Reply to Review by A.Desai

We thank A.Desai for the constructive review and the helpful comments. We provide here explicit responses to all comments and suggestions to improve the manuscript.

The different colors indicate: (grey:) Referee comment and (black:) author's response.

Major comment 1:

"Many larger flux tower syntheses rely on previously report two or one tower error metrics for estimating flux tower random error. The authors might want to compare their results with the earlier two-tower or model-tower or single tower based approaches and update some of the constants (for example the slope and offset) used in those. For example, I believe the Richardson paper includes an equation (linear fit) of NEE to error magnitude. How do the slopes and offsets compare? It's possible this is already there, and I missed it, in which case, emphasize it"

Maybe we misunderstand this point but: As it was outlined in Sect. 3.3. (now Sect.3.6), we did a comparison of uncertainty estimated with our extended two tower approach and the uncertainty estimate obtained with the classical two-tower approach (Hollinger u. a. 2004; Hollinger und Richardson 2005; Richardson u. a. 2006). Tab.2 summarizes the results of this comparison. Fig. 2 shows the results of the classical two-tower application. As outlined in Sect. 4.3 (ll. 562-569):

"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), and also the regression coefficients (Fig. 2-3; Fig.5-6, Tab. A1) do not show large differences. This can be expected since Richardson et al. (2006) applied their method for a very well-suited tower pair with low systematic differences, such that the classical approach and our extended approach should approximately converge. However, identical results are unlikely because even for two very similar neighboring sites some systematic differences occur. In addition, the random error is also expected to vary between sites (see e.g. Mauder et al., 2013) which is in part related to instrumentation."

Major comment 2:

"Similarly it might be interesting to estimate, given the criteria discovered here on maximum possible distance that is reliable and role of filtering corrections and estimate what % of towers in the current Fluxnet database could be amenable to such a paired tower analysis? A related interesting question, is, can the slope/offsets derived here be directly applied to any tower (as is done in some model-data assimilation work now)?"

Yes, it would be interesting to estimate this. However, it is not very trivial to answer this question. Our manuscript is the first one to provide information on the distance dependence of error estimates with a classical and an extended, more robust two-tower approach. But we conducted this study only for one tower type (in terms of height and instrumentation) and mostly for one ecosystem type (grassland). More research including different ecosystem types and larger distances is needed to give save recommendations in this respect. Similarly, the applicability of any literature slopes/offsets to estimate random uncertainty as a function of the flux magnitude depends on the accuracy requirements of the user. To get the order of magnitude of the uncertainty right, it is surely helpful to study the increasing body of literature presenting flux-uncertainty relations, derive from it the "uncertainty of the uncertainty", and apply a typical relation from this to own data with the "uncertainty of the uncertainty" in mind. For more detailed studies, however, uncertainty estimation results obtained for different towers and sites may be insufficient. As outlined in the conclusions (ll. 595- 603) uncertainty estimation results may differ, e.g. due to different environmental conditions or a different setup of the measurement devices.

Minor comments:

"P 11945 Line 14 Systematic errors are considered to remain constant for set of environmental conditions. This is confusing. u* is an environmental condition, right? Systematic error increases with low u*. Maybe a little rewording is needed."

Yes, we rephrased ll. 45-46: "Systematic errors are considered to remain constant for a longer time period (> several hours)."

"P 11946 Line 21 I don't think of instrumentation issues as "errors" but rather precision or sensitivity. Random error from instrument noise is not an error in the instrument per se. A true instrument error (bad calibration, bad laser) would lead to a systematic error."

This was an unfortunate terminology we used here and this is now corrected and clarified in the revised version of the manuscript. Our focus is on random measurement errors. Because referee #2 was also concerned about calling "flux footprint heterogeneity" an error we now reformulated this sentence (ll. 59-69):
"After a possible correction of the EC flux data for systematic errors a random error will remain which can arise from different sources such as (a) the assumption of a constant footprint area within a measurement interval and the negligence of flux footprint heterogeneity (e.g. due to temporal variability of wind direction, wind speed and atmospheric stability which cause temporal variations of the footprint area); (b) turbulence sampling errors which 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-minutes period; and (c) instrumentation deficits that can e.g. cause random errors in the measured variables (such as the CO2 mixing ratio and the vertical wind velocity) used to calculate the net CO2 flux, (Aubinet et al., 2011, p. 179; Flanagan and Johnson, 2005)"

"P 11946 Line 23 Some random errors can be corrected, given the list here. Flux footprint heterogeneity can be corrected some by using estimates of land cover and debasing techniques (such as Metzger et al., 2013). Also not sure how footprint error can actually be computed from the raw 10 Hz alone - i.e., the Mauder/Foken TK3 approach estimate of random error tells you mainly how variable the covariance is with time. It's unclear how that would incorporate flux footprint error."

See the response given to the question above.

"P 11955 Is SFD correction before or after u* filtering?"

Sfd-correction was done after applying the filtering for weather conditions (including u* filtering); this is clarified now in the revised version (sect.3.2 and sect.3.4):

ll. 229-230:"The extended two-tower approach with sfd-correction and the previously applied weather-filter"

ll. 330-301: "The weather-filter was applied before the (classical) uncertainty estimation and the sfd-correction."

"P 11959 Line 16 If noise and stochastic errors are truly a sigma and are independent, shouldn't they be added in quadrature? Though Mauder et al (2013) is published, some more details on what the exact nature of each noise computation is might help in understanding the characteristics. Just a sentence on each."

Yes, random errors should be added in quadrature. We now recalculated the reference error by adding in quadrature (Sect 3.6., ll. 364-369):
"Mauder et al. (2013) determine the instrumental noise based on signal autocorrelation. Following Finkelstein and Sims (2001) the stochastic error is calculated as the statistical variance of the covariance of the flux observations. Generally, σ_{cov}^{noise} was considerably lower than σ_{cov}^{stoch}. The total

raw-data based random error σ_{cov} [μmol $m^{-2}s^{-1}$] was calculated by adding σ_{cov}^{noise} and σ_{cov}^{stoch} "in quadrature" ($\sigma_{cov} = \sqrt{{\sigma_{cov}^{stoch}}^2 + {\sigma_{cov}^{noise}}^2}$) according to Aubinet et al. (2011, p.176)."

The new calculations resulted in different mean reference values σ_{cov} (Tab.2) as well as slightly changed delta-values (Percentage difference of two-tower based uncertainty estimate and reference, $\Delta\sigma_{cov}$ Tab.2). The new calculations hardly changed the results because of the smallness of instrumental noise.

"Table 2 - though it may make it messy, also a metric of the range of uncertainty estimates for each method and distance should be included. Also discussion of difference between night and day would help interpret other points made in the results (maybe a separate table or supplement?)"

Additional information on uncertainty was provided in Table A1 (supplementary information). Also confidence intervals for the regression slope (distance and method dependent) were given. We prefer not to add more information in Table 2. For differences between nighttime and daytime, see also our response on the next point addressed by the reviewer.

"Figure 5 - it appears from here that the reliability of the approach in terms of distance is different for night and day (when the slope changes significant occurs at different distances, as does the rˆ2). Is that a correct interpretation? If so, some discussion may be needed on why the paired tower approach works differently in day vs night."

We are not sure if we understand this question correctly. First of all: positive fluxes are not only nighttime fluxes, since wintertime data is included. We added some sentences in the discussion about the different results for positive and negative fluxes now (ll. 508-515):"

"Moreover, during nighttime and/or winter (positive NEE), some conditions associated with lower EC data quality such as low turbulence, strong stability, and liquid water in the gas analyzer path prevail more often than in summer and/or daytime (negative NEE). The less severe cases of such conditions are not always completely eliminated by the quality control. In time series of eddy-covariance fluxes this typically shows up as implausible fluctuations of the flux during calm nights. This is reflected by plots of NEE flux magnitude versus uncertainty (Fig.2-Fig.5) showing higher uncertainties for positive compared to negative NEE data which agrees with previous findings (e.g. Richardson et al., 2006)."

The fact that in our study half-hours flagged as low quality data by an advanced procedure (Mauder et al., 2013) were discarded, as well as our application of the sfd-correction, might explain why the difference between positive and negative fluxes in our study is lower than in others (e.g. Richardson et al., 2006). "

Point-to-point reply to interactive referee comment by anonymous referee #2

Thanks again for this helpful review and the constructive comments. A detailed reply to the three major comments by anonymous referee #2 is already summarized in our interactive comment (AC C5500). This point-to-point reply provides explicit responses to all comments and indicates how we improved our manuscript.

The different colors indicate: (grey:) Referee comment and (black:) author's response.

Major comments:

(1)"Relevance of the extended two-tower approach. The inherent problem of the presented research (formulated provocatively) boils down to the question: Who will need this approach? The authors use the random uncertainty assessment based on raw data processing (implemented by Mauder into the TK3 software) as a reference to validate their results. Of course the statement is correct that access to raw data is sometimes limited,and extra processing to retrieve random uncertainty from raw data requires additional work. However, if one has the choice of either setting up an additional eddy system and running it for a few months, or alternatively work on the raw data to get (more reliable?) random uncertainty estimates, the latter still seems to be the more convenient choice. So why bother with an extended two-tower approach? I see two pathways how to deal with this issue: Ideally, the authors can clearly point out where their own approach goes beyond what alternative approaches provide, i.e. where is the extra piece of information that cannot be obtained e.g. by analyzing the EC raw data? I'm sure there are some assumptions and uncertainties associated with each of the alternative approaches that can be used to highlight the benefit of this new method. In case it is not possible to claim any advantages of the extended two-tower approach over the raw data analysis, the authors need to clearly point out under what circumstances their approach might be applied: As I see it, this is only when a) no raw data access (or processing) is possible, and b) there is a nearby site in the chosen EC database that can be used as a reference site within the two-tower approach (i.e. similar environmental conditions, acceptable horizontal separation distance). This, however, would emphasize that there is only a very small niche for the presented approach."

To emphasize the relevance of our proposed extension of the two-tower approach we added in the introduction (p.3, ll. 95-101):

<u>"Moreover, a large amount of solid metadata about the setup of the EC measurement devices is required (but often not provided at second hand) to obtain reliable raw-data based uncertainty estimates adequately. Therefore a two-tower based approach has still a large group of users. In particular with regard to pairs of nearby towers from local clusters which play an increasing role in the monitoring strategies of e.g. ICOS and NEON, and have already been employed in case studies (e.g. Ammann et al., 2007)."</u>

(2) "**Footprint filtering:** The footprint filtering concept as presented in Section 3.6 is severely flawed! Simply comparing the fractional composition of land use types in the footprints of two towers doesn't give you ANY information on whether or not these footprints overlap. It can be total coincidence that these fractions are nearly identical, while the respective towers 'see' completely different areas (and are therefore statistically independent in the context of your study). And as you describe correctly in a different section, even a homogeneous patch of land can host totally different environmental conditions at the microscale that may affect the flux rates - the same is true for a footprint area that is composed of two land use types, so you cannot claim that the towers 'see' the same simply because they have a similar land use composition in their footprints. You need to analyze what the actual overlap of the footprint positions is, the land cover within doesn't matter!"

We repeated the footprint analysis storing the footprint grid of each half-hour and tower, which enabled us to directly compute the overlap for each half-hour. As a consequence, methodology Sect. 3.5 (formerly 3.6) strongly changed and the new resulting overlap percentages are mentioned in section 4.3. Note that it was not our intention to suggest that converging land-use type contributions mean overlap in general; rather, we argued that it is a good proxy in case of our particular constellation of towers and mapped target areas. As a consequence, the change in overlap percentages was only minor and did not change the discussion. However, we agree that the new direct method adds reliability and avoids the risk of inappropriately transferring the old ad-hoc method to other sites/studies. Therefore, this old indirect method is not mentioned any more in the revised manuscript.

(3)"**Sensitivity study on approach configuration** The choice of the 12hr moving window to filter out the systematic errors, as well as the 50% data coverage threshold for valid moving window averages, need to be supplemented by sensitivity studies. Both of these settings seem rather subjective, so the authors need to demonstrate how results might change with different settings, and why the chosen ones are the best option."

We now rerun the uncertainty analysis with different sizes of moving window sized and different thresholds. This rerunning revealed an error in the script we did not notice before: instead of applying the continuous data for calculating the running average, the table was filtered already at the beginning for data where only both EC1 and EC2 data were available at a certain half-hourly time step. We changed this now using the continuous data series for calculating the running average for the revised manuscript. This change slightly affected the uncertainty estimation results of Tab.2 as well as the regression plots for the sfd-corrected data (Fig.4, Fig.5, Fig.6). The rerunning of the uncertainty estimation for different moving average periods and data coverage percentage showed that results did not change considerably by the different setups (Tab.A3). However, as Tab. A2 shows the linear regression coefficients changed, in particular for the 173 m and 20.5 km distance with shorter time series. This was mainly due to the different amount of data left for the analysis. Because more *NEE* data remained after the sfd-correction for the 6 hour averaging interval, correlation coefficients were less uncertain for this averaging interval.

Tab. A2: R^2 for NEE uncertainty determined with the extended two-tower approach (including sfd-correction and weather-filter) as function of NEE_{corr} magnitude and for 20.5km EC tower distance. Results are given for different moving average time intervals (6 hr, 12 hr, 24hr) and data coverage percentages (25%, 50%, 70%) for the calculation of the sfd-correction factor (Eq.2)

R^2_ 173 m distance	**6h**	**12h**	**24h**
30%	0.81; 0.61; *(1588)*	0.8; 0.65; *(1557)*	0.67; 0.56; *(1427)*
50%	0.83; 0.48; *(1245)*	0.79; 0.37; *(1046)*	-; -; *(106)*
70%	0.74; 0.45; *(797)*	0.92; 0.39; *(309)*	-; -; *(0)*

R^2_20.5 km distance	**6h**	**12h**	**24h**
30%	0.73; 0.84; *(937)*	0.92; 0.72; *(904)*	0.84; 0.82; *(597)*
50%	0.58; 0.85; *(710)*	0.7; 0.43; *(463)*	-; -; *(32)*
70%	0.77; 0.78; *(408)*	0.66; 0.08; *(148)*	-; -; *(0)*

black: for negative NEE; grey: for positive NEE; (): total number of half-hourly NEE data left after sfd-correction and weather filter to build bins for NEE uncertainty versus NEE magnitude regressions.

We clarified in the text (Sect.3.3. ll. 289-301):

"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 correction term. The running averages were only calculated if at least 50% of the data for $NEE_{\text{-EC1-}}$ and $NEE_{\text{-EC2}}$ remained for averaging in that particular window. Due to the frequent occurrence of gaps in the data series the amount of available NEE_{corr} values considerably decreased by applying stricter criteria like 70% or 90% data availability (Tab. A2)."

In the discussion we clarified (ll. 488-505):

"Results indicate that an overestimation of the two-tower based uncertainty caused by different land surface properties in the footprint area of both EC towers can be successfully filtered out by the extended approach. It should be noted that a shorter moving average interval of the sfd-correction term (e.g. 6 hours instead of the applied 12 hours window; Tab.A2), results in slightly lower uncertainty estimates compared to the reference. This can be explained by a possible "over-correction" of the *NEE* data related to a too short moving average interval for calculating the sfd-correction term. It needs to be emphasized that the estimated mean *NEE* values of the moving average intervals are associated with uncertainty. As mentioned, the moving average 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 12hr running mean *NEE1* and *NEE2* values (NEE_{12}) as well as the respective means of *NEE1* and *NEE2* (NEE_{2T_12}) used to calculate NEE_{corr} (Eq.2) are uncertain because they still contain the random error part which cannot be corrected or filtered out. This uncertainty in the mean is expected to be higher for a shorter averaging interval such as 6 hours. Therefore, completely correcting the difference in mean *NEE* slightly overcorrects systematic differences in *NEE*. In general results were not very sensitive to different moving average sizes of the sfd-correction term and data coverage percentages defined for this interval (Tab.A3). "

Minor comments:

“p.11944ff: Introduction overall well structured, but much too long. The current version may be OK for a thesis, but for a manuscript many of the ’excursions’ are much too detailed. I added a few specific comments where paragraphs need to be shortened”

We shortened to introduction now accordingly

“p. 11945, 1st paragraph: no need to explain that many details of DA”

We agree, is removed now.

“p.11945, ll.8-11: there are many more reasons why a reliable uncertainty estimate of EC data is needed ..”

We agree. In the revised manuscript we say (ll. 38-41): “In this regard reliable EC data with appropriate uncertainty estimates are crucial for many application fields, such as the evaluation and improvement of land surface models (e.g. Braswell et al., 2005; Hill et al., 2012; Kuppel et al., 2012).”

“p.11945f: The description of systematic errors is much too long! It is fully sufficient to mention a few sources of systematic errors (e.g. not well developed turbulence, energy balance closure, etc), then add the citations. No need to explain the details in an introduction when none of these effects are investigated further within the presented study”

We agree, is changed in the revised version.

“p.11946, ll.6ff: this entire paragraph can be deleted. Again, the manuscript doesn’t treat EBD, so it’s just another source of systematic errors.”

This paragraph is deleted in the revised manuscript.

“p.11946, ll.20-22: I don’t really like to see the effect of changing footprint areas being called an error. The changing field of view of an eddy system causes variability in the data, but the resulting effect is not an error. The error would be to assume that the footprint area is stable, as is correctly being stated here.”

We reformulated this now (ll. 59-69):

“After a possible correction of the EC flux data for systematic errors a random error will remain which can arise from different sources such as (a) the assumption of a constant footprint area within a measurement interval and the negligence of flux footprint heterogeneity (e.g. due to temporal variability of wind direction, wind speed and atmospheric stability which cause temporal variations of the footprint area); (b) turbulence sampling errors which 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-minutes period; and (c) instrumentation deficits that can e.g. cause random errors in the measured variables (such as the CO_2 mixing ratio and the vertical wind velocity) used to calculate the net CO_2 flux, (Aubinet et al., 2011, p. 179; Flanagan and Johnson, 2005).”

“p.11947, ll.15ff: again, this is too much detail. It will be sufficient to cite that alternative approaches have been developed, which all have their own individual drawbacks.”

We don’t’ think this is too much detail and a brief summary of existing methods for EC flux uncertainty estimation is required at this point since this is the topic of the manuscript. So we kept it as it is.

“p.11949f: The section on the sites is pretty much comprehensive. The only info that is missing is the data acquisition, i.e. what data acquisition devices (and frequency) were used?”

At the end of section 2 (l. 177) we added: “Details on the EC data acquisition are summarized in Sect. 3.2.”

“p.11950f: Section 3.1 can be deleted. Anyone who wants to learn what eddy covariance is can check out a textbook. The only relevant information in this paragraph is your chosen sign convention for uptake and release, resp. (last sentences).”

We deleted this paragraph now and moved the most important information to the introduction (ll.29-33, ll. 52-55).

“p.11952, ll.1ff: some of the given info as well as the use of citations are inconsistent. Correction of spectral losses in the TK3 package is based on Moore (1986); footprint analyses are not part of the quality flagging procedure; quality flagging is mainly based on tests for stationariy and integral turbulence characteristics, as well as the horizontal orientation of the anemometer; the citation for the quality flagging is Foken et al. (2004); the used flag ranges (e.g. 1-3 for high quality data) should be given.”

Paragraph is modified now accordingly (Sect.3.1, ll.196-211):
“The EC raw data were measured with a frequency of 20 Hz and fluxes were calculated for intervals of 30 minutes. 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 EC conversions and corrections such as e.g. correction of spectral loss (Moore, 1986) 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 (Foken and Wichura, 1996). The tests on half hourly fluxes are the basis for a standardized quality flagging according to Foken et al. (2004) that classifies flux measurements as high (0), moderate (1) or low (2) quality data. For this analysis only flux measurements assigned to 0 or 1 were used, while low quality data were treated as missing values. Besides quality flags TK3.1 also provides footprint estimates (Kormann and Meixner, 2001) and uncertainty estimates that were used for interpreting and analyzing flux data. To avoid introduction of additional uncertainty no gap filling of flux time series was performed.”

“p.11952ff: it’s a bit confusing to read about weather filter and sfd-approach in this section (3.3) before these techniques are actually introduced. Would be nice if this could be improved. Otherwise OK.”

We considered to move the overview of the for correction schemes/techniques from beginning of Sect.3.2 (before Sect.3.3) to the beginning of Sect.3.6. However, this is unfavorable because we need to mention “sft-correction” and “weather-filter” a few times in Sect.3.2 Therefore we prefer not to change this order.

“p.11952, l.20: you mention earlier this distance is _34km ..”
Yes, 34 km is right, we corrected this misspelling now.

“p. 11956, ll.6ff: please add more details how this 12hr window was chosen. It also needs to be shown how the selection of this window influences the test performance! Separating between short-term variability and long-term trends is crucial for this approach!”

See reply to major comment 3 in interactive comment (AC C5500) and in this document.

“p.11957, ll.1ff: the 50% threshold is indeed quite low. Has a sensitivity study been performed how stricter thresholds influence the performance? If not, this should be added.”

See reply to major comment 3 in interactive comment (AC C5500) and in this document.

“p.11957f: Section 3.5 can be reduced to the statement ’filter for similar weather conditions followed Richardson et al. (2006)!“

We kept the explanation in this section in order to provide additional information about our specific application but shortened the explanation of the filter as suggested by the reviewer.

“p.11962, ll.14ff: there’s no need to write down all the numbers per case study, since these are given in the table. Reduce this section to the range of values, and point out some outstanding examples!”

We agree, is changed now.

"p.11963, ll.1ff: 'nearly identical' is a bit exaggerated here. There's still considerable scatter in this comparison, and particularly for the far distances not all systematic bias effects seem to have been removed"

We agree, this is reformulated in the revised version ("agree best with" instead of "nearly identical to"), ll. 450-454: "The uncertainty estimates $\sigma(\delta)_{corr,f}$ determined with the extended two-tower approach agree best with the independent reference values σcov for the EC tower distances 95m and 173 m, suggesting that those distances were most suitable for the application of the extended two-tower approach."

"p.11964f, ll.17ff: this whole section does not really belong into the discussion part, since it repeats the statements from introduction and methods that many factors can be responsible for small-scale ecosystem heterogeneity, and thus affect surface atmosphere exchange fluxes. All this should have been covered through your sfd correction."

We moved this part to Section 2 now and refer to it in the discussion (481-484): "As outlined in section 2, land surface properties related to management (e.g. nutrient availably due to fertilization), soil properties (bulk density, skeleton fraction), soil carbon-nitrogen pools, soil moisture and soil temperature are heterogeneously distributed at the Rollesbroich site."

p.11965, ll.22ff: this finding basically indicates that your current setup for the sdf correction does not fully cover all systematic differences in the flux measurements. Maybe you'll need a different configuration (e.g. averaging time) for larger distances? Or you are missing some influence factors when ecosystems show significant differences in their structure/properties?

Right. We changed the formulation in the revised manuscript and added some discussion on this (which also relates to the next comment), Sect.4.3, ll. 523-532:

"However, after applying the sfd-correction and the weather-filtering, the mean uncertainty estimate was still higher than the raw-data based reference value (Tab.2), suggesting that for these large EC tower distances the sfd-correction and the weather-filter do not fully capture systematic flux differences and uncertainty is still overestimated by the extended two-tower approach. This can have different reasons. We assume the major reason is that the weather-filter is supposed to capture all measured flux differences that can be attributed to different weather conditions at both EC towers which cannot be captured with the sfd-correction. Applying stricter thresholds could increase the efficiency of the weather filter but in our case the reduced dataset was too small to allow further analysis."

"p.11965, l.29: why counterintuitive? Do you really assume that the absolute distance is more important then the differences in ecosystem structure"

We would expect that differences increase as function of distance (related to meteorological conditions for example), but indeed ecosystem structure plays an important role. The sites which are 34km separated have different land use types (winter wheat instead of grassland) whereas the sites which are 20.5km separated have similar land use types. Therefore we found it counterintuitive. However, given the many factors which influence uncertainty estimates, we decided to delete "which is counterintuitive" now in order to avoid confusion.

"p.11968, ll.9-11: I don't think that your results database warrants the statement 'typically overestimated'. You would need more case studies to validate this. The only thing you found out so far is that in your tests, comparisons across distances of 20-30km resulted in an overestimation of random errors."

This is true, we now wrote "probably" instead of "typically" (ll. 591-594): "We therefore conclude that if no second EC tower is available at a closer distance (but available further away), a rough, probably overestimated *NEE* uncertainty estimate can be acquired with the extended two-tower approach even although environmental conditions at the two sites are not identical."

Additional changes in manuscript:

ll. 22-25: Abstract reformulated.

ll. 41-45 is reformulated: "When using the term 'uncertainty', we here focus on the random error following the definition in Dragoni et al. (2007). It differs from the systematic error in that it is unpredictable and impossible to correct (but can be quantified). Uncertainty doesn't accumulate linearly but "averages out" and can be characterized by probability distribution functions (Richardson et al., 2012)."

ll. 104-127: This paragraph was located at the beginning of Sect. 3.3 (Correction for systematic flux differences) before. Now think it fits better in the introduction.

273-276: Sentences changed slightly after moving previous paragraph to line 104-127

ll. 369-371: reformulated

l 481ff: "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)." deleted due to repetition.

ll. 522-523: reformulated: "$\Delta\sigma_{cov}$ was reduced by 85.7% for the 20.5km distance and 79.3% for the 34km if both sfd-correction and weather filter were used."

ll. 610-611: reformulated: "Applying very strict thresholds can lead to a too small dataset, especially if the measurement periods are short."

Tab.2: Values in table changed slightly due to continuous time series used now and new summing up of σ_{cov} (Sect.3.6) as suggested by referee 1 (A.Desai)

Fig1: Targets removed due to new footprint analysis (not based on target areas any more).

Fig.4 – Fig.6: Figures changed slightly due to continuous time series used now.

Prev. Fig.6 is Fig.4 now to maintain chronological order.

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

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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 (classical) 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 the classical two-tower approach and 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~~an 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.~~and decreased the sensitivity of results to tower distance. We therefore conclude that corrections for systematic flux differences (e.g. caused by different environmental conditions at both EC towers~~. It is concluded that the extension of~~) can help to apply 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.~~site pairs with less ideal conditions.

Style Definition: Tabelle: Space Before: 0 pt, After: 0 pt

Keywords: Eddy covariance, measurement uncertainty, random error, NEE, footprint, systematic flux differences

1 Introduction

The net ecosystem exchange of CO_2 between the land surface and the atmosphere (*NEE*) can be determined with the eddy covariance (EC) method. *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. During night-time, *NEE* is mainly a function of respiration and therefore positive fluxes predominate, whereas during (summer) daytime negative *NEE* values predominate because more CO_2 is assimilated than respired. Eddy covariance ~~(EC)~~CO_2 flux measurements ~~of the CO_2 flux~~ are commonly used to analyze the interactions between terrestrial ecosystems and the atmosphere~~. This~~ which is crucial for the understanding of climate-ecosystem feedbacks~~ as well as~~. In this regard reliable EC data with appropriate uncertainty estimates are crucial 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~~many application fields, such as the evaluation and improvement of 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~~.

When using the term ‘uncertainty’, we here focus on the random error 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.~~. It differs from the systematic error in that it is unpredictable and impossible to correct (but can be quantified). Uncertainty doesn’t accumulate linearly but “averages out” and can be characterized by probability distribution functions (Richardson et al., 2012). Systematic errors are considered to remain constant for a longer time period (> several hours). 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 sec. 3.1, a~~A main assumption is ~~e.g.~~ that turbulence is always well developed in the lowest atmospheric boundary layer and responsible for the mass transport while horizontal divergence of flow and advection are assumed to be negligible (Baldocchi, 2001). Moreover, the EC method is based on the mass conservation principle, which requires the assumption of steady state conditions of the meteorological variables (Baldocchi, 2003). ~~. In case of CO_2 fluxes, nighttime~~In case of CO_2 fluxes, night-time 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~~night-time 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-minutes 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).~~After a possible correction of the EC flux data for systematic errors a random error will remain which can arise from different sources such as (a) the assumption of a constant footprint area within a measurement interval and the negligence of flux footprint heterogeneity (e.g. due to temporal variability of wind direction, wind speed and atmospheric stability which cause temporal variations of the footprint area); (b) turbulence sampling errors which 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-minutes period; and (c) instrumentation deficits that can e.g. cause random errors in the measured variables (such as the CO_2 mixing ratio and the vertical wind velocity) used to calculate the net CO_2 flux (Aubinet et al., 2011, p. 179; Flanagan and Johnson, 2005).

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 et al., 2004; Hollinger and Richardson, 2005). 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).~~(Hollinger et al., 2004; Hollinger and Richardson, 2005). 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~~Alternatively, if the high-frequency raw-data of an EC tower are available, uncertainty ~~contributing to the total random error~~ can be estimated ~~with the random shuffle method~~directly from their statistical properties (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 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.~~The advantage is that a second tower or the utilization of additional tools such as a simple model to estimate the EC measurement uncertainty is no longer required. However, many data users do not have access to the raw-data but to processed EC data only. Moreover, a large amount of solid metadata about the setup of the EC measurement devices is required (but often not provided at second hand) to obtain reliable raw-data based uncertainty estimates adequately. Therefore a two-tower based approach has still a large group of users. In particular with regard to pairs of nearby towers from local clusters which play an increasing role in the monitoring strategies of e.g. ICOS and NEON, and have already been employed in case studies (e.g. Ammann et al., 2007). 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.

The classical two-tower approach (Hollinger et al., 2004; Hollinger and Richardson, 2005; 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 guarantee statistical independence. Hollinger and Richardson (2005) use threshold values for three variables (photosynthetically active photon flux density PPFD, temperature & 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 affect 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.

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~~removes 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.

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 ~ 1033mm per year (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~~ (Tab.1).~~. The measurement height of the sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, U.S.A.) and the open-path gas analyzer (Li7500, Li-Cor, Lincoln, NE, U.S.A.) 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 (Tab.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 Aug. 14^{th} and Oct. 30^{th} 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 (Tab.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 those in Rollesbroich and Kall-Sistig. The climate at the lowland site Merzenhausen is comparable to the one in Selhausen ~~in 13 km~~at a distance ~~to~~of 13 km from Merzenhausen, where the mean precipitation is ~ 690 mm/a and the yearly mean temperature ~9.8°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. Details on the EC data acquisition are summarized in Sect. 3.1.

Rollesbroich is part of the TERENO network (Zacharias et al., 2011). Information and additional data were collected showing that land surface properties are spatially heterogeneous distributed at the Rollesbroich site: (1) Single fields at the Rollesbroich site 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 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] as well as bulk density [g/cm^3] and content of rock fragments [%] measured from April-May 2011 in three soils horizons at 94 locations across the Rollesbroich site are spatially highly variable (H. Schiedung 2013, personal communication); (4) During the eddy covariance measurement period, soil moisture and soil temperature data were collected in 10 min. resolution at three depths (5 cm, 20 cm and 50 cm) and 84 points by the wireless sensor network (“SoilNet”; Bogena et al., 2009), calibrated for the Rollesbroich site by ~~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).~~

Qu et al., (2013). SoilNet data shows that soil moisture is heterogeneously distributed within the Rollesbroich site (Qu et al., 2014, submitted).

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 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 [mmol m^{-2} 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 ω (m s^{-1}):~~

$$F = \overline{\rho_a} \cdot \overline{\omega' \cdot c'}$$ ~~*Eq.*~~ ***0***

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

$$\overline{c' \cdot \omega'} = \sum_{k=0}^{n} \frac{[(\omega_k - \bar{\omega})(c_k - \bar{c})]}{n-1}$$ ~~***Eq. 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.~~3.1. EC data processing

The EC raw data were measured with a frequency of 20 Hz and fluxes were ~~calculated~~processed for flux intervals of 30 minutes. The complete processing of the data was performed with the TK3.1 software (Bayreuth, Department of Micrometeorology, Germany; ~~Mauder and Foken, 2011),~~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 EC conversions and corrections such as e.g. correction of spectral loss (Moore, 1986) 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~~ (Foken and Wichura, 1996). The tests on half hourly fluxes are the basis for a standardized quality flagging according to Foken et al. (2004) that classifies flux measurements as high (0), moderate (1) or low (2) quality data. For this analysis only flux measurements assigned to 0 or 1 were used, while low quality data were treated as missing values. Besides quality flags TK3.1 also provides footprint estimates (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~~that were used~~, while low quality data were treated as missing values.~~ for interpreting and analyzing flux data. To avoid introduction of additional uncertainty no gap filling of flux time series was performed.

~~3.3.~~3.2. Uncertainty estimation based on the two-tower approach

The two-tower approach (Hollinger et al., 2004; 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 [µmol $m^{-2}s^{-1}$] simultaneously measured at two different EC towers (NEE_1, NEE_2):

$$\sigma(\delta) = \frac{\sigma\,(NEE_1 - NEE_2)}{\sqrt{2}} \qquad \textit{Eq. } \cancel{3}1$$

Based on Eq.~~3~~1 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~~roving station (EC2) or – in case of the ~~32~~34 km EC tower distance – another permanent EC tower (EC3, Tab.1).

For comparison, the measurement uncertainty $\sigma(\delta)$ was calculated separately for each EC tower distance (Tab.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).~~

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

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2. The classical two-tower approach including a filter for similar weather~~ filter previously applied to the actual uncertainty estimation procedure (~~ conditions ~~of weather filter summarized in section~~(Sect. 3.~~5~~4).
3. The extended two-tower approach with an added correction for systematic flux differences (sfd-correction; ~~section~~Sect. 3.~~4~~3), without weather-filter.
4. The extended two-tower approach with sfd-correction and the previously applied 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~~1 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 $\sigma(\delta)$ [µmol 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~~Now class limits were ~~sorted and divided into 6~~set such that all groups with positive *NEE* values had an equal amount of half hourly data, the same holds for all groups with negative *NEE* values. 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~~schemes so that altogether 20x2 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 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 (Sect.3.4) and/or the sfd-correction~~.~~ (Sect.3.3). 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 x 4 schemes, 20 mean two-tower approach based *NEE* uncertainty estimates for the EC1 station were calculated by averaging the individual half hourly uncertainty values (Tab.2).~~ These mean uncertainty estimates were used to evaluate the effect of the EC tower distance as well as the sfd-correction ~~(sec.3.4)~~ and the weather-filter ~~(sec.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.~~3.3. Correction for systematic flux differences (sfd-correction)

~~The classical two-tower approach (Hollinger and Richardson, 2005; Hollinger et al., 2004; Richardson et al., 2006)~~Different environmental conditions and ~~is based on the assumption that environmental conditions for both EC towers are identical and flux footprints should not overlap to guarantee statistical independence. Hollinger and Richardson (2005) use threshold values for three variables (photosynthetically active photon flux density PPFD, temperature & 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 affect 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. Because these flux differences are not inherent to the actual random error of the measured *NEE* at one EC tower station they lead to an overestimation of the two-tower approach based uncertainty. Therefore, we extended the classical two-tower approach with a simple correction step for systematic flux differences (sfd-correction). The reason why systematic flux differences can 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.~~vary slowly. The sfd-correction introduced is similar to the second correction step in Kessomkiat et al. (2013, Equation 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~~An averaging time interval of 12 hours was used to calculate the running mean for the sfd-correction. For each moving average interval, the mean NEE_{12h} of one EC tower (separately for EC1 and EC2) [µmol m^{-2} s^{-1}] and the mean CO_2 flux averaged over both EC towers NEE_{2T_12h} [µmol m^{-2} s^{-1}] were calculated to define the sfd-correction term which was used to calculate the corrected NEE_{corr} [µmol m^{-2} s^{-1}]:

$$NEE_{corr} = \cancel{\frac{NEE_{2T\_12h}}{NEE_{12h}}}\frac{NEE_{2T\_12hr}}{NEE_{12h}} \cdot NEE \qquad \textbf{\textit{Eq. }}\cancel{4}2$$

NEE is the single half-hourly, processed *NEE* value [µmol 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.~~correction term. The running averages were only calculated if at least 50% of the data for $NEE_{\text{-EC1-}}$ and $NEE_{\text{-EC2}}$ remained for averaging in that particular window. Due to the frequent occurrence of gaps in the data series the amount of available NEE_{corr} values considerably decreased by applying stricter criteria like 70% or 90% data availability (Tab. A2). We assume a 12 hour averaging period to be long enough to exclude most of the random error part but short enough to consider daily changes of systematic flux differences. For a six hour interval for instance the uncertainty of the mean *NEE* is usually higher. For larger window sizes (24 or 48 hours) further analysis was hampered by too many data gaps, i.e. the 50% criterion was hardly ever fulfilled and not enough averages remained to allow for the two-tower based uncertainty estimation (Tab. A2). 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~~night-time (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_{EC1} and NEE_{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.~~3.4. 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”.

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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.~~Therefore a filter for similar weather conditions was applied in addition to the sfd-correction following 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~~ defined by a temperature difference ~~was~~ < 3°C; ~~the~~wind speed difference ~~in wind speed~~ < 1 m/s and ~~the~~ difference in PPFD < 75 µmol m^{-2} s^{-1}. The weather-filter was applied ~~for each half-hourly time step for both~~before the (classical) uncertainty estimation and the sfd-~~corrected dataset as well as for the non-corrected *NEE* data~~correction. 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.~~3.5. 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 half-hourly 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 corresponding measurement period (Tab.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).~~ (Mauder and Foken, 2011), a grid of estimated source weights (resolution 2 m, extension 1 km by 1 km) was computed for each half-hour and station position. The overlap between the footprints of two simultaneously measuring towers was then quantified as:

$$O_{12}(t) = \sum_{x=1}^{N} \sum_{y=1}^{M} min(f_1(x,y,t), f_2(x,y,t)) \quad \textit{Eq. 3}$$

The indices 1 and 2 indicate the tower and *t* the time (in our case, half-hour). *N* and *M* are the number of pixels in east-west and north-south direction, *x* and *y* the respective running indices. The minimum function min() includes the source weight *f* computed for the respective tower, x and y location, and half-hour. *O* is 1 if both source weight grids are identical, and 0 in case of no overlap. During stable conditions, the footprint area of a tower increases and can result in considerable source weight contributions from outside the modeling domain. Assuming that two footprints which overlap highly in the modeling domain likely continue to overlap outside the modeling domain, *O* as defined above might be low-biased in such cases. We therefore additionally considered a normalized version *O*/min($\Sigma\Sigma f_1$, $\Sigma\Sigma f_1$) as an upper limit estimate of the overlap. The overlap for the additional sites Kall and Merzenhausen more than 20 km away was assumed zero.

~~3.7.~~3.6. 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}]~~Mauder et al. (2013) determine the instrumental noise based on signal autocorrelation. Following Finkelstein and Sims (2001) the stochastic error is calculated as the statistical variance of the covariance of the flux observations. Generally, σ_{cov}^{noise} was considerably lower than σ_{cov}^{stoch}. The total raw-data based random error σ_{cov} [µmol m^{-2}s^{-1}] was calculated by adding σ_{cov}^{noise} and σ_{cov}^{stoch} "in quadrature" ($\sigma_{cov} = \sqrt{{\sigma_{cov}^{stoch}}^2 + {\sigma_{cov}^{noise}}^2}$) according to Aubinet et al. (2011, p.176). The mean reference σ_{cov} used for the evaluation of the two-tower based random error estimates was calculated by averaging the single ~~raw-data based *NEE* uncertainty~~ half-hourly σ_{cov} values ~~measured at~~for 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:

$$\Delta\sigma_{cov}[\%] = \frac{\sigma(\delta) - \sigma_{cov}}{\sigma_{cov}} * 100 \qquad \textbf{\textit{Eq.}}\ \cancel{5}4$$

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

4 Results

4.1. Classical two-tower based random error estimates

Fig.2 and Fig.3 show the linear regressions of the random error σ(δ) (also referred to as "standard error" or "uncertainty") as function of the *NEE* magnitude ~~determined with~~according to 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 σ(δ) and *NEE* is weak (p > 0.1), which is in particular true for the positive *NEE* values measured ~~at~~for 173 m and 20.5 km EC tower distances as well as for the negative *NEE* values ~~at~~for 20.5 km and 34 km distance. The 95% confidence intervals of the respective slopes and the intercepts are summarized in the Appendix (Tab.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 σ(δ) 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 σ(δ) for positive fluxes for separation distances of 173 m and 20 km whereas in most cases the linear correlation was weakened, mainly due 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 m/s, PPFD < 50 µmol m^{-2} s^{-1}, Temp < 2 °C), which caused a decline of samples in each group from e.g. n > 1000 to 24 or less, resulted in ~~an even weaker correlation of the flux magnitude and the random error σ(δ).~~little meaningful results.

As illustrated in Tab.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 σ(δ) 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~~from the Rollesbroich site. As a result of the weather-filtering, the mean uncertainty ~~estimate decreased~~was less overestimated for the distances 173m ~~(by 10.8%)~~ and 20.5 km~~ (by 13.6%).~~. However, for the 95 m and 34 km distance, the ~~mean~~overestimation of the uncertainty estimate increased by the weather-filtering ~~by up to 15% (95 m~~(Tab.2). 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~~of the classical two-tower approach ~~without weather filter (σ(δ)) and with weather filter (σ(δ)$_f$)~~ with the reference random error estimates σ_{cov}~~ (Tab.2)~~, indicates that ~~σ(δ) and σ(δ)$_f$~~both with and without weather filter the uncertainties were overestimated (Tab.2), for ~~each of the five~~all 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 *NEE* uncertainty estimated with the

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classical two-tower approach ~~results in an overestimation of the *NEE* uncertainty compared to~~is larger than the raw-data based ~~approach~~estimates (Tab.2).

4.2. Extended two-tower approach

The scatter plots in Fig.~~6~~4 illustrate the effect the sfd-correction (Eq.~~4~~2) had on the difference of the *NEE* data simultaneously measured at both EC towers ($NEE_{\text{-EC1-}}$ and $NEE_{\text{-EC2-}}$). 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 $NEE_{\text{-EC1-}}$ and $NEE_{\text{-EC2-}}$ was considerably reduced by the sfd-correction.

A comparison of Fig.2 and Fig.~~4~~5 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~~enhanced 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 >= 0.15 to R^2 >= 0.~~79 (with p <= 0.05).~~43.

Applying the sfd-correction (without weather-filter) reduced the mean uncertainty value by ~~36.7~~41.6% to 56.9% 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~~ EC tower distances from 8m to 34 km. 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} (Tab.2)~~

~~indicates~~indicate that the correction for systematic flux differences considerably improved the two-tower based uncertainty estimate~~: As Tab. 2 shows,~~ for the distances >8 m (Tab.2): The difference $\Delta\sigma_{cov}$ ~~of the independent uncertainty estimates $\sigma(\delta)_{corr}$ and σ_{cov}~~ was notably smaller ~~(<= 49.6~~(< 56.8%) 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~~(< 274.7%). 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~~6) 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~~23.3% and ~~17% compared to $\Delta\sigma_{cov}$ without the weather filter applied~~2.9% for the 20.5 km and the 34 km EC tower distance and reduced $\Delta\sigma_{cov}$ by 57.7% and 7.7%. The effect of the weather-filter on the uncertainty estimates of the shorter EC tower distances was very minor (Tab.2). ~~As shown in Tab.2, the~~The uncertainty estimates $\sigma(\delta)_{corr,f}$ determined with the extended two-tower approach ~~are nearly identical to~~agree best with the independent reference values σ_{cov} for the EC tower distances 95m 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 average percentage footprint overlap is ~~20.4%~~13% (normalized 19%) for the 95 m EC tower distance and only ~~0.9%~~4% (7%) for the 173m EC tower distance, it is ~~61.2%~~68% (80%) for the 8 m EC tower distance. The ~~more frequent overlapping~~stronger overlap 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 to 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 σ(δ) was still higher than the raw-data based reference value~~(Hollinger et al., 2004; Hollinger and Richardson, 2005). However, without applying the sfd-correction, the mean uncertainty estimate σ(δ) was higher than the raw-data based reference value σ_{cov} 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} of 0.~~69~~64 μmol m^{-2}s $^{-1}$ ~~(σ_{cov}^{noise} + σ_{cov}^{stoch})~~ for the dataset of the 8 m EC tower distance. The mean uncertainty value derived with the ~~classical~~extended two-tower approach $\sigma(\delta)_{corr,f}$ for the same dataset was ~~0.76 μmol m^{-2}s $^{-1}$ and thus~~lower than σ(δ) but still considerably 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

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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 (Tab.2).~~

For the larger separation distances 95 m or 173 m~~, footprints were~~ with notably less ~~overlapping and~~footprint overlap 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 (sec. 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)~~ As outlined in section 2, land surface properties related to management (e.g. nutrient availably due to fertilization), soil properties (bulk density, skeleton fraction), soil carbon-nitrogen pools, soil moisture and soil temperature are heterogeneously distributed at the Rollesbroich site. The effect~~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] 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 2013, personal communication); (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 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, in prep.). The affect~~ 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). Results indicate that an overestimation of the two-tower based uncertainty caused by different land surface properties in the footprint area of both EC towers can be successfully filtered out by the extended approach. It should be noted that a shorter moving average interval of the sfd-correction term (e.g. 6 hours instead of the applied 12 hours window; Tab.A2), results in slightly lower uncertainty estimates compared to the reference. This can be explained by a possible "over-correction" of the *NEE* data related to a too short moving average interval for calculating the sfd-correction term. It needs to be emphasized that the estimated mean *NEE* values of the moving average intervals are associated with uncertainty. As mentioned, the moving average 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 12hr running mean *NEE1* and *NEE2* values (NEE_{12}) as well as the respective means of *NEE1* and *NEE2* (NEE_{2T_12}) used to calculate NEE_{corr} (Eq.2) are uncertain because they still contain the random error part which cannot be corrected or filtered out. This uncertainty in the mean is expected to be higher for a shorter averaging interval such as 6 hours. Therefore, completely correcting the difference in mean *NEE* slightly overcorrects systematic differences in *NEE*. ~~. 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 effect respiration more directly than photosynthesis which also agrees with the findings in~~In general results were not very sensitive to different moving average sizes of the sfd-correction term and data coverage percentages defined for this interval (Tab.A3).

It is expected that systematic differences in measured *NEE* caused by spatially variable land surface properties are stronger during the night than during the day since they affect respiration more directly than photosynthesis (see e.g. 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.~~. Moreover, during night-time and/or winter (positive *NEE*), some conditions associated with lower EC data quality such as low turbulence, strong stability, and liquid water in the gas analyzer path prevail more often than in summer and/or daytime (negative *NEE*). The less severe cases of such conditions are not always completely eliminated by the quality control. In time series of eddy-covariance fluxes this typically shows up as implausible fluctuations of the flux during calm nights. This is reflected by plots of *NEE* flux magnitude versus uncertainty (Fig.2-3; Fig.5-6) showing higher uncertainties for positive compared to negative *NEE* data which agrees with previous findings (e.g. Richardson et al., 2006).

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 ~~(section 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~~ $\Delta\sigma_{cov}$ was reduced by ~~80~~85.7% for the 20.5km distance and ~~82~~79.3% for the 34km if both sfd-correction and weather filter were used. However, after applying the sfd-correction and the weather-filtering, the mean uncertainty estimate was still higher than the raw-data based reference value (Tab.2), suggesting that for these large EC tower distances the sfd-correction and the weather-filter do not fully capture systematic flux differences and uncertainty is still overestimated by the extended two-tower approach. This can have different reasons. We assume the major reason is that the weather-filter is supposed to capture all measured flux differences that can be attributed to different weather conditions at both EC towers which cannot be captured with the sfd-correction. Applying stricter thresholds could increase the efficiency of the weather filter but in our case the reduced dataset was too small to allow further analysis. 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. ~~for the large EC tower distances was still 33.2% and 49.6% higher than the raw-data based reference value (Tab.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.~~In contrast, such systematic differences were difficult to capture with the weather-filter because much lower thresholds would have been required.

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 (Tab.2~~), which is counterintuitive.~~). 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 (Tab.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 ~~(Tab.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 12hr moving averaging intervals which were used to calculate the sfd-correction term (section 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 12hr 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 they still contain the random error part that cannot be corrected or filtered out.~~ 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), and also the regression coefficients (Fig. 2-3; Fig.5-6, Tab. A1) do not show large differences. This can be expected since Richardson et al. (2006) applied their method for a very well-suited tower pair with low systematic differences, such that the classical approach and our extended approach should approximately converge. However, identical results are unlikely because even for two very similar neighboring sites some systematic differences occur. In addition, the random error is expected to vary between sites (see e.g. Mauder et al., 2013) which is in part related to instrumentation.~~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 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~~probably 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 ~~(Tab.1, Sec.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~~.~~ of the two-tower approach. While systematic differences of the weather conditions are expected to be captured by the sfd-correction, less systematic weather fluctuations e.g. 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~~too small dataset, especially if the

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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).

Appendix A

Tab. A1

Summary of the 95% confidence intervals for the linear regression coefficients of the NEE magnitudes - standard error relationships determined with Eq.1 for the four two two-tower based correction schemes and the five 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)	-0.036	-0.048	-0.024	0.227	0.125	0.329
	EC1 / EC2 (95 m)	-0.043	-0.072	-0.014	0.699	0.379	1.018
	EC1 / EC2 (173 m)	-0.052	-0.087	-0.017	0.485	-0.059	1.030
	EC1 / EC2 (20.5 km)	-0.085	-0.142	-0.028	1.033	0.312	1.754
	EC1 / EC3 (34 km)	-0.092	-0.129	-0.055	0.963	0.421	1.505
$NEE_{negative}$ / $\sigma(\delta)_{corr.f}$	EC1 / EC2 (8 m)	-0.040	-0.060	-0.019	0.211	0.053	0.369
	EC1 / EC2 (95 m)	-0.044	-0.074	-0.013	0.574	0.252	0.895
	EC1 / EC2 (173 m)	-0.071	-0.122	-0.021	0.272	-0.440	0.983
	EC1 / EC2 (20.5 km)	-0.106	-0.204	-0.009	0.493	-0.685	1.671
	EC1 / EC3 (34 km)	-0.070	-0.108	-0.031	0.981	0.346	1.616
$NEE_{positive}$ / $\sigma(\delta)$	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)	0.083	0.043	0.123	0.089	-0.106	0.284
	EC1 / EC2 (95 m)	0.074	0.054	0.094	0.165	0.094	0.236
	EC1 / EC2 (173 m)	0.172	-0.093	0.436	-0.110	-1.979	1.759
	EC1 / EC2 (20.5 km)	0.245	0.122	0.367	-0.328	-0.938	0.282
	EC1 / EC3 (34 km)	0.162	0.135	0.189	0.080	-0.015	0.175
$NEE_{positive}$ / $\sigma(\delta)_{corr.f}$	EC1 / EC2 (8 m)	0.078	0.037	0.118	0.101	-0.102	0.303
	EC1 / EC2 (95 m)	0.090	0.030	0.150	0.136	-0.142	0.414
	EC1 / EC2 (173 m)	0.163	-0.132	0.459	-0.040	-2.081	2.000
	EC1 / EC2 (20.5 km)	0.159	-0.094	0.413	0.072	-1.205	1.349

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EC1 / EC3 (34 km)	0.205	0.132	0.279	0.029	-0.278	0.337

*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 & with weather filter (f)
~~)~~
$\sigma(\delta)_{corr}$, $\sigma(\delta)_{corr,f}$: uncertainty estimated with extended two-tower approach

Tab. A2: R^2 for NEE uncertainty determined with the extended two-tower approach (including sfd-correction and weather-filter) as function of NEE_{corr} magnitude and for 20.5km EC tower distance. Results are given for different moving average time intervals (6 hr, 12 hr, 24hr) and data coverage percentages (25%, 50%, 70%) for the calculation of the sfd-correction factor (Eq.2)

	6h	**12h**	**24h**
30%	0.73; 0.84; *(937)*	0.92; 0.72; *(904)*	0.84; 0.82; *(597)*
50%	0.58; 0.85; *(710)*	0.7; 0.43; *(463)*	-; -; *(32)*
70%	0.77; 0.78; *(408)*	0.66; 0.08; *(148)*	-; -; *(0)*

black: for negative NEE; grey: for positive NEE; (): total number of half-hourly NEE left after sfd-correction and weather filter to build bins for NEE uncertainty versus NEE magnitude regressions (Fig.5 for 12h & 50 %)

Tab. A3: Relative difference [%] of mean uncertainty $\sigma(\delta)_{corr,f}$ estimated with the extended two tower approach and the reference σ_{cov} for EC tower distances > 8m

Diff	**$\Delta\sigma_{cov}$ (6h)**	**$\Delta\sigma_{cov}$ (12h)**	**$\Delta\sigma_{cov}$ (24h)**
30%	-0.8; 39.3	4.8; 55.5	10.9; 59.9
50%	-9.3; 32.5	-1.5; 41.2	-
70%	-10.5; 24.3	-5.2; 10.2	-

black: mean $\Delta\sigma_{cov}$ for 95m and 173m distance ; grey: mean $\Delta\sigma_{cov}$ for 20.5 km and 34 km distance

Acknowledgments. We are grateful to ExpeER (Experimentation in Ecosystem Research) for funding this work. The eddy covariance data were provided by TERENO and the Transregional Collaborative Research Centre 32 (TR32). We also thank Wittaya Kessomkiat for his support. Moreover, we thank Qu Wei for providing the SoilNet data and Henning Schiedung for providing the soil carbon and soil density data for the Rollesbroich site.

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Table Captions

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

Tab. 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).

Figure Captions

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Fig. 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

Fig. 2. NEE uncertainty σ(δ) determined with the classical two-tower approach as function of the NEE flux magnitude for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e). (Dashed line: linear correlation not significant (*p*>0.1))

Fig. 3. NEE uncertainty σ(δ) 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 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e). (Dashed line: linear correlation not significant (*p*>0.1))

Fig. 4. 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 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e)

Fig. 5. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq.~~3~~2) for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e) (Dashed line: linear correlation not significant (*p*>0.1))

Fig. ~~5~~6. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq.~~3~~2) including application of the weather-filter for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e) (Dashed line: linear correlation not significant (*p*>0.1))

~~Fig. 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 NEEcorr (right) for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e)~~

Tab. 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	–	13.05.2011 – 15.07.2013	514.7
EC2	50.6219012 N / 6.3040107 E 50.6219012 N / 6.3040107 E	Rollesbroich	8m	29.07.2011 – 06.10.2011 05.03.2013 – 15.05.2013	514.8
	50.6217990 N / 6.3027962 E 50.6210472 N / 6.3042120 E	Rollesbroich	95m	07.10.2011 – 15.05.2012 01.07.2013 – 15.07.2013	516.3 517.3
	50.6217290 N / 6.3016925 E	Rollesbroich	173m	24.05.2012 – 14.08.2012	517.1
	50.5027500 N / 6.5254170 E	Kall-Sistig	20.5 km	14.08.2012 – 01.11.2012 15.05.2013 – 01.07.2013	498.0
EC3	50.9297879 N / 6.2969924 E	Merzenhausen	34 km	10.05.2011– 16.07.2013	93.3

Tab. 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 (σ(δ), σ(δ)$_f$). and with the extended two-tower approach (sfd-correction), also with and without including a weather-filter (σ(δ)$_{corr}$, σ(δ)$_{corr,f}$). 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*	σ(δ) (Δσ$_{cov}$)	σ(δ)$_f$ (Δσ$_{cov}$)	σ(δ)$_{corr}$ (Δσ$_{cov}$)	σ(δ)$_{corr,f}$ (Δσ$_{cov}$)	σ$_{cov}$
8m	*3167*	0.76 (~~10.9~~18.8)	0.77 (~~12.4~~20.5)	0.~~48 (-29.8~~44 (-30.6)	0.~~49 (-28.1~~44 (-30.8)	0.~~69~~64
95m	*3620*	1.30 (~~101.4~~116.7)	1.50 (~~131.8~~149.4)	0.~~67 (3.9~~65 (8.2)	0.~~63 (-~~60 (0.2~~.6~~)	0.~~65~~60
173m	*2410*	2.04	1.82	1.~~05 (-~~03 (-	1.~~07 (-1.7~~00 (-	1.~~09~~03

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		(~~87.7~~98.5)	(~~67.4~~77.0)	0.3.~~7~~)	2.5)	
20.5 km	*2574*	2.72 (~~182.4~~200.6)	2.35 (~~144.1~~159.7)	1.~~44 (49.6~~52(67.8)	1.16 (28 (~~33.2~~.7)	0.~~96~~91
34 km	*15571*	2.73 (~~249.1~~274.7)	2.86 (~~265.5~~292.4)	1.~~25 (59.8~~18 (61.5)	1.~~17 (49.6~~14 (56.8)	0.~~78~~73
mean		1.91	1.86	0.98	0.93	0.~~83~~78

($\Delta\sigma_{cov}$): relative differences [%] between two-tower based uncertainty estimates and the references value σ_{cov} (Eq.~~5)~~4)

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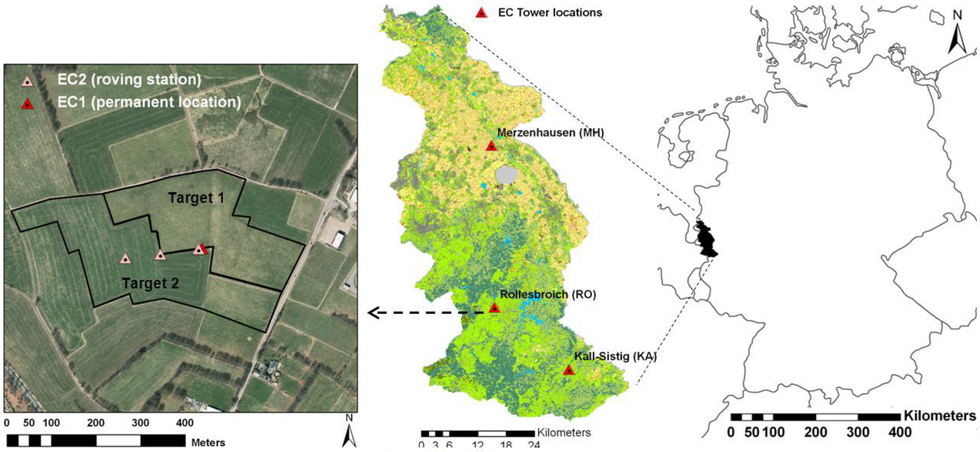

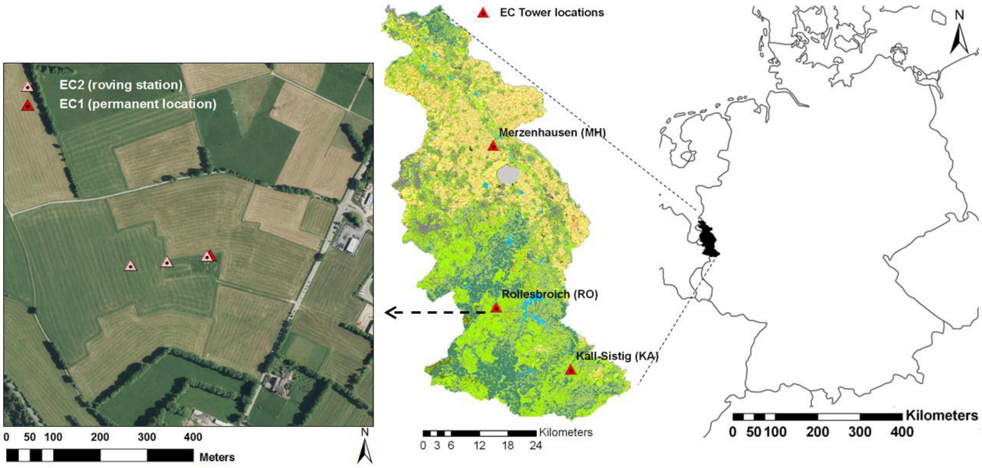

Fig. 1. Eddy covariance (EC) tower locations in the Rur-Catchment (center) including the Rollesbroich test site (left~~), with the target areas defined for the footprint analysis~~)

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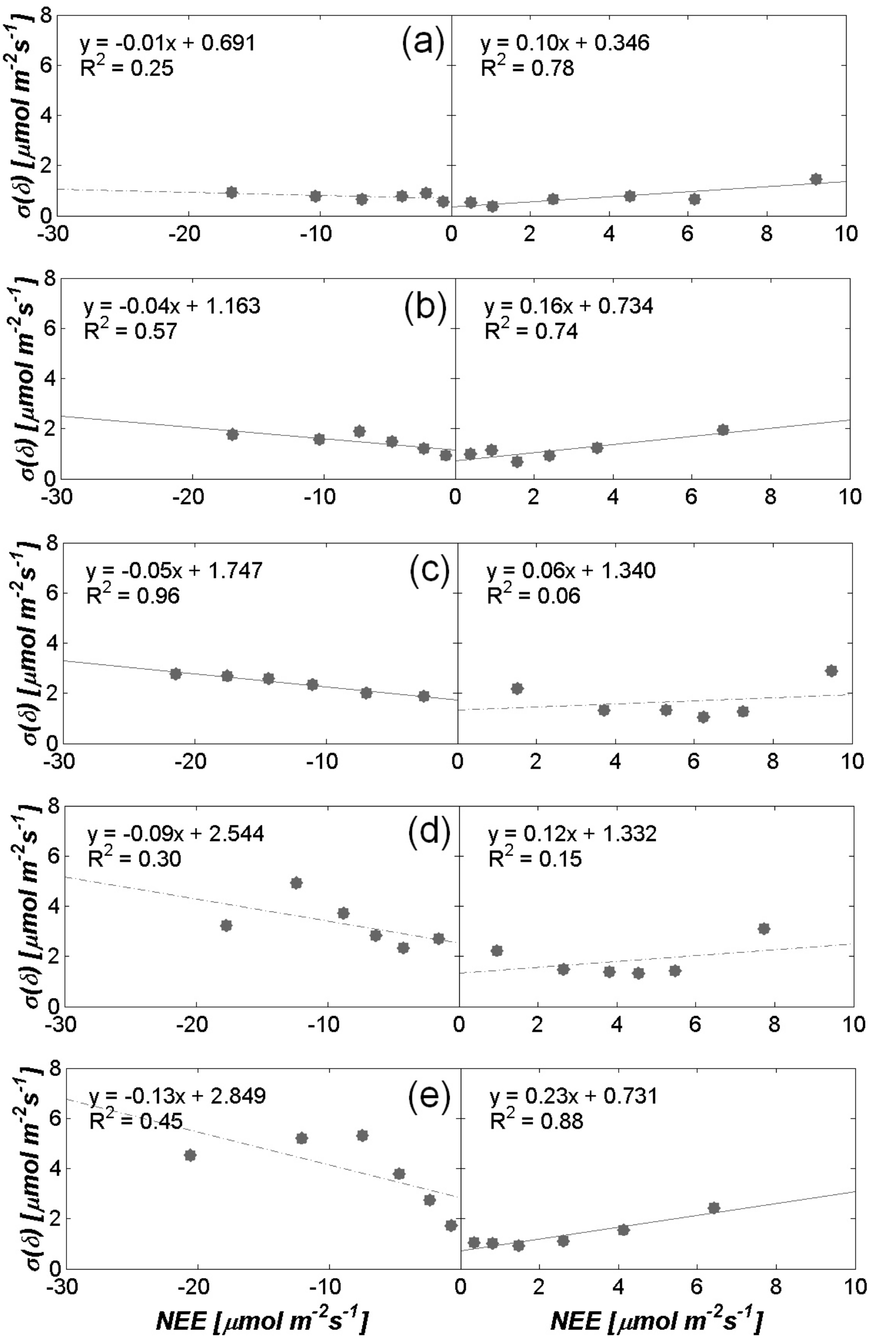
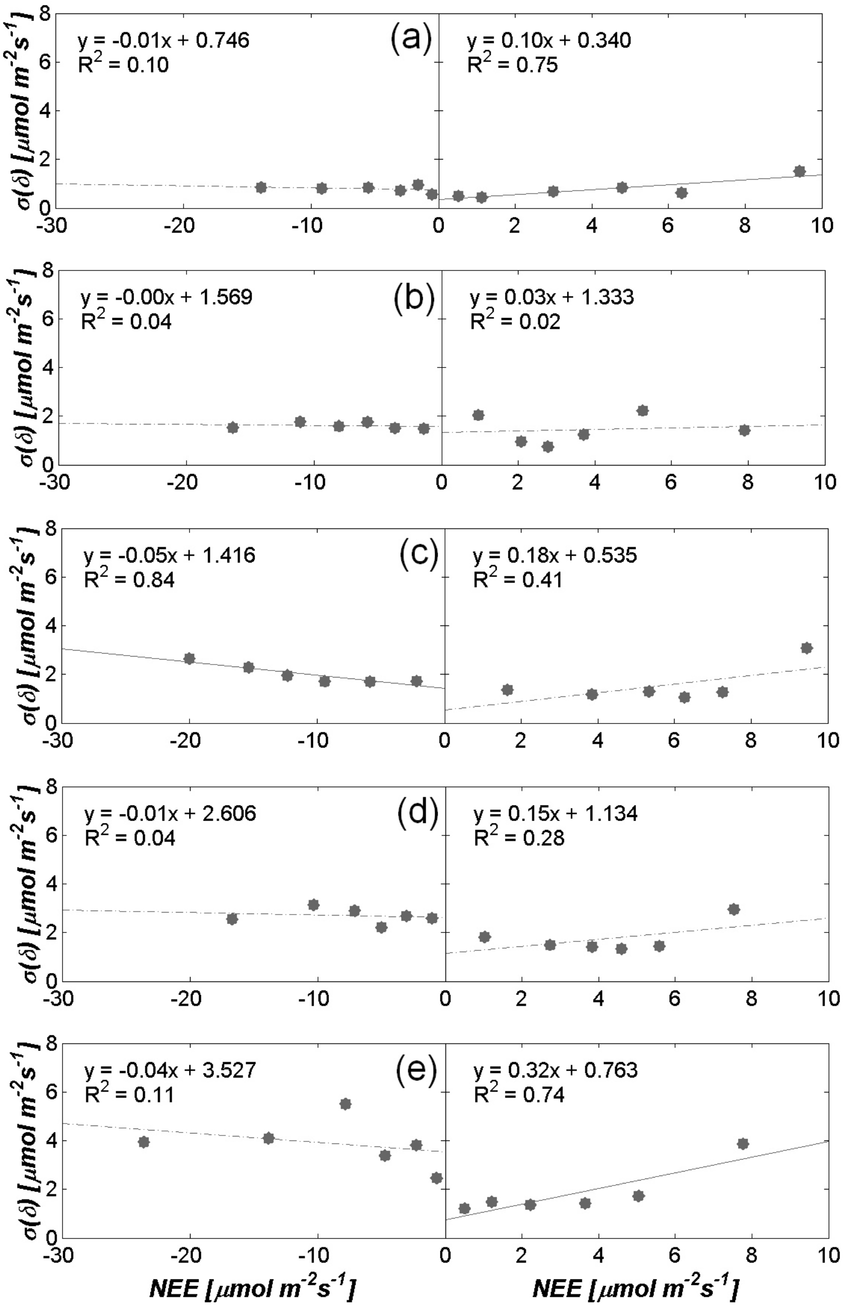


Fig. 2. NEE uncertainty σ(δ) determined with the classical two-tower approach as function of the NEE flux magnitude for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e). (Dashed line: regression slope not significantly different from zero (p>0.1))


(a)
y = -0.01x + 0.746
R2 = 0.10
y = 0.10x + 0.340
R2 = 0.75
(b)
y = -0.00x + 1.569
R2 = 0.04
y = 0.03x + 1.333
R2 = 0.02
(c)
y = -0.05x + 1.416
R2 = 0.84
y = 0.18x + 0.535
R2 = 0.41
(d)
y = -0.01x + 2.606
R2 = 0.04
y = 0.15x + 1.134
R2 = 0.28
(e)
y = -0.04x + 3.527
R2 = 0.11
y = 0.32x + 0.763
R2 = 0.74
σ(δ) [μmol m-2s-1]
NEE [μmol m-2s-1]
NEE [μmol m-2s-1]

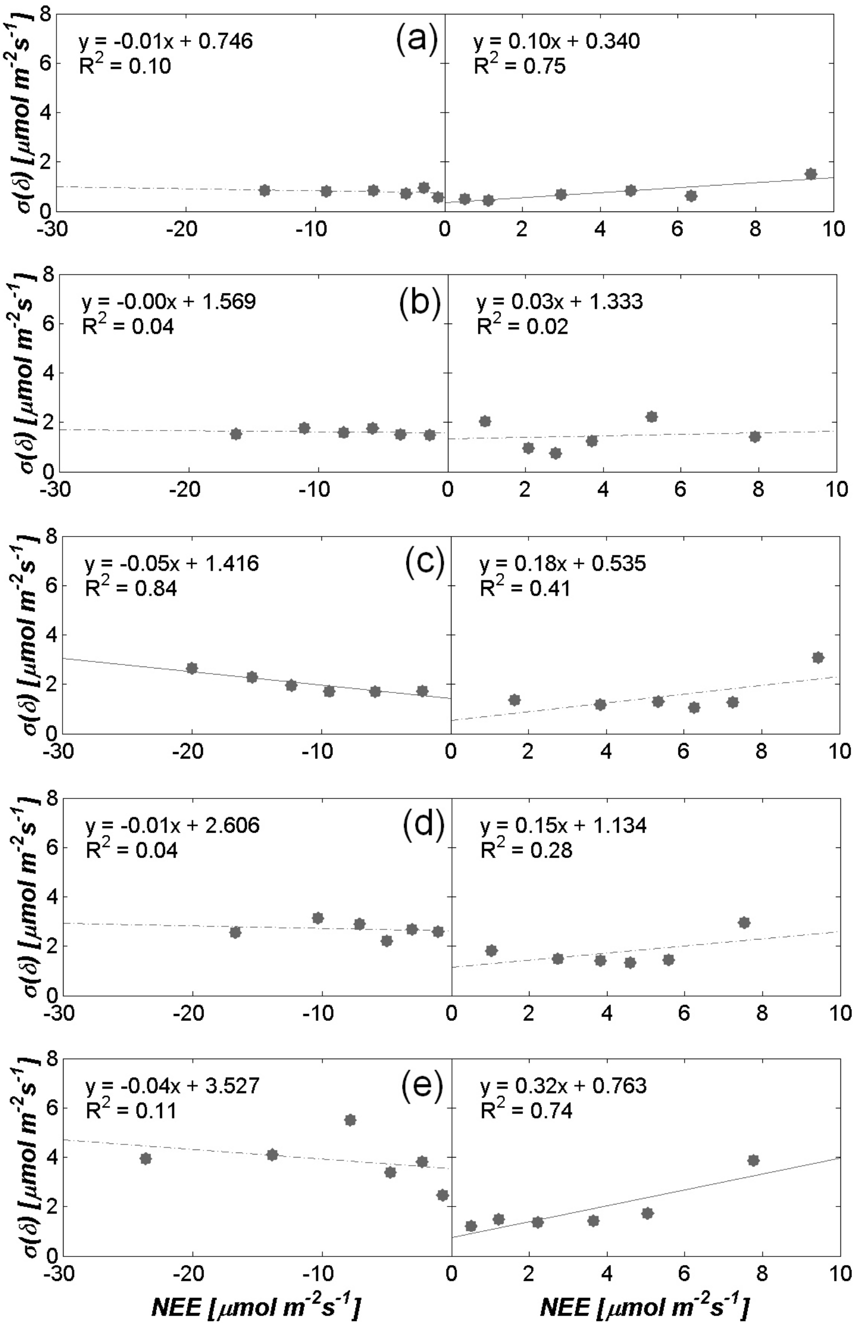


Fig. 3. NEE uncertainty σ(δ) determined with the classical two-tower approach as function of the NEE flux magnitude including the application of the weather-filter for the EC tower distances 8m

(a), 95m (b) , 173m (c), 20.5km (d) and 34km (e). (Dashed line: regression slope not significantly different from zero (p>0.1))

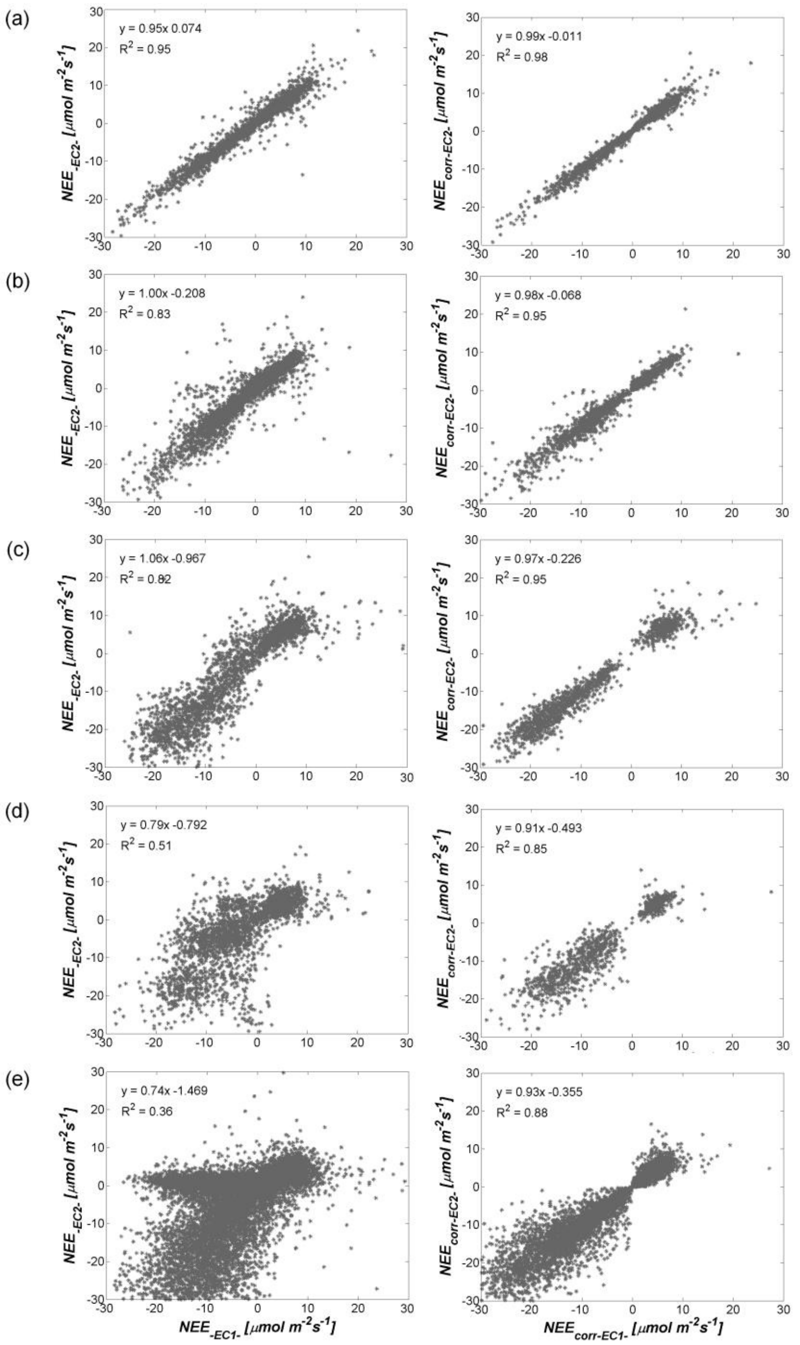
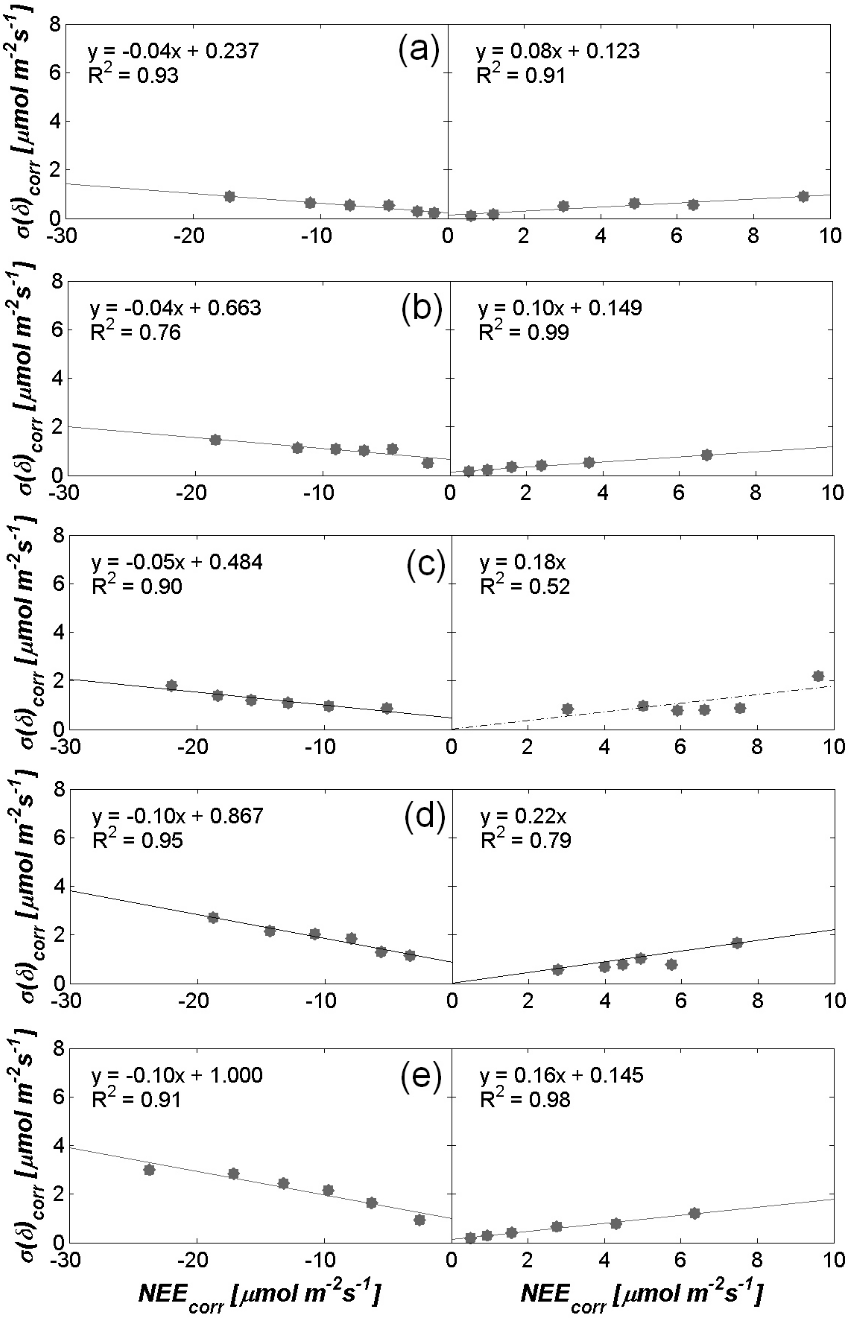


Fig.4. Scatter of the NEE measured at EC1 (NEE_{-EC1-}) and NEE measured at a second tower EC2/EC3 (NEE_{-EC2-}) for the uncorrected NEE (left) and the sfd-corrected NEE_{corr-} (right) for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34 km

1126



(a)
y = -0.04x + 0.237
R^2 = 0.93
y = 0.08x + 0.123
R^2 = 0.91
(b)
y = -0.04x + 0.663
R^2 = 0.76
y = 0.10x + 0.149
R^2 = 0.99
(c)
y = -0.05x + 0.484
R^2 = 0.90
y = 0.18x
R^2 = 0.52
(d)
y = -0.10x + 0.867
R^2 = 0.95
y = 0.22x
R^2 = 0.79
(e)
y = -0.10x + 1.000
R^2 = 0.91
y = 0.16x + 0.145
R^2 = 0.98
$\sigma(\delta)_{corr}$ [$\mu mol\ m^{-2}s^{-1}$]
NEE_{corr} [$\mu mol\ m^{-2}s^{-1}$]

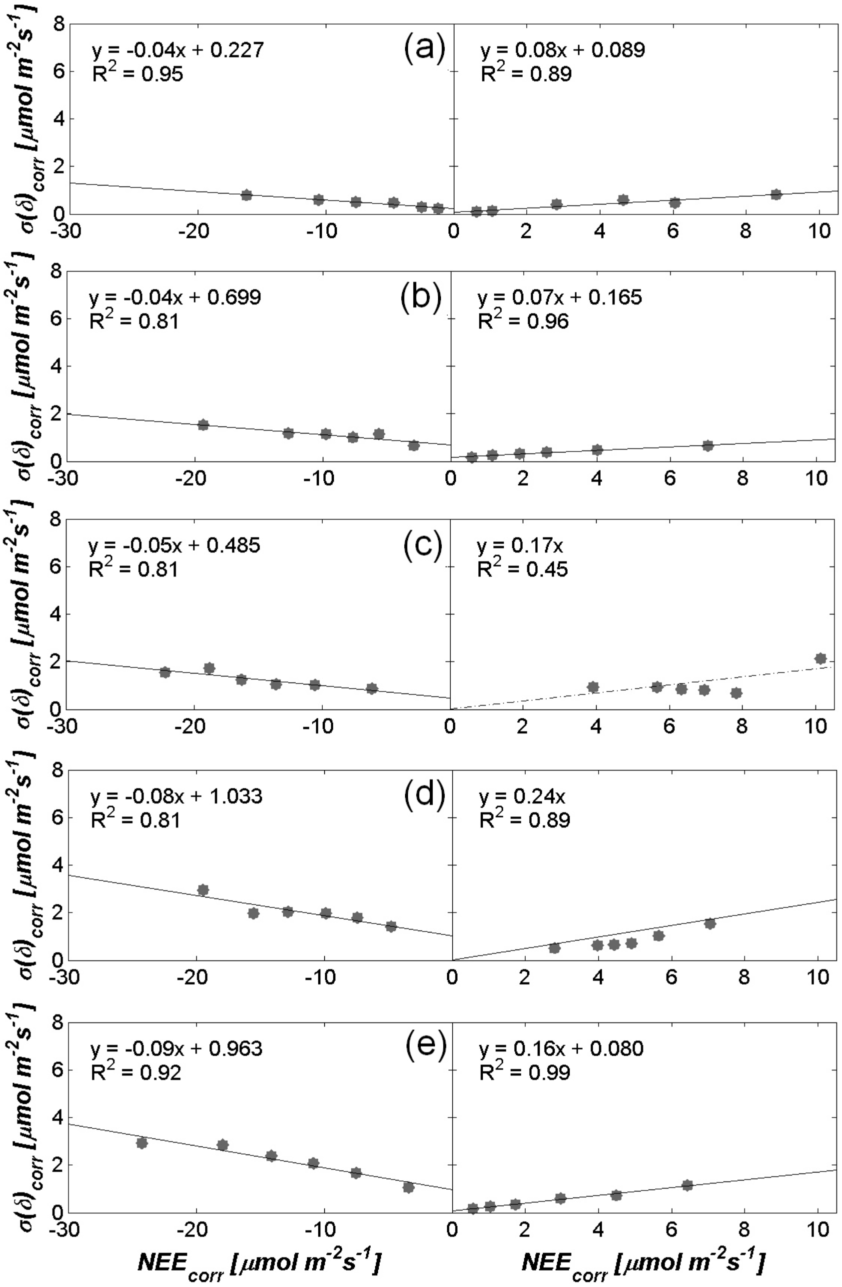
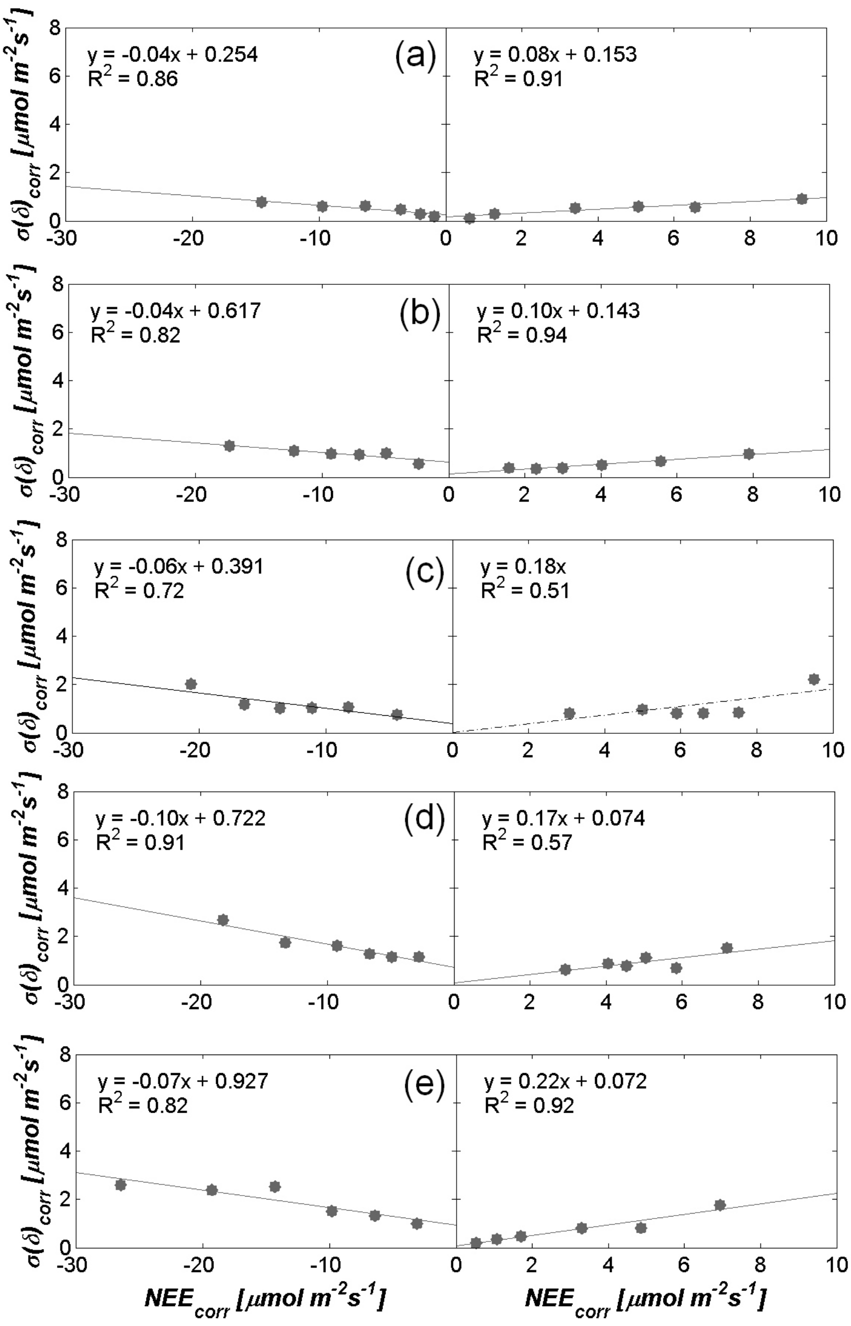


Fig.~~4~~5. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq.~~3~~2) for the EC tower distances 8m (a), 95m (b), 173m (c), 20.5km (d) and 34km (e) (Dashed line: regression slope not significantly different from zero (p>0.1))



y = -0.04x + 0.254
R2 = 0.86
(a)
y = 0.08x + 0.153
R2 = 0.91
y = -0.04x + 0.617
R2 = 0.82
(b)
y = 0.10x + 0.143
R2 = 0.94
y = -0.06x + 0.391
R2 = 0.72
(c)
y = 0.18x
R2 = 0.51
y = -0.10x + 0.722
R2 = 0.91
(d)
y = 0.17x + 0.074
R2 = 0.57
y = -0.07x + 0.927
R2 = 0.82
(e)
y = 0.22x + 0.072
R2 = 0.92
σ(δ)corr [μmol m-2s-1]
NEEcorr [μmol m-2s-1]

1132

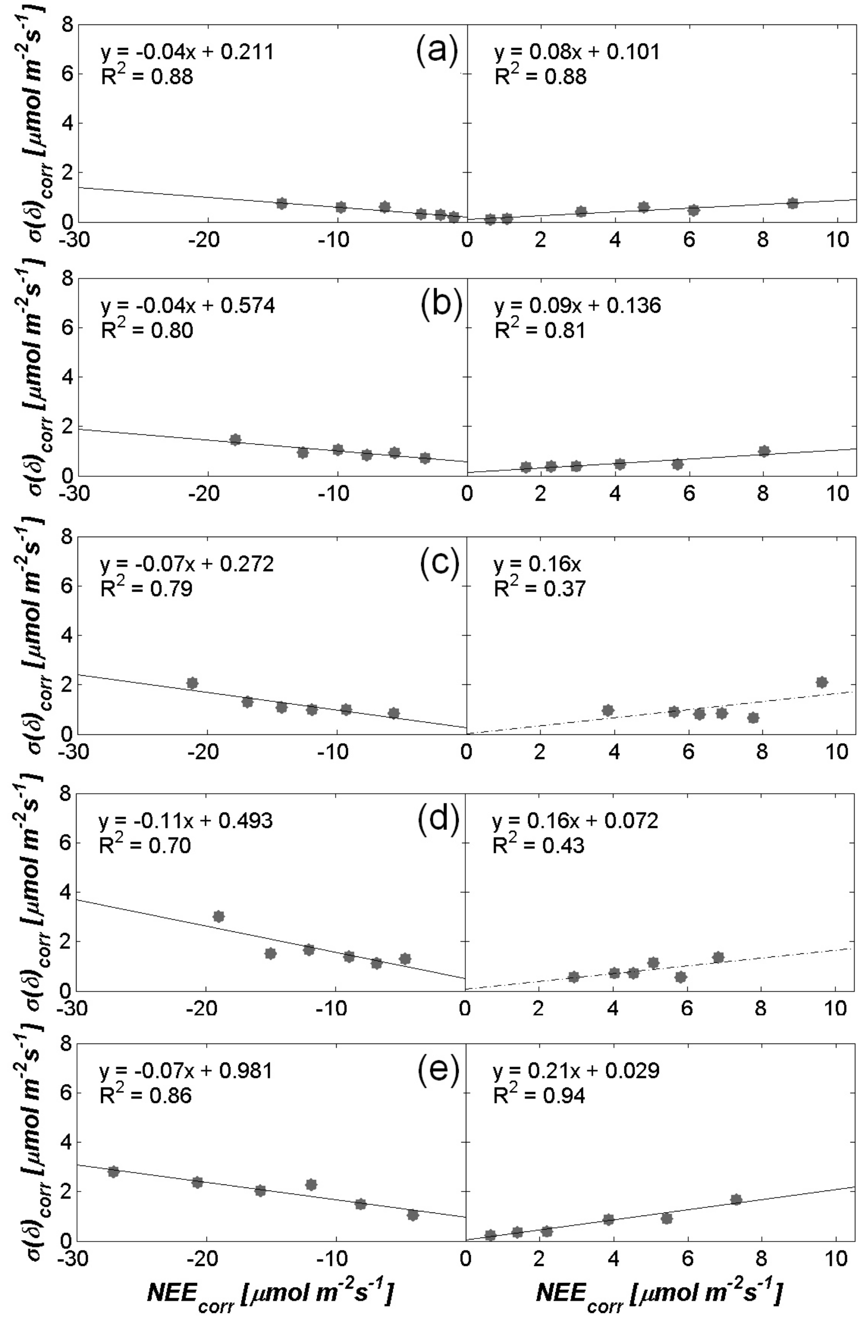


Fig.~~5~~6. NEE uncertainty $\sigma(\delta)_{corr}$ determined with the extended two-tower approach as function of sfd-corrected NEE_{corr} magnitude (Eq.~~3~~2) including application of the weather-filter for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d) and 34km (e) (Dashed line: regression slope not significantly different from zero (p>0.1))

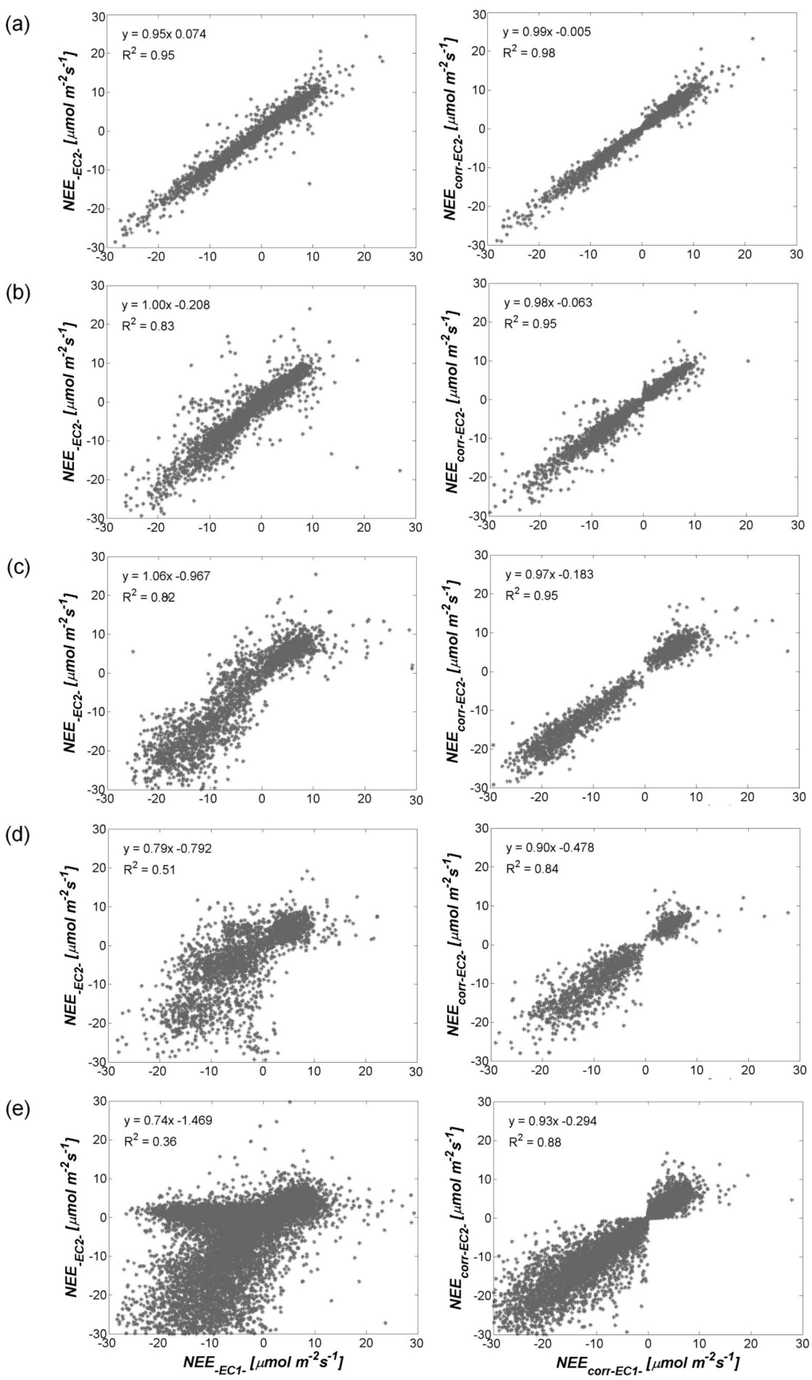


Fig.6. ~~Scatter of the NEE measured at EC1 (NEE~~ $\cancel{_{-EC1-}}$ ~~) and NEE measured at a second tower EC2/EC3 (NEE~~ $\cancel{_{-EC2-}}$ ~~) for the uncorrected NEE (left) and the sfd-corrected NEE~~ $\cancel{_{corr}}$ ~~(right) for the EC tower distances 8m (a), 95m (b) , 173m (c), 20.5km (d)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

~~*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 sec.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 & with weather filter (f)~~

~~$\sigma(\delta)_{corr}$, $\sigma(\delta)_{corr,f}$: uncertainty estimated with extended two-tower approach~~

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