) and mean annual precipitation is 950 mm (2007: 914 mm) (Swiss air quality monitoring network NABEL, 2008). Fog has a great importance on the local climate.

2.2 Instrumentation

The flux tower is located in direct vicinity to a small forest gap that originates from the heavy winter storm Lothar in 1999. EC instrumentation, consisting of a triaxial sonic anemometer (Gill Solent HS, Gill Instruments Ltd., Lymington, UK) and an open-path non-dispersive infrared gas analyzer (IRGA) model 7500 (Licor, Lincoln, Nebraska, USA), is mounted at a height of 47 m above ground, 15 m above the mean tree height. The upper platform of the tower is also equipped with instruments for measuring standard meteorological variables, such as radiation components (Kipp & Zonen CNR1, Delft, Netherlands), air temperature and relative humidity (Rotronic MP101A temperature and relative humidity probe, Bassersdorf, Switzerland). In vicinity of the flux tower, we measure soil heat flux (Hukseflux heat flux plate HFP01, Delft, Netherlands) as well as soil temperature and moisture (Decagon ECH_2O EC-20 probes, Pullman, WA, USA).

2.3 CO_2 concentration profiles

We installed a vertical CO_2 concentration profile with eight heights (0.1 m, 1 m, 3 m, 5 m, 9 m, 27 m, 44 m, 54 m) and a horizontal CO_2 profile with a distance of 60 m at 2 heights (0.1 m, 1 m) (Fig. 2). The horizontal profile is located in the vicinity of the flux tower (minimum distance 20 m) and is oriented along the prevailing wind direction at 1 m height (315°; Fig. 3). The vertical profile is running along the flux tower and continuing downwards to the local topographical minimum in 20 m distance to the tower (Fig. 2). Thus, the vertical CO_2 profile point at 0.1 m represents the local minimum, the measurement point at 9 m height is located 2 m above the tower base, and the

measurement point at 54 m corresponds to the EC measurement height. CO_2 intake hoses are connected to a home-built valve switching unit with continuously purged air inlets (Synflex^{TM}, Type 1300, I.D.:4 mm, Johannsen AG, Zurich, Switzerland). Airflow is directed through a small pump inside the valve switching unit to an IRGA (Licor Li-7000, Lincoln, Nebraska, USA). Thus, all twelve points of the vertical and horizontal profiles are measured by the same IRGA. The flow through the selection unit during measurements is kept at 1 l min^{-1} and at 0.4 l min^{-1} during purging. Switching of the air selection unit and storing of the IRGA analog output (CO_2 concentration, H_2O concentration, cell pressure and temperature) is controlled by a data logger (CR10, Campbell Scientific Inc., Loughborough, UK). Each inlet is consecutively selected for 30 s. Measurement interval for all 12 inlets is set to 10 min; single measurements are aggregated to 30 min averages values that are recorded. The reference flow path of the IRGA is constantly scrubbed with a soda lime and desiccant ($Mg(ClO_4)_2$) that is changed every few weeks when chemicals are exhausted. Every day a reference gas with a known CO_2 concentration is purged through the manifold. According to the drift of the daily reference gas measurements, CO_2 concentration values are corrected. Calibration of zero offset and span correction of the IRGA is done manually every few weeks.

2.4 Vertical meteorological profile

Also related to the local topographical minimum, vertical profiles of air temperature and relative air humidity (Fischer T/F-Sensors, type 431418, K. Fischer GmbH, Drebach, Germany), as well as wind speed and direction (Gill 2-D sonic anemometers, Gill Instruments Ltd., Lymington, UK) are measured at five heights (1 m, 5 m, 9 m, 27 m, 44 m) in addition to the EC reference height (54 m) (Fig. 2). Measurements are controlled and stored by a data logger (CR1000, Campbell Scientific Inc., Loughborough, UK). Measurement interval is 10 s and averages are recorded every 30 min. Additionally, we obtained meteorological data from the MeteoSwiss tower that is located on the Lägeren ridge (862 m a.s.l.), 2.6 km east of our tower (MeteoSwiss 2008). This point represents the highest measurement height of the vertical meteorological profile

of 190 m, related to the local topographical minimum.

2.5 EC data processing

EC raw data are collected digitally at 20 Hz by an ACER notebook, running the in-house *sonicreadHS* software on a Linux operating system. 30 min averages of CO_2 and water vapour fluxes are calculated off-line by the in-house software *ethflux*. Within this program, coordinate rotation is done by 2-D rotation (Mc Millen, 1988), as the planar fit method was identified to be not suitable for the Lägeren site (Goeckede et al., 2008). Quality check of the data is performed by the standard procedure of the CarboEurope network (steady-state test and integral turbulence characteristics test), as described by (Foken and Wichura, 1996). More details about the processing procedure are given in Hiller et al. (2008). The *ethflux* software participated in the CarboEurope intercomparison of EC software (Mauder et al., 2008). In this study, different EC data processing software packages were compared to the reference software TK2 for different data sets. Differences between calculated fluxes with *ethflux* and TK2 over short vegetation are explained by the different coordinate rotation routine, as *ethflux* uses a 2-D rotation with block averaging, while TK2 is based on a planar fit transformation. However, over tall vegetation, the calculated fluxes agreed quite well (regression slope 0.97 to 1.06) and the *ethflux* estimates were only slightly larger.

The 30 min CO_2 flux averages are corrected for the change of CO_2 storage below the measuring height of the EC instrumentation, derived from the vertical CO_2 profile. Data are accepted if they met all of the following criteria: (1) window dirtiness (house-keeping variable provided by the Li-7500 open-path instrument) <60%, (2) 11 mmol m^{-3} < CO_2 concentration <20 mmol m^{-3}, (3) −50 µmol m^{-2} s^{-1} < CO_2 flux <50 µmol m^{-2} s^{-1}, (4) −30 µmol m^{-2} s^{-1} < change of CO_2 storage < 30 µmol m^{-2} s^{-1}, (5) $u'w' < 0\,m^2\,s^{-2}$ (Eugster et al., 2003; 2007), (6) quality flag ≤ 1 (Foken and Wichura, 1996). Accepted data covered 63% of all available data.

2.6 Advection measurements

Horizontal advection (F_{HA}) is here defined as the advection flux surface-parallel along the slope due to drainage flow. Horizontal advection is calculated according to Eq. (1):

$$F_{HA} = \int_0^{z_r} \overline{u_c}(z) \frac{\partial \overline{c}}{\partial x} dz \quad (1)$$

with u_c = wind component along the CO_2 gradient measurement (m s^{-1}), z = integration height (m), z_r = height of EC measurements and $\frac{\partial c}{\partial x}$ = horizontal CO_2 concentration gradient (µmol m^{-4}) (Feigenwinter et al., 2004). The horizontal CO_2 gradient is estimated with the horizontal CO_2 profile described in the previous section. Wind speed measurements were obtained from the meteorological profile. Integration height is set to 2 m, according vertical profiles of wind speed, air temperature and CO_2 concentration (see Figs. 5 and 6).

Vertical advection (F_{VA}) is calculated according to Eq. (2):

$$F_{VA} = \int_0^{z} \overline{w}(z) \frac{\partial \overline{c}}{\partial z} dz, \quad (2)$$

with w = vertical wind speed (m s^{-1}), $\frac{\partial c}{\partial z}$ = vertical CO_2 concentration gradient (µmol m^{-4}) (Feigenwinter et al., 2004). According to Lee's (1998) notation for the vertical advection, Eq. (2) results in:

$$F_{VA} = \overline{w}(z_r) \left[\overline{c}(z_r) - \langle c \rangle \right], \quad (3)$$

whereby

$$\langle c \rangle = \frac{1}{z_r} \int_0^{z_r} \overline{c}(z) dz, \quad (4)$$

The vertical CO_2 concentration gradient is averaged across the eight heights of the vertical CO_2 profile described in the previous section. The mean vertical component of wind velocity is derived from the high frequency measurements of the 3-D sonic anemometer of the EC instrumentation on top of the tower. Tilt correction of the mean vertical velocity component was done according to (Feigenwinter et al., 2004):

$$\overline{w}(z_r) = \overline{w}(z_r)_{\text{measured}} - \sqrt{\overline{u}^2(z_r) + \overline{v}^2(z_r)} \tan\left[a_0 + a_1 \sin(\alpha + a_2)\right], \quad (5)$$

with u and v = measured wind components in x and y direction, α = wind direction in degree. The coefficients a_0, a_1 and a_2 were determined by a sinusoidal fit of the tilt angle against wind direction using the whole data set of the year 2007, resulting in a_0=2.293° (offset), a_1=21.226° (amplitude) and a_2=272.705° (phase shift).

2.7 Gap-filling and partitioning

To quantify the contribution of advection to the C budget, ecosystem fluxes, such as net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration (Reco) were calculated in three different ways: (1) from direct EC measurements (F_C) without u_* filtering, (2) from u_* filtered data with $u_* > 0.3\,\text{m}\,\text{s}^{-1}$ ($F_{C,u*}$) and (3) from data that were physically corrected for a) F_{HA} ($F_{C,HA}$) and b) F_{HA} and F_{VA} ($F_{C,HAVA}$) by incorporating each of the advection terms directly into the mass balance equation. Each data-set was subsequently gap-filled and partitioned into the gross fluxes GPP and Reco according to (Reichstein et al., 2002, 2005). For further information about the gap-filling and flux-partitioning procedure see also Moffat et al. (2007) and Falge et al. (2001).

2.8 Validation measurements

2.8.1 Soil respiration

Soil respiration (SR) chamber measurements were carried out campaign-wise during May to August 2007 at 17 plots within the EC flux tower footprint. Data were gap-filled and modeled based on temperature response functions. Details about measurement routine and data treatment can be found in Rühr et al. (2010).

2.8.2 Respiration derived from light response curves

An independent daily average of respiration was derived from the extrapolation of light response curves to zero light. The response of day-time NEE to PPFD was modeled within a ten-day moving window using a logistic sigmoid function (Moffat, 2010):

$$\mathrm{NEE} = 2F_{\mathrm{inf}}\left(\frac{1}{2} - \frac{1}{\left(1+e^{-2\alpha\frac{\mathrm{PPFD}}{F_{\mathrm{inf}}}}\right)}\right) + R$$

with F_{inf} = maximal ecosystem photosynthetic capacity [µmol $CO_2\,m^{-2}s^{-1}$], PPFD = photosynthetically active radiation [µmol photons $m^{-2}\,s^{-1}$], R = respiration term [µmol $CO_2\,m^{-2}\,s^{-1}$] and α = initial quantum yield.

2.8.3 Energy budget closure

The surface energy budget is defined as:

$$R_n - \mathrm{G} = \mathrm{LE} + \mathrm{H} + \Delta Q, \quad (6)$$

with R_n = net radiation, G = soil heat flux, LE = latent heat flux, H = sensible heat flux, ΔQ = energy budget closure gap. The magnitude of the energy budget closure is

used as an independent evaluation of the performance of EC flux estimates (Aubinet et al., 2000; Wilson et al., 2002). The energy balance ratio (EBR) gives an overall evaluation of the energy balance closure at longer time scales and is defined as:

$$\mathrm{EBR} = \frac{\sum(\mathrm{LE} + \mathrm{H})}{\sum(R_n - \mathrm{G})}.$$

Sensible and latent heat flux are derived from EC measurements. Mean soil heat flux is calculated from two soil heat flux plates installed side by side at 3 cm soil depth. Soil heat flux is corrected for the change of heat storage of the soil layer above the heat flux plates according to Montheith and Unsworth (1990). Measurements are controlled and stored by a data logger (CR10X, Campbell Scientific Inc., Loughborough, UK). Due to technical failure of our data logger, no reliable data for ground heat flux could be obtained during five weeks in summer 2007. For this period, we estimated soil heat flux as a fraction of R_n derived from available data (see e.g., Eugster et al., 1997). In general, soil heat flux is about 2% of R_n. Thus, the uncertainty in our estimates of G should not be of any importance in the context of this study.

Statistical analyses were carried out with the statistics software package R, version 2.4.1 (R Development Core Team, 2006). Outliers in variable x were defined as values outside the $\pm 3\sigma$ range of the empirical distribution of x.

3 Results

3.1 Advection patterns

Wind regimes above (54 m) and inside (1 m) the canopy were totally uncoupled for both unstable and stable conditions (unstable: $z/L < 0$, stable and neutral: $z/L \geq 0$, where z/L is the Monin-Obukhov stability parameter) (Fig. 3). Above the canopy, the wind was oriented along the ridge of the Jura mountain most of the time (West-East direction, Figs. 1 and 3). In the canopy, however, the wind regime was dominated by

a persistent local slope wind system with up-slope winds (South-East) during unstable conditions and down-slope wind (North-West) during stable conditions.

Stable stratification dominated during the night, leading to a pronounced diurnal cycle of the stability parameter z/L, friction velocity u_* and wind direction in the canopy (Fig. 4). However, although values of z/L were positive during night, its magnitude was comparatively small (on average <0.2), while u_*, though decreasing at night, was still relatively high (0.3–0.4 m s^{-1}), indicating good turbulent mixing and representativeness of the EC flux measurements.

All three vertical profiles (mean horizontal wind speed and air temperature, as well as CO_2 concentration) showed same patterns under unstable and stable conditions (Fig. 5). In general, wind speeds inside the canopy were relatively small, increasing above the canopy, thus creating a wind speed profile that was nearly logarithmic with height (Fig. 5a). The temperature profile showed a weak temperature inversion with a pronounced temperature maximum at 5 m height that decreased slightly at 1 m height (Fig. 5b). The constant temperatures across the canopy indicate good turbulent mixing of the air and development of just a shallow drainage layer. This was also confirmed by the vertical CO_2 concentration profile (Figs. 5c and 6). CO_2 concentrations across the canopy as well as the CO_2 flux at EC height showed large diurnal changes during ten representative days in June 2007, but only little vertical variation of CO_2 concentrations inside the canopy, indicating substantial vertical mixing. Thus, CO_2 gradients occurred mainly below 10 m height and were most pronounced below 2 m.

CO_2 fluxes followed closely the diurnal pattern of the CO_2 concentrations (Fig. 6): During the night CO_2 accumulated in the canopy due to respiration and low turbulence conditions. The onset of turbulence and plant assimilation in the morning stopped CO_2 accumulation and led to the typical CO_2 depletion during the day-light hours. The canopy storage term (Fig. 7b) showed only a small local minimum in the early evening, followed by a subsequent sharp depression during the first half of the night. Assuming constant CO_2 release by plants and soils during the night (Aubinet et al., 2005; Van Gorsel et al., 2007) and the decrease of turbulent mixing, indicated by the

decreasing u_* values, as well as the change of the wind direction in canopy (Fig. 4), the decrease of the storage term in the first half of the night might be attributed to non-turbulent fluxes, probably drainage flow. This interpretation is consistent with horizontal advection (F_{HA}) peaking in the early evening (Fig. 7c), exactly when u_* reached its minimum and z/L became positive (Fig. 4). That is, turbulent exchange was decreasing and the inversion layer was growing as the atmosphere became stable and the near surface winds completely aligned with the slope.

Although both advective fluxes showed a broad scatter, diurnal trends were found (Fig. 7c, d). Positive F_{HA} during night resulted generally from down-slope winds ($u_c > 0$) and a positive CO_2 gradient with higher CO_2 concentrations down slope ($\frac{\partial \bar{c}}{\partial x} > 0$), whereas during the day up-slope winds ($u_c < 0$) and a negative CO_2 gradient ($\frac{\partial \bar{c}}{\partial x} < 0$) predominated. Vertical advection fluxes (F_{VA}) were larger than F_{HA} and highly variable (Fig. 7d; note the different vertical scales). During the night high positive and negative values were observed and the scatter was pronounced and sometimes more erratic. During the day, when vertical CO_2 gradients were small advective fluxes, fluctuating around zero. On a daily basis, F_{VA} summed up to relatively small values due to the counteracting fluxes in both directions (Table 1). Diurnal patterns of both advective fluxes could be explained by the local wind system. As frequently observed over steep slopes, development of gravity flows through the forest understory due to surface radiative cooling in the evening caused a negative vertical flow and entrainment of air from above canopy to the soil. Early in the evening gravity flows started to develop (16:00 CET, $u_c < 0$ changed to $u_c > 0$) and the stable nocturnal boundary layer (SNBL) started to grow. Vertical velocity $\bar{w}$ was positive during the day (upward) and started to decrease sharply exactly when u_c has reached its maximum in down-slope direction (18:00 CET). That is, the growing SNBL has reached the sites elevation and air from above the canopy is entrained into the control volume, following the gravity flow through the forest understory ($\bar{w} < 0$). This is confirmed by the fact that highest positive F_{VA} occur when wind direction in the canopy is in down-slope direction (290–340°) (data not shown). The negative peak of F_{VA} around 17:00 CET (Fig. 7d) resulted from

a still positive $\bar{w}$ and the increasing negative vertical CO_2 gradient due to decreased mixing of the air.

Positive advection during night leads to depletion of CO_2 inside the control volume and consequently to an underestimation of the respiration flux by the EC instrumentation above the canopy. Thus, adding advective fluxes to F_C should theoretically correct for the underestimation of respiration during the night. Due to few erratically large fluxes of F_{VA} in both directions, correcting of F_C for F_{VA} resulted in a few unrealistic fluxes with respect to magnitude and sign, e.g. negative fluxes during night. Thus, for further analyses we had to remove night-time fluxes below $-5\,\mu mol\,m^{-2}\,s^{-1}$.

3.2 Contribution of advection to C budget

Night-time CO_2 fluxes that were normalised to 10 °C increased constantly with increasing u_* (Fig. 8a). Thus, by visual examination no u_* threshold could be identified at which the night-time CO_2 fluxes remained constant. Adding F_{HA} to the measured EC values increased night-time fluxes at low u_* values, but showed no effect for higher u_* values and a decrease for $u_* > 0.8\,m\,s^{-1}$ (Fig. 8b). Night-time fluxes that were corrected for both advective fluxes showed, contrary to the typical evolution of night-time fluxes with u_*, a tendency to decrease with increasing u_* (for $n_{u*\text{-class}} > 10$, $p = 0.11$, Fig. 8c). As a corollary then, correcting EC fluxes for F_{VA} is expected to overestimate the respiration flux, as was also confirmed by Fig. 9 and Table 2. However, on a daily basis F_{VA} summed up to almost zero. Therefore, it could be argued that over longer time scales (daily, seasonal, yearly) F_{VA} is not relevant for the site's C budget, whereas F_{HA} is, being predominantly positive and most significant at low u_* (Table 2). In fact, EC fluxes that were corrected only for F_{HA} showed good agreement to the u_* filtered data (linear regression with $Reco_{u*}$: slope: 0.77±0.04, intercept: $1.23\pm0.27\,\mu mol\,m^{-2}\,s^{-1}$, adj. $R^2 = 0.80$, $p < 0.001$). Estimated respiration loss between May to August 2007 was only 5% higher for $Reco_{u*}$($899\,g\,C\,m^{-2}$) than for $Reco_{HA}$($853\,g\,C\,m^{-2}$) (Table 2). Substantial differences occurred in June, with much higher respiration values for $Reco_{u*}$.

This was due to the fact that during that period of ten days 43% of night-time data were below the u_* threshold of 0.3 m s^{-1}, although F_{HA} was not very pronounced. A sudden short temperature peak led then to the large modeled respiration fluxes. Accounting for advection by the u_* filter resulted in 48% higher cumulative Reco$_{u*}$during May to August 2007 compared to Reco (Table 2), and questions whether replacing measured data by model results is the best possible approach to quantify ecosystem respiration. To answer this question, we validated our suggestions to (a) quantify advection via a simplified 2-D measurement approach, and (b) approximate these advection corrections with a u_* threshold of 0.3 m s^{-1}. Three independent approaches support our findings as reported in the following.

3.3 Validation of EC flux corrections

3.3.1 Soil respiration

Soil respiration (SR, Fig. 9) chamber measurements (Rühr et al., 2010) were correlated with Reco$_{HA}$ ($R = 0.53$) and Reco$_{u*}$ ($R = 0.49$) with an intercept of −1 day. This is a better correlation than what was found with uncorrected Reco ($R = 0.35$). Over the whole measurement period, SR contributed about 50% to Reco$_{u*}$ and Reco$_{HA}$ (Table 2), monthly contribution of SR to Reco$_{u*}$ and Reco$_{HA}$ ranged from 43% in May, over 50% in summer and to 76% in August (Fig. 9).

3.3.2 Light response curves

Daily respiration estimates that can be extracted from light response curve (LRC) intercepts (e.g., Moffat et al., 2007) were well correlated with daily means of respiration rates obtained directly by nocturnal EC measurements ($R = 0.74$), with those filtered by u_*, Reco$_{u*}$ ($R = 0.68$), and with those corrected for horizontal advection Reco$_{HA}$ ($R = 0.67$). Cumulated sum based on the LRC approach for the period May to August was lower (653 g C m^{-2}) than Reco$_{u*}$ and Reco$_{HA}$ (Table 2).

3.3.3 Energy budget closure

For the Lägeren forest, linear regression of the sum of turbulent heat fluxes to available energy for the period from May to August 2007 resulted in a slope of 0.78±0.01 and an intercept of 22.9±2.0 (adj. $R^2 = 0.84$, (Fig. 10), the EBR yielded 0.86. Under the assumption that advection impacts the accuracy of EC measurements, a higher energy budget closure should be reached by excluding data periods when high advection occurred. However, neither exclusion of periods with $F_{HA} > 2\,\mu mol\,m^{-2}\,s^{-1}$ (26.7%) was improving the energy budget closure at our site (slope: 0.77±0.01, intercept: 20.0±2.8, adj. $R^2 = 0.82$), nor the exclusion of F_{VA} outside the range of $\pm 10\,\mu mol\,m^{-2}\,s^{-1}$ (regression slope: 0.77±0.01, intercept: 20.2±3.1, adj. $R^2 = 0.82$).

4 Discussion

F_{HA} and F_{VA} at the Lägeren site showed different patterns. F_{VA} were much larger than F_{HA} and showed a broad scatter and an erratic behaviour, but over the course of a day positive and negative F_{VA} summed up to almost zero. F_{HA} was throughout positive and much more directional and systematic, following the diurnal mountain wind system. Whereas F_{HA} was caught very well by the u_* filter, F_{VA} produced unrealistic high fluxes when incorporated into the mass balance equation. In our discussion, we will focus on the following aspects that are of concern at almost any EC flux site: (1) our attempt to simplify the experimental set-up to quantify horizontal advection and its representativeness; (2) how important advection is for long-term C budgets and how it relates to the simpler but entirely empirical u_* correction and (3) how these estimates are linked to independently derived validation data.

4.1 Quantification of advection with a simple 2-D approach

Several studies have been published so far where advection was measured by multiple EC towers in a complex three-dimensional multi-level set-up (e.g., Staebler and Fitzjarrald, 2004; Heinesch et al., 2007; Feigenwinter et al., 2008; Leuning et al., 2008; Yi et al., 2008). However, this is not a practicable option for most of the flux tower sites. But, the occurrence of advection seems to be rather the rule than the exception, whereas its quantitative relevance in relation to turbulent fluxes is not known a priori at a given flux tower site. The best available knowledge presented in recent publications suggests that the quantitative relevance of advective fluxes should at least be tested at long-term EC flux sites, since no generally applicable rules could be derived from extensive field experiments on advection so far. Therefore we tested a relatively simple set-up for advection measurements based on the current knowledge of advection. It is well-known that cold-air drainage flow is very common at mountain sites due to local valley and slope wind systems (Wagner, 1938; Defant, 1949; Whiteman and Doran, 1993; Whiteman, 2000). This was confirmed at our study site, where wind field analyses showed strongly channeled winds above canopy and a pronounced diurnal cycle of wind directions inside the canopy. This 2-D character of the wind system gives the opportunity to reduce advection measurements to a 2-D approach, namely along the prevailing wind direction in canopy.

Total F_{HA} strongly depends on the chosen integration height: slight modifications of the integration height can result in large changes of the advection flux. According to Finnigan et al. (2003), a vertical integral of the non-turbulent horizontal flux divergence is necessary to close the mass budget. However, to achieve this, a multi-level set-up with all necessary measurements would be required. But as this is not practicable at most sites, the integration height is usually estimated by integrating or modeling the vertical wind, temperature and CO_2 concentration profiles (Aubinet et al., 2003; Feigenwinter et al., 2004; Kutsch et al., 2009). However, this can be relatively speculative. For example, we computed F_{HA} along the prevailing wind direction for a layer

depth of 2 m according to the measurement height of CO_2 gradients and wind vectors. It is thus possible that F_{HA} in total might be larger than the presented values. However, our vertical profiles of horizontal wind speed, temperature and CO_2 concentrations (Figs. 5 and 6) suggest that the drainage layer is relatively shallow due to a strong nocturnal gravitational flow along the steep slope. Thus, F_{HA} is most pronounced very close to the ground surface. Displacement of the CO_2 measurements to a height of 2 m in 2008 showed indeed a decreased horizontal CO_2 gradient (about 50% compared to 1 m), whereas horizontal wind speed remained unchanged (data not shown). Thus, an integration height larger than 2 m would not have been representative for our measurements and most likely would have led to an overestimation of the horizontal advection term. Gradient measurements carried out in 2008 and 2009 at 1 and 2 m above the ground and with one additional point in between our horizontal gradient (at distances 0, 12, 60 m) confirmed the observed patterns of horizontal advection as described above and showed repeatable characteristics. Therefore, we are convinced that the horizontal advection term as presented in this study is temporally and spatially valid, at least with regard to the vertical dimension. F_{HA}, obtained by this simple set-up, showed characteristic, well-known patterns, such as the pronounced diurnal cycle that closely follows the local wind system (Whiteman, 2000). Derived values are robust and well in the range of other studies that were conducted on sloping terrain (Marcolla et al., 2005; Feigenwinter et al., 2008).

4.2 Contribution of advection to C budget

Incorporation of advective fluxes directly into the mass balance equation is a highly controversial issue in the scientific discussion and was already addressed by several authors (see Aubinet et al., 2010). Analysing advection measurements of three different sites, Aubinet et al. (2010) concluded that advection can not be included “one to one” into the mass balance due to different measurement scales of advection and EC fluxes and too low spatial resolution of advection measurements. Physical correction of EC fluxes at the Lägeren site by measured horizontal and vertical advection was of

differing quality. Incorporating both advection terms directly into the mass balance, produced unrealistic biotic fluxes, e.g., negative fluxes during the night, and could mainly be attributed to the vertical advection term. But on a longer term basis, horizontal advection is assumed to have the biggest influence on the C budget of the Lägeren site, whereas F_{VA} seems to be of minor importance as fluxes, integrated over longer time scales, counterbalance themselves to almost zero. In contrast to this, Aubinet et al. (2010) identified F_{HA} to be the major problem for their three investigated sites. The Lägeren forest fixed 182 g C m^{-2} less than what direct EC measurements suggested over the observation period of four months when involving F_{HA} into calculations. Thus, F_{HA} accounted for 40% of the ecosystem's C budget. As F_{HA} is most prominent during the growing season (data not shown; cf., Yi et al., 2008) and the respiration flux is usually highest during summer time, we deduce that F_{HA} only plays a minor role during the dormant season. Thus, on an annual basis, F_{HA} should not exceed 40% of NEE.

The correction of night-time NEE data by the u_* filter approach is recommended as the method of choice by Aubinet (2008). Many studies have shown that the rejection of periods with low u_* values result in a systematic decrease of annual sums of NEE in the order of 50 to 200 g C m^{-2} a^{-1} (e.g., Falge et al., 2001; Carrara et al., 2003; Hui et al., 2004). Hereby, the decrease of NEE is a direct function of the choice made for the u_* threshold. In our case, calculations involving u_* filtering yielded 107 g C m^{-2} lower carbon uptake during May to August than EC measurements suggested. Data that were filtered by a u_* threshold of 0.3 m s^{-1} showed good agreement to $Reco_{HA}$ with a deviation of the seasonal sums only by 5%. We found that a u_* filter with a threshold of 0.3 m s^{-1} gives a good estimate of Reco for our study site. However, the simpler u_* filtering approach is purely empirical and at times it is unclear why there are large discrepancies between F_{HA} and the u_* derived respiration flux (e.g., Fig. 9, in June). Although horizontal advection and u_* were reasonably correlated, especially at lower u_* values (Fig. 8b), no overall firm relationship of hourly or daily values of advection to u_* could be established. This decoupling between advection and u_* was also observed in other studies (Marcolla et al., 2005; Yi et al., 2008; Kutsch et al., 2009).

4.3 Validation of EC flux corrections

In order to validate our various correction approaches we related the calculated fluxes to independently derived measurements. Soil respiration chamber measurements (Rühr et al., 2010) are in line with $Reco_{u*}$ and $Reco_{HA}$. Seasonal (50%) as well as monthly contributions of SR to $Reco_{u*}$ and $Reco_{HA}$ (40% in spring, 76% in late summer) are well in the range of values reported earlier (40 to 80% with increasing contribution from spring to fall (e.g., Curiel Yuste et al., 2005; Davidson et al., 2006).

Also, daily respiration estimates that were derived from extrapolation of light response curves to zero light showed good agreement to our $Reco_{u*}$ and $Reco_{HA}$ estimates ($r = 0.68$, $r = 0.67$), but values were lower and closer to the uncorrected Reco values. Underestimation of ecosystem respiration derived from daytime data up to 20% was already reported for similar comparisons of respiration estimates and attributed to inhibition of canopy respiration during daytime, footprint differences between day and night-time and differences between short term autotrophic carbon loss and longer term heterotrophic carbon loss (e.g., Falge et al., 2002; Xu and Baldocchi, 2004; Wohlfahrt et al., 2005). In contrast, Hutyra et al. (2008) found good agreement between mean annual ecosystem respiration of a tropical forest, derived by light curves and from nocturnal u_* filtered EC data.

Based on the first law of thermodynamics, in an ideal closed system outgoing energy is expected to balance incoming energy, resulting in a hypothetical 1:1 regression line. The regression slope of 0.79±0.0063 and intercept of 22.9±1.96 and EBR ratio of 0.86 for the period from May to August for the Lägeren site corresponds very well to the mean energy balance published for 22 FLUXNET sites (mean budget closure of 0.79, intercept range of −32.9 to 36.9, mean EBR = 0.84 (Wilson et al., 2002). For forest sites, mean budget closure values of average 0.80 to 0.87 were reported (Aubinet et al., 2000; Barr et al., 2006). These sites however, are located in far less complex topography, typically on flat ground. Based on the premise that the energy budget closure is a reliable quality measure of EC flux measurements, our measurements

carried out over complex terrain should then be of the same overall quality as those over flat terrain (cf. Hiller et al., 2008).

As advection is accounting for 40% of the C budget at our site and is a major factor for the underestimation of the turbulent fluxes, we hypothesized that exclusion of periods with strong advection should improve the energy budget closure (cf. Barr et al., 2006; Oncley et al., 2007). Our data, however, do not support this idea. One explanation might be that EC fluxes of water and sensible heat are more robust than CO_2 fluxes as stated by Lee and Hu (2002). A reason for the poor improvement of the energy budget closure could be that the slope of the regression line is primarily determined by the range of the incoming short-wave radiation, e.g., by day-time values. But as advection is most prominent during night at our study site, advection might affect the energy budget closure calculation only slightly. The energy budget closure gap can apparently not be explained by the occurrence of advection, at least not at our site. In summary, if the energy budget closure is considered a sound indicator for the quality of EC flux measurements, then our data presented here provide strong evidence that EC flux measurements carried out on a relatively steep but spatially homogeneous mountain slope are of comparable quality as sites with flat ground.

5 Conclusions

With a relatively simple measurement set-up, we got realistic and explainable estimates of horizontal advection for our research site. By physical correction of our EC data for horizontal advection we got reasonable estimates of fluxes on a daily, monthly and seasonal basis, that were in good agreement with data that were filtered by a u_* threshold of $0.3\,m\,s^{-1}$. A cross validation with (a) chamber measurements of soil respiration, (b) respiration fluxes derived from light response curves, and (c) the energy budget closure indicated that EC fluxes corrected for advection as we propose here are consistent with other flux estimates. However, this simplification can only be considered valid at sites with strongly channeled wind flow and thus a 2-D character of the flux footprint.

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Although steep sloping sites are commonly challenged as not suitable for EC measurements due to a large advection component, we could show that advection at the Lägeren site with a slope angle of 24° is well in the range with advection measurements on less steep slopes or even over flat terrain. Based on the energy budget closure criterion it can even be deduced that such mountain slope sites are as suitable for EC measurements as most other existing flux sites.

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References

Acevedo, O. C., Moraes, O. L. L., degrazia, G. A., Fitzjarrald, D., Manzi, A. O., and Campos, J. G.: Is friction velocity the most appropriate scale for correction of nocturnal carbon dioxide fluxes?, Agr. Forest Meteorol., 149, 1–10, 2009.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Gruenwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of annual net carbon and water exchange of forests: The euroflux methodology, in: Advances in ecological research, edited by: Fitter, A. H. and Raffaelli, D., Academic Press, 113–175, 2000.

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

Aubinet, M., Berbigier, P., Bernhofer, C., Cescatti, A., Feigenwinter, C., Granier, A., Gruenwald, T., Havrankova, K., Heinesch, B., Longdoz, B., Marcolla, B., Montagnani, L., and Sedlak, P.:

Comparing CO_2 storage and advection conditions at night at different carboeuroflux sites, Bound.-Lay. Meteorol., 116, 63–94, 2005.
Aubinet, M.: Eddy covariance CO_2 flux measurements in nocturnal conditions: An analysis of the problem, Ecol. Appl., 18, 1368–1378, 2008.
Aubinet, M., Feigenwinter, C., Bernhofer, C., Canepa, E., Lindroth, A., Montagnani, L., Rebmann, C., Sedlak, P., and Van Gorsel, E.: Direct advection measurements do not help to solve the nighttime CO_2 closure problem – evidence from three inherently different forests, Agr. Forest Meteorol., doi:10.1016/j.agrformet.2010.01.016, in press, 2010.
Baldocchi, D., Finnigan, J., Wilson, K., Paw U, K. T., and Falge, E.: On measuring net ecosystem carbon exchange over tall vegetation on complex terrain, Bound.-Lay. Meteorol., 96, 257–291, 2000.
Baldocchi, D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future, Glob. Change Biol., 9, 479–492, 2003.
Barr, A. G., Morgenstern, K., Black, T. A., McCaughey, J. H., and Nesic, Z.: Surface energy balance closure by the eddy-covariance method above three boreal forest stands and implications for the measurement of the CO_2 flux, Agr. Forest Meteorol., 140, 322–337, 2006.
Carrara, A., Kowalski, A., Neirynck, J., Janssens, I. A., Curiel Yuste, J., and Ceulemans, R.: Net ecosystem exchange of a mixed forest in belgium over 5 years, Agr. Forest Meteorol., 119, 209–227, 2003.
Curiel Yuste, J., Nagy, M., Janssens, I. A., Carrara, A., and Ceulemans, R.: Soil respiration in a mixed temperate forest and its contribution to total ecosystem respiration, Tree Physiol., 25, 609–619, 2005.
Davidson, E. A., Richardson, A. D., Savage, K. E., and Hollinger, D. Y.: A distinct seasonal pattern of the ratio of soil respiration to total ecosystem respiration in a spruce-dominated forest, Glob. Change Biol., 12, 230–239, 2006.
Defant, F.: A theory of slope winds, along with remarks on the theory of mountain winds and valley winds, in: Alpine meteorology: Translations of classic contributions by: Wagner, A., Ekhart, E., and Defant, F., Rep. PNL-5141/ASCOT-84-3, Pacific Northwest Laboratory, Richland, WA, 121 pp., 1949.
Eugster, W., McFadden, J. J., and Chapin, F. S.: A comparative approach to regional variation in surface fluxes using mobile eddy correlation towers, Bound.-Lay. Meteorol., 85, 293–307, 1997.

Eugster, W., Kling, G., Jonas, T., McFadden, J. J., Wuest, A., MacIntyre, S., and Chapin, F. S.: CO_2 exchange between air and water in an arctic alaskan and midlatitude swiss lake: Importance of convective mixing, J. Geophys. Res., 108(D12), 4362, doi:10.1029/2002JD002653, 2003.

Eugster, W., Zeyer, K., Zeeman, M., Michna, P., Zingg, A., Buchmann, N., and Emmenegger, L.: Methodical study of nitrous oxide eddy covariance measurements using quantum cascade laser spectrometery over a Swiss forest, Biogeosciences, 4, 927–939, 2007, http://www.biogeosciences.net/4/927/2007/.

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

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G. G., Clement, R., Davis, K. J., Elbers, J. A., Goldstein, A. H., Grelle, A., Granier, A., Gudmundsson, J., Hollinger, D., Kowalski, A., Katul, G., Law, B. E., Malhi, Y., Meyers, T., Monson, R. K., Munger, J. W., Oechel, W., Paw U, K. T., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Valentini, R., Wilson, K., and Wofsy, S.: Seasonality of ecosystem respiration and gross primary production as derived from fluxnet measurements, Agr. Forest Meteorol., 113, 53–74, 2002.

Feigenwinter, C., Bernhofer, C., and Vogt, R.: The influence of advection on the short term CO_2 budget in and above a forest canopy, Bound.-Lay. Meteorol., 113, 201–224, 2004.

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

Finnigan, J. J., Clement, R., Malhi, Y., Leuning, R., and Cleugh, H. A.: A re-evaluation of long-term flux measurement tehcniques. Part i: Averaging and coordinate rotation, Bound.-Lay. Meteorol., 107, 1–48, 2003.

Foken, T. and Wichura, B.: Tools for quality assessment of surface-based flux measurements, Agr. Forest Meteorol., 78, 83–105, 1996.

Food and Agriculture Organisation of the United Nations (FAO): online available at: http://www.fao.org and http://www.mountainpartnership.org, 2008.

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J. M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I. A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.-M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M. J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J. F., Valentini, R., Vesala, T., Verbeeck, H., and Yakir, D.: Quality control of CarboEurope flux data Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5, 433–450, 2008, http://www.biogeosciences.net/5/433/2008/.

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

Gu, L., Falge, E. M., Boden, T., Baldocchi, D. D., Black, T. A., Saleska, S. R., Suni, T., Verma, S. B., Vesala, T., Wofsy, S., and Xu, L.: Objective threshold determination for nighttime eddy flux filtering, Agr. Forest Meteorol., 128, 179–197, 2005.

Heinesch, B., Yernaux, M., and Aubinet, M.: Some methodological questions concerning advection measurements: A case study, Bound.-Lay. Meteorol., 122, 457-478, 2007.

Hiller, R., Zeeman, M. J., and Eugster, W.: Eddy-covariance flux measurements in the complex terrain of an alpine valley in switzerland, Bound.-Lay. Meteorol., 127, 449–467, 2008.

Huber, U. M., Bugmann, H., and Reasoner, M.: Global change and mountain regions: An overview of current knowledge. Advances in global chnage research, edited by: Huber, U. M., Bugmann, H., and Reasoner, M., Springer Berlin, 2005.

Hui, D., Wan, S., Su, B., Katul, G., Monson, R., and Luo, Y.: Gap-filling missing data in eddy covariance measurements using multiple imputation (mi) for annual estimations, Agr. Forest Meteorol., 121, 93–111, 2004.

Hutyra, L. R., Munger, J. W., E, H.-P., Saleska, S. R., Restrepo-Coupe, N., Daube, B. C., de Camargo, P. B., and Wofsy, S.: Resolving systematic errors in estimates of net ecosystem exchange of co_2 and ecosystem respiration in a tropical forest biome, Agr. Forest Meteorol., 148, 1266–1279, 2008.

Janssens, I. A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G. J., Folberth, G., Schlamadinger,

B., Hutjes, R. W. A., Ceulemans, R., Schulze, E. D., Valentini, R., and Dolman, A. J.: Europe's terrestrial biosphere absorbs 7 to 12% of european anthropogenic CO_2 emissions, Science, 300, 1538–1542, 2003.

Kutsch, W. L., Kolle, O., Rebmann, C., Knohl, A., Ziegler, W., and Schulze, E. D.: Advection and resulting CO_2 exchange uncertainty in a tall forest in Central Germany, Ecol. Appl., 18, 1391–1405, 2009.

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

Lee, X. and Hu, X.: Forest-air fluxes of carbon, water and energy over non-flat terrain, Bound.-Lay. Meteorol., 103, 277–301, 2002.

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

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, Funct. Ecol., 8, 315–323, 1994.

Luyssaert, S., Schulze, E. D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Ciais, P., and Grace, J.: Old-growth forests as a global carbon sink, Nature, 455, 213–215, 2008.

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

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grünwald, T., Heusinkveld, B., and Kolle, O.: Quality control of CarboEurope flux data – Part II: Inter-comparison of eddy-covariance software, Biogeosciences Discuss., 4, 4067–4099, 2007, http://www.biogeosciences-discuss.net/4/4067/2007/.

Metzger, M. J., Bunce, R. G. H., Leemans, R., and Viner, D.: Projected environmental shifts under climate change: European trends and regional impacts, Environ. Conserv., 35, 64–75, 2008.

Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D. Y., Richardson, A. D., Barr, A. G., Beckstein, C., Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J., Kattge, J., Noormets, A., and Stauch, V. J.: Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes, Agr. Forest Meteorol., 147, 209–232, 2007.

Moffat, A. M.: A new methodology to interpret high resolution measurements of net carbon

fluxes between the terrestrial ecosystems and the atmosphere, PhD, Friedrich Schiller University, Jena, 2010.
Montheith, J. L. and Unsworth, M. H.: Principles of environmental physics, Edward Arnold, London, 1990.
Moureaux, C., Debacq, A., Bodson, B., Heinesch, B., and Aubinet, M.: Annual net ecosystem carbon exchange by a sugar beet crop, Agr. Forest Meteorol., 139, 25–39, 2006.
Oncley, S. P., Foken, T., Vogt, R., Kohsiek, W., DeBruin, H. A. R., Bernhofer, C., Christen, A., van Gorsel, E., Grantz, D., Feigenwinter, C., Lehner, I., Liebethal, C., Liu, H., Mauder, M., Pitacco, A., Ribeiro, L., and Weidinger, T.: The energy balance experiment ebex-2000. Part I: Overview and energy balance, Bound.-Lay. Meteorol., 123, 1–28, 2007.
Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeosciences, 3, 571–583, 2006, http://www.biogeosciences.net/3/571/2006/.
R Development Core Team: R: A language and environment for statistical computing, in: R foundation for statistical computing Vienna, Austria, 2006.
Reichstein, M., Tenhunen, J. D., Roupsard, O., Ourcival, J. M., Miglietta, F., Peressotti, A., Pecchiari, M., Tirone, G., and Valentini, R.: Severe drought effects on ecosystem CO_2 and H_2O fluxes at three mediterranean evergreen sites: Revision of current hypotheses?, Glob. Change Biol., 8, 999–1017, 2002.
Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Gruenwald, T., Havrankova, 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., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm, Glob. Change Biol., 11, 1424–1439, 2005.
Rühr, N. K., Knohl, A., and Buchmann, N.: Environmental variables controlling soil respiration on diurnal, seasonal and annual time-scales in a mixed mountain forest in switzerland, Biogechemistry, doi:10.1007/s10533-10009-19383-z, in press, 2010.
Ruppert, J., Mauder, M., Thomas, C., and Luers, A.: Innovative gap-filling strategy for annual sums of CO_2 net ecosystem exchange, Agr. Forest Meteorol., 138, 5–18, 2006.
Schimel, D., Kittel, T. G. F., Running, S., Monson, R., Turnipseed, A. A., and Anderson, D.:

Carbon sequestration studied in western U.S. Mountains, EOS Trans. AGU, 83, 445–449, 2002.
Staebler, R. M. and Fitzjarrald, D. R.: Observing subcanopy CO_2 advection, Agr. Forest Meteorol., 122, 139–156, 2004.
Van Gorsel, E., Leuning, R., Cleugh, H. A., Keith, H., and Suni, T.: Nocturnal carbon efflux: Reconciliation of eddy covariance and chamber measurements using an alternative to the u*-threshold filtering technique, Tellus, 59, 397–403, 2007.
Van Gorsel, E., Leuning, R., Cleugh, H. A., Keith, H., Kirschbaum, M. U. F., and Suni, T.: Application of an alternative method to derive reliable estimates of nightime respiration from eddy covariance measurements in moderately complex terrain, Agr. Forest Meteorol., 148, 1174–1180, 2008.
Wagner, A.: Theory and observation of periodic mountain winds, in: Alpine meteorology: Translations of classic contributions by: Wagner, A., Ekhart, E., and Defant, F., Rep. PNL-5141/ASCOT-84-3, Pacific Northwest Laboratory, Richland, WA, 121 pp., 1938.
Whiteman, C. D. and Doran, J. C.: The relationship between overlying synoptic-scale flows and winds within a valley, J. Appl. Meteorol., 32, 1669–1682, 1993.
Whiteman, C. D.: Mountain meteorology: Fundamentals and applications, Oxford University Press, New York, Oxford, 355 pp., 2000.
Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B. E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., and Verma, S.: Energy balance closure at Fluxnet sites, Agr. Forest Meteorol., 113, 223–243, 2002.
Wohlfahrt, G., Anfang, C., Bahn, M., Haslwanter, A., Newesely, C., Schmitt, M., Droesler, M., Pfadenhauer, J., and Cernusca, A.: Quantifying nighttime ecosystem respirationof meadow using eddy covariance, chambers and modelling, Agr. Forest Meteorol., 128, 141–162, 2005.
World Conservation Monitoring Centre (WCMC) of the UNEP: online available at: http://www.unep-wcmc.org, 2008.
Xu, L. and Baldocchi, D.: Seasonal variation in carbon dioxide exchange over a mediterranean annual grassland in California, Agr. Forest Meteorol., 1232, 79–96, 2004.
Yi, C., Anderson, D. E., Turnipseed, A. A., Burns, S. P., Sparks, J. P., Stannard, D. I., and Monson, R. K.: The contribution of advective fluxes to net ecosystem exchange in a high-elevation, subalpine forest, Ecol. Appl., 18, 1379–1390, 2008.

Table 1. Mean daily fluxes and daily sums for EC fluxes (F_C), storage term (S_C), horizontal advection (F_{HA}) and vertical advection (F_{VA}). Day-time was defined as 06:00–18:00 h, night-time as 19:00–05:00 h.

	mean daily flux [µmol m^{-2} s^{-1}]			mean daily sum [g Cm^{-2}]		
	day-time	night-time	all	day-time	night-time	all
FC	−11.4	3.02	−8.38	2.87	0.42	2.45
SC	−0.36	0.67	0.31	−0.15	0.12	−0.03
FHA	0.9	1.42	2.32	0.19	0.28	0.47
FVA	−1.6	1.2	−0.4	−0.08	0.02	−0.06

Table 2. Cumulative sums of NEE, GPP and Reco for May to August 2007 based on EC data and different correction approaches for the forest site Lägeren. [a] Cumulative sums of NEE, GPP and Reco for May to August 2007 [g C m^{-2}]. [b] Percentage of cumulative sum of NEE, GPP and Reco of direct EC measurements (EC) in relation to the respective sum of the other variants.

	EC	EC ($u_* \geq 0.3$)		EC (F_{HA} corrected)		EC (F_{HA} and F_{VA} corrected)		LRC	SR
	Σ [a]	Σ [a]	b [b]	Σ [a]	b [b]	Σ [a]	b [b]		
NEE [g C m^{-2}]	-459	-352	0.77	-277	0.60	-328	0.71	-	-
GPP [g C m^{-2}]	-1068	-1252	1.17	-1130	1.06	1685	1.58	-	-
Reco [g C m^{-2}]	609	899	1.48	853	1.40	1356	2.23	653	456

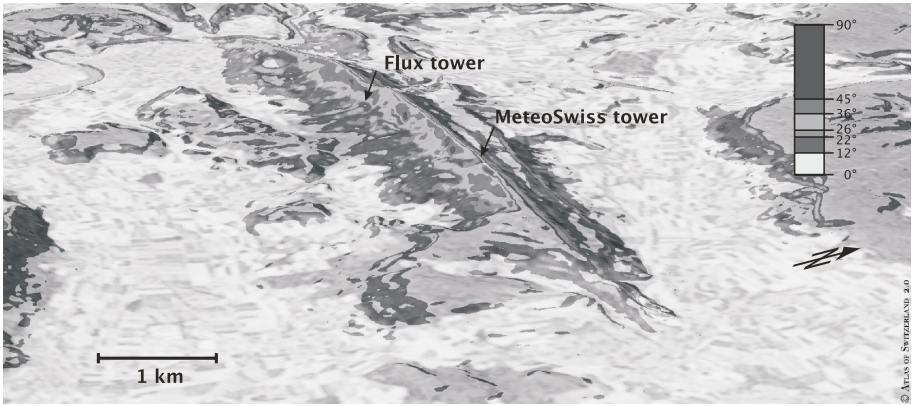

Fig. 1. The Lägeren mountain ridge. Colours indicate the slope angle of the respective area. The Lägeren flux tower and the MeteoSwiss tower are marked (reproduced with authorisation of swisstopo, JA082267).

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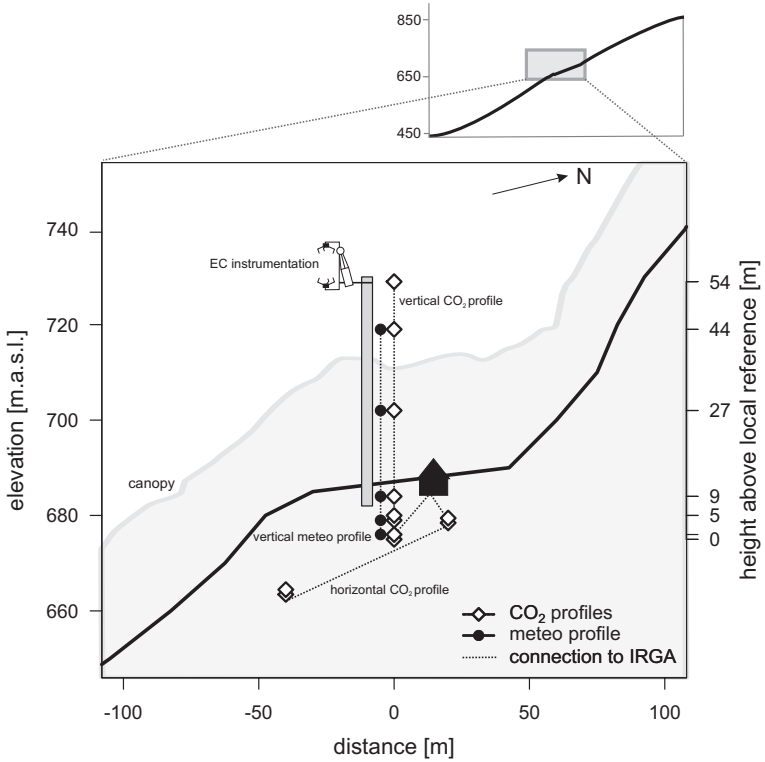

Fig. 2. Experimental set-up of EC flux and advection measurements. 675 m a.s.l. is used as local reference zero height. Note that the x- and y-axis have different scales. For details see text.

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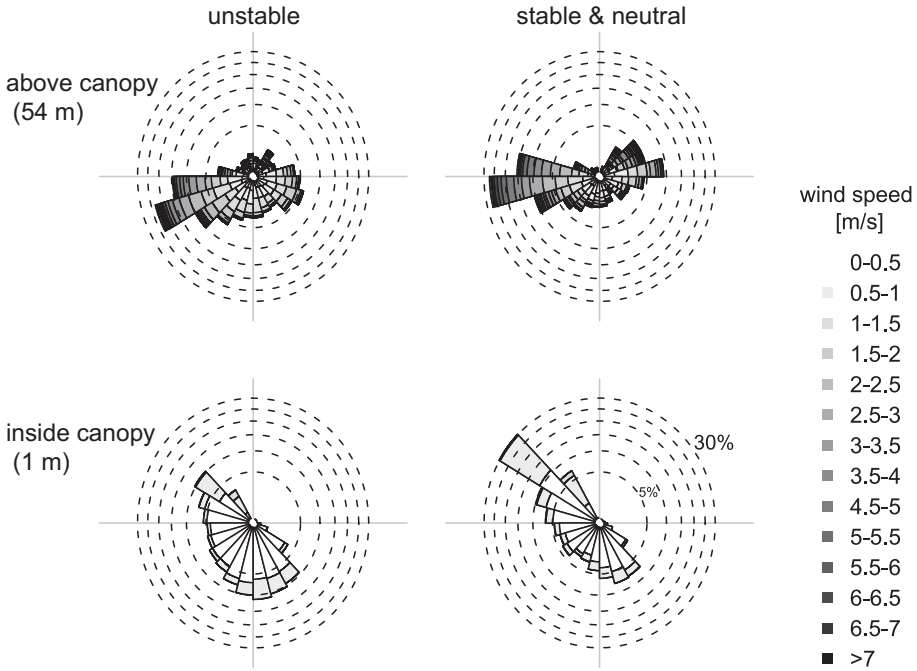

Fig. 3. Wind roses for above (54 m) and inside the canopy (1 m) for two stability classes (stable and neutral: $z/L >= 0$, unstable: $z/L < 0$). Each broken circle refers to 5% frequency classes in the respective wind direction sector. Data were measured during May to August 2007.

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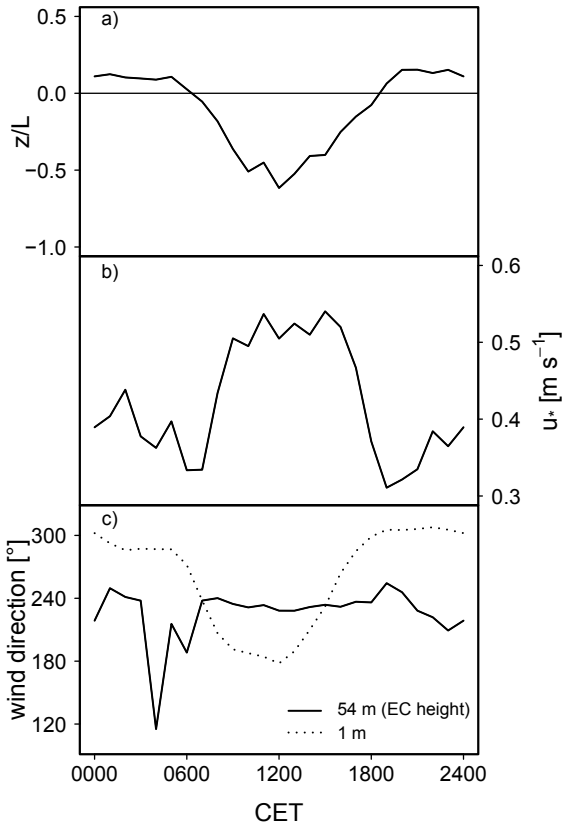

Fig. 4. Median diurnal cycles of **(a)** stability parameter z/L, **(b)** friction velocity u_* at EC height (54 m) and **(c)** wind direction at EC height (54 m, solid line) and inside the canopy (1 m, dotted line) during May to August 2007.

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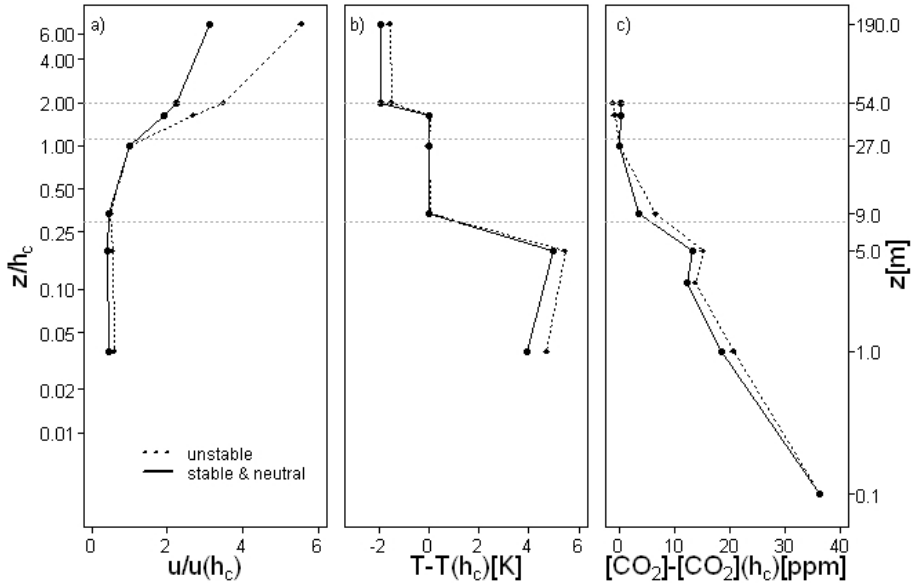

Fig. 5. Vertical profiles of **(a)** mean horizontal wind speed normalized by wind speed at canopy height (h_c=30 m), **(b)** mean difference of air temperature and air temperature at canopy height and **(c)** mean CO_2 concentrations for two stability classes. Solid lines indicate stable and neutral conditions, dotted lines unstable conditions. Left axis represents log-transformed height z, normalized by h_c, right axis indicates measurement height in m. The data point at 190 m is derived from the MeteoSwiss tower at the Lägeren ridge.

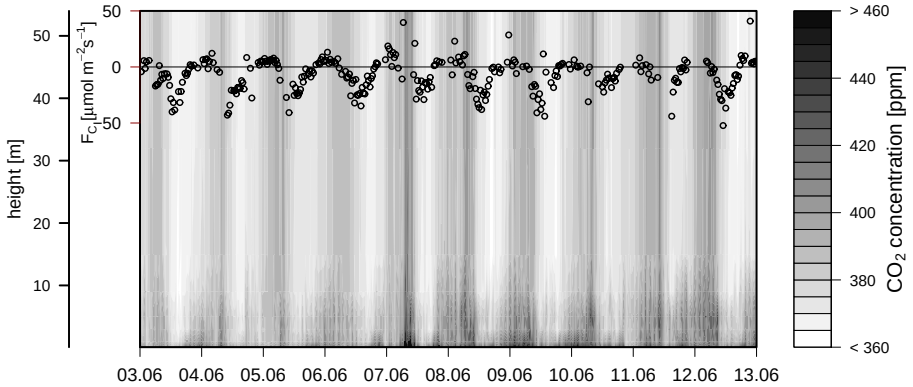

Fig. 6. Vertical profile of CO_2 concentrations and CO_2 flux during ten days in June 2007. The inset with open circles shows the net CO_2 flux measured by EC (30-min averages). Mean canopy height is 30 m.

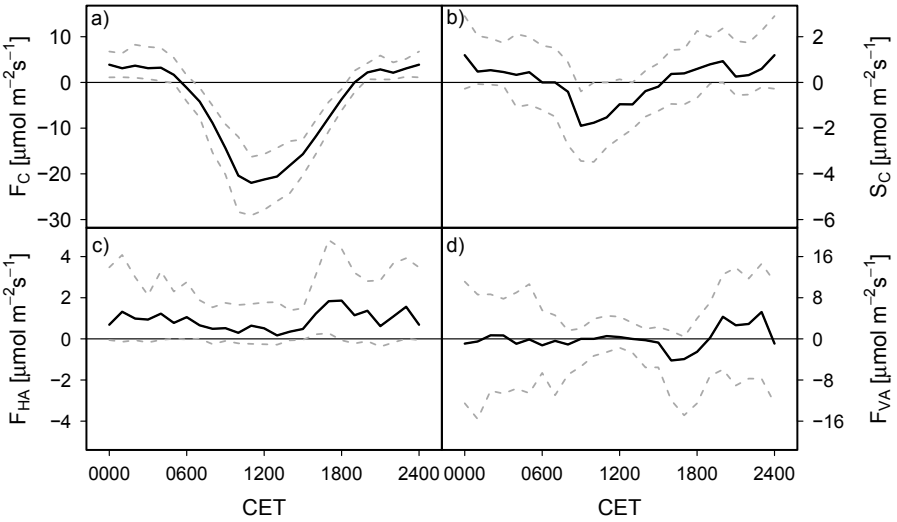

Fig. 7. Diurnal cycles of **(a)** CO_2 flux F_C, **(b)** storage term S_C, **(c)** horizontal advection F_{HA} and **(d)** vertical advection F_{VA} for the period of May to August 2007. Black lines indicate median values, grey broken lines inter quantiles (25%, 75%) of the respective fluxes. Note that y axes are different scales.

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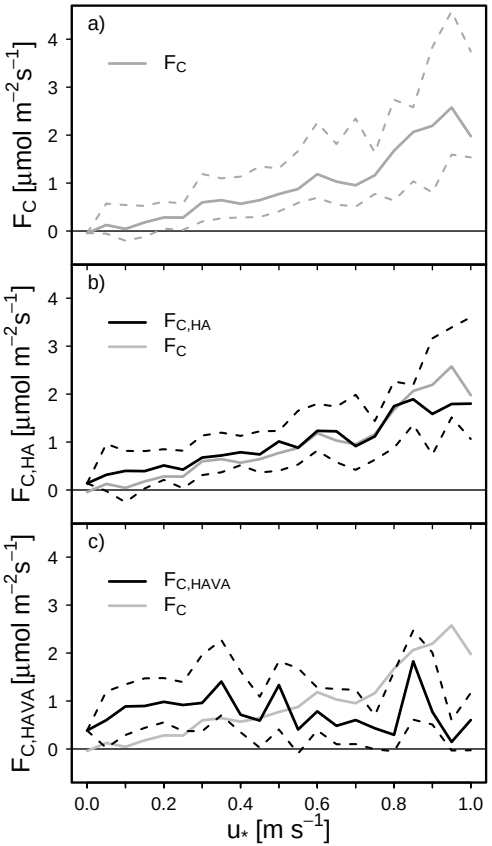

Fig. 8. Relationships of **(a)** night-time F_C, normalized to 10°C by the temperature response function according to Lloyd and Taylor (1994), **(b)** $F_{C,HA}$ and **(c)** $F_{C,HAVA}$ to classes of friction velocity u_* for the period of May to August 2007. Black lines indicate the median, grey broken lines the inter quantiles (25%, 75%) for the respective flux.

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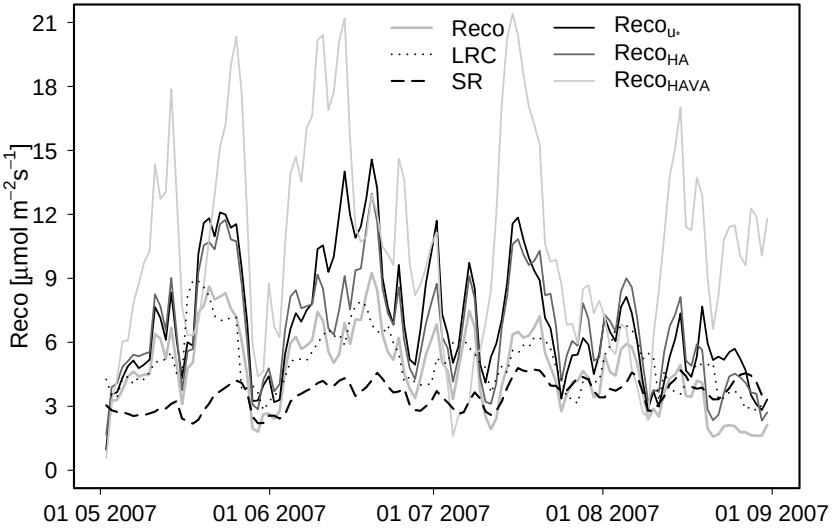

Fig. 9. Daily medians of Reco and soil respiration (SR) for the period from May to August 2007. Reco is derived according to Reichstein et al. (2002, 2005) from (1) direct EC measurements (Reco), (2) filtered by $u_* \geq 0.3$ (Reco$_{u*}$), (3) corrected for **(a)** F_{HA} (Reco$_{HA}$) and **(b)** F_{HA} and F_{VA} (Reco$_{HAVA}$) and (4) light response curves (LRC).

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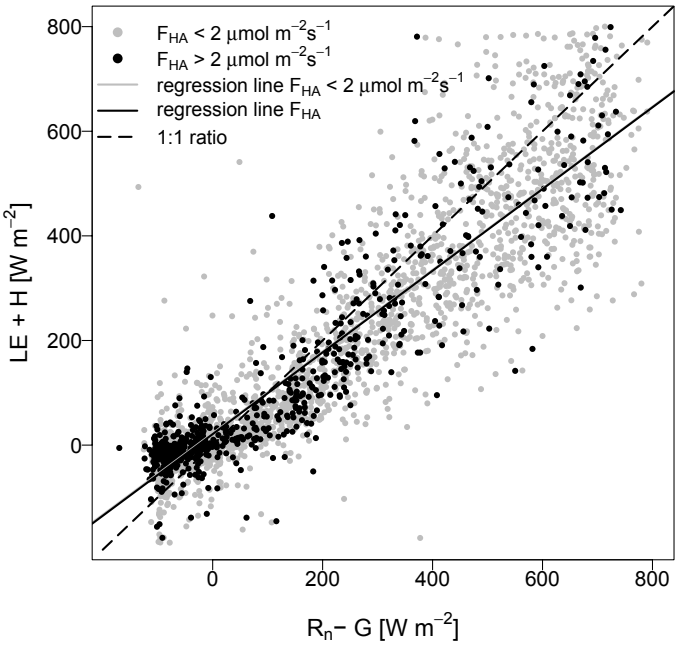

Fig. 10. Relationship between available energy (net radiation R_n – ground heat flux G) and turbulent fluxes (latent heat LE and sensible heat H) for the period from May to August 2007. Open circles indicate data points with advection <2 µmol m^{-2} s^{-1}, filled circles represent data points with horizontal advection >2 µmol m^{-2} s^{-1}. The 1:1 regression line is given in grey, the regression lines of the data points in black. They are nearly congruent and appear as one single line.

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