Dear Reviewer,

I would like to express sincere gratitude to the reviewer for the considerable time, care, and expertise devoted to evaluating our manuscript. The present submission represents the fourth revised version of the manuscript, and we fully recognize the reviewer's sustained effort across these successive rounds of review. The reviewer's careful reading, insightful questioning, and constructive suggestions have helped the clarification for the methodology, improvement to the consistency of the terminology and notation, strengthening the scientific analysis, and enhancing the overall presentation of the work. We have once again carefully considered every comment and revised the manuscript accordingly.

On behalf of all authors, I thank the reviewer's patience, continued engagement, and valuable contribution to improving our manuscript.

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

Sincerely yours,

Shao-Meng Li, Professor

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**General comments**

(1) *I would like to suggest defining concertation (c) as mole fraction multiplied by density once at the start of subsection 3.2 (in the paragraph where u, v and w are defined) and then referring to concentration throughout the rest of the section. Explain here that concentration can be derived by multiplying raw mole fraction measurements with MR and mass density. This combines the mole fraction and density into a single term in equations 3.2, 3.2, 3.4 and 3.5, making these equations consistent with the rest of the equations (and easier to read). It seems strange that half of the equations use concentration while the other half use mole fraction. There is then no need to explain this again in subsection 3.2.2. c' can also be defined here. Then c(tilde) can be defined when it is used (as is already the case), without the need to redefine c (with a different case). Make sure that the c(tilde) uses the same case (lower or upper case) as defined previously.*

**Response:** Thank you for this constructive suggestion. We have revised Sect. 3.2 to define a single lowercase $c$ at its first occurrence and use it consistently throughout the section.

Specifically, $c$ is now defined as the instantaneous $CO_2$ mass concentration:

$$c = M_R \chi_C \rho_{air}$$

where $\chi_C$ is the measured $CO_2$ mole fraction (ppm), $\rho_{air}$ is the concurrently measured air density (kg $m^{-3}$), and $M_R$ is the ratio of the molar mass of $CO_2$ to that of air. With these units, the equation yields $c$ directly in mg $m^{-3}$.

We have also defined the temporal mean and turbulent fluctuation at this point. For the Reynolds decomposition of the concurrent 10 Hz tower observations, each variable $q \in \{u, v, w, c\}$ was decomposed over non-overlapping 30 min intervals as

$$\bar{q} = \frac{1}{k}\sum_{i=1}^{k} q_i$$

And turbulent fluctuation:

$$q_i' = q_i - \bar{q}$$

where $k$ is the number of valid observations and is nominally 18,000 for a complete interval. This definition includes the $CO_2$ concentration fluctuation $c_i' = c_i - \bar{c}$; the fluctuations are therefore calculated relative to the corresponding 30 min means rather than running means.

Following the reviewer's suggestion, the products $M_R \chi_C \rho_{air}$ in the horizontal transport equations have been replaced with $c$. Equations (3.3)-(3.5) are therefore now expressed consistently in terms of $CO_2$ mass concentration.

The separate uppercase $C$ previously introduced in Sect. 3.2.2 has been removed. Lowercase $c$ is now used throughout Sect. 3.2 and all associated equations. In Sect. 3.2.2, $\tilde{c}$ denotes the seven-point moving-average-smoothed vertical profile of $c$. The tilde distinguishes smoothing across neighboring samples along the UAV profile from the 30 min temporal mean $\bar{c}$ used for the fixed tower observations. The corresponding smoothed wind-speed magnitude and air temperature are denoted by $\tilde{S}$ and $\tilde{T}$, respectively.

Revised text: "For clarity, $u$, $v$, and $w$ denote the instantaneous east-west, north-south, and vertical wind-speed components, respectively, with positive values indicating eastward, northward, and upward flow. Throughout this section, $c$ denotes the instantaneous $CO_2$ mass concentration (mg $m^{-3}$), calculated as: $c = M_R \chi_C \rho_{air}$, where $\chi_C$ is the measured $CO_2$ mole fraction (ppm), $\rho_{air}$ is the concurrently measured air density (kg $m^{-3}$), and $M_R$ is the ratio of the molar mass of $CO_2$ to that of air. With these units, the equation yields $c$ directly in mg $m^{-3}$. For the Reynolds decomposition of the concurrent 10 Hz tower observations, each variable $q \in \{u, v, w, c\}$ was decomposed over non-overlapping 30 min intervals as: $\bar{q} = \frac{1}{k}\sum_{i=1}^{k} q_i$, and turbulent fluctuation: $q_i' = q_i - \bar{q}$, where $k$ is the number of valid observations and is nominally 18,000 for a complete interval."

The specific revisions are shown in lines 403 to 411 of the revised manuscript.

Revised text: "Using the finite-layer formulation employed in the gradient calculation, the wind-speed and $CO_2$ differences between $z_1$ and $z_2$ are expressed over the same logarithmic height interval. Substitution into Eq. (3.7) gives

$$F_v = \kappa^2 (1 - R_i)^{1/2} \frac{(\tilde{S}_2 - \tilde{S}_1)(\tilde{c}_1 - \tilde{c}_2)}{\{\ln[(z_2 - d)/(z_1 - d)]\}^2} \quad (3.16)$$

The corresponding vertical turbulent contribution is

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

The specific revisions are shown in lines 542 to 544 of the revised manuscript.

(2) *There may be some confusion regarding the use of acronyms and abbreviations in the abstract. All terms must be defined at their first point of use in the abstract. They*

*should also be defined again at their first point of use in the main text. However, many authors prefer to avoid abbreviations in the abstract and conclusion all together, though this is down to author preference.*

**Response:** We have adopted the reviewer's preference to avoid technical abbreviations in the Abstract and Conclusions rather than defining and retaining them within these sections. We carefully reviewed both sections and removed abbreviations such as "UAV" and "EC." Depending on the context, these terms have been replaced with "unmanned aerial vehicle," "eddy covariance," "airborne observations," "airborne profiles," or another equivalent unabbreviated expression.

The corresponding line-specific changes are also described in our responses to Specific Comments 2 and 3.

**Specific comment**

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

• *Perhaps this should be in the past tense*

**Response:** Thank you for this comment. We have carefully rechecked the submitted manuscript and confirmed that the sentence already uses the past-tense form "was flown," rather than "is flown." Therefore, no revision was necessary for this sentence.

(2) *Line 31: "UAV"*

• *Please define this term.*

**Response:** Following the reviewer's General comments to avoid abbreviations in the abstract and conclusions, we have removed the abbreviation "UAV" from both sections rather than simply defining it at its first occurrence. All occurrences have been replaced with the full term "unmanned aerial vehicle". In the main text, "unmanned aerial vehicle (UAV)" is defined at its first occurrence, after which the abbreviation is retained.

Revised text: "A methodology for quantifying three-dimensional $CO_2$ emissions using an unmanned aerial vehicle was developed, evaluated, and applied to a forest ecosystem."

The specific revisions are shown in line 32 of the revised manuscript.

(3) *Line 42: "EC"*

• *Please define this term.*

**Response:** Following the reviewer's general suggestion to avoid abbreviations in the abstract and conclusions, we have removed the abbreviation "EC" from both sections rather than defining and retaining it. All occurrences have been replaced with "eddy covariance". In the main text, "eddy covariance (EC)" is defined at its first occurrence, after which the abbreviation is retained.

Revised text: "Validation against long-term $CO_2$ flux measurements from the permanently installed eddy covariance system shows that vertical $CO_2$ fluxes derived from the airborne observations agree well with the tower observations across seasons…"

The specific revisions are shown in line 43 of the revised manuscript.

(4) *Line 48: "pronounced"*

*• What does this mean? Can the level of diurnal variations be quantified? Perhaps it is better to omit this word, as it is quite strong.*

**Response:** To avoid overstating this result, we have removed "pronounced" from the sentence.

Revised text: "Measurements collected along the horizontal box-pattern flight paths further reveal diurnal variations in local canopy-air $CO_2$ mass transport…"

The specific revisions are shown in line 47 of the revised manuscript.

(5) *Line 115: "Horizontal fluxes are therefore commonly neglected or assumed to be negligible in EC flux measurements"*

*• I do not understand the point here.*

*• Earlier in this paragraph, it states that EC fluxes produce vertical fluxes. So, it is not possible to neglect horizontal fluxes if they cannot be measured in the first place.*

*• Consider rewording this.*

**Response:** Our intended point was that conventional single-tower eddy covariance measurements directly quantify the vertical turbulent $CO_2$ flux at a fixed location but do not resolve horizontal advective transport across the boundaries of a finite control volume. Therefore, horizontal advection is generally not included in local $CO_2$ budgets derived solely from eddy covariance observations, which implicitly assumes that its contribution is negligible. We have revised the text accordingly.

Revised text: "Conventional single-tower EC measurements quantify the vertical turbulent $CO_2$ flux at a fixed location but do not directly resolve horizontal advective transport across the boundaries of a finite control volume (Aubinet et al., 2002; Feigenwinter et al., 2004; Finnigan et al., 2003; Leuning et al., 2005). Consequently, the horizontal advective contribution is generally absent from local $CO_2$ budgets based solely on EC observations, which implicitly assumes that this contribution is negligible. This assumption may not hold under weakly turbulent or non-stationary conditions (Mahrt, 1998, 2010; Vickers and Mahrt, 1997)."

The specific revisions are shown in lines 111 to 118 of the revised manuscript.

(6) *Line 118: "In addition, although stationary towers can support measurements at multiple levels, conventional EC flux observations are typically obtained at one or a limited number of fixed heights."*

*• This sentence seems to directly contradict itself. It says that although EC measurements can be made at multiple levels, they can be obtained at a number of fixed heights, which is the same thing.*

*• I think the point being made here is that towers conventionally provide fluxes at discrete heights, while contentious measurements with height are difficult.*

*• But the UAV method presented in this work does not solve this, as UAV fluxes are only derived at fixed heights.*

**Response:** Our intention was not to suggest that the unmanned aerial vehicle method completely overcomes this limitation. Rather, we intended to describe the

observation geometry of conventional eddy covariance towers: they provide continuous time-series measurements, but generally at only one or a few discrete heights. We have revised this part of the paragraph accordingly. The advantages of the proposed method are described later in terms of flexible spatial sampling and the additional characterization of horizontal transport, rather than the continuous measurement of vertical fluxes.

Revised text: "In addition to not directly resolving horizontal advective transport, conventional eddy covariance systems generally provide continuous time series of vertical turbulent $CO_2$ fluxes at only one or a few fixed sensor heights. Even when several tower levels are instrumented, the observations remain vertically discrete and therefore do not provide a continuous vertical profile of $CO_2$ flux or directly resolve flux divergence throughout the lower atmosphere (Schmid, 2002)."

The specific revisions are shown in lines 118 to 124 of the revised manuscript.

(7) *Line 126: "accuracy"*

• *What sort of accuracy does this refer to? Perhaps this is spatial accuracy or mole fraction measurement accuracy.*

**Response:** Thank you for pointing out this ambiguity. Here, "accuracy" was intended to refer to the spatial resolution and near-surface sensitivity of satellite observations, rather than the accuracy of the $CO_2$ mole-fraction measurements themselves. We agree that the original wording was insufficiently specific and have revised the sentence to state the relevant observational limitations directly.

Revised text: "…but its limited sensitivity to near-surface vertical gradients and relatively coarse spatial resolution constrain its ability to resolve canopy-scale exchange processes"

The specific revisions are shown in lines 126 to 128 of the revised manuscript.

(8) *Line 201: "all of which satisfy the requirements for atmospheric wind and CO2 measurements in the lower boundary layer"*

• *This is not necessarily the case. It depends where sampling is conducted. Perhaps this resistance is adequate in this study but in very windy boundary layer conditions, this may not be sufficient wind resistance.*

**Response:** We have revised the text to limit the statement to the conditions of this study and to acknowledge this constraint.

Revised text: "Its maximum horizontal flight speed is 18 m $s^{-1}$, its maximum ascent rate is 4 m $s^{-1}$, and its rated maximum wind resistance is 14.4 m $s^{-1}$. These specifications were adequate for the conditions encountered during the present field campaign."

The specific revisions are shown in lines 207 to 208 of the revised manuscript.

(9) *Line 361: "emission"*

• *Should this be "flux" instead of "emission"? Emissions imply a net outward positive flux, while forest ecosystems can be net carbon dioxide sinks.*

• *The use of various terms for mass concentration seems to cause unnecessary over-*

*complication in this section. Some equations are given in terms of concentration and some use mole fraction. It would be better to use a consistent term in all equations.*
*• See other comments on this.*

**Response:** Thank you for this important comment. We agree that the meaning and sign convention of "emission" require further clarification in the context of a forest ecosystem. However, we respectfully retain the term "net $CO_2$ emission rate" because the primary quantity calculated using our control-volume mass-balance method, $E_C$, is not a flux density expressed per unit area. Instead, it is the spatially integrated net rate of $CO_2$ release or uptake associated with the UAV-defined control volume and is expressed in kg $h^{-1}$. The individual boundary fluxes are integrated to obtain this net emission rate.

In this study, "net $CO_2$ emission rate" is explicitly defined as a signed quantity. A positive value represents net $CO_2$ release, which may include $CO_2$ supplied by vegetation and soil respiration, whereas a negative value represents net $CO_2$ uptake, primarily associated with vegetation photosynthesis. Thus, the use of "emission" in this manuscript does not imply that the forest ecosystem is always a net $CO_2$ source; negative emission rates indicate that the ecosystem acts as a net $CO_2$ sink during the measurement period. These values represent the net result of the contributing source–sink and atmospheric transport processes and do not separately partition photosynthesis and respiration.

We have added this definition at the beginning of Sect. 3.2. We have also revised expressions such as "horizontal emission" and "vertical emission" to "the horizontal advective contribution to the net $CO_2$ emission rate" and "the vertical turbulent contribution to the net $CO_2$ emission rate," respectively. This distinguishes the individual transport components from the spatially integrated net emission rate.

Revised text: "3.2 UAV-based estimation of the net $CO_2$ emission rate

$CO_2$ emissions associated within the control volume defined by the virtual box were quantified using a mass-balance framework that integrates measurements obtained from box-pattern and profile-pattern UAV flights. Throughout this study, the term "net $CO_2$ emission rate" refers to a signed, control-volume-integrated mass-balance quantity expressed in (kg $h^{-1}$). Positive values represent net $CO_2$ release from the control volume and may include $CO_2$ supplied by vegetation and soil respiration, whereas negative values represent net $CO_2$ uptake, primarily associated with vegetation photosynthesis. Thus, a negative net emission rate indicates that the forest acts as a net $CO_2$ sink during the measurement period."

The specific revisions are shown in lines 367 to 376 of the revised manuscript.

Revised text: "3.2.1 Computation of the horizontal advective contribution to the net CO2 emission rate

The horizontal advective contribution to the net $CO_2$ emission rate was derived from box-pattern measurements by integrating the horizontal advective $CO_2$ flux across the four vertical walls of the virtual box. The integrated horizontal $CO_2$ emission rate can be written as

$$E_{C,H} = \oiint c(s,z)U_{\perp}(s,z)dsdz \quad (3.3)$$

where $E_{C,H}$ is the horizontal advective contribution to the net $CO_2$ emission rate…"

The specific revisions are shown in lines 441 to 448 of the revised manuscript.

Revised text: "3.2.2 Computation of the vertical turbulent contribution to the net CO2 emission rate

The vertical turbulent contribution to the net $CO_2$ emission rate…"

The specific revisions are shown in lines 474 to 476 of the revised manuscript.

The reviewer's second point concerning the inconsistent use of mole fraction and mass concentration has been addressed collectively in our response to the first point under General Comments.

(10) *Line 391: "mean components"*

• *Over how many data points and what time duration is this mean derived?*

**Response:** The mean wind components were calculated from the concurrent 10 Hz wind measurements collected by the eddy covariance flux tower over consecutive 30 min averaging intervals. Therefore, each complete averaging interval contained 18,000 raw observations for each wind component. The mean values were calculated using the valid observations within each interval after quality control. The turbulent fluctuations were then defined as the deviations of the instantaneous 10 Hz measurements from their corresponding 30 min means. We have added this information to Sect. 3.2 and clarified that these mean and fluctuating components were derived from the tower observations rather than from a running average of the UAV measurements.

Revised text: "Throughout this section, $c$ denotes the instantaneous $CO_2$ mass concentration (mg $m^{-3}$), calculated as: $c = M_R \chi_C \rho_{air}$, where $\chi_C$ is the measured $CO_2$ mole fraction (ppm), $\rho_{air}$ is the concurrently measured air density (kg $m^{-3}$), and $M_R$ is the ratio of the molar mass of $CO_2$ to that of air. With these units, the equation yields $c$ directly in mg $m^{-3}$. For the Reynolds decomposition of the concurrent 10 Hz tower observations, each variable $q \in \{u, v, w, c\}$ was decomposed over non-overlapping 30 min intervals as: $\bar{q} = \frac{1}{k}\sum_{i=1}^{k} q_i$,, and turbulent fluctuation: $q_i' = q_i - \bar{q}$, where $(k)$ is the number of valid observations and is nominally 18,000 for a complete interval."

The specific revisions are shown in lines 407 to 411 of the revised manuscript.

(11) *Line 393: "CO2 quantity"*

• *Quantity is not a good word. This should be defined as either a concentration or a mole fraction. Quantity could mean anything. In fact, upper-case C is defined nicely later on so it seems like it is defined twice. It would be better to define it nicely here instead.*

• *As far as I can see, there is no need to define a separate upper-case C later in the manuscript.*

• *It may be best to define a single lower-case c here (properly, as a concentration).*

• *See other comments on this.*

**Response:** As also described in our response to the first point under General Comments, we have now defined a single lowercase $c$ at its first occurrence in Sect. 3.2 as the instantaneous $CO_2$ mass concentration expressed in mg m$^{-3}$. It was calculated directly from the measured $CO_2$ mole fraction $\chi_C$, expressed in ppm, and the concurrently measured air density $\rho_{air}$, expressed in kg m$^{-3}$, as

$$c = M_R \chi_C \rho_{air}$$

where $M_R$ is the ratio of the molar mass of $CO_2$ to that of air. When these units are used, the $10^{-6}$ factor associated with ppm is numerically offset by the $10^6$ factor used to convert kilograms to milligrams. The equation therefore directly yields the $CO_2$ mass concentration in mg m$^{-3}$.

Revised text: "Throughout this section, $c$ denotes the instantaneous $CO_2$ mass concentration (mg m$^{-3}$), calculated as: $c = M_R \chi_C \rho_{air}$, where $\chi_C$ is the measured $CO_2$ mole fraction (ppm), $\rho_{air}$ is the concurrently measured air density (kg m$^{-3}$), and $M_R$ is the ratio of the molar mass of $CO_2$ to that of air. With these units, the equation yields $c$ directly in mg m$^{-3}$. For the Reynolds decomposition of the concurrent 10 Hz tower observations, each variable $q \in \{u, v, w, c\}$ was decomposed over non-overlapping 30 min intervals as: $\bar{q} = \frac{1}{k}\sum_{i=1}^{k} q_i$,, and turbulent fluctuation: $q_i' = q_i - \bar{q}$, where $(k)$ is the number of valid observations and is nominally 18,000 for a complete interval."

The specific revisions are shown in lines 403 to 411 of the revised manuscript.

We have removed the subsequent, separate definition of uppercase $C$ from Sect. 3.2.2. The lowercase $c$ is now used consistently for $CO_2$ mass concentration throughout Sect. 3.2 and in the associated equations. The profile-smoothed $CO_2$ mass concentration is correspondingly denoted by $\tilde{c}$. These revisions eliminate the previous duplication and ensure consistent terminology and notation throughout the section.

Revised text: "$F_v = -K_C \frac{\partial \tilde{c}}{\partial z}$"

The specific revisions are shown in line 503 of the revised manuscript.

"Using the finite-layer formulation employed in the gradient calculation, the wind-speed and $CO_2$ differences between $z_1$ and $z_2$ are expressed over the same logarithmic height interval. Substitution into Eq. (3.7) gives

$$F_v = \kappa^2 (1 - R_i)^{1/2} \frac{(\tilde{S}_2 - \tilde{S}_1)(\tilde{c}_1 - \tilde{c}_2)}{\{\ln[(z_2 - d)/(z_1 - d)]\}^2} \quad (3.16)$$

The corresponding vertical turbulent contribution is

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

The specific revisions are shown in lines 539 to 544 of the revised manuscript.

(12) *Line 395: "fluctuation"*

• *What is the meaning of this word here? What is the fluctuation with respect to? Is it a fluctuation compared to a running average? This word is not well defined here.*

**Response:** Here, the fluctuation refers to the deviation of each instantaneous 10 Hz tower observation from the temporal mean calculated over the corresponding non-overlapping 30 min averaging interval. It is therefore not calculated relative to a running

average. We have rewritten this sentence.

Revised text: "For the Reynolds decomposition of the concurrent 10 Hz tower observations, each variable $q \in \{u, v, w, c\}$ was decomposed over non-overlapping 30 min intervals as: $\bar{q} = \frac{1}{k}\sum_{i=1}^{k} q_i$, and turbulent fluctuation: $q_i' = q_i - \bar{q}$, where $(k)$ is the number of valid observations and is nominally 18,000 for a complete interval."

The specific revisions are shown in lines 407 to 411 of the revised manuscript.

(13) *Line 401: "turbulent fluctuation"*

• *It is important to explain how this turbulent fluctuation was derived from two-dimensional wind measurements. Was the average subtracted from a running mean?*

**Response:** We have clarified the derivation of the turbulent fluctuation in the preceding paragraph. The wind data were obtained from the three-dimensional ultrasonic anemometer on the flux tower rather than from two-dimensional wind measurements. For each non-overlapping 30 min interval, the mean of each wind component was subtracted from its instantaneous 10 Hz observations. Thus, the fluctuation was defined relative to the corresponding 30 min mean, rather than a running mean. At Line 401, $|u'|$ specifically denotes the absolute fluctuation of the east-west wind component, and its 95th percentile was calculated from the valid fluctuation values obtained after this decomposition.

Revised text: "For the horizontal component, the mean east-west wind component, $|\bar{u}|$, was typically 2-3 m $s^{-1}$, whereas the 95th percentile of $|u'|$, calculated from the instantaneous 10 Hz deviations from the corresponding 30 min means defined above, was less than 0.1 m $s^{-1}$."

The specific revisions are shown in lines 417 to 418 of the revised manuscript.

(14) *Line 430: "emission"*

• *Flux may be a better word. I would advise the authors to consider all instances of the word "emission" in this manuscript.*

**Response:** As explained in our response to Specific Comment 9, the primary quantity calculated by our method is an integrated emission rate rather than a flux density. To clarify this distinction, we have replaced "horizontal $CO_2$ emission" with "the horizontal advective contribution to the net $CO_2$ emission rate." Similarly, "vertical $CO_2$ emission component" has been replaced with "the vertical turbulent contribution to the net $CO_2$ emission rate." We now reserve "flux" for quantities expressed per unit area, such as the vertical $CO_2$ flux $F_v$, and use "net $CO_2$ emission rate" only for the signed, control-volume-integrated quantity $E_C$, for which positive and negative values represent net release and net uptake, respectively.

Revised text: "The vertical turbulent contribution to the net $CO_2$ emission rate was obtained by integrating the vertical $CO_2$ flux over the horizontal area enclosed by the box pattern."

The specific revisions are shown in line 494 of the revised manuscript.

(15) *Line 474: "The CO2 mass concentration C"*

*• Is this upper-case C the same as the lower-case c in the previous subsections? It would be better to define it once at the start of subsection 3.2, as it seems to be the same thing.*
*• See other comments regarding this.*

**Response:** Yes, the uppercase $C$ and the lowercase $c$ in the original manuscript referred to the same physical quantity, namely $CO_2$ mass concentration. We apologize for this inconsistent and duplicate notation. As suggested, and as described in our Specific Comment 11, we now define the lowercase $c$ only once at the beginning of Sect. 3.2. The separate definition of uppercase $C$ has been removed. Throughout Sect. 3.2.2 and its associated equations, $C$ and $\tilde{C}$ have been replaced consistently with $c$ and $\tilde{c}$, respectively. The symbol $\tilde{c}$ now specifically denotes the seven-point moving-average-smoothed vertical profile of $c$.

(16) *Line 509: "$\tilde{S}$ is the smoothed horizontal wind-speed magnitude; $\tilde{T}$ is the smoothed air temperature"*
*• Do these terms need to be defined again? They are already defined earlier in this subsection.*

**Response:** Thank you for this comment. We have removed these repeated definitions and retained only the explanations of the quantities introduced in this part of the subsection.

(17) *Line 540: "The horizontal component EC,H is calculated from the box-pattern observations along the lateral boundaries of each UAV-defined control volume."*
*• This sentence and the next do not seem to belong in this subsection, which is dedicated to the vertical turbulent flux component.*

**Response:** We have removed both sentences. The concluding paragraph of Sect. 3.2.2 now focuses exclusively on the calculation and evaluation of the vertical turbulent $CO_2$ flux and its contribution to the net $CO_2$ emission rate.

(18) *Line 588: "the uncertainty propagation method"*
*• Which uncertainty propagation method? There is no standard method. Does this mean that that the uncertainties were combined in quadrature?*

**Response:** Yes, the two uncertainty components were combined in quadrature. We have replaced it with an explicit description and equation.

Revised text: "Assuming that the residual wind-correction uncertainty and the instrument-related uncertainty were independent relative standard uncertainties, they were combined in quadrature and the final contribution of $\delta_V$ was estimated to be 28.5%."

The specific revisions are shown in lines 592 to 594 of the revised manuscript.

(19) *Line 666: "turbulent fluctuations"*
*• How is the turbulence derived? Is this the difference from a running average?*

**Response:** As explained in our response to Specific Comment 12 and 13, the turbulent fluctuations were derived by applying Reynolds decomposition to the concurrent 10 Hz tower observations over non-overlapping 30 min intervals. After

coordinate rotation, each fluctuation was calculated by subtracting the corresponding 30 min mean from the instantaneous observation; Therefore, the fluctuations were not calculated relative to a running mean. We have revised the text in Sect. 3.4 to make this procedure explicit while avoiding repetition of the detailed explanation already provided in Sect. 3.2.

Revised text: "where the primes denote the turbulent fluctuations defined in Sect. 3.2, which were calculated relative to the corresponding non-overlapping 30 min means."

The specific revisions are shown in lines 673 to 674 of the revised manuscript.

(20) *Line 887: "Net CO2 emission results"*

*• The title of this subsection should be reworded. This does not provide all net emission flux results, but only flux results from a single UAV flight. The plural "results" should certainly not be used for a single example.*

*• This is a single example, demonstrating the nature of fluxes from a single flight. This is certainly useful, but it is not clear here what this section is about. Was this eluded to earlier in the manuscript?*

*• I would recommend adding a few sentences at this start of this subsection describing what this is about. It is not entirely clear why a single UAV flight is being evaluated here.*

*• I would like to reiterate that all of this work is useful and should not be removed. It just needs to be clearer why this subsection is here, with a better subsection title and better motivation leading up to this in the introduction and methods sections.*

*• Perhaps this subsection can be swapped with the following subsection. This subsection is a specific example with a fixed box size. But this is just a suggestion for the authors to decide.*

**Response:** Thank you for this constructive comment. We have changed the subsection title to "4.3 Illustration of net $CO_2$ emission estimation for a representative UAV flight" The specific revisions are shown in line 894 of the revised manuscript.

We have also added an introductory paragraph explaining that this case is presented to demonstrate how the box-pattern and profile-pattern measurements are combined to quantify the horizontal and vertical contributions to the net $CO_2$ emission rate for an individual flight. The case was selected because it contained complete valid measurements and exhibited clear spatial $CO_2$ gradients under early-morning conditions, making it suitable for illustrating the influence of horizontal transport on the local mass balance. We now explicitly state that this example is intended as a process-level demonstration rather than a statistical summary of the complete dataset.

Revised text: "To illustrate the application of the developed box-profile framework at the individual-flight level, this subsection examines a representative early morning flight conducted on 8 August 2024 within the 100×100×50 $m^3$ control volume. Complete paired box-pattern and profile-pattern measurements were available for this flight, allowing the horizontal advective and vertical turbulent contributions to be combined to determine the local net $CO_2$ emission rate. This analysis is intended as a process-level illustration rather than a statistical summary of the complete dataset; the

spatial-scale analysis involving multiple observations is presented in Sect. 4.4."

The specific revisions are shown in lines 896 to 903 of the revised manuscript.

In addition, we have added brief descriptions in the Introduction section to introduce the purpose of this representative case before it is presented in Sect. 4.3. The broader evaluation involving multiple observations and different control volume sizes remains in Sect. 4.4.

Added text to the Introduction: "The analysis first evaluates the UAV-derived vertical fluxes against the flux tower measurements, then uses a representative single-flight case to illustrate how the horizontal and vertical transport contributions determine the local net $CO_2$ emission rate, and finally examines the spatial-scale dependence of the estimates using control volumes of different sizes."

The specific revisions are shown in lines 185 to 189 of the revised manuscript.

Finally, we would like to clarify the rationale underlying the organization of Sect. 4. Sections 4.1 and 4.2 first present the instrument comparison and flux-validation analyses. Building on the good agreement obtained from these comparisons, Sect. 4.3 provides a visual illustration of a representative net $CO_2$ emission rate estimate from a single UAV flight. Section 4.4 then extends the analysis by quantifying the net $CO_2$ emission rates for three control volume sizes and examining their spatial heterogeneity. We therefore retain the current order of Sects. 4.3 and 4.4.

(21) *Line 935: "Spatial heterogeneity of net CO2 emission"*

• *This subsection is excellent.*

**Response:** We thank the reviewer for this positive assessment and are pleased that the spatial heterogeneity analysis was found to be valuable. No revision was required in response to this comment.

(22) *Line 1011: "All emission estimates are expressed in kg h-1"*

• *Is this necessary?*

**Response:** Thanks. We have deleted this sentence.