Author response to the reviewers comment from Anonymous Referee #3 on the manuscript amt-2018-392: “Low-cost eddy covariance: a case study of evapotranspiration over agroforestry in Germany”

We thank you for your feedback, suggestions and helpful comments on the manuscript. In the current document we give a point-by-point answer on above mentioned referee report. We show first the referee comments (**RC**) and secondly the answer of the authors (**AR**). Changes made in the manuscript can be found in the track changes document attached to the current document. Figure numbers and references refer to the track-changes document, if not otherwise stated. We are still editing the manuscript and will perform minor changes explicitly stated in the text.

1. RC: *General comments*

This manuscript presents a test of a low-cost hygrometer manufactured by Bosch GmbH being used for eddy-covariance measurements. The sonic anemometer is the same as for regular eddy-covariance system being deployed. Another difference between the low-cost system and the regular system is the data acquisition, which is realized by a Raspberry Pi instead of a Campbell CR6 data logger. The regular EC system has a Licor LI7200 for measuring water vapor and CO2 fluctuations. I doubt that the data acquisition causes significant differences in the collected data since both systems are recording digitally. So, the main question of this study is, whether the precision and the spectral response characteristics of the Bosch hygrometer are sufficient for eddy covariance applications. The results of evapotranspiration show a good agreement, if adequate spectral corrections are applied, which leads the authors to the main conclusion that this low-cost system is an alternative when a larger number of measurement units is required for a certain application. I generally agree with this assessment; however, I suggest that a more extensive evaluation of the spectral response characteristics of the Bosch sensor based on the collected field data should be presented, e.g. the system’s cut-off frequency based on in-situ assessment method of Ibrom et al. (2007) and the transfer function of the Moncrieff et al. method. This would perhaps also better explain why the one method gave different results than the other.

1. AR: We included more information on the spectral response characteristics of the thermohygrometer. In detail, we derived the cut-off frequency and the sensor time constant from water vapour mole fraction spectra as a function of relative humidity. And we included information on the spectral correction factor for both the low-cost and conventional EC system. See the author response 5 of the current document for more information.

In a lab experiment we estimated the sensor time constant of the temperature and relative humidity sensor of the BME280. The time constant of the temperature sensor was 23.3 ± 0.9 s as a mean over 4 replications. Preliminary results showed a faster time response of the relative humidity sensor. The lab experiment will be continued in the next days and results will be included in the revised manuscript, perhaps in the Materials and Methods section.

Thank you for comment and suggestion on differences found between the two different high-frequency spectral corrections. One explanation of differences found for the two different high-frequency spectral corrections is the low amount of data. The in-situ assessment method of Ibrom et al. (2007) requires at least one month of data to successfully estimate the transfer functions cut-off frequency. For shorter time periods the cut-off frequency might not be appropriate. Therefore, the corrections might be performed in a wrong frequency range.

In contrast, for the high-frequency correction after Moncrieff et al. (1997) a transfer function is estimated for each 30-min period and is therefore independent on the amount of data. We will follow your advice and show first the cut-off frequencies in dependence on relative humidity for the Ibrom et al. (2007) spectral correction and second an average transfer function after Moncrieff et al. (1997) for the sites.

2. RC: *Minor comments*

Abstract: I find the abstract too long, I am not sure though, if this journal has any limits in that respect. E.g. the introductory sentences could be shortened. Nevertheless, I would suggest to mention the main results, perhaps even including information about the RMSE.

2. AR: We shortened the Abstract as shown below.

Abstract. ~~Eddy covariance has evolved as the method of choice for measurements of the ecosystem-atmosphere exchange of water vapour, sensible heat and trace gases. Under ideal conditions, eddy covariance provides direct and precise flux observations, commonly approximated from single-point eddy covariance measurements. While eddy covariance is appropriate over uniform terrain of infinite extent, heterogeneous land surfaces compromise the representativity of single-point measurements as a predictor for ecosystem-wide fluxes and violate assumptions of the eddy covariance method. Therefore heterogeneous~~ Heterogeneous land surfaces require multiple measurement units for spatially adequate sampling and representative fluxes. The complexity and cost of traditional eddy covariance ~~instruments~~ set-ups typically limits the feasible number of sampling units. Therefore, new low-cost eddy covariance systems ~~are required~~ provide ideal opportunities for spatially replicated sampling~~, not only to increase the representativity of turbulent fluxes at a single site, but also for experiments where replication is required to e.g. compare different ecosystems~~.

The aim of this study was to test the performance of a compact low-cost pressure, temperature and relative humidity sensor for the application of evapotranspiration measurements by eddy covariance over agroforestry and conventional agriculture in Germany. We performed continuous low-cost eddy covariance measurements over agroforestry and conventional agriculture for reference, at five sites across Northern Germany over a period of two years from 2016 to 2017. We conducted side-by-side measurements using a roving enclosed-path eddy covariance set-up to assess the performance of the low-cost eddy covariance set-up.

Evapotranspiration measured with low-cost eddy covariance compared well with fluxes from conventional eddy covariance. ~~Diel cycles of evapotranspiration were well represented at a 30-min resolution. The differences between low-cost and conventional eddy covariance at 30-min resolution were small relative to the diel amplitude of the fluxes.~~ The slopes of linear regressions for evapotranspiration comparing low-cost and conventional eddy covariance set-ups ranged from 0.86 to 1.08 for five out of ten sites, indicating a 14% flux underestimation and a 8% flux overestimation relative to the conventional EC set-up, respectively. Corresponding coefficients of determination, R^2 ~~values~~, ranged from 0.71 to 0.94 across sites. ~~This indicates that a high proportion of the flux variability of the conventional eddy covariance set-up is reproduced by the low-cost eddy covariance set-up.~~ The root mean square error for differences between latent heat fluxes obtained by both set-ups were small compared to the overall flux magnitude, with a mean and standard deviation of 34.23±3.2 W m^{-2}, respectively, across sites.

The spectral response characteristics of the low-cost eddy covariance set-up were inferior to the eddy covariance set-up in the inertial sub-range of the turbulent spectrum. The water vapour flux cospectrum of the low-cost eddy covariance set-up underestimated the theoretical slope of -4/3 stronger than the conventional eddy covariance set-up. This underestimation is mainly caused by the limited response time of the low-cost thermohygrometer of one second~~, which prevents eddies of a frequency higher than two times the response time to be adequately sampled by the thermohygrometer~~.

We conclude that low-cost eddy covariance sensors are an alternative to conventional eddy covariance sensors when~~spatial~~, first, replicates are required ~~or when the scientific questions require a larger number of measurement units. An appropriately chosen high-frequency correction method is essential for the slow response sensor. The new low-cost eddy covariance set-up is a viable alternative, particularly when~~ and, second, the spatial variability of fluxes

3. RC: *P2, L10-21: It is not clear how this is relevant for the topic of this paper. Perhaps omit these sentences, although they are correct.*

3. AR: We shortened this paragraph and focused on the most important parts.

1 Introduction

Eddy covariance (EC) is often the method of choice for measurements of the ecosystem-atmosphere exchange of water vapour, sensible heat, momentum and trace gases (Baldocchi (2003), Baldocchi (2014), Farahani et al. (2007)) over a variety of ecosystems. ~~However, the EC method has a number of assumptions and is therefore only valid for measurements under stationary conditions, i.e. no change of the means of the scalar quantity with time (c.f. Taylor's hypothesis of frozen turbulence), over horizontally homogeneous terrain in the presence of a mean zero vertical velocity component and a negligible density flux (Foken and Wichura (1996), Katul et al. (2012)). Above conditions are rarely met over real ecosystems.~~

~~The concept of the flux footprint (Schmid, 2002) allows to relate the observed fluxes to a spatial region of the underlying surface. Position and extent of the footprint can be optimized to fit the target surface by adjusting tower position and measurement height, respectively. However, in heterogeneous landscapes, there are situations where the footprint from a single tower can not adequately capture the spatial variability of the underlying surface. This is often the case in agriculture landscapes with multiple crops and in spatially heterogeneous ecosystems. At sites with spatial variability of surface cover this can mean, depending on the footprint extent, that~~ At ecosystems with spatial variability of surface cover, the representativity of the measured fluxes is limited by the flux footprint extend (Schmid, 2002). Either the spatial variability of fluxes ~~can either remain~~ remains undetected (for small footprints) or can not be resolved explicitly (for large footprints). Such heterogeneous ecosystems require multiple towers for spatially representative flux sampling.

While the single-tower approach is still most common for ecosystem studies, a few studies have performed replicated EC measurements. Davis et al. (2010) studied carbon fluxes over an arable site in South East Ireland. Loescher et al. (2017) used a set of two flux towers separated by a distance of 775 m for uncertainty estimation of EC flux measurements.

Replication of sampling points was traditionally limited by high costs and the complexity of conventional EC setups. Therefore, there is increasing interest in the development of low-cost sensors for different applications in the biogeosciences.

4. RC: *L9, L7: How were the clocks of the two systems synchronized and how good was this synchronization. It needs to be better than 0.05 s.*

4. AR: We agree that this sentence was misleading. We changed the line accordingly. This sentence should rather be understood as matching of data sets. The turbulence data, the 3D wind and the sonic temperature, were sampled with a frequency of 20 Hz and the air temperature, relative humidity and air pressure were sampled with a frequency of 8 Hz on two data acquisition systems, the CR6 logger and the RaspberryPi, respectively. We matched the two different time stamps during preprocessing according to the nearest neighbour time stamp. Regarding the synchronization of the two different data acquisition systems, the time stamp of the RaspberryPi was synchronized hourly with an online ntp server, whereas the time on the CR6 logger was manually set during regular maintenance visits.

We corrected for a time lag between the 3D wind velocity and the sonic temperature recorded with the CR6 logger and the water vapour mole fraction recorded with the RaspberryPi during preprocessing, using the cross correlation function ccf (R-package ccf). We assume that the drift of the two acquisition systems is inside the window of the cross correlation function of 62.5 s.

We ~~synchronized~~ matched the water vapour mole fraction calculated from the thermohygrometer data and the velocity components measured with the ultrasonic anemometer according to the nearest-neighbour date values to address the two different sampling frequencies of 8 Hz and 20 Hz, respectively. The two data acquisition systems (the CR6 logger and the RaspberryPi, respectively) were regularly manually synchronized. In detail, the RaspberryPi was synchronized with an online ntp server, whereas the CR6 logger was synchronized during regular maintenance visits.

5. RC: *P10, L17: Since you analyzed the spectra already, I suggest that you also empirically determine and present the cut-off frequency of the Bosch sensor, also in order to verify the response time provided in the specifications.*

5. AR: In the following we want to address the spectral response characteristics of the BME280 thermohygrometer in two ways, first, in terms of the cut-off frequency and as the derived sensor time constant and, second, in terms of the spectral correction factor for water vapour.

Cut-off frequency and sensor time constant

We estimated a theoretical cut-off frequency according to the given time constant, τ_c , with the following equation:

$$f_c = \frac{1}{2\pi\tau_c} \quad (1)$$

The nominal response time of the relative humidity sensor is one second for a step change in relative humidity from 0 to 90 and 90 to 0% relative humidity at 25°C ambient air temperature, as stated in the specifications. A theoretical cut-off frequency of 0.16 Hz (6.3 s) results from equation 1 from the current document.

In comparison to the theoretical cut-off frequency, we estimated a cut-off frequency from spectra of the the water vapour mole fraction. We estimated the cut-off frequency as the frequency of the intercept between the maximum water vapour spectral energy and the linear fit of the energy spectrum in the inertial sub-range (between ~ 0.1 and 1 Hz) on a double logarithmic scale. The signal below the cut-off frequency is attenuated.

Under field conditions the mean cut-off frequency was 0.063 ± 0.02 Hz for the low-cost set-up and 0.3 ± 0.2 Hz for the EC set-up across five plots and all humidity classes (30-90% relative humidity). The mean time constant calculated from the cut-off frequency was 2.802 ± 1 s for the EC-LC set-up and 0.648 ± 0.3 s for the EC set-up, respectively.

We found an exponential increase of the time constant with increasing relative humidity for both the EC and the EC-LC set-ups (see Figure 1 of the current document). We are not able to reproduce the response time of 1 s even under very dry ambient conditions. The main cause are different ambient conditions than given in the specifications. The estimated time constants consider a relative humidity dependency, but not a temperature dependency. For a temperature of 25 ± 1 °C the time constant for the water vapour spectra was equal to the time constant at 30% relative humidity.

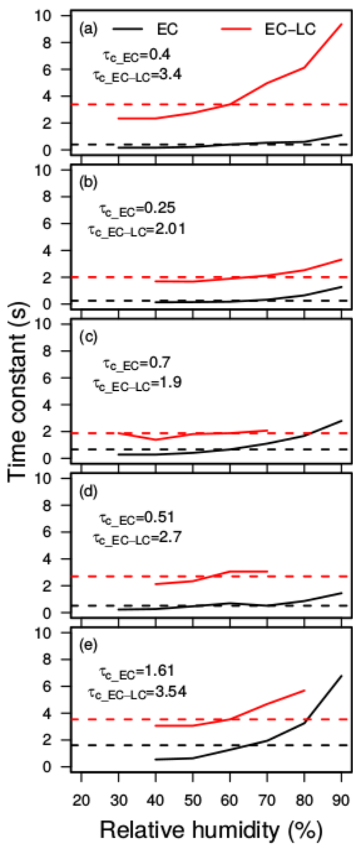

Figure 1: Time constant against relative humidity (from 20 to 90% in 10% classes) for the EC (black solid lines) and the EC-LC (red solid lines) set-up. Dashed lines and the values written correspond to the median time constant for the respective set-ups. Sites correspond to Dornburg AF, (a), Dornburg MC, (b), Forst AF, (c), Reiffenhausen AF, (d), and Wendhausen AF, (e).

Spectral correction factor for water vapour

Site	Spectral correction factor (-)		Spectral correction factor flux magnitude change (%)	
Method	**EC**	**EC-LC**	**EC**	**EC-LC**
Dornburg AF	1.12	1.78	6.9	40.82
Dornburg MC	1.21	3.05	14.3	60.9
Forst AF	1.1	1.99	9.9	47.7
Reiffenhausen AF	1.11	1.31	9.4	42.3
Wendhausen AF	1.19	1.74	5.9	21.83
Mean+-sd	**1.146** ±0.05	**1.974** ±0.65	**9.28** ±3.3	**42.7** ±14.1

Table 1: Median spectral correction factor and the impact of the spectral correction factor on the flux magnitude change.

We found a higher frequency correction factor for water fluxes (combines the correction for high and low-frequency losses) obtained by the EC-LC set-up than for the EC set-up with a median flux increase of 97.4% and 14.6% (see Table 1 and Figure 2 of the current document), respectively.

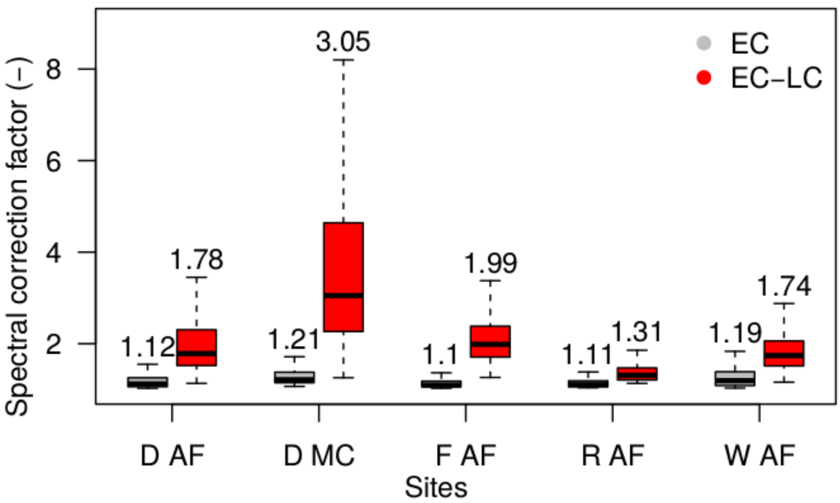

Figure 2: Box-whisker plot of spectral correction factors for the EC (grey) and the EC-LC (red) set-up for all sites, e.g. Dornburg AF, “D AF”, Dornburg MC, “D MC”, Forst AF, “F AF”, Reiffenhausen AF, “R AF” and Wendhausen AF, “W AF”. Values indicate the median spectral correction factor. Error bar

The effect of the spectral corrections on a flux magnitude increase was most pronounced for the low-cost set-up than for the conventional EC set-up with an overall flux magnitude increase of 42.7 ±14.1 % and 9.28 ±3.3 % for the EC-LC and the EC set-up, respectively (see Figure 3 and Table 1 of the current document).

We found the highest median spectral correction factor (3.05) and the highest flux magnitude increase (60.9%) caused by the high-frequency correction for the low-cost set-up of the monocultural agriculture plot of Dornburg. We interpret the higher spectral correction factor as caused by different measurement heights, with a measurement height of 3.5 m at the monocultural agriculture plot of Dornburg and a measurement height of 10 m at the agroforestry plot of Dornburg. At the lower tower high frequency eddies are more likely than at the taller tower. As the nominal time response (1 s) given in the specifications and the estimated time response are quite low, the flux loss is quite high and needs to be corrected for. We will include the information presented in the current document also in the revised manuscript.

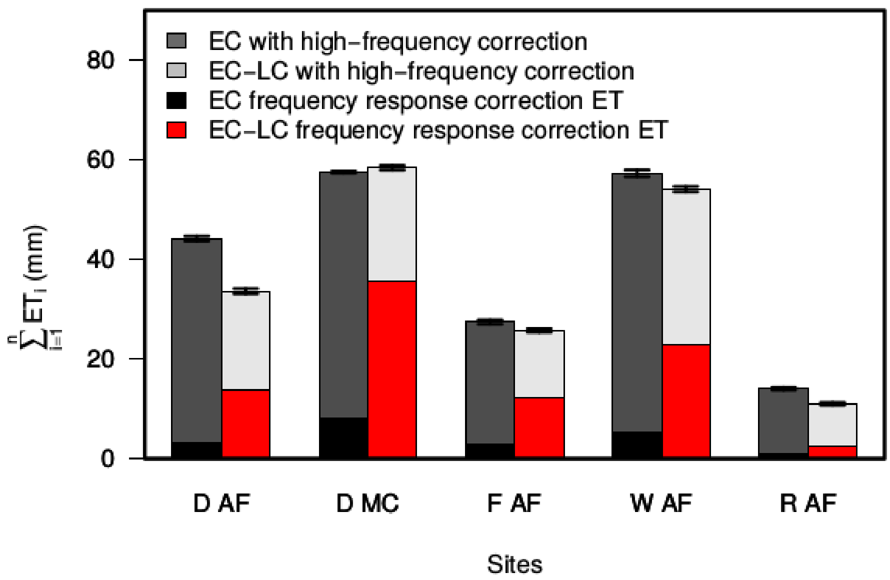

Figure 3: Barplot of cumulative sums of ET for the EC and the EC-LC set-up for all sites. Only data available at each time step and for both methods were used. The black and red bars indicate the summed ET corresponding to the frequency corrections. The error bars correspond to the summed random uncertainties, which were added to the cumulative evapotranspiration rates. Incomplete records with either of EC or EC-LC missing were omitted.