

Author comments to review of amt-2019-221

15 December 2019

We thank the two referees for their thoughtful comments on the manuscript. Below, all comments are repeated in *italics*, followed by our response typeset upright. Changes to the manuscript are highlighted in blue colour. The list of references and new figures are included below our responses.

A marked-up version of the revised manuscript is attached.

Comments from Anonymous Referee #1

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_{CO_2} 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 CO₂ 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_{CO_2} data collected below 9 m height for the calculation of the NBL budget. Instead, the lowest part of the x_{CO_2} 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_{CO_2} 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 CO₂ 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).

Comments from Anonymous Referee #2

General comments

Overall, this is an excellent and exciting paper. It demonstrates a novel application of UAS for atmospheric science and adds to an exciting literature concerning the new horizons this sampling

platform offers. It is a proof-of-concept study, intended to demonstrate the potential use of UAS in CO₂ biospheric respiration measurement. It identifies the challenge and importance of nocturnal respiration measurements and the gap that EC methods (and limited spatial scale of chambers) cannot fill. It proposes a mass balancing approach suited to night-time measurement, taking advantage of the assumption of a stable boundary layer. Given that this is an initial study, intended to open up a new direction in this field, some of the questions about the validity of the flux method itself (see specific comments) should be seen in that context, i.e. that this paper identifies a problem and suggests an innovative approach that can be built on and refined in future work. I believe the paper would be of great interest to readers of AMT and the quality of presentation, figures etc is excellent. I specifically praise the way the authors have carefully considered the specific challenges of rotary UAS sampling (i.e. the influence of downwash, instrument response time, etc) and proposes a solution to only use descent profiles to avoid disturbance and take into account response time. These factors are often overlooked and this paper serves as excellent guidance. The paper also compares UAS results with chambers and raises some interesting questions. I do have some important comments though. These concern the UAS flux approach and the way in which surface footprint and vertical mixing scales have been derived (see specific comments). I hope that these comments can be addressed or answered in a revised version of the paper. I see this method as something that can be improved upon in future work and perhaps the most important edits to the text could highlight the remaining uncertainties and challenges to the approach.

We appreciate that the referee sees our work as a valuable contribution to the scientific community. We share the view that the pilot study presented in our manuscript cannot fully answer all questions about the accuracy of the derived fluxes and associated footprints, but is a foundation that future works can build upon.

Specific Comments

1/ Use of STILT to define footprint: I have sympathy with the approach and I do not have a good alternative solution to accurate night-time footprint evaluation, however Lagrangian trajectories near to the surface are known to be subject to significant error/uncertainty. Surface trajectories tend to hug the surface and follow (typically) the 10 m wind vector suggested in the reanalysis met data used to drive the model (in this case ECMWF 0.1 IFS), i.e. upward/downward motions are suppressed. How many vertical levels does this version of ECMWF have and what resolution in the vertical domain used in the study?

The vertical resolution of the meteorological data is specified in the original manuscript at the end of Sect. 3.4: ‘The vertical resolution of the meteorological data depends on height above ground. The lowest layer extends from the ground to 10 m height, the following 5 layers extend from the top of the next lower layer to 31 m, 55 m, 80 m, 108 m and 138 m, respectively.’ The total number of layers is 89. In the revised manuscript we add the likewise relevant fact that ‘[The temporal resolution of the ECMWF IFS data is 3 h.](#)’

In order to test the hypothesis that vertical motions are suppressed in the transport model, we plotted the height of 200 out of the 10 000 particles as they travel backwards from the Fendt site. As an example we chose the particles released inside the nocturnal boundary layer at $z = 10$ m and particles released above the nocturnal boundary layer at $z = 100$ m on July 6 21:00 UTC (Fig. 3 and 4) and July 9 21:00 UTC (Fig. 5 and 6). Note that these are a small subset of the particle trajectories based on which the footprints presented in Fig. 13 and 14 in the discussion paper were calculated.

A prominent feature of the trajectories for 6 July is the absence of a stable boundary layer for travel distances greater than 5 km, which approximately corresponds to the time period before

20:00 UTC. In contrast, the trajectories for 9 July indicate a stable boundary layer throughout the time period between 18:00 UTC and 21:00 UTC. This would mean that accumulation in a shallow layer near the ground would have happened during a period of 1 h on 6 July and during a period of 3 h on 9 July. While the profiles measured by COCAP (Fig. 6 and 7 in the discussion paper) do suggest a weaker inversion layer on 6 July, a threefold difference in the accumulation seems too high. Additionally, the measurements at the 9 m mast presented in Fig. 8 in the discussion paper show that CO₂ has accumulated near the ground as early as 19:10 UTC on 6 July, an observation that cannot be explained without a stable boundary layer. This demonstrates that meteorological datasets are an imperfect description of the atmosphere and more generally underlines the referee’s point that transport modelling in the nocturnal boundary layer is subject to considerable uncertainties.

The hypothesis that STILT suppresses vertical motion, however, is clearly refuted by Fig. 3 through 6. Even within the strong inversion on 9 July the particles are frequently redistributed between the two lowermost layers of the meteorological dataset.

The approach used here is to release 10000 particles per time-step at very small increments in height up to some assumed mixing height (see comment below). I would raise some concerns with this approach. Perhaps an improvement may be to run STILT in ensemble mode – to perturb each trajectory with some assigned uncertainty (diagnosed from the ECMWF data or obtained by drone-based wind measurement variability in future) to the wind vector to examine advective uncertainty - Section 5 nicely acknowledges the future role of wind measurement. A set of releases at different heights is unlikely to recreate any meaningful 2D footprint as the trajectories will cluster along one singular wind vector (as Figure 13 tends to show) extracted from the ECMWF model grid (0.1 deg is ~ 10km of fetch after all), whereas an ensemble may at least give a better qualitative indication of the possible extremes of the fetch/footprint. This is likely to be the biggest source of uncertainty in any Lagrangian budgeting approach and I think it may be important to state this in the paper, even if an ensemble approach is not used in any revision.

The STILT model is stochastic in the sense that different realisations of vertical turbulent transport are used for each of the particles released, which is illustrated by Fig. 3 through 6. The particles reside at different vertical levels of the meteorological dataset for different periods of time, hence experiencing different advective transport. The horizontal dispersion resulting from this mechanism can be seen in Fig. 7. Over a travel distance of 10 km these 10 randomly chosen trajectories for 6 July and 9 July spread out over 1.5 km and 5 km, respectively. We do not have a reference at hand to compare to, but this spreading seems reasonable for a statically stable boundary layer. STILT makes use of the atmospheric stability as well as the wind variability between grid cells, vertical levels and time steps. We do not know which further uncertainty could be extracted from the meteorological dataset alone. On the other hand we fully agree that wind measurements alongside the NBL profiling would provide an estimate of the model error and could be used to determine the uncertainty of the footprints.

I realise that footprinting is extremely difficult but it would be useful to acknowledge just how difficult and error-prone it is. The same is true of EC footprints in topographically-variable environments of course.

We agree that the calculation of footprints is challenging, especially at the scale relevant for the NBL budgets. The discussion paper lists the limitations of our approach in Sect. 3.4, 4.7 and 5. We add to Sect. 4.7: ‘[Variability of the horizontal wind component within a grid cell and on time scales below three hours is neglected, possibly resulting in an underestimation of the footprint size. Likewise, terrain features that are smaller than a grid cell are not represented in the meteorological model.](#)’

2/ P.12 line 1 – why is it expected that “Surface fluxes are expected to be diluted into a column

that extends from the surface to 1/2 this height in each time step”? This seems rather arbitrary? Why is this expected? How was it derived from ECMWF data?

The respective paragraph describes how the STILT model represents vertical mixing. Like any model, it uses a simplified description of reality. In the case depicted in Fig. 5, for example, the STILT model has determined a boundary layer height of approximately 30 m. Whenever a particle resides below 1/2 this height, i.e. below 15 m, it is considered to be in contact with surface fluxes and a finite sensitivity to surface fluxes is assigned to this point of the particle’s trajectory. The boundary layer height is calculated using a modified Richardson number method (Lin et al., 2003). The threshold 1/2 has been chosen for computational efficiency; thresholds between 10 % and 100 % of the boundary layer height have been found to have insignificant effects on the footprints (Gerbig et al., 2003). We revised the description in Sect. 3.4: ‘To do so, the height up to which mixing occurs is estimated from the meteorological data using a modified Richardson number method (Lin et al., 2003). Surface fluxes influence air parcels within a column that extends from the surface to 1/2 this height in each time step (Gerbig et al., 2003).’

In a stable night-time boundary layer, what is the vertical mixing process assumed to reach this quantitative mixing-height value? In stable NBLs, vertical dilution is dominated by diffusion with some small residual vertical turbulence, e.g. the “fanning” Pasquill stability class.

The profiles depicted in Fig. 6 and 7 illustrate that vertical mixing does take place within a stable boundary layer. Profile #20, for example, taken on 9 July at 21:10 UTC, exhibits pronounced gradients both in virtual potential temperature and CO₂ dry air mole fraction up to a height of $z = 50$ m. Both rapid radiative cooling and the emission of CO₂ take place at the ground, so these gradients are the signature of vertical mixing. Molecular diffusion is slow; a CO₂ molecule in air at a temperature of 20 °C travels on average 1.6 m in a whole day (Karion et al., 2010). The main mechanism for vertical mixing in the stable NBL is turbulence generated by vertical wind shear due to friction at the surface.

Given that assumed vertical mixing timescales (and horizontal footprint) are key to deriving flux per unit area in the footprint using the proposed method, these quantities are key. This (and comments below and above) cause me to start to question the overall flux method as it stands.

This is a misunderstanding. The fluxes are derived from the NBL budgets by means of Equation 11 in the discussion paper, which does not contain any quantity that depends on the calculated footprint. The flux footprint is calculated from Equation 14 and is unitless. The value in each grid cell of the footprint is a measure of how much the flux in this grid cell influenced the flux derived from the NBL budget at the Fendt site.

Wouldn’t a much more conceptual and simple approach simply be to look at the temporal gradient in CO₂ throughout the NBL throughout the night and assume a fetch equivalent to the length scale of advection over that timescale (e.g. treating the NBL like a large-scale vented flux chamber, so long as footprint can be defined)? Such a concept would negate a diagnosis of any spatial heterogeneity in flux (arriving at a bulk net flux for a defined air mass volume) but I don’t have any confidence that the proposed approach can do anything better than this in reality (without a fleet of drones that is). In summary, I’m not convinced that any useful 2D footprint can be obtained, so averaging the accumulated NBL mass over any surface area is problematic, so a simplified NBL bulk net flux approach may be more meaningful?

The fluxes derived from NBL budgets are spatial and temporal averages, but this averaging takes place due to the transport in the atmosphere and the physical accumulation in the NBL. We do not apply averaging in the data processing. The role of the footprints is flux attribution to an area, not flux calculation. We agree that transport modelling is subject to errors and it is especially challenging in case of a shallow stable boundary layer. However, as the ECMWF IFS data used to drive the STILT model contains horizontally, vertically and temporally resolved

wind vectors, we are confident that our approach yields a more realistic footprint than an estimate based on a single mean wind vector.

3/ Other sources of flux uncertainty: These include the assumed background CO₂, any variability in upwind sources of CO₂ (i.e. variability in the background air mass entering the footprint over the time frame of the measurements), measurement error/precision, wind speed and direction variability etc. Section 4.2 and 4.6 addresses measurement error nicely and explores sensitivity, but not the other sources of flux error. Perhaps it would be good to note these in the paper, even if they cannot be determined or budgeted in this work, so that others following or improving on the work are aware.

The two sources for uncertainty of the assumed background CO₂ dry air mole fraction are measurement error (covered by sensitivity check 1) and spatial variability. The flux error stemming from spatial variability of the background air mass is covered by sensitivity check 2 as detailed in Sect. 4.6. Subgrid and sub-time-step variability of the wind are not represented in the model, except for the vertical turbulence parametrisation. We state this more clearly in Sect. 4.7 of the revised manuscript as detailed above.

4/ Use of w from ECMWF and the nature of night-time lifting or subsidence (page 11): I'm not sure that large scale vertical motions need to be considered in the proposed flux approach. The effect of subsidence is to suppress the night-time boundary layer, i.e. to move the night-time inversion lower. Lifting would act to lift the inversion and entrain air from above (diluting the NBL and therefore XCO₂). Since this approach treats the NBL as a flux chamber (in effect), this motion seems not to be important and implicit (i.e. manifest) in the concentration measurements themselves. Or have I interpreted this incorrectly?

Subsidence (lifting) is intrinsically tied to horizontal divergence (convergence) of air, which does affect the NBL budgets. Imagine a case with flat terrain and no advection at the measurement location. Without subsidence or lifting, the NBL-derived flux equals the surface flux at the measurement site. If lifting takes place, surface emissions originating from the vicinity of the site ‘pile up’ at the measurement location and the flux estimates will be too high. Taking into account that subsidence and lifting are relatively slow processes, we do not expect strong mixing and entrainment at the border between the NBL and the residual layer above. Conversely, in case of subsidence, some fraction of the local emissions are dispersed horizontally and not included in the NBL budget, resulting in too low flux estimates.

Technical comments

Remember to add spaces between quantities and units (e.g. 100km² on line 11) and other instances.

We use protected thin spaces to between quantities and units, which depending on the PDF viewer and zoom setting might be occasionally overlooked. We have checked again the typesetting of quantities and units in the manuscript and made it more consistent at several locations.

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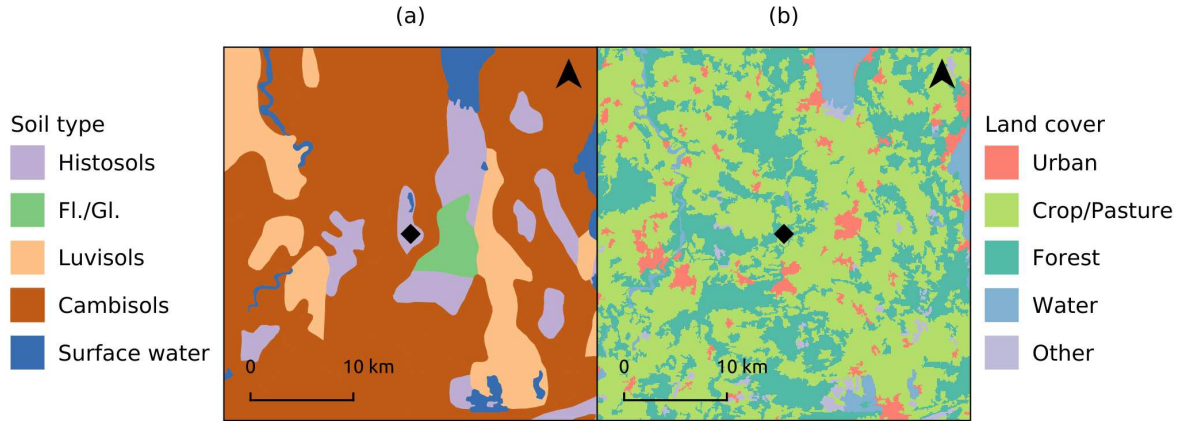


Figure 1: (a) Soil types in the region around the Fendt site, based on BGR (2013), denoted in WRB classification (IUSS Working Group WRB, 2015). ‘Fl./Gl.’ stands for ‘Fluvisols/Gleysols’. (b) Simplified land cover map (CORINE 2012 v18.5, European Environment Agency, EEA (2016)) of the same region. In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

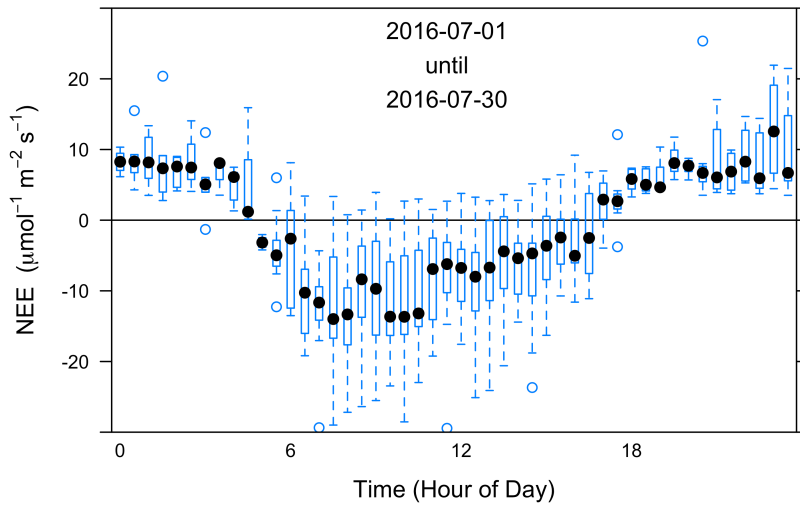


Figure 2: Statistics of NEE fluxes obtained with the EC technique during July 2016

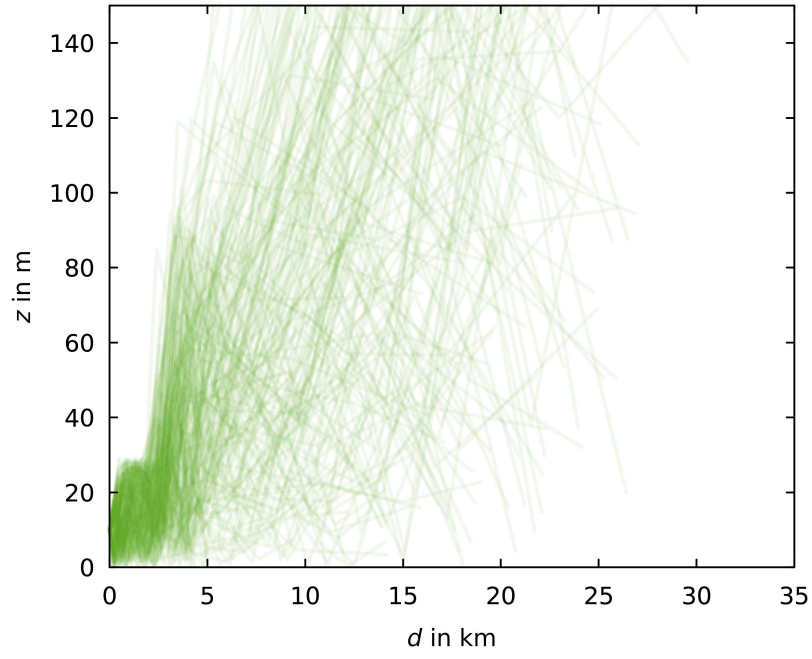


Figure 3: Height z versus distance travelled d of 200 particles released on 6 July at 21:00 UTC at a height of 10 m as they travel back in time until $t_0 = 18:00$ UTC

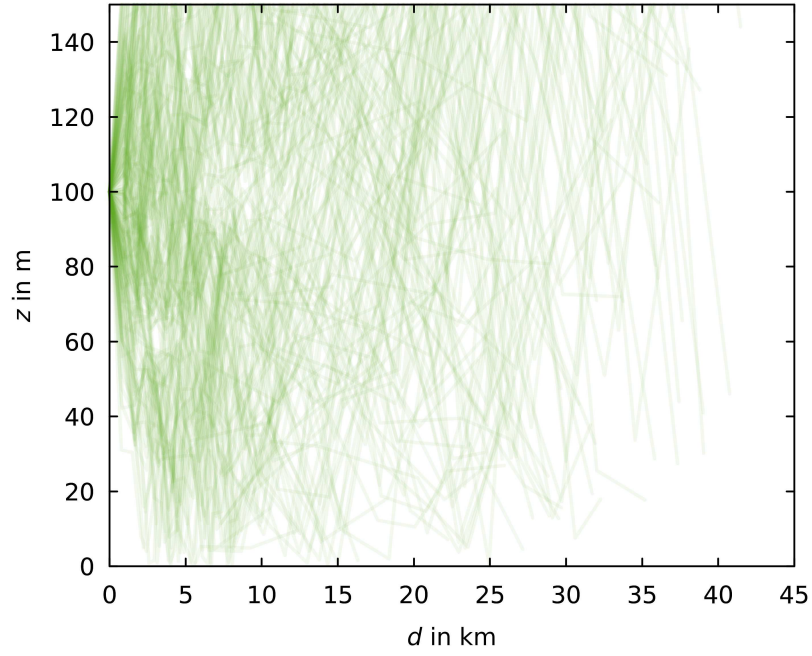


Figure 4: Same as Fig. 3, but for a release height of 100 m

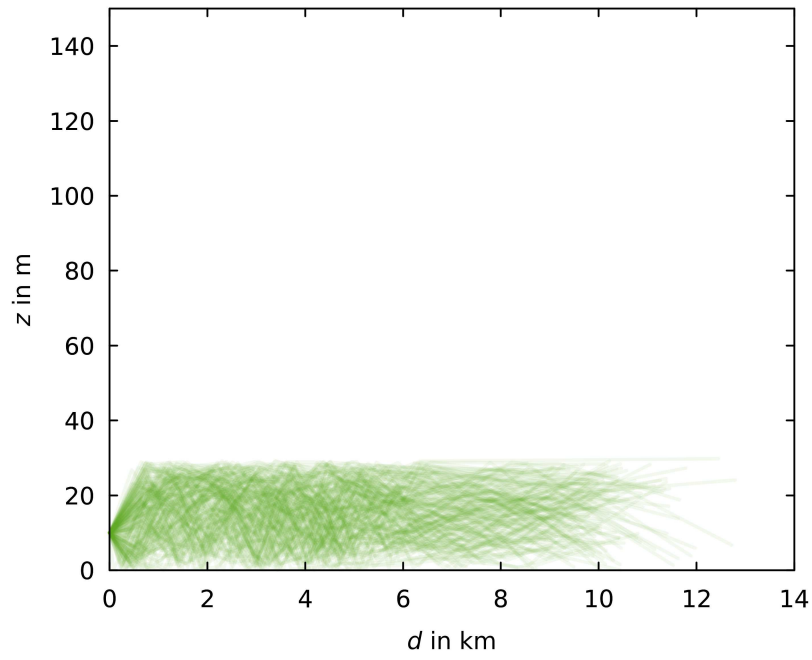


Figure 5: Same as Fig. 3, but for particle release on 9 July at 21:00 UTC

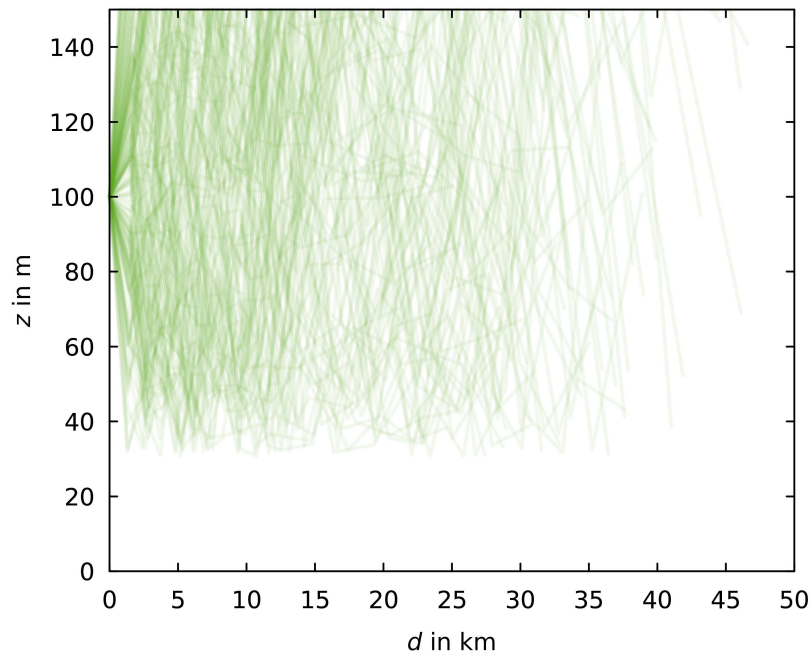


Figure 6: Same as Fig. 3, but for particle release on 9 July at 21:00 UTC at a height of 100 m

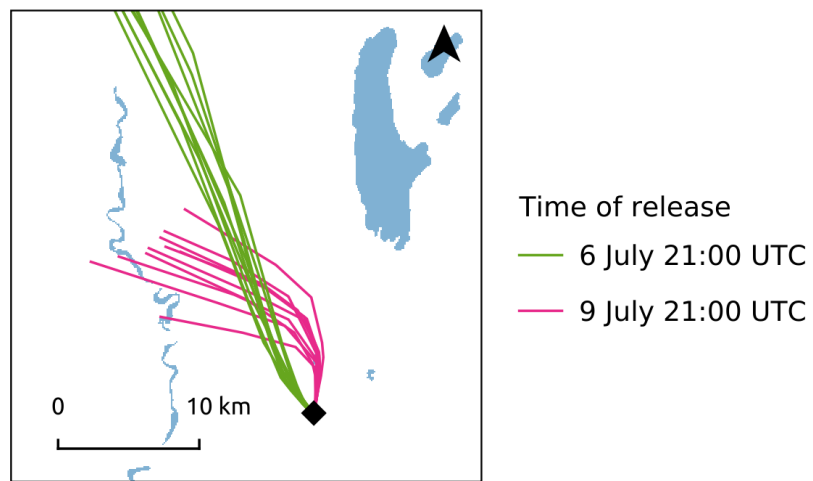


Figure 7: Trajectories of particles released at a height of 10 m at 21:00 UTC on two different days as they travel backwards until $t_0 = 18:00$ UTC of the same day

Surface flux estimates derived from UAS-based mole fraction measurements by means of a nocturnal boundary layer budget approach

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Abstract. The carbon exchange between ecosystems and the atmosphere has a large influence on the Earth system and specifically on the climate. This exchange is therefore being studied intensively, often using the eddy covariance (EC) technique. EC measurements provide reliable results under turbulent atmospheric conditions, but under stable conditions – as they often occur at night – these measurements are known to misrepresent exchange fluxes. Nocturnal boundary layer (NBL) budgets can provide independent flux estimates under stable conditions, but their application so far has been limited by rather high cost and practical difficulties. Unmanned aircraft systems (UASs) equipped with trace gas analysers have the potential to make this method more accessible. We present the methodology and results of a proof of concept study carried out during the ScaleX 2016 campaign. Successive vertical profiles of carbon dioxide dry air mole fraction in the NBL were taken with a compact analyser carried by a UAS. We estimate an average carbon dioxide flux of $12 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, which is plausible for nocturnal respiration in this region in summer. Transport modelling suggests that the NBL budgets represent an area on the order of 100 km².

1 Introduction

The terrestrial biosphere plays a major role in the carbon cycle. It has taken up approximately one quarter of the carbon emitted by human activities since 1750 (Ciais et al., 2013), but the future development of this land sink under a changing climate is uncertain. Given its importance, the biosphere–atmosphere exchange is being studied intensively. On the ecosystem level, sources and sinks of carbon dioxide and methane are commonly quantified using the eddy covariance (EC) technique (Baldocchi, 2003). During the day, when the air is turbulently mixed, the EC technique provides reliable direct measurements of net ecosystem exchange (NEE). However, EC measurements often misrepresent nighttime fluxes (Goulden et al., 1996; Gu et al., 2005). This is related to the stable stratification that often develops close to the surface at night. Stable conditions

violate assumptions underlying the EC technique ~~, namely that fluxes are transported predominantly by turbulence as opposed to advection and, in case of sporadic turbulent events in an otherwise stable layer, the assumption of stationarity~~ (see Aubinet et al., 2012 for a comprehensive discussion). Despite large efforts, there is currently no generally accepted solution how to obtain reliable measurements of nighttime fluxes using the EC technique (Gu et al., 2005; Aubinet et al., 2010; Hayek et al., 2018).

Daytime NEE consists of photosynthetic uptake and release of carbon through respiration. Nighttime NEE is governed by respiration only, as photosynthesis cannot take place without light. Photosynthetic uptake and total respiration fluxes ~~often have similar magnitude~~ are usually of the same order of magnitude., but with opposite sign. Therefore, even slight underestimation of nocturnal respiration can result in a considerable overestimation of an ecosystem's long-term carbon uptake. Furthermore, daytime fluxes are often partitioned into photosynthetic uptake and respiration using methods that rely on the nighttime measurements (Falge et al., 2001; Reichstein et al., 2005; Lasslop et al., 2010; Wohlfahrt and Galvagno, 2017). Errors in the nocturnal fluxes might compromise this partitioning.

The nighttime problem of EC measurements calls for complementary methods to quantify and potentially correct for the errors. Biometric approaches, including enclosure-based methods, plant growth assessment and stock inventories, are often employed to obtain independent estimates for NEE (Goulden et al., 1996; Wilson and Baldocchi, 2001; Campioli et al., 2016). However, these methods quantify the exchange of carbon on a much smaller spatial scale than EC measurements. The chambers typically used for determining soil respiration cover an area of less than one square meter, while the EC technique is sensitive to fluxes from an area of 10^4 – 10^6 m², depending on the site and on meteorological conditions (Chen et al., 2009). Given these different scales, comparing NEE values obtained using different methods is difficult. Inhomogeneities in the ecosystem under study, such as spatial variability of soil properties (e.g., texture, carbon content, nitrogen content), soil environmental conditions (e.g., soil temperature and moisture) or plant community composition can lead to biases in the comparison.

In the absence of a method with a sensitivity area similar to the EC technique, larger-scale flux estimates are the next best choice to better constrain the errors of EC measurements. Nocturnal boundary layer (NBL) budgets, first described by Choularton et al. (1995) and Denmead et al. (1996), provide such estimates. The NBL budget method makes use of the stable stratification at night, which can act as a flux-integrating enclosure. During clear nights, the emission of thermal radiation cools down the Earth's surface much faster than the air, owing to the surface's higher emissivity. An inversion layer forms, inhibiting exchange of air between the stable NBL and the neutral residual layer above (Stull, 1988). Any tracer emitted into the atmosphere is therefore accumulated within the NBL. By measuring the rate of accumulation, the tracer flux can be estimated.

Different setups have been used for NBL budgeting. Acevedo et al. (2004) measured CO₂ dry air mole fractions at a 12 m tower, sampling only the lowest parts of the NBL. Although they did not sample the whole layer, they were able to create a budget by determining an effective accumulation height from either heat flux or balloon-borne humidity and temperature measurements and assuming a uniform accumulation rate of CO₂ up to this height. Winderlich et al. (2014) used CO₂ and CH₄ dry air mole fraction measurements at 6 heights on a 301 m tall tower, yielding profiles that encompass the whole NBL during most nights. Often the NBL budget method is applied without a tower. A tethered balloon can lift a 100–300 m long

hose through which a ground-based gas analyser samples air from different heights (Choularton et al., 1995; Denmead et al., 1996; Culf et al., 1999). Alternatively, a light analyser can be carried by the tethered balloon directly (Pattey et al., 2002).

Despite providing unique information, the NBL budget method has been applied only infrequently in recent years. This might be related to the cost and operational limits of towers and tethered balloons. Unmanned aircraft systems (UASs) could make the NBL budget method more accessible. UASs with payload capacities on the order of 1 kg are now available for few thousand Euros. When equipped with lightweight trace gas analysers and meteorological sensors (Kunz et al., 2018) they have the potential to probe the NBL with large flexibility at low cost. Multicopters are a particularly attractive type of UAS for this kind of study, because their vertical take-off, vertical landing and hovering capability makes them easy to operate in a range of environments.

However, the air movement caused by a UAS can disturb the NBL and thereby compromise the measurements. A reliable NBL budget can be created only if this issue is addressed. A second challenge is not specific to UASs, but common to all NBL budgets: the area contributing to the budget depends heavily on the meteorological conditions and can extend far from the point of measurement. For a given time and site this footprint cannot be influenced by experimental design. Nevertheless, knowledge of the footprint is beneficial for the data analysis and interpretation of the results. In earlier NBL studies, this topic has received only basic treatment (Culf et al., 1999) or was ignored altogether.

To assess the suitability of UASs as measurement platforms for the creation of NBL budgets we carried out a proof of concept study. We deployed a carbon dioxide analyser on a multicopter and repeatedly sampled vertical profiles of the NBL during two nights in July 2016 as part of the ScaleX 2016 campaign in Fendt, Germany. In the following, we report on this study and present our findings. Section 2 is a description of the site and the available ground-based instrumentation, the airborne measurement system and the unmanned aircraft. In Section 3 we explain how we dealt with the disturbance caused by the UAS, which post-processing steps we carried out and how we created the NBL budget. Furthermore, we delineate how a Lagrangian transport model can be applied to identify the areas that contributed to the budget, i.e. how to determine the footprint of our flux estimates. In Section 4 we present and discuss the profiles taken by the UAS, the fluxes obtained from the NBL budget and a summary of the footprint analysis. We compare our observations to references and assess the robustness of our flux calculation. In Section 5 we summarise the merits and experimental challenges of our approach.

2 Site and instrumentation

2.1 Fendt site

The Fendt site is located in southern Germany in the Alpine Foreland (Fig. 1) at 11.060° N, 47.833° E (WGS84), 600 m above mean sea level. The site lies in a flat valley bordered by a gentle slope to the east and a steep slope leading to a 100 m higher plateau to the west. 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. The slopes to the east and west are covered with coniferous and mixed forest, respectively. Fendt belongs to the district Weilheim–Schongau, which has a population density of 139 km⁻² (Statistisches Bundesamt (Destatis), 2018, 35th percentile of all districts in Germany).

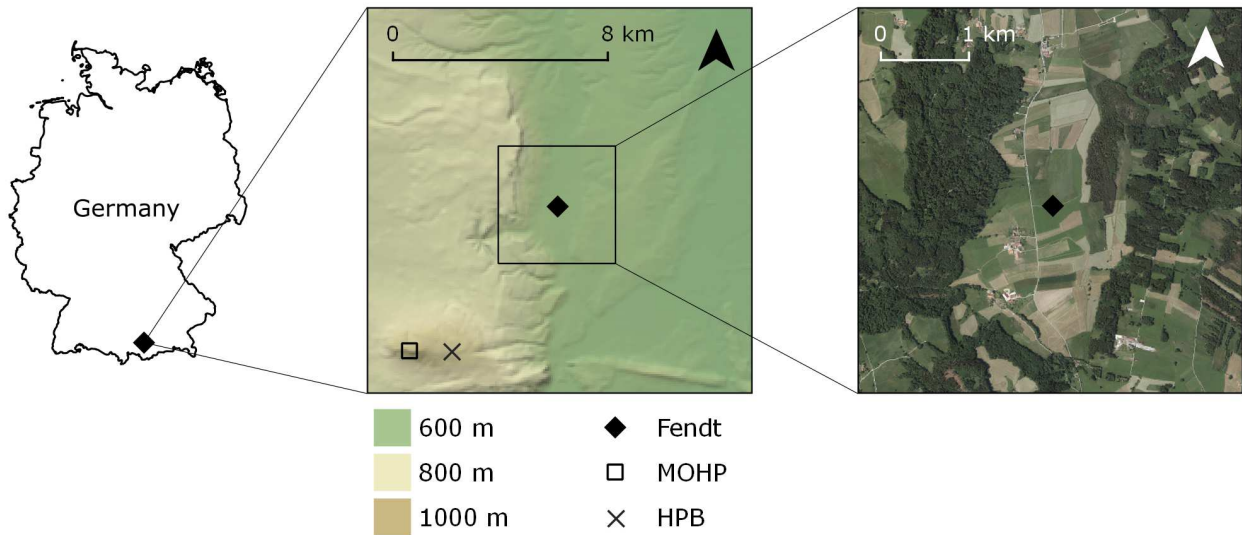


Figure 1. Location, topography and aerial image of the Fendt site and its surroundings. MOHP is the Meteorological Observatory Hohenpeißenberg, HPB is the ICOS station Hohenpeißenberg. Digital elevation model and aerial imagery by Bayerische Vermessungsverwaltung, www.geodaten.bayern.de.

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).

Five kilometres south-west of the Fendt site lies an isolated, 988 m high mountain, the “Hoher Peißenberg”. Close to its summit the German Weather Service (Deutscher Wetterdienst DWD) operates the Meteorological Observatory Hohenpeißenberg (MOHP) and the ICOS (Integrated Carbon Observation System) station Hohenpeißenberg (HPB, Fig. 1).

2.2 Ground-based instrumentation

Fendt is part of the TERENO (Terrestrial Environmental Observatories) network and is extensively instrumented for the purpose of long-term monitoring of land–atmosphere exchange (Mauder et al., 2013; Kiese et al., 2018). Complementary observations were made during the ScaleX 2016 campaign (Wolf et al., 2017). In the following, we list only those instruments that produced the data presented in this publication.

During the ScaleX 2016 campaign, CO₂ dry air mole fraction at a height of 1, 3 and 9 meters m above ground level was measured with a cavity ring-down spectrometer by successive sampling of air through three inlets installed at a 9 m high mast.

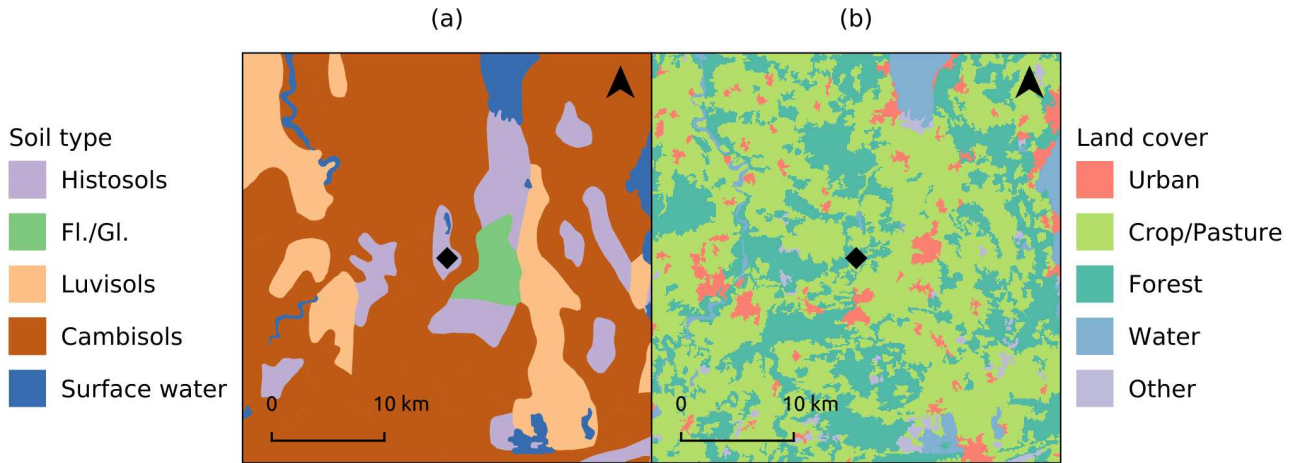


Figure 2. (a) Soil types in the region around the Fendt site, based on BGR (2013), denoted in WRB classification (IUSS Working Group WRB, 2015). ‘Fl./Gl.’ stands for ‘Fluvisols/Gleysols’. (b) Simplified land cover map (CORINE 2012 v18.5, European Environment Agency, EEA (2016)) of the same region. In both panels the location of the Fendt site is marked with a black diamond.

Each inlet was sampled once every 7.5 min, with occasional interruptions due to calibrations and other measurements. An EC system installed at 3.5 m height (Zeeman et al., 2017) quantified the turbulent exchange of CO_2 . Air temperature and upward as well as downward radiation were measured at 2 m height. Two sets of automated chambers were operated to determine the total NEE or respiration flux of grass and soil. One set comprised four LI-8100 long-term chambers (LI-COR, Lincoln, NE, USA), two with clear enclosure for measuring NEE and two with opaque enclosure for measuring respiration (Zhao et al., 2018). All four chambers covered an area of 317.8 cm^2 and will be referred to as “small chambers” from here on. The other set consisted of 5 custom-built opaque chambers covering an area of 2500 cm^2 , referred to as “big chambers” hereafter. All the instruments mentioned so far were located close to each other and our UAS flew within 200 m horizontal distance to each of them.

Besides the on-site instruments we use two more data sources for our analysis. One is the observation of cloudiness at the Meteorological Observatory Hohenpeißenberg, recorded every hour either by a person or an automated instrument. We consider these 5 km distant measurements representative for Fendt, with a potential time lag on the order of 1 h in case of synoptic events. The second non-local data source is the greenhouse gas monitoring system at the ICOS station Hohenpeißenberg, situated at 934 m above mean sea level. We use its measurements of the CO_2 dry air mole fraction at 131 m height above ground level, i.e. at 460 m above the Fendt site.

2.3 Airborne payload

For the study presented here, temperature, pressure, relative humidity and CO_2 dry air mole fraction of ambient air were measured using COCAP, the COmpact Carbon dioxide analyser for Airborne Platforms, developed at the Max Planck Institute for Biogeochemistry in Jena (see Kunz et al., 2018 for a detailed description). COCAP was mounted below the multicopter.

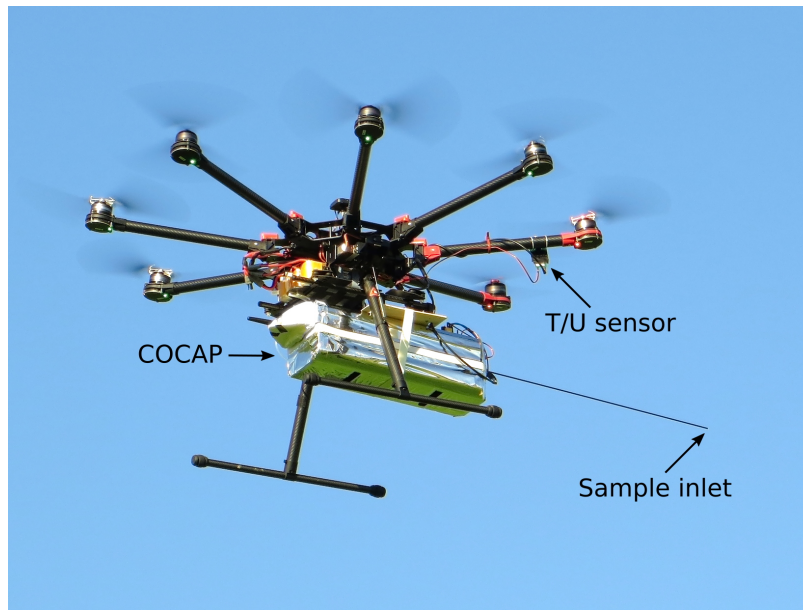


Figure 3. COCAP was carried by a multicopter during the ScaleX 2016 campaign. The position of the sample inlet for the CO₂ measurement and of the temperature and humidity sensor board are indicated.

Table 1. Measurement principles, uncertainties and calibration range of the airborne sensors

	CO ₂ dry air mole fraction	Temperature	Pressure	Humidity
Principle	nondispersive infrared	platinum resistance	piezoresistive	capacitive polymer
Uncertainty	see Section 4.1	0.15 °C	1.5 hPa	2 %
Cal. range	380–600 $\mu\text{mol} \cdot \mu\text{mol}^{-1}$	0–30 °C	400–1000 hPa	20–90 %

Air samples for the measurement of carbon dioxide dry air mole fraction were drawn from an inlet placed 30 cm below and 20 cm to the side of the rotors (Fig. 3). The temperature and humidity sensor board, requiring strong ventilation for fastest response, was placed directly below one of the rotors. The sensor for ambient pressure was located inside COCAP's housing, which was not hermetically sealed and therefore in equilibrium with ambient pressure.

- 5 The measurement principles employed by the different sensors as well as their measurement uncertainties are listed in Table 1. The uncertainty of the calibration is included in the measurement uncertainties reported.

2.4 Unmanned aircraft

During ScaleX 2016 COCAP was deployed on an S1000 multicopter (SZ DJI Technology, China) controlled by a Pixhawk autopilot (3D Robotics, Berkeley, CA, USA) running the Ardupilot APM:Copter V.3.3.3 Firmware. Take-off mass of the whole
10 system was 8 kg. The multicopter was powered by three lithium polymer batteries with a voltage of 22.2 V and a capacity of

5000 mAh each, achieving a maximum flight time of 12 min. Our special flight permit included nighttime flights, but because the take-off mass of our UAS exceeded 5 kg, all flights were limited to a maximum height of 150 m.

3 Methods

3.1 Disturbance by the UAS

5 A multicopter as a rotary-wing aircraft counterbalances gravity by accelerating air downwards through the movement of its rotors. The resulting displacement of air can interfere with in situ measurements, because air might be sampled at a location where it would normally not reside. In addition, volumes of air originating from different locations can be mixed together. The greater the displacement and mixing caused by the UAS, the greater is the potential impact on e.g. the measurement of a gradient. Air movement below and above the rotors is not symmetric: below a rotor, air is pushed downwards as a directed stream with high speed. In contrast, the air flow towards the rotor comes from different directions and has lower speed. The reader can easily confirm this with a fan or a hair dryer: while the outflow of air can be felt meters away, the inflow is hard to sense even near the rotor.

10 In view of the asymmetric flow pattern we expect that during ascent of the UAS air parcels are measured with negligible displacement from their undisturbed location. During descent, however, the sensors are moved into a volume that potentially has been flushed with air originating from several meters above. During hovering at a fixed location or during purely horizontal movement, the sensors might reside in a partially closed flow loop that extends below and aside the multicopter, effectively measuring a mixture of air from different locations.

For the study presented here, flying near the ground can have a particularly strong influence on the measurements for three reasons. Firstly, downward motion of the air stops at the ground and displaced air must move laterally or upwards, making a fast flow path back to the UAS more likely. Secondly, in our nighttime experiments the air near the ground is stably stratified. Therefore, air pushed downwards by the rotors experiences a restoring upward force, increasing the chance that closed flow loops form. Thirdly, the strongest gradients in temperature and CO₂ dry air mole fraction are present close to the ground, hence even a small displacement of air can have a large effect on the measured values.

25 In case of considerable horizontal air speed, due to either wind or horizontal flight, the rotor-induced airflow should have a smaller effect on measurements because the sampling system is moving away from air that has been displaced. We investigated this effect by flying horizontally at different speeds over a homogeneous meadow (see Section 4.4).

Based on the considerations above and the data presented in Sections 4.3 and 4.4 we create the NBL budget only from those measurements that were taken during ascent of the multicopter. The sensitivity of the NBL-derived fluxes to inclusion of hover and descent data is discussed in Section 4.5. Furthermore we discard COCAP's x_{CO_2} data collected below 9 m height for the calculation of the NBL budget. Instead, the lowest part of the x_{CO_2} 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_{CO_2} between the measurement locations. In Sect. 4.6 we discuss how the NBL-derived

fluxes are affected if the effect of the replacement with stationary measurements on the mean and spread of the data from the 9 m mast is not used the derived fluxes is discussed.

3.2 Correction for response time of sensors

On a moving platform the finite response time of sensors can be a source of measurement error, as the response time distorts the attribution of data points to time and location. COCAP's pressure and temperature sensors are fast enough for this effect to be neglected, but both the humidity and the CO₂ sensor require correction.

The response of a capacitive humidity sensor can be expressed as Miloshevich et al. (2004)

$$\frac{dU_m}{dt} = k(U_a - U_m). \quad (1)$$

U_a and U_m are ambient and measured relative humidity, respectively. The coefficient k is inversely related to the sensor's response time and might be temperature-dependent. Solving Equation 1 for U_a provides a simple way to compute true humidity from measurements. We use a 4th order Savitzky–Golay filter (Savitzky and Golay, 1964) with a length of 15 samples to compute $\frac{dU_m}{dt}$ while keeping high-frequency noise at an acceptable level. The coefficient $k = 14\text{s}$ was determined by an optimisation that minimises the difference between the corrected humidity profiles for ascent and descent. We tested a linear and quadratic dependence of k on ambient temperature, but found no improvement that would justify the additional degrees of freedom in the model.

The response of COCAP's CO₂ sensor is more complex. Its response to step-changes in CO₂ dry air mole fraction can be approximated as

$$x_{SC}(t) = \begin{cases} x_0 & \text{if } t < t_d \\ a(x_0 - x_\infty)e^{(t_d-t)/\tau_1} + (1-a)(x_0 - x_\infty)e^{(t_d-t)/\tau_2} + x_\infty & \text{if } t \geq t_d. \end{cases} \quad (2)$$

Here x_0 and x_∞ denote the CO₂ dry air mole fraction before and infinitely long after the step change, respectively, and t_d is the sensor's dead time.

We determined the coefficient a , the dead time t_d as well as the time constants τ_1 and τ_2 from experimental data collected in the field. With COCAP running in flight configuration, i.e. with the inlet tube attached, we connected a tube with gas flowing from a cylinder. We observed a dead time of $t_d = 5\text{s}$ between making the connection and the first change of COCAP's reading. The remaining parameters were found by least-squares regression of Equation 2 to the data, yielding $\tau_1 = 27\text{s}$ and $\tau_2 = 3.2\text{s}$.

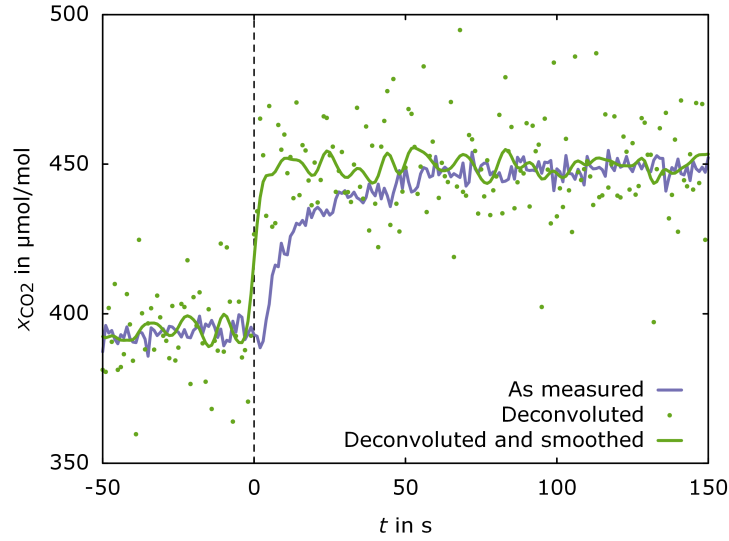


Figure 4. Response of COCAP to an abrupt change in CO₂ dry air mole fraction x_{CO_2} at the inlet at time $t = 0$ s. The measured signal reveals a dead time of 5 s of the sampling system. Furthermore, the step change in x_{CO_2} is smoothed out. Both effects are removed by deconvolution at the cost of higher noise. Smoothing the deconvoluted signal reduces the noise with only minor impact on the time response. Smoothing was carried out by convolution with a Gaussian of 5 s full width at half maximum (FWHM).

Ignoring noise and calibration error, any CO₂ signal x_a is reported by COCAP as the convolution of x_a with the CO₂ sensor's instrument function f (see Kunz et al. (2018)):

$$x_m(t) = (x_a * f)(t) \quad (3)$$

$$\text{with } f = \begin{cases} 0 & \text{if } t < t_d \\ \frac{1}{x_\infty - x_0} \cdot \frac{dx_{SC}}{dt} & \text{if } t \geq t_d. \end{cases} \quad (4)$$

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As x_{SC} is known from experiment, f can be calculated. The ambient signal x_a can be recovered from the measured signal x_m by deconvolution (Fig. 4). We carried out the deconvolution in Fourier space where it is equal to a division. In the numerical implementation it is important to discretise f in a way that does not underestimate the slope of f between the time steps t_d and $t_d + \Delta t$, because doing so would lead to a strong enhancement of the noise during the deconvolution of x_m with f . The opposite error, i.e. overestimating the slope between t_d and $t_d + \Delta t$, is less critical and just results in a slight smoothing.

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3.3 Calculation of the NBL budget

For a parcel of air in the atmosphere the following continuity equation holds (Leuning, 2004, Equation 6.2):

$$\sigma = \frac{\partial c}{\partial t} + \nabla \cdot (c \vec{u}) \quad (5)$$

$$= \frac{\partial c}{\partial t} + c(\nabla \cdot \vec{u}) + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z}. \quad (6)$$

Here σ is the strength of a volume source (or sink) of carbon dioxide (in units $\mu\text{mol} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$), c is the concentration of carbon dioxide and t denotes time. The components u , v and w of the wind vector \vec{u} point towards east (x -direction¹), towards north (y -direction) and upwards (z -direction), respectively. Molecular diffusion is neglected. Due to continuity of the air flow, the term $c(\nabla \cdot \vec{u})$ equals zero. If we follow an air parcel as it is transported by horizontal winds, those terms that contain a horizontal wind component vanish as well and Equation 6 is reduced to

$$\sigma = \frac{\partial c}{\partial t} + w \frac{\partial c}{\partial z}. \quad (7)$$

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Now we integrate vertically over those air parcels that form a vertical column over our site at the time of measurement (at earlier or later points in time, the air parcels are not aligned in a vertical column, unless the wind vector is equal at all heights):

$$\int_0^{z_t} \sigma dz = S = \int_0^{z_t} \frac{\partial c}{\partial t} dz + \int_0^{z_t} w \frac{\partial c}{\partial z} dz. \quad (8)$$

15 For our measurements, we choose $z_t = 125\text{m}$, so all biotic sources of carbon dioxide are within the column and S represents NEE.

Between a reference time t_0 (see below) and the time of a flight t_F the column has accumulated

$$\int_{t_0}^{t_F} S dt = \int_{t_0}^{t_F} \int_0^{z_t} \frac{\partial c}{\partial t} dz dt + \int_{t_0}^{t_F} \int_0^{z_t} w \frac{\partial c}{\partial z} dz dt \quad (9)$$

$$= \int_0^{z_t} c(z, t_F) dz - \int_0^{z_t} c(z, t_0) dz + \int_{t_0}^{t_F} \int_0^{z_t} w \frac{\partial c}{\partial z} dz dt. \quad (10)$$

¹Only here and in Eq. 6 x denotes a coordinate in space. Elsewhere in this publication x denotes the dry air mole fraction of a substance.

Dividing the accumulated amount of CO₂ by $t_F - t_0$ yields NEE averaged over this time span, denoted \bar{S} :

$$\frac{\int_{t_0}^{t_F} S dt}{t_F - t_0} = \bar{S} = \underbrace{\frac{\int_0^{z_t} c(z, t_F) dz - \int_0^{z_t} c(z, t_0) dz}{t_F - t_0}}_{(A)} + \underbrace{\frac{\int_{t_0}^{t_F} \int_0^{z_t} w \frac{\partial c}{\partial z} dz dt}{t_F - t_0}}_{(B)}. \quad (11)$$

- 5 Term A represents the enhancement in CO₂ concentration and term B the vertical exchange of CO₂. We choose t_0 as the time when the surface radiation balance becomes negative, i.e. the time when the stable NBL starts to form. A positive \bar{S} means emission of CO₂ from the surface into the atmosphere.

The CO₂ concentration c can be calculated from CO₂ dry air mole fraction x_{CO_2} , air temperature T and dry pressure p_d using the ideal gas constant R (Foken et al., 2012, p. 5):

$$10 \quad c = \frac{p_d}{RT} x_{\text{CO}_2}. \quad (12)$$

- As COCAP measures x_{CO_2} , T , p and relative humidity U , the integral $\int_0^{z_t} c(z, t_F) dz$ in Equation 11 term A is readily computed. However, each air parcel is sampled only once, at the time t_F when it passes the Fendt site. In order to evaluate the second integral in term A, $\int_0^{z_t} c(z, t_0) dz$, we assume horizontal and vertical homogeneity of the CO₂ dry air mole fraction at the time
15 t_0 , i.e. $x_{\text{CO}_2}(t_0)$ is assumed to be independent of l_1 , l_2 and z within the spatial domain relevant for our experiments. Thus we can calculate the second integral from the measurement of a different column at Fendt at t_0 .

- Note that this is a weaker assumption than the horizontal homogeneity of the CO₂ concentration *in the NBL* presumed in other studies Choularton et al. (1995); Culf et al. (1999); Acevedo et al. (2004). All natural environments exhibit a certain horizontal heterogeneity in S . The sign of the daytime CO₂ flux is generally negative, whereas the sign of the nighttime flux
20 is positive, but they are ~~often~~ usually of ~~similar~~ the same order of magnitude. Before t_0 , the convective boundary layer is well mixed up to a height of typically 1 km, whereas after t_0 a strong NBL confines emissions from the surface to the lowest ≈ 100 m of the atmosphere (see Sect. 4.3). Therefore, the horizontal heterogeneity in c caused by the horizontal heterogeneity in S is one order of magnitude smaller during day time than during the night. The convective mixing during the day also keeps vertical gradients inside the boundary layer low, hence the approximation of $x_{\text{CO}_2}(t_0)$ being independent of z is justified.

- 25 Term B in Equation 11 contains the product $w \partial c / \partial z$, which generally includes both turbulent exchange and subsidence. In a stable NBL, however, little turbulent exchange takes place. In the statically neutral residual layer above the NBL, turbulence is present, but the vertical concentration gradient in the residual layer and as a consequence the net vertical transport of CO₂ is small. Hence, we neglect turbulent exchange and identify $w \partial c / \partial z$ with subsidence or lifting. The vertical wind speed w due to subsidence at a height of 100 m is usually on the order of $100 \text{ m} \cdot \text{d}^{-1}$, i.e. very low and therefore challenging to measure. We

retrieve an estimate of w from the Integrated Forecast System (IFS) run by the European Centre for Medium-Range Weather Forecasts (ECMWF).

In order to calculate $\partial c/\partial z$ at different times between t_0 and t_F , we use a simple model for the growth of the NBL:

$$x_{\text{CO}_2}(t, z) = x_{\text{CO}_2}(t_F, \frac{t_F - t_0}{t - t_0} z) \quad (t_0 < t \leq t_F). \quad (13)$$

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Where $\frac{t_F - t_0}{t - t_0} z$ exceeds the maximum height of the profile measured at time t_F we assume the CO_2 dry air mole fraction to be equal to $x_{\text{CO}_2}(t_0)$. This model for the growth of the NBL can be visualized best by starting at t_F and looking back in time. At $t = t_F$ the factor $(t_F - t_0)/(t - t_F)$ is equal to unity and the model yields the measured profile. At earlier times, the measured profile is compressed in z -direction, such that the height of the NBL decreases linearly as we go back in time. As t approaches

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t_0 , the model yields a thin layer enriched with CO_2 at the surface and a constant CO_2 dry air mole fraction of $x_{\text{CO}_2}(t_0)$ above.

The concentration $c(t, z)$ is calculated from $x_{\text{CO}_2}(t, z)$ using Equation 12. To this end, we determine $p_d(t, z)$ and $T(t, z)$ by linear interpolation in time between the first profile of the night and the profile measured at t_F .

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In summary, the model for the growth of the NBL represents four simplifying assumptions: (1) During the night, the NBL height increases linearly, (2) the integral $\int_0^z x_{\text{CO}_2}(t, z) dz$ increases linearly with time, (3) the shape of the x_{CO_2} profile within the NBL remains the same throughout the night and (4) the dry pressure and temperature of an air column measured at Fendt are representative for the whole footprint of the measurement (see Sect. 3.4).

3.4 Footprint calculation

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The columns of air probed at Fendt at different times had a different history, depending on the wind field and atmospheric stability. Atmospheric transport models can identify the surface areas that have contributed to an observed tracer concentration, i.e. the footprint of an observation. We simulate atmospheric transport with STILT, the Stochastic Time-Inverted Lagrangian Transport model (Lin et al., 2003; Gerbig et al., 2003a), which is based on NOAA's HYSPLIT particle dispersion model (Stein et al., 2015). In our configuration, STILT launches 10 000 air parcels at different heights (see below) at every full hour during the period of our NBL measurements. Driven by meteorological data with a resolution of $0.1^\circ \times 0.1^\circ$ from the ECMWF IFS (European Centre for Medium-Range Weather Forecasts Integrated Forecast System), STILT calculates the back trajectories of these parcels until 10 h in the past. For each time step of the simulated transport the model determines the sensitivity of the CO_2 concentration in the parcel to the CO_2 flux at the surface. To do so, the height up to which mixing occurs is estimated from the meteorological data using a modified Richardson number method (Lin et al., 2003). Surface fluxes ~~are expected to be diluted into~~ influence air parcels within a column that extends from the surface to 1/2 this height in each time step (Gerbig et al., 2003b).

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The back trajectories calculated by STILT are then aggregated into mole fraction footprints on a regular grid with a resolution of $2 \text{ km} \times 2 \text{ km}$. As explained in the previous section we assume the x_{CO_2} distribution to be homogeneous in the lateral and

horizontal directions at time t_0 . We therefore restrict the aggregation to that part of each back trajectory that lies between t_0 and the time of measurement.

A single STILT run determines the sensitivity of an observation at a specific height to upwind fluxes. Formally, the mole fraction footprint of a measurement taken at the geographic location (l_1, l_2) at time t and observation height z can be written as $f(l_1, l_2, z, t | l_{G1}, l_{G2})$. As all our measurements were taken at the same horizontal location, the dependency of f on l_1 and l_2 will be omitted hereafter. The mole fraction footprint is a function whose value is the sensitivity to the surface flux at the grid cell specified by (l_{G1}, l_{G2}) in units of $[f] = \mu\text{mol} \cdot \text{mol}^{-1} \cdot \mu\text{mol}^{-1} \cdot \text{m}^2 \cdot \text{s}$. To determine the relative contribution of surface fluxes in different areas to our NBL-derived fluxes we need a different, but related function, the flux footprint f_F with units $[f_F] = \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \mu\text{mol}^{-1} \cdot \text{m}^2 \cdot \text{s} = 1$. The flux footprint is calculated by integration over an array of mole fraction footprints for different measurement heights, i.e. analogous to Equation 11 term A and Equation 12:

$$f_F(t | l_{G1}, l_{G2}) = \frac{\int_0^{z_t} \frac{p_d(z, t)}{RT(z, t)} \cdot f(z, t | l_{G1}, l_{G2}) dz}{t - t_0} \quad (14)$$

Dry pressure p_d and air temperature T at time t and height z are inter- or extrapolated from the measured profiles. The ensemble of mole fraction footprints comprises footprints for 12 different measurement heights between 10 m and 120 m in 10 m-steps.

The meteorological data we use have a horizontal resolution of $0.1^\circ \times 0.1^\circ$, corresponding to $11 \text{ km} \times 8 \text{ km}$ at the latitude of Fendt. Terrain features that are smaller than a grid cell, like the valley slope to the west of the Fendt site, cannot be represented at these resolutions. The vertical resolution of the meteorological data depends on height above ground. The lowest layer extends from the ground to 10 m height, the following 5 layers extend from the top of the ~~next-lower~~previous layer to 31 m, 55 m, 80 m, 108 m and 138 m, respectively. The temporal resolution of the ECMWF IFS data is 3 h.

4 Results and discussion

4.1 Uncertainty of x_{CO_2} measurements

The uncertainty of COCAP's x_{CO_2} measurements due to drift and calibration errors is about $1 \mu\text{mol} \cdot \text{mol}^{-1}$ (Kunz et al., 2018). The additional uncertainty caused by noise is dependent on the data treatment, as can be seen from Fig. 5. This Allan deviation plot (Allan, 1987) is based on measurements of a gas standard ($x_{\text{CO}_2} = 447.44 \mu\text{mol} \cdot \text{mol}^{-1}$) over a period of 1.4 h, taken in the field on 6 July 2016.

The curves illustrate that deconvolution amplifies noise in the data by a factor of 7 if no averaging is applied ($\tau = 1 \text{ s}$). However, if more than 100 samples are averaged ($\tau \geq 100 \text{ s}$), the difference between original and deconvoluted data becomes negligible and the uncertainty of the average due to noise is lower than $0.5 \mu\text{mol} \cdot \text{mol}^{-1}$. All our column integrals (see Section 3.3) have a sample size larger than 100.

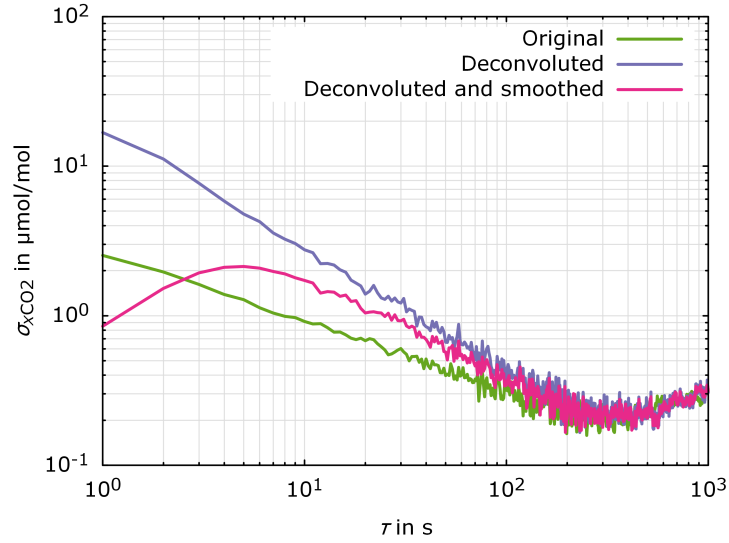


Figure 5. Allan deviation of CO₂ dry air mole fraction $\sigma_{x\text{CO}_2}$ as measured, after deconvolution and after deconvolution followed by smoothing (convolution with a Gaussian of 5 s FWHM) for different averaging periods τ . All three cases converge for averaging periods longer than 100 s.

Figure 5 also shows that the Allan deviation of deconvoluted data that has been smoothed by convolution with a Gaussian of 10 s full width at half maximum (FWHM) increases between $\tau = 1$ s and $\tau = 5$ s. This increase is an artefact caused by the autocorrelation that the smoothing induces. If COCAP was perfectly calibrated and exhibited no drift, any single point in the smoothed dataset would have an uncertainty of $2.1 \mu\text{mol}\cdot\text{mol}^{-1}$ (corresponding to $\tau = 5$ s), not $0.8 \mu\text{mol}\cdot\text{mol}^{-1}$ (corresponding to $\tau = 1$ s).

4.2 Meteorological conditions

From the data collected during ScaleX 2016 we calculate NEE for the nights 6–7 July and 9–10 July. The sun set at 19:15 UTC and 19:14 UTC on 6 and 9 July, respectively, and rose at 03:25 UTC and 03:27 UTC on 7 and 10 July, respectively. Both nights were free of precipitation. Cloud cover was high during the first night (see Fig. ure 6a), but the pronounced negative net radiation (Fig. ure 6b) indicates that the clouds were mostly transparent for outgoing long-wave radiation. In the second night the sky was clearer, resulting in a steadier radiation balance. During both nights, strong radiative cooling was observed. Air temperature decreased from 18 °C to 9 °C and from 24 °C to 11 °C over the course of the first and second night, respectively (Fig. ure 6c). In combination with low wind speeds (Fig. ure 6d) this lead to the development of a pronounced temperature inversion at the surface, i.e. a stable NBL. The change from positive to negative net radiation occurs approximately at $t_0 = 18:00$ UTC in both nights.

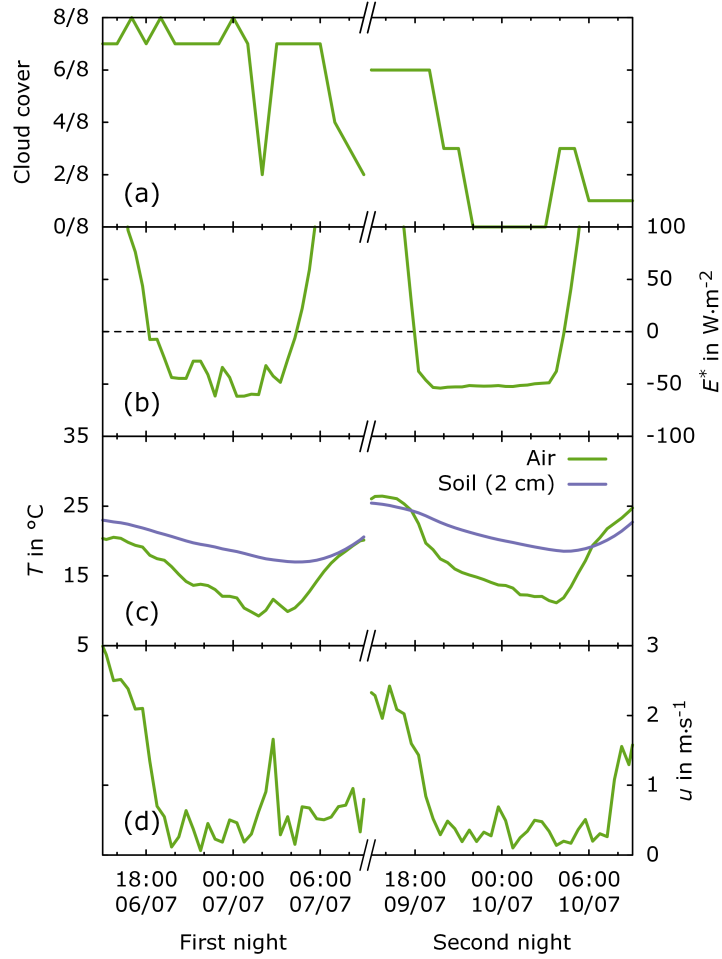


Figure 6. Meteorological conditions during the NBL soundings: (a) cloud cover, (b) net radiation E^* , (c) temperature T of air (2 m height) and soil (2 cm depth), (d) horizontal wind speed u (3.5 m height). Cloud cover was determined at MOHP, all other observations were made directly at Fendt.

4.3 Profiles

We carried out a total of 27 flights during the ScaleX 2016 campaign. For the calculation of a NBL budget we analyse those flights that took place after $t_0 = 18:00$ UTC and reached a height of at least 125 m. Twelve flights fulfil these criteria: flight 4 through 10 (first night, Fig.ure 7) and flight 19 through 23 (second night, Fig.ure 8). For display in panel b of Fig.ures 7 and 8 the CO_2 dry air mole fraction has been smoothed with a Gauss filter of 5 s FWHM. To prevent distortion in the vertical direction, the height above ground level z has been filtered the same way. For this reason, the upper end of the profiles in panel b is at slightly lower height than in panel a. Calculation of the NBL fluxes (see Section 4.5) was carried out with unfiltered x_{CO_2} and z .

During the first night, a stable NBL can be identified from the UAS profiles for flights 6 through 10. The upper end of the temperature inversion aligns with the top of the CO_2 enhancement to within 10–20 m. At the time of flights 6 and 8 through 10, the NBL has a height of 50–70 m, whereas the profile from flight 7 indicates a greater NBL height of ≈ 100 m. We interpret this as an indication that the column measured in flight 7 has been influenced by katabatic inflow of cool, CO_2 -enriched air at some point during the night, potentially hours before the flight and kilometers away from Fendt. This interpretation is supported by the flux estimates (see Section 4.5). The profiles from flight 5, which exhibit virtually no gradient, are discussed below.

During the second night, a stable NBL with a height of 50–70 m is visible in all profiles. The flight pattern had been refined and included two ascents and descents far enough from each other to avoid disturbance of the measurements in the second part by air movements caused during the first part. These redundant measurements give insight to the reliability of the measurement system and to the variability of temperature and CO_2 dry air mole fraction on small temporal and spatial scales. The data from flight 21 agrees well between each of the two ascents and descents, suggesting that disturbance by the UAS, instrument noise and drift are small compared to the observed signals. Flight 22 and 23 were carried out only one and two hours later, respectively, and followed the same flight track. However, the data from these flights reveals considerable differences between each of the two ascents and descents, especially in x_{CO_2} for heights below 50 m. We interpret this as natural variability on the scale of the flight track, i.e. ≈ 200 m in horizontal distance and ≈ 3 min in time. This small-scale variability is a source of random error in NBL budgets. In our flux calculations multiple ascents during the same flight are effectively averaged, resulting in a reduction of the random error.

The x_{CO_2} profiles measured during flight 20, 22 and 23 all exhibit a non-zero gradient with height in the region above the strong inversion, indicating that some CO_2 has escaped the stable NBL. This is supported by the profiles of virtual potential temperature, which are more inclined above the NBL in comparison to the first night. Both features might be the result of intermittent turbulence, a phenomenon often observed at night that can have different causes (see Aubinet (2008) and references therein). Our budgets include the measurements up to 125 m height, so any CO_2 that has been transported higher than this is missing in the budgets. In future campaigns, flights with a greater maximum height could be carried out to quantify the effect this has on the NBL-derived fluxes, or to extend the budget vertically.

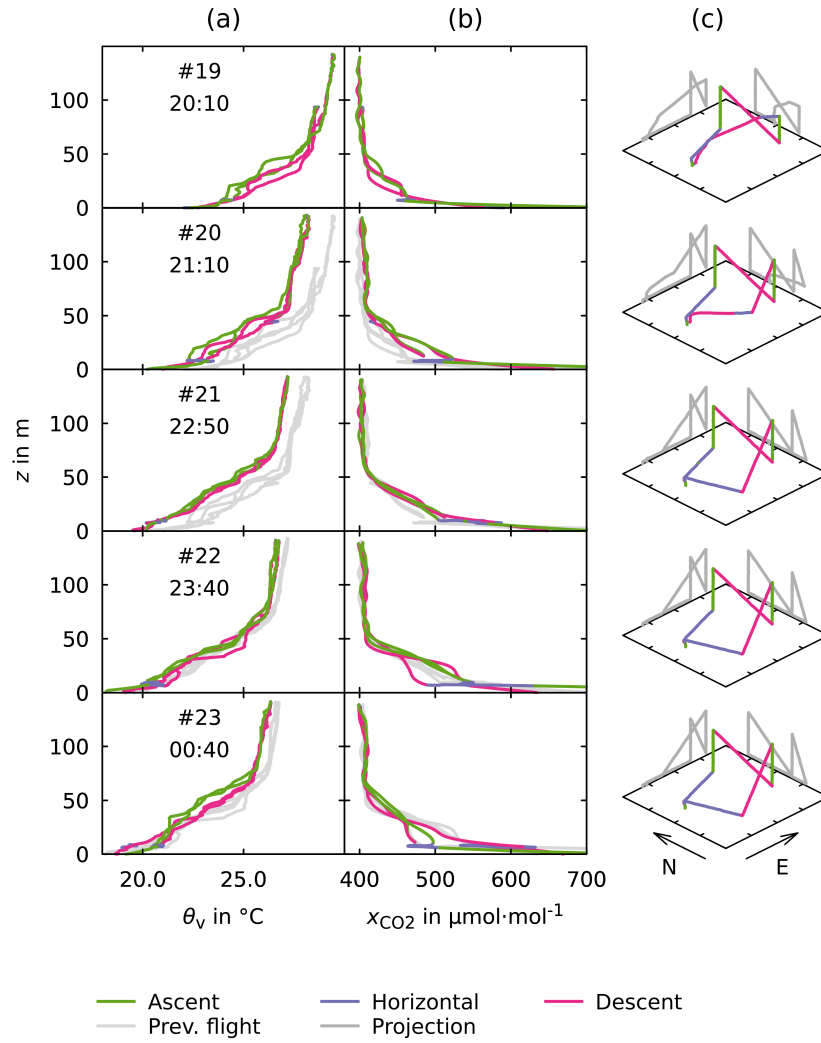


Figure 8. Same as Fig. 7, but for flights 19 through 23 carried out in the night from 9 to 10 July 2016. The axis for virtual potential temperature is shifted towards higher temperatures compared to Fig. 7, but covers the same span. All other axes are unchanged. The horizontal legs were flown at 10 m height.

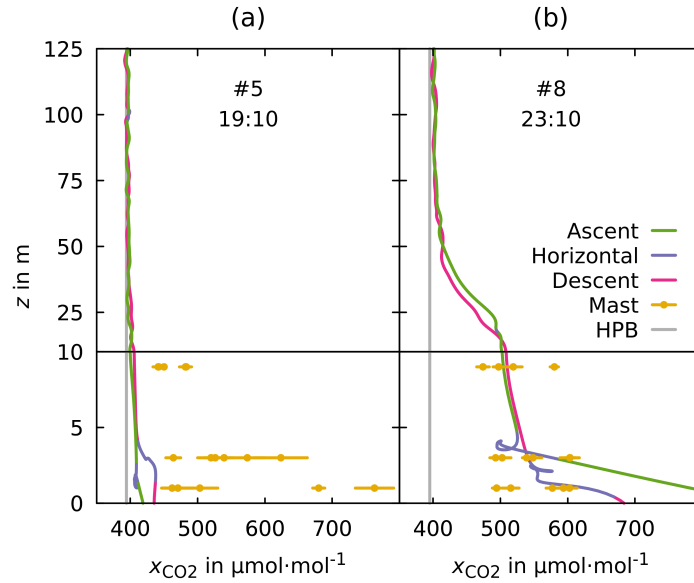


Figure 9. Comparison of x_{CO_2} measurements by COCAP, by the ICOS station Hohenpeißenberg (HPB) and by the on-site 9 m mast (a) for flight 5 and (b) for flight 8. The dots and bars are mean and standard deviation, respectively, for each 1-minute sampling period of the mast. Note that the scaling of the vertical axis changes at height $z = 10$ m.

The flight pattern used during the second night also included two horizontal transects at 10 m height that were flown at a ground speed of $3 \text{ m}\cdot\text{s}^{-1}$. Their purpose was to enable measurements of undisturbed air near the ground, but later analysis of flight 14 (see Section 3.1) revealed that the ground speed was insufficient to fully reach this goal.

The profiles for flight 5 are close to straight vertical lines, which would indicate a well-mixed atmosphere. However, they were measured under low wind speed one full hour after the surface radiation balance became negative, i.e. under conditions favourable for the development of a stable nocturnal boundary layer and accumulation of CO_2 near the ground. This apparent contradiction can be explained by comparing COCAP's data to stationary measurements. Fig. 9a shows the CO_2 profile taken by COCAP together with data from the 9 m mast and from HPB (see Sections 2.1 and 2.2). The diagram includes those measurements from the mast that fall into the time interval from 15 min before take-off to 15 min after landing. They reveal that the CO_2 dry air mole fraction near the ground was increased relative to the upper two thirds of the profile and fluctuated strongly, e.g. between 450 and $650 \mu\text{mol}\cdot\text{mol}^{-1}$ at 3 m height. These observations are in line with a weakly stable layer near the surface: Surface fluxes accumulated in this layer, but weak turbulent events caused e.g. by wind shear occasionally spread them out to higher layers. The disturbance by the multicopter during take-off or landing prevented COCAP from capturing this accumulation. On the other hand, the higher part of COCAP's profile, taken in the residual layer that is left over from the daytime mixed layer, matches the mean CO_2 dry air mole fraction measured at HPB during the time interval from 1 h before take-off to 1 h after landing. This agreement confirms that COCAP was working properly during the flight.

The profile from flight 8, carried out later in the same night, is consistent with the measurements at the 9 m mast (Fig. ure 9). We see two reasons for this difference to flight 5. Firstly, the radiative cooling (see Fig. ure 6) at the time of flight 8 (23:10) was stronger than at the time of flight 5 (19:10). The temperature gradient near the ground was not resolved during flight 5, but the weaker radiative cooling compared to the later flight has likely resulted in a weaker temperature inversion that allowed more vertical displacement of air by the multicopter. Secondly, the thicker NBL at 23:10 with a less steep CO₂ gradient close to the ground means that potential sampling of air parcels originating from above or below the multicopter did not affect the measurements during flight 8 as much as during flight 5.

At heights above 70 m the CO₂ profile from flight 8 approaches the measurements at HPB, indicating that the stable NBL retains most of the surface fluxes. Likewise, the CO₂ profiles of all other flights come near the measurements at HPB above the NBL (not shown). This suggests that any transport of CO₂ across the top of the NBL is small in magnitude.

The measurement of continuous profiles of the CO₂ dry air mole fraction up to heights of 100 m or more has been challenging in the past. In some studies, NBL budgets were therefore based on a measurement near the ground and an assumed gradient up to the top of the NBL. However, the complex shape of the profiles displayed in Fig. ures 7 and 8 suggest that neither the assumption of a constant (cf. Acevedo et al. (2004)) nor a linearly decreasing (cf. Culf et al. (1997)) CO₂ dry air mole fraction would properly represent the conditions at Fendt. The detailed structures resolved in our measurements also indicate great potential of combined measurements of meteorological parameters and trace gas mole fractions for studying small-scale phenomena in the NBL.

4.4 Disturbance by the UAS

The potential virtual temperature measured at heights between 10 and 60 m are generally higher during descent than during ascent. This effect is more pronounced for flights 19 through 23 (Fig. ure 8), likely due to the stronger temperature gradient compared to flights 5 through 10 (Fig. ure 7). The observed difference supports the reasoning of Section 3.1: As the multicopter descends, the onboard sensors measure warmer air that was pushed downwards by the rotors. Close to the ground (at heights below 10 -m) closed flow loops start to form and colder air from below the multicopter reaches the sensors during descent, as can be seen in the profiles from flights 6, 8, 9, 10 and 23.

Systematic differences between ascent and descent are less visible in the profiles of CO₂ dry air mole fraction, likely due to a larger variability of CO₂ within the nocturnal boundary layer. This variability is reflected in the difference in x_{CO_2} between each of the two ascents and descents in the flights 19 through 23, esp. flight 20 and 23.

Flight 14 was dedicated to the investigation of vertical mixing during horizontal movement at different air speeds. It was carried out on 7 July at 22:15 UTC. Winds were particularly low that night (on average 0.3 m·s⁻¹ between 22:00 and 22:30 UTC) and hence ground speed of the UAS was approximately equal to air speed. A stable nocturnal boundary layer had developed, as can be seen from the profiles of θ_v and x_{CO_2} measured during an earlier flight at 20:15 UTC (see Fig. ure 10 panels a and b). The UAS flew a spiral pattern at a height of 10 m above ground with decreasing ground speed (Fig. ure 10c). Throughout flight 14, COCAP's air inlet faced the direction of movement. The flight took place over a flat, homogeneous meadow. Hence, we assume that terrain and vegetation had caused no heterogeneity in the lateral distribution of temperature

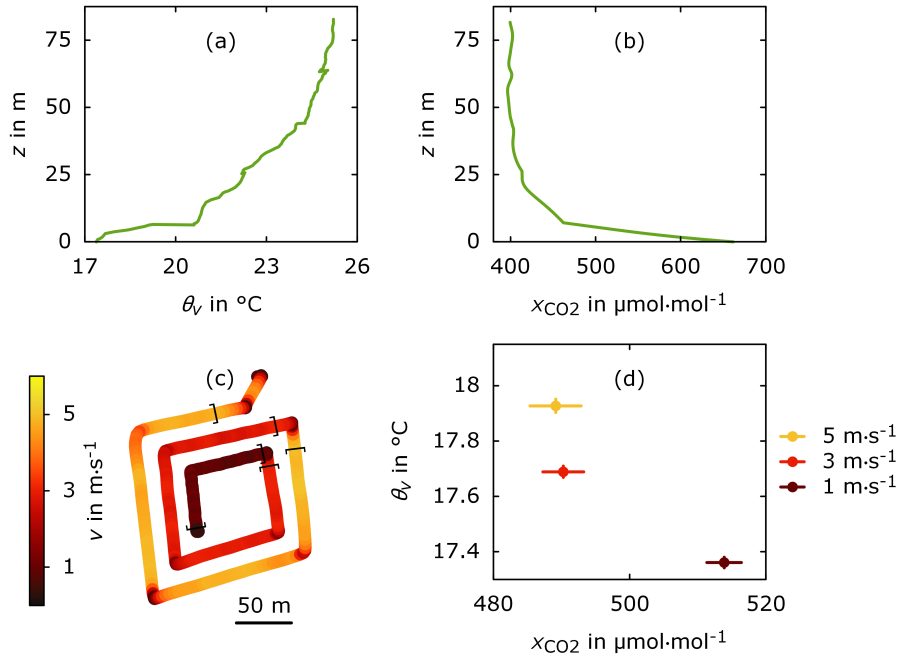


Figure 10. Vertical profiles of (a) virtual potential temperature θ_v and (b) CO_2 dry air mole fraction x_{CO_2} at 20:15 UTC on 7 July 2016. (c) Track of flight at 22:15 UTC on the same night coloured by horizontal ground speed. Three sections of nominal speed $5\text{ m}\cdot\text{s}^{-1}$, $3\text{ m}\cdot\text{s}^{-1}$ and $1\text{ m}\cdot\text{s}^{-1}$ are marked with brackets. Height was 10 m above ground throughout the flight. (d) Median of virtual potential temperature and CO_2 dry air mole fraction measured during those three sections of the flight. Bars represent the bootstrapped standard error of the median, see text for details. The standard error of the virtual potential temperature is so small that the vertical bars are barely visible. At lower speeds, θ_v is lower and x_{CO_2} higher, suggesting the sampling of air that originates from below the flight height.

and CO_2 . We analyse three sections of nominal speed $5\text{ m}\cdot\text{s}^{-1}$, $3\text{ m}\cdot\text{s}^{-1}$ and $1\text{ m}\cdot\text{s}^{-1}$. Figure 10d shows the median virtual potential temperature and CO_2 dry air mole fraction for each section. The standard error of the median was calculated by bootstrapping with 1000 samples generated from the empirical distribution of the measurements (Wilcox, 2012, pp. 43) and is depicted as horizontal and vertical bars.

- 5 The decrease of virtual potential temperature with decreasing speed in Figure 10d suggests that upward mixing of air from lower layers has a stronger influence on the measurements at lower speed. Likewise, the CO_2 dry air mole fraction measured at $1\text{ m}\cdot\text{s}^{-1}$ is $20\mu\text{mol}\cdot\text{mol}^{-1}$ higher than during faster flight. However, we did not observe a significant difference in x_{CO_2} between a ground speed of $3\text{ m}\cdot\text{s}^{-1}$ and $5\text{ m}\cdot\text{s}^{-1}$. The sample inlet for the CO_2 measurement extends 20 cm to the side of the rotors, while temperature and humidity are measured directly below a rotor (see Fig. 3). As the sample inlet was pointing
- 10 forward throughout the flight, it might have mostly avoided partially closed flow loops during movement at $5\text{ m}\cdot\text{s}^{-1}$, while the temperature and humidity sensors were still affected.

Table 2. Fluxes of CO₂ calculated from NBL budgets

Begin	End	Storage flux	Subsidence flux	Total flux
dd/mm HH:MM	dd/mm HH:MM (flight)	in $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	in $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	in $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
06/07 18:00	06/07 19:08 (#5)	13.7	0.0	13.7
	06/07 21:16 (#6)	12.3	-0.1	12.2
	06/07 22:14 (#7)	16.1	-0.2	15.9
	06/07 23:09 (#8)	11.3	-0.1	11.2
	07/07 00:21 (#9)	9.4	-0.1	9.3
	07/07 01:13 (#10)	8.4	-0.1	8.4
09/07 18:00	09/07 21:06 (#20)	17.2	-0.2	17.0
	09/07 22:48 (#21)	11.3	-0.1	11.2
	09/07 23:43 (#22)	11	-0.1	10.9
	10/07 00:35 (#23)	9.9	0.0	9.9

In summary, our results suggest that measurements taken during the ascent of the multicopter are more reliable than those taken during descent and hover. Horizontal transects at low heights can yield measurements that are contaminated with air from below the sampling height. This contamination is lower at higher horizontal air speed, because the multicopter moves away from the vortices it has created. Our experiment does not answer the question whether at 10 m height a horizontal speed of $5 \text{ m} \cdot \text{s}^{-1}$ is sufficient to avoid the contamination entirely.

4.5 Carbon dioxide fluxes

The first profiles of the first and second night were taken at 18:10 UTC (flight 4) and 20:10 UTC (flight 19), respectively. Hence, Flight 4 is representative for the x_{CO_2} profile at $t_0 = 18 : 00$ UTC, but flight 19 is not. We therefore need an estimate for the profile at t_0 . Due to the convective mixing that takes place during the day, the CO₂ dry air mole fraction within the boundary layer is nearly independent of height, an assumption that is supported by the profile from flight 4 (see Fig. 7). Assuming further that all surface fluxes were trapped in the developing NBL, air parcels above the NBL height should have preserved the CO₂ dry air mole fraction of the column between t_0 and the time of the first flight. Consequently, we assume the whole column $x_{\text{CO}_2}(t_0, z)$ to be equal to the mean dry air mole fraction of the first measured profile between 50 m and 125 m height. For consistency we apply this approach to both nights.

The fluxes we calculated from the NBL budgets are listed in Table 2, given as amount of CO₂ per time and surface area. The storage flux in Table 2 corresponds to term (A) in Equation 11, the subsidence flux to term (B) and the total flux is equal to \bar{S} , i.e. the NEE averaged over the time from t_0 to t_F . During both nights, horizontal convergence of air masses lead to lifting and consequently a negative subsidence flux. However, the subsidence flux was small compared to the storage flux, accounting

for about 1 percent of the total flux. An important consequence of the low subsidence flux is that errors stemming from the simplified model of the NBL growth (see Sect. 3.3) have only a minor influence on the uncertainty of the total flux.

The plausibility of our results can be checked against EC and chamber measurements taken at Fendt. Both the EC and the chamber measurements observed only the fluxes from the pasture at the site, while the NBL budget has a larger footprint. Even at low wind speeds of $0.5 \text{ m} \cdot \text{s}^{-1}$ air parcels travel 1.8 km every hour. Therefore, the NBL budget also includes sources that are located at several kilometres distance. Given the land cover around Fendt, those sources likely include forests, crop fields and potentially some residential areas (see Section Fig 14 and 15 for an exemplary footprints). Nevertheless, as pasture is the dominant land cover in the area, all three methods should agree in the order of magnitude of the CO_2 flux at night.

No EC measurements of acceptable quality are available for either of the nights we probed the NBL (Fig. ure 11). Conditions of strong radiative cooling combined with weak wind resulted in stable conditions and a violation of the assumptions underlying the EC technique. As a backup, we calculated the mean diurnal cycle from the EC measurements taken between 4 July 2016 00:00 -UTC and 11 July 2016 23:59 -UTC, a period that includes all our flights and was reasonably consistent in the diurnal variations of temperature. The result is presented in Fig. ure 11. All fluxes calculated from the NBL budget lie within the range of NEE observed by EC between 18:00 and 01:00 -UTC ($6\text{--}16 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). The later the flight at Fendt took place, the lower the NBL-based average NEE, indicating a decreasing flux over the course of the night. We interpret this, at least partially, as an effect of the temperature decrease during the night (Fig. ure 6), which reduces respiration. In contrast, NEE measured by the EC station increases during the night. However, an increase in respiration over the course of the night is implausible. Given the small number of EC measurements of acceptable quality this apparent trend is likely an artefact.

Figure 12 shows the NBL-derived fluxes in comparison to chamber measurements. Data from the small chambers is available only for the second night. Opaque chambers measure respiration, while clear chambers, the EC station and the NBL budget observe NEE. Therefore, a comparison of the fluxes obtained with these different techniques is only meaningful when photosynthesis is low or absent, i.e. roughly between sunset and sunrise. The convergence of the fluxes of the clear and dark chambers just after 18:00 -UTC suggests that photosynthesis has largely ceased as early as t_0 . Hence, throughout the time span for which we create the NBL budget NEE is dominated by respiration and all the different techniques are comparable. Surprisingly, the measurements with the big chambers yield fluxes only 1/3 as high as obtained with the small chambers, even though all chambers were deployed close to each other on the same meadow. Despite careful investigation the reason for this discrepancy has not yet been found. The NBL budget agrees in magnitude to the fluxes measured with the small chambers. Similarly to the NBL budget, all chamber measurements exhibit a negative trend in fluxes over the course of both nights.

In addition to in situ measurements at Fendt, the range of nighttime NEE of pasture and forests observed in other studies at central European sites with a climate similar to Fendt (Cfb or Dfb in the Köppen-Geiger classification according to Peel et al. (2007)) provides a plausibility check for the NBL budgets (Table 3).

We exclude crop fields from the comparison, as their NEE depends heavily on crop type and time of harvest. Compared to the literature values, NEE for Fendt derived from the NBL budget is on the high end of ranges reported for pasture and higher than most fluxes reported for forests. One explanation is that our measurements took place on two fair weather days in the warmest month of the year 2016, which likely resulted in higher respiration than observed on average over a longer

Table 3. Nighttime CO₂ fluxes observed in other studies (minimum–maximum of reported values)

Location	Land cover	Period dd/mm/yyyy	Method	Flux $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Source
Grillenbug, Germany	Pasture	02/07/2004– 16/07/2004	EC	3.9–10.2	Gilmanov et al. (2007)
Stubai Valley, Austria	Pasture	01/07/2002– 30/07/2002	EC	6–17	Wohlfahrt et al. (2005)
Stubai Valley, Austria	Pasture	01/07/2002– 30/07/2002	Chambers + model	6–11	Wohlfahrt et al. (2005)
Stuttgart, Germany	Pasture	13/08/2006– 17/11/2006	Chambers	1.3–3.2	Chen et al. (2014)
Waldstein– Weidenbrunnen, Germany	Managed spruce forest	01/06/2007– 15/07/2007	Mass balance	1–7	Siebicke et al. (2012)
Hesse, France	Managed beech forest	05/08/2005– 06/08/2005	EC	1.1–5.5	Longdoz et al. (2008)
Hainich, Germany	Unmanaged beech forest	12/08/2005– 30/09/2005	Mass balance	3–9	Kutsch et al. (2008)
Hainich, Germany	Unmanaged beech forest	12/08/2005– 30/09/2005	Bottom-up model	5–5.5	Kutsch et al. (2008)
Mooseurach, Germany	Managed spruce forest	01/01/2011– 31/12/2011	EC	–1–15	Hommeltenberg et al. (2014)

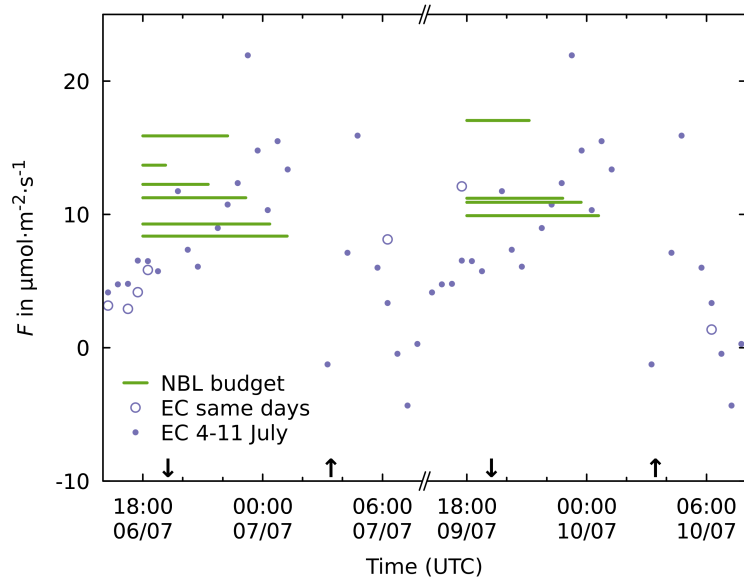


Figure 11. Comparison of vertical CO₂ fluxes F calculated from the NBL budget and using the EC method. The fluxes from the NBL budget are depicted as lines, where the vertical position of each line represents the average flux over the time span specified by the horizontal extend of the line. Open circles represent the quality-filtered EC measurements taken on the same days as the NBL measurements. Solid dots represent the mean diurnal cycle of the quality-filtered EC measurements averaged over the period from 4 July 2016 00:00-UTC to 11 July 2016 23:59-UTC. Upward and downward arrows mark the time of sunrise and sunset, respectively. NBL and EC agree in magnitude of NEE at night, but not in sign of trend.

period. 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.

- 5 -Another potential cause for higher fluxes observed with the NBL budget relates to the terrain at Fendt. At night, katabatic flows of cool, CO₂-rich air can stream down the steep slope west of the measurement site. Though Fendt is situated in a valley with only a shallow slope to the east, this inflow might lead to localised lifting of air that is not accounted for in the ECMWF IFS data and hence not included in our calculation of subsidence. The increased NBL height and high variability in the lowest 50 m observed during flight 7 as well as the higher flux derived from the NBL budget are an indication of such an inflow event.

10 4.6 Sensitivity of fluxes

The NBL budget is influenced by measurement uncertainty, incomplete knowledge about the state of the atmosphere and data selection. In order to quantitatively assess the influence of these factors on our results, we changed the procedure of calculating fluxes in either of the following ways:

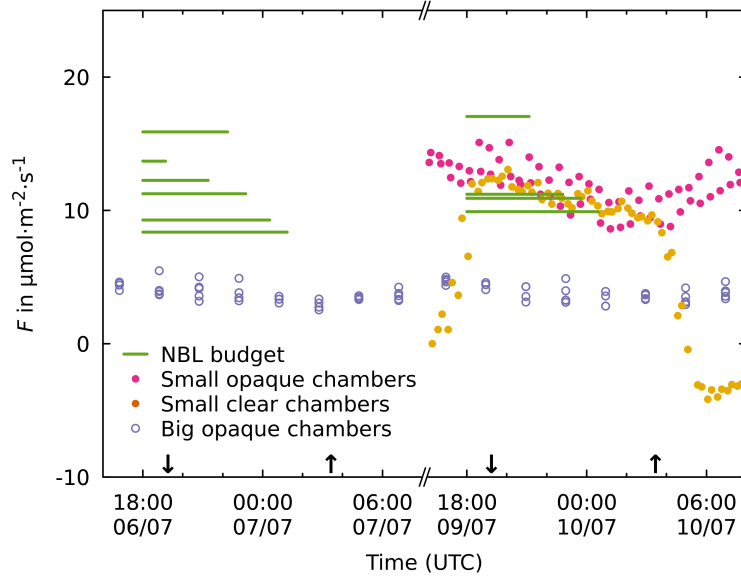


Figure 12. Comparison of CO₂ flux F calculated from the NBL budget and flux measured with different chambers. The Axis scaling and sunset/sunrise markers are the same as in Fig. ure 2. Nighttime fluxes observed with the small and the big chambers differ by a factor of three for unknown reasons. The NBL budget agrees in magnitude and sign of trend to the measurements with the small chambers.

1. by adding a bias of ± 2 m to the altitude measurements,
2. by adding a bias of $\pm 3 \mu\text{mol}\cdot\text{mol}^{-1}$ to x_{CO_2} of all but the first profile of each night,
3. by using COCAP data for the whole column instead of replacing x_{CO_2} in the lowest 9 m with stationary measurements taken at the 9 m mast,
- 5 4. by using COCAP data taken during the whole flight, i.e. using ascent, descent and hover instead of ascent only, or
5. by disregarding subsidence.

Check 1 accounts for the uncertainty of COCAP's pressure-based altitude measurements. Check 2 allows us to evaluate the influence of both the uncertainty of COCAP's x_{CO_2} measurements and the spatial heterogeneity of $x(t_0)$. The former is known from experiment (see Section 4.1) and the latter can be estimated from the CO₂ measurements at HPB. Assuming that the 131 m
 10 inlet at HPB is in the residual layer all night, the interquartile range of the x_{CO_2} measurements of a single night approximately reflects the variability of the background onto which fluxes accumulate. It amounts to $1.1 \mu\text{mol}\cdot\text{mol}^{-1}$ and $2.4 \mu\text{mol}\cdot\text{mol}^{-1}$ for the period from 18:00 -UTC to 02:00 -UTC in the first and second night, respectively. Check 3 and 4 relate to the disturbance caused by the UAS, which is discussed in Sections 3.1 and 4.4.

The mean fluxes for each night obtained using the changed procedures are summarised in Table 4. The largest difference
 15 to the normal ("No change") procedure occurs when x_{CO_2} is altered ($\pm 11\%$ for the first and $\pm 7\%$ for the second night,

Table 4. Sensitivity of CO₂ flux to different factors (see text for details). Unit of fluxes is $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

Night	No change	$z + 2 \text{ m}$	$z - 2 \text{ m}$	$x_{\text{CO}_2} + 3 \text{ ppm}$	$x_{\text{CO}_2} - 3 \text{ ppm}$	Whole flight	w/o 9 m mast	No subsid.
1	11.8	12.2 (+3 %)	10.6 (-10 %)	13.1 (+11 %)	10.5 (-11 %)	11.4 (-3 %)	10.8 (-8 %)	11.9 (+1 %)
2	12.3	12.7 (+3 %)	11.7 (-5 %)	13.1 (+7 %)	11.4 (-7 %)	11.9 (-3 %)	12.7 (+3 %)	12.4 (+1 %)

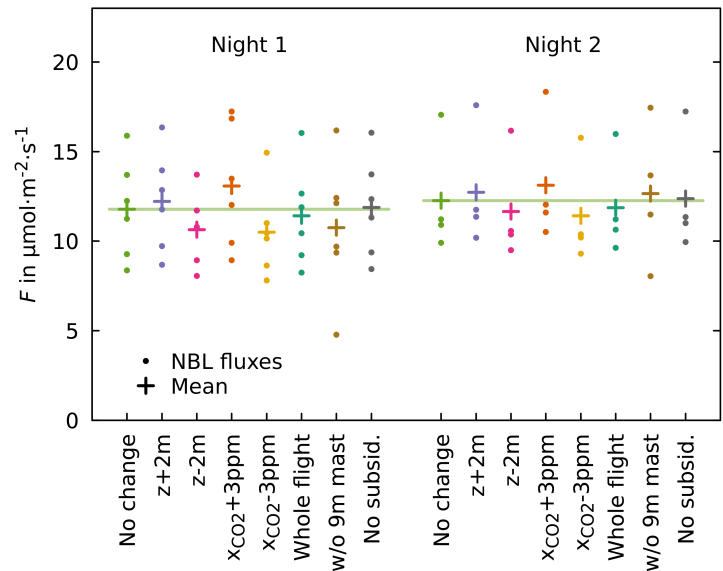


Figure 13. Sensitivity of CO₂ fluxes calculated from the NBL budgets to changes in calculation procedure. Dots denote the fluxes calculated for each flight, crosses mark the mean of these fluxes. The lines are visual aids to facilitate comparison to the mean flux of the normal (“No change”) procedure.

respectively). Changing the altitude or not using the data from the 9 m mast also have a considerable influence on the mean flux.

Figure 13 shows the values from Table 4 in graphical form. In addition, the fluxes calculated for each flight are depicted, visualising how their spread is affected by the different checks. A substantial increase in spread is observed only when the data from the 9 m mast is not used.

Overall, the results from the sensitivity checks indicate that the NBL method is robust against measurement uncertainty in the altitude and x_{CO_2} measurements, spatial heterogeneity of $x(t_0)$, disturbance of the NBL caused by the UAS and the effect of subsidence. It should be noted that the mean vertical wind extracted from the ECMWF IFS model was relatively small during

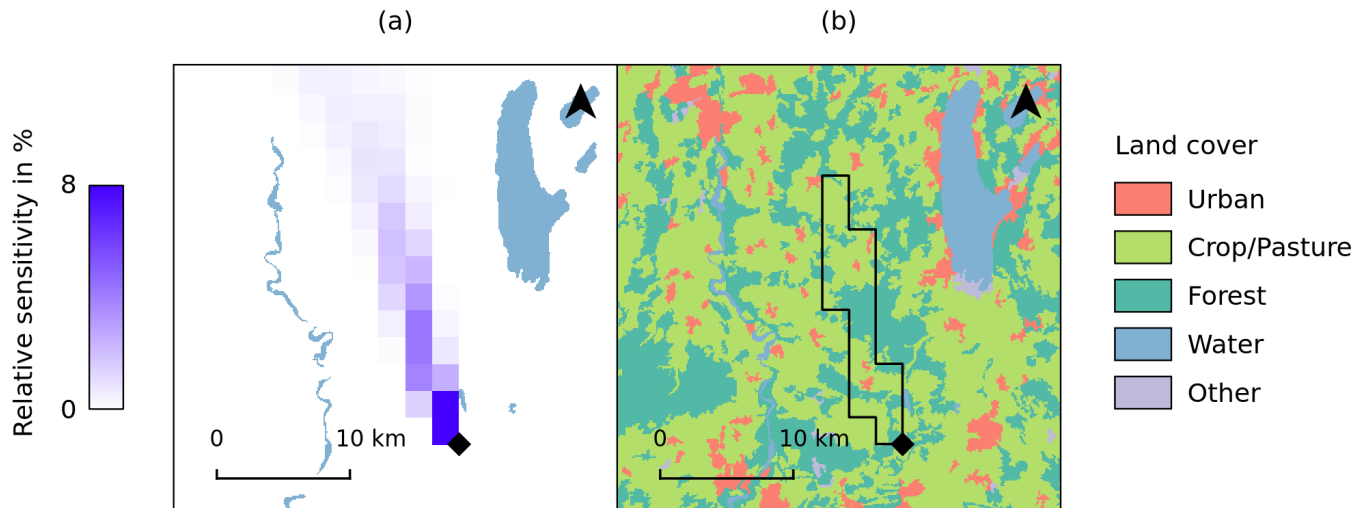


Figure 14. Footprint of an NBL budget at Fendt on 6 July 21:00 -UTC. (a) Relative contribution of each grid cell to the total sensitivity of the budget to surface fluxes. Water bodies depicted for orientation. (b) Contour of all grid cells with a relative sensitivity of 1% or higher on top of a simplified land cover map (CORINE 2012 v18.5, European Environment Agency, EEA (2016)). The area observed is dominated by forests, pasture and crop land.

the two nights of our measurements. Under different conditions, e.g. in a strong high pressure system, the effect of subsidence or lifting on the NBL budget could be much higher.

4.7 Flux footprint

Example flux footprints of one NBL budget of each night are visualised in Fig. 14 and Fig. 15.

- 5 The footprint depicted in Fig. 14 was calculated for a column of air passing Fendt on 6 July 2016 at 21:00 -UTC, i.e. close to the time of flight 6. The 1% contour of the footprint encloses an area of 60 km², which accounts for 60 % of the total sensitivity. The land cover map suggests that the NBL budget represents mainly the respiration of forests, pasture and crop lands north of Fendt, with little contribution from urban areas.

- 10 The footprint depicted in Fig. 15 was calculated for a column of air passing Fendt on 9 July 2016 at 21:00 -UTC, i.e. close to the time of flight 20. The 1% contour of the footprint encloses an area of 80 km², which accounts for 70 % of the total sensitivity. Again, the NBL budget is mainly influenced by forests, pasture and crop lands.

The footprints for other times during the two nights are similar in size, i.e. on the order of 100 km². They mostly cover the sector within 20 km north-west to north-east of Fendt.

- 15 We recognise that the relatively low spatial and temporal resolution of the ECMWF IFS meteorological model entails errors in the transport modelling. [Variability of the horizontal wind component within a grid cell and on time scales below three hours is neglected, possibly resulting in an underestimation of the footprint size. Likewise, terrain features that are smaller than a](#)

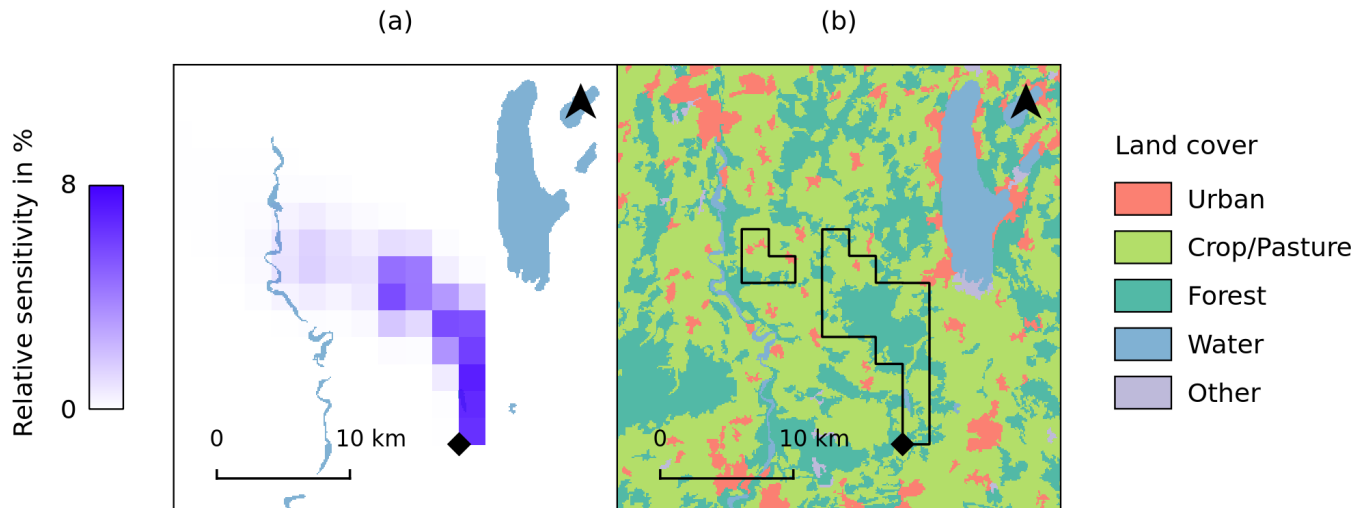


Figure 15. Same as Fig. 14, but for 9 July 21:00 -UTC

grid cell are not represented in the meteorological model. However, as our NBL budgets cover time scales of 1–7 hours and the footprints extend over many grid cells, sub-scale variability should play only a minor role. We are therefore confident that the model results provide a reasonable estimate of the region seen by the NBL budget method.

5 Conclusions and outlook

- 5 To the best of our knowledge, we have for the first time created nocturnal boundary layer budgets that are based on trace gas measurements with an unmanned aircraft. During two nights we repeatedly sampled the NBL with a multicopter carrying COCAP, a lightweight analyser designed for deployment on unmanned aircraft. Simultaneous measurement of CO₂ dry air mole fraction, air temperature, humidity and pressure allowed to quantify the rate of accumulation of carbon dioxide in the NBL. By applying deconvolution we could improve the temporal resolution of the CO₂ measurements, thus achieving a higher
- 10 vertical resolution of the profiles. We estimated the effect of subsidence or lifting on the NBL budgets with the help of weather forecast data and corrected the budgets accordingly. The respiration fluxes obtained from the NBL budgets are plausible in comparison to other flux measurements at the Fendt site, though on the high end of the range reported in the literature for sites with land cover and climatic conditions similar to Fendt. A potential positive bias in the obtained fluxes could be caused by convergence of cool, CO₂-rich air at the floor of the valley in which Fendt is located. The current data set does not allow to
- 15 confirm or rule out this effect. In a future campaign, however, simultaneous deployment of a second UAS on the elevated plateau west of the site could provide more insight, as downward transport of CO₂ should result in consistently lower accumulation and hence lower flux estimates obtained from NBL budgets on the plateau.

We have investigated how the disturbance of the NBL caused by a multicopter influences in situ measurements. We found that while flying close to the ground, air from below the UAS can reach the sensors, causing a bias if the respective quantity has a non-zero gradient. To prevent this bias from affecting the NBL budget we replaced the airborne x_{CO_2} measurements taken at low height with stationary measurements from a 9 m mast. At greater height, some of our profiles exhibit a systematic
5 difference between ascent and descent. During descent, the airborne sensors are moved into a volume of air that may have been disturbed by the downwash of the multicopter's rotors. Therefore, we use only data captured during ascent for NBL budgeting.

The robustness of our approach has been demonstrated by a sensitivity analysis. The largest uncertainty of the NBL budget is caused by spatial heterogeneity of the CO_2 dry air mole fraction in the late afternoon combined with the uncertainty of the CO_2 measurement. The estimated combined error in x_{CO_2} results in $\pm 11\%$ change of the mean of the fluxes obtained from the
10 NBL budget for the first night. Using only data from the UAS and not from the 9 m mast increased the spread of the fluxes, but changed their mean by no more than 10 %. This suggests that satisfactory NBL budgets can be created from UAS data even if no stationary measurements near the ground are available. For future studies, we suggest to position the sample inlet 50–100 cm above the rotors to further reduce the sampling of air that was displaced or mixed by the UAS.

The region that influences an NBL budget has often not been reported in past studies. We improved on this situation by
15 carrying out mesoscale modelling. While the driving meteorological data and the underlying topography do not resolve small structures at and below the scale of 1 km, our method gives at least an estimate of the region that influences the NBL budget. Under the conditions of our measurements the footprints were on the order of 100 km^2 in size. In situ wind measurements would ~~allow~~ ~~enable~~ the validation of the meteorological data and possibly ~~an~~ improvement of the transport modelling. Such measurements could be taken by UAS without the need for additional sensors (Mayer et al., 2012; Neumann and Bartholmai,
20 2015).

Future NBL studies could employ multiple UASs simultaneously to quantify spatial heterogeneity and horizontal gradients in the CO_2 dry air mole fraction. Firstly, this supports the analysis of the uncertainty of the NBL-derived fluxes. Secondly, concurrent profiles could yield constraints for the net advection of CO_2 .

While we carried out our measurements with multicopters, fixed-wing aircraft would also be capable platforms for NBL
25 studies. The vortices generated by their wings are slower and spread out wider than the concentrated downwash produced by the rotors of a multicopter. Therefore they should cause less interference with the NBL soundings and could provide precise measurements down to ground level. Additionally, their typically higher horizontal speed makes it easier to evade any disturbance that they create.

Another possibility to reduce the disturbance of measurements near the ground would be a different placement of the inlet.
30 Given the asymmetric flow pattern below and above a multicopter's rotors (see Section 3.1), sampling from several rotor diameters above the UAS should reduce the artefacts caused by closed flow loops.

NBL budgets based on UAS measurements are an effective and efficient tool for the quantification of nocturnal fluxes. Besides ecosystem respiration, it could also be applied to detect carbon dioxide emissions of other sources, e.g. urban areas. Small and lightweight sensors for other tracers such as methane would open up even more possibilities. Alternatively, compact

time-resolved sampling systems (Andersen et al., 2017) or long flexible tubing (Brosy et al., 2017) can be used in connection with conventional ground-based instrumentation to measure a whole range of species.

In summary, we have demonstrated that nocturnal surface flux estimates can be derived from UAS-based gas measurements by means of an NBL budget approach. Given the moderate cost of UAS and their minimal infrastructure requirements this innovation makes the NBL budget method for the quantification of surface fluxes much more accessible. Spurred by the increasing adoption of unmanned aircraft in geoscience and the development of miniaturized high-accuracy sensors for different tracers we foresee wide adoption of this technique in the coming years.

Code and data availability. Measurement data from the UAS, output of the STILT model, analysis scripts and instructions how to run them are available at <https://dx.doi.org/10.17617/3.2c>. Time series of cloudiness observed at MOHB can be downloaded from the Climate Data Center (https://opendata.dwd.de/climate_environment/CDC/). Time series of the CO₂ dry air mole fraction measured at HPB can be requested from DWD; contact: dagmar.kubistin@dwd.de

Author contributions. R.H.G., M.K. and J.L. conceptualised and carried out the UAS-based measurements and M.K. curated the data obtained. M.Z. coordinated the ScaleX campaign, operated the EC station and the small chamber measurements and curated the data obtained. R.G. operated the big chamber measurements and curated the data obtained. B.W. operated the x_{CO_2} measurements at the 9 m mast and curated the data obtained. M.S. was responsible for the operation of the ICOS HPB site and curated the data obtained. C.G. and F.-T. K. ran the STILT model. C.G., R.H.G., M.K. and J.L. analysed the data. M.K. wrote the original draft of this publication. All authors reviewed the draft. M.K. compiled the final manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We thank the scientific teams of the ScaleX Campaign 2016 for their contribution, especially Klaus Schäfer for coordination of work package 2, Caroline Brosy for taking care of the flight permissions and John E. Flatt for piloting the UAS. Thanks to the staff of DWD for providing meteorological and trace gas data from Hohenpeißenberg. We thank Ingo Völksch for soil data of the Fendt site. M.K. thanks Fanny Kittler for illuminative discussions about the EC method. We gratefully acknowledge the authors of various open-source software packages that were used in our study and for the preparation of the manuscript, in particular Inkscape, GIMP, GNU Octave (Eaton et al., 2017), gnuplot, LaTeX, LyX and QGIS. The colours in diagrams and maps are based on the work of Cynthia A. Brewer (Brewer, 2017), Peter Kovesi (Kovesi, 2015) and the Wikicarto 2.0 colour map (Wikipedia contributors, 2012). We thank the Max Planck Society for generous financial support. The TERrestrial Environmental Observatory (TERENO) pre-Alpine research is funded by the Helmholtz Association ATMO Programme and the Federal Ministry of Education and Research. M.Z. received support from the German Research Foundation (DFG; grant ZE 1006/2-1).

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