Response to Anonymous Referee #1

We thank the referee for their thoughtful comments on our manuscript.

Below, all comments are repeated in italics, followed by our response typeset upright. Changes to the manuscript are highlighted in blue colour.

General comments

The ms is focused on the application of multi rotor drones and custom build CO2 sensors to estimate nocturnal fluxes and storage in the lower boundary layer. This is a new application of a promising tool and a potential solution to a stability issue in flux measurements that is problematic to EC measurements and the budgetary numbers that we can provide during night-time. Nice work ! I have a few issues that in my opinion could strengthen the ms at this stage; As the authors also conclude, the flux estimates using the NBL seem high and more background information on the site could be useful to assess if the estimates are too high. Information like soil type and organic content as well as NEE flux during the day- time could help in this context, as well as the storage term calculated from the 9 m profile tower at the site. Since this is a well know methodology, but used in a new context it is of cause important to add credibility from as many other sources as possible, especially since the chamber measurements are quite ambiguous.

We added a soil type and land cover map (see Fig. 1) as well as the following description to Sect. 2.1 of the manuscript: 'While soil identification at the Fendt site resulted in Stagnosols at three locations, soil organic carbon (SOC) content was determined additionally at 20 locations within a regular grid. SOC content in 5cm depth varied between 4 and 11% at 5 cm depth, while at 50cm depth, values of up to 23% were obtained. The highest SOC contents were observed at the eastern side of the regular grid where a peat area is located. According to BGR (2013), organically rich soils (Cambisols and Histosols) prevail within 20 km radius around the Fendt site (Fig. 2a). The dominant land cover in this region are crops, pasture and forest (Fig. 2b).'

Additionally, we added measurement results from Mooseurach, a drained peatland forest site just 20 km to the East of Fendt (Hommeltenberg et al., 2014) to Table 3 and the following discussion to Sect. 4.5: 'Furthermore, Fendt lies in a region with organically rich soils (Fig. 2a). Soil organic carbon content has been shown to be positively correlated with microbial biomass (Habashi, 2016), suggesting particularly strong respiration under beneficial conditions. This explanation is supported by the measurements at Mooseurach (Table 3), a drained peatland forest 20 km to the East of Fendt, where respiration fluxes of up to 15 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ have been observed.'

NEE at Fendt measured by the EC station during July 2016 (Fig. 2) can exceed 10 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at night and -20 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ during the day. The mean nocturnal NEE is close to 8 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, but this is an average over different cut-and-collect management stages and weather scenarios during July. The high temperature and high soil moisture conditions at the time of our NBL measurements are not well represented in this average.

IMK-IFU runs another EC station at a grassland site near Rottenbuch, located approximately 12 km south-west of the Fendt site. NEE at the Rottenbuch site is on the same order of magnitude as the fluxes observed at the Fendt site (Zeeman et al., 2017).

The storage term calculated from the 9 m mast is already part of our NBL-budgets (as described in Sect. 3.1). Furthermore, Fig. 6 and 7 show that the accumulation of CO_2 takes place up to a height of 50–80 m, i.e. the 9 m mast can measure only an unknown fraction of the total storage. For these two reasons we think that storage fluxes calculated from the 9 m mast cannot serve as reference for the NBL-derived fluxes.

Taking all available evidence together, the NBL-derived flux estimates do not seem too high.

The instrumental setup seem to work well and fine, but I miss arguments for choosing a custom-made gas analyzer over those relatively cheap and light commercially available analyzers in the market, like e.g. LiCor Li-840 or others.

The specific requirements for a CO_2 analyser for unmanned aircraft and how COCAP meets them is detailed in Kunz et al. (2018), cited in Sect. 2.3 where we explain our setup. Interested readers can therefore easily get this background information and we would rather not reiterate it in this manuscript. In comparison to the LI-840 it should be noted that both instruments weigh around 1 kg, but COCAP contains sensors for ambient temperature, pressure and humidity, a data logger, a pump, a flow controller, as well as a radio for realtime data transmission, all of which are missing in the LI-840. Moreover, the effects of rapid changes in temperature and pressure (as they occur during UAS flights, but not in laboratory deployment) on the LI-840's x_{CO2} measurements would need to be evaluated before using it in this application.

Specific comments

We notice that the reviewer refers to version 1 of the manuscript, which was updated based on suggestions by the handling editor before the discussion phase started. Hence, the line numbers are slightly offset with respect to the discussion paper.

P2 L5: I would assume that sporadic turbulent events would be measured by EC but not molecular diffusion, please consider rephrasing.

Our intent here was to describe the roots of the EC nighttime problem in one sentence, but this likely resulted in oversimplification. Instead of substantially increasing the length of this paragraph, we now refer the reader to a text book: 'Stable conditions violate assumptions underlying the EC technique (see Aubinet et al., 2012 for a comprehensive discussion).'

Molecular diffusion is negligible for atmospheric transport on the scale of meters (Lee et al., 2005) and therefore not mentioned here.

P2 L7: you could mention storage estimates by use of concentration profiles in a tower, could be mentioned.

See above for small structures like the 9 m mast in Fendt. Utilizing a tall tower for obtaining nighttime NEE estimates is mentioned on p. 2 ll. 31–33.

P3 L:31: please provide crop type and vegetation stage.

We extended the first paragraph of Sect. 2.1: 'The valley floor is dominated by pasture and some crops, predominantly maize, which in Germany is typically sowed in April or May and harvested between September and November.'

P7 L13: It could give the impression that a tower of a considerable height is needed in addition to the UAV approach, is that so? Please specify

In our study we made use of the CO_2 dry air mole fraction measurements of an instrumented 9 m mast. However, in Sect. 4.6 we present fluxes calculated by using COCAP data only, i.e. disregarding the measurements at the mast. The spread of the fluxes increases, but the mean flux changes by only 8 % for the first and 3 % for the second night, hence a mast is not strictly necessary. We made the respective lines in Sect. 3.1 clearer: 'Furthermore we discard COCAP's x_{CO2} data collected below 9 m height for the calculation of the NBL budget. Instead, the lowest part of the x_{CO2} profile is defined by the stationary measurements at the 9 m mast at 1, 3 and 9 m height. Pressure and temperature at these levels are interpolated from COCAP's measurements. During flight, the horizontal distance between COCAP and the 9 m mast was lower than 150 m at any time. Hence, we do not expect pronounced horizontal gradients in x_{CO2} between the measurement locations. In Sect. 4.6 we discuss how the NBL-derived fluxes are affected if the data from the 9 m mast is not used.'

P11 L22: I guess if you could assume that day and night time fluxes were even in magnitude, you wouldn't have to measure the night. Consider rephrasing – order of magnitude maybe?

Thank you for this suggestion. We changed the respective sentence to 'The sign of the daytime CO_2 flux is generally negative, whereas the sign of the nighttime flux is positive, but they are usually of the same order of magnitude.'.

P22 L27: it is well known that chamber measurements can give quite different fluxes within short distances, and since the small are only available part of the time it would make sense to try to establish the storage term of the tower, for comparison.

We agree that spatial heterogeneity can lead to large differences in enclosure-based flux measurements. It is unclear, however, why agreement is high among all small chambers as well as among all big chambers, but poor between them. For the reasons explained above the storage term from the 9 m mast cannot serve as an independent reference.

Fig. 12 I'm not sure this increases the confidence in the method because it basically show a very wide range of possible flux during the two nights.

Each green horizontal line in Fig. 10 and 11 corresponds to one of the green dots in Fig. 12 ('No change'), so their spread is exactly the same. Part of the flux variability is a negative trend during the night, which might be a real phenomenon caused by temperature, as explained on p. 22, ll. 16–18. Moreover, the footprint of the NBL budgets changes over time, meaning that different areas with higher or lower respiration contribute to the NBL budgets with changing proportion, leading to another physical cause for variability in the NBL-derived fluxes.

In the sensitivity analysis the only substantial increase in spread occurs when the measurements from the 9 m mast are not used. Even in that case the small change in mean flux indicates that little or no bias is introduced. We see Fig. 12 as a valuable and honest depiction of the uncertainty of the NBL-derived fluxes. The repositioning of the air inlet suggested in the Conclusions might well be able to reduce the spread in the flux estimates.

P27 L4 check fig numbers

Corrected (already in the discussion paper).

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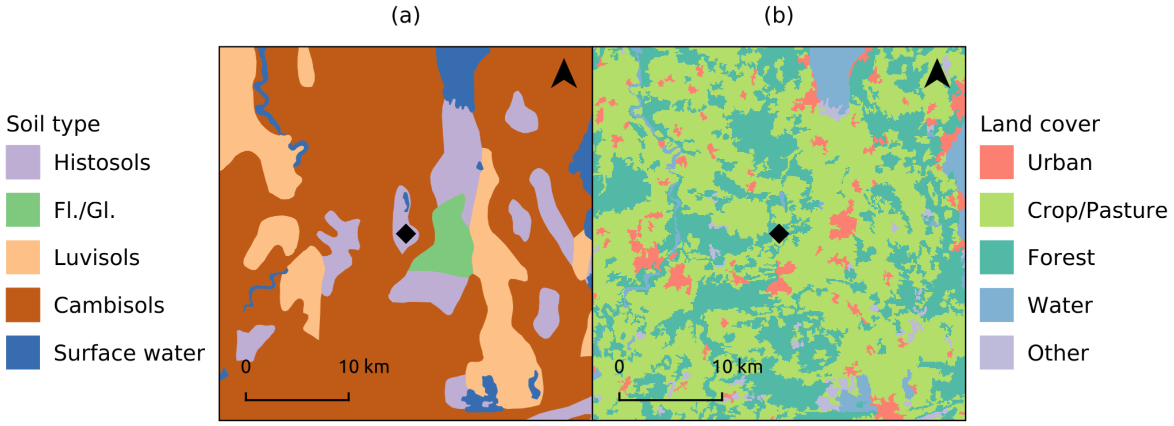

Figure 1: (a) Soil types in the region around the Fendt site, based on BGR (2013), denoted in WRB classification (IUSS Working Group WRB, 2015). ‘Fl./Gl.’ stands for ‘Fluvisols/Gleysols’. (b) Simplified land cover map (CORINE 2012 v18.5, European Environment Agency, EEA (2016)) of the same region. In both panels the location of the Fendt site is marked with a black diamond.

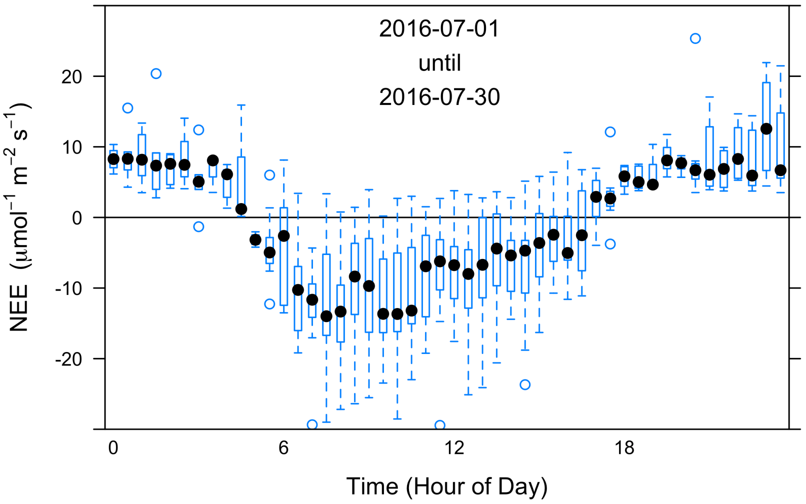

Figure 2: Statistics of NEE fluxes obtained with the EC technique during July 2016