Dear Editor and Reviewer,

We would like to sincerely thank the editor and reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions. These comments have been very helpful in improving the clarity, rigor, and overall quality of the manuscript.

We hereby submit the second revised version of our manuscript entitled "UAV-based method for measuring CO_2 emissions in forest ecosystems". In this revision, we have carefully considered all comments and revised the manuscript accordingly. In particular, we have clarified the purpose and interpretation of the horizontal flux analysis, improved the definitions and consistency of key terms and symbols, clarified the data sources and calculation procedures for the horizontal and vertical flux components, and substantially revised the uncertainty analysis to include both measurement-related and methodological uncertainties.

All revisions have been incorporated into the manuscript, and the modified text is highlighted in blue for clarity. Below, we provide a detailed point-by-point response to the reviewer's comments.

Sincerely yours,

Shao-Meng Li, Professor

The following is a point-to-point response to the two reviewers' comments.

General comments

(1) *I struggle to understand the point of the horizontal flux component of this work. The introduction states that "strong spatial heterogeneity" and "non-negligible horizontal transport processes" are responsible for introducing "substantial uncertainties into quantitative estimates of ecosystem-atmosphere" carbon dioxide exchanges. It then goes on to state that resolving horizontal transport is therefore required. Why? And how does this specific work help to achieve this. As far as I can see, this work shows variability in fluxes between different sized horizontal boxes above the tree canopy. What is the use of this analysis? This work simply confirms that forests are spatially heterogeneous. How does this horizontal analysis help in the overall aim of quantifying carbon dioxide fluxes between forest ecosystems and the atmosphere? This really must be emphasised and made totally clear in this manuscript.*

Response: We understand the reviewer's concern and agree that the vertical CO_2 flux between the forest canopy and the atmosphere is the primary quantity for quantifying ecosystem–atmosphere carbon exchange. We also agree that the horizontal fluxes calculated in this study should not be interpreted as net lateral CO_2 exchange between the entire forest ecosystem and the outside atmosphere. The UAV-defined boxes represent finite local control volumes above the canopy, not the perimeter boundary of the whole forest.

The purpose of the horizontal flux analysis is therefore not simply to confirm that forests are spatially heterogeneous, nor to estimate whole-forest horizontal export or import of CO_2. Rather, it is to diagnose whether local advective convergence or divergence is significant within the air volume in which vertical exchange is being interpreted. This is important because vertical flux measurements, including those from EC towers, are commonly interpreted under assumptions of horizontal homogeneity and negligible advection. When strong lateral CO_2 gradients and horizontal transport exist, the CO_2 concentration and vertical flux measured at one location may be influenced by air transported from adjacent areas. In such cases, vertical flux alone may not fully describe the local CO_2 mass balance above the canopy.

Thus, the horizontal analysis helps to identify the conditions under which vertical flux estimates are likely to be representative, and the conditions under which they may be affected by local advection and spatial heterogeneity. In our results, horizontal transport was small during well-mixed summer midday conditions, when vertical uptake dominated and fluxes were relatively insensitive to box size. In contrast, horizontal transport became comparable to or larger than the vertical turbulent component during weak-turbulence autumn morning conditions, indicating that the local CO_2 balance was strongly affected by advective redistribution. This distinction is useful because it shows when the assumption of negligible horizontal transport is reasonable and when it is not.

We have revised the Introduction and Conclusions to make this point clearer. Specifically, we now state that the horizontal flux component is used to diagnose local advective convergence/divergence and to evaluate the spatial representativeness of vertical flux measurements, rather than to represent net CO_2 exchange between the entire forest and the surrounding atmosphere.

The text added to the Introduction is: "Although vertical CO_2 flux is the primary quantity used to evaluate forest-atmosphere carbon exchange, horizontal advection can influence the local CO_2 mass balance above the canopy and affect the interpretation of vertical flux measurements under spatially heterogeneous or weakly mixed conditions. Therefore, measurements that characterize lateral CO_2 transport across finite control-volume boundaries are useful for diagnosing when the assumption of horizontal homogeneity is valid and when vertical flux measurements may be influenced by local advective convergence or divergence."

The specific revisions are shown in lines 86 to 93 of the revised manuscript.

The text added to the Conclusions is: "The horizontal flux analysis should therefore be interpreted as a diagnostic of local advective redistribution and spatial representativeness above the canopy, not as a measure of whole-forest lateral CO_2 export or import."

The specific revisions are shown in lines 1060 to 1062 of the revised manuscript.

(2) *In a formal scientific publication, it is important to clearly define any terms when they are first introduced in the manuscript. Please use consistent terminology throughout the manuscript and define any terms at their first point of use. This is the responsibility of the authors and not the responsibility of the reviewers, the editors or*

the copy-editing/typesetting staff. Even if a term may seem obvious (for example, t), this could mean temperature, time, thickness, torque or tonnes, as some examples. Or it could mean anything else, depending on how it is defined, especially in environmental science journals where conventions are less entrenched.

Response: In response to this comment, we carefully checked the entire manuscript and revised the text to ensure that key terms, variables, and symbols are defined when they first appear. In particular, we clarified the definitions of the coordinates (x), (y), and (z), the time variable (t), the CO_2 mole fraction and mass concentration, the horizontal and vertical flux components, the UAV-defined control volume, and the uncertainty terms used in Section 4.5.

(3) *How is EC,VT calculated for the different tests? The UAV conducts both vertical transects as well as box-type transects. Is the box-type data used for vertical fluxes when deriving horizontal components for different sized boxes or is the vertical transect data used? Please can this be clear in the manuscript. The methods section it states that "z1 and z2 correspond to 5 m below and 5 m above the target height, respectively, during the UAV ascent" when calculating EC,VT. From this, I assumed that the single vertical UAV transect was used to derive a single EC,VT value from each flight whilst separate corresponding EC,H values were derived from box sampling. But it looks like different EC,VT values are used, as the median EC,VT values given in Table 5 do not scale linearly with box area. What is the chosen "target height" (defined in section 2.3) used to derive the EC,VT values given in section 4.3 and why? I really think this could be made simpler to follow for a reader. I am expending a lot of effort in trying to ascertain which data is used in which way, with it still not being clear to me.*

Response: We agree that the previous manuscript did not explain clearly enough which UAV data were used to calculate the horizontal and vertical flux components, especially for the different box sizes. We have revised the manuscript to make the data flow and calculation procedure clearer.

We clarify that the box-pattern measurements were used to calculate only the horizontal transport contribution, $E_{C,H}$, by integrating the horizontal advective flux across the lateral boundaries of each UAV-defined control volume. The box-pattern data were not used to derive the vertical turbulent contribution, $E_{C,VT}$. Instead, $E_{C,VT}$ was calculated from the paired vertical profile measurements collected during the corresponding UAV flight, using the flux-gradient method.

For the vertical flux comparison with the EC tower and for the vertical turbulent contribution used in the box-based mass-balance calculation, the target height was approximately 31 m. This value corresponds to the midpoint between (z_1 = 26) m and (z_2 = 36) m, which were sampled during the UAV vertical ascent. This target height was chosen because it corresponds to the measurement height of the EC system on the nearby flux tower, allowing the UAV-derived vertical flux to be directly compared with the tower-derived vertical flux. The flux-gradient estimate therefore represents the layer-averaged vertical exchange over the 26-36 m height interval and is assigned to the midpoint height.

For each UAV flight, the horizontal and vertical components were therefore

derived from different but paired flight patterns: $E_{C,H}$ was obtained from the box-pattern boundary observations, whereas $E_{C,VT}$ was obtained from the corresponding vertical profile. We have revised the Methods and Results sections to state this explicitly. We also rechecked the description of Table 5 and clarified that the reported $E_{C,VT}$ values are derived from the vertical profile calculations for the corresponding UAV-defined control volumes, rather than from box-pattern data or from an unexplained vertical-flux calculation based on the box walls.

These revisions are intended to make the calculation pathway simpler to follow: box-pattern data are used for lateral transport, vertical profile data are used for vertical turbulent exchange, and the two components are then combined within the mass-balance framework.

The text added to the Section 3.2.2 is: "For each UAV flight, c was calculated from the vertical profile measurements rather than from the box-pattern measurements. The CO_2 gradient between (z_1 = 26) m and (z_2 = 36) m was used to estimate the vertical flux, and the resulting flux was assigned to the midpoint height of approximately 31 m. This height was selected because it corresponds to the EC flux measurement height of the nearby flux tower. In contrast, $E_{C,H}$ was calculated from the box-pattern observations along the lateral boundaries of each UAV-defined control volume."

The specific revisions are shown in lines 521 to 527 of the revised manuscript.

The text added to the Section 4.4 is: "In this analysis, $E_{C,H}$ was calculated separately for each box size using the corresponding box-pattern boundary observations, whereas $E_{C,VT}$ was derived from the paired vertical profile measurements collected during the same UAV flight."

The specific revisions are shown in lines 826 to 828 of the revised manuscript.

(4) *Serious work in required on the uncertainty explanation. There seems to be no analysis of methodological errors, associated with the flux quantification method itself, when deriving a so-called "total uncertainty". The authors themselves partially acknowledge this at the end of subsection 4.4.4. Instrumental, wind and thermodynamic variability are treated as the only sources of error, assuming the method itself to be free from error. Then a description of the way in which these errors are quantified is totally lacking in the manuscript. It simply states that "propagating these errors through the flux equations" allows a fractional error to be obtained. This is not adequate. In addition, the instrumental error includes errors in wind measurements, despite there being a separate term for wind error. This seems illogical and lacks rationale in the manuscript. I raised this issue in the previous review and the authors claim to incorporate all wind measurement uncertainty into the wind term. However, it appears that they have failed to remove the wind component from the instrumental term, resulting in it being counted twice.*

Response: We agree that the previous uncertainty explanation was not sufficiently detailed and that the original formulation did not adequately separate measurement-related uncertainty from methodological uncertainty. We also agree that including wind-related errors in both the instrumental uncertainty term and the wind uncertainty

term could lead to double counting.

To address this issue, we have substantially rewritten Section 4.5. First, the original instrumental uncertainty term, (δ_M), has been removed and replaced by a CO_2 analyzer uncertainty term, δ_{CO_2}, which includes only the uncertainty associated with CO_2 mole fraction measurements. All wind-related uncertainties, including ultrasonic anemometer accuracy, wind-speed correction uncertainty, wind-direction uncertainty, UAV attitude correction, and platform-induced flow distortion, are now included only in the wind uncertainty term, δ_V. This avoids double counting of wind measurement errors.

Second, we added an explicit discussion of methodological uncertainties associated with the UAV-based flux quantification framework itself. For the horizontal transport term, $E_{C,H}$, methodological uncertainty arises mainly from discrete sampling along the box-pattern flight path and the spatial reconstruction of lateral boundary fluxes. This uncertainty is now represented by $\delta_{spatial}$. We evaluated it by recalculating $E_{C,H}$ using alternative treatments of the discrete box-pattern observations, including linear interpolation, nearest-neighbor interpolation, and segment averaging. The resulting differences were used to estimate spatial reconstruction uncertainty, and a conservative value of $\delta_{spatial}$ = 8%) was adopted.

For the vertical turbulent contribution term, $E_{C,VT}$, methodological uncertainty is mainly associated with the flux-gradient approach. This uncertainty is now represented by $\delta_{gradient}$. Because the turbulent exchange coefficient used in the flux-gradient method depends on wind-related variables, including three-dimensional wind components and friction velocity, we propagated the wind-related uncertainty into the $E_{C,VT}$ calculation. Based on three representative cases, the resulting uncertainties were 3%, 2%, and 5%, respectively. Therefore, a conservative value of $\delta_{gradient}$ = 5%) was adopted.

Finally, the total uncertainty is now calculated by combining the CO_2 analyzer uncertainty, wind measurement uncertainty, and methodological uncertainties using quadrature addition. The revised total relative uncertainty is approximately 30%. We have revised Section 4.5 accordingly to provide the rationale, calculation procedure, and uncertainty components more clearly.

Revised text: "The uncertainty of the UAV-derived CO_2 emission estimates was evaluated by considering both measurement-related uncertainties and methodological uncertainties associated with the UAV-based three-dimensional flux quantification framework. The net CO_2 emission, E_C, was calculated from the horizontal transport contribution, $E_{C,H}$, and the vertical turbulent contribution, $E_{C,VT}$. Therefore, uncertainty was assessed for the input variables and calculation procedures involved in both terms.

The measurement-related uncertainty was divided into three components: CO_2 analyzer uncertainty (δ_{CO_2}) and wind measurement uncertainty (δ_V). These components were combined in quadrature to obtain the measurement-propagated uncertainty:

$$\delta_{meas}^2 = \delta_{CO_2}^2 + \delta_V^2 \quad (4.2)$$

Here, δ_{CO_2} represents the uncertainty associated with the measured CO_2 mole fraction,

including analyzer precision, calibration uncertainty, and short-term measurement noise. Wind-related uncertainty was included in δ_V, which includes uncertainty arising from the ultrasonic anemometer measurements, and the wind-correction procedure used to correct for these effects.

4.5.1 CO_2 analyzer uncertainty

The CO_2 analyzer uncertainty was estimated from the performance of the MIRA CO_2 analyzer and the ground-based intercomparison with the LI-7500 analyzer. The MIRA analyzer has an accuracy better than 0.2 ppm, whereas the CO_2 variations resolved during UAV sampling frequently exceeded several to tens of ppm. Therefore, the relative uncertainty associated with the CO_2 mole fraction measurement was small compared with the observed CO_2 gradients used in the flux calculations. In addition, the analyses shown in Figs. 4 and 5 indicate that the error caused by the MIRA CO_2 analyzer is almost negligible. Therefore, the contribution of δ_{CO_2} was conservatively set to 1%.

4.5.2 Wind measurement uncertainty

Wind measurement uncertainty was treated as a separate uncertainty component because wind speed and wind direction directly affect the horizontal transport term, and the turbulent exchange parameters used in the vertical flux calculation. For the uncertainty introduced by the wind-speed correction, based on the validation experiment reported by Yang et al. (2025), the corrected UAV wind speed showed a root mean square relative error of 0.28 compared with the meteorological tower reference measurements. Therefore, a conservative relative uncertainty of 28% was assigned to the residual wind-correction uncertainty. Additionally, the ultrasonic anemometer used on the UAV has a wind speed accuracy of ±0.2 m s^{-1} and a wind direction accuracy of ±1°. For typical flight-level wind speeds of 4-6 m s^{-1}, this corresponds to a relative error of about 5% in the horizontal wind components. Considering the combined effects of these two factors, the final contribution of δ_V was estimated to be 28.5% using the uncertainty propagation method.

4.5.3 Methodological uncertainty

In addition to measurement-related uncertainty, the UAV-based flux estimates are also affected by methodological uncertainty associated with the flux quantification framework itself.

For the horizontal transport term, $E_{C,H}$, methodological uncertainty arises mainly from discrete sampling along the box-pattern flight path, spatial reconstruction of lateral boundary fluxes. The resulting uncertainty is collectively referred to as $\delta_{spatial}$. Because the UAV samples the control-volume boundaries along discrete trajectories rather than continuously measuring the entire boundary surface, the reconstructed lateral flux depends on the interpolation or averaging method used to integrate the boundary observations. To evaluate spatial reconstruction uncertainty ($\delta_{spatial}$), $E_{C,H}$ was recalculated using alternative treatments of the discrete box-pattern observations, including linear interpolation (this study), nearest-neighbor, and segment averaging. The spread among the resulting $E_{C,H}$ estimates was used to quantify the uncertainty associated with boundary discretization and spatial reconstruction. Three representative cases from different seasons (spring morning: 12 May 2024; summer noon: 20 August

2023; and autumn noon: 3 December 2024) were selected for the calculation. Finally, the uncertainties in E_C calculated using the different methods were 6% (nearest-neighbor) and 8% (segment averaging), respectively. Therefore, this study conservatively adopted $\delta_{spatial}$=8% to represent the uncertainty caused by spatial reconstruction.

For the vertical turbulent contribution term, $E_{C,VT}$, the methodological uncertainty was mainly associated with the flux-gradient approach. Because the CO_2 analyzer uncertainty was small, the uncertainty in $E_{C,VT}$ was assumed to be dominated by uncertainty in the turbulent exchange coefficient, which was estimated from wind-related variables, including the three-dimensional wind components and friction velocity. Therefore, the flux-gradient uncertainty ($\delta_{gradient}$) was evaluated based on the wind-speed uncertainty. Based on the wind-correction validation and uncertainty propagation described above, the wind-related uncertainty was estimated to be 28.5%, which was used as a conservative uncertainty estimate for the turbulent exchange coefficient and propagated into the $E_{C,VT}$ calculation. The same three representative cases used for the uncertainty analysis of $E_{C,H}$ were also used for $E_{C,VT}$. The resulting uncertainties were 3%, 2%, and 5%, respectively. These values were relatively small because the friction velocity and turbulent exchange coefficient were calculated using temporal gradient interpolation, which partly smoothed random wind-speed errors and reduced their influence on the final $E_{C,VT}$ estimates. Therefore, this study conservatively adopted $\delta_{gradient}$=5% to represent the uncertainty associated with the flux-gradient methodology.

The combined uncertainty was therefore expressed as:

$$\delta^2_{combined} = \delta^2_{CO_2} + \delta^2_V + \delta^2_{spatial} + \delta^2_{gradient} \quad (4.3)$$

where $\delta_{spatial}$ represents the uncertainty associated with spatial reconstruction of lateral boundary fluxes, $\delta_{gradient}$ represents uncertainty associated with the vertical flux-gradient calculation.

4.5.4 Total estimated uncertainties

By combining the uncertainties components, including CO_2 analyzer uncertainty (δ_{CO_2}), wind measurement uncertainty (δ_V), and methodological uncertainty ($\delta_{spatial}$ and $\delta_{gradient}$), the total relative uncertainty of the UAV-derived CO_2 emission rates can be obtained through quadrature addition. Finally, the calculated total uncertainty was 30%."

The specific revisions are shown in lines 939 to 1026 of the revised manuscript.

Specific comment

(1) *Line 40: "evaluated against a collocated eddy-covariance (EC) flux tower"*

- *Consider replacing this with "evaluated against fluxes derived using a collocated eddy-covariance (EC) flux tower". It is not the EC tower itself that is compared but fluxes from the EC tower.*
- *It is not clear how a tower can be collocated with a UAV (i.e. in the same place). Maybe "nearby" is a better word than "collocated".*

Response: We have revised the sentence to specify that the UAV-derived fluxes were evaluated against fluxes derived from the EC measurements. We also replaced "collocated" with "nearby," because the UAV profile measurements and the EC system were located at two separate sites approximately 150–160 m apart.

Revised text: "The method was applied at a subtropical plantation forest and evaluated against fluxes derived using a nearby eddy-covariance (EC) flux tower."

The specific revisions are shown in line 41 of the revised manuscript.

(2) *Line 41: "Validation against a long-term flux tower"*

- *Again, it is not validation against a tower but validation against fluxes from a tower.*
- *Also it is not clear what a long-term flux tower is. I think the authors mean a permanently installed tower or a tower with a long-term installation.*

Response: We agree that the validation was performed against the flux measurements rather than against the tower itself. We also agree that the phrase "long-term flux tower" was ambiguous. Our intention was to refer to the long-term CO_2 flux observations obtained from the permanently installed eddy-covariance system at the site. We have revised the sentence accordingly.

Revised text: "Validation against long-term CO_2 flux measurements from a nearby, permanently installed eddy-covariance system shows that vertical CO_2 fluxes derived using the gradient method agree well with the EC observations across seasons, with a correlation coefficient of 0.9."

The specific revisions are shown in lines 42 to 43 of the revised manuscript.

(3) *Line 42: "gradient method"*

- *What is a gradient method? There is no information about any gradient method in the abstract up until this point.*

Response: We agree that the term "gradient method" was introduced without sufficient explanation in the abstract. To improve clarity, we have revised the sentence to briefly define the method as an approach that estimates vertical CO_2 fluxes from the measured vertical CO_2 concentration gradient together with a turbulence-based exchange coefficient.

Revised text: "Validation against long-term CO_2 flux measurements from a nearby, permanently installed eddy-covariance system shows that vertical CO_2 fluxes estimated from measured vertical CO_2 concentration gradients and a turbulence-based exchange coefficient (gradient method) agree well with the EC observations across seasons, with a correlation coefficient of 0.9."

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

(4) *Line 43: "correlation coefficient r of 0.9"*

- *How many individual flux estimates does this correspond to and over which time period (i.e. how many months and years).*

Response: We agree that the sample size and observation period should be stated explicitly. The reported correlation coefficient was calculated from 167 paired UAV- and EC-derived vertical CO_2 flux estimates collected between May 2023 and December

2024, covering a 20-month period across two calendar years. We have added this information to the abstract.

Revised text: "Validation against long-term CO_2 flux measurements from a nearby, permanently installed eddy-covariance system shows that vertical CO_2 fluxes estimated from measured vertical CO_2 concentration gradients and a turbulence-based exchange coefficient (gradient method) agree well with EC observations across seasons, with a correlation coefficient r of 0.9 (Based on 167 paired flux estimates collected between May 2023 and December 2024)."

The specific revisions are shown in lines 46 to 47 of the revised manuscript.

(5) *Line 44: "Horizontal measurements"*

• *What are horizontal measurements? All measurements have a horizontal and a vertical component. Does this mean measurements using horizontal profiles?*

Response: We thank the reviewer for pointing out this ambiguity. We agree that the phrase "horizontal measurements" is imprecise. Here, we intended to refer specifically to measurements collected along the closed horizontal box-pattern flight paths at multiple altitudes. We have revised the wording accordingly.

Revised text: "Measurements collected along the horizontal box-pattern flight paths further reveal pronounced diurnal variations in local canopy-air CO_2 mass transport: lateral advection dominates in the early morning, whereas vertical uptake prevails under well-mixed midday conditions."

The specific revisions are shown in lines 47 to 50 of the revised manuscript.

(6) *Line 47: "multi-scale grid boxes"*

• *Perhaps state that these are grid boxes in the horizontal plane (if I understand correctly). The vertical extent of each grid box remains the same.*

Response: We agree that the original phrase "multi-scale grid boxes" did not make clear that the control volumes differed only in their horizontal dimensions, while their vertical extent remained fixed. We have revised the text to clarify this point.

Revised text: "Sensitivity analysis of emission intensities across control volumes with different horizontal dimensions (50 × 50, 100 × 100, and 150 × 150 m^2) and a constant vertical extent of 50 m revealed stronger scale dependence during autumn mornings, indicating significant spatial heterogeneity in CO_2 emissions."

The specific revisions are shown in lines 51 to 52 of the revised manuscript.

(7) *Line 53: "complex"*

• *What is a complex forest?*

Response: We agree that "complex forest" is too vague and could be interpreted as referring to a specific forest type. Our intention was to describe forests with heterogeneous canopy structure, spatially variable source–sink distributions, and, in some cases, complex terrain. We have therefore replaced the term with more specific wording.

Revised text: "Overall, this UAV approach provides a flexible and reliable method for analyzing near-surface three-dimensional CO_2 transport over structurally

heterogeneous forests and complex terrain, helping to overcome the limited spatial coverage of traditional flux towers and remote sensing."

The specific revisions are shown in lines 57 to 58 of the revised manuscript.

(8) *Line 60: "however"*

• *There is no need for this word. This statement is not in contrast to the opening statement.*

Response: We agree that "however" is unnecessary because the sentence does not express a contrast with the preceding statement. We have therefore removed this word.

Revised text: "The atmospheric CO_2 budget is strongly influenced by biospheric carbon cycling."

The specific revisions are shown in lines 65 to 66 of the revised manuscript.

(9) *Line 72: "satellite-based remote sensing"*

• *I am a bit confused with what it trying to be said here. A satellite is a measurement platform. Satellite based remove sensing is a type of measurement method. I would recommend simply replacing this with the word "satellites" to be consistent with the start of this list.*

Response: We agree that "satellite-based remote sensing" refers to a measurement method, whereas the other items in the list refer to observational platforms. To improve parallel structure and consistency, we have replaced it with "satellites."

Revised text: "However, despite decades of carbon-cycle research using a range of observational platforms, including stationary towers, satellites, and manned aircraft (Baldocchi, 2003; Gioli et al., 2004; Jung et al., 2020)"

The specific revisions are shown in line 76 of the revised manuscript.

(10) *Line 72: "measurements"*

• *Remove this word. A measurement is not a platform.*

Response: We thank the reviewer for pointing this out. We have removed the word.

(11) *Line 73: "most existing methods"*

• *Most methods of what? Perhaps replace this with "most existing flux quantification methods".*

Response: We agree that "most existing methods" is too vague. We have therefore revised the phrase to "commonly applied flux quantification methods" to clarify that we are referring specifically to methods used to quantify ecosystem–atmosphere CO_2 exchange.

Revised text: "However, despite decades of carbon-cycle research using a range of observational platforms, including stationary towers, satellites, and manned aircraft (Baldocchi, 2003; Gioli et al., 2004; Jung et al., 2020), commonly applied flux quantification methods often resolve only selected components of three-dimensional CO_2 transport."

The specific revisions are shown in lines 77 to 78 of the revised manuscript.

(12) *Line 74: "inherently confined to either vertical or horizontal dimensions"*

- *I am totally lost here. Is this referring to measurement methods or sampling platforms? If this is referring to sampling platforms, I disagree. An aircraft can fly in three dimensions. Conversely, a stationary tower can be zero-dimensional (with no vertical or horizontal component), as they often measure at a single point (although some can also sample at multiple heights providing a vertical dimension).*
- *I hope there can be consistency on this point: a sampling platform is different to a measurement method. A sampling platform can be a satellite, an aircraft or a tower, for example. A measurement method can be Eddy covariance, Gaussian plume inversion or a Bayesian inversion (for example). Gaussian plume modelling is a method that can be applied to sampling from multiple platforms (for example, car sampling or UAV sampling).*

Response: We thank the reviewer for this important conceptual clarification. Our intended point was not that the platforms themselves are dimensionally constrained, but that many commonly used flux quantification methods explicitly resolve only part of the three-dimensional transport. For example, eddy covariance primarily quantifies vertical turbulent exchange, whereas aircraft-based mass-balance methods commonly focus on horizontal advective transport through control-volume boundaries. We have therefore rewritten this passage to distinguish clearly between sampling platforms and quantification methods.

Revised text: "However, despite decades of carbon-cycle research using a range of observational platforms, including stationary towers, satellites, and manned aircraft (Baldocchi, 2003; Gioli et al., 2004; Jung et al., 2020), commonly applied flux quantification methods often resolve only selected components of three-dimensional CO_2 transport. For example, eddy-covariance methods primarily quantify vertical turbulent exchange, whereas aircraft-based mass-balance approaches commonly emphasize horizontal advective transport. Consequently, simultaneous quantification of both horizontal and vertical CO_2 transport remains challenging (Leuning et al., 2008)."

The specific revisions are shown in lines 75 to 82 of the revised manuscript.

(13) *Line 80: "approaches"*

- *Please specify which approaches. Is this referring to flux quantification approaches?*

Response: We agree that the term "approaches" was too vague. Here, we intended to refer specifically to approaches used to measure and quantify ecosystem–atmosphere CO_2 fluxes. We have revised the wording accordingly.

Revised text: "As a result, flux measurement and quantification approaches capable of resolving both horizontal and vertical CO_2 transport are required."

The specific revisions are shown in lines 93 to 94 of the revised manuscript.

(14) *Line 80: "both horizontal and vertical CO2 transport"*

- *I do not understand how resolving horizontal transport helps to understand canopy-atmosphere carbon dioxide interactions. I understand that there is spatial heterogeneity, but why is it important to quantify the flux from one part of the forest to another part of*

the forest. The important thing here is the vertical flux between the forest and the overall atmosphere.

• *I agree that horizontal fluxes are important if fluxes between the entire forest and outside the forest and considered at the forest perimeter wall. But this study appears to look at the horizontal flux between one box area above the forest and another area above the forest. How is this useful?*

Response: We agree that the vertical CO_2 flux between the forest canopy and the atmosphere is the primary quantity for evaluating forest–atmosphere carbon exchange. We also agree that the horizontal fluxes quantified in this study should not be interpreted as net CO_2 exchange between the entire forest and the outside atmosphere, because the UAV sampling boxes represent finite local control volumes above the canopy rather than the perimeter of the whole forest ecosystem.

Our purpose in resolving horizontal transport was therefore not to estimate whole-forest lateral export or import of CO_2. Instead, the horizontal flux terms were used to diagnose local advective convergence or divergence within the UAV-defined control volume. This information is useful because horizontal advection can modify the CO_2 mass balance above the canopy, influence the interpretation of vertical flux measurements, and indicate whether a single-point tower measurement is representative under spatially heterogeneous conditions. In complex terrain or heterogeneous canopy conditions, CO_2 measured at one location may be affected by air transported from adjacent areas. Quantifying the horizontal transport across the boundaries of the local control volume therefore helps identify when the assumption of horizontal homogeneity is weak and when vertical fluxes alone may not fully describe the local CO_2 balance.

(15) *Line 82: "the most widely"*

• *Consider changing this to "a widely".*

Response: We agree that "the most widely used method" is unnecessarily absolute. We have therefore revised the wording to "a widely used method."

Revised text: "The eddy-covariance (EC) technique is a widely used method for quantifying ecosystem-scale vertical CO_2 fluxes."

The specific revisions are shown in line 95 of the revised manuscript.

(16) *Line 99: "In addition, stationary towers (e.g. EC flux towers) provide flux information at a fixed height"*

• *I disagree. Stationary towers can provide sampling at multiple heights.*

Response: We agree that stationary towers can support measurements at multiple heights, and the original wording was too general. Our intended point was that conventional eddy-covariance flux measurements are commonly obtained at one or a limited number of fixed heights, which restricts their ability to characterize continuous vertical variations in CO_2 transport and flux divergence. We have revised the text accordingly.

Revised text: "In addition, although stationary towers can support measurements at multiple levels, conventional eddy-covariance flux observations are typically obtained at one or a limited number of fixed heights. This limits their ability to

characterize continuous vertical variations in CO_2 transport and to determine flux divergence through the lower atmosphere."

The specific revisions are shown in lines 113 to 117 of the revised manuscript.

(17) *Line 109: "vertical fluxes are difficult to determine"*

• *Why?*

Response: In this context, "manned aircraft" refers primarily to fixed-wing aircraft. Although fixed-wing aircraft can obtain vertical profile information through climbing, descending, or spiral flight paths, they cannot hover or conduct localized, near-vertical profiling at a fixed horizontal position in the same manner as a rotary-wing UAV. Their forward motion also couples horizontal displacement with changes in altitude, making it more difficult to resolve fine-scale vertical CO_2 gradients over a specific forest control volume. We have revised the text to clarify this distinction.

Revised text: "Likewise, manned fixed-wing aircraft campaigns provide regional-scale observations of pollutant distributions and enable mass-balance approaches to emission estimation (Cambaliza et al., 2014). However, fixed-wing aircraft cannot hover or perform localized, near-vertical profile measurements at a fixed horizontal position, as rotary-wing UAVs can. Because changes in altitude are accompanied by substantial horizontal displacement, resolving fine-scale vertical CO_2 gradients and deriving vertical fluxes over a specific control volume is more challenging (Gordon et al., 2015)."

The specific revisions are shown in lines 122 to 128 of the revised manuscript.

(18) *Line 120: "over short time"*

• *Stationary towers can also measure over short time scales.*

Response: We agree that stationary towers can also provide measurements at short time scales. Our intended point was that UAVs can sample spatial variability across multiple locations and altitudes within a relatively short period, rather than that they uniquely provide short-timescale measurements. We have revised the sentence accordingly.

Revised text: "Compared with stationary towers, UAVs can directly characterize spatial variability in CO_2 concentrations across multiple locations and altitudes within a relatively short sampling period, without relying on an assumption of horizontal homogeneity (Witte et al., 2017).

The specific revisions are shown in lines 137 to 138 of the revised manuscript.

(19) *Line 123: "these UAV applications"*

• *Which UAV applications? I do not follow this.*

Response: We agree that the phrase "these UAV applications" was ambiguous. Here, we intended to refer specifically to previous UAV studies that measured greenhouse-gas concentration, but did not directly quantify CO_2 fluxes. We have revised the sentence to make this explicit.

Revised text: "Nonetheless, previous UAV studies focused primarily on measurements of greenhouse-gas concentrations and generally did not demonstrate

direct CO_2 flux quantification, partly because accurate wind-speed measurements from a moving rotary-wing platform can be affected by both propeller-induced airflow disturbances (Soltaninezhad et al., 2025; Thielicke et al., 2021) and rapid changes in UAV attitude during flight, including variations in pitch, roll, and yaw (Yang et al., 2024). These effects introduce additional uncertainty into flux calculations."

The specific revisions are shown in lines 141 to 143 of the revised manuscript.

(20) *Line 125: "both of which"*

• *I do not understand what this is referring to. Both of what?*

Response: We agree that the phrase "both of which" was ambiguous. Our intended meaning was that accurate wind-speed measurements from a moving rotary-wing UAV can be affected by both propeller-induced airflow disturbances and rapid changes in UAV attitude. We have revised the sentence to state this explicitly.

Revised text: "Nonetheless, previous UAV studies focused primarily on measurements of greenhouse-gas concentrations and generally did not demonstrate direct CO_2 flux quantification, partly because accurate wind-speed measurements from a moving rotary-wing platform can be affected by both propeller-induced airflow disturbances (Soltaninezhad et al., 2025; Thielicke et al., 2021) and rapid changes in UAV attitude during flight, including variations in pitch, roll, and yaw (Yang et al., 2024). These effects introduce additional uncertainty into flux calculations."

The specific revisions are shown in lines 141 to 147 of the revised manuscript.

(21) *Line 255: "a lower elevation (~15 m lower)"*

• *15 m is a large change in elevation. Please can the authors comment on the topography of the area. Was the take-off location in a ditch? If so, it is very important that the UAV flew at a fixed height above ground level, rather than above take-off level.*

Response: The approximately 15 m elevation difference between Sites A and B reflects the naturally undulating topography of the study area. Within approximately 1 km² surrounding the flux tower, the land surface consists primarily of continuous low hills and gentle slopes, with slope angles ranging from approximately 2.8° to 13.5° and local relative elevation differences of approximately 10–30 m. Thus, the site is characterized by continuously rolling low-hill terrain rather than a uniformly flat surface.

We also clarify that, because of the complex terrain, the UAV flight altitudes reported in this study were referenced to the take-off elevation at Site B, rather than maintained at a fixed height above the local ground surface along the entire flight path. Consequently, the actual height above local ground level varied spatially along the flight route. We have revised the manuscript to explicitly describe the regional topography and clarify the altitude reference used for the UAV flights.

Revised text: "The terrain within approximately 1 km² 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 Sites A and B 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 at Site B; consequently, the actual height above the local ground surface varied spatially along the flight path."

The specific revisions are shown in lines 273 to 280 of the revised manuscript.

(22) *Line 256: "which facilitates safe UAV operations"*

• *Why does being 15 m below the tower help to facilitate UAV operations?*

Response: We agree that the original sentence could be interpreted as suggesting that the lower elevation of Site B facilitated UAV operations. This was not our intended meaning. Site B was selected because its relatively open forest-gap structure provided sufficient clearance for safe UAV take-off and landing. We have revised the sentence to remove the ambiguous reference to elevation and to clarify the reason for selecting Site B.

Revised text: "To evaluate the performance of the UAV platform for vertical CO_2 flux measurements, flights were conducted at Site B, approximately 160 m southeast of the flux tower at Site A, 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 specific revisions are shown in lines 271 to 273 of the revised manuscript.

(23) *Line 265: "results from 168 flights were retained for analysis"*

• *So what is the cumulative flight time of these good flights? The time of the discarded flights (above) is a bit irrelevant.*

Response: We agree that the cumulative duration of the flights retained after quality control is more relevant than the total duration including discarded flights. The 168 flights retained for analysis corresponded to a cumulative flight time of approximately 70 h. We have revised the manuscript accordingly and removed the cumulative flight time associated with the complete set of flights.

Revised text: "From May 2023 to December 2024, a total of 209 UAV flights were conducted at the site. After quality control, including the removal of flights affected by rainfall and other conditions that could compromise instrument performance, 168 flights, corresponding to approximately 70 h of cumulative flight time, were retained for analysis."

The specific revisions are shown in lines 286 to 290 of the revised manuscript.

(24) *Line 267: "seasons"*

• *Are these meteorological or astronomical seasons?*

Response: The seasons used in this study are Northern Hemisphere meteorological seasons, defined using three-month periods: spring as March-May, summer as June-August, autumn as September-November, and winter as December-February. We have added this definition to the manuscript.

Revised text: "These included 40 flights in spring, 55 in summer, 53 in autumn, and 20 in winter, with seasons defined according to the Northern Hemisphere meteorological seasons: March-May, June-August, September-November, and

December-February, respectively."

The specific revisions are shown in lines 290 to 293 of the revised manuscript.

(25) *Line 328: "becomes sufficiently mixed"*

• *Why does a species need to be sufficiently mixed? A mass balance approach should be able to account for high (or low) concentration emission plumes, so long as all hotspots (or coldspots) are sufficiently measured.*

Response: We agree that a species does not need to be sufficiently mixed for a mass-balance approach to be valid. Spatially heterogeneous concentration fields, including localized hotspots or coldspots, can be accounted for provided that the concentration and wind fields across the control-volume boundaries are sampled with sufficient spatial coverage and resolution. Our intended point was that the boundary fluxes must be adequately characterized and that the system should remain approximately steady during the measurement period. We have therefore removed the statement that the emitted CO_2 must become sufficiently mixed and revised the text accordingly.

Revised text: "This approach assumes that the CO_2 concentration and wind fields across the control-volume boundaries are sampled with sufficient spatial coverage and that atmospheric conditions remain steady or quasi-steady during the measurement period. Under these conditions, the net emission rate can be inferred from the fluxes crossing the boundaries of the control volume."

The specific revisions are shown in lines 353 to 357 of the revised manuscript.

(26) *Line 351: "u, v"*

• *Please define these vectors here (see comment below).*

Response: We have revised the text to define (u) as the east-west wind-speed component, with (u>0) indicating flow toward the east; (v) as the north-south wind-speed component, with (v>0) indicating flow toward the north; and (w) as the vertical wind-speed component, with (w>0) indicating upward flow. Their corresponding turbulent fluctuations are denoted by (u'), (v'), and (w'), respectively.

Revised text: "Here, the mean wind components ($\bar{u}$, $\bar{v}$, $\bar{w}$) were determined separately for each UAV flight using all quality-controlled observations collected during that flight. The (u) component denotes the east-west wind speed, with (u>0) indicating flow toward the east; the (v) component denotes the north-south wind speed, with (v>0) indicating flow toward the north; and (w) denotes the vertical wind-speed component, with (w>0) indicating upward flow. The corresponding turbulent fluctuations (u', v', w') were calculated by subtracting the 30 min mean value of each component from its instantaneous measurement."

The specific revisions are shown in lines 376 to 383 of the revised manuscript.

(27) *Line 352: "30-minute period"*

• *Each flight was on average 29 minutes long (100 minutes of flight time by 209 flights). So where did this 30-minute averaging period come from?*

• *What was done for any flights of less than 30 minutes?*

Response: We thank the reviewer for identifying this inconsistency. The reference to a fixed 30 min averaging period was inaccurate. Individual UAV flight durations varied, and some flights lasted less than 30 min. In the actual data processing, the mean wind components were calculated separately for each flight using all quality-controlled observations collected during that flight, rather than using a fixed 30 min averaging window. For flights shorter than 30 min, the complete valid measurement period of that flight was used. The turbulent wind components were then calculated by subtracting the corresponding flight-period mean from the instantaneous measurements. We have revised the manuscript accordingly and replaced "30 min mean" with "flight-period mean."

Revised text: "Here, the mean wind components ($\bar{u}$, $\bar{v}$, $\bar{w}$) were determined separately for each UAV flight using all quality-controlled observations collected during that flight. The (u) component denotes the east-west wind speed, with (u>0) indicating flow toward the east; the (v) component denotes the north-south wind speed, with (v>0) indicating flow toward the north; and (w) denotes the vertical wind-speed component, with (w >0) indicating upward flow. The corresponding turbulent fluctuations (u', v', w') were calculated by subtracting the 30 min mean value of each component from its instantaneous measurement."

The specific revisions are shown in lines 377 to 378 of the revised manuscript.

(28) *Line 355: "mean horizontal wind speed"*

- *This does not make sense as the mean horizontal wind speed is by definition the average of a scalar, with u(bar) instead defined above as a vector components.*
- *If u(bar) is the mean horizontal wind speed, what is v(bar)? u(bar) can be the zonal wind component and v(bar) can be the meridional wind component (following the convention). Or perhaps the authors set u(bar) to be in the direction of mean wind direction, in which case v(bar) (which is orthogonal to u(bar)) is automatically zero in magnitude.*
- *In any case, u(bar) should be clearly defined above (where it is first introduced) rather than being defined here.*

Response: We thank the reviewer for identifying this ambiguity. We agree that ($\bar{u}$) should not have been described as the mean horizontal wind speed, because it denotes only one component of the horizontal wind vector. As defined at its first occurrence, ($\bar{u}$) represents the mean east-west wind component and ($\bar{v}$) represents the mean north-south wind component. We did not rotate the coordinate system so that ($\bar{u}$) was aligned with the mean wind direction.

To distinguish the scalar horizontal wind speed from its vector components, we now use $\overline{U_h} = \sqrt{\bar{u}^2 + \bar{v}^2}$ to denote the magnitude of the mean horizontal wind vector. Similarly, the magnitude of the horizontal turbulent fluctuation is denoted by $U_h' = \sqrt{u'^2 + v'^2}$. We have revised the definitions at their first occurrence and corrected the subsequent notation accordingly.

Revised text: "Here, the mean wind components ($\bar{u}$, $\bar{v}$, $\bar{w}$) were determined

separately for each UAV flight using all quality-controlled observations collected during that flight. The (u) component denotes the east-west wind speed, with (u>0) indicating flow toward the east; the (v) component denotes the north-south wind speed, with (v>0) indicating flow toward the north; and (w) denotes the vertical wind-speed component, with (w >0) indicating upward flow. The corresponding turbulent fluctuations (u', v', w') were calculated by subtracting the flight-period mean of each wind component from its instantaneous measurement."

Revised subsequent text: "For the horizontal terms, the u-component was used for comparison. The mean u-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."

The specific revisions are shown in lines 383 to 386 of the revised manuscript.

(29) *Line 356: "main contributor"*

• *What does it mean to be a main contributor to a term? Both concentration and wind speed effect fluxes multiplicatively. So there is no main contributor, as far as I can see.*

Response: We agree that "main contributor" was not appropriate, because the flux term is determined multiplicatively by concentration, air density, and wind speed, and no single variable alone can be described as the main contributor to the flux term. Our intended comparison was between the magnitude of the mean-wind component and that of the turbulent wind fluctuation used in the horizontal transport calculation. Specifically, the $\bar{u}$ was typically 2-3 m/s, whereas the 95th percentile of the corresponding turbulent fluctuation (u') was less than 0.1 m/s. This indicates that the horizontal advective transport associated with the mean wind is much larger than the horizontal turbulent transport term under our measurement conditions.

We have revised the text to remove "main contributor" and to state the scale comparison more explicitly.

Revised text: "For the horizontal terms, the u-component was used for comparison. The mean u-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. Because the mean horizontal wind component was more than one order of magnitude larger than the turbulent fluctuation, the horizontal advective transport term ($E_{C,H}$) was much larger than the horizontal turbulent transport term ($E_{C,HT}$) under the measurement conditions in this study. For the vertical flux terms, the reverse is true; the mean vertical wind, ($\bar{w}$), was typically less than 0.02 m/s, whereas the 95th percentile of the vertical turbulent fluctuation, 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. This scale comparison indicates that the vertical turbulent transport term, ($E_{C,VT}$), was expected to be substantially larger than the vertical advective transport term, ($E_{C,V}$), under the measurement conditions in this study."

The specific revisions are shown in lines 383 to 389 of the revised manuscript.

(30) *Line 357 "horizontal turbulent velocity"*

• *Which direction does this refer to? The horizontal plane has two dimensions.*

Response: As described in our response to Comment 28, we have revised this part

of the manuscript to explicitly define the wind components and to clarify that the comparison was made using the (u) component.

(31) *Line 367: "EC,M"*
• *Unfortunately, this equation is useless at this stage as none of the terms in the equation have been defined.*
(32) *Line 367: "MR"*
• *What is this?*
(33) *Line 367: "χC"*
• *What is this?*
(34) *Line 367: "ρa"*
• *What is this?*
(35) *Line 367: "t"*
• *What is this?*
(36) *Line 367: "x"*
• *What is this?*
(37) *Line 367: "y"*
• *What is this?*
(38) *Line 367: "z"*
• *What is this?*

Response: We have revised this section by defining all variables before presenting the equation. Specifically, $E_{C,M}$ is now defined as density-related term, M_R as the molar mass of CO_2, χ_C as the CO_2 mole fraction, ρ_{air} as the air density, t as time, and x, y, and z as the three spatial coordinates in the east-west, north-south, and vertical directions, respectively. These definitions have been added to improve the clarity and readability of the equation.

Revised text: "The density-related term ($E_{C,M}$) can be expressed as

$$E_{C,M} = M_R \iiint \chi_C \frac{d\rho_{air}}{dt} dxdydz \quad (3.2)$$

where M_R is the ratio of the molar mass of CO_2 to that of air, χ_C is the CO_2 mole fraction, ρ_{air} is the air density, t is time, and x, y, and z denote the east-west, north-south, and vertical spatial coordinates, respectively. Thus, x and y describe the horizontal directions, whereas z represents the vertical direction."

The specific revisions are shown in lines 397 to 402 of the revised manuscript.

(39) *Line 382: "mole fraction"*
• *"Mole fraction" and "mixing ratio" are used interchangeably throughout the manuscript. Please use one term consistently. I think "mole fraction" is better as it is a more precise definition of the concentration.*
(51) *Line 551: "mole fraction"*
• *"Mole fraction" and "mixing ratio" are used interchangeably throughout the manuscript. Please use one term consistently. I think "mole fraction" is better as it is a more precise definition of the concentration.*
(56) *Line 718: "mole fraction"*

• *"Mole fraction" and "mixing ratio" are used interchangeably throughout the manuscript. Please use one term consistently. I think "mole fraction" is better as it is a more precise definition of the concentration.*

(57) *Line 732: "mole fraction"*

• *"Mole fraction" and "mixing ratio" are used interchangeably throughout the manuscript. Please use one term consistently. I think "mole fraction" is better as it is a more precise definition of the concentration.*

Response: We have revised all instances of "mixing ratio" throughout the manuscript to "mole fraction" for consistency.

(40) *Line 384: "flight trajectory"*

• *It is important to state that this represents a closed loop (i.e. the start and end of each s coordinate should be in the same location) to avoid any hole in the flux field.*

Response: We have revised the manuscript to clarify that the horizontal flight trajectory forms a closed loop, such that the start and end points of the along-track coordinate (s) correspond to the same spatial location. This ensures that the control-volume boundary is closed and that no gap is introduced in the reconstructed flux field.

Revised text: "The along-track coordinate (s) was defined along the horizontal flight trajectory, which formed a closed loop around the control volume. Therefore, the start and end points of (s) correspond to the same spatial location, ensuring a closed control-volume boundary and avoiding gaps in the reconstructed flux field."

The specific revisions are shown in lines 417 to 421 of the revised manuscript.

(41) *Line 392: "flight distance"*

• *Perhaps specify that this is the distance between consecutive sampling points.*

Response: We have revised the text to clarify that this term refers to the along-track distance between consecutive sampling points.

Revised text: "and Δs_j represents the along-track distance between two consecutive sampling points along the closed-loop flight trajectory."

The specific revisions are shown in lines 428 to 430 of the revised manuscript.

(42) *Line 394: "To suppress small-scale variability"*

• *Please specify that this refers to variability in the vertical direction.*

• *What is the purpose of suppressing this variability? Why not include it in the overall flux calculation?*

(43) *Line 394: "moving average"*

• *I am totally lost. The consecutive values are in which dimension? Is this an average over time or over altitude? How many transects were performed at each measurement height?*

• *As far as I can see, a single line flux value is obtained at each height for each flight. So what is there to average over?*

Response: We agree that the term "moving average" was confusing in this context. The averaging was not performed over time, nor was it intended to remove vertical variability from the flux calculation. For each UAV flight, one closed-loop transect was

conducted at each measurement height, yielding one line-flux value for that height. The consecutive values therefore refer to line-flux values at adjacent measurement heights in the vertical direction.

Our purpose was to convert the line-flux values obtained at discrete heights into layer-averaged fluxes for the altitude intervals between adjacent flight levels. Thus, the vertical variability was still included in the overall flux calculation through the differences among altitude layers. We have revised the text to avoid the misleading phrase "suppress small-scale variability" and to clarify that this step represents averaging between adjacent altitude levels, rather than temporal averaging.

Revised text: "For each UAV flight, one closed-loop transect was conducted at each measurement height, yielding one line-flux value for that height. To obtain fluxes for discrete altitude intervals, line-flux values at adjacent measurement heights were averaged in the vertical direction. The resulting layer-averaged fluxes were then used in the total horizontal CO_2 emission calculation"

The specific revisions are shown in lines 431 to 435 of the revised manuscript.

(44) *Line 408: "The resulting vertical fluxes were assumed to be representative of the broader domain, an assumption evaluated through direct comparison with eddy covariance (EC) flux tower measurements (see Section 4.2.1)."*

• *If the vertical sampling from a UAV is deemed to be equally good as sampling from a flux tower, what is the point of the additional horizontal fluxes? It seems like the vertical work is sufficient according to what is stated here.*

Response: We agree that the original sentence could be misinterpreted as implying that the UAV-derived vertical flux alone was sufficient to represent the broader domain, which was not our intention. The comparison with EC tower measurements was used only to evaluate whether the UAV-based vertical flux estimates were reasonable relative to an established flux-measurement method. It was not intended to imply that vertical flux measurements alone fully characterize the CO_2 exchange within the control volume.

The horizontal fluxes provide additional information that cannot be obtained from vertical flux measurements alone. Specifically, they quantify lateral CO_2 transport across the boundaries of the finite control volume and help identify the influence of horizontal advection under heterogeneous canopy, complex-terrain, and weakly mixed atmospheric conditions. We have revised the text to clarify this distinction.

Revised text: "The resulting vertical fluxes were compared with eddy covariance (EC) flux tower measurements to evaluate the reliability of the UAV-derived vertical flux estimates (see Section 4.2.1). This comparison was not intended to imply that vertical fluxes alone represent the full CO_2 mass balance of the control volume. Instead, the horizontal flux terms were calculated separately to quantify lateral CO_2 transport across the control-volume boundaries, which provides information on local advection and spatial heterogeneity that cannot be obtained from vertical flux measurements alone."

The specific revisions are shown in lines 447 to 454 of the revised manuscript.

(45) *Line 420: "concentration"*

• *What sort of concentration (in which units)? It this a mass concentration? Is this a volumetric concentration? A mole fraction is a type of concentration too.*

Response: We used mass concentration in this calculation. We have revised the text accordingly and provided the corresponding units.

Revised text: "$\bar{c}$ was obtained by converting the measured CO_2 mole fraction (expressed in ppm) to mass concentration (expressed in mg/m^{-3}) using the concurrently measured temperature and pressure during the UAV profile flight."

The specific revisions are shown in lines 463 to 466 of the revised manuscript.

(46) *Line 424: "friction velocity"*

• *In which direction is this fraction velocity? The horizontal plane has two dimensions.*

Response: We clarify that the friction velocity, (u_*), is not a wind-speed component in a particular horizontal direction. Instead, it is a scalar quantity derived from the turbulent momentum flux and represents the intensity of turbulent momentum exchange near the surface. The commonly used formula for friction velocity u_* is:

$$u_* = \left[\overline{u'w'}^2 + \overline{v'w'}^2\right]^{1/4}$$

Therefore, it does not correspond specifically to either the east-west or north-south wind component.

(47) *Line 443: "wind speed"*

• *Is this a scalar (absolute) wind speed or does this term refer to a vector wind component with a certain direction in the horizontal plane?*

Response: We clarify that "wind speed" in this sentence refers to the scalar wind-speed magnitude, not to a vector wind component in a specific horizontal direction. It therefore represents the absolute magnitude of the wind vector used in the calculation. We have revised the text to use "wind-speed magnitude" to avoid ambiguity.

Revised text: "$\Delta\bar{\theta}$ and $\Delta\bar{u}$ represent the changes in the temperature and wind-speed magnitude between the layers (Δz)"

The specific revisions are shown in lines 487 to 488 of the revised manuscript.

(48) *Line 455: "surface-layer mean wind profile"*

• *Is this a scalar wind profile or a wind vector profile with an associated direction?*

Response: Same as described in our response to Comment 47, this wind profile is scalar. We have revised the text to use "vertical profile of the mean wind-speed magnitude" to avoid ambiguity.

Revised text: "the vertical profile of the mean wind-speed magnitude ($\bar{u}$) was expressed as"

The specific revisions are shown in lines 500 to 501 of the revised manuscript.

(49) *Line 507: "The air inlets of the two analyzers were positioned at the same height to ensure sampling of the same air mass"*

• *According to my understanding, the UAV conducted an extended vertical profile from which sampling at the same height as the EC instrumentation was used. It was not that*

the UAV was necessarily positioned at a certain height.

Response: We clarify that the comparison described in Section 4.1 was not an in-flight UAV comparison. As stated at the beginning of Section 4.1, this part of the study involved ground-based intercomparison experiments between the two CO_2 analyzers. During these experiments, the air inlets of the two analyzers were positioned at the same height to ensure that both instruments sampled air from the same height level under the same near-surface conditions. The UAV was not used for this intercomparison, and no extended UAV vertical profile was involved in this specific analysis.

(50) *Line 522: "The MIRA measurements tend to report slightly lower CO2 mixing ratios than the LI-7500."*

• *I see the opposite from Figure 4. Maybe provide the mole fraction averages for both datasets for comparison.*

Response: We have revised the sentence to provide the mean CO_2 mole fraction measured by each analyzer. The comparison shows that the MIRA measurements were only slightly lower than those from the LI-7500, with average values of approximately 451.7 ppm and 451.8 ppm, respectively.

Revised text: "The MIRA measurements, with an average value of approximately 451.7 ppm, tended to report slightly lower CO_2 mole fractions than the LI-7500 measurements, which had an average value of approximately 451.8 ppm."

The specific revisions are shown in lines 574 to 576 of the revised manuscript.

(52) *Line 569: "z2=26 m and z1=36 m"*

• *Please clarify that this is from the vertical profile sampling data during UAV flights, rather than the box sampling data.*

Response: Agreed. These two heights were derived from the vertical profile sampling data collected during the UAV flights, rather than from the horizontal box-pattern sampling data. We have revised the text to state this explicitly.

Revised text: "the UAV-derived vertical flux was calculated using vertical profile sampling data collected during the UAV flights at z_1=26 m and z_2=36 m."

The specific revisions are shown in lines 621 to 623 of the revised manuscript.

(53) *Line 585: "sample size"*

• *So does each sample refer to a single UAV flight? Or were multiple fluxes obtained from a single UAV flight? This point could be made clearer in this manuscript.*

Response: We clarify that, in this analysis, each sample refers to one UAV flight after quality control. For each retained UAV flight, one set of flux estimates was obtained, including the horizontal flux derived from the box-pattern flight and the vertical flux derived from the vertical profile flight. Therefore, the sample size represents the number of retained UAV flights, rather than multiple independent flux samples obtained from a single flight. We have revised the text to make this definition clearer.

Revised text: "the table reports the sample size of the number of retained UAV flights (n)"

The specific revisions are shown in line 639 of the revised manuscript.

(54) *Line 707: "physiological"*

• *Could this be "photosynthetic"?*

Response: We agree that "photosynthetic" is more specific and appropriate in this context than "physiological," because the sentence refers to CO_2 uptake associated with plant photosynthesis. We have revised the text accordingly.

Revised text: "Autumn fluxes are weaker, reflecting declining photosynthetic activity, while winter fluxes cluster near zero, with negligible uptake or slight emissions across all periods."

The specific revisions are shown in line 761 of the revised manuscript.

(55) *Line 717: "UAV measurement results"*

• *Why is this subsection entitled "UAV measurement results"? The previous subsection also contains UAV measurement results. I think this subsection is dedicated to net fluxes including the box-type sampling data.*

Response: The purpose of this subsection is specifically to present the net CO_2 fluxes derived from the box-pattern sampling data, together with the vertical flux component. Therefore, we have revised the subsection title to make its focus clearer.

Revised text: "4.3 Net CO_2 emission results"

The specific revisions are shown in line 771 of the revised manuscript.

(58) *Line 749: "Therefore, the positive Ec primarily reflects net CO2 inflow driven by horizontal transport (i.e., lateral convergence) rather than local vertical emission from the canopy."*

• *But does this help us to understand net carbon dioxide exchange with the overall atmosphere? This result shows that there is a next flux between the inside and the outside of a box over the tree canopy. Some boxes will have a net negative flux and some boxes will have a net positive flux. As the entire forest is not placed inside a horizontal box, this does not show the net flux from the entire forest to outside the forest (to the overall atmosphere). So what is the point?*

Response: We agree that the net flux calculated for a finite UAV sampling box should not be interpreted as the net CO_2 exchange between the entire forest ecosystem and the overall atmosphere. The UAV box does not enclose the whole forest, and positive or negative net fluxes for individual boxes mainly indicate lateral CO_2 convergence or divergence within a local control volume above the canopy.

The purpose of this analysis is therefore not to estimate the whole-forest net ecosystem exchange, but to quantify the local CO_2 mass balance within a finite control volume and to identify the role of horizontal transport. This information is useful because horizontal advection can influence local CO_2 accumulation or depletion, affect the interpretation of vertical flux measurements, and indicate whether the assumption of horizontal homogeneity is valid. We have revised the text to clarify this limitation and the intended interpretation of the box-based net fluxes.

Revised text: "Therefore, the positive E_c primarily reflects net CO_2 inflow into the finite UAV sampling box driven by horizontal transport, that is, lateral convergence

within the local control volume. This result should not be interpreted as the net CO_2 exchange between the entire forest ecosystem and the overall atmosphere, because the UAV box only encloses a limited area above the canopy. Instead, the box-based flux calculation is intended to quantify local CO_2 mass balance and to diagnose the contribution of horizontal advection, which can affect the interpretation and spatial representativeness of vertical CO_2 flux measurements."

The specific revisions are shown in lines 803 to 810 of the revised manuscript.

(59) *Line 754: "This underscores the importance of resolving spatial gradients and lateral boundary fluxes-features that can be captured by UAV sampling but are not directly observable from a single-point flux tower measurement."*

• *Why? To achieve what?*

Response: We agree that the original sentence did not clearly explain why resolving spatial gradients and lateral boundary fluxes is important. Our intention was not to suggest that these measurements directly provide the net CO_2 exchange of the entire forest with the atmosphere. Rather, resolving spatial gradients and lateral boundary fluxes helps diagnose horizontal advection within a local control volume, quantify local CO_2 accumulation or depletion, and evaluate whether a single-point flux tower measurement is representative under spatially heterogeneous conditions. We have revised the sentence to make this purpose explicit.

Revised text: "This highlights the importance of resolving spatial gradients and lateral boundary fluxes in order to diagnose horizontal advection and local CO_2 redistribution within the UAV sampling box. These processes can affect the interpretation and spatial representativeness of vertical flux measurements from a single-point flux tower, but they are not directly observable from the tower measurement alone."

The specific revisions are shown in lines 813 to 818 of the revised manuscript.

(60) *Line 759: "To verify whether net emissions (EC) calculated using the mass-balance approach differ across spatial scales"*

• *Why? What is the point of proving this? We know that forest emissions are heterogeneous.*

Response: We agree that forest CO_2 exchange is expected to be spatially heterogeneous, especially in forest ecosystems with complex terrain and heterogeneous underlying surfaces. However, the purpose of this analysis was not simply to demonstrate that such heterogeneity exists. Instead, our objective was to use the UAV-based three-dimensional CO_2 emission model developed in this study to quantitatively evaluate whether net CO_2 emissions differed significantly among the three control volumes considered here, and to further examine how these differences varied across seasons and times of day.

More specifically, this analysis allowed us to quantify the magnitude of net CO_2 emission differences among different spatial scales and to assess whether the observed differences were mainly associated with horizontal transport or vertical exchange. In addition, by comparing different seasonal and diurnal periods, we aimed to identify

when such heterogeneity was most pronounced, for example whether stronger differences occurred during midday in summer or nighttime in winter. We have revised the text to clarify that the purpose of this subsection is to quantify spatial-, seasonal-, and diurnal-scale differences in net CO_2 emissions using the UAV-based three-dimensional flux framework, rather than merely to confirm the known spatial heterogeneity of forest CO_2 exchange.

(61) *Line 763: "The vertical contribution term EC,VT and the horizontal transport contribution term EC,H within each control volume were separately computed as per the detailed outlines above."*

• *The outlines above do not explain how EC,VT was calculated from box-type sampling. It does not say which "target height" was chosen and why. It does not say whether the vertical transect from each UAV flight was used or if the box sampling was somehow used to obtain a vertical flux.*

Response: We clarify that $E_{C,H}$ was calculated from the box-pattern sampling data, whereas $E_{C,VT}$ was calculated from the vertical profile sampling data collected during the corresponding UAV flight. The box-pattern sampling was not used to derive the vertical turbulent flux.

For the calculation of $E_{C,H}$, as described in Section 2.3, we have specified that the box flights were conducted at heights of 35, 40, 45, 50, 60, and 85 m. According to Eq. (3.5) in Section 3.2.1, the data collected at each height were used to calculate the corresponding fluxes, which were then integrated to obtain the horizontal CO_2 emission.

For the calculation of $E_{C,VT}$, as described in Section 2.3, the data used for the vertical flux calculation were collected at heights of 26 and 36 m. $E_{C,VT}$ was then calculated according to Eq. (3.17) in Section 3.2.2.

In addition, the $E_{C,H}$ and $E_{C,VT}$ values obtained from the above calculations represent the horizontal and vertical emission components, respectively, for the entire control volume, rather than emissions at a specific height.

(62) *Line 770: "To ensure the validity of the comparison, measurements from the three virtual control volumes must be obtained within 20 minutes of each other"*

• *I am confused. Each flight (of on average 29 minutes) included sampling of each of the three control volumes. Why not just compare three fluxes for different control volumes from each flight? I do not understand why there is this 20-minute requirement. Were fluxes from different UAV flights compared? This seems like a strange approach.*

Response: We thank the reviewer for pointing out this confusion. We agree that the original statement regarding the 20-minute requirement was unclear and could be misleading. Fluxes from different UAV flights were not compared in this analysis. Instead, for each retained UAV flight, the sampling covered all three virtual control volumes, and the three corresponding flux estimates were calculated from the same flight. Therefore, the comparison among the three control volumes was made on a flight-by-flight basis, using fluxes obtained under the same meteorological conditions and within the same sampling period.

The 20-minute statement was intended to emphasize temporal consistency among

measurements, but because all three control volumes were sampled within the same UAV flight, this additional criterion was unnecessary and confusing. We have removed this statement.

(63) *Line 815: "Table 5"*

• *According to my understanding, EC,VT is calculated from the single vertical transect conducted during each UAV flight. If this is the case, why do the EC,VT values not scale linearly with box size, for each box size? For example, the median EC,VT is -2.77 for the 50x50x50 box. I would expect it to be -11.08 for the100x100x50 box as it is four times bigger, in terms of surface area. And the fact that the 150x150x50 box is larger than -13.6 (-12.5) is even stranger. I am not sure what is happening here. The vertical flux should be independent of the box size, unless the box sampling is used to derive EC,VT using some unexplained method.*

Response: The $E_{C,VT}$ values reported in Table 5 were not obtained by simply scaling the value from the 50 × 50 × 50 m control volume according to the horizontal surface area. Instead, $E_{C,VT}$ was calculated separately for each UAV-defined control volume using the vertical flux information derived from the corresponding UAV vertical profile measurements.

Therefore, the differences in $E_{C,VT}$ among the three control volumes do not follow a strictly linear scaling with box size. This is mainly because of spatial heterogeneity in CO_2 concentration gradients and turbulent transport above the forest canopy. In a complex forest ecosystem with heterogeneous canopy structure and terrain, enlarging the control volume does not simply add a spatially uniform vertical flux over a larger surface area. Instead, different control volumes include different portions of the heterogeneous canopy-atmosphere exchange field, which can lead to non-linear changes in the calculated vertical contribution.

(64) *Line 877: "independent sources"*

• *These are not independent sources. The wind measurement error is treated as one error component, yet the anemometer error is incorporated into the instrumental error.*

Response: We have rewritten Section 4.5.

We agree that the original wording "independent sources" was inappropriate, because some uncertainty components are not fully independent. In particular, the anemometer-related error should not be included in both the instrumental error term and the wind measurement uncertainty term.

To avoid this ambiguity and potential double counting, we have revised the uncertainty framework. The original instrumental error term δ_M was replaced by the CO_2 analyzer uncertainty term, δ_{CO_2}, which includes only the uncertainty associated with CO_2 mole fraction measurements. All wind-related uncertainties, including the ultrasonic anemometer accuracy, UAV attitude correction, platform-induced flow distortion, wind-correction algorithm uncertainty, and wind-vector projection uncertainty, were included only in δ_V. We also removed the term "independent sources" and revised the text to describe these as uncertainty components.

Revised text: "The measurement-related uncertainty was divided into three

components: CO_2 analyzer uncertainty (δ_{CO_2}) and wind measurement uncertainty (δ_V). These components were combined in quadrature to obtain the measurement-propagated uncertainty:

$$\delta_{meas}^2 = \delta_{CO_2}^2 + \delta_V^2 \quad (4.2)$$

Here, δ_{CO_2} represents the uncertainty associated with the measured CO_2 mole fraction, including analyzer precision, calibration uncertainty, and short-term measurement noise. Wind-related uncertainty was included in δ_V, which includes uncertainty arising from the ultrasonic anemometer measurements, and the wind-correction procedure used to correct for these effects.

4.5.1 CO_2 analyzer uncertainty

The CO_2 analyzer uncertainty was estimated from the performance of the MIRA CO_2 analyzer and the ground-based intercomparison with the LI-7500 analyzer. The MIRA analyzer has an accuracy better than 0.2 ppm, whereas the CO_2 variations resolved during UAV sampling frequently exceeded several to tens of ppm. Therefore, the relative uncertainty associated with the CO_2 mole fraction measurement was small compared with the observed CO_2 gradients used in the flux calculations. In addition, the analyses shown in Figs. 4 and 5 indicate that the error caused by the MIRA CO_2 analyzer is almost negligible. Therefore, the contribution of δ_{CO_2} was conservatively set to 1%.

4.5.2 Wind measurement uncertainty

Wind measurement uncertainty was treated as a separate uncertainty component because wind speed and wind direction directly affect the horizontal transport term, and the turbulent exchange parameters used in the vertical flux calculation. For the uncertainty introduced by the wind-speed correction, based on the validation experiment reported by Yang et al. (2025), the corrected UAV wind speed showed a root mean square relative error of 0.28 compared with the meteorological tower reference measurements. Therefore, a conservative relative uncertainty of 28% was assigned to the residual wind-correction uncertainty. Additionally, the ultrasonic anemometer used on the UAV has a wind speed accuracy of ±0.2 m s^{-1} and a wind direction accuracy of ±1°. For typical flight-level wind speeds of 4-6 m s^{-1}, this corresponds to a relative error of about 5% in the horizontal wind components. Considering the combined effects of these two factors, the final contribution of δ_V was estimated to be 28.5% using the uncertainty propagation method."

The specific revisions are shown in lines 945 to 977 of the revised manuscript.

(65) *Line 897: "Propagating these errors through the flux equations"*

- *How are wind direction measurement uncertainties propagated through the equations? The equations do not include wind direction.*
- *Please can some details be provided about how exactly these errors are propagated in the flux equations. It seems a bit vague.*

Response: We have rewritten Section 4.5.2 according to the reviewer's suggestion. The wind-direction analysis has already been discussed in Yang et al. (2025). In that study, the final uncertainty of the UAV wind-speed correction, compared with the wind

speed measured by the flux tower, was 28%, including both wind-direction and wind-speed errors. Therefore, this issue is not discussed repeatedly in this subsection.

Revised text: "4.5.2 Wind measurement uncertainty

Wind measurement uncertainty was treated as a separate uncertainty component because wind speed and wind direction directly affect the horizontal transport term, and the turbulent exchange parameters used in the vertical flux calculation. For the uncertainty introduced by the wind-speed correction, based on the validation experiment reported by Yang et al. (2025), the corrected UAV wind speed showed a root mean square relative error of 0.28 compared with the meteorological tower reference measurements. Therefore, a conservative relative uncertainty of 28% was assigned to the residual wind-correction uncertainty. Additionally, the ultrasonic anemometer used on the UAV has a wind speed accuracy of ±0.2 m s^{-1} and a wind direction accuracy of ±1°. For typical flight-level wind speeds of 4-6 m s^{-1}, this corresponds to a relative error of about 5% in the horizontal wind components. Considering the combined effects of these two factors, the final contribution of δ_V was estimated to be 28.5% using the uncertainty propagation method."

The specific revisions are shown in lines 964 to 977 of the revised manuscript.

For the propagation of wind-speed uncertainty, we analyzed it in the vertical turbulent contribution term in Section 4.5.3.

Revised text: "For the vertical turbulent contribution term, $E_{C,VT}$, the methodological uncertainty was mainly associated with the flux-gradient approach. Because the CO_2 analyzer uncertainty was small, the uncertainty in $E_{C,VT}$ was assumed to be dominated by uncertainty in the turbulent exchange coefficient, which was estimated from wind-related variables, including the three-dimensional wind components and friction velocity. Therefore, the flux-gradient uncertainty ($\delta_{gradient}$) was evaluated based on the wind-speed uncertainty. Based on the wind-correction validation and uncertainty propagation described above, the wind-related uncertainty was estimated to be 28.5%, which was used as a conservative uncertainty estimate for the turbulent exchange coefficient and propagated into the $E_{C,VT}$ calculation. The same three representative cases used for the uncertainty analysis of $E_{C,H}$ were also used for $E_{C,VT}$. The resulting uncertainties were 3%, 2%, and 5%, respectively. These values were relatively small because the friction velocity and turbulent exchange coefficient were calculated using temporal gradient interpolation, which partly smoothed random wind-speed errors and reduced their influence on the final $E_{C,VT}$ estimates. Therefore, this study conservatively adopted $\delta_{gradient}$=5% to represent the uncertainty associated with the flux-gradient methodology."

The specific revisions are shown in lines 999 to 1015 of the revised manuscript.

(66) *Line 901: "methodological effects"*

• *What are the methodological effects and have they been quantified? I cannot see any analysis of methodological uncertainties in this work.*

Response: We have rewritten Section 4.5 and this sentence has been deleted.

(67) *Line 904: "includes uncertainties arising from sensor performance"*

• *But I thought wind measurement errors were dealt with within the instrumental error above. That is what the text says. It is being included twice.*

Response: We have rewritten Section 4.5 and this sentence has been deleted.

(68) *Line 916: A conservative δV ≈8-22% is assigned to this uncertainty term.*

• *Is this uncertainty range arbitrarily assigned or computed. The word "assigned" implies that this range is made up.*

• *Assuming these uncertainty ranges are somehow computed, how is their computation achieved. There is no detail here. It is impossible to know whether this uncertainty has any value without these details.*

• *Assuming the wind speed has a certain percentage error, how is this converted into an error in the flux? Is it by propagating the error in the equations, as for the instrumental error? Please describe this.*

Response: We have rewritten Section 4.5 and this sentence has been deleted.

(69) *Line 919: "Temperature and pressure effects"*

• *The authors can include this if they insist, but air density variations over a flight of approximately 29 minutes are likely to be negligible. This could be summarised in one sentence and ignored from the uncertainty analysis.*

Response: We have rewritten Section 4.5 and this sentence has been deleted.

(70) *Line 931: "independent components"*

• *They are not independent. Wind measurement errors appear in both instrumental and wind uncertainties, according to the description given in the text.*

Response: We have rewritten Section 4.5 and this sentence has been deleted.

(71) *Line 933: "total relative uncertainty"*

• *It is not a total uncertainty, as it assumes that there are no methodological errors. There is a sentence at the end of the paragraph partially confirming this. So I do not really understand the point of this uncertainty if it is an incomplete uncertainty. What is the value of this incomplete uncertainty analysis?*

Response: We have rewritten Section 4.5 according to the reviewer's suggestion, and methodological uncertainty is discussed in Section 4.5.3.

Revised text: "4.5.3 Methodological uncertainty

In addition to measurement-related uncertainty, the UAV-based flux estimates are also affected by methodological uncertainty associated with the flux quantification framework itself.

For the horizontal transport term, $E_{C,H}$, methodological uncertainty arises mainly from discrete sampling along the box-pattern flight path, spatial reconstruction of lateral boundary fluxes. The resulting uncertainty is collectively referred to as $\delta_{spatial}$. Because the UAV samples the control-volume boundaries along discrete trajectories rather than continuously measuring the entire boundary surface, the reconstructed lateral flux depends on the interpolation or averaging method used to integrate the

boundary observations. To evaluate spatial reconstruction uncertainty ($\delta_{spatial}$), $E_{C,H}$ was recalculated using alternative treatments of the discrete box-pattern observations, including linear interpolation (this study), nearest-neighbor, and segment averaging. The spread among the resulting $E_{C,H}$ estimates was used to quantify the uncertainty associated with boundary discretization and spatial reconstruction. Three representative cases from different seasons (spring morning: 12 May 2024; summer noon: 20 August 2023; and autumn noon: 3 December 2024) were selected for the calculation. Finally, the uncertainties in E_C calculated using the different methods were 6% (nearest-neighbor) and 8% (segment averaging), respectively. Therefore, this study conservatively adopted $\delta_{spatial}$=8% to represent the uncertainty caused by spatial reconstruction.

For the vertical turbulent contribution term, $E_{C,VT}$, the methodological uncertainty was mainly associated with the flux-gradient approach. Because the CO_2 analyzer uncertainty was small, the uncertainty in $E_{C,VT}$ was assumed to be dominated by uncertainty in the turbulent exchange coefficient, which was estimated from wind-related variables, including the three-dimensional wind components and friction velocity. Therefore, the flux-gradient uncertainty ($\delta_{gradient}$) was evaluated based on the wind-speed uncertainty. Based on the wind-correction validation and uncertainty propagation described above, the wind-related uncertainty was estimated to be 28.5%, which was used as a conservative uncertainty estimate for the turbulent exchange coefficient and propagated into the $E_{C,VT}$ calculation. The same three representative cases used for the uncertainty analysis of $E_{C,H}$ were also used for $E_{C,VT}$. The resulting uncertainties were 3%, 2%, and 5%, respectively. These values were relatively small because the friction velocity and turbulent exchange coefficient were calculated using temporal gradient interpolation, which partly smoothed random wind-speed errors and reduced their influence on the final $E_{C,VT}$ estimates. Therefore, this study conservatively adopted $\delta_{gradient}$=5% to represent the uncertainty associated with the flux-gradient methodology.

The combined uncertainty was therefore expressed as:

$$\delta^2_{combined} = \delta^2_{CO_2} + \delta^2_V + \delta^2_{spatial} + \delta^2_{gradient} \quad (4.3)$$

where $\delta_{spatial}$ represents the uncertainty associated with spatial reconstruction of lateral boundary fluxes, $\delta_{gradient}$ represents uncertainty associated with the vertical flux-gradient calculation."

The specific revisions are shown in lines 978 to 1020 of the revised manuscript.

(72) *Line 943: "quantify three-dimensional CO2 transport"*

• *Is this the correct terminology? Is it the transport that was quantified or the flux? Perhaps the transport was characterised rather than being quantified.*

Response: We agree that the original phrase "quantify three-dimensional CO_2 transport" was not sufficiently precise. In this study, the UAV observations were used to characterize three-dimensional CO_2 transport patterns, whereas the calculated quantities were CO_2 fluxes and emission terms, including E_C, $E_{C,H}$, and $E_{C,VT}$. Therefore, we have revised the wording to distinguish between characterizing transport

processes and quantifying fluxes.

Revised text: “This study developed and field-evaluated a UAV-based methodology to quantify three-dimensional CO_2 emission over a forest ecosystem by explicitly resolving both vertical exchange and horizontal advection within a three-dimensionally unified mass-balance approach”

The specific revisions are shown in line 1030 of the revised manuscript.

(73) *Line 952 “Pearson correlation coefficient”*

- *From how many samples is this value derived?*

Response: The Pearson correlation coefficient was calculated from 167 paired samples, each consisting of one UAV-derived vertical CO_2 flux estimate and the corresponding EC tower-derived CO_2 flux estimate. We have revised the text to include the sample size.

Revised text: “with a Pearson correlation coefficient of $r = 0.9$ based on 167 paired samples”

The specific revisions are shown in line 1039 of the revised manuscript.

(74) *Line 965: “local CO_2 budget”*

- *What does this mean? Does a “local” scale correspond to a box above the tree canopy?*

Response: In this context, “local CO_2 budget” refers to the CO_2 mass balance within the UAV-defined control volume above the forest canopy, rather than the CO_2 budget of the entire forest ecosystem. The local scale therefore corresponds to the finite sampling box enclosed by the UAV box-pattern flight path. We have revised the wording to make this definition explicit and to avoid confusion with ecosystem-scale carbon budgets.

Revised text: “indicating that advection-driven convergence/divergence may substantially shape the CO_2 mass balance within the UAV-defined control volume above the forest canopy”

The specific revisions are shown in lines 1050 to 1052 of the revised manuscript.