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Assessing the method-specific differences in quantification of CO_2 advection at three forest sites during the ADVEX campaign

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ABSTRACT

The new method for CO_2 advective flux computation, based on the air mass-conservation principle, MCA (Montagnani et al., 2009) is applied to datasets collected at the three forest sites of Renon, Wetzstein and Norunda during the ADVEX campaign. Values of advective flux, calculated for 1 month at each site, are compared to those obtained using the more common method which computes the advective fluxes along vertical and horizontal CO_2 gradients, GA (Feigenwinter et al., 2008).

According to both methods, night-time CO_2 advection values were found to be positive at the sloping sites of Renon (MCA, 8.88 μmol m^{-2} s^{-1}, GA, 14.30 μmol m^{-2} s^{-1}) and Wetzstein (MCA, 2.82 μmol m^{-2} s^{-1}, GA, 3.07 μmol m^{-2} s^{-1}) and negative at the flat site of Norunda (MCA, −3.00 μmol m^{-2} s^{-1}, GA, −8.12, μmol m^{-2} s^{-1}), where the occurrence of extremely high negative advection values was calculated at night according to both methods. Daytime advection was found to be generally small and negative at all sites following both methods, while standard deviations were found to be generally higher according to the GA method.

Half-hourly calculated values were found to be similar during some periods, while in others, characterized by specific wind conditions, substantial differences were present. The coefficient of correlation (r^2) between the two estimates was 0.15 for Renon, 0.55 for Wetzstein and 0.45 for Norunda.

Three methodological aspects were considered to identify the reasons for the observed differences in CO_2 advections estimates: the correction factor used to attain mass conservation, the air incompressibility assumption and the vertical interpolation of wind velocities were found all to be scarcely correlated to observed differences.

These results indicate that general information concerning sign and daily courses of CO_2 advection estimates can already be taken from direct measurements, but there are still unresolved theoretical and computational issues affecting their quantitative reliability.

1. Introduction

Tower-based systems performing eddy covariance measurements represent a vital source of information concerning the biological activity of a wide range of ecosystems. Such systems, which now compose a global network (Baldocchi, 2008), give experimentalists and modelers the unprecedented opportunity to directly relate mass and energy flux to climate variability. Essential information is provided on the global carbon cycle and its interannual variability (Luyssaert et al., 2007; Reichstein et al., 2007) and on the hydrological cycle (Teuling et al., 2009).

However, due to the specificity of the eddy covariance method, which moves from a Lagrangian approach and is not related to a defined control volume, it is difficult to quantify its uncertainty, since the chance of performing a direct cross-check with other ground-based systems in order to quantify net ecosystem production (NEP) is lacking.

Interestingly, in NEP estimates uncertainty in the quantification of measurement uncertainty itself appears to be particularly important. Probably reflecting the different approach used, previous works by Lavigne et al. (1997), Kruijt et al. (2004) and

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Loescher et al. (2006) suggest that the uncertainty may be large, particularly at night, while others, e.g., Papale et al. (2006) and Richardson et al. (2008) reach different conclusions.

It is still questioned whether the EC system is able to perform self-corrections, based on the u^* threshold filtering technique (Fan et al., 1995; Goulden et al., 1996; Gu et al., 2005) or based on the use of evening data to model night-time fluxes (van Gorsel et al., 2007, 2008), or whether it is necessary to substitute all night-time data with flux values calculated using different methods, such as continuous soil chamber measurements. Alternative to these techniques is the direct measure of the flux component, advection, which is generally missing. This term appears to be the most difficult to measure, due to its intrinsically three-dimensional nature, which requires a very complex setup for its quantification.

In the last few years, an increasing number of works have been published, aimed at directly quantifying advection. These works can be divided into three groups according to the different approaches used. A first method moves from the theoretical derivation of vertical advection obtained by Lee (1998), which used a planar-fit rotation to compute the vertical wind component. It was later integrated by the horizontal advection component, measured along a CO_2 gradient on a sloping forest by Aubinet et al. (2003). Several adaptations of this method were later presented, some still using a 1D approach to quantify the vertical advection component (e.g., Baldocchi et al., 2000; Mammarella et al., 2007), others using a 2D approach (e.g., Turnipseed et al., 2004; Marcolla et al., 2005) and others using a fully 3D experimental setup (Feigenwinter et al., 2004, 2008; Staebler and Fitzjarrald, 2004; Yi et al., 2008; Leuning et al., 2008).

A second method was theoretically derived by Vickers and Mahrt (2006). This method still computes separately the vertical and horizontal fluxes, but computes differently the vertical wind component, starting from the mass continuity equation. This method was later used for purposes of comparison by Leuning et al. (2008).

A third method was derived by Montagnani et al. (2007, 2009) and applied to data of a single site. This method computes the fluxes along the aerial surfaces of the control volume after correction of the wind field to attain mass conservation. Wind components are not rotated. The first application of this approach to other sites is presented in this study.

This paper focuses on the quantification of the differences obtained in advection flux computation (Fca = horizontal + vertical advection) using the ADVEX dataset and the two different approaches published up to now which used these data. We compare the results obtained at the three ADVEX sites by Feigenwinter et al. (2008) with the gradient approach (GA), in which vertical advection (F_{VA}) is quantified following the Lee (1998) method and is summed to horizontal advection (F_{HA}) calculated following Aubinet et al. (2003), with improvement of the method (see also Feigenwinter et al., this issue-a) and the mass-conservation approach (MCA), the theoretical background of which is fully described in Montagnani et al. (2009).

In this study, information is also given on the uncertainty arising from some of the assumptions generally used in advection flux computation, such as air incompressibility, and uncertainty in storage flux computation which, together with Fca and the turbulent flux (Fct), concur in NEE quantification.

2. Materials and methods

2.1. Sites and experimental set-up

The three sites selected for the ADVEX campaign represent topographical conditions of various complexity: Renon (South Tyrol, Italy) is located on an alpine slope of about 11°; Wetzstein (Thuringia, Germany) is located on a ridge, in hilly terrain; Norunda (Uppland, Sweden) is on a plain (Fig. 1).

At the three sites the vegetation was mainly composed of spruce (*Picea abies* (L.) Karst.). There was an almost pure plantation at Wetzstein, while pines were also present at the other two sites: Cembran pine (*Pinus cembra* L.) at Renon and Scotch pine (*Pinus sylvestris* L.) at Norunda. In spite of the large latitudinal gradient (extremes were 60°05′ Norunda and 46°35′ Renon) the climate was similar at the three sites, all belonging to the Dfb climate according to Köppen, since the latitude effect on air temperature was compensated by a decreasing elevation, ranging from the 1735 m in Renon to the 780 m in Wetzstein and the 45 m above sea level in Norunda. Average effective leaf area density (LAI) was also quite similar, 5.1 at Renon (Marcolla et al., 2005), 4.0 at Wetzstein (Anthony et al., 2004) and 4.5 at Norunda (Lagergren et al. (2005). However, reported Net Ecosystem Production (NEP) differed widely at the three sites: by using the eddy covariance methodology and the u^* filtering approach, Valentini et al. (2000) indicated that Norunda was a source of CO_2 (see also Lindroth et al., 1998), while Renon was reported as a strong sink (450 gC m^{-2} y^{-1}), higher than Wetzstein, which was found to be nearly carbon neutral, 4 gC m^{-2} y^{-1} (Anthony et al., 2004). Based on different data selection and interpolations, however, Rebmann et al. (this issue) report for the Wetzstein site a larger carbon sink, ranging from 63 to 251 gC m^{-2} during the years 2002–2007.

Wind regimes were markedly different. At Renon a slope wind system prevailed (see also Feigenwinter et al., this issue-a), while at Wetzstein and Norunda a mesoscale circulation prevailed above the canopy. Below the canopy wind directions were often decoupled from above conditions at all sites, and this feature was particularly frequent at night.

Profiles of CO_2 molar fraction measured at night revealed the highest CO_2 values at Norunda, up to 576 μmol mol^{-1} at 12 m above ground (see also Feigenwinter et al., this issue-b, for details), with irregular profiles and rapid changes in mole densities, at Wetzstein was found the smallest CO_2 accumulation above the ground, and at Renon more regular CO_2 gradients with a logarithmic shape within the canopy were observed.

The experimental setup, as described by Feigenwinter et al. (2008), consisted at the three sites of four external towers, representing the corners of a control volume of approximately 3×10^5 m^3. These towers were 30 m high at Renon and Norunda (maximal tree height about 25–29 m), 24 m high at Wetzstein, where the maximal tree height was 21.6 m (Moyano et al., 2008). The instrumental setup used for advective flux computation, as described in Feigenwinter et al. (2008), consisted of two CO_2/H_2O close-path analyzers (Li 6262, LICOR, Lincoln, NE, USA) that sampled the air at 16 points by using a multi-valve-system (MVS) and twenty 3D sonic anemometers installed on the five towers (81000V, RM-Young, MI, USA and R3, Gill Instruments, Lymington, UK). The anemometers were placed vertically with respect to the geopotential with the help of an inclinometer and the azimuth was defined targeting a geographical object.

In addition, for the computation of advection according to the mass-conservation approach, air temperature was measured by means of 75 μm unscreened chromium-constantan thermocouples, type E (FW3—Campbell Scientific Inc. (CSI) Logan, UT, USA); air pressure was measured, in a single location at each site, by a CS 105 (CSI) at Renon and at Wetzstein, and by a PTA 427, Vaisala, Finland, at Norunda. The mass-conservation method requires also the use of a digital elevation model (DEM) of the terrain. For the Renon and Wetzstein sites the DEM of the terrain was used, as in Montagnani et al. (2009). For the Norunda site, which is almost flat, the available DEM indicated no unevenness in the terrain, so the basis of the control volume was assumed flat.

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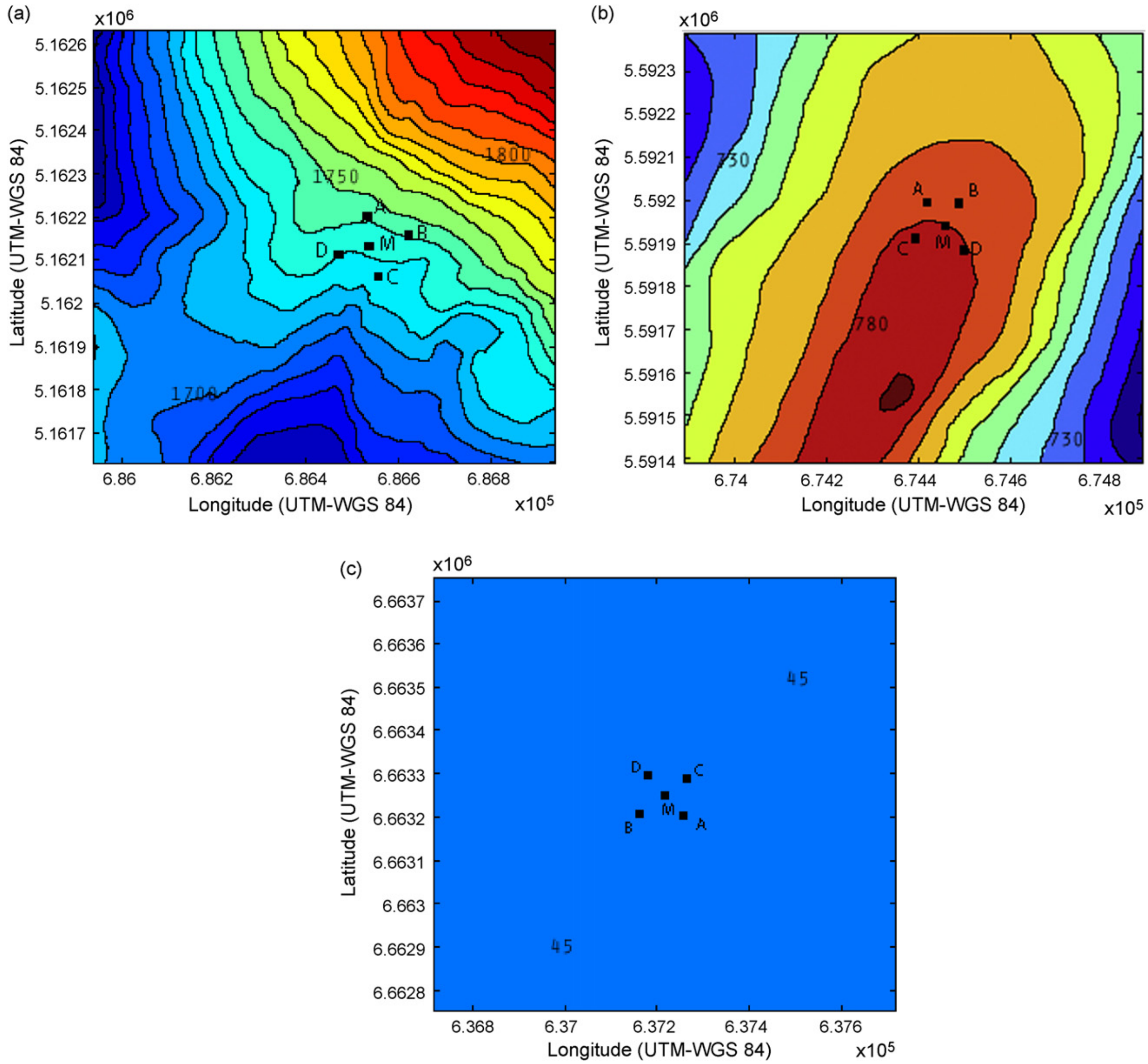

Fig. 1. Maps of the ADVEX experimental sites: Renon (a); Wetzstein (b) and Norunda (c). Elevation distance between contour lines is 10 m. Areas represented are 1 km × 1 km. Black squares and letters (A, B, C, D and M) refer to meteorological towers used in the experiment, numbers refer to elevation above the sea level, in meters.

2.2. Computational procedure

The two methods compared in this study can be considered as formally derived from the same expression of mass conservation, where a source or sink (S_b) of a trace gas (e.g., CO_2) can be defined as:

$$S_b = \frac{\partial n_c}{\partial t} + \nabla \cdot (n_c \mathbf{u}) \tag{1}$$

where n_c represents the moles of CO_2 per unit volume, ∇ is the divergence operator and $\mathbf{u}$ is the wind vector.

After Reynolds decomposition and averaging it reads

$$S_b = \frac{\partial \bar{n}_c}{\partial t} + \nabla \cdot (\bar{n}_c \bar{\mathbf{u}}) + \nabla \cdot (\overline{n'_c \mathbf{u}'}) \tag{2}$$

By separating the divergence terms into their components, equation 2 can be rewritten in the form:

$$S_b = \frac{\partial \bar{n}_c}{\partial t} + \bar{u}\frac{\partial \bar{n}_c}{\partial x} + \bar{v}\frac{\partial \bar{n}_c}{\partial y} + \bar{w}\frac{\partial \bar{n}_c}{\partial z} + \bar{n}_c\left(\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z}\right) + \frac{\partial \overline{u' n'_c}}{\partial x} + \frac{\partial \overline{v' n'_c}}{\partial y} + \frac{\partial \overline{w' n'_c}}{\partial z} \tag{3}$$

where $\partial \bar{n}_c/\partial t$ is the storage term, $\bar{u}(\partial \bar{n}_c/\partial x) + \bar{v}(\partial \bar{n}_c/\partial y) + \bar{w}(\partial \bar{n}_c/\partial z) + \bar{n}_c((\partial \bar{u}/\partial x) + (\partial \bar{v}/\partial y) + (\partial \bar{w}/\partial z))$ is the advection term and $(\partial \overline{u' n'_c}/\partial x) + (\partial \overline{v' n'_c}/\partial y) + (\partial \overline{w' n'_c}/\partial z)$ represent the turbulent flux.

The advection terms, by applying the rule of calculus, can be rewritten as (e.g., Sun et al., 1998)

$$\frac{\partial(\bar{n}_c \bar{u})}{\partial x} + \frac{\partial(\bar{n}_c \bar{v})}{\partial y} + \frac{\partial(\bar{n}_c \bar{w})}{\partial z} \tag{4}$$

In the gradient approach (GA), the air is assumed as incompressible and the dilution effect of water vapour is neglected (but see Kowalski and Serrano-Ortiz, 2007). Assuming also that continuity equation is satisfied with observed wind components, Eq. (4) is reduced to

$$\bar{u}\frac{\partial(\bar{n}_c)}{\partial x} + \bar{v}\frac{\partial(\bar{n}_c)}{\partial y} + \bar{w}\frac{\partial(\bar{n}_c)}{\partial z} \tag{5}$$

In synthesis, the gradient approach, following Lee's (1998) theoretical development for vertical advection measurements, requires two different computations, one for the vertical component and one for the horizontal. The GA approach uses reference axes along the x (east), y (north) and z (normal to surface) directions. On applying this approach to the 3D ADVEX setup, it was necessary to integrate these equations in the control volume defined by measurement points sited on its external corners. In the formulation of Feigenwinter et al. (2008), the vertical advective flux (F_{VA}) was computed as the average of vertical advection obtained at the four external towers

$$F_{VA} = \frac{1}{V_m}\frac{1}{4}\sum_i \overline{w_i}(z_r)(\overline{c}_i(z_r) - \langle \overline{c_i} \rangle) \tag{6}$$

where V_m is the molar volume of air, $\overline{w_i}(z_r)$ is the vertical wind velocity at the reference height above the ground, $\langle \overline{c_i} \rangle$ denotes the average CO_2 concentration (in wet air) inside the control volume.

The horizontal advective flux was computed as

$$F_{HA} = \frac{1}{V_m}\frac{\Delta z}{N}\sum_{nx,ny,nz}\left(\overline{u}\frac{\Delta\overline{c}}{\Delta x}(x_j, y_k, z_l) + \overline{v}\frac{\Delta\overline{c}}{\Delta y}(x_j, y_k, z_l)\right) \tag{7}$$

where x, y, and z denote easting, northing and vertical directions, see also Feigenwinter et al. (this issue-a), for further details. In the case of F_{VA}, the coordinates refer to the vertical velocity computed following an 18 sector planar-fit, while F_{HA} is computed following a modified terrain-following system.

In the mass-conservation approach (MCA), by integrating Eq. (2) over the control volume, we obtain

$$\iiint_V S_c dV = \iiint_V \frac{\partial \bar{n}_c}{\partial t} dV + \iiint_V \nabla\cdot(\bar{n}_c \bar{\mathbf{u}}) dV + \iiint_V \nabla\cdot(\overline{n_c' \mathbf{u}'}) dV \tag{8}$$

If we apply the Gauss theorem over the divergence terms we obtain

$$\iiint_V S_c dV = \iiint_V \frac{\partial \overline{n_c}}{\partial t} dV + \iint_S n_c \bar{\mathbf{u}}\cdot d\mathbf{S} + \iint_S \overline{n_c' \mathbf{u}'}\cdot d\mathbf{S} \tag{9}$$

By using this approach, the advection term can be directly computed along the control volume as

$$Fca = \iint_S \bar{n}_c \bar{\mathbf{u}}\cdot d\mathbf{S} = \iint_S \bar{n}_c \bar{u} \cos\theta dS \tag{10}$$

where θ here is an angle between the average wind vector, $\bar{\mathbf{u}}$, and differential surface vector $d\mathbf{S}$ and n_c is the CO_2 concentration expressed as mole density. Due to the discretization of the aerial surface of the control volume, and the assumption of the vertical direction normal to the geopotential surface, oriented surface elements $d\mathbf{S}_i$ are approximated to finite elements $\Delta\mathbf{S}_i$, oriented along the orthogonal axes x, y and z, which are parallel or perpendicular to wind vector component u, v and w, thus simplifying computation.

At this point this method encountered an experimental problem, arising from the circumstance that input data rarely satisfied the mass-conservation requirement, due to measurement errors, the representativeness of the data, spatial discretization, or inaccuracies of the interpolation algorithms used. It was therefore necessary to apply a mass-correction algorithm to assure mass conservation.

Observed deficit or excess of dry air, ΔQ, must be forced to zero. For practical purposes this correction can be applied only to the term $\nabla\cdot(\bar{n}_{tot}\bar{\mathbf{u}})$ of the mass conservation of dry air

$$\frac{\partial \bar{n}_{tot}}{\partial t} + \nabla\cdot(\bar{n}_{tot}\bar{\mathbf{u}}) + \nabla\cdot(\overline{n_{tot}' \mathbf{u}'}) = 0 \tag{11}$$

where (n_{tot}) is mole density of dry air including CO_2. This approximation can be justified assuming that the spurious inflow or outflow of dry air, arising from experimental or computational problems, are generally much greater than $\partial\bar{n}_{tot}/\partial t$ and $\overline{n_{tot}' \mathbf{u}'}$, terms that will be assumed as negligible.

To force $\nabla\cdot(\bar{n}_{tot}\bar{\mathbf{u}})$ to zero, a correction factor, *cf*, is introduced. It is formed by the ratio of the mass-conservation deficit/excess in the whole control volume, $\Delta Q = \sum_i(\bar{n}_{tot_i}\bar{u}_i \Delta S_i)$ and the overall sum of the absolute values of the elementary fluxes, $\sum_i |\bar{n}_{tot_i}\bar{u}_i \Delta S_i|$

$$cf = \frac{\Delta Q}{\sum_i |\bar{n}_{tot_i}\bar{u}_i \Delta S_i|} \tag{12}$$

The term $\bar{n}_{tot}\bar{\mathbf{u}}\cdot d\mathbf{S}$ for each elementary surface is therefore multiplied by the term (1 + *cf*), which is larger than 1 when $\Delta Q > 0$ (i.e., the outflow is larger than inflow). The contrary happens when $\Delta Q < 0$, and 1 + *cf* is smaller than 1.

Correction of the wind (and air density) field to attain mass conservation is necessary when the MCA method is applied to experimental data: if not used, the computation of fluxes measured along the control volume surfaces leads to spurious CO_2 fluxes two orders of magnitude greater than those obtained with the MCA (Montagnani et al., 2009).

In the present work, we use the methodology based on a single correction factor, *cf*, for the three wind components calculated in each half-hour, but we highlight that a more elaborated methodology based on the application of a mass-consistent wind model is under study (Canepa et al., this issue).

The control volume is laterally defined by the four external towers in both methods, but with different resolutions: 10 m in the GA and 1 m in the MCA. The lowest level is in both cases defined by the soil and the top is defined in a different way: according to the planar-fit calculated from measured wind data in the case of GA, following a plane parallel to the main slope of the terrain in the case of MCA. This plane was set at 30 m above the ground at Renon and Norunda, 22 m at Wetzstein. According to both methods, the whole vegetation was included in the control volume.

There are elements of approximation and simplification in using both approaches. Firstly, sparse data measured in a heterogeneous control volume are used to reconstruct vectorial and scalar fields. In the GA approach, subjectivity is introduced in the computation of vertical wind velocity, which could be computed differently following different rotation procedures (see also Vickers and Mahrt, 2006), the air incompressibility is assumed a priori and the effect of water vapour dilution is not considered. In the MCA, the coordinates are univocally defined according to geopotential and vertical velocity is not rotated. This avoids subjectivity, but exposes the method to experimental errors connected to misalignment of the anemometers. The two methods require interpolations for CO_2 mole densities and wind velocities. In addition, MCA requires the reconstruction of the 3D dry air density field, which was modeled using available measured values of air temperature, H_2O molar fraction and air pressure, see Montagnani et al. (2009) for details.

The interpolations used in the GA and MCA methods were also different. Here, we consider the effect of interpolation of vertical wind velocities on CO_2 advection estimates. The simplest, linear interpolation was used in the MCA, while for the GA a modified interpolation scheme was applied between the two uppermost measurements levels (see Feigenwinter et al., 2008).

In addition, in the MCA elements of the air mass balance such as $\partial\bar{n}_{tot}/\partial t$ and $\overline{n_{tot}' \mathbf{u}'}$ are arbitrarily forced to zero. We can therefore expect differences in computation of the CO_2 advection (Fca) arising from multiple factors.

2.3. Data selection

Within the datasets obtained in the three campaigns, periods of 1 month each were selected for each site. We used the data collected in the month of July 2005 at Renon, in two periods of 15 days each at the beginning of the months of May and June at

Table 1
Mean and standard deviation values of advective fluxes measured at the three sites. Night and day values are considered in time intervals 21:00–03:00 h and 09:00–15:00 h, respectively. The correction factor, *cf*, used to attain the mass conservation following the MCA is also reported.

Site	Period	*n*	GA		MCA			
			CO_2 flux (μmol m^{-2} s^{-1})		CO_2 flux (μmol m^{-2} s^{-1})		*cf* (adimensional)	
			Average	SD	Average	SD	Average	SD
Renon	Total	1191	5.87	13.60	3.13	7.36	−0.008	0.070
	Night	318	14.30	14.75	8.88	7.79	0.036	0.062
	Day	292	−4.37	5.23	−1.34	3.65	−0.056	0.046
Wetzstein	Total	1374	1.47	3.90	1.20	3.22	−0.045	0.097
	Night	342	3.07	4.45	2.82	3.17	−0.033	0.084
	Day	331	−0.33	1.94	−0.51	1.75	−0.059	0.103
Norunda	Total	1189	−4.06	16.73	−2.57	16.43	−0.001	0.059
	Night	330	−8.12	23.55	−3.00	22.71	0.016	0.051
	Day	259	−0.51	4.16	−2.34	6.16	−0.022	0.062

Wetzstein and in August 2006 at Norunda. Periods were selected within the ADVEX dataset to represent the most favorable conditions encountered during the experimental campaign, with the highest percentage of valid data. Data collected during periods of heavy rain or during calibration periods were discarded. In addition, we eliminated from both the datasets used for comparison all the data collected when computations with the MCA were not possible, e.g., due to the failure of a single thermocouple. After this selection, the two datasets contained 1191 half-hourly values for Renon, 1374 for Wetzstein and 1189 for Norunda (see Table 1). In addition, a week period from the Norunda dataset, characterized by large oscillations in the advection flux (10–17 September 2006), was also considered.

3. Results

3.1. Comparison of advection flux

3.1.1. Fca at the Renon site

At Renon, Fca was found to be positive on the average following both the methods. Average and standard deviation values (5.87 ± 13.60 μmol m^{-2} s^{-1}) estimated by the GA were higher than the ones (3.13 ± 7.36 μmol m^{-2} s^{-1}) calculated by the MCA. It is worth noting that if the advective flux calculated with the GA is extrapolated to the whole year, keeping its proportionality with the sum of Fca and Fct, the Renon site would be transformed into a source of CO_2, while with the MCA it would only decrease its sink strength, reaching the estimates of aboveground biomass increment obtained from forest inventories (Bascietto et al., 2003), in the range between 120 and 200 gC m^{-2} y^{-1}.

Looking at the daily course of CO_2 advection estimates (Fig. 2a), we can see that both computational approaches produce negative values during the day and positive values at night. The daily trend is also different, with MCA values negative in the evening, at the time of maximum storage onset, a feature not present in the GA daily course.

Observing in detail the half-hourly calculated values (Fig. 3a), we can find some days in which the two methods show similar behaviour, while in others they are completely different. This is particularly evident during the '*Tramontana*' (synoptic north wind) conditions, when GA values showed very large values, approximately one order of magnitude larger than the MCA values. Overall, the coefficient of correlation between the two CO_2 advection estimates was $r^2 = 0.15$.

3.1.2. Fca at the Wetzstein site

The Wetzstein dataset showed the best agreement between the two methods. When averaged over the entire period, advection flux was found to be positive with both methods, 1.47 ± 3.90 μmol m^{-2} s^{-1} following GA, 1.20 ± 3.22 μmol m^{-2} s^{-1} following MCA (Table 1), thus indicating both a lower mean and lower scatter in half-hour values when the latter method was used. The correlation coefficient between the two CO_2 advection estimates was the highest of the three sites ($r^2 = 0.55$). The average daily courses of advection values calculated with the two methods (Fig. 2b) was found to be similar. However, GA showed higher averaged flux values in the morning and MCA in the evening. It is worth noting that with both methods, calculated advection flux does not compensate for the high turbulent fluxes irregularly observed at night. Conversely, they show increased positive advective values in the nights characterized by turbulent flux higher than average (Fig. 3b), thus enhancing the night-to-night difference in the total flux, since the CO_2 storage in the canopy air layer was nearly negligible at that site. This could be physically justified only assuming a large pressure-pumping effect, enhancing the emission of CO_2 stored in soil (Rayment and Jarvis, 2000; Flechard et al., 2007). The finding of high advection values during nights characterized by high friction velocity clearly contradicts the expectations for a compensatory effect of advection with respect to turbulent flux at low u^* values, on which the threshold filtering technique is based, see also Aubinet et al. (this issue), Rebmann et al. (this issue), and Zeri et al. (this issue).

3.1.3. Fca at the Norunda site

At this site, great heterogeneity in CO_2 mole density was found, even in the upper part of the canopy air space, where wind velocities are higher, thus giving the potential for extremely high CO_2 advection fluxes. Events of high CO_2 mole density, with up to 576 μmol mol^{-1} of CO_2 at 12 m above ground at some towers (see also Feigenwinter et al., this issue-b), were observed irregularly during the nights or early mornings, and on these occasions extremely high negative advection values were measured following both the methods. When averaged along the day, results of the two methods showed both similarities and differences (Fig. 2c). The coefficient of correlation between the CO_2 advection estimates obtained using the two methods was $r^2 = 0.45$. Mean values of Fca were -4.06 ± 16.73 and -2.57 ± 16.43 μmol m^{-2} s^{-1}, if calculated with the GA and MCA methods, respectively. This indicates that independently of the method used, the effect of Fca summation on the turbulent and storage terms is the shifting of the Norunda site toward a sink status.

If we consider the daily course of Fca, we find a pronounced daily pattern with the GA method, with large night (here defined as the central 6 h around midnight, from 21:00 to 3:00 h) negative fluxes (on average, -8.12 μmol m^{-2} s^{-1}) and values close to zero during the day (-0.51 μmol m^{-2} s^{-1}), here defined as the central 6 h around noon, from 9:00 to 15:00 h. The pattern shown by the MCA is quite different: the highest averaged negative values were found in the morning, while smaller negative values were recorded

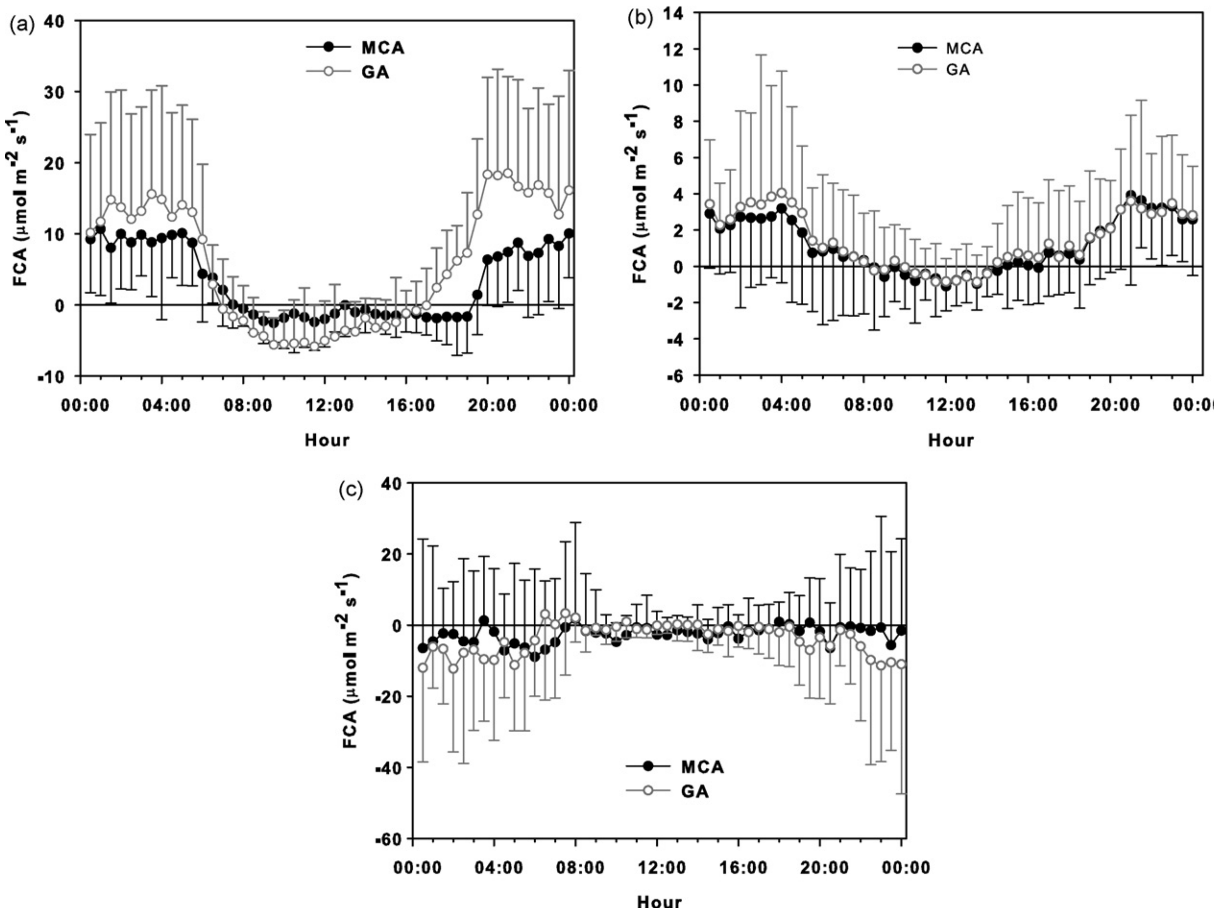

Fig. 2. Averaged daily courses of CO_2 advection estimates (Fca) at the three measurement sites: Renon (a), Wetzstein (b) and Norunda (c). Grey, open symbols refer to CO_2 advection flux estimated by the gradient approach (GA); black symbols refer to estimates based on the mass-conservation approach (MCA). Error bars represent positive or negative standard deviation.

during the night ($-3.00\ \mu mol\ m^{-2}\ s^{-1}$) and also during the day ($-2.34\ \mu mol\ m^{-2}\ s^{-1}$). Both results were affected by much scatter, of similar magnitude, as expressed by the standard deviation (Fig. 2c), which was largest at night and smallest in the day. Examining in detail half-hour calculated fluxes, it is possible to see that at least during some periods advection values were quite similar (Fig. 3c).

3.2. Seeking possible explanations for observed differences in advective flux computation

3.2.1. Effect of deviation from mass conservation

The adjustment method used to attain air mass conservation is a possible cause of different results obtained by the two flux calculation approaches described. The present adjustment method imposes a numerical modification of the product of air density and wind on the surface of the control volume. This numerical modification may alter the real fluxes due to limits in its accuracy.

However, looking at Fig. 4, where the correction factor used to attain mass conservation is shown, and comparing it with Fig. 3, where calculated advective fluxes are shown, no clear relationship appears between the datasets. As an example, during the synoptic north wind period (*'Tramontana'*, see also Feigenwinter et al., this issue-a) the difference between GA and MCA values is extremely high, while the correction factor is low.

At all the sites, differences between the two estimates were largest when *cf* was positive, so indicating a net spurious outflow of dry air from the control volume, but not at its maximal values, in the range 0.05–0.1. These conditions were found for instance during north winds at Renon, during west winds at Wetzstein and during the night, without any clearly prevailing wind direction, at Norunda. The coefficient of correlation between *cf* and the differences between MCA and GA was always low: the highest was found at Wetzstein ($r^2 = 0.11$) and close to zero at the other two sites.

Interestingly, the magnitude of the correction factor (*cf*) was similar in the three study cases characterized by a largely different topographical complexity (Table 1 and Fig. 4). This suggests that with the instrumental setup used in the ADVEX experiment, the amplitude of *cf* may be mostly dependent on the heterogeneous flow field resulting from the irregular drag exerted by tree crowns (Yi, 2008), and only to a lower extent from the interaction between winds and topography.

3.2.2. Effect of the air incompressibility assumption

One of the reasons for the differences between the advective fluxes calculated with the two methods may be air incompressibility: it is assumed by the GA, while it is not by the MCA, where dry air can change its density in space depending on temperature and water vapour measured values.

In order to evaluate the relevance of the incompressibility assumption we performed a test on the MCA. The test was performed by comparing calculated advective fluxes for the Renon site in two different ways: (1) dry air mole density was left free to vary with measured values of temperature and pressure for each half hour averaging period; (2) the values of the same quantities

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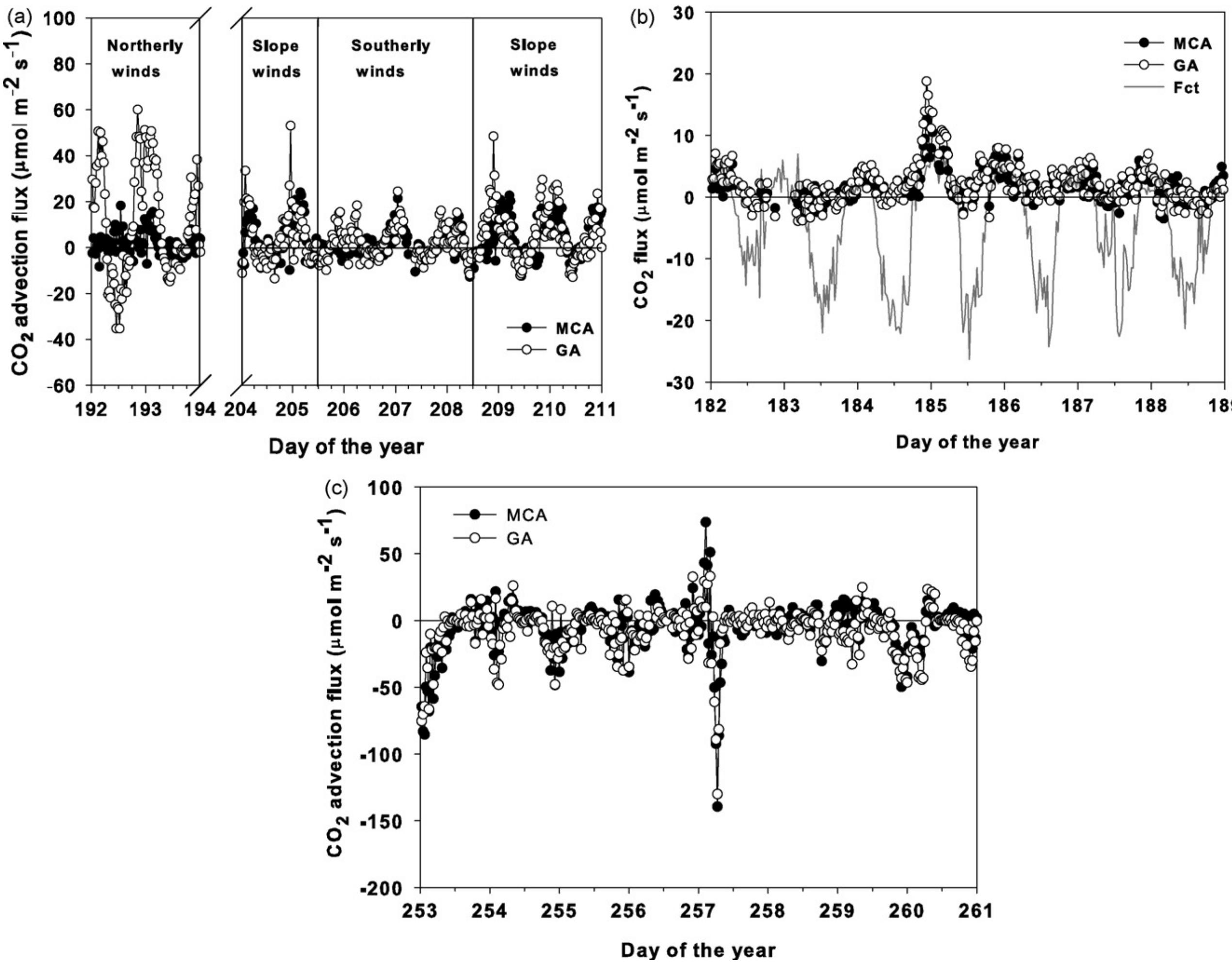

Fig. 3. Half-hourly advection estimates during selected periods at Renon (a), Wetzstein (b) and Norunda (c). Black filled symbols refer to CO_2 advection estimates following the mass-conservation approach (MCA); open symbols refer to estimates following the gradient approach (GA). (a) Indicates also wind conditions experienced at the Renon site. (b) Reported the turbulent flux measured at Wetzstein on the central tower M.

were kept constant for the whole study period and equal to their average values for the whole study period itself. In this comparison, we were not interested in the strength of the relation between the two estimates, as given by the coefficient of correlation (r^2), but in the agreement between them.

We therefore used the Bland–Altman plot (Altman and Bland, 1983; Bland and Altman, 1986). The results are shown in Fig. 5, where it is possible to note that the variation of at least one method depends on the magnitude of the measurements, but there are no systematic differences between the two estimates. If the scope of advection measurements is to produce annual NEE sums, the simplification introduced in MCA computation by the air incompressibility assumption is acceptably good (see also Moncrieff et al., 1996), although there is an overall small (<1 μmol m^{-2} s^{-1}) reduction of precision in half-hourly estimates of Fca.

3.2.3. Effect of different interpolation of vertical wind profiles

One of the key points in the mass-conservation approach is the reconstruction of a 3D mass-consistent wind field starting from available measurements. So it is interesting to understand to what extent the interpolation algorithms for the wind profiles reconstruction affect the computed flux values. Therefore, the elaborated vertical interpolation scheme, partially logarithmic, as proposed by Feigenwinter et al. (2008), was used in comparison to the algorithm used by Montagnani et al. (2009) which applies a linear interpolation between measured values of the three wind components, assuming zero values at the ground.

Results concerning the Renon site are shown in Fig. 6. Looking at the Bland–Altman plot, it is possible to see that a proportional error exists with an increase in the magnitude of the measurements, with the linear interpolation scheme tending to give higher values, so in the opposite direction with respect to observed differences between the two estimates. If we assume that the vertical profile which follows Feigenwinter et al. (2008) is correct, we conclude that the linear interpolation in the reconstruction of wind profiles leads in average to systematic positive bias in Fca estimates, and is therefore not acceptable for estimates of half-hourly values and annual sums. The difference is however relatively small, in average 0.3 μmol m^{-2} s^{-1}.

4. Discussion

As shown by Montagnani et al. (2009), uncertainties in advection flux estimates following the MCA may come from different sources: (a) accuracy and precision in the measurements of the input parameters for their calculation, such as wind direction and velocity, air temperature, air pressure, CO_2 and H_2O mole densities; (b) number, spatial distribution and representativeness of sampling points; (c) interpolation functions for

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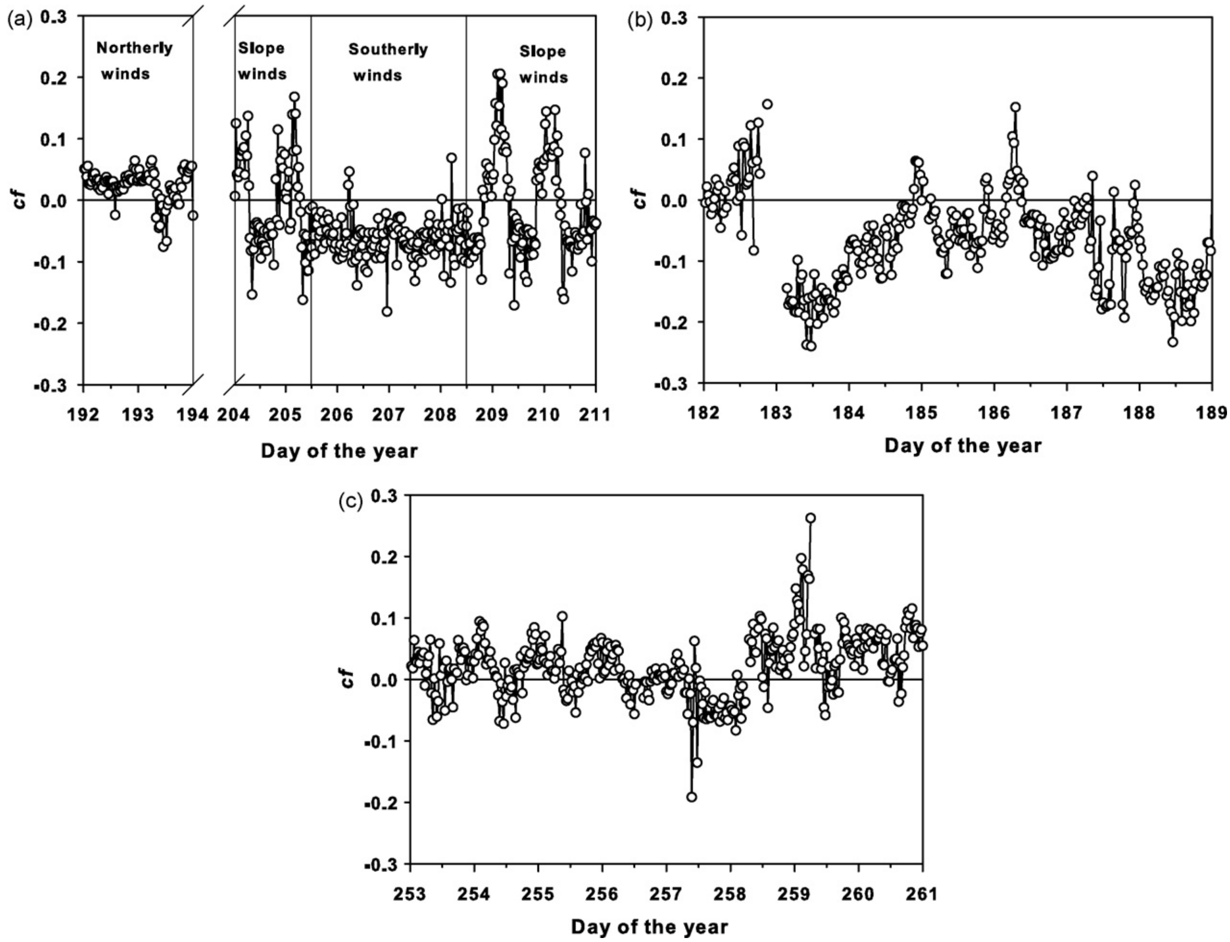

Fig. 4. Correction factor (*cf*) calculated from deficit/excess of mass conservation in the control volume and used, in the form (1 + *cf*), as multiplying factor to attain mass conservation from measured data of dry air density and wind velocity components. Periods represented are the same selected for Fig. 3. Half-hourly values calculated for Renon (a), Wetzstein (b) and Norunda (c).

obtaining the 3D wind field; (d) the correction procedure used to attain air mass conservation.

Uncertainties in advection flux computed using the GA also depend on points (a) and (b). Major uncertainties may arise from vertical flux computation. Vertical wind component measurements are difficult to take with available instrumentation. The methods developed to resolve this instrumental issue, such as the Lee method (Lee, 1998), the tilt angle method (Paw U et al., 2000),

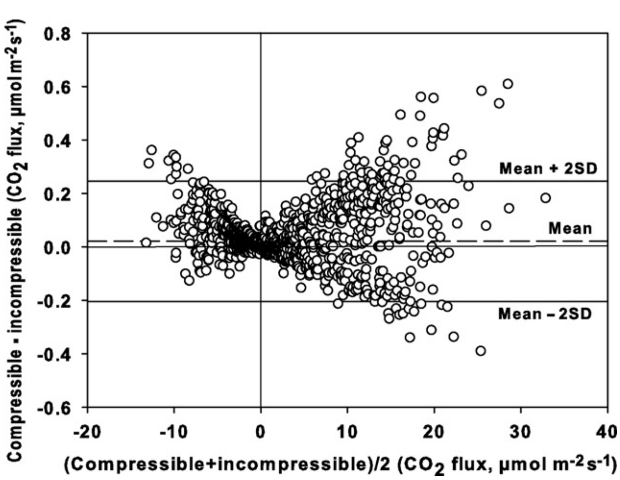

Fig. 5. Relation between CO_2 advection flux calculated by the mass-conservation approach assuming the air as compressible, taking also into account the effect of water vapour mole density, or considering the air as incompressible. Bland–Altman plot. Data refer to the Renon site.

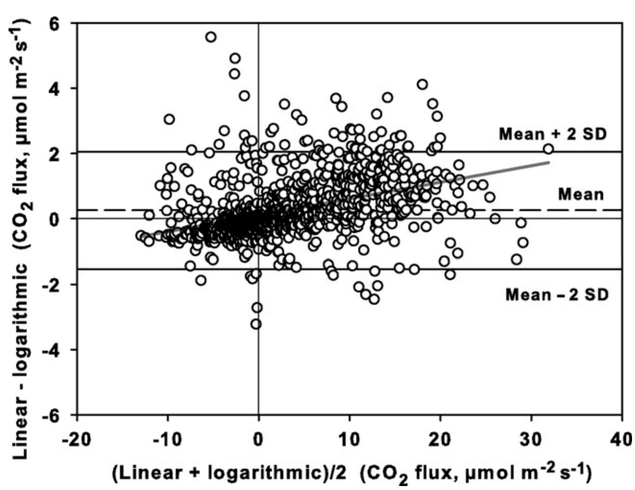

Fig. 6. Relation between CO_2 advection flux calculated by the mass-conservation method, following two different interpolation of vertical profiles of wind velocity: the vertical linear interpolation and the interpolation scheme proposed by Feigenwinter et al. (2008), which applies a logarithmic interpolation at the top of the canopy air space. Bland–Altman plot. Data refer to the Renon site.

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the planar-fit method (Wilczak et al., 2001) and the divergence method based on the continuity equation (Vickers and Mahrt, 2006), lead to different vertical wind velocity estimates. Leuning et al. (2008) showed that vertical advection flux may vary greatly if calculated from the continuity equation or from the values measured by the 3D sonic anemometer.

An additional source of discrepancy between the two methods is the implicit assumption done in the GA that mass continuity is satisfied by measured wind components. Eq. (5) is less sensitive to temporal and spatial variation of wind velocity than Eq. (4), so the GA can give different estimates due to this assumption, see Sun et al. (2007) for further details.

The differences observed between the two methods were found to be largest at the Renon site, where, due to its complex topography, the planar-fit method is known to encounter difficulties in reducing vertical wind velocity residuals (Göckede et al., 2008). At this site, uncertainties in vertical advection computation following the GA are also expected to be particularly high. The differences observed between the results obtained using the two methods in '*Tramontana*' wind conditions can also be explained by the different interpolations used, by the algorithm employed to attain mass conservation and by the presence of divergence of turbulent flux of dry air ($\overline{n'_{tot}\mathbf{u}'}$), not considered in the MCA computation.

Here, we suggest that the use of the continuity equation (Vickers and Mahrt, 2006) may be an interesting third term of comparison in Fca computation, and may show whether or not the discrepancies between the results obtained with the two methods arise from the limits in the assumptions underlying one of the methods applied.

Another point must be stressed in relation to the observed high advection fluxes at Norunda, of similar sign and magnitude, but far from biological likelihood following both methods. At that site these large flux events (e.g., day 257, Fig. 3c) are produced by large horizontal CO_2 gradients measured in the central part of the canopy air space (Feigenwinter et al., this issue-b). If these fluxes are produced by air masses rich (or poor) of CO_2, produced elsewhere, and passing across the control volume, they should be balanced by similar storage fluxes (Fcs) of opposite sign.

However, although Fca and Fcs were found frequently of opposite sign, they rarely cancelled each other. One reason is that the Fcs is generally computed as the difference between following half-hour mean values. We tested that if Fcs is computed, more correctly, as the difference between the CO_2 molar densities measured at the end and at the beginning of each measurement period, it is larger as expected (Finnigan, 2006), but still does not balance the extremely large advection values.

Studies on computational fluid dynamics to model the 3D air movements within the canopy could help explaining the reason for observed Fca, which unrealistic magnitude appears not to be associated to a computational issue, but to an experimental one, probably tied to sampling points representativity.

5. Summary

The comparison of CO_2 advection values calculated for the three ADVEX sites shows that mass conservation and gradient methods are coherent in the indication of the sign of mean advection flux, which was found to be positive at Renon and Wetzstein, and negative at Norunda. However, the extent of the mean advection values is different: the advection flux was found to be larger in absolute values if computed with the gradient method.

Average daily courses showed a similar pattern, but with significant differences between the computational approaches used in mean values and in standard deviations. Large differences in CO_2 estimates were observed at night, and also at evening and morning, with the GA generally showing higher absolute values. Calculated advective fluxes were found to be similar in most conditions but large differences were found during some specific wind conditions, namely during the synoptic north wind at Renon and during the west wind at Wetzstein.

The analysis of the effect of the air incompressibility assumption showed that it is small and not systematic. A relatively larger and systematic difference in calculated flux is obtained by applying different interpolation algorithms to reconstruct the vertical wind profiles. Overall, however, the effect of these computational differences was small, or in the opposite direction to observed differences in CO_2 advection estimates.

This work confirms the relevance in CO_2 advection estimates of the computational method applied, as already found by Vickers and Mahrt (2006) and Leuning et al. (2008), indicating a key role in the overall uncertainties for the treatment of wind velocity measurements.

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