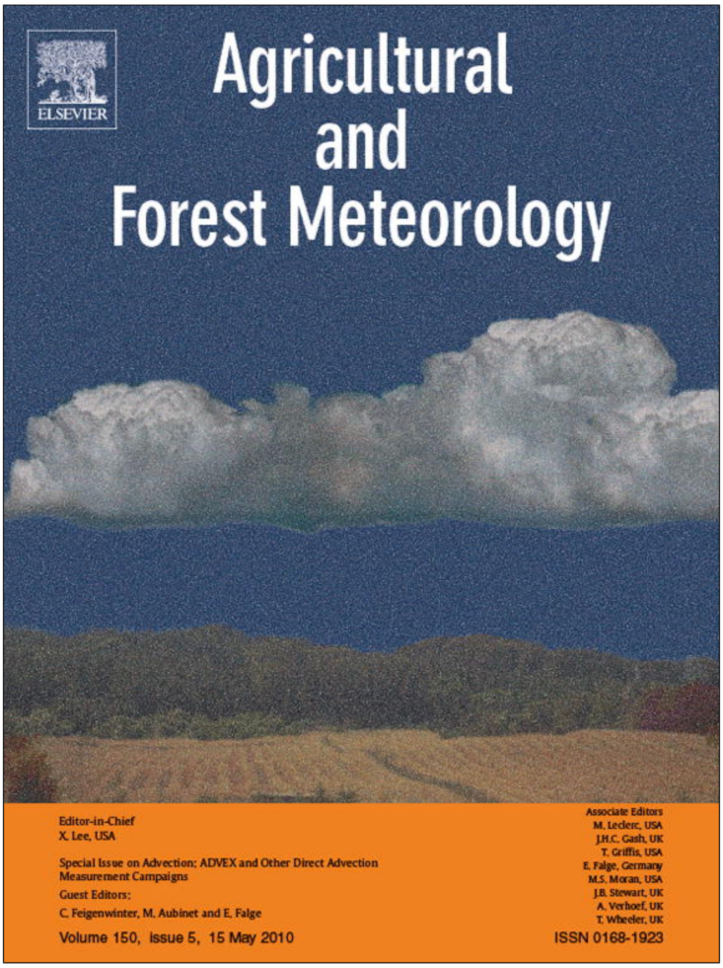
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Direct advection measurements do not help to solve the night-time CO_2 closure problem: Evidence from three different forests

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ABSTRACT

The ADVEX project involved conducting extensive advection measurements at three sites, each with a different topography. One goal of the project was to measure the $[CO_2]$ balance under night-time conditions, in an attempt to improve NEE estimates.

Four towers were arranged in a square around a main tower, with the sides of the square about 100 m long. Equipped with 16 sonic anemometers and $[CO_2]$ sampling points, the towers were installed to measure vertical and horizontal advection of $[CO_2]$. Vertical turbulent fluxes were measured by an eddy covariance system at the top of the main tower.

The results showed that horizontal advection varied greatly from site to site and from one wind sector to another, the highest values being reached when there were large friction velocities and fairly unstable conditions. There was less variation in vertical advection, the highest values being reached when there were low friction velocities and stable conditions.

The night-time NEE estimates deduced from the mass balance were found to be incompatible with biologically driven fluxes because (i) they varied strongly from one wind sector to another and this variation could not be explained in terms of a response of the biologic flux to climate, (ii) their order of magnitude was not realistic and (iii) they still showed a trend vs. friction velocity.

From a critical analysis of the measurement and data treatment we concluded that the causes of the problem are related to the representativeness of the measurement (control volume size, sampling resolution) or the hypotheses underlying the derivation of the $[CO_2]$ mass balance (ignoring the horizontal turbulent flux divergence). This suggests that the improvement of eddy flux measurements by developing an advection completed $[CO_2]$ mass balance at night would be practically difficult.

1. Introduction

The eddy covariance technique is the most frequently used method for estimating $[CO_2]$ fluxes exchanged between the land surface and the atmosphere. Despite its success, however, it is known to generally underestimate the fluxes at night, during periods of low air mixing. This problem was first detected by Goulden et al. (1996) and was confirmed in many subsequent studies (Aubinet et al., 2000; Gu et al., 2005).

Two methods may be applied to overcome this problem. The filtering approach involves removing from the time series measurements obtained when net ecosystem exchange (NEE) is poorly represented by eddy flux measurements. When needed, the data gaps created in this way can be filled using parameterisations, look-up tables, modelling or neural networks (Falge et al., 2001; Papale et al., 2006). A problem with this approach is that both the filtering criteria and the data gap filling procedures are based on empirical approaches and suffer from a great degree of uncertainty (Moffat et al., 2007; Richardson et al., 2006).

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An alternative approach is based on the mass conservation equation of carbon dioxide and involves directly measuring the advection terms. In this paper we refer to this approach as the 'advection completed mass balance' (ACMB).

The CO_2 mass balance equation is derived from the instantaneous mass conservation equation that states that the CO_2 produced or absorbed by the biological source/sink is either stored in the air or removed by flux divergence (Aubinet et al., 2000). After applying Reynolds decomposition, integration over a control volume of height h, and sides $2L$, ignoring the horizontal turbulent flux divergence and the horizontal variation of the vertical flux, and applying the continuity equation, the mass conservation equation reads (Finnigan, 1999; Feigenwinter et al., 2004):

$$NEE = \int_0^h \frac{1}{V_m}\left[\frac{\partial \bar{c}}{\partial t}\right]dz + \frac{1}{V_m}(\overline{w'c'})_h + \int_0^h \frac{1}{V_m}\overline{w}(z)\frac{\partial \bar{c}}{\partial z}dz + \frac{1}{4L^2}\int_{-L}^{+L}\int_{-L}^{+L}\int_0^h \frac{1}{V_m}\left(\overline{u}\frac{\partial \bar{c}}{\partial x} + \overline{v}\frac{\partial \bar{c}}{\partial y}\right)dzdxdy. \quad (1)$$

where NEE represents the net ecosystem exchange; c is the molar mixing ratio of CO_2 to dry air; V_m is the molar volume of dry air; u, v and w represent the wind velocity components in the horizontal (x, y) and vertical (z) directions, respectively. The overbars represent time averages and prime departures from those averages. This equation in itself is a simplification in that it assumes horizontal homogeneity of the three first RHS terms and ignores horizontal turbulent fluxes. A more general equation was put forward by Finnigan *et al.* (2003). In Equation (1) the NEE should be representative of the biological source/sink strength term, which we refer to in this paper as the 'biotic flux'. The ACMB approach therefore involves estimating the biotic flux as the sum of the four RHS terms in Equation 1. The four terms are: F_S, the storage of CO_2 in the air of the control volume; F_C, the vertical turbulent transport; F_{VA}, the vertical advection; and F_{HA}, the horizontal advection.

Lee (1998) was the first to estimate NEE by adding vertical advection to the CO_2 balance. He proposed computing vertical advection as:

$$F_{v\Delta} = \bar{w}(\bar{c}_h - \langle c \rangle) \quad (2)$$

Where, $\bar{c}_h$ represents $[CO_2]$ at the top of the control volume and $\langle c \rangle$ a $[CO_2]$ averaged between this height and the soil. This approach remained incomplete, however, as horizontal advection was not included in the budget (Finnigan, 1999). Estimates based on the ACMB approach were first proposed by Aubinet et al. (2003), followed by Feigenwinter et al. (2004), Staebler and Fitzjarrald (2004, 2005), Marcolla et al. (2005), Aubinet et al. (2005), Sun et al. (2007), Heinesch et al. (2008), Yi et al. (2008), Leuning et al. (2008) and Tota et al. (2008).

In 2005, the ADVEX project was launched to provide more complete advection estimates in order to improve ACMB flux estimates. This involved arranging four 30 m-high towers in a square, around a main tower, with each side of the square about 100 m long; the towers were fully equipped with wind velocity, temperature and $[CO_2]$ profile measurements (16 sampling points of each), and were installed at sites already equipped with an eddy covariance system. The set-up was rotated among three European forest sites, each of them characterized by a specific topography: an Alpine slope (Renon/Ritten, Italy), a hill-crest (Wetzstein, Germany) and a flat site (Norunda, Sweden). In addition to using the same set-up, similar data collection and computation procedures were used at the three sites. At each site the project was implemented for 2–4 months. A complete description of the set-up and the first results were presented by Feigenwinter et al. (2008).

The main goal of this paper is to assess the ability of the ACMB approach to provide realistic estimates of the biotic CO_2 fluxes in night-time conditions. In the absence of independent NEE estimates, one possibility is to evaluate the robustness of ACMB estimates by testing their independence of meteorological factors that should not affect NEE. As at night, NEE results from ecosystem respiration, it should depend only on temperature and, to a lesser degree, soil humidity. Night-time ACMB estimates should thus remain independent of other variables as long as they do not co-vary with temperature. In particular, our work tested how independent the night-time ACMB estimates were of friction velocity and wind direction. The first approach is not new: the dependence of night flux estimates on u^* has been often used to question the validity of eddy flux measurements in night-time conditions (Goulden et al., 1996) and the ability of ACMB to offset this dependence has been used as a quality test, in particular by Marcolla et al. (2005) and Mammarella et al. (2007). The analysis of the dependence of ACMB estimates on wind direction has been studied, so far as we know, only by Heinesch et al. (2008).

After presenting and discussing the relation between F_{VA}, F_{HA} and friction velocity and stability at each site and for different wind sectors, the ACMB flux estimate independence of wind direction and friction velocity will be tested. As this independence will not be established, an error analysis will be developed in order to assess the causes of the mismatch. Finally, a bibliographical review will be provided in order to evaluate the generality of these results.

2. Material and methods

The measurement set-up, data collection and advection computation procedures we used are common to many papers in this special issue and were described in detail by Feigenwinter et al. (2008). We outline the main features here.

2.1. Site description

The Renon/Ritten site (RE) is situated at 1735m a.s.l. in the Italian Alps, 12 km NNE of Bolzano in Alto Adige, Italy. Its topography is characterized by an alpine slope with a mean slope of about 11° in a N–S direction. The site is covered mainly by unevenly aged Norway spruce varying between 20 m and 30 m high. About 60 m upslope to the north of the main tower there is a pasture that breaks the wind fetch in the predominant night-time wind direction. The undergrowth varies widely from sparse to dense. The climate is characterized by low temperatures, high precipitation and, often, high wind speeds (average annual temperature 4.1 °C, annual precipitation 1010 mm). The meteorological conditions during the measurement period were dominated by a very persistent local slope wind system with upslope S–SW winds during the day and downslope NNW winds during the night. This situation covered about 75% of the measurement period. The rest of the period was synoptically dominated either by the "Tramontana", a cold and strong wind, which blows consistently for a few days from the north also during daytime and penetrating into the canopy, or by persistent moderate warm winds from S to SW, also blowing during the night.

The Wetzstein site (WS) is situated at 782 m a.s.l., almost on the crest of an SSW–NNE aligned ridge in the Thuringian forest in Germany, with steep slopes to the ESE and WNW. The site is covered by 50-year-old Norway spruce that provides a homogeneous canopy at a height of about 22 m. The fetch exceeds 500 m in all directions. The undergrowth is very sparse, with well-defined trunk spaces reaching a height of about 10 m. The climate is temperate humid (average annual temperature 5.9 °C, annual precipitation 840 mm). During the measurement period, due to its location on the top of a ridge, the site was very wind exposed and the meteorological conditions were affected by the prevailing synoptic winds that generally blew from the SW and, during some periods, from East. In the canopy, winds blew mainly across the ridge, either from ESE or WNW. During the day, wind velocities in the canopy layer were generally low whereas at night they were significantly higher than at the Renon or the Norunda site

The Norunda site (NO) is about 30 km north of Uppsala in Sweden, at 45 m a.s.l. in a cold-temperate to boreal climate. The topography is flat, with a forest of trees about the same height (25 m) extending at least 1 km in all directions. The main species are Norway spruce and Scots pine. The forest floor is covered mainly with mosses, shrubs and big stones with diameters up to 1.5 m. The mean annual temperature is 5.4 °C and the annual precipitation is 520 mm. During the measurement period winds blew from all directions with a slight SW dominance above the canopy.

Inside the canopy, winds came mainly from the S to E sector during both day and night. More details for the three sites is given by Feigenwinter et al. (2008), for the RE site by Marcolla et al. (2005) and Montagnani et al. (2009) and for the NO site by Lindroth et al. (1998).

2.2. Measurement system

A similar set-up was used at the three sites. Four towers were placed around a main tower, forming a square with a side-length of about 100 m. Each tower was equipped with instruments for measuring [CO_2] (Li6262/7000, Li-Cor, Lincoln, US) and the wind vector (81000 V, R.M. Young Meteorological Instruments, MI, US; R3, Gill Instruments Ltd., UK) at four levels. [CO_2] was also measured in a crosswise transect between the towers at a height of 1.5 m. The sampling frequency of all the infrared gas analyzers (IRGAs) was set in order to allow one sampling at each point every 160 seconds. The concentrations and advection estimates were averaged over half an hour, i.e. over eleven concentration samples. The instrument types and measurement heights are given in Table 1. More details on data collection frequency and procedures, tube characteristics, filters, functioning mode and sampling sequence have been given by Feigenwinter et al. (2008).

2.3. Advection computation

For vertical advection, vertical velocity was computed using a sectorwise planar fit method (Paw U et al., 2000; Wilczak et al., 2001). A modified linear interpolation scheme was used to derive vertical profiles from the measured [CO_2] and the horizontal wind velocities at the four levels.

For horizontal advection, [CO_2] values and the horizontal wind components u and v were obtained at each point of a 10 × 10 m grid between the four towers by bi-linear interpolation from the vertical tower profiles. The horizontal [CO_2] gradients in the x (East) and y (North) directions were derived by linear interpolation of the concentration differences between the grid points in the respective directions. Horizontal advection was then calculated at each grid point for each respective layer. Total horizontal advection was computed by vertical integration up to the height of the control volume (30 m for RE and NO, 24 m for WS), followed by an averaging in the xy-plane.

2.4. Data sorting and treatment

Only night-time half-hourly estimates of F_C, F_S, F_{HA} and F_{VA} were considered in the analysis. In order to eliminate any possible co-variation of temperature and wind direction or friction velocity, the temperature dependence of CO_2-fluxes was removed, using an inverted Q_{10} relationship:

$$F_X^N = F_X Q_{10}^{\frac{10-T}{10}} \tag{3}$$

where F_X and $F_X{}^N$ are the real and the temperature independent fluxes, respectively, and T is the temperature. The value of Q_{10} was fixed at 2 (Kätterer et al., 1998).

The temperature independent flux estimates were then separated into two sectors characterized by the wind direction above the canopy (32–33 m high). The wind sectors were chosen to give the best possible discrimination among different synoptic conditions. The selection was based on the local wind distribution (Feigenwinter et al., 2008, Fig. 3) and was therefore specific for each site. At the WS site the data were split between a "Western" (180–360°N) and an "Eastern" (0–180°N) sector, at the NO site between a "North Eastern" (315–135°N) and a "South Western" (135–315°N) sector, and at the RE site between a "Northern" (270°–90°N) and a "Southern" (90°–270°N) sector. The distinction between the (North) Eastern and (South) Western sectors was made in order to take account of the general North European synoptic conditions, West (East) winds usually being associated with (anti) cyclonic conditions. In addition, at WS the separation between sectors was more or less parallel with the hill-crest. At RE, the partitioning into Eastern and Western sectors was not relevant, the wind regime being driven instead by slope winds; the data were therefore split between the Northern and Southern sectors associated with downslope and upslope flows, respectively.

In each wind sector, the data were then categorized into friction velocity (u^*) or stability classes ($\zeta = \frac{z-d}{L}$; where d is the displacement height, estimated as 0.75 canopy height, and L is the Obukhov length) and bin averaged. For the bin-averaging, the classes were divided into 10 sub-classes of identical population sizes. In each class, therefore, the bin averages did not correspond to the same friction velocities or stability parameters. The 95% confidence interval was estimated as twice the standard error of the distribution in each class. The number of half-hourly measurements used in each wind sector is given in Table 2.

3. Results

3.1. Vertical advection

Figs. 1 and 2 show clearly that F_{VA} varied with friction velocity and stability measured above the canopy and that similar patterns

Table 1
ADVEX main tower and complementary tower instrumentation.

	Renon/Ritten (RE), Italy	Wetzstein (WS), Germany	Norunda (NO), Sweden
Main tower equipment			
Sonic	Gill HS (Gill instruments, U.K)	Gill R3 (Gill Instruments, U.K.)	USA-1 (METEK GmbH, Germany)
	Li7500, Li6262	Li6262 24 m, 33 m	
IRGA Height	32 m		Li7500 33 m
Wind profile	1.5 m, 6 m, 12 m	1.5 m, 3 m, 8.8 m	1.5 m, 8.5 m
[CO_2] profile	/	8 points from 0.1 to 30 m	13 points from 1.5 to 100 m
Additional tower equipment			
Heights ([CO_2], wind and temperature profiles)	1.5 m, 6 m, 12 m, 30 m	1.5 m, 4.4 m, 8 m, 24 m	1.5 m, 6 m, 12 m, 30 m

Table 2
Number of data in each sector of the sites.

	Western (Northern)	Eastern (Southern)
Wetzstein (12 April to 19 June 2006)	719	448
Renon (5 May to 15 September 2005)	1205	510
Norunda (7 July to 18 September 2006)	431	592

occurred at the sites: in five of the six site-sectors (WS, RE North and NO), positive F_{VA} values were observed under lower friction velocities and more stable conditions and negative F_{VA} values at larger friction velocities and less stable conditions. The limit at which F_{VA} sign changes varies according to the site, between 0.2 and 0.4 ms^{-1} for friction velocity and between 0.05 and 0.5 for stability. There was an exception at RE South where F_{VA} remained positive and high throughout the friction velocity and stability ranges (Figs. 1b and 2b). In addition, a specific behaviour was apparent at NO, F_{VA} becoming negative at very low friction velocity and in strongly stable conditions (Figs. 1c and 2c).

As F_{VA} results basically from the product of vertical velocity and vertical [CO_2] difference (Equation 2), its evolution with u* could result from a dependency of either these two variables to u*. Fig. 3 shows that the CO_2-differences (computed as in Equation 2) remained negative over the whole friction velocity range for all sectors at all the sites. Therefore, the F_{VA} sign inversion in Fig. 1

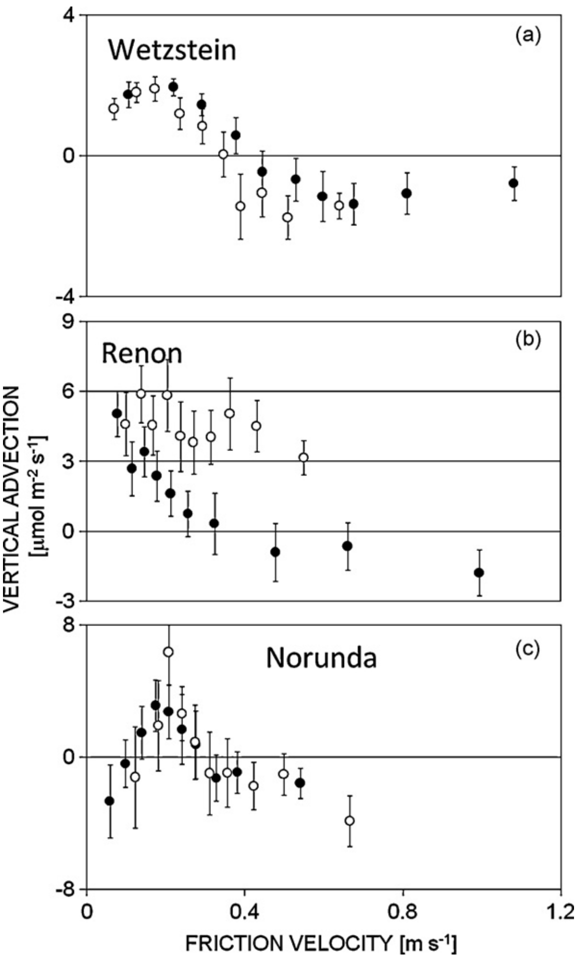

Fig. 1. Dependency of night-time vertical advection on friction velocity; a: Wetzstein (WS). Filled circles: Western sector; Open circles: Eastern sector; b: Renon (RE). Filled circles: Northern sector; Open circles: Southern sector; c: Norunda (NO); filled circles: North Eastern; open circles: South Western. Error bars represent the standard error.

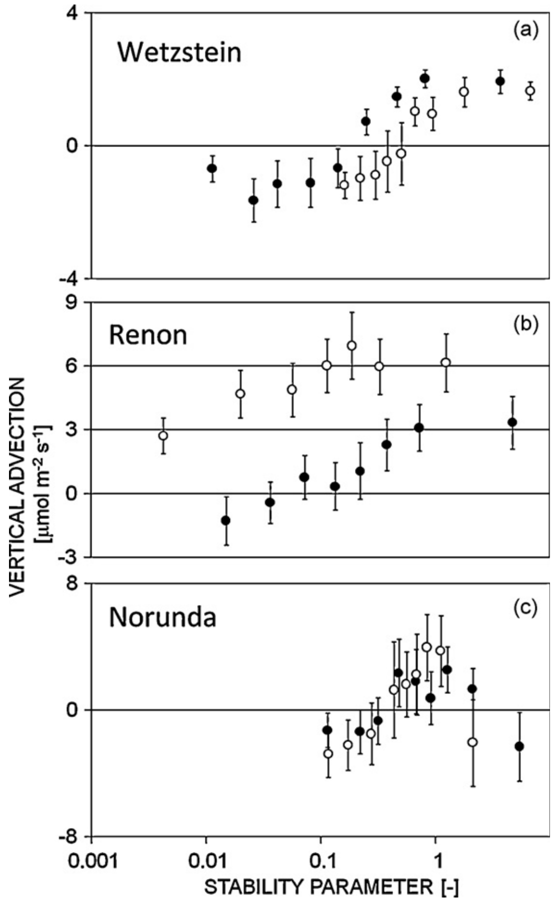

Fig. 2. Dependency of night vertical advection on stability parameter; a: Wetzstein (WS); b: Renon (RE); c: Norunda (NO). Legend: as for Fig. 1.

results from a vertical velocity direction change. Such changes (from downward to upward with increasing u*) were observed at about 0.3–0.4 m s^{-1} in all the site sectors except for one. At NO there was another change (from upward to downward with increasing u*) at about 0.1 m s^{-1}.

Fig. 3 also shows that the [CO_2] differences increased with decreasing friction velocity at the RE and NO sites, as a result of air mixing lessening below the canopy, as reported for several sites by Lee (1998), Marcolla et al. (2005), Aubinet et al. (2005) or Su et al. (2008a, b). This increase was not observed at WS, where [CO_2] differences remained low even at low friction velocities. This could be due to a CO_2 removal by a divergent subcanopy flow directed down the local slopes.

Finally, Fig. 3 shows that the CO_2 build up was much greater at NO (30 μmol mol^{-1}) than at RE (8 μmol mol^{-1}) and WS (< 3 μmol mol^{-1}). This range can be related mainly to different below-canopy mixing regimes. Indeed average ratios of below (1.5 m height) to above canopy wind velocities, were much lower than 0.1 at NO while exceeding 0.2 at the other sites.

In summary, there was a clear dependency of F_{VA} on friction velocity at the three sites, resulting from variations in vertical [CO_2] differences and in vertical velocities. There were some common features at the three sites, such as a change of sign in vertical velocity at about 0.3–0.4 m s^{-1} and a decrease in vertical [CO_2] difference with increasing friction velocity probably due to below-canopy mixing increase. Apart from this, F_{VA} did not vary significantly between the wind sectors, except at RE site. Finally, there were also large differences between sites: Feigenwinter et al. (2008) showed that F_{VA} at NO resulted from the combination of a

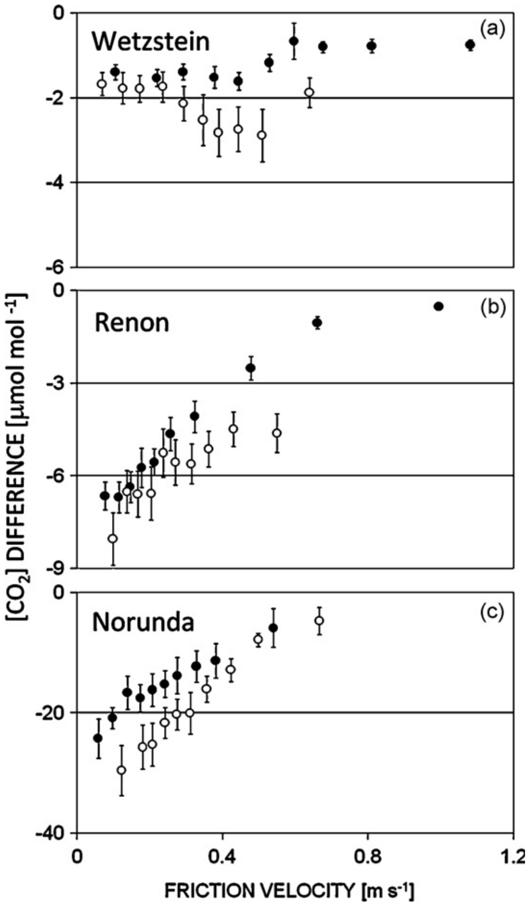

Fig. 3. Dependency of vertical concentration difference on friction velocity; a: Wetzstein (WS); b: Renon (RE); c: Norunda (NO). Legend: as for Fig. 1.

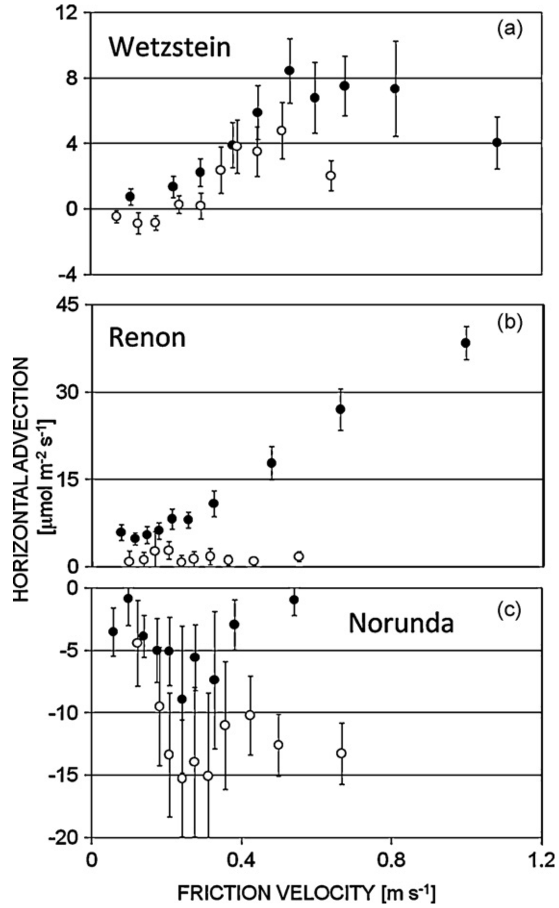

Fig. 4. Dependency of night-time horizontal advection on friction velocity; a: Wetzstein (WS); b: Renon (RE); c: Norunda (NO). Legend: as for Fig. 1.

very low and changing vertical velocity with large [CO_2] gradients, at WS from the combination of larger vertical velocities associated with lower concentration gradients, and at RE (North) from the combination of important vertical [CO_2] gradients and vertical velocities. This suggests that the mechanisms underlying F_{VA} differed from one site to another. A detailed analysis of these differences is presented by Zeri et al. (2010) and Rebmann et al. (2010) for WS, Feigenwinter et al. (2010a) for RE and Feigenwinter et al. (2010b) for NO.

3.2. Horizontal advection

The evolution of F_{HA} with friction velocity and stability is presented in Figs. 4 and 5. Here again, despite all the differences between sites and wind sectors, there were some similarities: in most cases, F_{HA} was small at lower friction velocities ($u^* < 0.2\ \mathrm{m\,s^{-1}}$) and stronger stable conditions ($\zeta > 0.1$–1) and increased in absolute value with increasing u^* or decreasing ζ. At larger u^* there was more variability: at WS and NO a maximal (in absolute value) F_{HA} was reached at $u^* = 0.5\ \mathrm{m\,s^{-1}}$ and $0.2\ \mathrm{m\,s^{-1}}$, respectively, beyond which F_{HA} decreased at WS and remained constant at NO. In contrast, no such maximum was observed at RE, where F_{HA} continuously increased with u^* in the North sector and remained small and fairly constant all along the u^* range in the South sector.

Clear differences appeared between the sites and, in contrast to F_{VA}, between the wind sectors at the same site. Under similar friction velocity, the ratio between averaged F_{HA} could vary from 2 to 3 at WS and NO and reached more than 15 at RE.

There were also clear differences between the sites, F_{HA} being systematically negative at NO, but systematically positive at the other two sites, reaching 37 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ at RE North, going down to -15 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ at NO and never exceeding 9 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ at WS. These values generally exceeded the turbulent flux values, the ratios between F_{HA} and the turbulent fluxes being about 10, 3 and 1-2 at RE, NO and WS, respectively.

As the mechanisms responsible for these effects were specific to the sites, they are discussed in particular papers (Zeri et al., 2010; Feigenwinter et al., 2010a,b). Here, we focus on the main F_{HA} characteristics and highlight some unexpected results that go against common perceptions about horizontal advection.

First, the results confirmed that F_{HA} could be positive or negative at the sites, as reported in earlier studies: Aubinet et al. (2003) and Feigenwinter et al. (2004) reported negative values and Marcolla et al. (2005) positive values. Aubinet (2008) showed that both situations were possible, depending on the sign of the source intensity gradient upwind of the control volume.

Second, the F_{HA} magnitudes were quite surprising, reaching up to 2–10 times the biotic fluxes. Of course, from a theoretical point of view, this is not absolutely impossible as these large fluxes could be compensated by negative vertical advection (Aubinet et al., 2003; Feigenwinter et al., 2004). We showed, however, that F_{VA} was about one order of magnitude lower than F_{HA}, as well as turbulent and storage fluxes, so such compensation was not provided.

Third, it is worth noting that at each site the F_{HA} signs were the same in both wind sectors (Figs. 4 and 5). This is because that, at each site, the relative orientations of the [CO_2] gradient and the

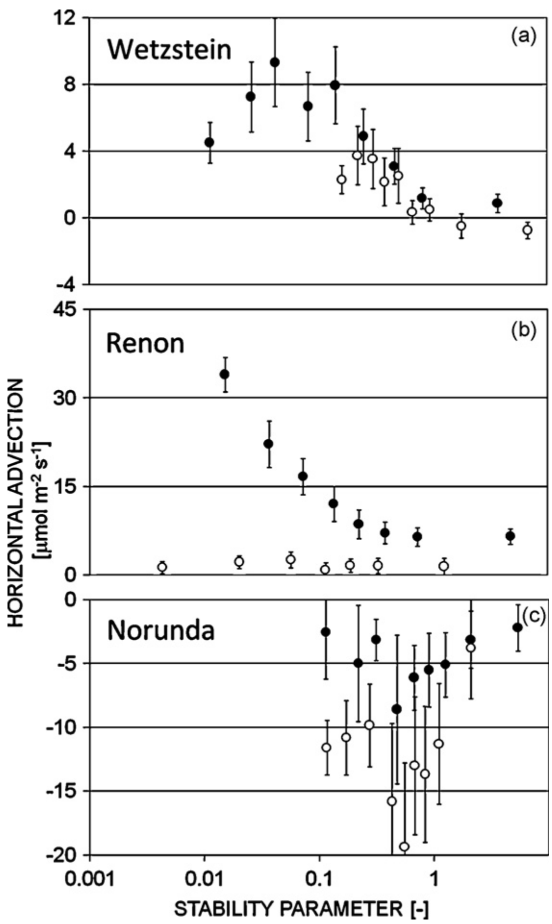

Fig. 5. Dependency of night-time horizontal advection on stability parameter; a: Wetzstein (WS); b: Renon (RE); c: Norunda (NO). Legend: as for Fig. 1.

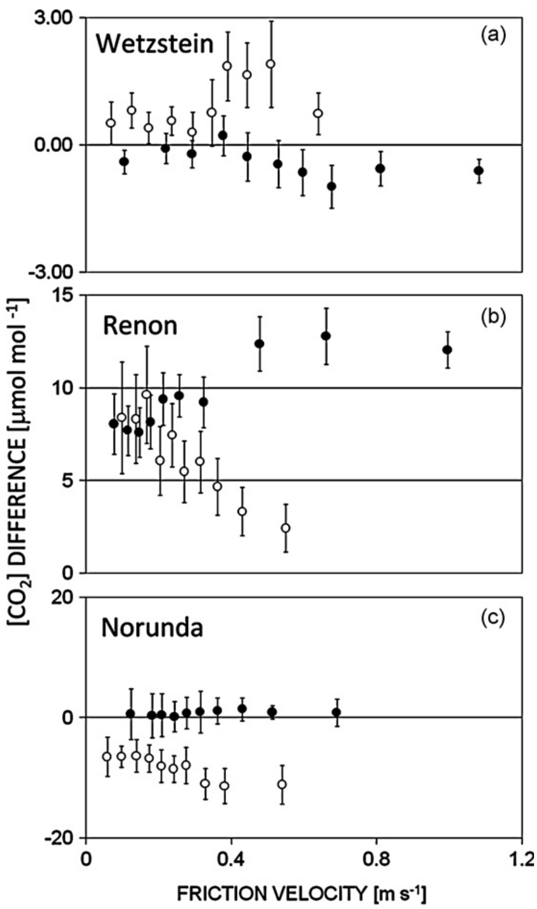

Fig. 6. Dependency on friction velocity of horizontal $[CO_2]$ difference. For details see text; a: Wetzstein (WS); b: Renon (RE); c: Norunda (NO). Legend: as for Fig. 1.

below-canopy wind velocity were always the same, whatever the wind sector (representative of the wind direction above the canopy). When wind velocities below and above the canopy were well coupled (i.e., below-canopy wind velocity orientation changed with the wind sector), this was possible only if the $[CO_2]$ gradient direction also changed with the wind sector. This was notably the case at WS (Fig. 6), as discussed by Zeri et al. (2010). In contrast, when the $[CO_2]$ gradient direction did not change with wind direction, which was the case at the other sites, the wind velocity direction could not change as strongly below the canopy as above it, implying a decoupling between the two flows. Feigenwinter et al. (2010a), (Fig. 5) showed that at RE, under Southern wind conditions, a downslope (i.e., Northern) wind was maintained below the canopy, which explains the positive, albeit smaller, F_{HA}.

Fourth, horizontal advection did not decline with u* and in some cases, even increased with it. This contradicts the common perception that F_{HA} decreases at large friction velocity due to more efficient air mixing and the corresponding reduction of $[CO_2]$ gradients. Fig. 6 shows that there were still significant horizontal $[CO_2]$ differences under large u* in all sectors at the sites, apart from NO South West. It is also in contradiction with the classical interpretation that night flux underestimation is due to the development of advection under low mixing (Massman and Lee, 2002).

Finally, important F_{HA} values could also be observed at flat and homogeneous sites, as was the case at NO (Figs. 4c and 5c). This also contradicts a common perception that advection results mainly from the non-horizontality or heterogeneity of sites.

3.3. CO_2 balance at night

The evolution of different NEE estimates with u* is represented in Fig. 7 for the three sites and different wind sectors. Estimates, based on eddy flux and storage (the two first RHS terms in Equation 1), are shown in the left column. They present the usual shape of stable values of CO_2-fluxes at large u* and decreasing fluxes with decreasing u*, indicating a flux underestimation at low friction velocities. However, the ACMB flux estimates (right column) did not provide more defensible estimates of biotic fluxes because of the characteristics outlined below:

3.3.1. At all the sites, systematic differences appeared between advection completed fluxes in each wind sector

For example, in well-mixed conditions ($u^* = 0.5\ m\ s^{-1}$), the average NEE varied by a factor greater than 2 in the sectors at RE (Fig. 7h) or moved from positive in the North East sector to negative in the South West sector at NO (Fig.7i). At these sites, the introduction of advection in the balance increased the difference between sectors. WS was the only site where the difference between sectors was reduced by the introduction of advection

3.3.2. The order of magnitude of the fluxes was often not compatible with biotic fluxes

Bin-averaged values up to $15\ \mu mol\ m^{-2}\ s^{-1}$ and $35\ \mu mol\ m^{-2}\ s^{-1}$ were observed at WS (Fig. 7g) and RE (Fig. 7h), respectively, whereas negative NEE estimates were obtained at NO (Fig. 7i). While the NO result is clearly unrealistic because it suggests that the site behaved as a CO_2 sink at night, the WS and RE results are

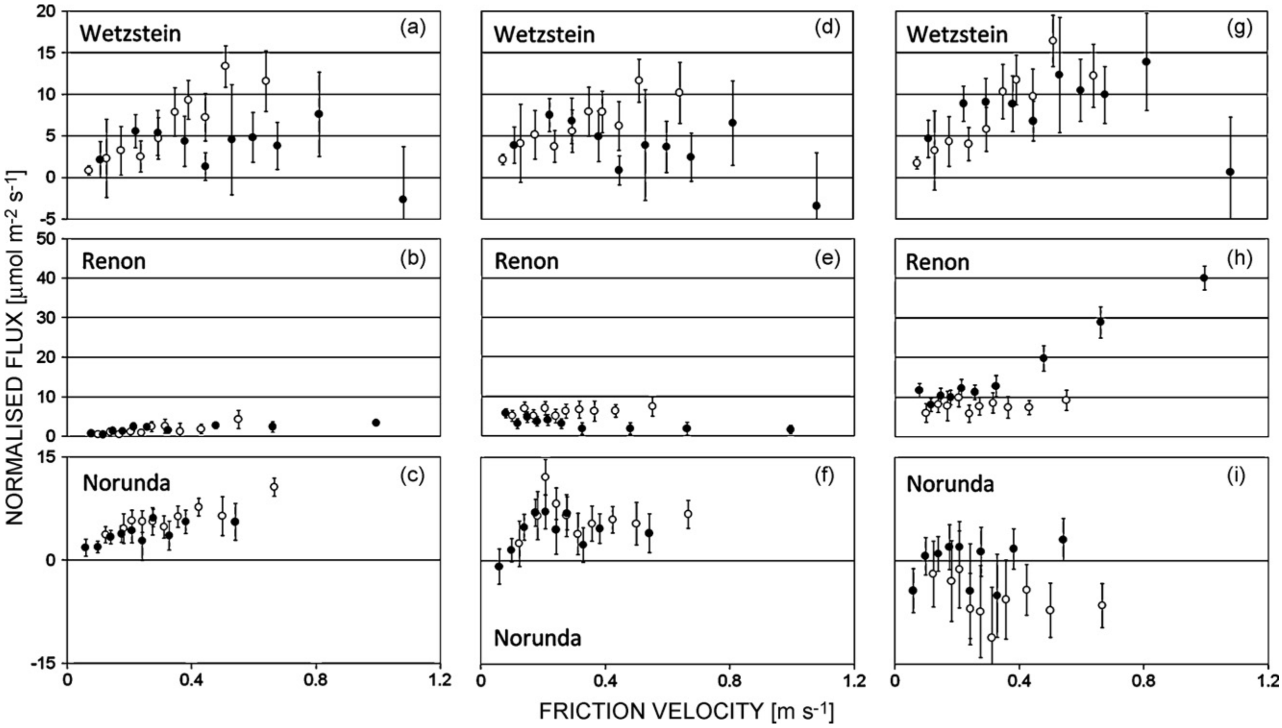

Fig. 7. Dependency on u* of CO_2 flux measured at night. Left column: sum of turbulent flux and storage. Central column: flux deduced from an incomplete ACMB, including turbulent flux, storage, and vertical advection. Right column: flux deduced from ACMB, including turbulent flux, storage, horizontal and vertical advection; a, d, g: Wetzstein (WS); b, e, h: Renon (RE); c, f, i: Norunda (NO). Legend: as for Fig. 1.

also unlikely given the biotic flux estimates obtained using other techniques. At RE, Rodeghiero and Cescatti (2005) showed that soil respiration was always lower than 7 μmol m^{-2} s^{-1}, suggesting that total ecosystem respiration there would rarely exceed 10 μmol m^{-2} s^{-1}, whereas at WS, Rebmann et al. (pers. comm.), using chamber and biometric measurements, obtained total ecosystem respiration estimates that were half the values predicted by Fig. 7g

*3.3.3. The ACMB approach does not suppress the tendency of fluxes to increase with u**

In four of the six sectors, introducing advection did not offset the flux decline, but maintained or even amplified it

4. Discussion

The preceding results suggest that including advection in the mass balance introduces not only random but also systematic errors. In particular, only systematic errors could explain the differences observed between wind sectors or friction velocity classes. These errors were not linked to the mass balance equation principle itself but to the way it was implemented. Errors can be theoretical (non-fulfilment of the hypotheses underlying Equation 1) or experimental (in the evaluation of advection terms), the latter possibly being instrumental, computational or linked to spatial sampling. We review these possibilities here.

4.1. Theoretical errors

Equation 1 is based on the hypothesis that horizontal turbulent flux divergence is negligible. This hypothesis was generally accepted in the preceding experimental advection studies. To our knowledge, only two studies have referred to direct horizontal flux divergence: Moderow et al. (2007) estimated it for sensible heat flux, and Staebler and Fitzjarrald (2004) for CO_2 on the basis of sensible heat flux. They found that it was about 30% of the mean advection. However, Staebler and Fitzjarrald (2004) recalled that there are no guidelines in the literature to measure and treat these fluxes so that they can just conclude that they could be significant enough to warrant further study.

4.2. Instrumental errors

An analysis of the measurement errors affecting direct advection measurements was developed by Heinesch et al. (2007). They showed that the most critical points concerned the vertical velocity (for estimating F_{VA}) and horizontal [CO_2] concentration differences (for estimating F_{HA}). The latter is the most critical in this case because the inconsistencies that affected the ACMB estimates in Fig. 7 resulted mainly from the F_{HA} term. The set-up used for [CO_2] measurement was especially designed to avoid systematic errors in the horizontal concentration gradient. To this end, all concentrations at a certain height were measured with the same IRGA to avoid offset problems between the instruments (see Feigenwinter et al., 2008). As a result, measurements at the same level were not taken simultaneously. However, they were scanned every 3 minutes and averaged every half hour. Meyers et al. (1996) showed that the error introduced by such a sampling strategy is random and not systematic. Heinesch et al. (2007), who used a similar set-up at the Vielsalm site, quantified the random error affecting [CO_2] difference as $\sqrt{2}$ times those affecting [CO_2]. The latter was estimated by capturing a high frequency [CO_2] signal below the canopy, sampling it several times at a given frequency using a random point of departure each time, and considering the standard deviation of the mean concentrations they obtained. Using the same approach, we evaluated the random error for F_{HA} at each site in this study. The frequency distribution of the absolute random errors is given in Fig. 8. It appears that, in 90% of the cases, the error affecting half-hourly F_{HA} estimates was lower than 5 μmol m^{-2} s^{-1}. The random error affecting the bin

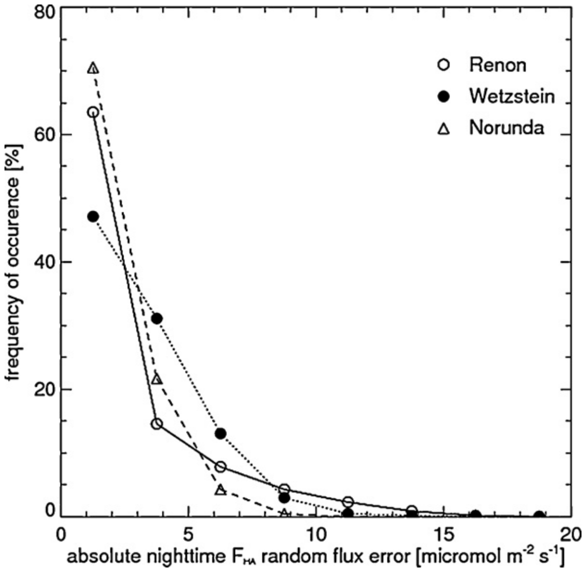

Fig. 8. Frequency distribution of the random error on F_{HA} at the three sites. Open circles RE, closed circles WS, open triangles NO.

averages presented in Figs. 4 and 5 was therefore always lower than 0.75 μmol m^{-2} s^{-1}, which is not enough to explain the differences observed.

Even if they were unlikely to be responsible for the discrepancies observed in this study, the errors for F_{VA} deserve attention. Systematic errors on vertical velocity could result from the application of an incomplete tilt correction (i.e. that would not completely offset a vertical velocity component due to topography or sensor deflection). Vickers and Mahrt (2006) found severe discrepancies between the vertical velocities computed using different tilt correction algorithms. Heinesch et al. (2007) also found large differences between vertical wind measurements made at the same location under different wind directions. Leuning et al. (2008) observed large discrepancies between vertical velocity estimates obtained using a single point and a mass balance approach. Before our study, an analysis of the sensitivity of the vertical velocity estimates to the rotation procedure was conducted, with four methods being compared. It showed that the choice of the method introduced no systematic differences. In all ADVEX studies, the sector-wise planar fit method was applied. Feigenwinter et al. (2010a,b), however, suggested that in the presence of complex topography vertical velocity could suffer from an incomplete tilt correction, which could lead to systematic errors. This could explain the large F_{VA} values observed throughout the u* range in RE South. Except for this case, F_{VA} did not vary greatly between wind sectors at a given site, suggesting that the impact of systematic errors on vertical velocity on the ACMB was limited.

4.3. Computational errors

Feigenwinter et al. (2008) showed that the F_{HA} computation procedures presented in the literature are not standardised, different methods being used by each team. However, if the procedure choice could induce some errors, it is unlikely to create systematic differences between different wind sectors. It is worth noting that the results obtained by Canepa et al. (2010), using a mass consistent approach at RE did not contradict our conclusions.

Systematic differences could remain between sectors if temperature correlates with wind direction or friction velocity, and if this effect was not entirely removed by the application of Equation 3. This equation was applied with a typical Q_{10} of 2 and was not adjusted for each site. In practice, if temperature was not clearly correlated with friction velocity, it could differ between the two wind sectors at each site. The average differences between real and temperature independent fluxes were about 36%, 4% and 20% at WS, RE and NO respectively. These differences were clearly limited and could not explain the F_{HA} differences between wind sectors and friction velocity classes.

4.4. Spatial sampling errors

One of the most likely causes of the observed differences was that the spatial resolution of the [CO_2] network was insufficient to take account of small-scale field heterogeneities. The horizontal distance between the four vertical profiles used to compute F_{HA} and F_{VA} was about 100 m, and the system could not catch heterogeneities at a smaller scale. An analysis (results not shown here) of smaller resolution (about 20 m) diagonal [CO_2] transects suggested that the horizontal [CO_2] gradient was not always homogeneously distributed in the control volume, leading to strong point-to-point F_{HA} variability. This suggests that the F_{HA} estimates could be strongly affected by the presence of small zones with larger concentrations ('hot spots') and were therefore hardly representative of the whole system. The cause of the presence of these hot spots was not clear. Extensive soil respiration measurements at the sites did not allow us to relate the hot spots to soil CO_2 source strength. One possibility could be that streamline undulations close to the soil, generated by micro-topographical changes or other factors, could at some places lift air that was usually closer to the soil and therefore richer in CO_2. As the vertical [CO_2] gradient was steep close to the soil, these undulations could create an artificial horizontal [CO_2] difference, as the sampling points were all placed at the same height above the soil. The detection of such a phenomenon, however, would require a much denser [CO_2] and wind velocity measurement network, which is not affordable at present.

In view of the large inconsistencies affecting F_{HA}, it is possible that a partial ACMB approach, using only vertical advection, although incomplete and not defensible from a theoretical point of view (Finnigan, 1999), would introduce lower errors. The evolution of NEE estimates with u*, using this approach, is presented in Fig. 7 (central column). If NEE estimates had an order of magnitude that was more realistic and less variable with wind direction, they showed a large variability and, in most cases, still underestimated the fluxes at low u*. This suggests that the application of a partial ACMB approach would not provide better NEE estimates at our sites.

The results presented here are specific to the sites investigated in this study. Although many studies have been published recently, attempting to estimate NEE using a partial (Lee, 1998; Baldocchi et al., 2000; Mammarella et al., 2007) or complete ACMB (Aubinet et al., 2003; Feigenwinter et al., 2004; Paw et al., 2004; Staebler and Fitzjarrald, 2004; Marcolla et al., 2005; Heinesch et al., 2008; Leuning et al., 2008), none of them, apart from Heinesch et al. (2008), evaluated the robustness of ACMB estimates by studying their dependence on wind direction and only a few tested their insensitivity to u*. These authours generally evaluated ACMB estimates consistency by comparing them with estimates obtained with soil chambers or modelling. All the studies concluded that ACMB generally amplified the spread of half-hourly estimates, making them difficult to interpret. Although some of these authors found the approach 'encouraging' (Baldocchi et al., 2000; Staebler and Fitzjarrald, 2004) because it provided a partial improvement of average NEE estimates, only two of them (Marcolla et al., 2005; Mammarella et al., 2007) considered the average NEE estimates using ACMB to be more reliable than those obtained using u* filtering. The approach used by these two authors remains debatable, however, for different reasons: Mammarella et al. (2007) did not perform a complete ACMB because they did not evaluate horizontal advection. They claimed that horizontal advection was negligible at their site, but did not check it. Marcolla et al. (2005), at RE, computed advection by combining [CO_2] measurements and velocity measurements taken during independent campaigns. In these conditions, their measurements couldn't take account of the large flux variability that appeared among different synoptic conditions, as highlighted in the present study. Feigenwinter et al. (2004) working at the Tharandt site and Aubinet et al. (2003) at the Vielsalm site concluded that horizontal and vertical advection were of the opposite sign and thus partially cancelled each other out and their sum was highly uncertain, making the ACMB approach difficult to use at their sites, even to estimate average fluxes. Reviewing the Vielsalm data, Heinesch et al. (2008) showed that vertical advection and ACMB flux estimates were affected by a strong dependence on wind direction and concluded that the ACMB approach did not allow CO_2 balance closure. In their case, the problem appeared linked mainly to vertical advection estimates. Leuning et al. (2008), using a different set-up, based on perforated tubing arranged parallel to the soil, found that the ACMB estimates were in reasonable agreement with soil chamber measurements, but mentioned that this was fortuitous, due to large uncertainties in both vertical and horizontal advection. They identified the uncertainties as resulting mainly from vertical velocity and horizontal concentration gradients, as stated earlier, and considered that the errors in advection estimates were mainly systematic.

This review indicates that, at this stage, there is no study that could demonstrate the robustness and defensibility of fluxes computed using the ACMB approach.

5. Conclusions

Our study sought to demonstrate the potential of the ACMB approach for accurately evaluating NEE at night.

The results showed that advection was subject to great variability not only from site to site but also, at a given site, from one wind sector to another. This suggested that CO_2 balances using advection estimates based on long-term averages could not reliably depict the real fluxes occurring at the sites.

In addition, the ACMB estimates of NEE were found to be generally unrealistic, given the biotic fluxes, suggesting that advection measurements were affected by an important systematic error. Even if all methodical aspects remain unsolved, it seems clear that the main causes of error were not related to the measurements themselves or to the data treatment, but derived from an under-representativeness of the samplings. The size of the investigated control volume and the number of sampling points was probably insufficient to describe advection precisely enough. As our study involved an unusually big effort to estimate the CO_2 balance terms accurately, it is questionable whether increasing measurement resolution further is feasible.

As conditions similar to the ADVEX project cannot be reproduced at each eddy flux site, one objective of our measurements was to detect night-time periods when the eddy flux and storage terms dominated the mass balance. This would be helpful in identifying alternatives to the u^* selection criteria for data filtering. Unfortunately, our measurements did not provide consistent information, as the largest advection estimates were obtained in well-mixed conditions, when no filtering is usually applied. Given the incompatibility of the ACMB results with biotic fluxes, it seems clear that this problem is related to the advection estimates.

In conclusion, although attractive from a theoretical point of view, the ACMB approach does not seem to be a practicable one for improving the CO_2 mass balance closure at night with affordable means in terms of manpower and equipment. Until now the most defensible night-time NEE estimates remain those obtained by using filtering approaches. Research should be directed to improve the filtering criteria. In particular, Acevedo et al. (2009) proposed to replace the friction velocity by the variance of vertical component, which is not contaminated by mesoscale movements. Besides, van Gorsel et al. (2007) proposed to estimate the night CO2 flux from the maximum of the eddy flux plus change in storage term in the period after sunset when stable stratification develops. These methods should be contemplated as alternatives to the u^* filtering.

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