Response to the comments by reviewer #1

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 paper describes a study to conduct UAV surveys of GHG profiles (and emissions) using an interesting onboard-UAV GHG analyser in a test study in Jena and then in the Arctic to compare UAV-derived emissions with those from EC towers. The main outputs of the paper relate to the demonstration of the sensor-UAV platform and its uses, and the flux results themselves for e.g. Arctic ecosystems. It would be a valuable and interesting read to those following AMT and a growing community using UAVs for GHG emission work. It is a nice demonstration of a new system.

The paper is well written (thank you for no obvious typos) and well presented. There is careful attention to detail on instrument characterisation and calibration and a clear explanation of the study and its methods (except for flux uncertainties – see specific comments below). I recommend the paper for publication with some thoughts about the relatively minor and constructive comments below.

We thank the reviewer for this very positive overall evaluation of our study.

Specific comments:

A paper by O'Shea et al (below) looked at the spatial scalability of EC and chamber fluxes in the Arctic to 100s km scales using aircraft mass balance. May be useful to briefly discuss this in the intro when discussing Arctic scalability approaches.

O'Shea, S. J. et al.: Methane and carbon dioxide fluxes and their regional scalability for the European Arctic wetlands during the MAMM project in summer 2012, Atmos. Chem. Phys., 14, 13159-13174, doi:10.5194/acp-14-13159-2014, 2014.

Response to the comment #1

Thanks for reviewer's suggestion, the manuscript lines 39 – 41 will be revised as follows:

"As an option for larger-scale flux observations, aircraft-based measurement campaigns can be conducted, addressing the scaling issues as well as bridging the gaps between bottom-up and top-down estimates (O'Shea et al., 2014, Chang et al., 2014; Sweeney et al., 2015; Parazoo et al., 2016; Wolfe et al., 2018; Barker et al., 2022)."

Line 55: As written, it would indicate that this is an exhaustive list, but it is really only a few examples (so maybe add, "e.g."). A recent paper that has calculated UAV emissions using GHG analysers onboard include the ref below.

Yong, H, et al, 2024: Lessons learned from a UAV survey and methane emissions calculation at a UK landfill, https://doi.org/10.1016/j.wasman.2024.03.025

Response to the comment #2

Thanks for reviewer's suggestion, the manuscript lines 52 – 56 will be revised as follows:

"In the past, three different approaches have been applied to quantify the emission rates with UAVs: using a coil-shaped long stainless-steel tubing called Aircore to collect gas samples (e.g. Karion et al., 2010; Andersen et al., 2018, 2023; Morales et al., 2022), collecting atmospheric air in discrete samples via flasks (e.g. Lampert et al., 2020), and measuring the in situ mole fractions onboard the UAV with compact GHG analyzers (e.g. Galfalk et al., 2021; Kunz et al., 2018, 2020; Tuzson et al., 2020; Oberle et al., 2019; Liu et al., 2022, Yong, H, et al, 2024)."

Section 2.5 – The flux-gradient method is really interesting. Can you say anything about flux uncertainty here, i.e. can you quantify an uncertainty and what sources of error/bias may affect the fluxes calculated and why? You mention that only a small dataset is needed – this is true for the equations given in themselves, but doesn't a small dataset mean you may not capture any uncertainty or variability? Can you offer more guidance here on the method and its limitations and thoughts on spatial and temporal sampling? I see later that there are +/- flux values in table 3, but it isn't clear how these UAV flux uncertainties have been calculated – are they a statistical variability on many measured fluxes, or are they forward-modelled uncertainties on a single total flux? I see that the uncertainties are sometimes a factor 5 greater than the fluxes themselves (and always >100%) – can you comment on this? There is mention on line 357 that uncertainty is due to the small vertical gradients in GHG concs – but why? To know this, the reader needs info on how flux error is propagated and what it's sensitive to. This needs quite a bit more explanation in the text, as uncertainty is equally (if not more) important than the flux itself (especially when it is higher than the flux itself as it is in this case).

Response to Comment#3

Thanks for the reviewer comment. One of the major challenges of the flux-gradient approach is the estimation of the eddy diffusivity parameter. Here we assume a neutral stratification and logarithmic wind profile to first estimate the friction velocity from the mean horizontal wind speed as was described in Foken (2017). To estimate the eddy diffusivity, we used the wind profile method that was described in Zhao et al. (2019).

Another source of the uncertainty is the vertical gradient of the mass concentration of CO_2 and CH_4 relative to the background signal variability. As the background signal variability increases the uncertainty is expected to increase. Additionally, instrument drift of CO_2 and CH_4 analyzers are also contributing to the calculated uncertainties in here. However, the differentiation of the background signal variabilities and the instrument drift is not trivial in here since the measurements were conducted over natural ecosystems. The reviewer correctly stated that having small dataset implies less temporal variability is captured, and less information is available for the assessment of uncertainties. This can in principle be compensated having multiple profiles from the same location. However, there is a tradeoff between spatial and temporal variability as the flight time is limited by the battery lifetime.

Accordingly, a decision needs to be made whether sampling multiple profiles over the same location or covering more locations within the target area better serves the objectives of the study. The limitations of the profile method mainly lie in the assumption of neutral stability condition.

Additionally, in some profiles due to the combination of the insufficient sampling time with the non-stationary behavior of the wind speed profiles, the slope of the logarithmic fitting might become negative, in which condition the method cannot be applied. The calculated uncertainty is a modelled uncertainty for a single flux value using Monte Carlo simulation. The Monte Carlo simulations were run using 0.95 of probability which corresponds to 20000 iterations. To do that, we generated synthetic wind speed data assuming normal distribution where we used the measured mean and standard deviation values at each altitude. Similarly, the mass concentrations of CH_4 and CO_2 were assumed to have normal distribution. Subsequently, using mean and standard deviation of the measured mass concentrations of CH_4 and CO_2 at each altitude, synthetic mass concentrations data were generated. Using these synthetic data, we estimated uncertainties of friction velocities and calculated the uncertainties for F_{CO2} and F_{CH4}. The observed high uncertainties as explained above are mostly related to the combination of high background signal variability and instrument drift relative to the observed vertical gradient of CH_4 and CO_2 mass concentrations. The result for which an uncertainty almost four times greater than the flux itself was observed might be due to non-stationarity of the observed wind speed profile.

To address the reviewer comment, manuscript lines 205 – 208, 357 – 363, and 379 – 383 will be revised as follows

"To perform the Monte Carlo simulations, we first generated normally distributed synthetic data for wind speed and mass concentrations of CH_4 and CO_2 based on the measured means and standard deviations at each altitude. These generated synthetic data were then used to estimate the uncertainties of the friction velocities as well as the fluxes of CO_2 (F_{CO2}) and CH_4 (F_{CH4}) (for more details please see Veen and Cox, 2021)."

"The relatively high uncertainties of the calculated fluxes (see also Table 3) are to the largest part due to the small vertical gradient of CO_2 and CH_4 relative to the combination of background signal variations and instrument drift. This can be seen e.g. from the panels in Fig. 9 where only the profile part $z \leq 10$ m of the boundary layer was illustrated. In most cases observed in this study, the deviations in the signal are higher than the vertical gradient. Here, the assumption of neutral stability and logarithmic profiles might also contribute to the observed high uncertainties. "

"As a future profiling strategy, UAV ascending speed will be reduced and the measurements above 25 m AGL will be omitted to avoid the footprint contamination. In addition, the start altitude of the profile flight should be closer to the ground, ideally around 2 – 3 m AGL. This will allow us to have multiple profiles within one flight set, and help to reduce the uncertainties."

Measuring winds on UAVs: I sympathise with the team and their woes with measuring winds using anemometers on UAVs. It is not easy. There is some recent work on this, where mounting the anemometer more than 2.5 rotor diameter has been shown to negate the flow field problem.

It may be useful to briefly mention that winds remain a challenge but that there are ways to improve (this is also discussed in the Yong et al., 2024 paper referenced above).

Response to comment #4

Thanks for the reviewer comment. Indeed, it is a challenge to get the characteristics of the wind speed using an anemometer mounted on a UAV, and the measurements might be biased especially due to propeller downwash. Here, the compromise needs to be made between downwash impact and flight stability, and we think placing the anemometer 65 cm (app. 1.2D) above the rotor plane is a good compromise.

To address the reviewer comment, we will revise manuscript lines 109 – 113 as follows:

"However, measuring wind characteristics with an anemometer mounted on a UAV still remains a challenge, and compromises need to be made between potential bias due to propellers and the flight stability. We decided to place the anemometer about 1.2D above the rotor plane for best system performance (the potential uncertainty sources and more information can be found in Yong et al, 2024)."

Technical comments:

Line 84 – space between unit and quantity needed (e.g. "20m") Check throughout.

Response to technical comment#1

Thanks for the reviewer comment, we will revise the manuscript line 84 as follows, and checked (and corrected, where needed) similar uses of units throughout the manuscript:

"The core area of the experiment consists of several 20 m x 20 m vegetation patches and hosts 60 different plant species."

References

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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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Yong, H., Allen, G., Mcquilkin, J., Ricketts, H. and Shaw, J.T., 2024. Lessons learned from a UAV survey and methane emissions calculation at a UK landfill. *Waste Management*, *180*, pp.47-54.

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