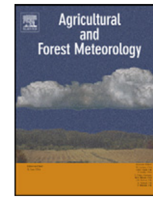
Agricultural and Forest Meteorology 150 (2010) 665–673

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



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

Christian Feigenwinter [a,b,*], Leonardo Montagnani [c,d], Marc Aubinet [a]

[a] Gembloux Agricultural University, Physique des Biosystèmes, Gembloux, Belgium
[b] University of Basel, Institute of Meteorology, Climatology and Remote Sensing, Basel, Switzerland
[c] Forest Service and Agency for the Environment, Autonomous Province of Bolzano, Bolzano, Italy
[d] Free University of Bolzano/Bozen, Bolzano, Italy

ARTICLE INFO

Article history:
Received 14 November 2008
Received in revised form 23 March 2009
Accepted 14 May 2009

Keywords:
Slope flows
CO_2 transport
Net ecosystem exchange
Advection
Forest ecosystems
ADVEX

ABSTRACT

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

1. Introduction

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

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

0168-1923/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2009.05.009

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

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

2. Site and experimental setup

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

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

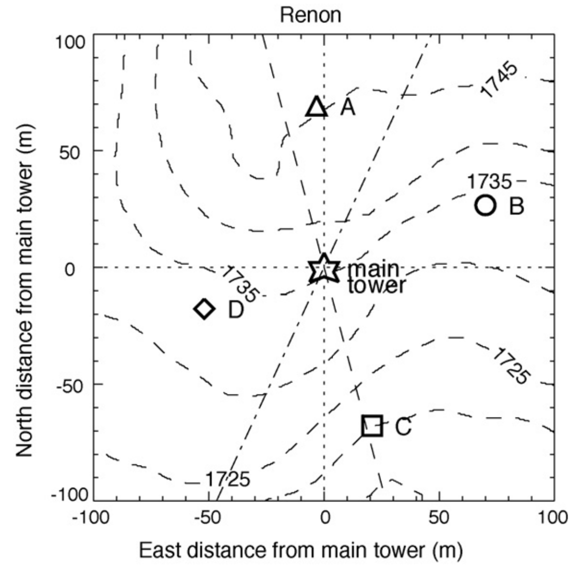


Fig. 1. Tower locations and topography. ADVEX towers A, B, C and D are located around the main tower in the center. Thick dashed and dashed-dotted lines refer to slices in Figs. 4 and 6.

3. Spatial integration of measurements

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

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

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

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

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

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

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

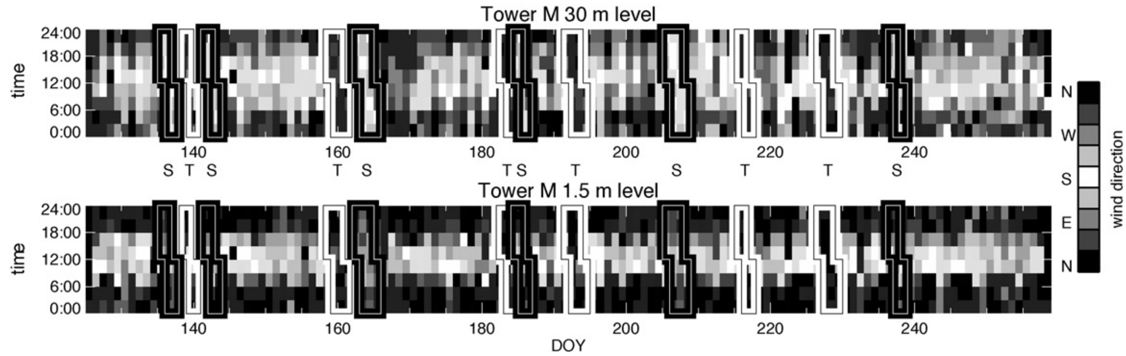


Fig. 2. Wind directions at main tower at 30 m (top) and 1.5 m (bottom). 3 h averages. Black colour refers to downslope wind from the North, white colour refers to upslope wind from the South. Periods for Tramontana and Southerlies are highlighted and marked with "T" and "S", respectively.

where F_C is the vertical turbulent flux of CO_2 measured by eddy covariance technique at 33 m a.g.l. at the main tower. Standard processing (Aubinet et al., 2000) was used for the calculation of F_C.

4. Results: CO_2 transport under different meteorological conditions

A persistent slope wind system with downslope winds during the night and upslope winds during the day prevailed for most of the time (75%) at the site during the measurement campaign. Onto this local wind system was sometimes superimposed one of two different large scale synoptic situations, the "Tramontana" and the "Southerlies" (covering about 12% of the campaign duration each). For this study, periods for each class were visually selected from Fig. 2 according to the criteria described in the following sections. The data of the selected days were then averaged in order to obtain mean diurnal patterns. Table 1 gives an overview of the selected days for the three classes.

A common feature of all three situations is the positive $[CO_2]$ gradient in downslope direction during nighttime. Together with the nightly downslope flow, this generally results in a positive value for F_{HA} and thus an additional source term if accounted for in NEE (FE08). In the following sections the three situations are analyzed in detail.

4.1. Local slope wind system

Fig. 3 shows the situation for "Local" conditions during nighttime and daytime in the slope parallel planes of the four measurement heights. The direction of sub-canopy flow is strongly influenced by the topography in the immediate vicinity of the towers. This is best observed in the lowest level at tower D, where the slope falls from Northeast to Southwest rather than from North to South as at the other towers. Flow directions in the canopy at tower D are thus significantly different when compared to the other towers as well during nighttime and daytime. The wind direction above canopy follows the large scale topography. Highest and lowest $[CO_2]$ during nighttime are observed at towers C and D, respectively, which means that the direction of the $[CO_2]$ gradient

Table 1
Selected days for each meteorological class (refer also Fig. 2).

Local	Tramontana	Southerlies
All remaining 103 days	138.5–140.5	135.5–137.5
	158.5–161.5	141.5–143.5
	182.5–184.5	162.5–165.5
	191.5–194.5	184.5–186.5
	215.5–217.5	205.5–208.5
	226.5–229.5	236.5–238.5
	15 Days	15 Days

(and thus its components in *x*,*y*-direction) in the control volume is variable. This has an important impact on the total amount of F_{HA} and on the single local values of F_{HA} at the grid points in particular. According to Eq. (1a)–(1c), F_{HA} depends on the angle between the direction of the concentration gradient and the wind vector in the respective vertical layer (see also Yi et al., 2008). This is accounted for by applying the presented method of calculation in a 3D context. For the specific case of Local conditions, F_{HA} in the 1.5 m plane is mainly negative in the Northwest of the main tower, while it is strongly positive in the southern part of the control volume. Note that also during the day a weak $[CO_2]$ gradient establishes in the lowest canopy layer.

CO_2 accumulates close to the forest floor during nighttime, as shown in Fig. 4a along a slice through the control volume in downslope direction. The vertical $[CO_2]$ gradient is largest in the lower trunk space and the largest mean concentrations are observed in the downslope region of the main tower at tower C, where the stand is characterized by the densest vegetation and the highest trees. Together, this results in a mean maximum nighttime value of about 10 μmol $m^{-2}\,s^{-1}$ for F_{HA}, notably with large scatter. During daytime the air in the control volume is well mixed and concentration differences disappear nearly completely (Fig. 4b).

4.2. Tramontana

The Tramontana, a persistent (1–3 days) strong wind from the north, amplifies the downslope drainage flow during nighttime and suppresses the upslope flow above the forest canopy during daytime. In contrary to the Local situation the horizontal $[CO_2]$ gradient consistently points in downslope direction in the whole control volume but with a similar magnitude, despite of supposed better mixing of the air in the canopy space due to higher wind speeds. Therefore the significantly higher wind velocities (Fig. 5a) increase the amount of F_{HA} during these conditions. During the day, the buoyancy in the canopy is still strong enough to enforce an upslope flow in the trunk space south of the main tower as shown in Fig. 6a.

4.3. Southerlies

Similar to the Tramontana, periods with continuing flow but from the south were observed. During these Southerlies, the daytime upslope flow is supported and enhanced compared to Local conditions. During nighttime, the downslope flow only establishes in the trunk space and most pronounced early in the night. In the crown space and above the canopy the wind blows consistently upslope all night long (Figs. 5 and 6b). This leads to periods of several hours with opposite flow directions in and above the canopy and extreme wind shear. The effect of such flow patterns on the amount of F_{HA} is exactly the contrary when

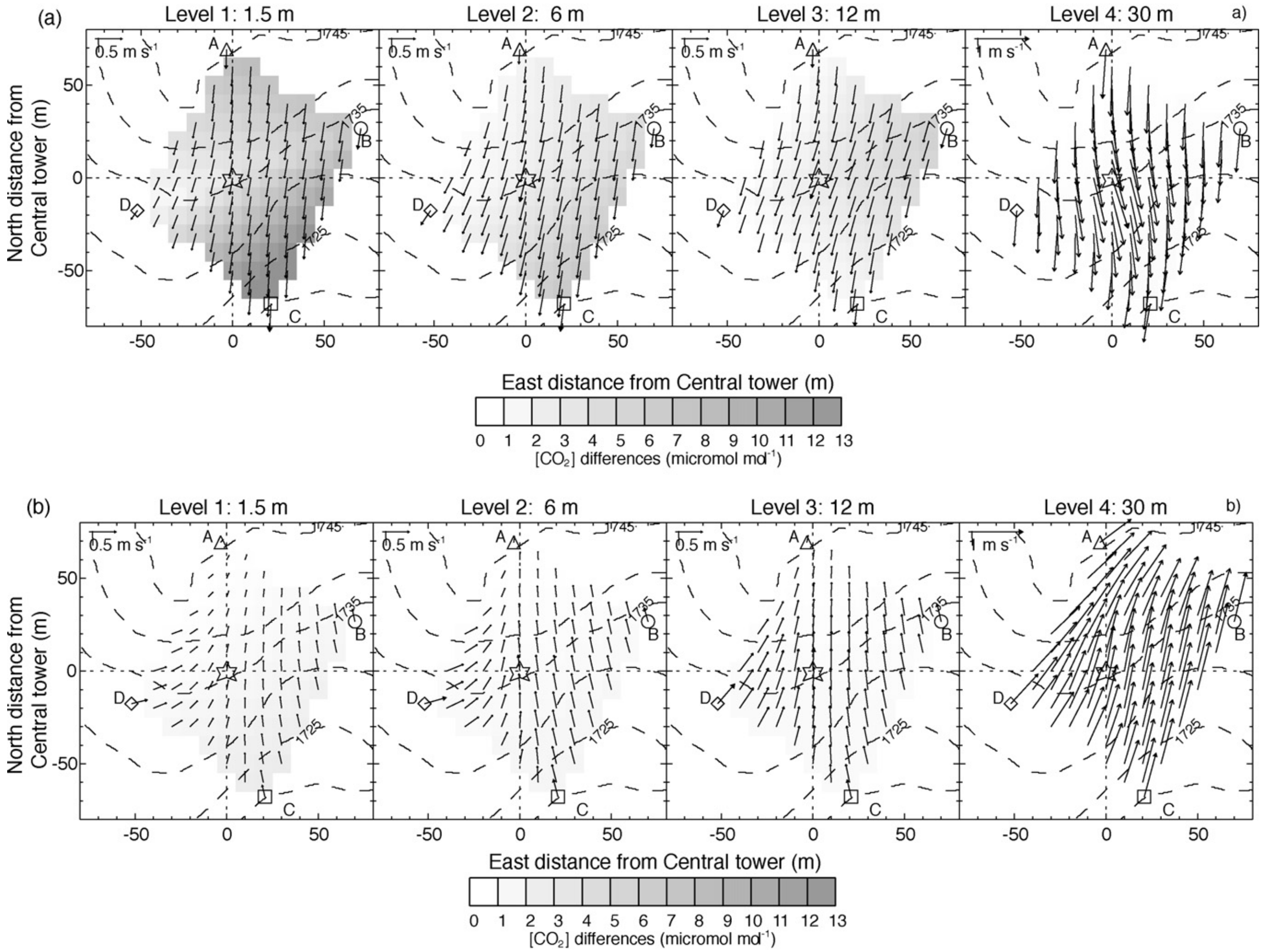


Fig. 3. Average flow patterns and CO_2 concentration differences for Local conditions during (a) nighttime (0300 h, top) and (b) daytime (1200 h, bottom). Arrows refer to slope parallel wind vectors at levels 1.5, 6, 12 and 30 m a.g.l., respectively (from left to right). A wind velocity of 1 m s^{-1} is scaled with 60 m (levels 1–3) and 30 m (level 4) on *x*,*y*-axis. Greyscales refer to the difference in CO_2 concentration relative to the point with the lowest concentration.

compared to the Tramontana situation. The positive non-turbulent horizontal advective flux in the trunk space is compensated by the flux caused by the upslope winds in the crown space and above the canopy during nighttime. [CO_2] distribution is similar to the Local situation with lowest concentrations around tower D in the West.

5. Discussion

5.1. Vertical advection

The mean diurnal courses of F_{VA} and its components are shown in Fig. 7. The components mean vertical velocity and the vertical [CO_2] gradient (and thus F_{VA}) are strongly dependent on the respective meteorological conditions. The vertical concentration gradient is lower at night during both, Tramontana and Southerlies conditions because of better mixing of the air in the canopy due to higher wind velocities (Tramontana) or extreme wind shear (Southerlies) compared to the Local situation. According to Eq. (1b) the sign of F_{VA} is determined by the direction of the tilt corrected mean vertical wind component, because the vertical CO_2 concentration gradient is always negative at night. F_{VA} is therefore generally positive at night because of mean downward flow and the corresponding negative mean vertical velocity component. However, as shown in Fig. 7, this pattern is modified against nearly zero mean F_{VA} during Tramontana conditions, but with notable large scatter and a skewed distribution. Highest F_{VA} (together with most negative mean vertical wind component) is observed early at night when the wind blows upslope above the canopy but downslope close to the ground, a characteristic feature of the Southerlies situation.

The pattern of the mean vertical wind component probably suffers from an imperfect tilt correction algorithm as addressed in Vickers and Mahrt (2006) and Heinesch et al. (2007). Though the planar fit method established itself as a quasi standard tilt correction procedure for data processing in the FLUXNET community during the last years, there may be other approaches that are better suited especially for complex terrain as met at the site under consideration. One could for example consider applying the planar fit correction separately to the three meteorological situations under consideration. This has no impact on F_{VA} for the local situation, but would reduce the amount of the vertical wind component, and thus F_{VA}, substantially for Southerlies conditions. However, a detailed investigation of this subject is out of the scope of this paper and to figure out the true meteorological mean vertical velocity remains still a very challenging task (Lee et al., 2004).

5.2. Horizontal advection

Generally the nighttime patterns of the [CO_2] distribution in the control volume show the same main features, namely highest [CO_2] at tower C and thus a horizontal CO_2 gradient in downslope

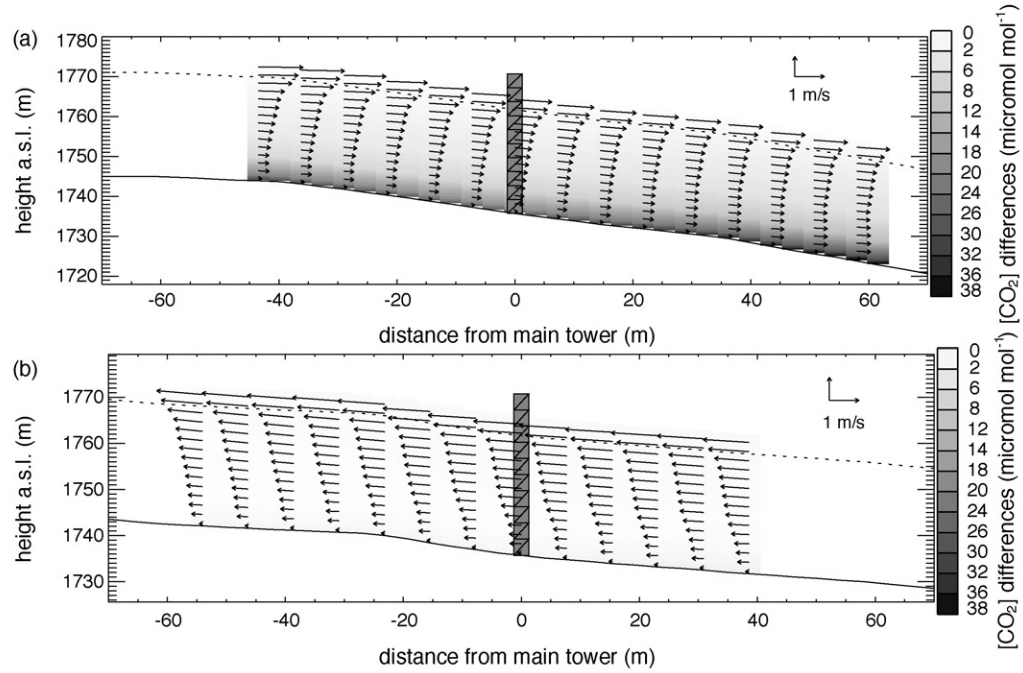


Fig. 4. Slice through the control volume: (a) along the dashed line in Fig. 1 during nighttime (top) and (b) along the dashed-dotted line in Fig. 1 during daytime (bottom) under Local conditions. The dotted line refers to mean canopy height. Greyscales refer to the difference in CO_2 concentration relative to the point with the lowest concentration.

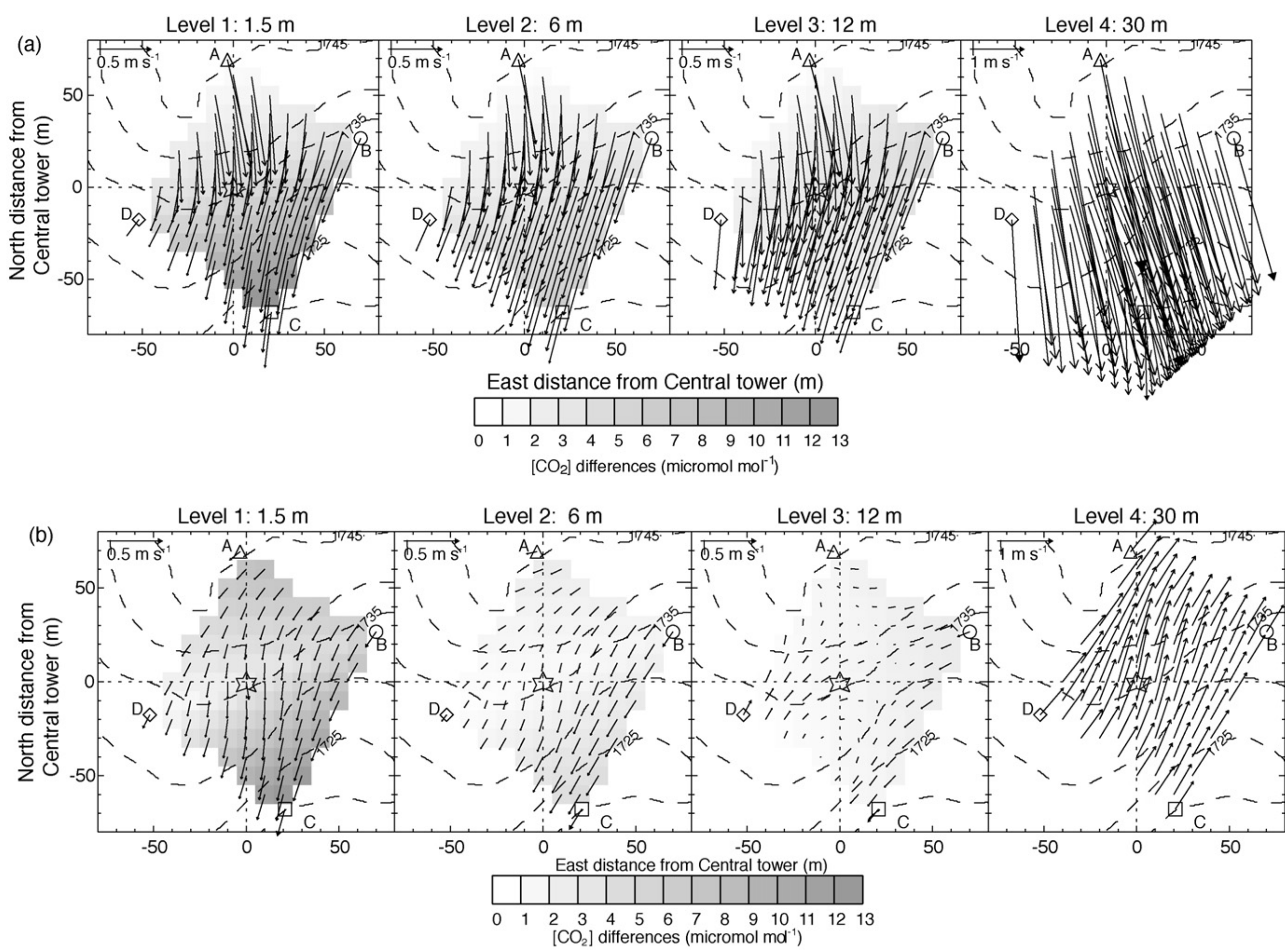


Fig. 5. Same as Fig. 3 but for average nighttime flow patterns and $[CO_2]$ differences for (a) Tramontana (0300 h, top) and (b) Southerlies (2200 h, bottom).

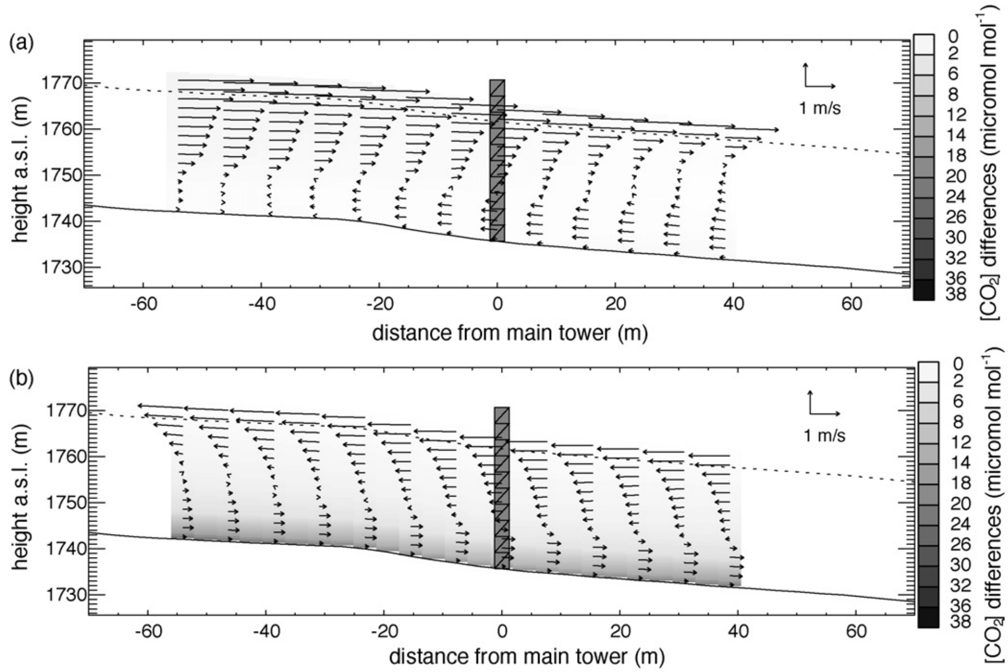


Fig. 6. Slice through the control volume along the dashed-dotted line in Fig. 1 (a) for daytime during Tramontana (top) and (b) for nighttime during Southerlies (bottom).

direction. However, there are some slight, but relevant distinctions, which become obvious when comparing Figs. 3 and 5. The distribution is most simple during Tramontana with lowest concentrations upslope at tower A and equal concentrations at towers D and B. The mean distribution changes for Southerlies and Local, when we observed lowest concentration at tower D. This results in a change of direction of the horizontal [CO_2] gradient in the control volume and thus in a change of sign of F_{HA} at certain grid points. Such features are hardly detectable with a 2D setup.

Fig. 8 shows the main characteristics of F_{HA} under the discussed meteorological and synoptic conditions. The region of largest F_{HA} is always in the trunk space. Considering F_{HA} for NEE would significantly increase the nightly source for Local and especially for Tramontana conditions, but contributes not essentially during the Southerlies situation. The result for Local conditions reflects the findings in FE08, where the whole period of the campaign was analyzed, and also partly the findings in Marcolla et al. (2005). However, at least for Tramontana conditions, F_{HA} occasionally reaches extremely high values

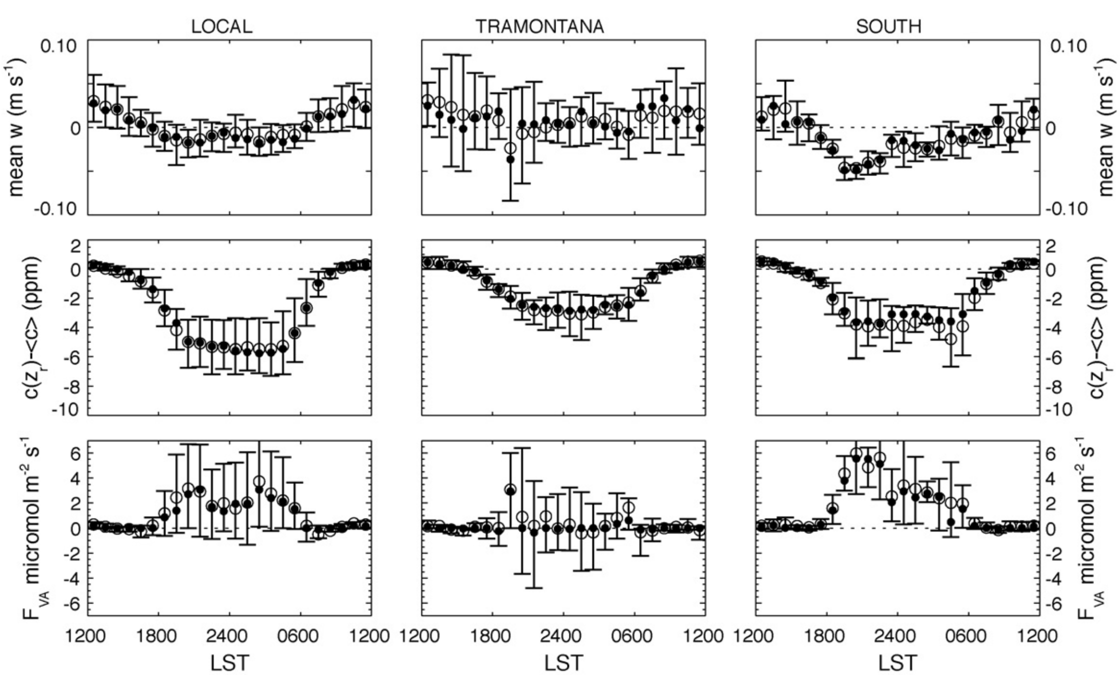


Fig. 7. Mean diurnal course of F_{VA} (bottom) and its components mean vertical wind velocity (top) and the difference between CO_2 concentrations at the reference level and in the volume below (center). Open circles refer to mean values, filled circles refer to the median and error bars indicate the range between the 75 and the 25 percentile, respectively. From left to right: Local, Tramontana and Southerlies.

Table 2
Summary of flow and advection properties during Local, Tramontana and Southerlies conditions. Size of arrows refers to relative wind velocity (upslope ↑ and downslope ↓), "+" and "−" signs refer to direction and relative amount of total advection.

		Local		Tramontana		Southerlies	
		Wind	Advection	Wind	Advection	Wind	Advection
Day	Above Canopy	↑	−	↓	−−	↑	−
	Sub	↑	0	↑	0	↑	0
Night	Above Canopy	↓	+	↓	++	↑	0
	Sub	↓	++	↓	+++	↓	+

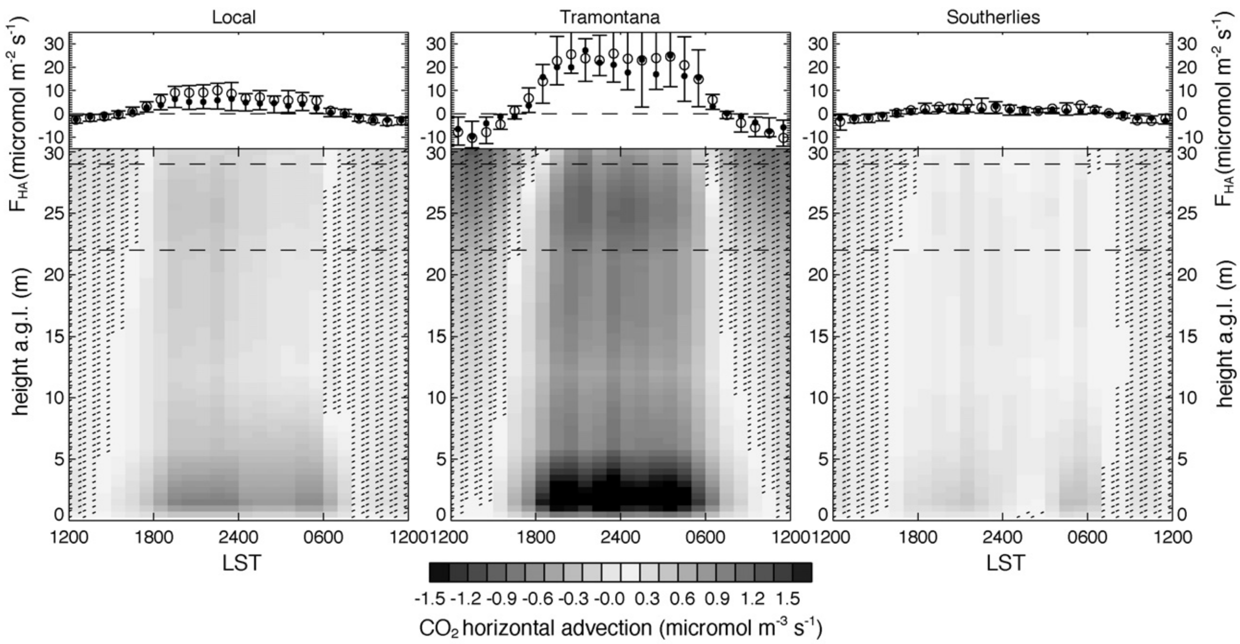


Fig. 8. Bottom: Evolution of mean F_{HA} with height. Top: mean diurnal course of F_{HA}. Open circles refer to mean values, filled circles refer to the median and error bars indicate the 50 percentile range. From left to right: Local, Tramontana and Southerlies.

which cannot simply be explained by physical processes and it shows a large scatter. This is not really surprising, since the similar large scatter in F_{HA} was occasionally observed in the frame of the ADVEX campaign at other CarboEurope sites in Wetzstein, Germany and Norunda, Sweden, though under completely different topography, but with the same experimental setup (FE08). In fact, most advection studies report large day to day variability of the non turbulent advective fluxes (e.g., Aubinet et al., 2003; Staebler and Fitzjarrald, 2004; Feigenwinter et al., 2004; Marcolla et al., 2005; Sun et al., 2007; Yi et al., 2008). F_{HA} during Tramontana conditions reveals one of the major problems in the estimation of horizontal advection, namely the measurement uncertainty of the horizontal gradient, which was also determined as a major source of error by Heinesch et al. (2007). Fig. 8 (center) implies high advective fluxes throughout the canopy, but in particular at the top, where the horizontal gradient is very small. Differences in [CO_2] at the 30 m level between all ADVEX towers were in the range of ± 2 μmol mol^{-1} throughout during daytime and nighttime. This is very close to the specification of the Li-6262. Wind velocities at the 30 m level frequently exceeded 5 m s^{-1} during Tramontana situations. It is obvious that the product of such values results in relatively large fluxes of high uncertainty in the above canopy region, which however contribute to a large amount to the total flux.

Nevertheless, if averaged over a sufficient long period, consistent patterns can be derived, which provide a qualitative, and, for Local and Southerlies conditions, even a reliable quantitative estimate of F_{HA} and its impact on NEE.

6. Summary and conclusions

The present study investigates how the vertical and horizontal CO_2 transport is governed and modified by a persistent slope wind system under different meteorological conditions, distinguishable by the differing direction of the above canopy flow from the most frequent Local situation. The main deviations from the local slope wind system are the downslope flow above the canopy during daytime for Tramontana situations and, vice versa, the upslope flow above the canopy during nighttime for Southerlies conditions. During these periods, the flow in the canopy still develops according to the classical rules of slope wind systems (upslope wind during the day and downslope wind during the night) but is modified by the synoptically induced flow above the canopy. This results in a substantial amplification and attenuation of the "normal" flow. Depending on the magnitude and the direction of the horizontal and vertical CO_2 concentration gradient and the respective meteorological situation, the pattern of the non-turbulent CO_2 transport, as expressed by vertical advection F_{VA} and horizontal advection F_{HA}, experiences characteristic modifications if compared to the most common Local situation.

Advective fluxes of CO_2 are most important during nighttime, only a weak negative F_{HA} was observed during the day. As a consequence, the "Local" positive horizontal advective fluxes F_{HA} are enhanced during Tramontana situations and reduced during Southerlies conditions, because the horizontal CO_2 concentration gradient is always similar (highest CO_2 concentration in the south) for nighttime periods. It is assumed that the gradient results from a combination in land-use change and source heterogeneities. About 150 m in upslope direction of the main tower is a pasture, which is assumed respiring less CO_2 than the forest. Additionally, the densest forest and the highest trees are located in downslope direction of the main tower. In contrary to F_{HA}, the vertical advective flux F_{VA} is significantly enhanced during Southerlies. This mainly results from the relatively large negative value of the vertical wind component in the early night, when the wind shear is largest. These findings are summarized in Table 2.

Since the turbulent CO_2 flux during nighttime is generally small at the Renon site (FE08, Montagnani et al., 2009), adding the advective fluxes to NEE as suggested in Eq. (2) would significantly increase nighttime *NEE* and thus reduce the reported sink of 450 g C m^{-2} y^{-1} (Valentini et al., 2000) of this forest. Considering published typical soil respiration values at 10 °C (SR_{10}) for the Renon site, ranging from 3.7 to 5.7 μmol m^{-2} s^{-1} (Janssens et al., 2003; Rodeghiero and Cescatti, 2005; Montagnani et al., 2009), and assuming that the soil respiration represents about 63% of total ecosystem respiration (TER) as suggested by Janssens et al. (2001), advection corrected nighttime NEE would roughly increase by a factor of 1.8 and 3 for Local and Tramontana conditions, respectively, while during Southerlies it would remain substantially unchanged. These factors would read 3, 6 and 2 for Local, Tramontana and Southerlies, respectively, if TER is estimated from the sum of nighttime F_C and F_S during well mixed conditions with typical values of about 3.4 μmol m^{-2} s^{-1} (Marcolla et al., 2005; Montagnani et al., 2009). Though there is still much uncertainty in the absolute magnitudes, the consistent patterns justify confidence in the direction and partly in the magnitude of these fluxes and their impact on long-term *NEE*. In this case, uncertainty in magnitude mainly results from the combination of small horizontal [CO_2] gradients with high wind velocities, as occurs during the Tramontana situation. We also showed how a slope wind system in connection with the horizontal and vertical CO_2 concentration gradient influences the evolution of the non turbulent advective fluxes, and how a slope wind system may be modified by superimposed synoptic conditions. It is expected that the described effects may also occur at flux tower sites with similar topography and vegetation.

Acknowledgements

This work is a contribution to the CarboEurope-Integrated Project (CE-IP) of the European Commission (GOCECT2003-505572). The corresponding author's work was additionally financed by grants from the Gembloux Agricultural University, Belgium, and from the University of Tuscia, Viterbo, Italy. Special thanks goes to Stefano Minerbi and the personnel of the Renon/Ritten Forest Station. The scientists and technicians of the involved teams are highly acknowledged: Olaf Kolle, Martin Hertel and Waldemar Ziegler from the Max Planck Institute for Biogeochemistry, Jena, Germany; Ronald Queck, Uta Moderow, and Uwe Eichelmann from the Institute of Hydrology and Meteorology of the Technical University of Dresden, Germany; Michel Yernaux and Alain Debaqc from the Gembloux Agricultural University, Belgium, and Meelis Mölder and Fredrik Lagergren from Lund University, Sweden. The corresponding author's thanks go to Roland Vogt and Eberhard Parlow from the Institute of Meteorology, Climatology and Remote Sensing at University Basel, Switzerland, for their support in instrumentation and infrastructure. The ADVEX field activities would not have been possible without the substantial support from all participating institutions. We also thank the two anonymous reviewers who provided helpful comments to improve this manuscript.

References

Aubinet, M., 2008. Eddy covariance CO_2 flux measurements in nocturnal conditions: an analysis of the problem. Ecol. Appl. 18 (6), 1368–1378.

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

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

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

Cescatti, A., Marcolla, B., 2004. Drag coefficient and turbulence intensity in conifer canopies. Agric. Forest Meteorol. 121, 197–206.

De Araújo, A.C., Kruijt, B., Nobre, A.D., Dolman, A.J., Waterloo, M.J., Moors, E.J., de Souza, J.S., 2008. Nocturnal accumulation of CO_2 underneath a tropical forest canopy along a topographical gradient. Ecol. Appl. 18 (6), 1406–1419.

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

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

Grace, J., 2005. Role of forest biomes in the global carbon balance. In: Griffiths, H., Jarvis, P.G. (Eds.), The Carbon Balance of Forest Biomes. Taylor & Francis Group, Abingdon, UK, pp. 19–45.

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

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

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

Janssens, I.A., Dore, S., Epron, D., Lankreijer, H., Buchmann, N., Longdoz, B., Brossaud, J., Montagnani, L, 2003. Climatic influences on seasonal and spatial differences in soil CO_2 efflux. In: Valentini, R. (Ed.), Canopy Fluxes of Energy. Water and Carbon Dioxide of European Forests. Springer, Berlin, (Ecol. Stud.), pp. 235–256.

Janssens, I.A., Lankreijer, H., Matteucci, G., Kowalski, A.S., Buchmann, N., Epron, D., Pilegaard, K., Kutsch, W., Longdoz, B., Grünwald, T., Montagnani, L., Dore, S., Rebmann, C., Moors, E.J., Grelle, A., Rannik, Ü., Morgenstern, K., Oltchev, S., Clement, R., Gudmundsson, J., Minerbi, S., Berbigier, P., Ibrom, A., Moncrieff, J., Aubinet, M., Bernhofer, C., Jensen, N.O., Vesala, T., Granier, A., Schulze, E.-D., Lindroth, A., Dolman, A.J., Jarvis, P.G., Ceulemans, R., Valentini, R., 2001. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. Global Change Biol. 7, 269–278.

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

Lee, X., Finnigan, J., Paw, U.K.T., 2004. Coordinate systems and flux bias error. In: Lee, X., Massman, W., Law, B. (Eds.), Handbook of Micrometeorology. Kluwer Academic Publishers, , ISBN: 1-4020-2264-6 pp. 33–66.

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

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

Mahrt, L., Vickers, D., Nakamura, R., Soler, M.R., Sun, J., Burns, S., Lenschow, D.H., 2001. Shallow drainage flows. Bound. Lay. Meteorol. 101, 243–260.

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

Montagnani, L., Manca, G., Canepa, E., Georgieva, E., Acosta, M., Feigenwinter, C., Janous, D., Kerschbaumer, G., Lindroth, A., Minach, L., Minerbi, S., Mölder, M., Pavelka, M., Seufert, G., Zeri, M., Ziegler, W., 2009. A new mass conservation approach to the study of CO_2 advection in an alpine forest. J. Geophys. Res., 114, D07306, doi:10.1029/2008JD010650.

Paw, U.K.T., Falk, M., Suchanek, T.H., Ustin, S.L., Chen, J., Park, Y.-S., Winner, W.E., Thomas, S.C., Hsiao, T.C., Shaw, R.H., King, T.S., Pyles, R.D., Schroeder, M.,

Matista, A.A., 2004. Carbon dioxide exchange between an old-growth forest and the atmosphere. Ecosystems 7, 513–524.
Rodeghiero, M., Cescatti, A., 2005. Main determinants of forest soil respiration along an elevation/temperature gradient in the Italian Alps. Global Change Biol. 11, 1024–1041.
Staebler, R.M., Fitzjarrald, D.R., 2004. Observing subcanopy CO_2 advection. Agric. Forest Meteorol. 122, 139–156.
Sun, J., Burns, S.P., Delany, A.C., Oncley, S.P., Turnipseed, A.A., Stephens, B.B., Lenschow, D.H., LeMone, M.A., Monson, R.K., Anderson, D.E., 2007. CO_2 transport over complex terrain. Agric. Forest Meteorol. 145, 1–21.
Valentini, R., Matteucci, G., Dolman, H., Schultze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Lousteau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.
Vickers, D., Mahrt, L., 2006. Contrasting mean vertical motion from tilt correction methods and mass continuity. Agric. Forest Meteorol. 138, 93–103.
Whiteman, C.D., 2000. Mountain Meteorology: Fundamentals and Applications. Oxford University Press.
Wilczak, J., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Bound. Lay. Meteorol. 99, 127–150.
Yi, C., Anderson, D.E., Turnipseed, A.A., Burns, S.P., Sparks, J., Stannard, D., Monson, K.R., 2008. The contribution of advective fluxes to net ecosystem CO_2 exchange in a high-elevation, subalpine forest ecosystem. Ecol. Appl. 18 (6), 1379–1390.
Yi, C., Monson, R., Zhai, Z., Anderson, D., Lamb, B., Allwine, G., Turnipseed, A., Burns, S., 2005. Modeling and measuring the nocturnal drainage flow in a high-elevation, subalpine forest with complex terrain. J. Geophys. Res. 110, D22303, doi:10.1029/2005JD006282.