Referee #1

We are truly grateful to your critical comments and thoughtful suggestions. In accordance with the comments, the manuscript has been thoroughly revised in content; the revisions have been marked in red. All references to figure(s), table(s), section(s), page(s), and line(s) refer to the revised manuscript unless otherwise stated.

General Comments:

The authors are to be commended for confronting a major challenge. I believe in much of their introduction regarding the need to increase the spatial density of flux observations, and the potential for UAV platforms to fulfill this need. The paper contains much methodological detail regarding UAV wind measurements and assessment, aspects of the paper that I do not feel qualified to evaluate. However, I can assess eddy covariance methodologies for determining surface fluxes, and I am afraid that the authors as yet fall short regarding both the implementation and error assessment.

From reading the text, it is unclear to me whether the authors have (1) incorrectly determined the fluxes of CO_2 ***and*** H_2O***, or simply (2) incorrectly described the methodology that they applied. I suspect the former, based on the comment below regarding the text at line 479. In any event, the paper requires major revision to clarify these points, and possibly to modify both the eddy covariance methodology and also the assessment of its errors and sensitivity to environmental parameters. I also believe that the presentation of the data could be improved significantly as described below.***

Re: Thank you for your insightful comments. Most of the above comments are handled more specifically bellow. We have substantially revised this manuscript in both the methodology for error assessment and the relative contents. In particular, aspects involving the calculation of turbulent fluxes (including the necessary corrections) and the error analysis of wind and flux measurements have been thoroughly revised. Your comments are very helpful to improve the quality of the manuscript.

Specific Comments

Q1. 82 - As the authors note "The EC method is a well-developed technology for directly measuring vertical turbulent flux...". Decades of experience that has shown that the covariances between the vertical wind and the densities of CO_2 ***(*** ρc ***) and*** H_2O ***(*** ρv ***) - measured directly by the EC150 - do not define the turbulent fluxes of these gases, as the authors seem to believe (lines 250-251). This is because fluctuations in these variables are predominantly caused by temperature fluctuations (due to heat exchange), and*** ρc ***also fluctuates because of varying humidity (due to evaporation). See comment regarding line 269 below.***

Re: The original sentence (Lines 251-253 in the original manuscript) for describing the method of EC flux measurement may be not appropriate, and it created ambiguity for readers. In this study, the calculation of turbulent fluxes, especially for latent heat and CO_2 flux, included necessary correction for air density fluctuations (WPL correction). In order to clearly express the methodology for calculation the turbulent fluxes by UAV-based EC system in this study, we modified and added necessary descriptions in the revised manuscript and supplement materials as follows:

Lines 251-253, in the revised manuscript, the original sentence is revised to "In the final stage, based on the EC technology and spatial averaging, the turbulent flux is calculated using the covariances of vertical wind (w) with air temperature (T_a) for sensible heat flux (H), with water vapor density (q) for latent heat flux (LE), and with CO_2 density (c) for CO_2 flux (F_c), and with the necessary correction."

Lines 256-256, in the revised manuscript, we added the follow text: "Detailed calculation procedure and formulas of H, LE, and F_c used by the present UAV-based EC system are provided in Supplement Part B, including spatially averaging, coordinate rotation, and necessary correction (i.e., WPL correction for LE and F_c)."

In the revised Supplement Part B, this section provided a detailed description of the process and methodology for calculating turbulent fluxes and error analysis.

Q2. 162 - The choice of the Bohai Sea as the place for the in-flight calibration campaign is quite unfortunate. Its waters are cool, particularly relative to continental temperatures in September, and therefore the magnitude and spectra of the temperature fluctuations that tend to dominate fluctuations in ρc and ρv are not representative of what might be encountered in many other environments. Indeed, the authors note that stable atmospheric conditions prevailed during the campaign (lines 174-175), implying that turbulence is supressed during this assessment of the ability to measure turbulent fluxes. If this limitation cannot be removed from the analysis, it should at least be noted.

Re: The main objective of calibration flight is to acquire the mounting misalignment angle in the heading (ϵ_ψ) and pitch (ϵ_θ) between the 5HP (five-hole probe) and the CG (center of gravity) of the UAV. The calibration flight should be carried out under specific atmospheric conditions to ensure a continuous, stable and ground-independent wind component.

The common assumptions for calibration flight include 1) low turbulence or turbulent transport (i.e., no disturbance), 2) a constant mean horizontal wind, and 3) mean vertical wind near zero (Drüe and Heinemann, 2013; Vellinga et al., 2013; Van Den Kroonenberg et al., 2008) (Lines 177-180). These assumptions are usually well satisfied above the ABL or under stable atmospheric conditions. Over the sea surface, due to its uniform and cool surface property, the turbulence fluctuations are weaker than that over the land surface, making where a more ideal environment to conduct calibration flight (Lines 180-183). Accordingly, we revised the original sentence (Lines 166-169, in the original manuscript) as follows:

Lines 177-183, in the revised manuscript: "The assumptions for calibration flight include 1) low turbulence or turbulent transport (i.e., no disturbance), 2) a constant mean horizontal wind, and 3) mean vertical wind near zero (Drüe and Heinemann, 2013; Vellinga et al., 2013; Van Den Kroonenberg et al., 2008). This allows identical wind components for several consecutive straights in opposite or vertical flight directions. These assumptions are usually well satisfied above the ABL or under stable atmospheric conditions (Drüe and Heinemann, 2013). Over the sea surface, due to its uniform and cool surface property, the turbulence fluctuations are weaker than that over the land surface (Mathez and Smerdon, 2018), making where a more ideal environment to conduct calibration flight."

Q3. 261-262 - "In this study, the objective is not to quantify the actual flux exchange between the surface and the atmosphere, but rather to assess the sensitivity of the calculated turbulent flux to external parameters." The quality of a UAV-based eddy covariance system for measurements turbulent flux (reflecting the title of the paper) cannot be assessed without determining whether it quantifies the actual surface exchange. As an example, if the system reports an unbelievable uptake of 50 µmol m-2 s-1 of CO2 uptake, its quality is likely low whatever its sensitivity to external parameters. For this reason, I believe that the authors should indeed provide magnitudes of the fluxes that they are characterizing. This is particularly so given methodological uncertainties regarding how the fluxes are determined (see comment regarding line 82 above, and 269 below).

Re: In accordance with your comment, when analyzing the flux measurement error, we also provided the magnitudes of the fluxes. In Section 3.2 of the revised manuscript, the relationship between the estimated relative flux measurement error and the flux magnitude was show in Figure 9. Accordingly, the original sentence (Lines 261-262 in the original manuscript) was removed.

Q4. 269 - The authors cite Metzger et al. (2012) regarding the calculation of turbulent fluxes. Since Metzger et al. (2012) did not measure CO2 fluxes, the citation at line 269 is insufficient to document the data processing and corrections needed to determine the turbulent CO2 flux. Users of an open-path IRGA must address the issue of "density corrections", and cite an appropriate reference (Webb et al., 1980, Correction of flux measurements for density effects due to heat and water vapor transfer. Quart J Roy Meteorol Soc 106:85–100; or perhaps Kowalski et al.,2021, Disentangling Turbulent Gas Diffusion from Non-diffusive Transport in the Boundary Layer. Boundary-Layer Meteorol 179, 347–367. https://doi.org/10.1007/s10546-021-00605-5). Otherwise, the results are inconsistent with what we know about biological activity.

Re: In the revised manuscript (Lines 256-258) and Supplement Part B, we supplemented the detailed calculation procedure and formulas of sensible heat, latent, and CO_2 flux, including spatially averaging, coordinate rotation, and necessary correction (i.e., WPL correction for LE and F_c). Inaccuracies in literature citations have also been corrected (Lines 133-135).

Q5. 273-278 - There is a problem with randomly generated errors for input variables, because some of these variables tend to be correlated. For example, over the sea in stable atmospheric conditions, the heat flux is downward and the vapor flux is presumably upward. Therefore,

temperature and humidity are negatively correlated. If, for some reason, errors in the measurement of temperature and humidity are correlated, then this can badly bias the eddy covariance. Correlated errors could arise for many reasons including faulty instrumentation, sampling errors, and flow distortion. A Monte Carlo simulation that presumes independence of such variables will miss this sort of problem, and therefore is not an appropriate tool for error assessment.

Re: In the revised manuscript, the original Monte Carlo error simulation method used to estimate the measurement error of geo-referenced wind and turbulent flux has been removed. Instead, we used the partial derivatives of the full calculation equation for geo-referenced wind and turbulent flux to estimate the measurement error in wind and fluxes. The detailed methods and procedures to estimate the measurement error of geo-referenced wind vector and turbulent fluxes were gave in Supplement Part A and Part B.

For estimating the measurement precision of geo-referenced wind, in the revised manuscript, we used the linearized Taylor series expansions derived by Enriquez and Friehe (1995) (in the revised Supplement Part A) to determine the sensitivities of each of the geo-referenced wind vector components with respect to the relevant variables. Then, combined these sensitivity terms to estimate the overall measurement error (1σ) in the geo-referenced 3D wind vector. The results were provided in Section 3.1 of the revised manuscript. It concluded that the measurement precision for geo-referenced wind vector is related to the true airspeed and heading of the UAV (Lines 425-437). For a true airspeed of 30 m s^{-1} for the current UAV-based EC system during the cruising, the maximum measurement error in the northward, eastward, and vertical velocities of the geo-referenced wind components were calculated as approximately 0.06, 0.07, and 0.06 m s^{-1}, respectively (Lines 438-441).

For flux measurements, in this study, we mainly focused on the error caused by instrumental noise due to they are related not only to the system performance, but also to the minimum resolvable capability for the flux to be measured. In the revised manuscript, we added a section (Section 2.4.2) to illustrate the methods for estimating flux measurement error caused by instrumental noise by combining the covariance uncertainty estimated by RS method (Eq. 6 in the revised manuscript) and the propagation of errors in flux correction terms (Eqs. S29-S31 in Supplement Part B). In the revised Supplement material Part B, we gave the detailed equations to calculate the fluxes of sensible heat, latent heat, carbon dioxide (CO_2), and the method to quantify the measurement uncertainty in them due to instrument noise. The results were given in Section 3.2 of the revised manuscript, and the flux measurement error caused by instrumental noises was estimated at 0.03 μmol m^{-2} s, 0.02 W m^{-2}, and 0.08 W m^{-2} for the measurement of CO_2 flux, sensible and latent heat flux, respectively (Lines 522-536).

Q6. 396 - As noted above (see comment regarding line 273), the method used to determine the least resolvable flux magnitude is not believable.

Re: Please see the answers to Q5. In the revised manuscript, we used the partial derivatives of the full calculation equation for geo-referenced wind and turbulent flux to estimate the measurement error in wind and fluxes. These partial derivative equations were given in Supplement Part A and Part B. Accordingly, we assumed a minimum required signal-to-noise ratio of 10:1, and estimated the least resolvable wind speed and flux magnitude. Accordingly, the text was modified as follow:

Lines 441-443, in Section 3.1 of the revised manuscript, we gave the results of the estimated least resolvable wind speed: "Then, we assume that a minimum signal-to-noise ratio of 10:1 is required to measure the wind components with sufficient precision for EC measurements (Metzger et al., 2012). Accordingly, in the real environments, horizontal and vertical wind speed greater than 0.7 m s^{-1} and 0.6 m s^{-1} can be reliably measured, respectively (Table 2)."

Lines 532-533, in Section of the revised manuscript, we gave the results of the estimated least resolvable flux magnitude: "At last, using the signal-to-noise ratio of 10:1, the minimum magnitudes for reliably resolving the CO_2 flux, sensible and latent heat fluxes were estimated as 0.3 μmol m^{-2} s, 0.2 W m^{-2}, and 0.8 W m^{-2}, respectively."

Q7. 399 - Regarding sensor drift, the authors should take care to examine the effects of any lens contamination (Serrano-Ortiz et al., 2008, Consequences of uncertainties in CO2 density for estimating net ecosystem exchange by open-path eddy covariance, Boundary-Layer Meteorology, 126, 209-218.), which would seem to be a problem in an environment rich in sea salt. To be clear, such errors arise as a consequence of the necessary density corrections when measuring gas densities with an open-path IRGA.

Re: Thanks a lot for this comment. UAV EC flux measurements do not need to take into account of the problem of lens contamination due to the signal quality of the IRGA was checked before each flight measurement to ensure that the measurement of gas concentration is not affected by lens contamination. Accordingly, we added the necessary explanation text in the revised manuscript as follow:

Lines 361-362, in Section 2.4.2: "For EC measurement from our UAV, the signal quality of the IRGA is checked before each flight measurement to ensure that the measurement of gas concentration is not affected by lens contamination."

Q8. 479 - "a sensitivity test was conducted by adding an error of ±30 % to the calibrated value of each calibration parameter." Serrano-Ortiz et al. (2008) showed that just a 5% in the CO2 density can cause CO2 flux errors in excess of 13%, due to the influence of density corrections. The fact that the authors of this study found such small errors in the CO2 flux (Table 4) strongly hints that they are not correcting for density effects, and therefore that their error analysis is inadequate. It also causes me to strongly doubt the claim of a 0.4 μmol m-2 s-1 least resolvable magnitude for the CO2 flux.

Re: The main objective of the sensitivity test is to understand the relevance of the calibration parameters for the measurement of geo-referenced wind vector and turbulent flux. Four calibration parameters included in the sensitivity test, including three mounting misalignment angles ($\epsilon_\psi, \epsilon_\theta, \epsilon_\phi$) between the 5HP and the CG of the UAV and one temperature recover factor ($\epsilon_r = 0.82$). The reliability of these calibration parameters directly affects the uncertainty of wind measurement and then indirectly affects the uncertainty of flux measurements (Vellinga et al., 2013). The sensitivity test method used in this study was similar to Vellinga et al. (2013), but in order to highlight the perturbation affected by the uncertainty in calibration parameters, an error of $\pm 30\ \%$ was added to their optimum value (Section 2.4.4 in the revised manuscript).

Serrano-Ortiz et al. (2008) analysed the error relevance between the measurement of CO_2 density and CO_2 flux, however, this study analysed the error relevance between the acquired calibration parameters $(\epsilon_\psi, \epsilon_\theta, \epsilon_\phi, \epsilon_r)$ and wind measurement as well as flux. As mentioned above, these calibration parameters do not directly affect the precision of flux measurements. The claim of a 0.4 μmol m^{-2} s^{-1} least resolvable magnitude for the CO_2 flux (Line 397 in the original manuscript) was revised to 0.3 μmol m^{-2} s^{-1} according to new error analysis method (Section 3.2 in the revised manuscript and Supplement Part B) in the revised manuscript. In the revised manuscript, these small errors or claimed least resolvable magnitudes for flux measurement are related only to instrument noise. Generally speaking, the effect of instrumental noise on the uncertainty of flux measurement is very small (Metzger et al., 2012; Mauder et al., 2013).

Q9. 583 - Change "Forth" to "Fourth".

Re: This mistake has been revised in the revised manuscript.

References:

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