Response to the comments by reviewer #2

In the response letter below, we copied the original comments by the reviewer in black, while our answer statements to these comments are printed in blue. All line numbers given in the response refer to the original submission before editing.

This manuscript presents a novel UAV-GHG platform and its applications on characterizing and quantifying GHG emissions and fluxes for natural ecosystems over heterogeneous terrains. UAV-GHG flux measurement is an innovative topic, and the applied methodology is sound. This paper is well written, and the methodology is clearly presented. It consists of GHG sensors' lab tests including Allan deviation tests. However, how will the sensors perform against temperature changes and water vapor. These parameters would impact the analyzers' performance especially for the field applications. Please refer to Comment 5 and 6 on the laboratory tests. This study conducts demonstration flights in Jena comparing to EC tower measurements and comprehensive grid flights in Stordalen Mire (Arctic ecosystem).

This paper is highly suitable for AMT. I would recommend publication after consideration of the following comments and minor corrections.

We would like to thank reviewer for his/her valuable comments that helped to improve our manuscript.

Specific comments:

1. Section 3.1 Laboratory tests of gas analyzers would fit better to Section 2.1. Logically, the analyzers should be introduced first before describing the integrated UAV platform. Field site descriptions would be more suitable before the section flight strategies.

Response to Comment #1

Thanks for the reviewer comment. We will move the section of the laboratory test before describing the UAV platform. The field site description was already given before the section of flight strategies.

2. Section 2.2, how long is the inlet and what are the flow rates for both sensors? Is time synchronization considered for the system (GPS, CO2 and CH4 readings, etc.)?

Response to Comment #2

Thanks for the reviewer comment. The inlet tubing is about a 1 m long, and the flow rates of the sensors are about 0.6 l/min. The time synchronization was achieved logging all data to a Teensy microcontroller, here we used Aeris Strato analyzer time, which has an internal RTC (Real Time Clock) to synchronize all the data. However, the Strato analyzer has a problem of deviation from true frequency (i.e. jitter), which means that the collected data is not exactly 2

Hz but between 1.99 - 2.01 Hz. Therefore, we aggregate all the data (UAV and scientific data) to 1s during the post-processing and do the further calculations. Following the reviewers suggestion, we eliminated the minor time lag between the analyzers and anemometer due to inlet tubing length which was estimated to be around 1 s. The updated the carbon flux calculations and the grid survey flights results were slightly changed; however, our main findings have not been affected by this update.

To address the reviewer comment, the manuscript lines 114 – 118, 303 – 308 and 339 – 341, and Figures 6-9 as well as Table 3 will be revised as follows:

"Due to a frequency deviation issue (i.e., jitter) with the Strato analyzer, the collected data were slightly off from the intended 2 Hz (between 1.99 - 2.01 Hz). Therefore, we aggregated all data including UAV movement (translational and rotational motion data), gas analyzers, and anemometer data to 1 s during post-processing step. Additionally, the time lag associated with the inlet tubing length (about 1 s) was also compensated in a post-processing step."

"Here, only data from the 11/09/2023 flights were selected, since all areas were sampled within the same day. The means of the mole fractions were 425.12 ppm for CO_2 and 2004.62 ppb CH_4, with standard deviations of 1.07 ppm and 3.66 ppb, respectively. Figure 8 emphasizes that the mole fractions over the significant section of the total area (about 35 and 26% of CO_2 and CH_4, respectively) do not overlap with the designated threshold (i.e. $\mu \pm \sigma$, where μ is the mean, and σ is the standard deviation) which again highlights the pronounced signal variability over heterogeneous landscapes."

"All conducted flights show CH_4 emissions, and the average emissions when the wind was blowing from the east side of the measurement location (47.48 ± 75.13 mgCH_4 m^{-2} d^{-1}) was found to be higher compared to those from the westerly directions (15.62 ± 39.59 mgCH_4 m^{-2} d^{-1})."

Table 3. Estimated friction velocities (u_*) and fluxes of CH_4 (F_{CH_4}) and CO_2 (F_{CO_2}) from the vertical profiles and corresponding uncertainties. Reference values ($_{Twr}$) were derived using observations from the ICOS EC tower at Stordalen Mire.

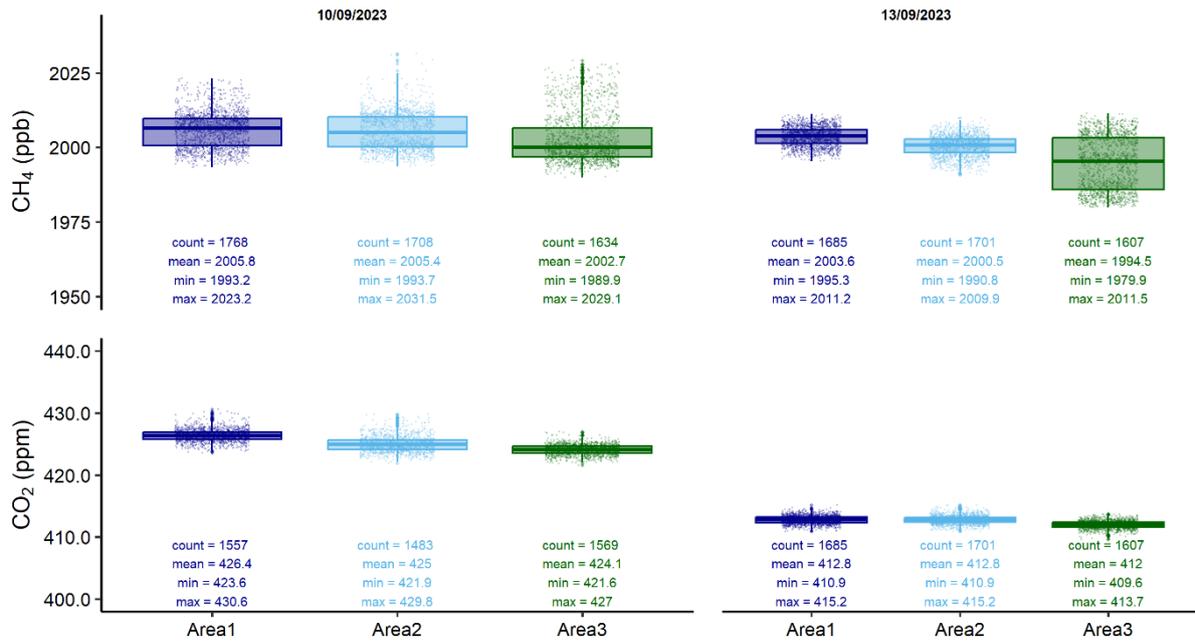| Flight Date	u_* (m s^{-1})	$u_{*,Twr}$ (m s^{-1})	F_{CH_4} (mgCH_4 m^{-2} d^{-1})	$F_{CH_4,Twr}$ (mgCH_4 m^{-2} d^{-1})	F_{CO_2} (gCO_2 m^{-2} d^{-1})	$F_{CO_2,Twr}$ (gCO_2 m^{-2} d^{-1})
07/09	0.22±0.08	0.22	12.07±47.44	15.84±49.83	5.23±9.33	-1.37
08/09	0.37±0.10	0.27	31.08±69.59	13.95±6.52	-13.11±31.45	-3.73
09/09	0.21±0.06	0.18	19.16±31.74	-1.36±7.98	-16.58±12.05	-6.92
15/09	0.23±0.14	0.38	63.88±80.67	10.86±9.29	-5.29±13.36	-3.80

Figure 6. CH₄ and CO₂ mole fractions measured by UAV from the grid survey flights on 11/09 and 13/09/2023. The measured data points (~2 Hz) were shown while the outliers were represented as diamonds. Basic statistics including the number of data points as count, mean, min, and max values were denoted underneath each corresponding box plot.
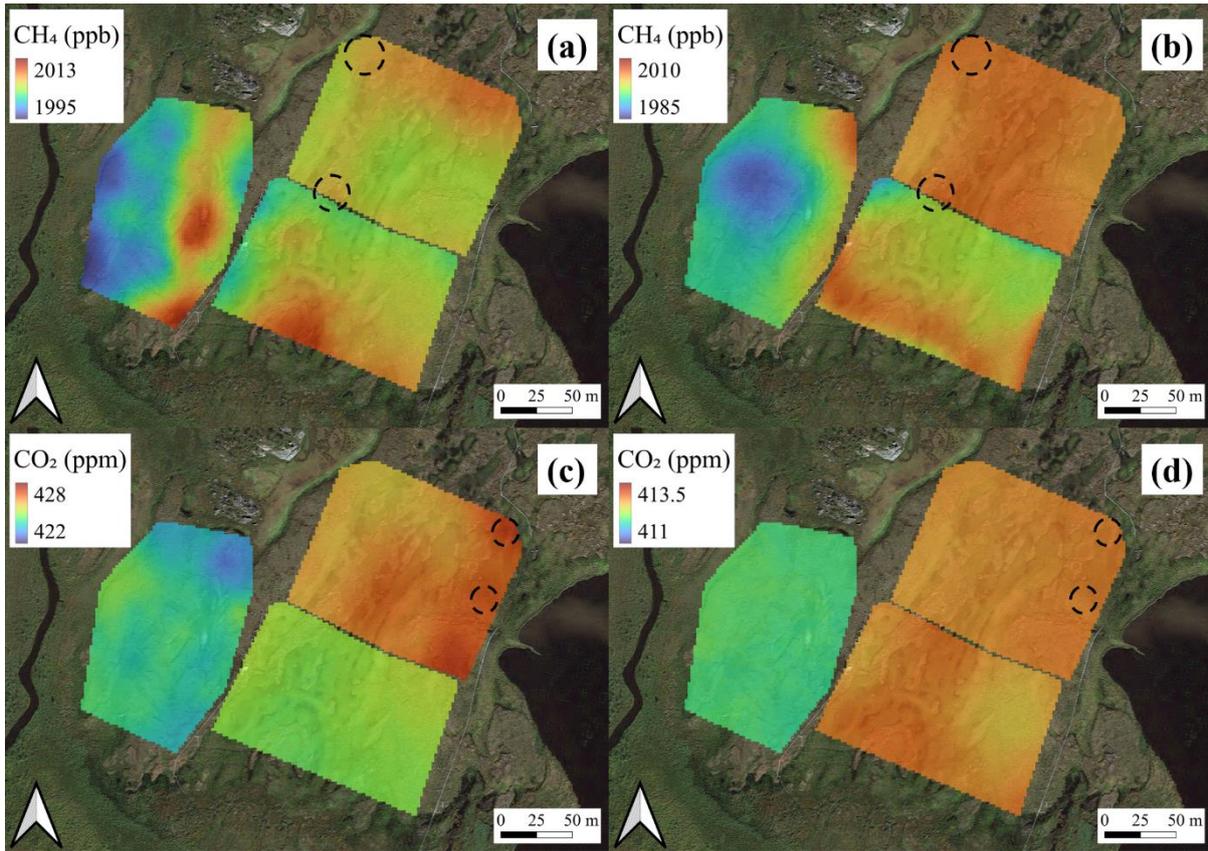
Figure 7. Interpolated CH$_4$ and CO$_2$ mole fractions, (overlayed on satellite image from © Google Maps), using Kriging algorithm of the grid surveys that were conducted on 11/09/2023 (a) and (b), and on 13-14/09/2023 (c) and (d). Note that, legends are different for each measurement day to highlight the potential hotspots. Here, color gradients from blue to red were used where blue colors represent low and red colors represent high mole fractions. Potential hotspots were enclosed by black dashed lines.
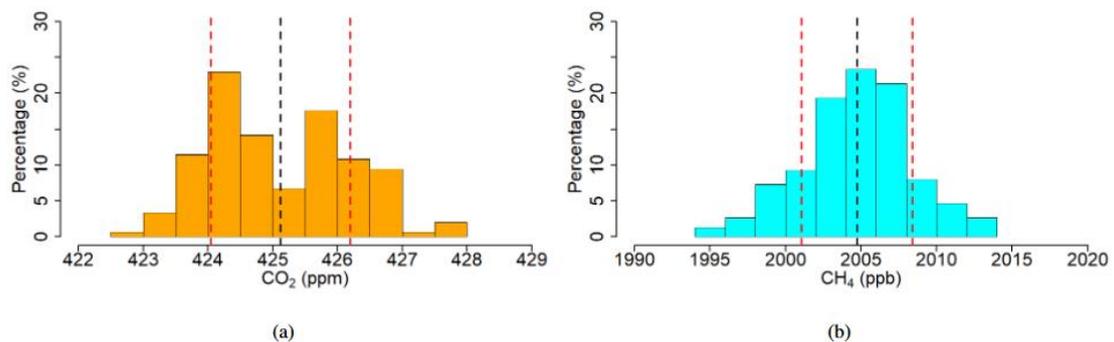

Figure 8. The distribution of spatially averaged CO$_2$ (a) and CH$_4$ (b) mole fractions of all three areas combined. Black dashed lines are the corresponding averages while the red dashed lines are the $\pm\sigma$, where σ is the standard deviation.
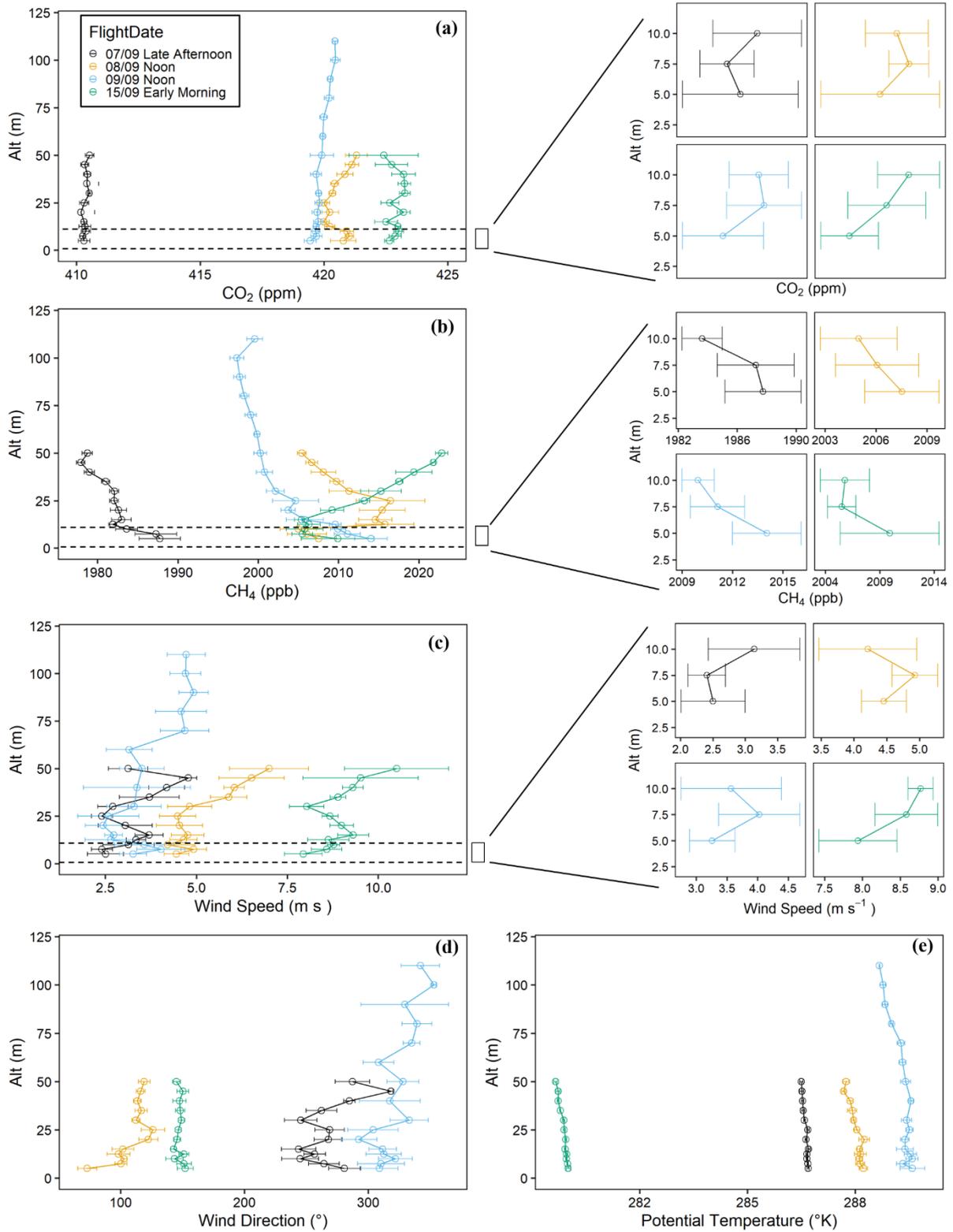
Figure 9. Vertical profiles of (a) CO_2, (b) CH_4, (c) Wind speed, (d) Wind direction, and (e) Potential temperatures. Here each symbol represents the average of each 10-s block, and horizontal lines represent the standard deviations. Profiles of Wind speed, CH_4, and CO_2 close to the surface ($z \leq 10$ m) were provided as a close look-up next to the corresponding figures.

3. Line 119, what data were pre-processed (from anemometer or GHG sensors)? And how the low-quality data were defined?

Response to Comment #3

Thanks for the reviewer comment. All data that were collected during flight were pre-processed. Anemometer data were processed to correct the wind speed measurements due to UAV motion (i.e. roll, pitch and yaw). On the other hand, CO_2 data were preprocessed due to observed unphysical spikes that were explained in line 153. Additionally, CH_4 and CO_2 data were processed to correct the possible drift during the flight using calibration gases. Here, the low-quality data were specifically related to the CO_2 data where the unphysical spikes were observed. To clarify this in the manuscript, line 119 will be revised as follows:

"Data collected by the UAV platform was pre-processed to correct or remove low-quality data related to sporadic spikes in CO_2 data."

4. Line 148 with known CO2 and CH4 mole fractions here, could you track the criterion of these cylinders and provide information here? Please refer to Liu et al., (2022) Laboratory tests part as an example.

These cylinders follow the current WMO calibration scales (WMO N2O X2006A, WMO CO2 X2019, WMO CH4 X2014A) through a set of standards that were calibrated by NOAA. More information about these can be found from these flask report https://dx.doi.org/10.17617/3.8r. While working on this reviewer comment, we actually realized the target concentrations of the cylinders were slightly different to those we used previously, which was subsequently fixed. Please see response to Comment #2 for the updated calculations, which show only very minor differences. According to the reviewer request, this information will be added, and the manuscript lines 148 – 153 will be revised as follows:

"To remove potential offsets in the calibration of the analyzers (see Section 3.1), we sampled high and low, resp., calibration gases with known CO_2 and CH_4 mole fractions (341.19±0.01 ppm and 543.1±0.01 ppm, and 1722.0±0.1 ppb and 2990.3±0.1 ppb) before and after each flight day for about 5 minutes. These gas cylinders were calibrated following WMO calibration scales (WMO CO2 X2019, WMO CH4 X2014A) through a set of standards that were calibrated by NOAA (for more information see Heimann et al., 2022)."

5. The long-term test conducted in the laboratory lasted for four hours with a linear drift for CO2. The CO2 sensor may be still warming-up for four hours. Are there any long-term tests over 24 hours performed? Calibration on the field was applied every 24 hours. How large are the sensor's drifts over 24h?

Response to Comment#5

Our CO_2 sensor warms up within 20-30 minutes after powering up. Please see Fig.1 for the cell temperature during the measurements. As can be seen the cell temperature is very stable throughout the measurement period of about 4 hours. Additionally, the calibration on the field was applied each day before and after flights; however, this does not mean that the analyzer kept running for 24 hours. Over the course of one flight (battery allows for about 20 minutes of flight time), the drift is expected to be around 0.18 ppm. Each flight experiment lasted for a maximum of 2-3 hours, and the expected overall drift would thus be about 1-2 ppm. Based on the calibrations executed at start and end of the experiment, this drift will be corrected afterward.
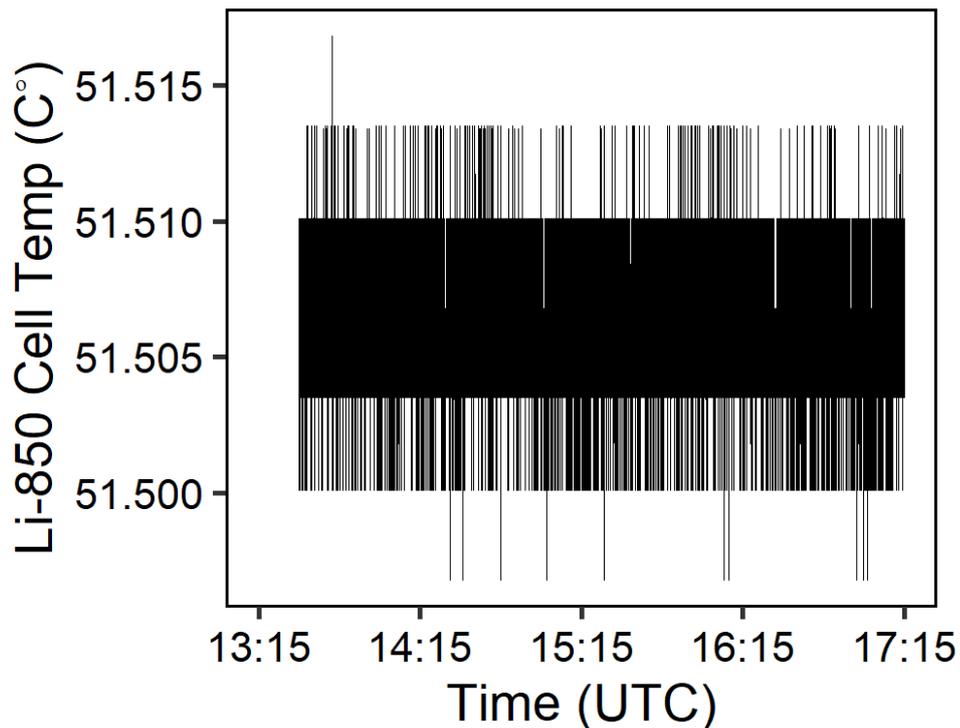

Fig.1. Licor Li-850 cell temperature during 4 hours of measurements.

6. Laboratory tests, how was the sensors' performance against water vapor and temperature changes? The field campaign lasts for days, how large is the temperature difference and the humidity during the day? Will these changes during the day impact the sensors' performance?

Response to the comment#6

Unfortunately, we could not conduct tests of sensor performance against changes in the temperature. However, we conduct preliminary test modifying the humidity. We observed that changes of 20 – 25% of relative humidity cause about 1-2 ppm of offset in the CO_2 measurements and about 10 ppb in CH_4 measurements. However, our measurements were only preliminary since the water vapor measurements needs to be handled carefully, i.e. flushing the analyzer cells and the tubing requires very long time which we were not able to do due to limited resources. Nevertheless, during our flights the observed changes in

humidity was always below 2%. Fig. 2 shows the observed variations of the humidity during all the flights that were conducted in this study. Considering these observed variations in the humidity levels, the offset in measured gas concentrations are expected to be within the provided uncertainty limits.
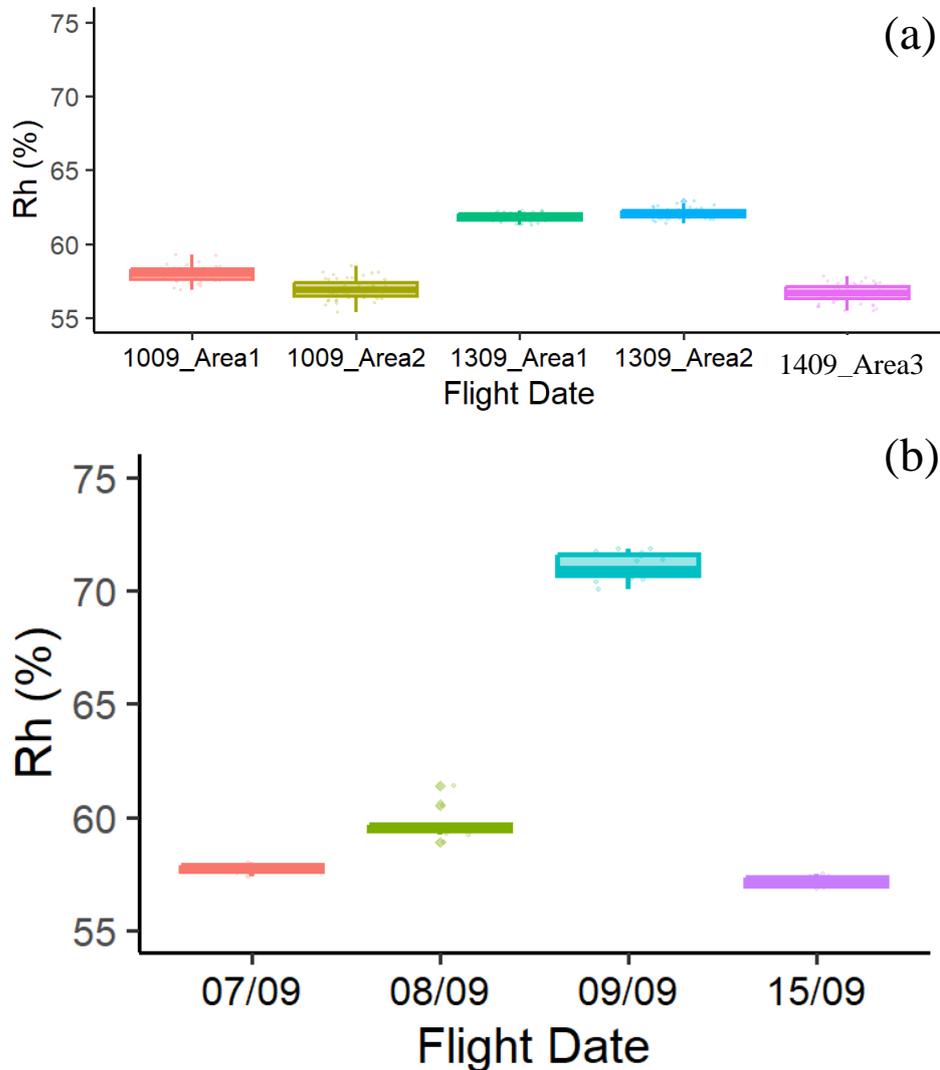

Fig.2. Variability of the humidity levels (a) during each grid survey flights and (b) during vertical profile flights.

7. Line 154-155, could you explain the numbers (380 ppm,460 ppm, etc.) chosen to filter the dataset?

Response to Comment #7

The procedure described in the highlighted text passage was intended to eliminate implausible data points captured by the analyzer. To set these hard thresholds, we checked the ICOS tower data of CO_2 dry mole fraction between 01/01/2022 – 31/12/2023 (see Fig.

3 below). As can be seen almost all of the data fall within the range 380 to 460 ppm, which is bracketed by red dotted lines.
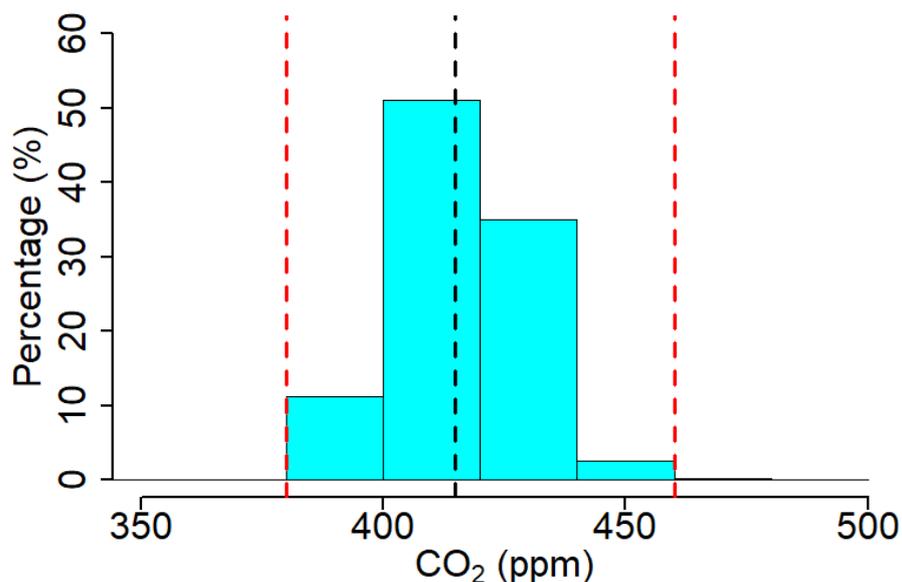

Fig. 3. Histogram of the CO_2 dry mole fraction measured by the ICOS tower for the period 2022/23. Here, the black dashed line represents the mean value, while red dashed lines represent the selected threshold boundaries indicating the plausible data range.

To address the reviewer comment, the manuscript lines between 153 – 154 will be revised as follows:

"We first employed hard thresholds that omitted CO_2 mole fractions below 380 ppm and above 460 ppm. These plausibility limits were derived from long-term observations the nearby ICOS tower CO_2 measurements."

8. Table 3 shows the estimated fluxes corresponding to large uncertainties. It would be nice to add a paragraph here to discuss how the large uncertainties were obtained. What are the sources attributed to the uncertainty? Any thoughts to improve the methodology to reduce the uncertainty? The instruments' noise can also impact on the flux error.

Response to the comment#8

Reviewer one requested similar additions regarding uncertainties in the flux profile method applied here. Please see our response to the comment #3 of the reviewer #1 for a detailed answer.

Technical corrections:

1. Line 167: Fig.5 shows before Fig.2 in the text. Please correct the order.

<u>Response to technical comment #1</u>

Thanks for the reviewer comment. The manuscript line 167 will be removed and line 174 will be revised as follows:

"The starting altitude of the vertical profile flights over the area were set to 5 m AGL."

2. Line 182: Eq.10 should be replaced by Eq. 9.

<u>Response to technical comment #2</u>

Thanks for the reviewer comment. We will revise the manuscript line 182 as follows:

"Firstly, a logarithmic curve was fitted to the vertical mean wind profile as given in Eq. 9 (Foken, 2017; Tagesson, 2012):"

3. Line 185: Eq.10 should be replaced by Eq. 9.

<u>Response to technical comment #3</u>

Thanks for the reviewer comment. We will revise the manuscript line 185 as follows:

"where κ is the von Karman constant [-] that is equal to 0.4, z is the measurement height [m AGL], and z_0 is the roughness length [m]. Eq. 9 can be rewritten as"

<u>References</u>

Foken, T.: Micrometeorology, pp. 33–81, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-25440-6_2, 2017.

Zhao, J., Zhang, M., Xiao, W., Wang, W., Zhang, Z., Yu, Z., Xiao, Q., Cao, Z., Xu, J., Zhang, X., et al.: An evaluation of the flux-gradient and the eddy covariance method to measure CH_4, CO_2, and H_2O fluxes from small ponds, Agricultural and Forest Meteorology, 275, 255–264, 2019.

Heimann, M., Jordan, A., Brand, W. A., Lavrič, J. V., Moossen, H., & Rothe, M. (2022). The atmospheric flask sampling program of MPI-BGC, Version 13, 2022. Edmond – Open Research Data Repository of the Max Planck Society, 1-60. doi:10.17617/3.8r.

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