Dear Editor and Reviewer,

Thank you very much for your careful evaluation and constructive comments. We are especially grateful to the reviewer for the time and effort devoted to this manuscript over three rounds of detailed reviews. These reviews and comments have greatly helped us in improving the manuscript through multiple revisions. In each revision, we have carefully considered all General and Specific Comments and have revised the manuscript extensively. In particular, we improved the consistency of terminology and notation, clarified the treatment of horizontal advection and turbulent wind statistics, revised the data-selection description in Sect. 4.4, and reorganized and updated the uncertainty analysis. We believe that these revisions have substantially improved the clarity, consistency, and scientific presentation of the manuscript. Through the efforts of the Reviewer and our detailed revisions and responses, I sincerely hope, and truly believe, that the manuscript measures up to the high standards of scientific publications in general and this journal in particular.

Below, we provide a detailed point-by-point response to each comment and describe the corresponding revisions.

Sincerely yours,

Shao-Meng Li, Professor
on behalf of all authors

General comments

(1) *The authors have failed to use consistently defined terms in this manuscript. u(bar) changed from the "mean east-west wind speed" to "mean wind-speed magnitude" within subsection 3.2. This makes it very difficult to review. I already raised this point in two previous rounds of review. If the authors are unable to rectify their terminology in any further revision, I suggest that this manuscript be rejected. This is totally unacceptable in a scientific publication, regardless of quality scientific content.*

In addition, as with the previous versions of this manuscript, terms are not defined at their first point of use, leading to confusion. It is generally conventional to define a term once at its first point of use and then to use the abbreviated term for the remainder of the manuscript (except in the abstract and maybe the conclusion), rather than interchanging between the two.

I hope the authors can appreciate that a reviewer is tasked with evaluating the scientific content of a publication and not to spend hours trying to check whether the equations and the terms are consistent. Please can the authors make an effort to resolve these issues before submission, to make reviewing the scientific content of this interesting work far easier.

Response: Thank you for raising this issue again. We sincerely apologize for the inconsistent terminology and notation in the previous version of the manuscript. We agree that a scientific manuscript should use each symbol, term, and abbreviation with

a single, clearly defined meaning, and that the inconsistencies in the previous version made the manuscript unnecessarily difficult to review.

In response, we have carried out a comprehensive review of the terminology, mathematical notation, variable definitions, and abbreviations throughout the manuscript, paying particular attention to Sect. 3.2. The previous use of u and $\bar{u}$ for more than one physical quantity has been removed. The symbols u, v, and w are now used consistently for the instantaneous east-west, north-south, and vertical wind components, with the corresponding mean quantities and turbulent fluctuations defined separately. The horizontal wind-speed magnitude used in the UAV vertical-profile calculation is now represented by a separate symbol and is no longer denoted by u or $\bar{u}$.

We have also revised the notation used for the UAV vertical profiles. Quantities smoothed using the seven-point moving average are now denoted by a tilde, rather than an overbar, so that they are not confused with the 30 min temporal means used for the fixed EC tower data. Similarly, ambiguous expressions such as "mean concentration" have been replaced by terms that explicitly describe the corresponding smoothed CO_2 mass-concentration profile values.

In addition to these notation changes, we carefully checked the full manuscript to ensure that terms and abbreviations are defined at their first occurrence and are used consistently thereafter. Repeated definitions have been removed, and informal or ambiguous terminology has been replaced where necessary. These revisions are also described in detail in our responses to the relevant Specific Comments.

We appreciate the reviewer's patience in identifying these issues over the previous review rounds. We have treated this comment as a manuscript-wide issue rather than as a local correction and have made a concerted effort in the present revision to ensure that the terminology and notation are internally consistent and that the scientific content can be evaluated without unnecessary ambiguity.

(2) *The end of the first paragraph explains that horizonal advection can "affect the interpretation of vertical flux measurements" in "spatially heterogeneous or weakly mixed conditions". This is a major improvement from the previous version of the manuscript. However, a detailed reason for this lacking. This point should be expanded on clearly here as this underpins the motivation for a key component of this work. I appreciate that the penultimate sentence of the first paragraph adds some reasoning, but it is a bit vague with no citations.*

Response: We have expanded the first paragraph of the Introduction to describe the underlying mechanism more clearly. Under weakly mixed conditions, suppressed vertical turbulent transport can allow CO_2 to accumulate within and below the forest canopy. Over heterogeneous or sloping terrain, drainage flows and other local advective motions can subsequently transport this accumulated CO_2 laterally and generate horizontal CO_2 gradients. Horizontal advective convergence or divergence can therefore contribute to the local CO_2 mass balance. Because a single EC tower directly measures the vertical turbulent flux at its measurement location, the observed vertical flux may not fully represent the local ecosystem–atmosphere exchange when horizontal

transport is appreciable. Measurements of lateral CO_2 transport across finite control volume boundaries are therefore useful for diagnosing when the assumption of horizontal homogeneity is valid and when horizontal advection may influence the spatial representativeness of tower-based vertical flux measurements.

We have also added supporting references in this part of the Introduction. These revisions are consistent with, and described in more detail in, our responses to Specific Comments 7-9.

(3) *The method with which turbulent wind fluctuations are calculated is concerning and not adequately described. Apparently, each wind component is subtracted from its 30-minute average. This is fine if all 30 minutes of measurements are made at a single location. However, if the UAV is moving, this assumes that the three-dimensional wind field is independent of height and lateral position (which is unlikely).*

Response: Thank you for raising this concern. We agree that the previous description was unclear and could be interpreted as indicating that the 30 min mean wind components and turbulent fluctuations were calculated from measurements collected by the moving UAV. This was not the case, but a mistake in the previous version. We thank you for spotting the issue. We further explain this mistake in response to Specific Comments 22 and 24.

The mean and turbulent wind statistics used in Sect. 3.2 to assess the relative magnitudes of the horizontal advective/turbulent terms and the vertical advective/turbulent terms were derived from concurrent measurements made by the fixed EC flux tower, not data collected from the UAV as previously described. Because these measurements were obtained continuously at a fixed location, the standard 30 min averaging interval could be applied to calculate the mean wind components and the corresponding turbulent fluctuations. Therefore, measurements collected by the UAV at different heights or horizontal positions were not combined to calculate these 30 min turbulent fluctuations, and no assumption of a spatially uniform three-dimensional wind field along the UAV flight path was made for this diagnostic comparison.

We have revised Sect. 3.2 to state explicitly that this comparison is based on the fixed EC tower measurements and have clearly separated this tower-based diagnostic calculation from the UAV measurements used subsequently in the horizontal and vertical flux calculations. The processing of the EC tower data, including the 30 min averaging interval, is also described in the stationary tower data-processing subsection. Please also refer to our responses to Specific Comments 22 and 24, particularly Specific Comment 24, where the data source and the calculation of the mean and turbulent wind components are explained in detail.

(4) *Subsections 4.2 and 4.3 are nicely written.*

Response: Thank you for the positive assessment of Subsections 4.2 and 4.3. We appreciate the reviewer's encouraging comment and are pleased that these sections are now presented clearly.

(5) *Subsection 4.4 needs some work. It is not clear which flights and which data are*

being used and in which way. There is confusion between UAV flights and "days of observations". Does one UAV flight occur on each day of observation for each time period? Or can multiple flights take place in a single autumn morning, for example?

Response: We have revised Sect. 4.4 to clarify the data-selection procedure and the relationship between observation days and UAV flights. A total of 168 UAV flights were retained after quality control for the overall study, but only a subset was used for the spatial-heterogeneity analysis. Because the purpose of Sect. 4.4 was to examine spatial-scale dependence rather than seasonal or diurnal variability, we restricted the analysis to observations obtained within the same season and time-of-day period and further required valid observations for all three control volume sizes. After applying these criteria, seven observation days from the summer-noon period and seven observation days from the autumn-morning period were retained for the analysis.

An observation day does not necessarily correspond to a single UAV flight. Multiple UAV measurements could be conducted within the same observation period on a given day, and the analysis used the measurements that satisfied the data-quality and control volume completeness criteria. We have revised the text to make this distinction explicit and to avoid using "observation day" and "UAV flight" interchangeably. We have also clarified the corresponding observation windows: 13:00–14:00 for the selected summer-noon days and 06:00–07:00 for the selected autumn-morning days.

Please also refer to our responses to Specific Comments 47-50, particularly Specific Comments 47 and 48, where the selection criteria and the distinction between observation days and UAV flights are explained in detail.

Specific comment

(1) *Line 37: "is flown"*

• *Perhaps this should be in the past tense*

Response: We have changed "is flown" to "was flown" in the revised manuscript.

Revised text: "Within a mass-balance framework, the UAV measurement system was flown along horizontal loops at multiple heights together with vertical ascent flight tracks"

The specific revisions are shown in line 37 of the revised manuscript.

(2) *Line 38: "simultaneously"*

• *Is it simultaneous? As far as I understand, the vertical transect is used for vertical fluxes and the horizontal transect is used for horizontal fluxes. This means the measurements are not used simultaneously. They are close in time, but not simultaneous.*

Response: We have removed "simultaneously" and revised the sentence to clarify that the two complementary flight patterns were used to quantify the horizontal advective and vertical turbulent CO_2 transport components, respectively.

Revised text: "…acquiring data along the flight tracks that were used to quantify horizontal advective and vertical turbulent carbon dioxide emission components, respectively."

The specific revisions are shown in lines 38 to 40 of the revised manuscript.

(3) *Line 42: "a nearby"*

• *The definite article should be used here, as this is referring to the EC system referred to in the previous sentence, rather than some other permanently installed system.*

• *I think the adjective "nearby" is unnecessary here as it is already used in the previous sentence to describe the EC system.*

Response: We have revised "a nearby, permanently installed eddy-covariance system" to "the permanently installed EC system" in the revised manuscript.

Revised text: "Validation against long-term CO_2 flux measurements from the permanently installed eddy-covariance system…"

The specific revisions are shown in line 42 of the revised manuscript.

(4) *Line 42: "eddy-covariance"*

• *Replace this with "EC". It has been defined in the previous sentence.*

Response: We have replaced "eddy-covariance" with "EC" in the revised manuscript.

Revised text: "Validation against long-term CO_2 flux measurements from the permanently installed EC system shows that …"

The specific revisions are shown in line 42 of the revised manuscript.

(5) *Line 44: "turbulence-based exchange coefficient"*

• *Perhaps make it clearer that this refers to a UAV coefficient, as opposed to the aforementioned carbon dioxide concentration gradient, which is from the EC tower. It should be clearer what is being compared with what and from which sampling platform each of these terms refers to.*

Response: We agree that the original wording did not clearly distinguish the quantities derived from the UAV measurements from those obtained from the EC tower. Both the vertical CO_2 concentration gradient and the turbulence-based exchange coefficient used in the gradient method were derived from the UAV profile measurements. These quantities were then used to calculate the UAV-derived vertical CO_2 flux, which was subsequently compared with the vertical CO_2 flux measured by the EC tower. We have revised the sentence to make the respective measurement platforms and quantities explicit.

Revised text: "Validation against long-term CO_2 flux measurements from the permanently installed EC system shows that UAV-derived vertical CO_2 fluxes, calculated from UAV-measured vertical CO_2 gradients using a turbulence-based exchange coefficient derived from the UAV wind profiles, agree well with EC observations…"

The specific revisions are shown in lines 43 to 45 of the revised manuscript.

(6) *Line 79: "For example, eddy-covariance methods primarily quantify vertical turbulent exchange, whereas aircraft-based mass-balance approaches commonly emphasize horizontal advective transport."*

• *Please provide some citations to support these assertions.*

• *As far as I am aware, all EC fluxes are vertical emissions to the atmosphere. I am not aware of any horizontal eddy covariance work. The word "primarily" implies that EC is mostly for vertical fluxes rather than entirely for vertical fluxes.*

Response: We have revised the sentence to state explicitly that EC methods quantify vertical turbulent exchange. We have also added references to support both the EC and aircraft-based mass-balance approaches.

Revised text: "For example, eddy-covariance methods quantify vertical turbulent exchange (Baldocchi, 2003), whereas aircraft-based mass-balance approaches commonly quantify emissions from horizontal advective transport across control volume boundaries (Cambaliza et al., 2014; Gordon et al., 2015)."

The specific revisions are shown in lines 79 to 82 of the revised manuscript.

(7) *Line 81: "Consequently, simultaneous quantification of both horizontal and vertical CO_2 transport remains challenging (Leuning et al., 2008)"*

• *From this opening paragraph, it is still not clear why this is necessary. It seems like a challenge with no clear purpose.*

• *What is the point of evaluating the horizontal flux from the overall forest to a small horizontal area within the forest?*

Response: Thank you for this important comment. We agree that this sentence was too general and did not clearly explain the scientific purpose of considering both horizontal and vertical CO_2 transport. We have therefore removed this sentence from the revised manuscript and clarified the motivation for evaluating horizontal transport in the subsequent text.

(8) *Line 88: "affect the interpretation of vertical flux measurements under spatially heterogeneous or weakly mixed conditions."*

• *Why? Please explain.*

• *Why do weakly mixed or spatially heterogeneous conditions effect the vertical flux.*

• *This is a key motivation for this work, so it demands adequate explanation.*

• *Please provide some citations to support this statement and the following sentence.*

Response: Thanks. Under weakly mixed conditions, vertical turbulent transport is suppressed, allowing CO_2 to accumulate within and below the canopy. In heterogeneous or sloping terrain, this accumulated CO_2 can subsequently be transported laterally by drainage flows or other local advective motions. As a result, horizontal convergence or divergence can contribute to the local CO_2 mass balance, while a single-point EC system measures only the vertical turbulent flux at its measurement location. Consequently, the measured vertical flux may not fully represent the local ecosystem-atmosphere CO_2 exchange under such conditions. Previous studies have reported that horizontal advection and drainage flows can become important under stable or weak-turbulence conditions and can contribute to discrepancies in tower-based carbon-flux estimates. We have therefore expanded the explanation in the Introduction and added relevant references to support this statement.

Revised text: "Under weakly mixed conditions, suppressed vertical turbulent transport can lead to CO_2 accumulation within and below the canopy, while terrain-

induced drainage flows and spatial heterogeneity can promote lateral transport and generate horizontal CO_2 gradients. Consequently, horizontal advective convergence or divergence can contribute to the local CO_2 mass balance, such that vertical turbulent flux measured at a single tower may not fully represent the local ecosystem-atmosphere exchange (Aubinet et al., 2002; Feigenwinter et al., 2004; Leuning et al., 2008). Measurements that characterize lateral CO_2 transport across finite control volume boundaries are therefore useful for diagnosing when the assumption of horizontal homogeneity is valid and when local advection may influence may influence the spatial representativeness of vertical flux measurements."

The specific revisions are shown in lines 88 to 95 of the revised manuscript.

(9) *Line 90: "Therefore"*

• *Is this word correct? This is currently written as the previous sentence being a reason for the current sentence (i.e. use of the word "therefore"). Instead, this sentence could be used to explain the previous sentence in support of it.*

Response: We have revised and expanded the preceding text to explain how weak mixing and spatial heterogeneity can lead to lateral CO_2 transport and influence the local CO_2 mass balance. In the revised context, the following sentence now represents a direct consequence of this explanation; therefore, we have retained "therefore" to introduce the motivation for characterizing lateral CO_2 transport.

Revised text: "Measurements that characterize lateral CO_2 transport across finite control volume boundaries are therefore useful for diagnosing when the assumption of horizontal homogeneity is valid and when local advection may influence may influence the spatial representativeness of vertical flux measurements."

The specific revisions are shown in line 96 of the revised manuscript.

(10) *Line 126: "UAV"*

• *What does this acronym mean? Please define all acronyms used in this manuscript at their first point of use.*

Response: We have revised the text to introduce it as "unmanned aerial vehicles (UAVs)" at first use. We have also carefully checked the manuscript to ensure that all acronyms are defined when they first appear and are used consistently thereafter.

Revised text: "However, fixed-wing aircraft cannot hover or perform localized, near-vertical profile measurements at a fixed horizontal position, as rotary-wing unmanned aerial vehicles (UAVs) can."

The specific revisions are shown in line 131 of the revised manuscript.

(11) *Line 131: "rotating wing"*

• *Replace this with "rotary-wing".*

Response: Thank you for this correction. We agree that "rotary-wing" is the appropriate term. We have therefore replaced "rotating wing" with "rotary-wing" in the revised manuscript.

Revised text: "Recent advances in rotary-wing UAV platforms and lightweight sensor technologies have created new opportunities for atmospheric measurements over

complex environments…"

The specific revisions are shown in line 137 of the revised manuscript.

(12) *Line 137: "characterize"*

• *This sentence does not make sense. Perhaps add "UAVs" before the word "characterize".*

Response: We have added "UAVs" before "characterize" to correct the sentence and improve its clarity.

Revised text: "Compared with stationary towers, UAVs can characterize spatial variability in CO_2 mole fractions across multiple locations and altitudes within a relatively short sampling period, without relying on assumptions of horizontal homogeneity (Witte et al., 2017), thereby enabling the identification of emission or uptake hotspots that may be missed by ground-based observations (Khan et al., 2012)."

The specific revisions are shown in line 143 of the revised manuscript.

(13) *Line 173: "horizontal mass flux estimates"*

• *Please specify that this refers to carbon dioxide fluxes.*

Response: We have revised it to "horizontal CO_2 mass flux estimates" in the revised manuscript.

Revised text: "While horizontal CO_2 mass flux estimates derived from this platform have been previously evaluated and validated in field measurements (Han et al., 2024), vertical fluxes derived from such a platform have not been evaluated until now…"

The specific revisions are shown in line 179 of the revised manuscript.

(14) *Line 221: "3-d"*

• *Please define this as "three dimensional". "d" could mean something else in a different context.*

Response: We have replaced "3-d" with "three-dimensional" in the revised manuscript.

Revised text: "The payloads include a closed-path CO_2 analyzer and a three-dimensional ultrasonic anemometer, with their specifications summarized in Table 2."

The specific revisions are shown in line 227 of the revised manuscript.

(15) *Line 231: "with its air inlet set next to the anemometer sonic sensors to ensure spatially consistent wind and CO2 concentration measurements."*

• *This is a very good idea.*

• *Consider replacing "concentration" with "mole fraction" here and throughout the manuscript, for consistency.*

Response: We have replaced "CO_2 concentration measurements" with "CO_2 mole fraction measurements" at Line 231 and have checked the manuscript to ensure consistent use of this terminology where appropriate.

Revised text: "The CO_2 analyzer (MIRA Ultra N_2O/CO_2, Aeris Technologies, USA) was mounted beneath the UAV body to measure CO_2 volume mole fractions in

air, with its air inlet set next to the anemometer sonic sensors to ensure spatially consistent wind and CO_2 mole fraction measurements."

The specific revisions are shown in line 239 of the revised manuscript.

(16) *Line 258: "eddy covariance (EC)"*

• *This has already been defined. I am not sure why it is being defined again.*

Response: We have removed the repeated definition and now use "EC" directly at Line 258.

Revised text: "This station is one of the core flux observation sites of the China Flux Observation Research Network (ChinaFLUX) and is equipped with a comprehensive EC measurement system (Yu et al., 2006)."

The specific revisions are shown in line 265 of the revised manuscript.

(17) *Line 270: "Site B"*

• *Is it necessary to define Site A and Site B? The word "site" implies that the locations are distant from each other. The authors can keep this if they insist, but it may be better to simply use the "tower" and the "UAV take-off" location.*

Response: We agree that defining the two nearby locations as "Site A" and "Site B" may unnecessarily imply that they are separate field sites. We have therefore removed these labels and now refer to the two locations directly as the "flux tower" and the "UAV take-off location" throughout the manuscript.

Revised text: "To evaluate the performance of the UAV platform for CO_2 vertical flux measurements, flights were conducted from a UAV take-off location approximately 160 m southeast of the flux tower, where the relatively open forest structure allowed safe UAV take-off and landing. The UAV-derived fluxes were then directly compared with tower-based measurements (Fig. 2a). The terrain within approximately 1 km^2 surrounding the flux tower is characterized by continuous low hills and gentle slopes, with slope angles of approximately 2.8°–13.5° and local relative elevation differences of approximately 10-30 m. The approximately 15 m elevation difference between the flux tower and the UAV take-off location is therefore part of the naturally undulating low-hill terrain. Owing to this topographic variability, all UAV flight altitudes reported in this study are referenced to the take-off elevation of the UAV take-off location; consequently, the actual height above the local ground surface varied spatially along the flight path. Within a radius of approximately 350 m northwest of the UAV take-off location, only a limited number of low-rise buildings below the forest canopy used exclusively for scientific research are present, resulting in minimal anthropogenic influence on the measured CO_2 fluxes. Such an experimental condition provides a representative forest ecosystem setting in which UAV-derived fluxes can be evaluated against flux tower observations."

The specific revisions are shown in lines 276 to 293 of the revised manuscript.

(18) *Line 272: "The UAV-derived fluxes"*

• *Figure 2a does not show UAV-derived fluxes.*

Response: We agree that Fig. 2a shows the UAV flight tracks and the relative

locations of the flux tower and UAV take-off location, rather than the UAV-derived fluxes themselves. We have therefore removed the reference to Fig. 2a from the sentence describing the flux comparison and revised the surrounding text accordingly.

Revised text: "To evaluate the performance of the UAV platform for CO_2 vertical flux measurements, flights were conducted from a UAV take-off location approximately 160 m southeast of the flux tower, where the relatively open forest structure allowed safe UAV take-off and landing (Fig. 2a). The UAV-derived vertical fluxes were then directly compared with the tower-based EC measurements."

The specific revisions are shown in line 279 of the revised manuscript.

(19) *Line 325: "Because the EC system is installed at 31 m, UAV-derived CO2 vertical fluxes used data from 26 and 36 m to enable direct comparison with tower-based EC measurements."*

• *It may be useful to remind the reader here that these are all heights above UAV take-off level.*

Response: We have revised the sentence to specify that the reported UAV sampling heights are referenced to the UAV take-off elevation.

Revised text: "Because the EC system is installed at 31 m above ground level, UAV-derived CO_2 vertical fluxes were calculated using profile data collected at 26 and 36 m, thereby bracketing the EC measurement height for comparison with the tower-based EC measurements."

The specific revisions are shown in lines 334 to 337 of the revised manuscript.

(20) *Line 331: "CO2 mole fractions"*

• *The values in panel b do not appear to be mole fractions but some sort of mole fraction enhancement. It is impossible for carbon dioxide mole fraction to be 0 ppm.*

Response: Thank you for pointing this out. We agree that the values shown in Fig. 3b do not represent absolute CO_2 mole fractions. They represent CO_2 mole fraction enhancements relative to a reference/background value. We have therefore revised the text and figure caption to explicitly describe the plotted quantity as the CO_2 mole fraction enhancement rather than the absolute CO_2 mole fraction.

Revised text: "(b) The spatial distribution of CO_2 mole fraction anomaly obtained through flight-path fitting and screen linear interpolation for the morning flight on 8 August 2024."

The specific revisions are shown in line 341 of the revised manuscript.

(21) *Line 347: "met tower"*

• *What is a met tower?*

Response: Thank you for pointing this out. We agree that "met tower" was informal and insufficiently defined. We have therefore replaced it with the full term "meteorological tower" in the revised manuscript.

Revised text: "The algorithm was validated with three-dimensional wind measurements at multiple levels on an 80 m meteorological tower..."

The specific revisions are shown in line 358 of the revised manuscript.

(22) *Line 350: "CO2 emission estimation based on UAV measurements"*

• *Throughout this subsection, terms are defined in a confusing order. For example, it would be better to first present c before presenting c(bar). Similarly, w(bar) is presented before w. It is easier to follow the notation if the vertical wind speed is defined before the mean vertical wind speed.*

• *There are also problems with the idea of c(bar) being a mean concentration, as it is not clear in this manuscript what this is an average over.*

Response: Thank you for this helpful comment. We have reorganized the definitions so that the instantaneous variables are introduced first, followed by their corresponding mean quantities and then the turbulent fluctuations. Specifically, u, v, and w are first defined as the instantaneous east-west, north-south, and vertical wind components, respectively, followed by the corresponding mean components $\bar{u}$, $\bar{v}$ and $\bar{w}$, and finally the turbulent fluctuations u', v', and w'.

We also identified an error in the original description of the wind-component comparison. The mean and turbulent wind statistics used to assess the relative magnitudes of the horizontal advective/turbulent terms and the vertical advective/turbulent terms were derived from the concurrent EC flux-tower measurements, rather than from the UAV measurements. The tower data were processed using 30 min averaging intervals, as described in Sect. 3.4. We have corrected this description in Sect. 3.2 and now explicitly distinguish the tower-based diagnostic comparison from the UAV measurements used in the subsequent flux calculations.

In addition, we have clarified the definition of the CO_2 variable and removed ambiguous use of the term "mean concentration" where the quantities simply represent CO_2 mass concentrations at specified sampling heights.

Revised text: "To investigate the contributions of individual transport components to the net CO_2 emission, the TERRA framework was updated here, particularly with respect to the treatment of the vertical flux, so that the vertical turbulent flux could be calculated directly from the UAV measurements rather than parametrized through an entrainment assumption.

For clarity, u, v, and w and denote the instantaneous east-west, north-south, and vertical wind-speed components, respectively, with positive values indicating eastward, northward, and upward flow. Their corresponding mean components are denoted by $\bar{u}$, $\bar{v}$ and $\bar{w}$, and the turbulent fluctuations are defined as $u' = u - \bar{u}$, $v' = v - \bar{v}$, and $w' = w - \bar{w}$. Similarly, c denotes the instantaneous CO_2 quantity used in the corresponding flux formulation, $\bar{c}$ denotes its mean value, and $c' = c - \bar{c}$ denotes the corresponding fluctuation.

To assess the relative importance of the mean and turbulent wind components and thereby evaluate the relative magnitudes of the corresponding transport terms in Eq. (3.1), we used concurrent wind measurements from the EC flux tower. The tower data were processed using 30 min averaging intervals, as described in Sect. 3.4. For the horizontal component, the mean east-west wind component, $|\bar{u}|$, was typically 2-3 m/s, whereas the 95th percentile of the corresponding turbulent fluctuation, $|u'|$, was less than 0.1 m/s. Thus, the mean horizontal wind component was more than one order of

magnitude larger than the turbulent fluctuation, indicating that $E_{C,H}$ was substantially larger than $E_{C,HT}$ under the observed conditions.

For the vertical component, the opposite relationship was observed. The magnitude of the mean vertical wind component, $|\overline{w}|$, was typically less than 0.02 m/s, whereas the 95th percentile of $|w'|$ reached approximately 0.3 m/s. Thus, the vertical turbulent fluctuation was more than one order of magnitude larger than the mean vertical wind component, indicating that $E_{C,VT}$ was substantially larger than $E_{C,V}$. On this basis, the vertical advective term was neglected in Eq. (3.1)."

The specific revisions are shown in lines 384 to 399 of the revised manuscript.

(23) *Line 370: "horizontal and vertical directions"*

• *Add the word "respectively" here.*

Response: We have revised the sentence accordingly.

Revised text: "… $E_{C,HT}$ and $E_{C,VT}$ represent the integrated turbulent fluxes in the horizontal and vertical directions, respectively, and accounts for changes in CO_2 mass associated with air-density variations."

The specific revisions are shown in line 381 of the revised manuscript.

(24) *Line 382: "turbulent fluctuations (u′, v′, w′) were calculated by subtracting the 30 min mean value of each component from its instantaneous measurement."*

• *Does this 30-minute mean represent sampling from the full duration of each flight? What if a flight was less than 30 minutes. Just above it says that average wind components were derived using sampling from the full duration of each flight. Are these the same average values given above (u(bar), v(bar) and w(bar))? If so, it is easier to say so clearly. If a different 30-minute calculation is used, why?*

• *This turbulence value is only valid if 30 minutes of sampling has been conducted at a fixed location. The wind vertical wind speed at ground level is not the same as the vertical wind speed at 50 m. Yet if an average of all wind speed, regardless of height, is used to calculate turbulent parameters, how can this be justified?*

• *A similar issue exists with horizontal wind components with increasing height. The wind speed at 50 m is higher than wind speed at ground level. So, the calculated turbulence will be more positive at the ground and more negative at 50 m. So, it is not really a turbulence value, if it uses measurements from the full duration of each flight.*

Response: Thank you for raising this important point. As clarified in our response to Specific Comment 22, the original manuscript incorrectly implied that the 30 min mean wind components and the corresponding turbulent fluctuations were calculated from the UAV measurements collected over the full flight duration. This was not the case.

The comparison between the mean wind components and turbulent fluctuations was based on concurrent wind measurements from the fixed EC flux tower. The tower measurements were obtained at a fixed location and processed using the standard 30 min averaging interval described in Sect. 3.3. Thus, $\bar{u}$, $\bar{v}$ and $\overline{w}$ used in this diagnostic comparison are the 30 min mean wind components derived from the EC tower data, and u', v', and w' are the corresponding departures from those 30 min

means.

Revised text: "To assess the relative importance of the mean and turbulent wind components and thereby evaluate the relative magnitudes of the corresponding transport terms in Eq. (3.1), we used concurrent wind measurements from the EC flux tower. The tower data were processed using 30 min averaging intervals, as described in Sect. 3.4. For the horizontal component, …"

The specific revisions are shown in lines 396 to 399 of the revised manuscript.

(25) *Line 384: "was"*

• *Use of the present tense is probably better here, as the comparison is presented just here, rather than this being a comparison done in the past.*

Response: This paragraph has now been substantially rewritten to clarify the data source, averaging procedure, and comparison of the mean and turbulent wind components. The original wording containing "was" has therefore been removed in the revised manuscript.

(26) *Line 416: "un"*

• *It may be better to use a different letter than u, to avoid confusion with the easterly wind component.*

Response: We have replaced with throughout Sect. 3.2.1, where $U_{\perp}$ denotes the wind-speed component normal to the horizontal flight path.

Revised text: "where $E_{C,H}$ is the horizontal CO_2 emission, $U_{\perp}(s,z)$ is the wind speed component normal to the flight path at point (s,z)."

The specific revisions are shown in lines 429 to 430 of the revised manuscript.

(27) *Line 462: "3.7"*

• *Why is air density used in this equation if it is already incorporated into c(bar)?*

Response: Thank you for pointing this out. We have removed the air-density term from Eq. (3.7) and revised the subsequent derivation accordingly to maintain consistency. We have also clarified the definition and units of in the revised manuscript.

(28) *Line 463: "$\bar{c}$ was obtained by converting the measured CO2 mole fraction (expressed in ppm)"*

• *Is c(bar) an average concentration? It has not been clearly defined here. If so, what duration is it averaged over? If is in not an average, why use a bar?*

Response: For this comment. We agree that the overbar notation was ambiguous because it could be interpreted as a temporal mean. In our calculation, the CO_2 vertical profile is smoothed using a seven-point moving average before the gradient is evaluated. The quantity previously denoted by $\bar{c}$ was therefore intended to represent a locally smoothed profile value rather than a time average at a fixed height. To remove this ambiguity, we now use a tilde notation: $\tilde{C}$ denotes the seven-point moving-average-smoothed CO_2 mass-concentration profile. We explicitly state that the moving average is applied along the UAV vertical profile, not over a fixed-duration time interval.

Revised text: "Before calculating the vertical gradients, the UAV profiles of CO_2

mass concentration, horizontal wind-speed magnitude, and air temperature were smoothed using a seven-point moving average applied along the vertical profile. To distinguish these locally smoothed profile quantities from the 30 min temporal means used for the fixed EC tower data, a tilde is used throughout this subsection. Thus, $\tilde{C}(z)$, $\tilde{S}(z)$, and $\tilde{T}(z)$ denote the smoothed CO_2 mass concentration, horizontal wind-speed magnitude, and air temperature, respectively. The CO_2 mass concentration C (mg/m^3) is obtained by converting the UAV-measured CO_2 mole fraction (ppm) using the concurrently measured temperature and pressure. The tilde therefore denotes profile smoothing across neighboring samples rather than a temporal mean at a fixed height."

The specific revisions are shown in lines 472 to 477 of the revised manuscript.

(29) *Line 474: "u*"*

- *It would be better to use a different letter to avoid confusion with the easterly wind speed.*

Response: We have retained this symbol because it is the conventional and widely used notation for friction velocity (u_*) in atmospheric boundary-layer meteorology and turbulence studies. To change it to a different symbol would cause confusions to researchers in these fields. In the revised manuscript, we have reorganized the notation for the other wind variables and no longer use to denote the horizontal wind-speed magnitude in Sect. 3.2.2. Instead, a separate symbol is used for the horizontal wind-speed magnitude, while remains exclusively defined as the east-west wind component. We therefore believe that retaining the standard notation for u_* is clear and consistent with established convention.

(30) *Line 475: "the vertical gradient of the mean wind speed."*

- *This is not the gradient of the mean wind speed. According to the start of this subsection, u(bar) is the mean of the easterly wind component. So its derivative cannot be something else.*
- *It should clearly state which wind speed this refers to. If it is an overall horizontal wind speed magnitude, this should be stated this clearly.*
- *If an absolute horizontal wind speed magnitude is used here, then a different letter to "u" should definitely be used here. A term cannot be redefined in the middle of a paper.*

Response: The quantity used in the vertical-gradient calculation is the horizontal wind-speed magnitude, not the east-west wind component u. We have rewritten this part of the subsection and now denote the horizontal wind-speed magnitude by S. After seven-point profile smoothing, the quantity is written as $\tilde{S}$. The previous use of $\bar{u}$ for two different physical quantities has been removed.

Revised text: "Before calculating the vertical gradients, the UAV profiles of CO_2 mass concentration, horizontal wind-speed magnitude, and air temperature were smoothed using a seven-point moving average applied along the vertical profile. To distinguish these locally smoothed profile quantities from the 30 min temporal means used for the fixed EC tower data, a tilde is used throughout this subsection. Thus, $\tilde{C}(z)$, $\tilde{S}(z)$, and $\tilde{T}(z)$ denote the smoothed CO_2 mass concentration, horizontal wind-speed magnitude, and air temperature, respectively. The CO_2 mass concentration C (mg/m^3)

is obtained by converting the UAV-measured CO_2 mole fraction (ppm) using the concurrently measured temperature and pressure. The tilde therefore denotes profile smoothing across neighboring samples rather than a temporal mean at a fixed height."

The specific revisions are shown in lines 468 to 477 of the revised manuscript.

(31) *Line 487: "$\Delta\bar{u}$"*

- *u(bar) is the easterly wind component, according to the start of this subsection.*

(32) *Line 488: "wind-speed magnitude"*

- *Please specify that this refers to the easterly wind component and not the full horizontal wind speed.*

(33) *Line 489: "$\bar{\theta}$"*

- *What is this? I can see above that Δθ(bar) is the smoothed temperature change, but θ(bar) has not been defined.*

(34) *Line 489 "$\bar{u}$"*

- *Please specify which of the two definitions for u(bar) applies here?*

Response: We agree that these symbols were not defined consistently. In the revised subsection, $\Delta\bar{u}$ is replaced by the difference in the smoothed horizontal wind-speed magnitude, $\tilde{S}_2 - \tilde{S}_1$. The phrase "wind-speed magnitude" is now explicitly defined as the horizontal wind-speed magnitude. The previously undefined $\bar{\theta}$ notation is replaced by $\tilde{T}$, which denotes the seven-point moving-average-smoothed air-temperature profile. Thus, $\tilde{S}$ and $\tilde{T}$ have unique definitions throughout the subsection.

Revised text: "$R_i \approx R_B = \frac{g}{\tilde{T}_m} \cdot \frac{(\tilde{T}_2 - \tilde{T}_1)(z_2 - z_1)}{(\tilde{S}_2 - \tilde{S}_1)^2}$, $\tilde{T}_m = (\tilde{T}_1 + \tilde{T}_2)/2$ (3.12)

where g is gravitational acceleration; $\tilde{S}$ is the smoothed horizontal wind-speed magnitude; $\tilde{T}$ is the smoothed air temperature; and the subscripts 1 and 2 denote values evaluated from the smoothed vertical profiles at the lower and upper heights z_1 and z_2, respectively. These quantities are profile-smoothed values, not temporal averages obtained while the UAV remained at a fixed height."

The specific revisions are shown in lines 509 to 513 of the revised manuscript.

(35) *Line 500: "mean wind-speed magnitude"*

- *This is the second time that u(bar) has been defined. At the start of the subsection, it is the easterly wind component. Now it is the overall wind speed magnitude.*
- *It is unacceptable and totally confusing for defined terms to change in the manuscript, especially mid-way through a single subsection.*

Response: We agree. Reusing $\bar{u}$ for the overall wind-speed magnitude after it had already been defined as the mean east-west component was confusing and inappropriate. We have removed this redefinition entirely. The logarithmic wind-profile equations now use $\tilde{S}$ exclusively for the smoothed horizontal wind-speed magnitude, while u retains only its earlier meaning as the east-west wind component.

Revised text: "Because the forest canopy is aerodynamically rough, the wind profile is expressed using the displacement-height form of the neutral logarithmic wind profile (Raupach, 1994). The smoothed horizontal wind-speed magnitude is written as

$\tilde{S}(z) = \frac{u_*}{\kappa} ln \frac{z-d}{z_0}$ ”

The specific revisions are shown in lines 517 to 520 of the revised manuscript.

(36) *Line 514: “3.16”*

• *This equation includes air density. However, air density is already incorporated into c, which is derived from mole fraction.*

(39) *Line 520: “3.17”*

• *This equation includes air density. However, air density is already incorporated into c, which is derived from mole fraction.*

Response: Consistent with the correction to Eq. (3.7), the air-density factor has been removed from Eq. (3.16), because $\tilde{C}_1$ and $\tilde{C}_2$ are already CO_2 mass concentrations rather than mole fractions.

Revised text: “$F_v = \kappa^2(1-R_i)^{1/2} \frac{(\tilde{S}_2-\tilde{S}_1)(\tilde{C}_1-\tilde{C}_2)}{\{\ln[(z_2-d)/(z_1-d)]\}^2}$ (3.16)

where $\tilde{C}_1$ and $\tilde{C}_2$ are the smoothed CO_2 mass concentrations evaluated from the seven-point moving-average profile at z_1 and z_2, respectively. They are obtained from the measured CO_2 mole fractions after conversion to mass concentration using the concurrently measured temperature and pressure.

The corresponding vertical CO_2 emission component is

$E_{C,VT} = A\kappa^2(1-R_i)^{1/2} \frac{(\tilde{S}_2-\tilde{S}_1)(\tilde{C}_1-\tilde{C}_2)}{\{\ln[(z_2-d)/(z_1-d)]\}^2}$ (3.17)”

The specific revisions are shown in lines 530 to 532 of the revised manuscript.

(37) *Line 526: “at using”*

• *Should this be “and using”?*

Response: Thank you for catching this typographical error. The sentence has been rewritten, and the erroneous phrase “at using” has been removed.

(38) *Line 515: “mean concentrations”*

• *Is this a mean concentration or a smoothed concentration from seven datapoints? A mean concentration implies that a mean was obtained at a single fixed height when in reality, the UAV was constantly moving.*

Response: The values used at z_1 and z_2 are not temporal means obtained while the UAV remained at fixed heights. They are values evaluated from the seven-point moving-average-smoothed vertical CO_2 profile. We have therefore replaced “mean concentrations” with “smoothed CO_2 mass concentrations” and denote them by $\tilde{C}_1$ and $\tilde{C}_2$. The revised text explicitly states that the smoothing is applied across neighboring samples along the vertical profile.

Revised text: “$F_v = \kappa^2(1-R_i)^{1/2} \frac{(\tilde{S}_2-\tilde{S}_1)(\tilde{C}_1-\tilde{C}_2)}{\{\ln[(z_2-d)/(z_1-d)]\}^2}$

where $\tilde{C}_1$ and $\tilde{C}_2$ are the smoothed CO_2 mass concentrations evaluated from the seven-point moving-average profile at z_1 and z_2, respectively.”

The specific revisions are shown in lines 530 to 532 of the revised manuscript.

(40) *Line 530: "Finally, the three-dimensional net CO2 emission was obtained using the original observations."*

• *I am lost. I think the word "finally" is confusing here.*

Response: We have rewritten the concluding sentences of Sect. 3.2.2 to state directly that the horizontal component is calculated from box-pattern measurements, the vertical turbulent component is calculated from the paired profile measurements, and the net three-dimensional CO_2 emission is obtained by combining these two components.

Revised text: "For each UAV flight, $E_{C,VT}$ is calculated from the paired vertical profile measurements rather than from the box-pattern observations. For the comparison with the EC system, z_1 = 26 m and z_2 = 36 m above the UAV take-off elevation are used, and the resulting flux is assigned to the midpoint height of approximately 31 m. The horizontal component $E_{C,H}$ is calculated from the box-pattern observations along the lateral boundaries of each UAV-defined control volume. The net three-dimensional CO_2 emission is then obtained by combining the horizontal component from the box-pattern measurements with the vertical turbulent component from the paired profile measurements. The reliability of the vertical flux estimates from Eq (3.16) is evaluated against the EC flux tower observations in Section 4.2.1."

The specific revisions are shown in lines 537 to 546 of the revised manuscript.

(41) *Line 549: "318"*

• *This equation uses u', which is defined as the fluctuation in the east-to-west wind component.*

Response: We agree that the notation was potentially confusing because was previously introduced as the east-west wind component. For the EC flux-tower calculation in Sect. 3.3, however, the wind data were coordinate-rotated before the turbulent statistics were calculated. After rotation, represents the streamwise wind component aligned with the mean horizontal wind direction, rather than the original east–west component. Accordingly, in Eq. (3.18) denotes the fluctuation of this rotated streamwise wind component. We have revised the text to make this distinction explicit and to avoid confusion with the geographical east–west wind component defined earlier in the manuscript.

Revised text: "Fluxes were computed over 30 min averaging intervals, and coordinate rotation, virtual temperature correction, and frequency-response correction were applied to ensure high-quality vertical flux estimates. For the EC calculations, the measured wind components were first transformed into a streamline coordinate system through coordinate rotation. In this rotated coordinate system, u_s denotes the streamwise wind component aligned with the mean horizontal wind direction."

The specific revisions are shown in lines 658 to 661 of the revised manuscript.

(42) *Line 550: "3.19"*

• *This equation is incorrect as c is defined as being in kg m−3. The density is incorporated twice.*

Response: We have removed the air-density term from Eq. (3.19) and revised the accompanying definition accordingly.

Revised text: "$F_v = \overline{w'c'}$"

The specific revisions are shown in line 665 of the revised manuscript.

(43) *Line 560: "same height"*

• *Please remind the reader that this refers to height above take-off level for the UAV. This means that the actual height is offset.*

Response: We apologize that the original wording was not sufficiently clear and may have led to a misunderstanding. The "same height" referred to here does not describe UAV and flux-tower measurements conducted at two different locations. Rather, this was a ground-based instrument intercomparison in which the UAV-mounted MIRA analyzer and the LI-7500 analyzer used by the EC system were placed side by side at the same location. Their sampling inlets were positioned at the same height and as close to each other as practicable so that the two analyzers sampled the same air mass simultaneously. Therefore, the UAV take-off elevation is not relevant to this particular comparison experiment. We have revised the description in Sect. 4.1 to make the experimental configuration explicit and to avoid this ambiguity.

Revised text: "To evaluate the consistency between the two CO_2 analyzers, a ground-based co-located intercomparison experiment was conducted using the open-path CO_2/H_2O gas analyzer (LI-7500) employed in the EC system and the closed-path analyzer (MIRA) used on the UAV. During the experiment, the two analyzers were placed side by side at the same ground location. Their sampling inlets were positioned at the same height and as close to each other as practicable to ensure that both instruments sampled the same air mass simultaneously."

The specific revisions are shown in lines 670 to 676 of the revised manuscript.

(44) *Line 620: "Pearson correlation coefficient (r)"*

• *It would be better to define this properly in the previous subsection, when r is first introduced.*

Response: We have revised Sect. 4.1 to define as the Pearson correlation coefficient at its first occurrence. Subsequent occurrences now use consistently without redefining the term.

Revised text: "The data are closely distributed around a narrow band of the fitted linear regression line, with a Pearson correlation coefficient of r = 0.986."

The specific revisions are shown in lines 705 to 707 of the revised manuscript.

(45) *Line 623: "at z1=26 m and z2=36 m."*

• *This is very confusing, as in the previous section, it says that measurements between 26 m and 36 m were used. Instead, here it says that measurements at 26 m and at 36 m were used.*

• *Measurements between two locations and at two locations are very different things.*

• *If the authors have used measurements between these two heights, the simple solution is to replace the word "at" with "between".*

• *If only a single measurement at 26 m is used and a single measurement at 36 m is used, then I am totally lost.*

Response: We have replaced "at z_1=26 m and z_2=36 m" with "between z_1=26 m and z_2=36 m" and revised the surrounding text to make the calculation procedure explicit.

Revised text: "For the comparison with the EC system installed at 31 m above ground, the UAV-derived vertical flux was calculated from the smoothed vertical profile measurements between z_1=26 m and z_2=36 m relative to the UAV take-off elevation."

The specific revisions are shown in lines 735 to 737 of the revised manuscript.

(46) *Line 706: "This suggests that the UAV-based method is generally capable of reproducing the variability of CO2 fluxes observed by the EC system, while tending to underestimate flux magnitudes under stronger exchange conditions."*

• *Why?*

Response: The RMA slopes below unity indicate a modest compression of the UAV-derived flux range relative to the EC measurements. One possible explanation is that the UAV gradient method derives the vertical flux from a smoothed CO_2 vertical profile over a finite height interval. Under strong exchange conditions, steep and rapidly varying CO_2 gradients may therefore be partially attenuated by the profile smoothing, leading to smaller retrieved flux magnitudes. In addition, the UAV profile represents a relatively short sampling period, whereas the EC flux is calculated over a 30 min averaging interval, so short-term atmospheric non-stationarity may also contribute to the observed differences. Because these mechanisms were not independently quantified in the present study, we have revised the text to present them as possible explanations rather than demonstrated causes.

Revised text: "The corresponding slopes are 0.871 (95% CI: [0.732, 0.986]) for early morning and 0.916 (95% CI: [0.750, 1.087]) for midday, both close to unity but slightly lower than 1, indicating a modest compression of the UAV-derived flux range relative to the EC measurements. Thus, although the UAV-based method reproduces the observed variability reasonably well, the magnitude of stronger fluxes tends to be attenuated. A possible explanation is that the gradient method derives fluxes from a smoothed CO_2 vertical profile over a finite height interval, which may partially attenuate steep or rapidly varying gradients under strong exchange conditions. Differences in temporal sampling between the relatively short UAV profile and the 30 min EC averaging interval may also contribute to the observed differences."

The specific revisions are shown in lines 816 to 825 of the revised manuscript.

(47) *Line 834: "Under such a requirement"*

• *Which requirement? Why does the aforementioned statement on selecting summer noon and autumn morning measurements result in seven days of data being required? Autumn lasts roughly 90 days.*

Response: Thank you for pointing this out. We agree that the original description of the data-selection procedure was not sufficiently clear and may have led to the impression that selecting summer-noon and autumn-morning measurements itself

resulted in seven days of observations. This was not our intended meaning.

Although 168 UAV flights were retained after quality control for the full study period, the number of observations becomes considerably smaller when the dataset is further separated by season and time of day. For the spatial-heterogeneity analysis, our objective was to compare the three control volume sizes under meteorological and ecosystem conditions that were as comparable as possible. We therefore restricted the analysis to measurements obtained within the same season and the same time-of-day period, thereby reducing the influence of seasonal and diurnal variability on the statistical comparison.

In addition, only observations for which valid measurements were available for all three control volume sizes (50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3) were retained, because a complete set of the three spatial scales was required for a meaningful within-period comparison. After applying these criteria, the summer-noon and autumn-morning datasets provided suitable samples and also showed relatively good agreement with the flux-tower comparisons presented in Sect. 4.2. We therefore selected seven observation days from summer noon and seven observation days from autumn morning for the subsequent spatial-heterogeneity analysis.

We have rewritten the corresponding paragraph in Sect. 4.4 to explicitly describe these selection criteria and to clarify that the seven days refer to seven days for each period, rather than seven days in total.

Revised text: "A total of 168 UAV flights were retained after quality control for the overall study. However, the number of observations within a specific season and time-of-day period was substantially smaller. Because the purpose of this analysis was to assess spatial-scale dependence, rather than seasonal or diurnal variability, only measurements obtained within the same season and time-of-day period were compared, thereby minimizing differences in ecosystem activity and atmospheric conditions. In addition, only cases with valid observations for all three control volume sizes (50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3) were retained to ensure an internally consistent comparison across spatial scales. After applying these criteria, seven observation days from summer noon and seven observation days from autumn morning were selected for the spatial-heterogeneity analysis. An observation day did not necessarily correspond to a single UAV flight; multiple UAV measurements could be conducted within the selected time window on the same day. These two periods also showed relatively good agreement between UAV-derived vertical fluxes and EC observations in Sect. 4.2."

The specific revisions are shown in lines 946 to 960 of the revised manuscript.

(48) *Line 835: "seven days of observations"*

- *So, does this mean seven days in autumn and seven days in summer or was the combined data collected over seven days?*
- *Does each day of observation correspond to a single UAV flight?*

Response: The dataset used for the spatial-heterogeneity analysis consisted of seven observation days during summer noon and seven observation days during autumn morning, i.e., 14 observation days in total. The phrase "seven days of observations" has

therefore been revised to make this distinction explicit.

We have also clarified the relationship between observation days and UAV flights in the revised manuscript. An observation day does not necessarily imply a single UAV flight; rather, the analysis retained the UAV measurements that satisfied the data-quality criteria and provided valid observations for all three control volume sizes within the selected season-time-period category. We now report both the number of observation days and the corresponding number of retained UAV flights to avoid ambiguity.

Revised text: "A total of 168 UAV flights were retained after quality control for the overall study. However, the number of observations within a specific season and time-of-day period was substantially smaller. Because the purpose of this analysis was to assess spatial-scale dependence, rather than seasonal or diurnal variability, only measurements obtained within the same season and time-of-day period were compared, thereby minimizing differences in ecosystem activity and atmospheric conditions. In addition, only cases with valid observations for all three control volume sizes (50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3) were retained to ensure an internally consistent comparison across spatial scales. After applying these criteria, seven observation days from summer noon and seven observation days from autumn morning were selected for the spatial-heterogeneity analysis. An observation day did not necessarily correspond to a single UAV flight; multiple UAV measurements could be conducted within the selected time window on the same day. These two periods also showed relatively good agreement between UAV-derived vertical fluxes and EC observations in Sect. 4.2."

The specific revisions are shown in lines 955 to 960 of the revised manuscript.

(49) *Line 839: "fixed tower varied by less than 8% during the comparison period."*

- *What exactly is the comparison period? Does this represent all of the EC fluxes for the full duration of each of the UAV flights used in each analysis?*
- *Is this 8% value a variation between average fluxes collected over seven days? Is this an average variation of each discrete flux measurement collected over the period of each UAV flight over seven days?*

Response: Here, the comparison refers to the EC flux measurements corresponding to the selected UAV observation periods on the seven summer-noon days and the seven autumn-morning days used in the spatial-heterogeneity analysis. Specifically, the summer-noon comparison used the EC flux measurements corresponding to the UAV observations conducted between 13:00 and 14:00 on each of the seven selected days, whereas the autumn-morning comparison used the corresponding EC measurements between 06:00 and 07:00 on each of the seven selected days. The reported 8% and 5% values characterize the variability among these corresponding tower-flux observations across the selected days; they do not refer to variability within a single UAV flight or to all EC measurements over the full season. We have revised the text to define the comparison period and the basis of these percentages explicitly.

Revised text: "For the seven selected summer-noon observation days, UAV measurements were conducted between 13:00 and 14:00 under predominantly

southeasterly winds. The EC flux measurements corresponding to these UAV observation periods varied by less than 8% among the seven selected days. Similarly, for the seven selected autumn-morning observation days, UAV measurements were conducted between 06:00 and 07:00 under predominantly southwesterly winds, and the corresponding EC flux measurements varied by less than 5% among the seven selected days. These relatively small variations indicate that the selected observations within each season-time-period subset were obtained under broadly comparable ecosystem-exchange conditions. The selected datasets were intended to provide internally comparable subsets for evaluating spatial-scale dependence rather than to represent the full seasonal climatology."

The specific revisions are shown in lines 961 to 971 of the revised manuscript.

(50) *Line 847: "-0.25, -0.30, and -0.24"*

- *I am totally lost. Do these values correspond to autumn morning or summer noon?*
- *This sentence does not make sense in general and needs to be rewritten.*
- *Are these values an average of all UAV fluxes over a seven-day period. It is not at all clear what these values represent and where the come from.*

Response: The values -0.25, -0.30, and -0.24 mg m^{-2} s^{-1} correspond specifically to the summer noon dataset. They are the mean area-normalized net CO_2 emission intensities calculated for the 50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3 control volumes, respectively, using the seven selected summer noon observation days. These values do not refer to the autumn morning dataset. We have rewritten the sentence to explicitly state the observation period, the corresponding control volume sizes, and the statistical meaning of the reported values.

Revised text: "If the CO_2 source-sink distribution in this region were spatially uniform, e_C would be expected to be similar among the three control volume sizes, i.e., $e_C(150) \approx e_C(100) \approx e_C(50)$. For the seven selected summer noon observation days, the e_C were -0.25, -0.30, and -0.24 mg m^{-2} s^{-1} for the 50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3 control volumes, respectively (Fig. 10). These consistently negative values indicate net CO_2 uptake during the summer noon period, while the relatively small differences among the three spatial scales suggest weak scale dependence under these conditions."

The specific revisions are shown in lines 972 to 978 of the revised manuscript.

(51) *Line 851: "ANOVA"*

- *What is this? This has not been defined.*

Response: We have revised the text to define it as "one-way analysis of variance (ANOVA)" when first introduced and use the abbreviation consistently thereafter.

Revised text: "Furthermore, one-way analysis of variance (ANOVA) shows the mean differences in e_C among the three scales were not significant"

The specific revisions are shown in line 979 of the revised manuscript.

(52) *Line 877: "Table 5"*

- *The eighth row is called "Mdian". I think this should be "Median".*

Response: Thank you for pointing this out. We have corrected it to "Median" in the eighth row of Table 5.

Revised text: "$E_{C,VT}$ Median"

The specific revisions are shown in line 1012 of the revised manuscript.

(53) *Line 888: "uncertainty of the method used in this study (15%)"*

• *Where does this 15% uncertainty value come from? I have not seen this before.*

Response: Thank you for pointing this out. We apologize for the confusion. The 15% value was the uncertainty estimate used in the second version of the manuscript and was inadvertently retained in this sentence when the uncertainty analysis was updated in the current revision. In the revised manuscript, the total relative uncertainty of the UAV-derived emission estimates is approximately 30%, as described in Sect. 4.5. We have therefore corrected the value from 15% to 30% in Sect. 4.4 to ensure consistency with the updated uncertainty analysis.

Revised text: "The differences among box sizes are substantially larger than the uncertainty of the method used in this study (30%)…"

The specific revisions are shown in line 1018 of the revised manuscript.

(54) *Line 893: "In contrast"*

• *Why is this in contrast to the preceding paragraph?*

Response: Our intention was to contrast the autumn morning conditions with the summer noon case discussed earlier, particularly with respect to the relative importance of horizontal transport. We have therefore revised the sentence to make the comparison explicit.

Revised text: "Compared with the summer noon conditions, the role of horizontal transport becomes much more pronounced during autumn mornings."

The specific revisions are shown in lines 1023 to 1024 of the revised manuscript.

(55) *Line 898: "median EC,H values range"*

• *This is presented as a range of EC,H values. However, it took me some time to understand what this was a range over. In fact, this is a range over different sized boxes, of which there are only three. It would be better to give all three values, rather than a range over three values.*

Response: We have revised the text to report the median $E_{C,H}$ values individually for the 50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m³ control volumes, respectively. We have made the same revision for the corresponding $E_{C,VT}$ values to improve clarity.

Revised text: "For the 50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3 control volumes, the median $E_{C,H}$ values were 0.0687, 0.0817, and 0.273 kg h^{-1}, respectively, whereas the corresponding median $E_{C,VT}$ values were -2.77, -13.6, and -12.5 kg h^{-1}, respectively."

The specific revisions are shown in lines 989 to 992 of the revised manuscript.

Revised text: "Specifically, for the 50 × 50 × 50, 100 × 100 × 50, and 150 × 150 × 50 m^3 control volumes, the median $E_{C,H}$ values were 0.105, 3.52, and 6.41 kg h^{-1},

respectively, whereas the corresponding median $E_{C,VT}$ values were 0.033, 3.73, and 4.85 kg h^{-1}, respectively."

The specific revisions are shown in lines 1028 to 1031 of the revised manuscript.

(56) *Line 938: "Computation of uncertainties"*

• *Consider placing this uncertainty subsection at the end of the methods section. It is not really a flux result so it may be better to know the flux uncertainty before the flux is presented.*

Response: We have moved the original Sect. 4.5, "Computation of uncertainties," to the end of the Methods section, following the CO_2 emission estimation based on UAV measurements. The section numbering and relevant cross-references have been updated accordingly.

The specific revisions are shown in line 547 of the revised manuscript.

(57) *Line 945: "three components"*

• *I only see two components here.*

Response: Thank you for pointing this out. We have corrected "three components" to "two components" in the revised manuscript.

Revised text: "The measurement-related uncertainty was divided into two components…"

The specific revisions are shown in line 554 of the revised manuscript.

(58) *Line 947: "combined in quadrature"*

• *This approach is only valid for independent standard deviation uncertainties. Perhaps state this assumption here.*

Response: We have added this assumption explicitly in the revised manuscript.

Revised text: "Assuming that the two uncertainty components are independent and represent standard-deviation-type uncertainties, they were combined in quadrature to obtain the measurement-propagated uncertainty"

The specific revisions are shown in lines 555 to 557 of the revised manuscript.

(59) *Line 992: "Three representative cases"*

• *Why use three cases? Why not use all of the flights? Is it too computationally demanding? Some reasoning would be welcome here.*

Response: In preparing the current revision, we devoted substantial effort to recalculating and restructuring the uncertainty analysis, and we believe that the present treatment provides a sufficiently comprehensive assessment of the major uncertainty sources affecting the UAV-derived flux estimates.

For the methodological uncertainty analysis in particular, the objective was to evaluate the sensitivity of the flux calculation to alternative processing approaches rather than to derive a separate methodological uncertainty for every individual UAV flight. Extending the full set of alternative reconstruction and recalculation procedures to all flights would require a very large additional computational effort. We therefore selected three representative cases spanning different seasons and observational

conditions to evaluate the methodological sensitivity, and conservatively adopted the largest uncertainty obtained from these cases. We have added this rationale to the revised manuscript to make the basis of the analysis clearer.

Revised text: "Because the purpose of this analysis was to assess the methodological sensitivity of the flux calculation rather than to derive a separate methodological uncertainty for every individual UAV flight, three representative cases spanning different seasons and observational conditions were selected for the analysis: spring morning (12 May 2024), summer noon (20 August 2023), and autumn noon (3 December 2024). Applying the full set of alternative reconstruction and recalculation procedures to all UAV flights would require substantial additional computation. Given that the uncertainty analysis in the present study already considers the major measurement-related and methodological uncertainty sources, these representative cases were used to provide a practical assessment of the sensitivity associated with spatial reconstruction."

The specific revisions are shown in lines 607 to 616 of the revised manuscript.

(60) *Line 995: "uncertainties in EC calculated using the different methods"*

• *What about linear interpolation results?*

Response: Linear interpolation is the spatial reconstruction method adopted in the main flux calculation in this study and was therefore used as the reference method in the methodological uncertainty analysis. The reported uncertainties of 6% and 8% represent the differences in the estimates obtained using the nearest-neighbor and segment-averaging methods, respectively, relative to the estimates obtained using linear interpolation. Therefore, no separate uncertainty value was assigned to linear interpolation itself in this comparison. We have revised the manuscript to make the reference role of linear interpolation explicit.

Revised text: "Linear interpolation is the method used for the primary $E_{C,H}$ calculation in this study and was therefore treated as the reference method. The $E_{C,H}$ estimates obtained using nearest-neighbor interpolation and segment averaging were compared with those obtained using linear interpolation, and the resulting relative differences were used to quantify the sensitivity of to the spatial-reconstruction method."

The specific revisions are shown in lines 602 to 606 of the revised manuscript.

(61) *Line 996: "respectively"*

• *Why is this word here? What are these uncertainties respective to? Does each uncertainty correspond to a single season?*

• *These values should each use data from each of the three seasons.*

Response: The values of 6% and 8% do not correspond to individual seasons. For both alternative reconstruction methods, all three representative cases (spring morning, summer noon, and autumn noon) were included in the methodological sensitivity analysis. The 6% value corresponds to the relative difference obtained using the nearest-neighbor reconstruction compared with the linear-interpolation reference, whereas the 8% value corresponds to the relative difference obtained using segment averaging, again based on the three representative cases. We have revised the text,

please refer to Point 60 in the Specific Comments.

The specific revisions are shown in lines 602 to 606 of the revised manuscript.

(62) *Line 1000: "Because the CO2 analyzer uncertainty was small"*

• *This point should not really matter. When evaluating the vertical methodological uncertainty, the instrumental uncertainty should be irrelevant.*

Response: We have removed this statement and revised the paragraph so that the methodological uncertainty in $E_{C,VT}$ is discussed independently of the instrumental uncertainty.

Revised text: "For the vertical turbulent contribution term, $E_{C,VT}$, the methodological uncertainty was mainly associated with the flux-gradient approach and, in particular, with the estimation of the turbulent exchange coefficient from wind-related variables, including the three-dimensional wind components and friction velocity. To evaluate the sensitivity of $E_{C,VT}$ to this part of the methodology, perturbations in the wind-related inputs were propagated through the flux-gradient calculation ($\delta_{gradient}$). Based on the wind-correction validation described above, a relative perturbation of 28.5% was applied to the wind-related inputs used to derive the turbulent exchange coefficient…"

The specific revisions are shown in lines 622 to 629 of the revised manuscript.

(63) *Line 1017: "4.3"*

• *The gradient uncertainty is based on the wind uncertainty. Therefore, these terms are interdependent and cannot ordinarily be combined in quadrature.*

Response: We have revised the uncertainty analysis accordingly. The $\delta_{gradient}$ value is retained only as a diagnostic measure of the sensitivity of the vertical flux-gradient calculation to wind-related perturbations, but it is no longer included as an independent term in the total uncertainty calculation. The total relative uncertainty is now calculated from the independent contributions of the CO_2 analyzer uncertainty, wind measurement uncertainty, and spatial-reconstruction uncertainty. This gives a total relative uncertainty of approximately 29.6%, which is rounded to approximately 30%.

Revised text: "The resulting uncertainties were 3%, 2%, and 5% for the three representative cases. The largest value (5%) was used to characterize the sensitivity of the vertical flux-gradient calculation to wind-related perturbations. Because the sensitivity of the vertical flux-gradient calculation was derived by propagating the wind-related uncertainty, $\delta_{gradient}$ and δ_V were not treated as independent uncertainty components. To avoid double counting, $\delta_{gradient}$ was therefore excluded from the quadrature calculation of the total uncertainty. Assuming that the remaining uncertainty components are independent, the total relative uncertainty ($\delta_{combined}$) was calculated:

$$\delta_{combined}^2 = \delta_{CO_2}^2 + \delta_V^2 + \delta_{spatial}^2 \quad (3.19)"$$

The specific revisions are shown in lines 631 to 640 of the revised manuscript.

(64) *Line 1030: "emission"*

• *The word "fluxes" may be better here, as "emission" insinuates that a positive outward flux is taking place.*

Response: We have replaced "emission" with "fluxes" in this sentence to use a more neutral and accurate description of the measured CO_2 exchange.

Revised text: "This study developed and field-evaluated a UAV-based methodology to quantify three-dimensional CO_2 fluxes over a forest ecosystem…"

The specific revisions are shown in line 1069 of the revised manuscript.