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Uncertainty analysis of eddy covariance CO_2 flux measurements for different EC tower distances using an extended two-tower approach

H. Post, H. J. Hendricks Franssen, A. Graf, M. Schmidt, and H. Vereecken

Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

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Correspondence to: H. Post (h.post@fz-juelich.de)

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Abstract

The use of eddy covariance CO_2 flux measurements in data assimilation and other applications requires an estimate of the random uncertainty. In previous studies, the two-tower approach has yielded robust uncertainty estimates, but care must be taken to meet the often competing requirements of statistical independence (non-overlapping footprints) and ecosystem homogeneity when choosing an appropriate tower distance. The role of the tower distance was investigated with help of a roving station separated between 8 m and 34 km from a permanent EC grassland station. Random uncertainty was estimated for five separation distances with an extended two-tower approach which removed systematic differences of CO_2 fluxes measured at two EC towers. This analysis was made for a dataset where (i) only similar weather conditions at the two sites were included and (ii) an unfiltered one. The extended approach, applied to weather-filtered data for separation distances of 95 m and 173 m gave uncertainty estimates in best correspondence with the independent reference method The introduced correction for systematic flux differences considerably reduced the overestimation of the two-tower based uncertainty of net CO_2 flux measurements, e.g. caused by different environmental conditions at both EC towers. It is concluded that the extension of the two-tower approach can help to receive more reliable uncertainty estimates because systematic differences of measured CO_2 fluxes which are not part of random error are filtered out.

1 Introduction

Eddy covariance (EC) measurements of the CO_2 flux are commonly used to analyze the interactions between terrestrial ecosystems and the atmosphere. This is crucial for the understanding of climate-ecosystem feedbacks as well as for an improved representation of vegetation and related processes (photosynthesis, respiration, transpiration, etc.) in land surface models. EC fluxes are used to evaluate and to improve

BGD

11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

land surface models. Because both model predictions and measurements comprise errors and because measurements are sparse in geographical space, the application of data assimilation and parameter optimization approaches in climate-ecosystem research is increasing (e.g. Braswell et al., 2005; Hill et al., 2012; Kuppel et al., 2012). These approaches allow for an identification of model deficits and can enhance model accuracy. During data assimilation (DA) model estimates are updated or corrected with measurement data that are weighted by the according uncertainty values. Therefore, a reliable uncertainty estimate of the EC measurement data is necessary for DA based studies (Richardson et al., 2008, 2006). Due to the widespread application of land surface models which are often combined with data assimilation and parameter estimation approaches there is a need for reliable EC data uncertainty estimates.

Following the definition in Dragoni et al. (2007) we denote uncertainty as the random error which differs from the systematic error in terms of properties and sources. Systematic errors are considered to remain constant for a given set of environmental conditions. Ideally they can be corrected, but in case of EC measurements this is still limited by either our understanding of various error sources or insufficient background data. Systematic errors arise not only from instrumental calibration and data processing deficits, but also from unmet underlying assumptions about the meteorological conditions (Richardson et al., 2012). As described in Sect. 3.1, a main assumption is, e.g. that turbulence is always well developed in the lowest atmospheric boundary layer and responsible for the mass transport. In case of CO_2 fluxes, nighttime respiration is often underestimated due to low wind velocities conditions and a temperature inversion which hinders the upward carbon dioxide transport (Baldocchi, 2001). Hence, nighttime data are commonly rejected for further analysis (Barr et al., 2006). Besides, the sum of measured energy fluxes (latent heat, sensible heat and ground heat flux) is often found to be 10–30 % smaller than the measured net radiation which refers to an energy closure problem (Foken, 2008; Foken et al., 2006; Wilson et al., 2002). Possible reasons for this energy balance deficit (EBD) are (a) the negligence or incorrect estimation of the energy storage in the canopy and the soil (Kukharets et al., 2000) and (b) the underestimation of turbulent energy fluxes and/or an overestimation of the available energy (Wilson et al., 2002). The latter is closely linked to (c) an omission of low or high frequency turbulent fluxes (Foken, 2008; Wilson et al., 2002) and the situation that (d) land surface heterogeneity can even on flat terrain induce advection (Finnigan, 2008; Foken et al., 2006; Liu et al., 2006; Panin et al., 1998).

Sometimes, measured energy fluxes are corrected for EBD (e.g. Todd et al., 2000; Twine et al., 2000; Hendricks Franssen et al., 2010). Because atmospheric CO_2 transport processes are very similar to those of latent and sensible heat and because their calculation with the eddy covariance method is based on the same physical assumptions, the energy balance closure problem might also result in a systematic underestimation of errors of the CO_2 fluxes (Mauder et al., 2010; Foken, 2008; Wilson et al., 2002). However, the correction of measured CO_2 fluxes with the EBD is not widely accepted, because the connection between energy- and CO_2 deficits has not been firmly proven and depends on the actual reason for the imbalance (Barr et al., 2006; Foken et al., 2006; Wilson et al., 2002). In a comparison of EC and chamber measurements, Graf et al. (2013) found different biases for CO_2 flux and latent heat flux, and only the latter showed some relation to the EBD of the EC systems. Oren et al. (2006) also pointed out that errors related to the EBD do not necessarily translate to errors in measured CO_2 which is supported by findings of Scanlon and Albertson (2001).

After a possible correction of the EC flux data for systematic errors a random error will remain which originates e.g. from instrumentation errors, flux footprint heterogeneity or turbulence sampling errors (Flanagan and Johnson, 2005). The uncertainty cannot be corrected or predicted like systematic errors due to its random character but can be quantified by statistical analysis and characterized by probability distribution functions (Richardson et al., 2012). Errors due to flux footprint heterogeneity are related to the simplifying assumption that the flux footprint originates from one (constant) footprint area within the measurement interval. However, temporal variability of e.g. wind direction, wind speed and atmospheric stability cause temporal variations of the the footprint area. Turbulence sampling errors are related to the fact that turbulence is a highly stochastic process and especially the sampling or not sampling of larger eddies is associated with considerable random fluctuations of fluxes, even if they are already averaged over a 30 min period.

Within the past decade, several approaches have been proposed to quantify the uncertainty of eddy covariance CO_2 flux measurements. With the "two-tower" or "paired tower" approach simultaneous flux measurements of two EC towers are analyzed (Hollinger and Richardson, 2005; Hollinger et al., 2004). For the uncertainty quantification with the two-tower approach, it is necessary that environmental conditions for both towers are nearly identical (Hollinger and Richardson, 2005; Hollinger et al., 2004). However, most eddy covariance sites do not have a nearby second EC tower to provide nearly identical environmental conditions. Therefore, Richardson et al. (2006) introduced the "one-tower" or "24 h differencing" method which is based on the two-tower approach. The main difference is that the uncertainty estimate is based on differences between fluxes measured on subsequent days if environmental conditions were similar on both days. Because most often environmental conditions are not the same on two subsequent days (Liu et al., 2006), the applicability of this method suffers from a lack of data and the random error is overestimated (Dragoni et al., 2007). The model residual approach (Dragoni et al., 2007; Hollinger and Richardson, 2005; Richardson et al., 2008) calculates CO_2 fluxes with a simple model and compares calculated values with measured values. The model residual is attributed to the random measurement error. The method is based on the assumption that the model error is negligible, which is however a very questionable assumption. The instrumental uncertainty contributing to the total random error can be estimated with the random shuffle method (Billesbach, 2011). Finkelstein and Sims (2001) introduced an operational quantification of the instrumental noise and the stochastic error by calculating the auto- and cross-covariances of the measured fluxes. This method was implemented into a standard EC data processing scheme by Mauder et al. (2013). In contrast to the previous approaches this method uses the high-frequency raw-data. The advantage is that a second tower or the utilization of additional tools such as a simple model to estimate the EC measurement

BGD
11, 11943–11983, 2014

uncertainty is no longer required. Hence, the raw-data based uncertainty estimate is not affected by not fulfilled underlying assumptions such as similar environmental conditions or a correct simulation model. However, because many data users do not have access to the raw-data but to processed EC data only, random error estimates by the raw-data based approach are not commonly available. Therefore a two-tower based approach is still of great potential. Important advantages of the two-tower approach are (1) its simplicity and user friendliness, (2) its usability for relatively short non gap-filled time series of several months, and (3) the independence of a model. Given the fact that site specific, adequate uncertainty estimates for eddy covariance data are very important but still often neglected due to a lack of resources, we are aiming to advance the two-tower approach so that it can also be applied if environmental conditions at both eddy covariance towers are not very similar.

The main objectives of this study were (1) to analyze the effect of the EC tower distance on the two-tower based CO_2 flux measurement uncertainty estimate and (2) to extend the two-tower approach with a simple correction term that corrects for systematic differences in CO_2 fluxes measured at the two sites. This extension follows the idea of the extended two-tower approach for the uncertainty estimation of energy fluxes presented in Kessomkiat et al. (2013). The correction step is important for providing a more reliable random error estimate. In correspondence with these objectives we analyzed the following questions: what is an appropriate EC tower distance to get a reliable two-tower based uncertainty estimate? Can the random error be quantified in reasonable manner with the extended two-tower approach, even though environmental conditions at both EC towers are clearly not identical? The total random error estimated with the raw-data based method (Mauder et al., 2013) was used as a reference to evaluate our extended two-tower approach based results.

BGD
11, 11943–11983, 2014

2 Test sites and EC Tower setup

The Rollesbroich test site is an extensively used grassland site, located in the Eifel region of western Germany (Fig. 1). The mean temperature in Rollesbroich is ~ 7.7 °C and the mean precipitation is ~ 1033 mm $year^{-1}$ (Korres et al., 2010). Predominating soil types at the site are Cambisols with a high clay and silt content (Arbeitsgruppe BK50, 2001). The grass species grown in Rollesbroich are mainly ryegrass, particularly perennial ryegrass (lolium perenne) and smooth meadow grass (poa pratensis) (Korres et al., 2010). A permanent eddy covariance tower (EC1) is installed at the Rollesbroich site since May 2011 at a fixed position (Table 1). The measurement height of the sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and the open-path gas analyzer (Li7500, Li-Cor, Lincoln, NE, USA) is 2.6 m above ground. The canopy height in the two target areas of EC1 (Fig. 1) was measured every 1–2 weeks and varied between 0.03 m and 0.88 m during the measurement period. A second EC tower, the roving station (EC2), has been installed at four different distances (8 m, 95 m, 173 m and 20.5 km) from EC1 for time periods ranging between 3 and 7.5 months (Table 1). The EC2 location "Kall-Sistig" 20.5 km north-east of Rollesbroich is another grassland site with similar environmental conditions as Rollesbroich. The vegetation in Kall-Sistig is extensively managed C3 grass, the same as for Rollesbroich. However, the average plant height measured between 14 August and 30 October 2012 was lower (~ 0.15 m) than the respective average for Rollesbroich (~ 0.2 m), which is also true for the plant height measured in May and June 2012 (Kall-Sistig: ~ 0.22 m; Rollesbroich: ~ 0.29 m). As in Rollesbroich, clayey-silty Cambisols are most widespread (Arbeitsgruppe BK50, 2001) The mean temperature for the entire measurement interval in Kall-Sistig (Table 1) measured at the EC station is 11.4 °C and the soil moisture 32 % compared to 11.0 °C and 35 % in Rollesbroich (same time interval for averaging). Additionally a third EC tower was located in Merzenhausen in ~ 34 km distance to EC1 (Fig. 1). Merzenhausen (MH) is an agricultural site, where winter wheat was grown during the measurement period. Both the land use conditions and the average weather conditions differ from

BGD
11, 11943–11983, 2014

those in Rollesbroich and Kall-Sistig. The climate at the lowland site Merzenhausen is comparable to the one in Selhausen in 13 km distance to Merzenhausen, where the mean precipitation is $\sim 690\,\text{mm}\,\text{year}^{-1}$ and the yearly mean temperature $\sim 9.8\,^{\circ}\text{C}$ (Korres et al., 2010). The soils are mainly Luvisols with some patches of Kolluvisols (Arbeitsgruppe BK50, 2001). The measurement devices of EC2 and EC3 are the same as the EC1 devices and were installed in 2.6 m above ground as well. Both, the sonic anemometers and the open-path gas analyzers have been calibrated every 1–3 months thoroughly and consistently. Rollesbroich is part of the TERENO network (Zacharias et al., 2011) and in this regard equipped with multiple measurement devices in addition to the EC towers, such as the wireless sensor network "SoilNet" (Bogena et al., 2009).

3 Data and methods

3.1 The eddy covariance method

The net ecosystem exchange of CO_2 between the land surface and the atmosphere (NEE) can be determined with the eddy covariance method. Eddy covariance stations measure the wind speed in three dimensions and simultaneously the gas concentration with an infrared gas analyzer (Pumpanen et al., 2009) at a temporal resolution of e.g. 10 or 20 Hz. The height of the measurement devices is usually ~ 1.5–3 m at agricultural and grassland sites and > 20 m at forest sites (e.g. Hollinger et al., 2004). In the lowest atmospheric boundary layer close to the land surface turbulent flow predominates. Accordingly, the eddy covariance method determines the turbulent mass transfer assuming that all vertical mass transport within this part of the boundary layer is transported by turbulent flow (so called "eddies"). The EC-method assumes that horizontal divergence of flow and advection are negligible, and therefore the terrain where EC stations are located is ideally flat and the land surface homogeneous (Baldocchi, 2001). A main fundament which allows the utilization of the EC method is the mass

BGD
11, 11943–11983, 2014

conservation principle, which requires the assumption of steady state conditions of the meteorological variables (Baldocchi, 2003).

By sampling both wind speed in three dimensions and the CO_2 concentration over time, the vertical net flux density F of CO_2 [$\text{mmol m}^{-2}\,\text{s}^{-1}$] across the canopy–atmosphere interface can be calculated as a function of the dry air molar density ρ_a, the CO_2 mixing ratio c [mmol m^3] and the vertical wind velocity ϖ (m s^{-1}):

$$F = \overline{\rho_a} \times \overline{\varpi' \times c'} \tag{1}$$

The prime denotes fluctuations around the mean; the bar the average over the measurement interval (e.g. half hour), i.e.:

$$\overline{c' \times \varpi'} = \sum_{k=0}^{n} \frac{\left[\left(\varpi_k - \overline{\varpi}\right)\left(c_k - \overline{c}\right)\right]}{n-1} \tag{2}$$

with n being the number of measurements during the measurement interval.

The CO_2 mixing ratio c is equal to the ratio of the CO_2 molar density ρ_c to the dry air molar density ρ_a, implying the necessity of a correction (Webb et al., 1980) if CO_2 concentration was originally measured per unit volume (as in our case).

NEE is positive if the amount of CO_2 released to the atmosphere via respiration is higher than the amount of CO_2 assimilated during photosynthesis. In contrast, negative NEE values denote a higher CO_2 uptake and a net flux from the atmosphere into the ecosystem.

3.2 EC data processing

The EC raw data were measured with a frequency of 20 Hz and fluxes were calculated for intervals of 30 min. The complete processing of the data was performed with the TK3.1 software (Bayreuth, Department of Micrometeorology, Germany; Mauder and Foken, 2011), using the standardized strategy for EC data calculation and quality assurance presented in detail by Mauder et al., 2013. The strategy includes established

BGD
11, 11943–11983, 2014

EC conversions and corrections such as e.g. correction of spectral loss and correction for density fluctuations (Webb et al., 1980). It includes tests on high frequency data (site specific plausibility limits, statistical spike detection) as well as on processed half hourly fluxes such as stationarity and integral turbulence tests, footprint analysis (Kormann and Meixner, 2001) and uncertainty estimates for final fluxes. All tests lead to a standardized quality flagging with data flagged as high, moderate or low quality data. For this analysis only high and moderate quality data were used, while low quality data were treated as missing values. To avoid introduction of additional uncertainty no gap filling was performed.

3.3 Uncertainty estimation based on the two-tower approach

The two-tower approach (Hollinger and Richardson, 2005; Hollinger et al., 2004; Richardson et al., 2006) defines the random error of NEE eddy covariance measurements as the standard deviation $\sigma(\delta)$ of the difference between the CO_2 fluxes [$\mu mol\, m^{-2}\, s^{-1}$] simultaneously measured at two different EC towers (NEE_1, NEE_2):

$$\sigma(\delta) = \frac{\sigma(NEE_1 - NEE_2)}{\sqrt{2}} \tag{3}$$

Based on Eq. (3) we calculated the two-tower based uncertainty estimates using the NEE_1 data measured at the permanent EC tower in Rollesbroich (EC1) and the NEE_2 data of a second tower which was either the rowing station (EC2) or – in case of the 32 km EC tower distance – another permanent EC tower (EC3, Table 1). For comparison, the measurement uncertainty $\sigma(\delta)$ was calculated separately for each EC tower distance (Table 1) and independently for each of the following schemes:

1. the classical two-tower approach (Hollinger and Richardson, 2005; Hollinger et al., 2004; Richardson et al., 2006)

BGD
11, 11943–11983, 2014

2. the classical two-tower approach including a weather-filter previously applied to the actual uncertainty estimation procedure (conditions of weather filter summarized in Sect. 3.5)

3. the extended two-tower approach with an added correction for systematic flux differences (sfd-correction; Sect. 3.4), without weather-filter

4. the extended two-tower approach with weather-filter

The uncertainty estimate of the two-tower approach is obtained by dividing the NEE data series into several groups ("bins") according to the flux magnitude and then using Eq. (3) to calculate the standard deviation $\sigma(\delta)$ for each group (Richardson et al., 2006). Finally, a linear regression function between the flux magnitude and the standard deviation can be derived. The linear correlation of the uncertainty and the flux magnitude can be explained by the fact that the flux magnitude is a main driving factor for the random error and can explain about 63 % of the variance in the CO_2 flux error as shown in a case study by Richardson et al. (2006). Accordingly, we calculated the standard deviation $\sigma(\delta)$ [$\mu mol\,m^{-2}\,s^{-1}$] based on 12 groups of the CO_2 flux magnitude; six groups for positive and six groups for negative fluxes. Fixed class limits for the flux magnitude would have led to a different number of samples in each group. Separately for positive and negative NEE values, the data were sorted and divided into 6 groups with an equal amount of half hourly data. For each single group the standard deviation $\sigma(\delta)$ was calculated using the single half-hourly flux differences of NEE_1 and NEE_2. The corresponding mean NEE magnitude for each group member was determined by averaging all half-hourly means of NEE_1 and NEE_2 in the respective group. Then, the linear regression equation was derived separately for negative and positive NEE values using the 6 calculated standard deviations $\sigma(\delta)$ and the 6 mean NEE values. This procedure was carried out for each dataset of the five EC tower distances and again for each of the four uncertainty estimation methods so that altogether 20 × 2 linear regression equations were derived. The significance of the correlation between the NEE magnitudes and the standard deviations $\sigma(\delta)$ was tested with the p value determined

BGD
11, 11943–11983, 2014

with the Student's t test based on Pearson's product moment correlation coefficient r. Moreover, the 95 % confidence intervals of the slope and the intercept for each liner regression equation were determined. The linear regression equations were calculated imposing as constraint an intercept ≥ 0, because a negative standard deviation is not possible. With those linear regression equations, the uncertainty for the individual half-hourly NEE measurement values of the permanent EC tower in Rollesbroich (EC1) were estimated using the individual half-hourly NEE_1 values [µmol m^{-2} s^{-1}] as input (x) to calculate the corresponding uncertainty $\sigma(\delta)$ [µmol m^{-2} s^{-1}] (y).

The described calculation of the individual NEE uncertainty values was done for all half hourly NEE data, including those data points that were discarded by the weather filter and/or the sfd-correction. Hence, for each of the four two-tower based uncertainty estimation schemes the same amount of individual NEE uncertainty values was generated In correspondence with the NEE uncertainty datasets generated for the 5 EC tower distances × 4 schemes, 20 mean two-tower approach basedNEE uncertainty estimates for the EC1 station were calculated by averaging the individual half hourly uncertainty values (Table 2). These mean uncertainty estimates were used to evaluate the effect of the EC tower distance as well as the sfd-correction (Sect. 3.4) and the weather-filter (Sect. 3.5) on the two-tower based uncertainty estimation. Even though Hollinger et al. (2004) and Richardson and Hollinger (2005) already pointed out that the two-tower approach assumes similar environmental conditions and non-overlapping footprints, we applied the classical approach for all EC tower distances, even if these basic assumptions were not fulfilled, to allow for a comparison of the results before and after the usage of the weather-filter and the sfd-correction (extended two-tower approach).

3.4 Correction for systematic flux differences (sfd-correction)

The classical two-tower approach (Hollinger and Richardson, 2005; Hollinger et al., 2004; Richardson et al., 2006) is based on the assumption that environmental conditions for both EC towers are identical and flux footprints should not overlap to guar-

BGD
11, 11943–11983, 2014

antee statistical independence. Hollinger and Richardson (2005) use threshold values for three variables (photosynthetically active photon flux density PPFD, temperature and wind speed) to determine whether environmental conditions are equivalent. Independent of this definition, our understanding of "environmental conditions" includes both weather conditions and land surface properties such as soil properties (texture, density, moisture, etc.), plant characteristics (types, height, density, rooting depth, etc.) nutrient availability and fauna (rabbits, earthworms, microorganisms, etc.), which are irregularly distributed and effect respiration and/or photosynthesis. Strictly speaking, if footprints do not overlap 100 %, the assumption of identical environmental conditions is already not fulfilled. When applying a two-tower based approach it is important to assure that systematic differences of the measured fluxes which are partly caused by within site or among site heterogeneity are not attributed to the random error estimate of the measured NEE. Our assumption that even within a site with apparently one uniformly distributed vegetation type (and for very short EC tower distances) land surface heterogeneity can cause significant spatial and temporal variability in measured NEE is e.g. supported by Oren et al. (2006). They found that the spatial variability of ecosystem activity (plants and decomposers) and LAI within a uniform pine plantation contributes to about half of the uncertainty in annual eddy covariance NEE measurements while the other half is attributed to micrometeorological and statistical sampling errors. This elucidates the relevance of considering systematic flux differences caused by within site ecosystem heterogeneity when calculating a two-tower based uncertainty estimate.

The introduced sfd-correction ensures that the random error estimate determined with a two-tower approach does not include systematic flux differences because they are not inherent to the actual random error of the measured NEE at one EC tower station In addition to different land surface properties other factors such as instrumental calibration errors can cause systematic flux differences between two towers. Therefore we extended the classical two-tower approach with a simple correction step for systematic flux differences (sfdcorrection). The reason why systematic flux differences can

BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

statistically be separated quite easily from random differences of the EC flux measurements is their fundamentally different behavior in time: random differences fluctuate highly in time whereas systematic differences tend to be constant over time or show slow variations. The sfd-correction introduced is similar to the second correction step in Kessomkiat et al. (2013, Eq. 6 therein), but adapted to the measured NEE instead of latent and sensible heat fluxes. To define the correction term it was necessary to find a moving averaging interval that is long enough to exclude most of the random error part but short enough to consider daily changes of these systematic flux differences. Twelve hours (including 24 half hourly time steps) were found to be a suitable time interval to calculate the running mean for the sfd-correction term. This period also corresponds well with the coefficient of spatial variation (CV) which Oren et al. (2006) found to be stable after ∼ 7 daytime and ∼ 12 nighttime hours in case of a uniform pine plantation.

For each moving averaging interval, the meanNEE_{12h} of one EC tower (separately for EC1 and EC2) [$\mu mol\,m^{-2}\,s^{-1}$] and the mean CO_2 flux averaged over both EC towers $NEE_{2T_{12h}}$ [$\mu mol\,m^{-2}\,s^{-1}$] were calculated to define the sfdcorrection term which was used to calculate the corrected NEE_{corr} [$\mu mol\,m^{-2}\,s^{-1}$]:

$$NEE_{corr} = \frac{NEE_{2T_{12h}}}{NEE_{12h}} \times NEE \quad (4)$$

NEE is the single half-hourly, processed NEE value [$\mu mol\,m^{-2}\,s^{-1}$] of one EC tower. Only if both NEE data, $NEE_{\text{-EC1-}}$ for the permanent EC1 tower and $NEE_{\text{-EC2-}}$ for the second tower, were available at a particular half hourly time step and if both values were either positive or negative the respective data were included to calculate the sfd-correction term. The correction was done separately for positive and negative fluxes, due to the different sources, properties and magnitudes of the CO_2 flux measurements and different errors for daytime (negative) and nighttime (positive) fluxes (e.g. Goulden et al., 1996; Oren et al., 2006; Wilson et al., 2002). NEE_{corr} was calculated only if at least 50 % of the data for $NEE_{\text{-EC1-}}$ and $NEE_{\text{-EC2-}}$ were available for a particular moving averaging interval. Due to the frequent occurrence of gaps in the data series the amount of available NEE_{corr} values considerably decreased by applying this 50 % criterion. Hence it was not possible to choose a stricter criterion such as 70 % or 90 % data availability. The final sfd-corrected $NEE1_{corr}$ values for EC1 and $NEE2_{corr}$ values for EC2 should not be understood as corrected NEE flux data. They were used only to enhance the two-tower based uncertainty estimation in a way that systematic flux differences which cause an overestimation of the uncertainty are filtered out. Moreover, systematic flux differences at two EC towers are not to be confused with systematic errors, which are independent of the uncertainty estimation method and optimally corrected before the random error is estimated.

3.5 Filter for weather conditions

For larger distances of two EC towers, such as the 20.5 km and 34 km distance in this study, different weather conditions can cause differences of the measured fluxes in addition to the different land surface properties. Some weather variables (e.g. temperature) are following a clear diurnal and annual course and differences in e.g. temperature at two EC towers are therefore relatively constant. This is expected to cause rather systematic differences in the measured NEE which can be captured with the sfd-correction. However, other variables such as wind speed or incoming short wave radiation are spatially and temporally much more variable, for example related to single wind gusts or cloud movement. Differences in the measured fluxes at two EC towers caused by those spatial-temporally highly variable weather variables cannot be captured well with the sfd-correction term due to this "random character". However, a weather filter can account for this because it compares the differences in weather variables at each single time step. Hence, we additionally applied a weather filter to investigate its effect on the two-tower based uncertainty in comparison to the sfd-correction. Some of the most important variables directly affecting the measured fluxes are the photosynthetic active radiation (PAR), the temperature and the wind speed. Those variables were also used in e.g. Hill et al. (2012) and Richardson et al. (2006) as indicators for similar environmental conditions. Accordingly, a filter for different weather conditions was introduced to only include half hourly NEE data, if the weather conditions at the second EC tower are similar to those at the permanent EC1 tower location in Rollesbroich. Following the definition in Richardson et al. (2006), similar weather conditions were assumed to be present if the temperature difference was $< 3\,^{\circ}C$; the difference in wind speed $< 1\,m\,s^{-1}$ and the difference in PPFD $< 75\,\mu mol\,m^{-2}\,s^{-1}$. The weather-filter was applied for each half-hourly time step for both the sfd-corrected dataset as well as for the non-corrected NEE data. As shown e.g. in Tsubo and Walker (2005), the incoming short wave radiation (or solar irradiance SI) and the photosynthetically active radiation (PAR) are linearly correlated. Accordingly SI and PPFD measured at the EC1 station in Rollesbroich were also linearly correlated. Because direct PPFD measurements were not available for all measurement periods, we derived a linear regression equation on the basis of all SI and PPFD data for the permanent EC tower station (EC1). Using this equation, missing PPFD values were estimated if only SI but no PPFD data were available at a certain time step.

3.6 Footprint analysis

The footprint analysis was applied to quantify the percentage footprint overlap of the two EC-stations during the measurement periods. This information was not used to filter the data but to allow for a better understanding of the mean uncertainty estimates for the different scenarios. Using the analytical model of Kormann and Meixner (2001) implemented in the TK3.1 software (Mauder et al., 2013), the cumulative source contribution was quantified separately for two contiguous areas adjacent to the tower. Both contiguous areas (target 1 and target 2; Fig. 1) were covered with grass, but managed by different farmers. The footprints of two halfhourly flux measurements were defined as “overlapping”, if the difference of target 1 between EC1 and EC2 was $< 5\,\%$ and if the difference of target 2 between EC1 und EC2 was also $< 5\,\%$. Using this criterion, the percentage footprints overlap for a certain EC tower distance over the correspond-

BGD
11, 11943–11983, 2014

ing measurement period (Table 1) was calculated by dividing the number of NEE data with overlapping footprints (×100) by the total number of NEE data available for the same measurement period. This implies that the calculated average footprint overlap [%] for a particular EC tower distance is not the total percentage area of footprint overlap but the percentage of time steps CO_2 fluxes originate from nearly the same area (defined by target 1 and target 2).

3.7 Comparison measures

To compare and evaluate the two-tower based uncertainty estimates, we calculated random error estimates based on Mauder et al. (2013) as a reference. This reference method is independent of the two-tower based approach, because data of only one EC tower are used to quantify the random error of the measured fluxes and raw data instead of the processed fluxes are used. The raw-data based random error estimates – the instrumental noise σ_{cov}^{noise} and the stochastic error σ_{cov}^{stoch} – were calculated independently. Generally, the instrument noise σ_{cov}^{noise} was considerably lower than the stochastic error σ_{cov}^{stoch}. The total raw-data based random error σ_{cov} was calculated by adding σ_{cov}^{noise} and σ_{cov}^{stoch} The absolute random error σ_{cov} [μmol m^{-2} s^{-1}] used for the evaluation of the two-tower based random error estimates was calculated by averaging the single raw-data based NEE uncertainty values measured at the permanent EC1 tower in Rollesbroich. In order to be consistent with the two-tower based calculations, exactly the same half hourly time steps of the EC1 data series used for the two-tower based uncertainty estimation were used to calculate the corresponding mean reference values σ_{cov}. As indicator for the performance of the two-tower based uncertainty estimation schemes applied for the five different EC tower distances, the relative difference $\Delta\sigma_{cov}$ [%] of a two-tower based uncertainty value [μmol m^{-2} s^{-1}] and the reference value σ_{cov} [μmol m^{-2} s^{-1}] was calculated:

$$\Delta\sigma_{cov}[\%] = \frac{\sigma(\delta) - \sigma_{cov}}{\sigma_{cov}} \times 100 \tag{5}$$

BGD
11, 11943–11983, 2014

Then, $\Delta\sigma_{cov}$ values were compared for the different EC tower separation distances and two-tower based uncertainty estimation schemes outlined in Sect. 3.3. The performance of the two-tower based uncertainty estimation was considered better if σ_{cov} [%] was smaller.

4 Results

4.1 Classical two-tower based random error estimates

Figures 2 and 3 show the linear regressions of the random error $\sigma(\delta)$ (also referred to as "standard error" or "uncertainty") as function of the NEE magnitude determined with the classical two-tower approach (without sfd-correction) for the different EC tower distances without weather-filter (Fig. 2) and with weather-filter (Fig. 3). The dashed linear regression lines denote that the linear correlation between $\sigma(\delta)$ and NEE is weak ($p > 0.1$), which is in particular true for the positive NEE values measured at 173 m and 20.5 km EC tower distances as well as for the negative NEE values at 20.5 km and 34 km distance. The 95 % confidence intervals of the respective slopes and the intercepts are summarized in the Appendix (A1). Uncertainty estimation with the classical two-tower approach is critical for those larger distances because measured flux differences caused by different environmental conditions at both EC towers can superimpose the random error signal which e.g. originates from instrumental or turbulence sampling errors. This weakens the correlation of the random error and the flux magnitude. This is not surprising since Hollinger et al. (2004) and Richardson and Hollinger (2005) already pointed out that similar environmental conditions are a basic assumption of the two-tower approach. Therefore, statements of how the weather filter affects the mean uncertainty estimate $\sigma(\delta)$ for those large distances need to be treated with caution. The weather-filtering only increased the correlation between the flux magnitude and the random error $\sigma(\delta)$ for positive fluxes for separation distances of 173 m and 20 km whereas in most cases the linear correlation was weakened, mainly due

BGD
11, 11943–11983, 2014

to a decreased number of samples in each averaging group of the NEE flux magnitude. Therefore, testing stricter weather-filter criteria (e.g. wind speed $< 0.5\,\mathrm{m\,s^{-1}}$, PPFD $< 50\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$, $T < 2\,^{\circ}\mathrm{C}$) which caused a decline of samples in each group from $n > 1000$ to 24 or less, resulted in an even weaker correlation of the flux magnitude and the random error $\sigma(\delta)$.

As illustrated in Table 2, the mean NEE uncertainty estimate based on the classical two-tower approach increased as a function of EC tower distance. However, without applying the weather-filter the mean uncertainty $\sigma(\delta)$ was nearly identical for the two largest distances (20.5 km and 34 km), although e.g. the land cover and management in Merzenhausen (EC3 tower at 34 km separation) were different to the Rollesbroich site. As a result of the weather-filtering, the mean uncertainty estimate decreased for the distances 173 m (by 10.8 %) and 20.5 km (by 13.6 %). However, for the 95 m and 34 km distance, the mean uncertainty estimate increased by the weather-filtering by up to 15 % (95 m). This implies that for the classical two-tower approach (without sfd-correction) weather-filtering did not clearly reduce the overestimation of the uncertainty for largest EC tower distances (20.5 km and 34 km) where weather-filtering is expected to be particularly relevant.

Comparing the mean uncertainty estimates determined with the classical two-tower approach without weather filter ($\sigma(\delta)$) and with weather filter ($\sigma(\delta)_f$) with the reference random error estimates σ_{cov} (Table 2) indicates that $\sigma(\delta)$ and $\sigma(\delta)_f$ were overestimated for each of the five EC tower differences. This could be expected for the large distances, because basic assumptions for the application of the classical two-tower approach are violated for these large distances. But results illustrate that even for short EC tower distances the classical two-tower approach results in an overestimation of the NEE uncertainty compared to the raw-data based approach (Table 2).

4.2 Extended two-tower approach

The scatter plots in Fig. 6 illustrate the effect the sfd-correction (Eq. 4) had on the difference of the NEE data simultaneously measured at both EC towers ($\mathrm{NEE_{\text{-}EC1\text{-}}}$ and

NEE_{-EC2-}). The sfd-correction reduced the bias and scattering, because systematic differences of the measured fluxes, e.g. induced by different environmental conditions, were removed. As expected, the effect of the sfd-correction was considerably higher for the larger EC tower distances because environmental conditions are also expected to differ more if the distance of two locations is larger. For the 8 m EC tower distance for instance, the effect of the sfd-correction is very minor because footprints are often nearly overlapping. However, for the EC tower distances ≥ 173 m, the bias and scattering of NEE_{-EC1-} and NEE_{-EC2-} was considerably reduced by the sfd-correction.

A comparison of Figs. 2 and 4 illustrates how the sfd-correction affected the linear regression of the NEE standard error as function of NEE flux magnitude: the sfd-correction considerably improved the correlation of NEE_{corr} and the standard error $\sigma(\delta)_{corr}$ for the EC tower distances 20.5 km and 34 km from $R^2 \geq 0.15$ to $R^2 \geq 0.79$ (with $p \leq 0.05$).

Applying the sfd-correction (without weather-filter) reduced the mean uncertainty value by 36.7 % for the 8 m distance, 48.4 % for the 95 m distance, 48.7 % for the 173 m, 47 % for the 20.5 km distance, and 54.2 % for the 34 km EC tower distance. Comparing the relative differences $\Delta\sigma_{cov}$ (Eq. 5) of the mean two-tower based uncertainty estimates and the raw-data based reference value σ_{cov} (Table 2) indicates that the correction for systematic flux differences considerably improved the two-tower based uncertainty estimate: as Table 2 shows, the difference $\Delta\sigma_{cov}$ of the independent uncertainty estimates $\sigma(\delta)_{corr}$ and σ_{cov} was notably smaller (≤ 49.6 %) for all distances except the 8 m distance compared to $\Delta\sigma_{cov}$ between σ_{cov} and the uncertainty estimate $\sigma(\delta)$ determined with the classical two-tower approach (≤ 249.1 %). The most considerable improvement was achieved for the 95 m EC tower distance ($\Delta\sigma_{cov}$ = 101.4 % before and −2.6 % after sfd-correction) and the 173 m distance ($\Delta\sigma_{cov}$ = 87.7 % before and −1.7 % after sfd-correction). Additional application of the weather-filter (Fig. 5) on the sfd-corrected NEE_{corr} data reduced the mean uncertainty estimate $\sigma(\delta)_{corr}$ by 11.0 % for the 20.5 km EC tower distance and by 6.4 % for the 34 km distance and improved the uncertainty estimates by 33.3 % and 17 % compared to $\Delta\sigma_{cov}$ without

BGD
11, 11943–11983, 2014

the weather filter applied. The effect of the weather-filter on the uncertainty estimates of the shorter EC tower distances was very minor (Table 2). As shown in Table 2 the uncertainty estimates $\sigma(\delta)_{corr,\,f}$ determined with the extended two-tower approach are nearly identical to the independent reference values σ_{cov} for the EC tower distances 95 m and 173 m suggesting that those distances were most suitable for the application of the extended two-tower approach. The NEE uncertainty $\sigma(\delta)_{corr,\,f}$ estimated for the grassland site Rollesbroich agree well with the NEE uncertainty values for grassland sites by Richardson et al. (2006), ranging between ~ 0.2 µmol CO_2 m^{-2} s^{-1} in winter months and ~ 1 µmol CO_2 m^{-2} s^{-1} in summer months.

4.3 Discussion

The results show that the two-tower based uncertainty estimates (both classical and extended two-tower approach) were smallest for the 8 m distance. This can be explained with the results of the footprint analysis: while the percentage footprint overlap is 20.4 % for the 95 m EC tower distance and only 0.9 % for the 173 m EC tower distance, it is 61.2 % for the 8 m EC tower distance. The more frequent overlapping of the 8 m distance footprint areas is associated with a more frequent sampling of the same eddies. As a consequence part of the random error was not captured with the two-tower approach. If EC towers are located very close to each other (< 10 m) and the footprint overlap approaches 100 %, only instrumental errors and stochasticity related sampling of small eddies will be captured with the two-tower based uncertainty estimate. Because the EC measurements are statistically not independent if the footprints are overlapping, the classical EC tower method is not expected to give reliable uncertainty estimates for very short EC tower distances (Hollinger and Richardson, 2005; Hollinger et al., 2004). However, without applying the sfd-correction, the mean uncertainty estimate $\sigma(\delta)$ was still higher than the raw-data based reference value which includes both the instrumental noise σ_{cov}^{noise} and the stochastic error σ_{cov}^{stoch}. The raw-data based instrumental noise σ_{cov}^{noise} itself was only 0.04 µmol m^{-2} s^{-1}

BGD
11, 11943–11983, 2014

of 0.69 µmol m^{-2} s^{-1} ($\sigma_{cov}^{noise} + \sigma_{cov}^{stoch}$) for the dataset of the 8 m EC tower distance. The mean uncertainty value derived with the classical two-tower approach for the same dataset was 0.76 µmol m^{-2} s^{-1} and thus higher than σ_{cov}^{noise} suggesting that even at 8 m EC tower distance instrumentation errors were only a minor part of the two-tower based uncertainty estimate. This is in correspondence with the result that the sfd-corrected uncertainty estimate was lower than the reference for the 8 m distance (Table 2).

For the larger separation distances 95 m or 173 m, footprints were notably less overlapping and turbulence sampling errors are almost fully accounted for by a two-tower approach. (It should be noted that forest stations, with a typically larger aerodynamic measurement height and footprint size, will require larger separation distances.) However, different land surface properties and management are more likely for the larger separation distances and can cause systematic flux differences that should not be attributed to the random error estimate. The effect of within site heterogeneity of land surface properties on the spatial and temporal variability in measured NEE and how it contributes to the uncertainty in annual NEE measurements is e.g. shown in Oren et al. (2006). Different information and data were available showing that land surface properties are spatially heterogeneous distributed at the Rollesbroich site: (1) single fields at the Rollesbroich site including the two target areas (Sect. 3.6) are managed by different farmers. Information the land owners provided, as well as periodic camera shots and grass height measurements around the EC towers indicated that the timing of fertilization and grass cutting as well as the amount of manure applied varied between the single fields (and the two target areas of the footprint analysis) during the measurement period, (2) soil type distribution as displayed in the German soil map shows heterogeneity (Arbeitsgruppe BK50, 2001), (3) soil carbon and nitrogen pools [g kg^{-1}] as well as bulk density [g cm^{-3}] and skeleton fraction [%] measured from April–May 2011 in 3 layers at 94 locations across the Rollesbroich site are spatially highly variable (H. Schiedung, personal communication, 2013), (4) during the eddy covariance measurement period, soil moisture and soil temperature data were collected in 10 min. resolution in 3 depths (5 cm, 10 cm and 20 cm) at 84 points by the wireless

BGD
11, 11943–11983, 2014

sensor network ("SoilNet"; Bogena et al., 2009), calibrated for the Rollesbroich site by Qu et al. (2013). This data shows that both soil moisture and soil temperature are heterogeneous within the site (Qu et al., 2014). The effect of soil moisture, soil temperature and soil properties on CO_2 fluxes (respiration mainly) is well known (e.g. Herbst et al., 2009; Flanagan and Johnson, 2005; Xu et al., 2004; Lloyd and Taylor, 1994; Orchard and Cook, 1983) as well as the role of grassland management (e.g. Allard et al., 2007). It is expected that systematic differences in measured NEE caused by those spatial variable land surface properties are stronger during night than during day since they affect respiration more directly than photosynthesis which also agrees with the findings in Oren et al. (2006). However, since our focus was on estimating the total uncertainty of measured NEE and since it is expected that the sfd-correction also captures systematic differences in weather conditions (e.g. temperature, solar radiation) that strongly determine the magnitude of carbon uptake during day, we did not distinguish between the uncertainty of daytime and nighttime data. At very large EC tower distances (20.5 km, 34 km) footprints were not overlapping and the environmental conditions were considerably different; in particular for the EC tower setup Rollesbroich/Merzenhausen with different land use (grassland/crop) and climate conditions (Sect. 2). For those distances, the relative difference $\Delta\sigma_{cov}$ between the reference value σ_{cov} and $\sigma(\delta)$ (classical two-tower approach) was much larger than for the relative difference $\Delta\sigma_{cov}$ between σ_{cov} and $\sigma(\delta)_{corr,\,f}$ (extended two-tower approach). The uncertainty estimate improved by 80 % for the 20.5 km distance and 82 % for the 34 km if both sfd-correction and weather filter were used. However, after applying the sfd-correction and the weather-filtering, the mean uncertainty estimate for the large EC tower distances was still 33.2 % and 49.6 % higher than the raw-data based reference value (Table 2) suggesting that these large EC tower distances were less suitable for estimating the NEE uncertainty on the basis of the extended two-tower approach compared to the 95 m and 173 m distance. The absolute corrected and weather-filtered uncertainty value $\sigma(\delta)_{corr,\,f}$ [μmol m^{-2} s^{-1}] was slightly lower for the 34 km EC tower distance than for the 20.5 km EC tower distance (Table 2), which is counterintuitive.

BGD
11, 11943–11983, 2014

The raw-data based reference value σ_{cov} [µmol m^{-2} s^{-1}] however was also smaller for the 34 km dataset than for the 20.5 km dataset which can be related to the different lengths and timing (i.e., different seasons) of the measurement periods for each of the five EC tower distances: the roving station was moved from one distance to another within the entire measurement period of ~ 27 months. During this entire time period of data collection, the length and timing of the single measurement periods varied for the five EC tower separation distances (Table 1). This is not optimal because the random error is directly related to the flux magnitude and the flux magnitude itself is directly related to the timing of the measurements. Because in spring and summer flux magnitudes are higher, the random error is generally higher as well (Richardson et al., 2006). To reduce this effect, we captured spring/summer as well as autumn/winter months in each measurement period (Table 1). However, the timing of the measurements and the amount of data available were not the same for the five EC datasets In particular the permanent EC tower in Merzenhausen (EC3 in 34 km distance to EC1) was measuring considerably longer (> 2 years) than the roving station did for the other four EC tower distances. Therefore, differences of the mean uncertainty estimates for the five measurement periods were partly independent of the EC tower distance. This effect gets obvious when looking at the mean uncertainties σ_{cov} estimated with the reference method, which should be independent of the distance but were also found to be different for each dataset of the five EC tower distances. Against this background, statements about how EC tower distances affect the two-tower based uncertainty estimate need to be treated with caution.

Another point that should be emphasized is that there is an uncertainty in mean NEE values of the 12 h moving averaging intervals which were used to calculate the sfd-correction term (Sect. 3.4). As mentioned the moving averaging interval should be long enough to exclude random differences of the simultaneously measured fluxes but short enough to limit the impact of non-stationary conditions. However, the 12 h running mean NEE_1 and NEE_2 values (NEE_{12h}) as well as the respective means of NEE_1 and NEE_2 ($NEE_{2T_{12h}}$) used to calculate NEE_{corr} (Eq. 4) are uncertain because

BGD
11, 11943–11983, 2014
Uncertainty analysis of eddy covariance CO_2 flux measurements
H. Post et al.

they still contain the random error part that cannot be corrected or filtered out. Therefore, completely correcting the difference in mean NEE slightly overcorrects systematic differences in NEE.

In general, the weather-filter did not improve the uncertainty estimates as much as the sfd-correction. However, this does not imply that differences in weather conditions are negligible when applying the extended two-tower approach for larger EC tower distances In fact the systematic part of measured EC flux differences between both towers caused by (steady, systematic) among-site differences in weather conditions were already partly captured with the sfd-correction. In contrast such systematic differences were difficult to capture with the weather-filter because it was not possible to define weather-filter criteria that allow the assumption of data similarity without reducing the dataset too much for further meaningful analysis.

5 Conclusions

When estimating the uncertainty of eddy covariance net CO_2 flux (NEE) measurements with a two-tower based approach it is important to consider that the basic assumptions of identical environmental conditions (including weather conditions and land surface properties) on the one hand and non-overlapping footprints on the other hand are contradicting and impossible to fulfill. If the two EC towers are located in a distance large enough to ensure non overlapping footprints, different environmental conditions at both EC towers can cause systematic differences of the simultaneously measured fluxes that should not be included in the uncertainty estimate. This study for the grassland site Rollesbroich in Germany showed that the extended two-tower approach which includes a correction for systematic flux differences (sfd-correction) can be used to derive more reliable (less overestimated) uncertainty estimates compared to the classical two-tower approach. An advantage of this extended two-tower approach is its simplicity and the fact that there is no need to quantify the differences in environmental conditions (which is usually not possible due to a lack of data). Comparing the uncertainty estimates for

BGD
11, 11943–11983, 2014

five different EC tower distances showed that the mean uncertainty estimated with our extended two-tower approach for the 95 m and 173 m distances were nearly identical to the random error estimated with the raw-data based reference method. This suggests that these distances were most appropriate for the application of the extended two-tower approach in this study. Also for the largest EC tower distances (20.5 km, 34 km) the sfd-correction significantly improved the correlations of the flux magnitude and the random error and significantly reduced the difference to the independent, raw data based reference value. We therefore conclude that if no second EC tower is available at a closer distance (but available further away), a rough, typically overestimated NEE uncertainty estimate can be acquired with the extended two-tower approach even although environmental conditions at the two sites are not identical.

A statement about the transferability of our experiment to other sites and EC tower distances requires further experiments. However, we assume transferability is given if both EC towers are located at sites of the same vegetation type (e.g. C3-grasses, C4-crops, deciduous forest, coniferous forest, etc.). Flux differences caused by a different phenology can be very hard to separate from the random error estimate, even though they are expected to be mainly systematic and could therefore be partly captured with the sfd-correction. Moreover, the EC raw data should be processed in the same way (as done here) and the measurement devices should be identical and installed at about the same measurement height. Important is also that the instruments are calibrated thoroughly and consistently Because this was true for the three EC towers included in this study (Table 1, Sect. 2), we conclude that systematic flux differences that are corrected for with the sfd-correction arise mainly from different environmental conditions whereas calibration errors are assumed to have a very minor effect. If those prerequisites are not given, it is very difficult to distinguish and quantify sources of measured flux differences and get reliable uncertainty estimates based on the two-tower approach. Different weather conditions at both EC tower sites are a main drawback for two-tower approach applications. While systematic differences of the weather conditions are expected to be captured by the sfd-correction, less systematic weather fluctuations e.g.

BGD
11, 11943–11983, 2014

related to cloud movement, are difficult to be filtered of the two-tower based uncertainty estimate. Applying very strict thresholds is good in theory but can in practice lead to a reduction of the data in a way that afterwards it often cannot be applied for further statistical analysis. This is in particular problematic if the measurement periods are short as in this study. If EC raw data is available we recommend to use an uncertainty estimation scheme like the one presented in Mauder et al. (2013).

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BGD
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BGD
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BGD
11, 11943–11983, 2014

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BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

Table 1. Measurement periods and locations of the permanent EC towers in Rollesbroich (EC1) and Merzenhausen (EC3) and the roving station (EC2).

	Coordinates	Sitename	Distance to EC1	Measurement period	alt. (m)
EC1	50.6219142° N/6.3041256° E	Rollesbroich	–	13 May 2011–15 Jul 2013	514.7
EC2	50.6219012° N/6.3040107° E 50.6219012° N/6.3040107° E	Rollesbroich	8 m	29 Jul 2011–6 Oct 2011 5 Mar 2013–15 May 2013	514.8
	50.6217990° N/6.3027962° E 50.6210472° N/6.3042120° E	Rollesbroich	95 m	7 Oct 2011–15 May 2012 1 Jul 2013–15 Jul 2013	516.3 517.3
	50.6217290° N/6.3016925° E	Rollesbroich	173 m	24 May 2012–14 Aug 2012	517.1
	50.5027500° N/6.5254170° E	Kall-Sistig	20.5 km	14 Aug 2012–1 Nov 2012 15 May 2013–1 Jul 2013	498.0
EC3	50.9297879° N/6.2969924° E	Merzenhausen	34 km	10 May 2011–16 Jul 2013	93.3

BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

Table 2. Mean NEE uncertainty [µmol m^{-2} s^{-1}] for five EC tower distances estimated with the classical two-tower approach, with and without including a weather-filter ($\sigma(\delta)$, $\sigma(\delta)_f$). and with the extended two-tower approach (sfd-correction), also with and without including a weather-filter ($\sigma(\delta)_{corr}$, $\sigma(\delta)_{corr,\,f}$). The table also provides the random error σ_{cov} [µmol m^{-2} s^{-1}] estimated with the raw-data based reference method (Mauder et al., 2013).

EC tower distance	N	$\sigma(\delta)$ ($\Delta\sigma_{cov}$)	$\sigma(\delta)_f$ ($\Delta\sigma_{cov}$)	$\sigma(\delta)_{corr}$ ($\Delta\sigma_{cov}$)	$\sigma(\delta)_{corr,\,f}$ ($\Delta\sigma_{cov}$)	σ_{cov}
8 m	3167	0.76 (10.9)	0.77 (12.4)	0.48 (−29.8)	0.49 (−28.1)	0.69
95 m	3620	1.30 (101.4)	1.50 (131.8)	0.67 (3.9)	0.63 (−2.6)	0.65
173 m	2410	2.04 (87.7)	1.82 (67.4)	1.05 (−3.7)	1.07 (−1.7)	1.09
20.5 km	2574	2.72 (182.4)	2.35 (144.1)	1.44 (49.6)	1.28 (33.2)	0.96
34 km	15 571	2.73 (249.1)	2.86 (265.5)	1.25 (59.8)	1.17 (49.6)	0.78
mean		1.91	1.86	0.98	0.93	0.83

($\Delta\sigma_{cov}$): relative differences [%] between two-tower based uncertainty estimates and the references value σ_{cov} (Eq. 5).

BGD
11, 11943–11983, 2014

Table A1. Summary of the 95 % confidence intervals for the linear regression coefficients between the 6 average NEE magnitudes and the 6 corresponding standard errors determined with Eq. (3) as described in Sect. 3.3 for the 4 two two-tower based correction schemes and the 5 EC tower distances.

Variables:	Two towers:	m	m_{lower}	m_{upper}	b	b_{lower}	b_{upper}
$NEE_{negative}/\sigma(\delta)$	EC1/EC2 (8 m)	−0.012	−0.041	0.017	0.691	0.442	0.940
	EC1/EC2 (95 m)	−0.045	−0.099	0.010	1.163	0.680	1.647
	EC1/EC2 (173 m)	−0.052	−0.067	−0.036	1.747	1.537	1.957
	EC1/EC2 (20.5 km)	−0.088	−0.272	0.097	2.544	0.696	4.392
	EC1/EC3 (34 km)	−0.130	−0.330	0.069	2.849	0.772	4.926
$NEE_{negative}/\sigma(\delta)_f$	EC1/EC2 (8 m)	−0.008	−0.043	0.026	0.746	0.497	0.995
	EC1/EC2 (95 m)	−0.005	−0.036	0.026	1.569	1.286	1.853
	EC1/EC2 (173 m)	−0.055	−0.088	−0.021	1.416	1.009	1.824
	EC1/EC2 (20.5 km)	−0.011	−0.087	0.066	2.606	1.929	3.284
	EC1/EC3 (34 km)	−0.039	−0.190	0.113	3.527	1.737	5.317
$NEE_{negative}/\sigma(\delta)_{corr}$	EC1/EC2 (8 m)	−0.039	−0.054	−0.025	0.237	0.102	0.372
	EC1/EC2 (95 m)	−0.045	−0.080	−0.010	0.663	0.305	1.021
	EC1/EC2 (173 m)	−0.053	−0.078	−0.028	0.484	0.108	0.860
	EC1/EC2 (20.5 km)	−0.098	−0.130	−0.066	0.867	0.501	1.233
	EC1/EC3 (34 km)	−0.097	−0.140	−0.054	1.000	0.399	1.602
$NEE_{negative}/\sigma(\delta)_{corr,f}$	EC1/EC2 (8 m)	−0.039	−0.061	−0.017	0.254	0.082	0.427
	EC1/EC2 (95 m)	−0.040	−0.067	−0.014	0.617	0.350	0.883
	EC1/EC2 (173 m)	−0.064	−0.118	−0.009	0.391	−0.343	1.125
	EC1/EC2 (20.5 km)	−0.096	−0.138	−0.055	0.722	0.287	1.157
	EC1/EC3 (34 km)	−0.073	−0.120	−0.026	0.927	0.206	1.647
$NEE_{positive}/\sigma(\delta)$	EC1/EC2 (8 m)	0.101	0.027	0.174	0.346	−0.024	0.715
	EC1/EC2 (95 m)	0.161	0.028	0.294	0.734	0.285	1.183
	EC1/EC2 (173 m)	0.061	−0.284	0.406	1.340	−0.775	3.455
	EC1/EC2 (20.5 km)	0.118	−0.272	0.507	1.332	−0.500	3.164
	EC1/EC3 (34 km)	0.235	0.113	0.356	0.731	0.323	1.140
$NEE_{positive}/\sigma(\delta)_f$	EC1/EC2 (8 m)	0.101	0.020	0.182	0.340	−0.080	0.760
	EC1/EC2 (95 m)	0.029	−0.299	0.357	1.333	−0.114	2.780
	EC1/EC2 (173 m)	0.179	−0.122	0.480	0.535	−1.316	2.385
	EC1/EC2 (20.5 km)	0.145	−0.174	0.464	1.134	−0.365	2.632
	EC1/EC3 (34 km)	0.320	0.059	0.580	0.763	−0.330	1.857
$NEE_{positive}/\sigma(\delta)_{corr}$	EC1/EC2 (8 m)	0.085	0.048	0.122	0.123	−0.072	0.317
	EC1/EC2 (95 m)	0.103	0.090	0.116	0.149	0.105	0.193
	EC1/EC2 (173 m)	0.178	−0.061	0.418	−0.037	−1.619	1.545
	EC1/EC2 (20.5 km)	0.222	0.061	0.382	−0.168	−0.985	0.650
	EC1/EC3 (34 km)	0.164	0.135	0.193	0.145	0.045	0.245
$NEE_{positive}/\sigma(\delta)_{corr,f}$	EC1/EC2 (8 m)	0.080	0.046	0.114	0.153	−0.027	0.333
	EC1/EC2 (95 m)	0.100	0.064	0.135	0.143	−0.019	0.305
	EC1/EC2 (173 m)	0.182	−0.068	0.431	−0.057	−1.698	1.585
	EC1/EC2 (20.5 km)	0.175	−0.035	0.384	0.074	−0.997	1.145
	EC1/EC3 (34 km)	0.218	0.126	0.309	0.072	−0.277	0.421

$*m_{lower}$; m_{upper}: lower and upper 95 % confidence interval for slope m
$*b_{lower}$; b_{upper}: lower and upper 95 % confidence interval for intersect b
$\sigma(\delta)$, $\sigma(\delta)_f$: uncertainty estimated with classical two-tower approach without and with weather filter (f)
$\sigma(\delta)_{corr}$, $\sigma(\delta)_{corr,f}$: uncertainty estimated with extended two-tower approach

BGD
11, 11943–11983, 2014

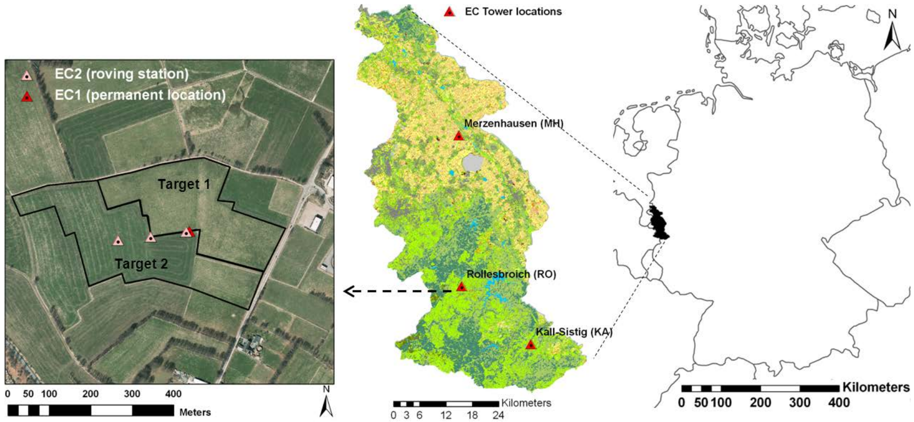

Figure 1. Eddy covariance (EC) tower locations in the Rur-Catchment (center) including the Rollesbroich test site (left), with the target areas defined for the footprint analysis.

BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

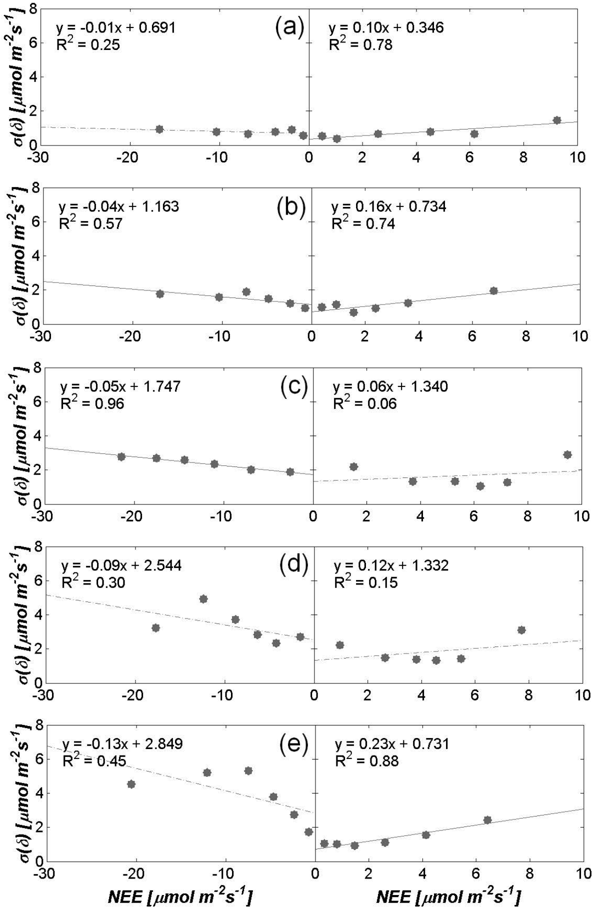

Figure 2. NEE uncertainty $\sigma(\delta)$ determined with the classical two-tower approach as function of the NEE flux magnitude for the EC tower distances 8 m **(a)**, 95 m **(b)**, 173 m **(c)**, 20.5 km **(d)** and 34 km **(e)**. (Dashed line: regression slope not significantly different from zero ($p > 0.1$).)

BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

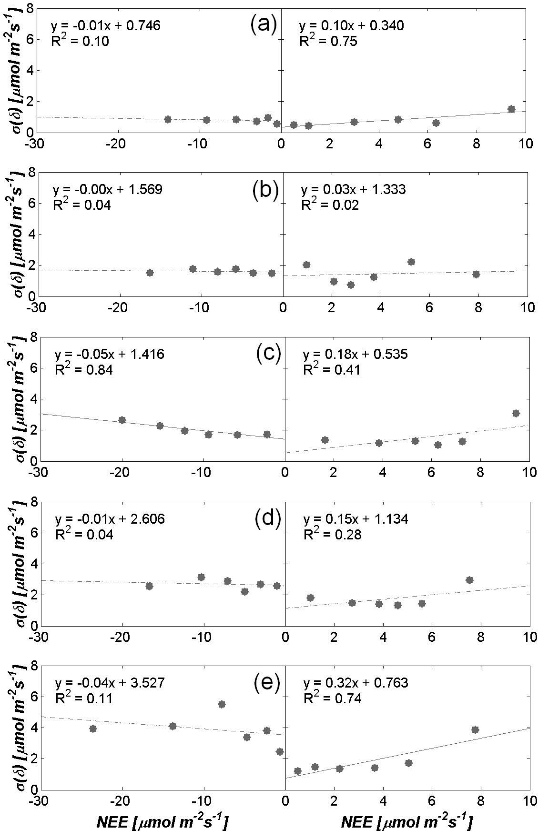

Figure 3. NEE uncertainty $\sigma(\delta)$ determined with the classical two-tower approach as function of the NEE flux magnitude including the application of the weather-filter for the EC tower distances 8 m **(a)**, 95 m **(b)**, 173 m **(c)**, 20.5 km **(d)** and 34 km **(e)**. (Dashed line: regression slope not significantly different from zero ($p > 0.1$).)

BGD
11, 11943–11983, 2014

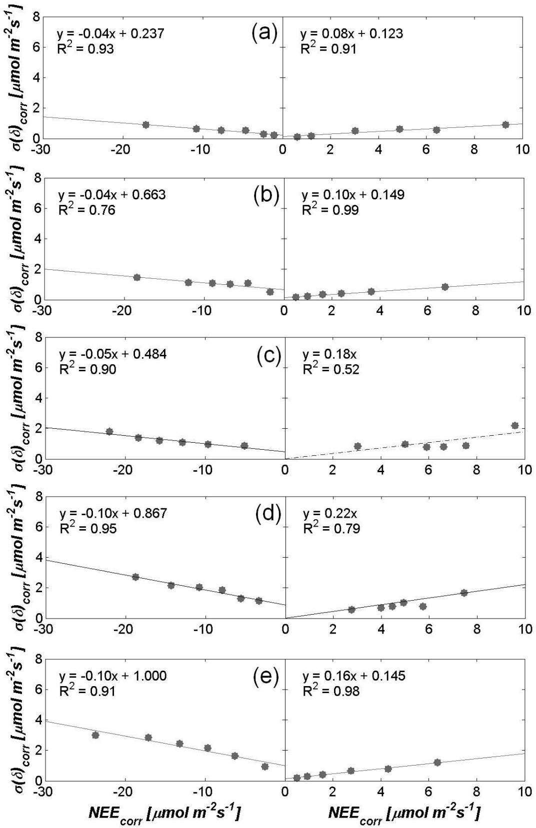

Figure 4. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq. 3) for the EC tower distances 8 m **(a)**, 95 m **(b)**, 173 m **(c)**, 20.5 km **(d)** and 34 km **(e)**. (Dashed line: regression slope not significantly different from zero ($p > 0.1$).)

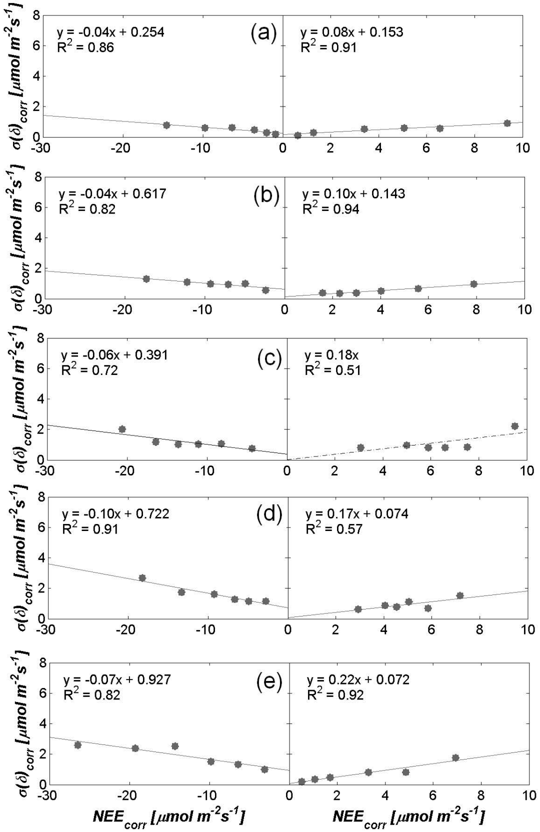

Figure 5. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq. 3) including application of the weather-filter for the EC tower distances 8 m **(a)**, 95 m **(b)**, 173 m **(c)**, 20.5 km **(d)** and 34 km **(e)**. (Dashed line: regression slope not significantly different from zero ($p > 0.1$).)

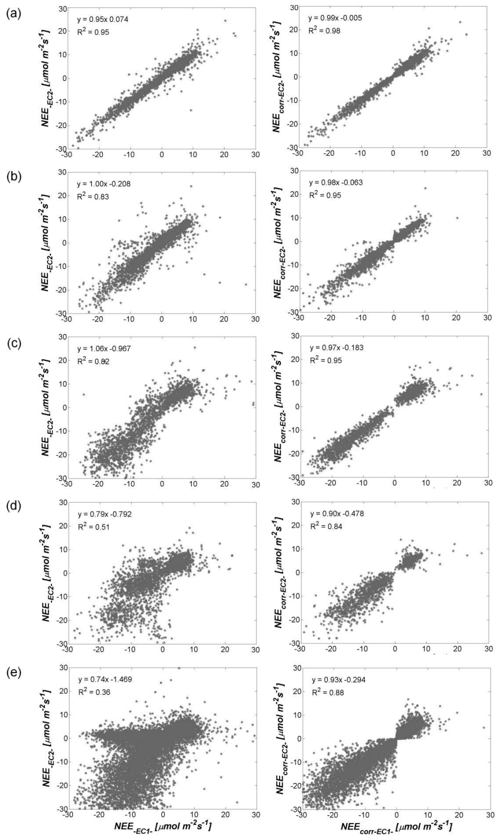

Figure 6. Scatter of the NEE measured at EC1 (NEE_{-EC1-}) and NEE measured at a second tower EC2/EC3 (NEE_{-EC2-}) for the uncorrected NEE (left) and the sfd-corrected NEE_{corr} (right) for the EC tower distances 8 m **(a)**, 95 m **(b)**, 173 m **(c)**, 20.5 km **(d)** and 34 km.

BGD
11, 11943–11983, 2014

Uncertainty analysis of eddy covariance CO_2 flux measurements

H. Post et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion