

Multiple quality tests for analysing CO₂ fluxes in a beech temperate forest

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Abstract. Eddy covariance (EC) measurements are widely used to estimate the amount of carbon sequestered by terrestrial biomes. The decision to exclude an EC flux from a database (bad quality records, turbulence regime not adequate, footprint problem,...) becomes an important step in the CO₂ flux determination procedure. In this paper an innovative combination of existing assessment tests is used to give a relatively complete evaluation of the net ecosystem exchange measurements. For the 2005 full-leaf season at the Hesse site, the percentage of rejected half-hours is relatively high (59.7%) especially during night-time (68.9%). This result strengthens the importance of the data gap filling method. The data rejection does not lead to a real improvement of the accuracy of the relationship between the CO₂ fluxes and the climatic factors especially during the nights. The spatial heterogeneity of the soil respiration (on a site with relatively homogenous vegetation pattern) seems large enough to mask an increase of the goodness of the fit of the ecosystem respiration measurements with a dependence on soil temperature and water content when the tests are used to reject EC data. However, the data rejected present some common characteristics. Their removal lead to an increase in the total amount of CO₂ respired (24%) and photosynthesised (16%) during the 2005 full-leaf season. Consequently the application of our combination of multiple quality tests is able improve the inter-annual analysis. The systematic application on the large database like the CarboEurope and FLUXNET appears to be necessary.

mate change and therefore for the future of the vegetation (Houghton et al., 1998). The quantification of CO₂ fluxes at the ecosystem-atmosphere interface is one of the primordial steps to improve our knowledge about the ecosystem carbon budget. The eddy covariance (EC) technique (Aubinet et al., 2000) provides the opportunity to have a direct measure of these fluxes. Sites equipped with EC systems spread around the world (Baldocchi et al., 2001) with, at the present time, more than 400 stations (<http://www-eosdis.ornl.gov/FLUXNET>), some of them have been running continuously for more than 10 years. The EC technique is based on high frequency (10–20 Hz) records of wind speed components, sonic temperature, CO₂ and H₂O concentrations and includes a post processing procedure with several methodological choices (Finnigan et al., 2003). The method requires periods with developed atmospheric turbulent regime (Feigenwinter et al., 2004; Rebmann et al., 2005). For example, during quite nights, the CO₂ produced by the respiration of the ecosystem components can be stored by the canopy air or blown horizontally by advection (Paw et al., 2000) and is not registered by the EC system. For our temperate beech forest site (Hesse, France), some corrections with canopy air storage measurement and selection of the data without advection (Aubinet et al., 2005) are performed but they don't completely erased all the problems as short-term net CO₂ flux fluctuations during night-time (Longdoz et al., 2004) without any biophysical explanation are still observed. The question of the presence of instrumental anomalies, non stationary conditions, footprint outside of our beech forest have then arise to explain these observations. These problems lead to errors and propagation of uncertainties that are able to mask some properties of biophysical processes. The amount of data produced is so large that the visual detection and removing of non adequate data is impossible. The improvement of the EC dataset quality by automatic procedure has become a real challenge for the EC scientific community (Richardson et al., 2006a; Papale et al., 2006).

1 Introduction

Carbon dioxide exchanges between the terrestrial ecosystems and the atmosphere are of major importance for cli-



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Different authors have presented several tests for the selection of the EC data (Vickers and Mahrt, 1997; Foken and Wichura, 1996; Göckede et al., 2004) and several methods to fill the gaps existing in the dataset (Falge et al., 2001; Hui et al., 2004; Ruppert et al., 2006; Moffat et al., 2007). In this study, we combine most of the tests proposed for the CO₂ flux. This innovative grouping is applied to the records from the Hesse site for the full-leaf 2005 season. This period presents some reasonably standard climatic conditions (no extreme events). The duration of the period is short enough to assume relatively stable ecosystem response to environmental factors and long enough to provide a sufficient quantity of data (even after quality tests selection) to analyse these responses. The impact of our relatively complete combination of tests is evaluated by comparison with the datasets including or not including the records incriminated by the tests. The analysis is performed on the relationships between CO₂ fluxes and climatic factors and on the total fluxes accumulated during the full-leaf 2005 season.

2 Material and methods

2.1 Site

All the data used in the present analyses come from an experimental plot located in the state forest of Hesse (48°40'N, 7°04'E, North-east of France). This site belongs to the CarboEurope network. The climate is temperate with 860 mm and 9.3°C for mean annual rainfall and air temperature (mean on 30 years 1974–2003). The stand is composed mainly (90%) of Beech (*Fagus sylvatica*). For the period considered in this paper (full-leaf season from 15 May to 14 October 2005) the trees were 39 years old and 17 m high (mean value), the LAI (5.1 m²m⁻²) and tree density (2916 stem/ha) were relatively low compared to the previous years (mean LAI 7.3 m²m⁻²) because of the thinning performed during the winter 2004–2005. The gentle slope (approximately 3% going down in the Northeast direction) is sufficient to induce advection during the stable nights (Aubinet et al., 2005). The distance between the EC tower and the forest edge varies with wind direction from 390 m to 1610 m. The full-leaf season selected (2005) can be qualified as relatively normal when compared to the mean climate of the 30 previous years. The mean air temperature is slightly lower (16.0–16.4°C) and even if the total amount of precipitation is higher (381–241 mm) the cumulative global radiation is also more important (2957–1846 MJ m⁻²) for 2005. A more detailed description of the site can be found in Granier et al. (2000a, b).

2.2 Flux measurements

The net CO₂ fluxes between the ecosystem and the atmosphere (F_c) were measured with an eddy covariance system composed by a sonic anemometer Solent R3 (Gill Instruments Ltd, Lymington, UK) and an infrared gas analyser Li-

Cor 6262 (Li-Cor Inc., Lincoln, NE, USA). The anemometer measuring the three components of the wind velocity and sonic temperature (u , v , w , T) at 20 Hz is located on a tower at 23.5 m above ground. The IRGA measuring CO₂ and H₂O concentrations at 10 Hz is located at the ground level, analysing the air sucked from a sampling point close to the anemometer with an air flow rate of 6 l min⁻¹. A mass flow controller (Model 5850, Brooks, Veenendaal, Netherlands) controls the airflow. The computer acquires the data with the software EddyMeas (Kolle and Rebmann, 2007). To improve u , v and w data, correction for sonic anemometer angle of attack errors is performed (Nakai et al., 2006). This error becomes significant when the wind vector angle to the horizontal plane is superior to 20° (threshold value depending on the sonic anemometer type). It is provoked by transducers self-sheltering or flow distortion induced by the anemometer frame. For each half-hour, the F_c fluxes are calculated from high frequency w and CO₂ concentration measurements using block averaging operator (Finnigan et al., 2003) and planar fit as coordinates rotation method (Wilczak et al., 2001). Finally, frequency correction applied to F_c follows the procedure proposed by Aubinet et al. (2000).

The net ecosystem exchange (NEE) is obtained by the summation of F_c and change in CO₂ storage in the canopy air (Sc). Sc corresponds to the difference between the total amount of CO₂ below the eddy covariance measurement height, at the beginning and the end of the half-hour. This amount of CO₂ is determined from a profile of concentration estimated from measurements at 6 different heights (22 m, 10.4 m, 5.2 m, 2 m, 0.7 m, 0.2 m). These measurements are performed with an infrared gas analyser Li-Cor 6262 (Li-Cor Inc., Lincoln, NE). For each level, the concentration used for the Sc computation is the average of the values recorded during 10 s after purge. More information about tubing, pumps and filters used are given in Granier et al. (2000b).

2.3 Data check procedure

The eddy covariance data treatment used in this study includes several tests (Fig. 1) to detect flux sampling problems, periods with advection, low climatic stationarity or when flux is coming out of the target forest plot. After removal of periods corresponding to break-down and maintenance of the EC and profile systems, the records are first flagged following Vickers and Mahrt (1997). The objective is to identify abnormalities that may result from instrumental or data recording problems coming from the anemometer or the IRGA (corresponding to hard flag in Vickers and Mahrt). For each half-hour, the tests on high frequency measurements of vertical wind velocity and CO₂ concentration identify first the presence of spikes and flag the half-hour or remove the spikes according to the percentage of presence. After that, flag is activated if unrealistic values or discontinuities of mean or variance are detected. Finally higher-moment statistics (skewness and kurtosis) and standard deviation are computed and

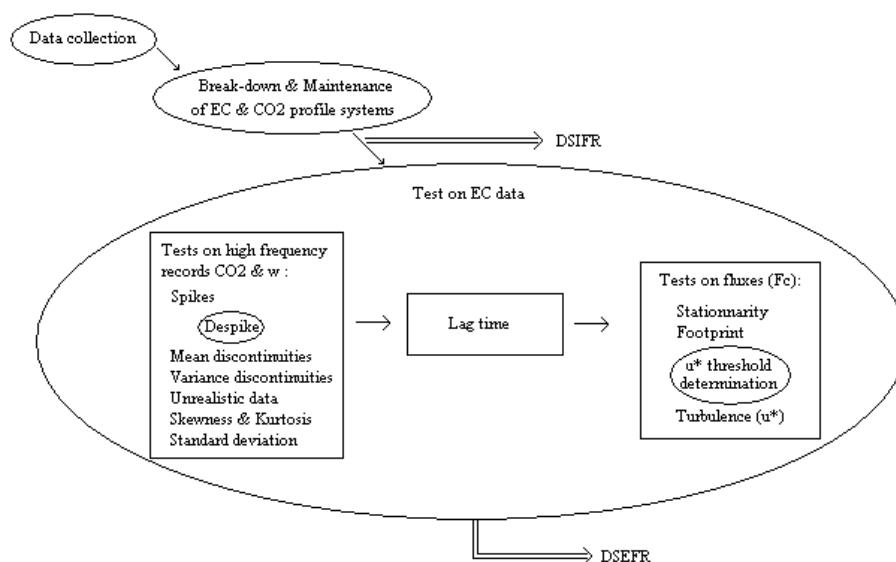


Fig. 1. General scheme of the data check procedure including the different tests applied on the data belonging to the Data Set Including/Excluding Flagged Records (DSIFR/DSEFR).

the half-hour is flagged if one of these parameters is outside of the tolerable range. The criteria to define a spike, an unrealistic value, a discontinuity and a tolerable range for spike percentage, higher-moment statistics and standard deviation are based on threshold values. As proposed by Vickers and Mahrt (1997), the thresholds are empirically adjusted for the Hesse site by inspection of frequency distributions of the parameters tested. The objective is to flag any records with obvious instrument problems. This threshold determination procedure realised for the Hesse 2005 full-leaf season can be illustrated by the choice of upper limit of the tolerable range for the kurtosis of CO₂ concentration (C) data, which is the more selective test (see results section). The upper limit of the kurtosis is set to 7.9 to be sure to flag the half-hour record like the one presented in the Fig. 2a. Indeed, the kurtosis of this half-hour is 8.1 because of few irregularities (too large to be considered as spikes) that happen at regular interval indicating their instrumental origins. This half hour record has to be flagged. Moreover, we have not found any half-hour with a lower kurtosis and presenting apparent instrumental problem. For example, turbulence with varying intensity (Fig. 2b) can explain a kurtosis slightly lower than the threshold (7.7) and should not be flagged. After the thresholds set up, the flag procedure is automatic and contrary to Vickers and Mahrt (1997) all the half-hours flagged have not been individually analysed to verify the origin of the flux-sampling problem. This procedure is not materially feasible when it is applied to large datasets. In consequence it is possible that a few correct fluxes are flagged but this conservative procedure, excluding a maximum of technical anomalies, is preferable.

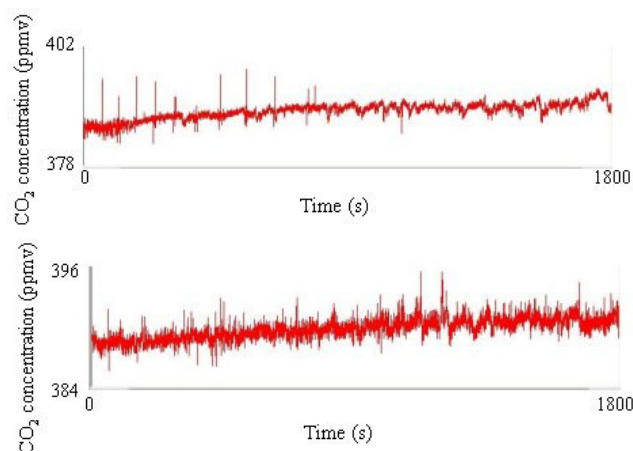


Fig. 2. (a) Example of high frequency records of CO₂ concentration (16 May 18:30 GMT) with instrumental anomalies. (b) Example of high frequency record of CO₂ concentration (18 July 22:00 GMT) with turbulence regime with varying intensity.

The last test to detect instrumental abnormalities is the verification of the airflow rate in the tubing transporting the air from the sampling point (at the top of the tower) to the EC IRGA. This rate is controlled and measured by a mass flow controller (Tylan 261, Tylan Corporation, Torrance, CA, USA). It is set to 61 min⁻¹ leading to a constant time lag of 4.8 s between w and C measurements. The flag is activated when the airflow rate is 10% below or above the desired value. This range is chosen because the post-processing programme is able to correct any deviation of the time lag in this range.

Additional tests do not refer to instrumental abnormalities. The first one check the F_c stationarity following the procedure presented by Foken and Wichura (1996). The F_c value determined for the half-hour period is compared to the mean out of six 5-min F_c from the same period. The flag is activated when the difference between both values (due for example to changing weather conditions) is above 30% so when the F_c data could not be used for fundamental research (Foken et al., 2004). The second test verifies if the footprint area is located in the targeted ecosystem (young beech plots of the Hesse forest). The Schuepp model (Schuepp et al., 1990) modified by Soegaard et al. (2003) determines the F_c footprint area. The record is flagged when more than 10% of F_c is coming from patches located out of Hesse beech forest. The spatial resolution used corresponds to patches delimited by circles centred on the tower with diameters multiples of 50 m and lines passing by the tower and separated from each others by an 5° angle. The forest edge is determined with the Hesse land use map already utilized in Rebmann et al. (2005) and Gockede et al. (2007). The last test confirm if the turbulent regime is developed enough to applied the EC method (u^* test). This u^* has been elaborated because different authors (Staebler et al., 2004; Aubinet et al., 2005) have shown that NEE estimated by summation of F_c and Sc can underestimate CO₂ exchanges during periods with low turbulence (low friction velocity u^*). Night-time $Reco$ measurements clearly highlight this underestimation. At constant temperature, $Reco$ drops down when u^* decreases. This observation has no apparent biophysical explanation. At the Hesse site, additional measurements have proven that some CO₂ emitted during night by the ecosystem components goes out of the forest by horizontal advection when air mixing is limited (Aubinet et al., 2005). This CO₂ is not detected by the eddy covariance or profile concentration measurement systems explaining flux underestimation. We have established a u^* threshold below which $Reco$ is not correctly measured by a two step procedure. In the first step, the temporal variability of $Reco$, mainly due to temperature fluctuations, is determined. Using data during periods without water stress and no flagged by the previous tests, the dependence of $Reco$ on temperature is fitted (regression algorithm presented in the following section) by a Q_{10} relationship (Black et al., 1996):

$$Reco = Reco_{Tref} \cdot Q_{10}^{\left(\frac{T-Tref}{10}\right)} \quad (1)$$

where Q_{10} is the parameter reflecting the temperature sensibility and $Reco_{Tref}$ is the $Reco$ value for a reference temperature ($Tref$). Each half-hour $Reco$ is then divided by $Q_{10}^{\left(\frac{T-Tref}{10}\right)}$ to obtain a value $Reco_s$ that should be relatively constant during non water stressed periods. The second step consists in distributing $Reco_s$ in u^* classes. For each class, we compute $\overline{(Reco_s)}_{cl}$ corresponding to the $Reco_s$ class average, and $\overline{(Reco_s)}_{hi}$ corresponding to the $Reco_s$ averaged on all the data with u^* above the upper limit of the class. The ob-

jective is to detect the classes with a $\overline{(Reco_s)}_{cl}$ significantly ($p < 0.05$) lower than $\overline{(Reco_s)}_{hi}$ (comparison procedure described in Sect. 2.5). Among the latter classes, the one with the higher u^* is selected. The u^* threshold corresponds then to the upper limit of this class.

2.4 Datasets

Two datasets are established both compiling the main micrometeorological variables (global radiation, air and soil temperature, photosynthetic photon flux density, soil water content, air humidity, friction velocity...) and the NEE values for the 7344 half-hours between the 15 May and 14 October 2005. In the first dataset, the gaps in the NEE correspond only to the breakdown and maintenance periods. This dataset is called DSIFR (DataSet Including Flagged Records) in the following (Fig. 1). In the other dataset, in addition, the records flagged by the tests are removed and replaced by gaps (DataSet Excluding Flagged Records, DSEFR, Fig. 1). Two different dataset partitioning are applied during the analysis. The partitioning between night and day is based on global radiation (R_g) with night records corresponding to R_g below 3 Wm^{-2} . During night-time NEE corresponds to ecosystem respiration ($Reco$) and during daytime to the sum of gross primary productivity (GPP) plus $Reco$. The second division aims at isolating the periods without soil water stress for $Reco$. As soil respiration represents usually the major part of $Reco$ (Law et al., 1999; Longdoz et al., 2000) and because Ngao (2005) has demonstrated that soil respiration in the Hesse forest is limited by water depletion when soil water content on the first 10 cm (SWC) is below $0.2 \text{ m}^3 \text{ m}^{-3}$; we have adopted this threshold for the dataset partitioning.

2.5 Statistical analysis and regression

All the statistical analysis and non-linear regressions are performed by Statgraphics Plus software (Statistical Graphics Corp., Herndon, VA, USA). A t-test is used to compare two data samples and determine whether they are significantly different. During the t-test the threshold to consider significant difference is set to $p < 0.05$ and the equality of the two samples variance is assumed. ANOVA (F-test) is used for the multi-groups comparison with the same p threshold value. The non-linear regressions are used to determine the relationship between meteorological variables and fluxes. The algorithm is an iterative procedure, determining the parameters that minimize the residual sum of squares (Marquardt method). For some of the regressions with a single independent variable, it is suitable to reduce the possible impacts of other variables and spatial heterogeneity. Then the regressions are performed with bin-average fluxes where the averages are performed for independent variable classes. The averages are weighted with weights proportional to the reciprocals of the squared standard errors (Murtaugh, 2007).

Table 1. Number of half-hours flagged by the different tests and fraction to the total 2005 full-leaf period (MFC corresponds to mass flow controller). The values given for the three last tests are computed from a dataset where the half-hours flagged by the three first tests on anomalies have been excluded. The total value corresponds to the number of half-hours flagged by at least one test (not equal to the sum because of data flagged by more than one test).

Test	Flag	
	<i>n</i>	%
Anemometer anomalies	117	1.6
CO ₂ IRGA anomalies	2297	31.3
MFC anomalies	5	0.1
Stationarity	898	12.2
Footprint	76	1.0
u^*	903	12.3
Total	4038	55.0

3 Results-discussion

3.1 Tests control results

Among the 7344 half-hours treated, only 2.1% correspond to total breakdown (mainly electricity failure) or maintenance of the EC system and 2.6% to specific maintenance or bad functioning of the profile sampling system. On the remaining *F_c* data (7001 values), flags are activated on 55.0% of the data (4038 half-hours). Consequently, following our procedure 59.7% of the total period is not acceptable in the DSEFR. This is a relatively high percentage but not very surprising in regard to the proportion already presented in the literature. Rebmann et al. (2005) flagged 28% of the Hesse *F_c* for the summer 2000 only with the stationarity test. Even if the flagging procedure is not completely identical, Vickers and Mahrt (1997) flagged during their measurement campaigns one-third of the records with the variance discontinuity test and one-half because of too large kurtosis.

In our procedure, the causes of the *F_c* flags can be divided in six categories: anemometer, CO₂ IRGA and mass flow controller malfunctioning, lack of stationarity, too large footprint and too low u^* . The percentages of *F_c* flags due to each category are presented in the Table 1. The values given for the three last tests are computed from a dataset where the half-hours flagged by the three first tests on anomalies have been excluded. Three tests appear to be highly restrictive: CO₂ IRGA anomalies, u^* and stationarity. The percentage of stationarity flags is lower to that estimated by Rebmann et al. (2005) for the Hesse summer 2000 (28%) but the data were not selected before through the CO₂ anomalies test as here. The sum of all the half-hours flagged by the different tests (4296) exceeds the total value given in the Table 1 (4038) because of multi-flagged data

Table 2. Number of half-hours flagged by the different tests concerning the CO₂ anomalies and fraction to the total 2005 full-leaf period. The total value corresponds to the number of half-hours flagged by at least one test (not equal to the sum because of data flagged by more than one test).

Test	Flag	
	<i>n</i>	%
Spikes	2	0.0
Mean discontinuities	6	0.1
Variance discontinuities	18	0.3
Absolute limits	6	0.1
Skewness	923	12.6
Kurtosis	2197	29.9
Standard deviation	110	1.5
Total	2297	31.3

To go one step further in the analysis and according to the Sect. 2.3, we subdivided the CO₂ IRGA flag into seven tests: spikes, mean discontinuity, variance discontinuity, absolute limits, skewness, kurtosis and standard deviation. The higher percentage of bad data is obtained by the kurtosis test (Table 2) with flags on 29.9% of the total period. This predominance of the flag activation by the kurtosis test has also been observed by Vickers and Mahrt (1997) on their own measurements and comes perhaps from the fact that high moments values are probably affected by intermittent turbulent regime in addition to instrumental anomalies. As for Table 1, the sum of all the half-hours flagged by the different CO₂ IRGA tests (3262) exceeds the total value (2297) because of multi-flagged data. Only two half-hours are flagged by the spike test. Indeed, the sudden variations in the records are often larger than the maximum width of what can be considered as spike (4 points equivalent to 0.4 s). These variations are taken into account in the higher-moment statistics explaining their relatively high percentages of flags.

3.2 Friction velocity thresholds

Before to applied the u^* test, the threshold have to be determined (see Sect. 2.3.). The u^* test will be used to exclude some records only from in DSEFR (Fig. 1) but we have determined the u^* threshold for the two datasets to estimate the impact of all other tests presented here (applied before the u^* one) on this value (for few EC sites the u^* test is used without applying first other tests). Because the Q₁₀ relationship fit depends on the available dataset, the u^* threshold determination procedure is applied separately on DSIFR and DSEFR. The Q₁₀ relationship fit on the *Reco* data (night *NEE*) are performed excluding soil water stress periods (*Reco_s* representing 17% of the total period). The bin-average is used to erase the impact of the *Reco_s* values affected by horizontal advection. We tested soil temperatures at 10 and 5 cm depth as

Table 3. Characteristics of the Q_{10} function fit applied on the DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR) with the bin-average technique. Numbers inside parenthesis are standard errors/confidence interval.

Dataset	Independent variable	$Reco_{10}$ ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Q_{10}	R^2
DSIFR	T_{S10}	3.2 (0.21/0.43)	1.9 (0.26/0.55)	0.55
	T_{S5}	3.4 (0.32/0.67)	1.7 (0.34/0.73)	0.30
DSEFR	T_{S10}	3.6 (0.24/0.50)	1.8 (0.25/0.53)	0.49
	T_{S5}	3.5 (0.30/0.65)	1.9 (0.35/0.74)	0.44

independent variables. The results of these fits are presented in Table 3. The 10 cm depth soil temperature (T_{S10}) is chosen because of its better general aptitude to explain the $Reco$ variations. This is probably due its superior ability to take into account the spatial heterogeneity, because the 10 cm depth soil temperature value is an average of six measurements while the 5 cm temperature is measured with only one sensor. The $(Reco_s)_{cl}$ and $(Reco_s)_{hi}$ (see Sect. 2.3.) are compared for each u^* classes (0.02 m s^{-1} width). Among the classes giving a $(Reco_s)_{cl}$ significantly lower than $(Reco_s)_{hi}$, the one with the higher u^* has 0.09 and 0.11 m s^{-1} as lower and upper limits. This result is valid for the two datasets. For DSIFR, the $(Reco_s)_{cl}$ and $(Reco_s)_{hi}$ of this class are respectively 3.45 and $4.86 \mu\text{mol m}^{-2} \text{s}^{-1}$ (p -value=0.001). For DSEFR, $(Reco_s)_{cl}$ and $(Reco_s)_{hi}$ are 2.85 and $4.21 \mu\text{mol m}^{-2} \text{s}^{-1}$ (p -value=0.0005). Consequently (see Sect. 2.3.), the u^* threshold is set to 0.11 m s^{-1} for the flag determination in DSEFR. This value fully agrees with the one obtained by Papale et al. (2006) for Hesse 2001 and 2002 while the determination method was different (Reichstein et al., 2005). This result suggests that the u^* threshold is relatively constant with time. The u^* filter is apply for both night and daytime and reject respectively 31.3% and 9.0% of the half-hours for a total of 12.3% but a part of these half-hours were already flagged by an other test. Then, when u^* filter is the last test employed, it is responsible of an increase of the gap fraction from 50.3% to 59.7% in DSEFR. This increase is especially large for night-time (from 50.9% to 68.9%) illustrating the presence of advection events.

Even if our conservative way to set the thresholds for the Vickers and Mahrt (1997) instrumental malfunctioning tests can be responsible of a slightly overestimation of the percentage of data removed in DSEFR, it's high value, especially during night-time (68.9%), stresses the importance of the data gap filling method (Moffat et al., 2007).

3.3 Temporal variability of ecosystem respiration

The temporal variability of $Reco$ is usually attributed to temperature and soil water content variation (Carlyle and Ba Than, 1988; Richardson et al., 2006b). To separate the influence of these two environmental factors, the periods without any soil water stress (Sect. 2.4) are selected to analyse

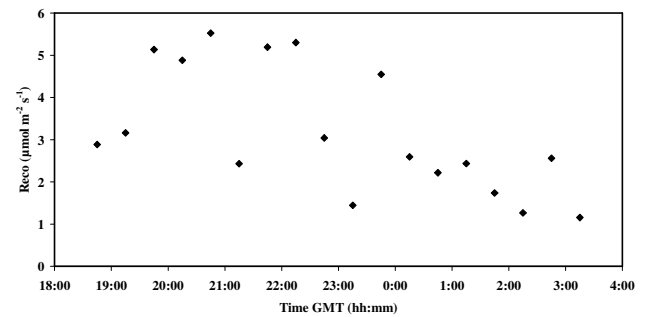


Fig. 3. Time evolution of $Reco$ (with short-term fluctuations) during the night-time between the 5 and 6 August.

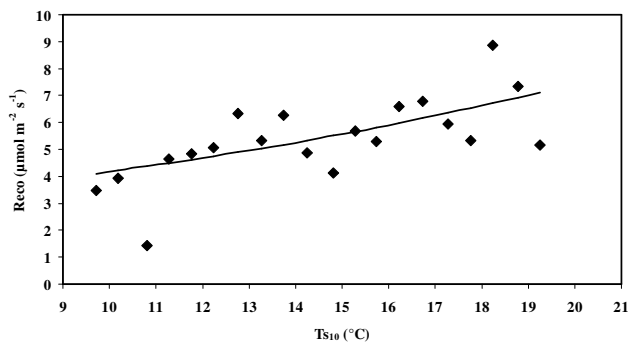
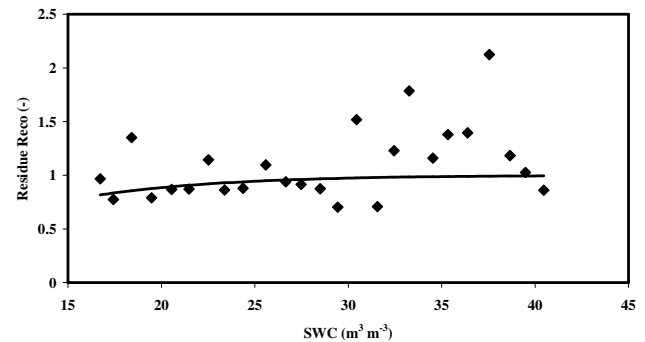
the temperature effect with a Q_{10} function. The regression is performed with T_{S10} as explained above. After computing the residues of this regression on all the $Reco$ values, they are used to simulate SWC impact with a Gompertz function (Janssens et al., 2003) :

$$f(SWC) = \exp(-\exp(a-b \cdot SWC)) \quad f(SWC) = \exp(-\exp(a-b \cdot SWC)) \quad (2)$$

where a and b are two parameters. The $Reco$ complete function (multiplication of the Q_{10} and Gompertz functions) is compared to the data to indicate the degree of temporal variability explained by T_{S10} and SWC . When this procedure is applied on the DSIFR and DSEFR half-hour data, the determination coefficients (r^2) are very low (respectively <0.01 and 0.02). This can reflect the fact that Q_{10} and Gompertz functions are not the perfect parameterisation to simulate ecosystem respiration but this explanation is not sufficient to justify so low r^2 . The other possibility is the existence of factors different from T_{S10} and SWC as major causes of the temporal variability of $Reco$. The time evolution of the microbial population, available soil carbon content or root and aerial biomass can be evoked to explain the temporal variability of $Reco$. However they have too low variations compared to the short-term variations of $Reco$ measurement (Fig. 3). The change in footprint seems to be a more likely candidate as it could happen between two consecutive half-hours. However, this hypothesis implies

Table 4. Characteristics of the Q₁₀ and Gompertz functions fit applied (with bin-average technique) on DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR). Numbers inside parenthesis are standard errors/confidence interval.

Function	Dataset	$Reco_{10}$ ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Q_{10}	R^2
Q ₁₀	DSIFR	3.2 (0.21/0.43)	1.9 (0.26/0.55)	0.55
	DSEFR	4.2 (0.31/0.65)	1.8 (0.28/0.58)	0.45
–	–	a	b	R^2
Gompertz	DSIFR	1.7 (2.65/5.47)	19.0 (14.3/29.6)	0.23
	DSEFR	0.93 (3.2/6.59)	15.1 (16.8/34.8)	0.12

**Fig. 4.** $Reco$ dependence on soil temperature at 10 cm depth. The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Q₁₀ function.**Fig. 5.** Influence of the soil water content (first 10 cm depth) on the residues of the relationship between $Reco$ and Ts_{10} . The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Gompertz function.

a noteworthy ecosystem spatial heterogeneity and it is not apparently the case for the Hesse site that has a reasonably homogenous vegetation type and age. To give some indications about the possible impact of footprint changes on $Reco$ temporal variability, we select measurements for a narrow range of Ts_{10} (from 11.5°C to 12.5°C) and excluding soil water stress period. These measurements are compared according to their provenance from a geographical sector. This comparison cannot completely replace a full analysis combining footprint model and detailed map of soil respiration but this map is not yet available. Moreover, the subdivision in patches with homogeneous soil respiration that would result from this procedure will probably lead, in the DSEFR case, to a too low number of data per patch to investigate the temperature and soil water impact for many patches. Our $Reco$ comparison between the geographical sectors shows differences. The more evident one appears when the East-Southeast sector (wind direction between 75° and 155°) is compared to the sector including the other wind directions. The ecosystem in the East-Southeast sector (mean $Reco=6.01 \mu\text{mol m}^{-2} \text{s}^{-1}$) produces significantly more CO₂ ($p=0.034$) than the ecosystem out of this zone (mean $Reco=3.99 \mu\text{mol m}^{-2} \text{s}^{-1}$). When sectors with 45° width are determined, the ANOVA performed on 5 groups (not enough data between 225°–360°) gives a statis-

tically significant difference between the 5 means ($p=0.029$). The large $Reco$ disparity found with this ANOVA (up to almost $4 \mu\text{mol m}^{-2} \text{s}^{-1}$) has a sufficient order of magnitude to potentially explain many of the short-term $Reco$ variations. One of the possible causes of this heterogeneity could be the soil respiration dependence on carbon to nitrogen content ratio (C/N). Ngao (2005) has demonstrated this dependence but it could be completely incriminated if the soil C/N map (work in progress) shows a spatial heterogeneity in agreement with the results of the geographical sectors analysis.

To overcome the spatial heterogeneity problem in the study of the Ts_{10} and SWC influences on $Reco$, we use the bin-average technique. The bin-averaged Q₁₀ (with $T_{ref}=10^\circ\text{C}$) and Gompertz regressions are presented in Figs. 4 and 5. Bin-average improves clearly the goodness of fit (Table 4) with Ts_{10} being the main explaining factor for $Reco$ temporal variability, as usually found (Richardson et al., 2006b). $Reco_{10}$ (Table 4) are higher than the value for the equivalent parameter found for soil respiration, as expected (Rs_{10} from 1.5 to $2.4 \mu\text{mol m}^{-2} \text{s}^{-1}$, Ngao, 2005) because of the leaves and aerial wood CO₂ production. However, Rs_{10} represents 65% to 36% of the CO₂ sources according to the soil plot investigated. The percentage for the less productive soil plots are low compared to the mean European forests

Table 5. Characteristics of the Michaelis-Menten function fit applied (with bin-average technique) on DataSet Including Flagged Records (DSIFR) and DataSet Excluding Flagged Records (DSEFR). Numbers inside parenthesis are standard errors/confidence interval.

Dataset	α	GPP_{2000}	R^2
DSIFR	-0.052 (0.0022/0.0045)	-22.8 (0.33/0.67)	0.99
DSEFR	-0.072 (0.0053/0.0112)	-24.7 (0.43/0.91)	0.98

value (69%, Janssens et al., 2001) but there are perhaps not representative of fluxes measured by the EC system. Contrary to $Reco_{10}$, the Q_{10} value is lower in our study (Table 4) compared to the Q_{10} estimated for soil (2.55, Ngao, 2005). This is coherent with the contribution of aerial biomass to $Reco$ that includes sources less sensible to T_{s10} than the soil.

The tests filtering does not lead to an increase of the coefficient of determination (it's even a decrease) of the regressions (for the bin-average and simple cases). The moderate validity of the relationships to describe the ecosystem respiration and fill the night gaps in the database implies that any overestimation of data rejection rate during night could lead to an increase of the uncertainty of the $Reco$ (and then NEE) seasonal or annual estimation. In this context, the use of the u^* filter to detect advection events could perhaps be improved (Aubinet et al., 2005; Ruppert et al., 2006). Nevertheless, the fact that the regression curves for DSIFR and DSEFR give differences in $Reco$ that range from 19.8% to 34.4% in the 5°C–20°C T_{s10} interval, proves that the data eliminated by this filtering are not evenly distributed.

3.4 Temporal variability of gross primary productivity and net ecosystem exchange

In the two datasets, the GPP is calculated for daytime half-hours showing valid NEE measurements (91% for DSIFR and 46.7% for DSEFR). For each time step, the $Reco$ simulated with the parameterisation presented in the previous section is subtracted from the NEE measurement to achieve GPP . The existence of two $Reco$ parameter sets (DSIFR and DSEFR) leads to two GPP time series. The main factor influencing GPP is the photosynthetic photon flux density ($PPFD$, $\mu\text{mol m}^{-2} \text{s}^{-1}$). This influence is parameterised with the Michaelis–Menten relationship adapted by Falge et al., (2001):

$$GPP = \frac{\alpha \cdot PPFD}{1 - \frac{PPFD}{2000} + \frac{\alpha \cdot PPFD}{GPP_{2000}}}$$

$$GPP = \frac{\alpha \cdot PPFD}{1} - \frac{PPFD}{2000} + \frac{\alpha \cdot PPFD}{GPP_{2000}} \quad (3)$$

where α is the ecosystem quantum yield ($\mu\text{mol m}^{-2} \text{s}^{-1}$) and GPP_{2000} ($\mu\text{mol m}^{-2} \text{s}^{-1}$) is the GPP for $PPFD$ equals to

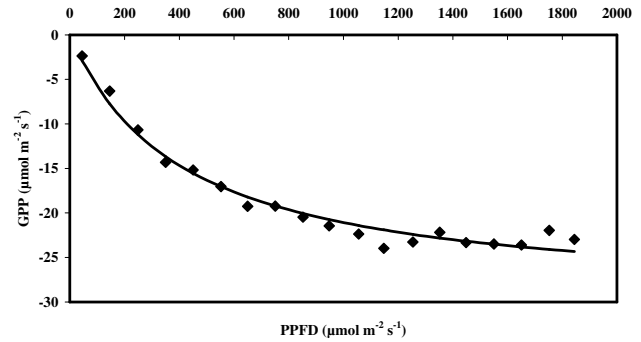


Fig. 6. GPP dependence on photosynthetic photon flux density. The dots correspond to the bin-averaged measurements for DSEFR and the line to the fit with a Michaelis-Menten function.

$2000 \mu\text{mol m}^{-2} \text{s}^{-1}$. The r^2 of the regression of this relationship on half-hours data are 0.57 (DSIFR) and 0.52 (DSEFR), thus much higher than the $Reco$ - T_{s10} ones in the same conditions (<0.01 and 0.02). The lower dispersion of the experimental points around the parameterisation curve is probably due to the lower spatial variability for GPP comparing to soil respiration. This comes from the lower spatial variability in vegetation characteristics comparing to the soil ones. To improve the GPP - $PPFD$ relationship, the bin-average method is also implemented. This allows hiding spatial variability and possible control of other environmental factors like air temperature (T_a) or vapour pressure deficit (VPD). The influence of GPP - $PPFD$ appears then extremely clearly (Fig. 6, Table 5). The residues of this parameterisation don't show any dependence on T_a or VPD . This is not surprising in view of the full-leaf 2005 season climate (relatively humid and temperate). Like for $Reco$, the data selection with the assessment tests do not improve the quality of the regression. This is demonstrated by the a DSEFR r^2 lower than the DSIFR one (Table 5). However, the difference between the parameters obtained with these regressions gives significant variation in GPP between DSIFR and DSEFR cases whatever $PPFD$. The difference ranges from 7.0 to 38.3% when $PPFD$ vary from 2050 to $0 \mu\text{mol m}^{-2} \text{s}^{-1}$. This result suggests that the data eliminated by the filtering possess a common feature.

3.5 Total $Reco$, GPP and NEE

Total $Reco$, GPP and NEE is calculated for the 2005 full-leaf season by summing the half-hour values in the datasets gap filled by their respective own parameterisations presented above. The difference between the values for DSIFR and DSEFR reveals the impact of the test procedure. The test application leads to an increase from 658.0 gC m^{-2} to 816.1 gC m^{-2} for $Reco$ (24.0% of variation, 158.1 gC m^{-2}). Only a minor part of this increase (9.0%, 14.2 gC m^{-2}) comes from the difference between the environmental factors of the gaps of the two datasets. To estimate this percentage, the gaps of

the DSEFR were filled with the parameter set of DSIFR. The rest of the increase is instigated by the change of the parameter sets when the DSEFR are chosen. A similar analysis was performed for the *GPP*. The *GPP* generated by DSIFR and DSEFR are respectively -1246.7 and -1440.6 gC m⁻², therefore they let to an assimilation increase of 193.9 gC m⁻² (15.6%). However, the impact of the environmental factors is larger (27.3%, 52.9 gC m⁻²). For *NEE*, the tests induce a sequestration rise of 35.8 gC m⁻² (6.1%). Comparing to the results for *GPP* and *Reco*, the effect of the environmental factors is higher (98.2%,) because this effect is cumulative when *GPP* is added to *Reco* to obtain *NEE* in opposition with the part induced by the choice of the parameter sets (DSIFR or DSEFR).

It is important to note that the impact of the quality tests on the different CO₂ fluxes have the same order of magnitude than the expected year to year *NEE* and especially *Reco*, and *GPP* variations with regards to the value already published for forests under similar climate (Aubinet et al., 2002; Carrara et al., 2003). Therefore, application of the quality tests is able to strongly influence the inter-annual analysis. This conclusion is still valid even if we do not take into account the data gap filling method, considering that a *NEE* variation of 38.7 gC m⁻² are only a result from the gap characteristics.

4 Conclusions

The different tests presented in this paper are rarely applied, together and systematically, on large datasets. The results for the 2005 Hesse full-leaf season give an overview of their possible contribution. The high percentage of flagged data detected strengthens the importance to continue the work on data selection and data gap filling methods, especially during night. The strict data selection does not modify the u^* threshold.

One of the expected contributions of the quality tests was the reduction of the unexplained short-term *Reco* fluctuations. This was not achieved because of the large spatial heterogeneity of *Reco*. Even for a site with homogeneous vegetation like Hesse, the *Reco* temporal variation analysis should probably be studied from the respiration spatial heterogeneity point of view, before focusing on the data quality. In this context, the way to proceed seems to first apply a footprint model combined with a soil respiration map before to select the data and study the inter-annual variability.

Apparently, the tests have an impact on the dataset properties. On the one hand, the data elimination changes the relationship between the CO₂ fluxes and the environmental factors. On the other hand, the general features of the gaps differ when the quality tests are applied. Consequently, the gap filling by the parameterisations, using the environmental factors as independent variables, produce different *Reco* and *GPP* values for DSIFR and DSEFR. Even if this conclusion should be confirmed with other parameterizations or

model, the total *Reco*, *GPP* and *NEE* for the 2005 full-leaf season vary by respectively 24, 16 and 6%, with more important *GPP*, more CO₂ produced by respiration processes and higher net sequestration when tests are applied. The combination of these tests have the potential ability to influence the inter-annual analysis for the CO₂ fluxes. Their systematic application on large databases like from the CarboEurope and FLUXNET experiments seems necessary.

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References

- Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J. A., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the Annual Net Carbon and Water Exchange of Forest: The EUROFLUX Methodology, *Adv. Ecol. Res.*, 30, 114–173, 2000.
- Aubinet, M., Heinesch, B., and Longdoz, B.: Estimation of the carbon sequestration by a heterogeneous forest: night flux correction heterogeneity of the site and inter-annual variability, *Glob. Change Biol.*, 8, 1053–1071, 2002.
- Aubinet, M., Berbigier, P., Bernhofer, C., Cescatti, A., Feigenwinter, C., Granier, A., Grünwald, T., Havrankova, K., Heinesch, B., Longdoz, B., Marcolla, B., Montagnani, L., and Sedlak, P.: Comparing CO₂ storage and advection conditions at night at different CarboEuroflux sites, *Bound.-Lay. Meteorol.*, 116, 63–94, 2005.
- Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, K. T., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities, *Bull. Am. Meteorol. Soc.*, 82, 2415–2434, 2001.
- Black, T. A., Den Hartog, G., Neumann, H.H., Blanken, P. D., Yang, P. C., Russell, C., Nesic, Z., Lee, X., Chen, S. G., Staebler, R., and Novak, M. D.: Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest, *Glob. Change Biol.*, 2, 219–229, 1996.
- Carlyle, J. C. and Ba Than, U.: Abiotic controls of soil respiration beneath an eighteen-year-old *Pinus radiata* stand in south-eastern Australia, *J. Ecol.* 76, 654–662, 1988.
- Carrara, A., Kowalski, A. S., Neiryneck, J., Janssens I. A., Curiel Yuste, J., and Ceulemans, R.: Net ecosystem CO₂ exchange of mixed forest in Belgium over 5 years, *Agricultural and Forest Meteorology* 119, 209–227, 2003.
- Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N.

- O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, H., Moors, E., Munger, J. W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., and Wofsy, S. C.: Gap filling strategies for defensible annual sums of net ecosystem exchange, *Agric. For. Meteorol.* 107, 43–69, 2001.
- Feigenwinter, C., Bernhofer, C., and Vogt, R.: The influence of advection on the short term CO₂ budget in and above a forest canopy, *Boundary-Layer Meteorol.*, 113, 201–224, 2004.
- Finnigan, J.J., Clements, R., Malhi, Y., Leuning, R., and Cleugh, H.: A re-evaluation of long-term flux measurement techniques. Part I: averaging and coordinate rotation, *Bound.-Lay. Meteorol.*, 107, 1–48, 2003.
- Foken, T. and Wichura, B.: Tools for quality assessment of surface-based flux measurements, *Agric. For. Meteorol.*, 78, 83–105, 1996.
- Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B., and Munger, W.: Post-field data quality control, in: *Handbook of Micrometeorology*, edited by: Lee, X., Massman, W., Law, B. E., Kluwer, Dordrecht, 181–208, 2004.
- Göckede, M., Rebmann, C., and Foken, T.: Use of footprint modelling for the characterisation of complex meteorological flux measurement sites, *Agric Forest Meteorol.*, 127 (3), 175–188, 2004.
- Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J. M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I. A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.-M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M. J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J. F., Valentini, R., Vesala, T., Verbeeck, H., and Yakir, D.: Quality control of CarboEurope flux data - Part I: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, *Biogeosciences*, 5, 433–450, 2008, <http://www.biogeosciences.net/5/433/2008/>.
- Granier, A., Biron, P., and Lemoine, D.: Water balance, transpiration and canopy conductance in two beech stands, *Agric. For. Meteorol.* 100, 291–308, 2000a.
- Granier, A., Ceschia, E., Damesin, C., Dufrêne, E., Epron, D., Gross, P., Lebaube, S., Ledantec, V., Le Goff, N., Lemoine, D., Lucot, E., Ottorini, J. M., Pontailler, J. Y., and Saugier, B.: The carbon balance of a young beech forest, *Funct. Ecol.*, 14, 312–325, 2000b.
- Houghton, R. A., Davidson, E. A., and Woodwell, G. M.: Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance, *Glob. Biogeochem. Cy.* 12, 25–34, 1998.
- Hui, D. F., Wan, S. Q., Su, B., Katul, G., Monson, R., and Luo, Y. Q.: Gap-filling missing data in eddy covariance measurements using multiple imputation (MI) for annual estimations, *Agric. For. Meteorol.*, 121, 93–111, 2004.
- 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, U., 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., and Valentini, R.: Productivity overshadows temperature in determining soil and ecosystem respiration across European forests, *Glob. Change Biol.*, 7(3), 269–278, 2001.
- Janssens, I. A., Dore, S., Epron, D., Lankreijer, H., Buchmann, N., Longdoz, B., Brossaud, J., and Montagnani, L.: Climatic influences on seasonal and spatial differences in soil CO₂ efflux, in: *Fluxes of Carbon*, edited by: R. Valentini, Water and Energy of European Forests, Springer-Verlag, Berlin, 235–253, 2003.
- Kolle, O. and Rebmann, C.: Eddysoft – Documentation of a Software Package to Acquire and Process Eddy Covariance Data, Technical Reports – Max-Planck-Institut für Biogeochemie 10, 88, 2007.
- Law, B. E., Ryan, M. G., and Anthoni, P. M.: Seasonal and annual respiration of a ponderosa pine ecosystem, *Glob. Change Biol.*, 5, 169–182, 1999.
- Longdoz, B., Aubinet, M., and Franois, L. M.: Model of forest carbon sequestration incorporating aerial wood radiative budget, *Agric. For. Meteorol.*, 125, 83–104, 2004.
- Longdoz, B., Yernaux, M., and Aubinet, M.: Soil CO₂ efflux measurements in a mixed forest: impact of chamber disturbances, spatial variability and seasonal evolution, *Glob. Change Biol.*, 6, 907–917, 2000.
- Moffat, A. M., Papale, D., Reichstein, M., Hollinger, D. Y., Richardson, A. D., Barr, A. G., Beckstein, C., Braswell, B. H., Churkina, G., Desai, A. R., Falge, E., Gove, J. H., Heimann, M., Hui, D., Jarvis, A. J., Kattge, J., Noormets, A., and Stauch, V. J.: Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes, *Agric. For. Meteorol.*, 147 (3–4), 209–232, 2007.
- Murtaugh, P. A.: Simplicity and complexity in ecological data analysis, *Ecology*, 88 (1), 56–62, 2007.
- Nakai, T., van der Molen, M. K., Gash, J. H. C., and Kodama, Y.: Correction of sonic anemometer angle of attack errors, *Agricultural and Forest Meteorology*, 136, 19–30, 2006.
- Ngao, J.: Determinism of ecosystem respiration in a beech forest, Ph.D. Thesis, University Henri Poincaré Nancy I, 2005.
- Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., S. Rambal, Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, *Biogeosciences*, 3, 571–583, 2006, <http://www.biogeosciences.net/3/571/2006/>.
- Paw U. K. T., Baldocchi, D. D., Meyers, T. P., and Wilson, K. B.: Correction of eddy-covariance measurements incorporating both advective effects and density fluxes, *Bound.-Lay. Meteorol.*, 97, 487–511, 2000.
- Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., Buchmann, N., Carrara, A., Cescatti, A., Ceulemans, R., Clement, R., Elbers, J. A., Granier, A., Grünwald, T., Guyon, D., Havrankova, K., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, J., Montagnani, L., Moors, E., Nardino, M., Ourcival, J. M., Rambal, S., Rannik, Ü., Rotenberg, E., Sedlak, P., Unterhuber, G., Vesala, T., and Yakir, D.: Quality analysis ap-

- plied on eddy covariance measurements at complex forest sites using footprint modelling, *Theor. Appl. Climatol.*, 80, 121–141, 2005.
- Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havr'ankov'a, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, *Glob. Change Biol.*, 11, 1424–1439, 2005.
- Richardson, A. D., Hollinger, D. Y., Burba, G. G., Davis, K. J., Flanagan, L. B., Katul, G. G., William Munger, J., Ricciuto, D. M., Stoy, P. C., Suyker, A. E., Verma, S. B., and Wofsy, S. C.: A multi-site analysis of random error in tower-based measurements of carbon and energy fluxes, *Agric. Forest Meteorol.*, 136, 1–18, 2006a.
- Richardson, A. D., Braswell, B. H., Hollinger, D. Y., Burman, P., Davidson, E. A., Evans, R. S., Flanagan, L. B., Munger, J. W., Savage, K., Urbanski, S. P., and Wofsy, S. C.: Comparing simple respiration models for eddy flux and dynamic chamber data, *Agric. Forest Meteorol.* 141, 219–234, 2006b.
- Ruppert, J., Mauder, M., Thomas, C., and Lüers, J.: Innovative gap-filling strategy for annual sums of CO₂ net ecosystem exchange, *Agricultural and Forest Meteorology*, 138, 5–18, 2006.
- Schuepp, P.H., Leclerc, M.Y., MacPherson, J.I., and Desjardins, R.L.: Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation, *Bound.-Lay. Meteorol.*, 50, 355–373, 1990.
- Soegaard, H., Jensen, N. O., Boegh, E., Hasager, C. B., Schelde, K., and Thomsen, A.: Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling, *Agricultural and Forest Meteorology*, 114, 153–173, 2003.
- Staebler, R. M. and Fitzjarrald, D. R.: Observing subcanopy CO₂ advection, *Agric. Forest Meteorol.*, 122, 139–156, 2004.
- Vickers, D. and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, *J. Atmos. Oceanic. Tech.*, 14, 512–526, 1997.
- Wilczak, J. M., Oncley, S. P., and Stage, S. A.: Sonic anemometer tilt correction algorithms, *Bound.-Lay. Meteorol.*, 99, 127–150, 2001.