We appreciate the reviewers' support for publication and will address the suggested corrections and clarifications thoroughly in our revised manuscript. In this response document, *reviewer comments are shown in gray italic text*, and our responses are provided in black.

First reviewer comments and response:

Summary: This paper applies the canopy physics (Makar et al., 2017) in CMAQ. Apparently, the science has already been done by Makar et al. (2017). But the implementation in a more open-sourced and widely used community model (CMAQ) and the use the process analysis tool for deeper insights provides a lot of extra scientific value on top of Makar et al. (2017), and worthy of publication in Atmospheric Chemistry and Physics after some corrections and clarifications.

Major comments:

However, this work has one potentially important conceptual/theoretical issue. The presence of canopy creates segregation between in-canopy and above-canopy air, and this work indeed shows its importance. However, the presence of plant canopy also enhances the mixing immediately above the canopy by generating extra eddies (Harman and Finnigan, 2007). Ignoring this effect leads to underestimation of overall near-surface (z ~ 0 – 2h) vertical mixing. If redesigning and rerunning the numerical schemes/experiments are not feasible, some quantitative arguments are required to explore the size of its potential effects on simulation ozone.

Response:
We appreciate the reviewer's insightful observation regarding the enhanced mixing in the roughness sublayer due to coherent eddies generated at the canopy top, as discussed in Harman and Finnigan (2007). This is a known mechanism that can increase vertical mixing just above the canopy (especially under neutral and stable conditions), which may not be fully resolved in our current parameterization framework under USEPA The Community Multiscale Air Quality (CMAQ) Modeling System.

In this study, we apply simplified canopy turbulence parameterizations adapted from Makar et al. (2017), in which reductions in turbulent diffusivity are vertically averaged across existing CMAQ model layers. Although the vertical K_{can}(z) is calculated by integrating K with vertical resolution of $\Delta z = 0.5$ m (same as for photolysis attenuation, described in line 261 to 268), the CMAQ model retains its native vertical resolution (first layer : 0 ~ 40 m and second layer : 40 ~ 80 m) and does not explicitly resolve the roughness sublayer or introduce additional vertical layers above the canopy. Therefore, while some impact of canopy-related turbulence is considered (in canopy: K_{can} (0 ~ FCH) and above canopy: K_{can} (FCH ~ top of first layer)), the specific enhancement of mixing associated with canopy-top eddies is not explicitly represented in CMAQ.

We have added clarification in the revised Method (line 263 to 268) and Discussion (line 829 to 838) section to acknowledge this method limitation and discuss uncertainties effect of K_{can}. Based on typical values of the vorticity thickness and mixing length scales near the canopy top (Harman and Finnigan, 2007), we estimate that neglecting this enhanced mixing could lead to an underestimation of vertical diffusivity K_{can} in the first model layer (0 – 40 m above surface) by approximately when +2.5% ~ +5% in unstable condition (late morning to afternoon); +10% ~ +20% in stable condition (evening and early morning). This could partially affect simulated O_3 profiles by modulating the vertical exchange between canopy and above-canopy air. Other detail information about K_{can} uncertainty estimate can be found in supplementary document (Fig. S4).

We note that the implementation of a more detailed multilayer canopy structure, including explicit roughness sublayer treatment, is currently underway in a separate effort (Ivanova et al., 2024, in preparation). This ongoing development will consider a pathway to address the above-canopy mixing-layer dynamics in future applications.

On a similar note, stating dry deposition as "a second effect that's not covered" (L 139 - 140) is confusing, and contradictory to the fact that the authors keep referencing changes in deposition rates (e.g. L 558, table 4). Please clarify and provide quantitative arguments/references about why this is ignored, and how much would that affect the result.

Response:
We thank the reviewer for pointing out the inconsistency regarding our description of dry deposition. We agree that the current wording in Lines 139–140 may be misleading and have revised it for clarity.

In this study, we focus on implementing parameterizations for in-canopy photolysis attenuation and turbulence-driven vertical diffusivity based on Makar et al. (2017), within the existing 3D structure of CMAQv5.3.1. While changes in chemical concentrations (e.g., O_3, NO_x, and all other gas species) inevitably influence dry deposition fluxes computed by the model, we do not modify or reparameterize the dry deposition scheme itself for in-canopy conditions. The standard CMAQ dry deposition parameterizations remain applied at the lowest model layer, without explicit adjustment for within-canopy microphysics or vertical foliage profiles.

We acknowledge that in one-dimensional (1D) canopy-resolving models, dry deposition can be treated as a function of canopy heigh, LAI vertical distribution, and leaves density across multiple vertical levels. However, due to the structural limitations of the 3D CTM framework used here and our goal of minimizing core model changes, dry deposition is represented using CMAQ's existing one-layer 'big-leaf' parameterization without explicit consideration of vertical canopy structure. Deposition fluxes respond indirectly to changes in near-surface concentrations driven by in-canopy photolysis attenuation and turbulence effects.

We have updated the relevant text (line 138 to 141) to clarify this point and to avoid implying that dry deposition was ignored entirely. We also briefly note in the revised Discussion that incorporating multilayer canopy deposition processes is a promising direction for future work, particularly for species such as O_3, HNO_3, and organic acids that are sensitive to leaf-surface interactions.

Minor comments

- *L32: Unclear. What is 75.2% drop in first-layer O_3?*

Thank you for pointing this unclear point, this should be 75.2% drop in first-layer O_3 chemical production. We have updated it.

- *L 420 – 425: The word "variability" is vague and confusing, making the whole paragraph hard to understand, especially the final sentence. Please rewrite with more precise and understandable terminologies.*

Thank you for this suggestion. We have edited the manuscript and now it read:

"Figure 4 shows that the canopy parameterization improves the diurnal pattern of hourly mean O_3 concentrations at most AQS sites affected by canopy effects. Between 9:00 and 14:00 local time, the Canopy simulation better captures the observed spread in ozone levels, with its vertical extent more closely aligning with the broader distribution seen in observations than the Base case. This suggests that the updated parameterization more accurately represents the magnitude of daytime ozone variability. The enhanced spread in the Canopy case arises from the more discrete and intermittent nature of turbulent eddies, as represented by Raupach's near-field approach to vertical diffusivity (Eqs. 2–3). This formulation suppresses vertical diffusivity near the canopy top, particularly under stable or weakly mixed conditions, which can lead to localized accumulation or depletion of ozone within the canopy layer, thereby increasing spatial and temporal variability across sites and hours."

- *L 462: what is "lowering O_3 diurnal profile"?*

Thank you for this suggestion. We have replaced it by "reduce the mean level of the near-surface O_3" in the manuscript and now it read:

"These processes collectively reduce the mean level of the near-surface (i.e., first model layer) O_3 diurnal profile in the Canopy simulation compared to the Base case (Figure 4). "

- *L 511: "within the canopy" or "within the first model layer"?*

Thank you for this suggestion. We have edited the manuscript and now it read:

"In the Canopy case (solid shaded lines in Figure 7a), the daytime maximum near-surface O_3 chemical production rate within the first model layer (red line) becomes all negative (maximum: -1 ppb hr^{-1}) compared to the Base case.."

- *L 531: "larger"*

Thank you, we have corrected this typo.

- *L 535: notation on left hand side is sloppy*

Thank you, we have corrected the left-hand side to "$\partial \left[O_{3_{vdiff}}\right]/\partial t$" , which means the rate of O_3 due to vertical diffusion:

$$\frac{\partial \left[O_{3_{vdiff}}\right]}{\partial t} = -\left\{\frac{\partial K}{\partial z}\frac{\partial [O_3]}{\partial z} + K\frac{\partial^2 [O_3]}{\partial z^2}\right\}$$

- *Table 4/5: The explanation could be much clearer if total O_x budget is analyzed in addition*

Thank you for this suggestion, we have added the table 4b for O_x ($NO_2 + O_3$) budget for addition oxidizing capacity information and description in line 715 to 726.

"To further quantify the integrated oxidant budget in canopy-affected regions, Table 4b summarizes the average daily total O_x ($O_3 + NO_2$) processing rates in the first and second model layers. In the first layer, both Ox chemical production and reduction decrease substantially under the canopy scheme, by 65.1% and 71.5%, respectively. Dry deposition also decreases slightly (−8.9%), while vertical and horizontal transport processes show smaller changes. The net Ox budget in the first layer decreases by 68.3%, indicating a strong suppression of near-surface oxidant cycling under canopy influence. In contrast, the second layer shows minimal changes between the canopy and base cases. O_x chemical production and reduction remain nearly unchanged (<0.2%), and transport terms differ by less than ±1%. These results highlight that the canopy parameterization substantially affects oxidant chemistry and fate near the surface, while impacts aloft are minimal. Including the Ox budget offers a clearer picture of how chemical and physical processes are reorganized by canopy effects in the lowest layers."

- *L723: Does more NO_x become NO_2 matter through promoting NO_x deposition, since NO_2 deposits much more rapidly than NO?*

Yes, table 4a for first model layer explain the deposition process changes, the NO_x deposition increases 31.2% (from 2.66 to 3.49 ppb d^{-1}), and the major change is caused by NO_2 deposition increase from 2.59 to 3.44 ppb d^{-1} (32.7%). We have enhanced this into section 3.3 line 709 to 714, now it read:

"In addition, the canopy parameterization enhances surface removal of NO_x through dry deposition. As shown in Table 4a, total NO_x deposition in the first model layer increases by 31.2% (from 2.66 to 3.49 ppb d^{-1}), primarily due to a 32.7% increase in NO_2 deposition (from 2.59 to 3.44 ppb d^{-1}). These results indicate that the shift in chemical partitioning toward more NO_2 formation driven by increased titration and reduced photolysis and promotes stronger NO_x removal through deposition, especially under canopy effect."

Second reviewer comments and response:

Wang and coauthors present an advancement in regional scale chemical transport modeling by implementing in-canopy photolysis attenuation and turbulence into the CMAQ model. The authors provide a thorough evaluation of the canopy parameterization's impact on O3 concentrations and above/below canopy processing rates across multiple sites, and the study is a valuable step toward improving surface air quality predictions in forested environments and beyond. The comments below are intended to clarify certain methodological choices and their defense, and suggest additional context where relevant to further strengthen the manuscript. After addressing these comments, I believe that this manuscript is suitable for publication in ACP.

My major comment concerns the treatment of dry deposition and sub-canopy O3 processing rates. Surface O3 predictions are known to be sensitive to dry deposition parameterizations, which are constrained by time-varying environmental drivers that influence both the accuracy and variability of modeled O3 (e.g., Hardacre et al., 2015; Visser et al., 2021). It would be valuable to discuss whether improvements in O3 representation in the canopy-parameterized model might also be achieved through alternative or updated dry deposition schemes. In particular, could a change in the dry deposition parameterization alone, or the application of a surrogate vertical treatment (e.g., Silva et al., 2020) similar to what is used in Kcan(z), lead to comparable impacts on model–observation agreement? If a dedicated sensitivity analysis is not feasible within the current scope of the study, I recommend at least acknowledging this potential source of uncertainty and its implications for interpreting the canopy model's performance. I also suggest including the specific dry deposition scheme used in this study in Table 1 to aid reader clarity.

Response:

We appreciate the reviewer's thoughtful comment on the importance of dry deposition and its role in sub-canopy and near-surface ozone concentrations. We agree that dry deposition is a key factor influencing O_3 processing budget and model–observation agreement, especially in forested environments.

In this study, the dry deposition of O_3, NO_x, and other gas species is calculated using the M3Dry scheme implemented in CMAQ v5.3 configuration for surface layer (Hogrefe et al., 2023), following the formulation described by (Pleim et al., 1984 and Pleim and Ran, 2011). The M3Dry approach applies a resistance-in-series framework to estimate deposition velocities, incorporating grid-scale aerodynamic resistance, quasi-laminar boundary layer resistance, and surface resistance (Ran et al., 2016; Pleim and Ran, 2011; Galmarini et al., 2021). These resistances are dynamically calculated based on meteorological variables (e.g., temperature, humidity, wind speed) and land-surface characteristics (e.g., LAI, land-use type) provided by the WRF-NOAH model (Ran et al., 2016). This enables land-cover and time-dependent dry deposition rates that respond to surface conditions. However, the M3Dry deposition setup is still follow the "one big leaf assumption" and not consider the **inside** canopy effects (unlike photolysis and eddy diffusivity calculation in this study).

Nonetheless, based on our process analysis results (Section 3.2.2; Fig. 7a), we find that changes in O_3 concentration are predominantly driven by altered vertical mixing and chemical processing, which peak earlier in the day (between 8 and 10 AM). In comparison, the contribution from dry deposition—while non-negligible—peaks later (between 11 AM and 1 PM) and plays a secondary role in driving overall O_3 changes. We have clarified the dry deposition scheme and its assumptions in line 138 to 141, line 284 to 288, and Table 1, and added a discussion of this limitation and its implications in Section 4.

Similarly, do you anticipate that sub-grid vertical resolution of in-canopy chemistry and VOC emissions would meaningfully affect first-layer concentrations and processing rates? For example, you cite articles that show that VOCs and NOx have a vertical gradient (due to changes in leaf area and proximity to soil) and thus the chemical processing rate of O3 in the lower half of the canopy will be different than the upper half (e.g., Vermeuel, et al. 2024). It is unclear whether CMAQ's first-layer treatment captures this integrated vertical effect or whether the vertical averaging of Kcan(z), in the absence of a corresponding treatment for dry deposition and chemistry, could introduce systematic biases, particularly in grid cells with relatively short canopy heights. While the effect of chemistry is touched upon briefly in Section 3.3, a more explicit acknowledgment of this potential limitation, and an estimate or qualitative discussion of the scale of uncertainty it could introduce, would provide important context for readers assessing the robustness of the chemical representation.

We appreciate the reviewer's insightful comment on the role of sub-grid vertical structure in shaping first-layer O_3 and NO_x concentrations and processing rates. While CMAQ maintains a fixed vertical resolution (with the first layer typically spanning 0–40 m), we recognize that key reactive species such as VOCs and NO_x can exhibit strong vertical gradients within the canopy, especially due to heterogeneous emission sources and light attenuation. These gradients can lead to differences in O_3 chemical production between the upper and lower parts of the canopy, as highlighted by Vermeuel et al. (2024) and other studies.

In our canopy implementation, the photolysis attenuation and turbulence diffusivity (K_{can}) were both calculated using a fine vertical resolution of $\Delta z = 0.5$ m. This approach captures the height-dependent variations in light availability and turbulence across the full vertical extent of the first model layer, encompassing both the canopy interior and the region above the canopy top. The resulting profiles are then vertically integrated over each model layer (e.g., 0 – 40 m) to generate effective layer-average values used in CMAQ's chemistry and transport calculations. While this approach does not explicitly resolve sub-layer chemical reactions, it preserves the first-order impacts of canopy height, structure, and shading on the O_3 photochemical environment.

It is also important to note that in the current CMAQ configuration, biogenic VOC emissions from vegetation are calculated using the BEIS model with a "big-leaf" approach, without accounting for vertical heterogeneity in VOC emission or in-canopy chemistry. As a result, any vertical gradients in VOC emissions (e.g., higher isoprene production near the upper canopy) are not explicitly represented, which may introduce systematic biases in modeled first-layer concentrations and reactivity, particularly in grid cells with relatively short canopy heights.

In our implementation, canopy effects are only activated when the forest canopy height exceeds 10 m (approximately one-fourth of the first model layer depth). According to the canopy height and land cover data used in this study, most canopy-affected grid cells fall within the 10–30 m range (see Fig. S1), and our analysis is primarily focused on those with moderate to tall forest cover. Nonetheless, we acknowledge that the vertical averaging approach may not fully capture chemical or emission gradients in shorter canopies, and this remains an area for further improvement.

We have clarified this point in the revised manuscript (Section 2.2, Lines 263–268) and added a discussion of this limitation in the updated Discussion section. Additionally, we are actively addressing these limitations in ongoing work to develop a multi-layer canopy chemistry and deposition module (see https://github.com/noaa-oar-arl/canopy-app). This framework will enable explicit treatment of leaf-level VOC fluxes and sub-canopy chemical and deposition processes, which we view as an important next step for improving air quality model representation in forested environments.

Specific Comments

Line 153: Adding in a short definition of what forest clumping index is would help clarify how threshold criteria #5 is calculated.

We have added a concise explanation of the forest clumping index (CLU) in the revised manuscript to improve clarity regarding threshold criterion #5 in Line 155 to 160. Now it read:

"The CLU is a unitless parameter ranging from 0 to 1 that describes the spatial distribution of foliage within the canopy. A CLU value of 1 indicates randomly distributed leaves, while lower values reflect increasing aggregation or "clumping" of leaf area (Makar et al., 2017; CHEN and BLACK, 1992; Chen et al., 2005)). The clumping index is used in conjunction with LAI to estimate the light extinction through the canopy and thus the fraction of direct radiation reaching the ground."

In criteria #5, we define a canopy as optically and dynamically significant only if more than "55% of incoming solar radiation" is attenuated before reaching the ground and "the canopy height exceeds 18 m". This is calculated using the formulation:

$EXP(-0.5*LAI*CLU) < 0.45$ and $FCH > 18$ m

This combination of LAI, CLU, and forest canopy height (FCH) helps ensure that canopy parameterizations are only applied where shading and turbulence effects are expected to meaningfully influence near-surface chemistry and transport.

Lines 171–186: The phrasing of this section is somewhat confusing. The text defines canopy threshold criteria by describing conditions under which grid cells do not qualify, while italicizing the qualifying metrics. To improve clarity, consider consistently framing each criterion in terms of what qualifies as a canopy. For example: "1. The LAI exceeds a minimal threshold for forest cover (i.e., more likely to have canopy shading or turbulence changes): LAI > 0.1." Line 250: The frequent references to Makar et al. (2017) may reduce accessibility for readers unfamiliar with that study, such as those who are interested in just CMAQ improvements. To improve clarity, I recommend including Eqs. 4–9 from Makar et al. (2017) in the Supplementary Information.

We appreciate the reviewer's thoughtful feedback regarding the clarity of Section 2.3 (Lines 171–186) and the presentation of the canopy threshold criteria. We have revised the section Line 179 - 189 to consistently describe each criterion in terms of what qualifies a grid cell as being affected by the canopy, aligning with the reviewer's suggested phrasing. Now it read:

1. The LAI exceeds a minimum threshold, suggesting that the grid cell likely has sufficient canopy shading or turbulence effects: LAI > 0.1.

2. The canopy height (FCH) is substantial relative to the model's vertical resolution, such that it occupies at least one-fourth of the first model layer (which spans ~40 meters): FCH > 10 m.
3. The population density is low enough to indicate that the grid cell is not dominated by urban influence: POPU < 10,000 people per 10 km² (i.e., < 1,000 people per km²).
4. The forest fraction (FRT) exceeds 0.5, indicating that more than half of the land use in the grid cell is covered by forest, consistent with a contiguous forest canopy: FRT > 0.5.
5. The canopy is tall enough and dense enough to significantly reduce incident light reaching the surface, defined by the condition that less than 55% of incoming light reaches the ground: EXP(-0.5 × LAI × CLU) < 0.45 and FCH > 18 m.

Additionally, in response to the comment regarding repeated references to (Makar et al., 2017), we have included the relevant equations (originally numbered Eqs. 4–9 in Makar et al., 2017) in the Supplementary Information of the revised manuscript. This addition will help readers better understand the underlying turbulence and photolysis parameterizations used in the canopy implementation without requiring them to access the original reference.

We thank the reviewer again for these helpful suggestions, which have improved the clarity and accessibility of the manuscript.

Line 260-261: Please clarify how the sub-grid $K_{can}(z)$ values are incorporated into CMAQ's first model layer. Is a vertical average used to replace K(z1)? How sensitive is this approach to canopy height, particularly when canopy heights fall well below the vertical extent of the first layer?

We appreciate the reviewer's question regarding the implementation of sub-grid *Kcan*(z) within CMAQ's vertical structure. In our approach, the eddy diffusivity *Kcan* is computed at a fine vertical resolution (Δz = 0.5 m) from the ground to the top of the canopy using the formulation from Makar et al. (2017), and extended up to the top of CMAQ's first model layer (approximately 40 m). These sub-grid *Kcan*(z) values are then vertically integrated and averaged over the full extent of the first CMAQ model layer to yield a layer-mean *Kcan* value, which replaces the default K(z1) in CMAQ's vertical mixing scheme. This method enables CMAQ to incorporate the effects of canopy-induced reductions in turbulent diffusivity, even without explicitly resolving the roughness sublayer or sub-canopy layers.

To address the reviewer's concern about sensitivity to canopy height: in our implementation, canopy effects are only applied in grid cells where forest canopy height (FCH) exceeds 10 m, which is approximately one-fourth of the first model layer depth. As shown in Figure S1, most affected grid cells in our domain fall within the 10–30 m canopy height range. This ensures that the vertical averaging approach meaningfully captures turbulence reductions across both the canopy interior and the region just above the canopy. However, we acknowledge that for canopy heights much smaller than the first model layer, the averaging may dilute the canopy signal, potentially underestimating the effect in regions with shorter vegetation or patchy land cover. This limitation is now clarified in Section 2.2 (Lines 263-268) and discussed further in the revised Discussion (Section 4 Line 829 – 838 and Fig. S4).

Line 358-359: The term "indirect effect" is mentioned a few times. It would be helpful to define a quantitative or operational threshold for when a site is considered indirectly impacted by canopy processes.

We appreciate the reviewer's suggestion to clarify the term "indirect effect." In our study, indirectly impacted sites refer to grid cells that do "not" meet the five canopy threshold criteria and therefore do not activate the canopy-adjusted turbulence (K_{can}) or photolysis attenuation parameters. However, because CMAQ is an Eulerian grid-based model, the chemical and physical effects from canopy-affected grid cells can propagate through horizontal and vertical transport. As a result, even non-canopy grid cells can experience changes in pollutant concentrations (e.g., O_3, NO_x) indirectly due to interactions with air masses influenced by canopy processes. Thus, we define "indirect effect" operationally as changes in modeled chemical concentrations at grid cells where the canopy scheme is not explicitly applied, but where the air masses may have been influenced by adjacent or upwind canopy-affected regions. This clarification has now been added to the revised manuscript (Lines 353–356).

Table 2: Across the U.S. Domain, ME, NME, and R do not change for Hourly O3 and MDA8 O3. Does this mean that the variability in O3 is dominated by non-canopy sites? R for hourly O3 also does not change for the Canopy scenario. You mention improvements in variability in the daytime diel profile but is that compensated for by poorer nighttime values?

We thank the reviewer's comments, the statistical metrics such as Mean Error (ME), Normalized Mean Error (NME), and correlation coefficient (R) across the full U.S. domain show minimal change between the Base and Canopy scenarios (Table 2). This is expected, as only ~19% of AQS sites fall within grid cells directly impacted by canopy effects (see Fig. 2), while the majority of the domain is not affected by the parameterizations. Thus, the aggregated statistics across the full domain are dominated by non-canopy sites, where ozone variability remains largely unchanged.

To better highlight the impact of the canopy parameterization, we separately report model performance at canopy-affected sites (Table 2, rows labeled "Canopy effect"), where more notable improvements in MB and FB are observed.

For hourly O_3, the correlation coefficient (R) is primarily influenced by the model's ability to capture the diurnal pattern, particularly the timing and magnitude of peak and minimum concentrations. Our canopy implementation helps reduce the systematic bias in O_3 concentrations by lowering nighttime and early morning values, which contributes to a more realistic diurnal shape. This process like reduce over estimated value (like reduce the slope of regression model line), but not improve the relationship between model and observational data. Therefore, this adjustment does not significantly improve the mean error (ME) or normalized mean error (NME), likely due to persisting uncertainties in emission pattern, meteorology, and deposition processes within the base model configuration.

Line 421-422: Visual inspection of Figure 4 does not clearly support the claim that variability predictions have improved. Please provide a statistical metric, such as coefficient of variation or standard deviation, to demonstrate this more convincingly.

We thank the reviewer for this valuable comment. Upon reflection, we believe that Figures 4(b) and 4(c)—which present hourly statistical metrics, mean bias (MB) and fractional bias (FB), respectively—already provide compelling statistical evidence of improved variability in the Canopy scenario. (see model performance metric formula definitions in supplementary document)

In Figure 4(b), the hourly MB boxplots show that the Canopy case reduces overall bias, especially during daytime hours (0:00–14:00 LT). This suggests reduced variability in bias across the 235 canopy-affected AQS sites. Similarly, Figure 4(c) demonstrates a clear reduction of the FB in the Canopy case, with most boxes centered closer to zero throughout the day and night. These consistent reductions in spread, particularly in FB (which normalizes by magnitude), reflect improved model mean and a closer to observed O_3.

Therefore, while Figure 4(a) focuses on absolute concentration values, Figures 4(b) and (c) are mean bias (MB) and fraction bias (FB) and serve as direct statistical diagnostics of variability and support our claim. We have provided the hourly MB and FB table in support document (table S3) to show the hourly details of canopy effect on MB and FB.

Lines 424–425: It would be helpful to further explain how "The larger variability in the canopy model is impacted by the more discrete nature of the turbulent eddies using Raupach's approach to K diffusivities." by reading lines 419-425 or looking at Figure 4 alone. An additional sentence or two clarifying the mechanism would benefit readers.

We appreciate the reviewer's suggestion to further clarify the mechanism behind the statement regarding the "more discrete nature of the turbulent eddies" in the Canopy model. While our previous revision (Lines 420–425) discussed how the updated parameterization improves the spread of ozone concentrations, we agree that the connection between discrete eddy structure and increased ozone variability deserves a more explicit explanation.

To address this, we have edited paragraph in Section 3.1 Lines 428 - 438 of the revised manuscript:

"Figure 4 shows that the canopy parameterization improves the diurnal pattern of hourly mean O_3 concentrations at most AQS sites affected by canopy effects. Between 9:00 and 14:00 local time, the Canopy simulation better captures the observed spread in ozone levels, with its vertical extent more closely aligning with the broader distribution seen in observations than the Base case. This suggests that the updated parameterization more accurately represents the magnitude of daytime ozone variability. The enhanced spread in the Canopy case arises from the more discrete and intermittent nature of turbulent eddies, as represented by Raupach's near-field approach to vertical diffusivity (Eqs. 2–3). This formulation suppresses vertical diffusivity near the canopy top, particularly under stable or weakly mixed conditions, which can lead to localized accumulation or depletion of ozone within the canopy layer, thereby increasing spatial and temporal variability across sites and hours."

Technical Corrections

Line 69: I suggest changing big leaf to "big-leaf" to stay consistent with your naming.

Thank you, we have changed this in consistent words.

Line 81: Is there an extra "and" in "…may drive and chemical processes…"?

Thank you, we have removed the "and" in this sentence.

Line 524: "More negative" could be replaced with "decreases" for clarity.

Thank you, we have replaced it with "decreases."

Line 531: Typo: "la7rger" should be corrected to "larger".

Thank you, we corrected it.

Reference:

Pleim, J., Venkatram, A., Yamartino, R.: ADOM/TADAP Model Development Program: The Dry Deposition Module; Ontario, Ministry of the Environment, 4, 1984.

CHEN, J. M. and BLACK, T. A.: Defining leaf area index for non-flat leaves, Plant, Cell & Environment, 15, 421-429, https://doi.org/10.1111/j.1365-3040.1992.tb00992.x, 1992.

Chen, J. M., Menges, C. H., and Leblanc, S. G.: Global mapping of foliage clumping index using multi-angular satellite data, Remote Sensing of Environment, 97, 447-457, https://doi.org/10.1016/j.rse.2005.05.003, 2005.

Galmarini, S., Makar, P., Clifton, O. E., Hogrefe, C., Bash, J. O., Bellasio, R., Bianconi, R., Bieser, J., Butler, T., Ducker, J., Flemming, J., Hodzic, A., Holmes, C. D., Kioutsioukis, I., Kranenburg, R., Lupascu, A., Perez-Camanyo,

J. L., Pleim, J., Ryu, Y. H., San Jose, R., Schwede, D., Silva, S., and Wolke, R.: Technical note: AQMEII4 Activity 1: evaluation of wet and dry deposition schemes as an integral part of regional-scale air quality models, Atmos. Chem. Phys., 21, 15663-15697, 10.5194/acp-21-15663-2021, 2021.

Hogrefe, C., Bash, J. O., Pleim, J. E., Schwede, D. B., Gilliam, R. C., Foley, K. M., Appel, K. W., and Mathur, R.: An analysis of CMAQ gas-phase dry deposition over North America through grid-scale and land-use-specific diagnostics in the context of AQMEII4, Atmos. Chem. Phys., 23, 8119-8147, 10.5194/acp-23-8119-2023, 2023.

Makar, P. A., Staebler, R. M., Akingunola, A., Zhang, J., McLinden, C., Kharol, S. K., Pabla, B., Cheung, P., and Zheng, Q.: The effects of forest canopy shading and turbulence on boundary layer ozone, Nature Communications, 8, 15243, 10.1038/ncomms15243, 2017.

Pleim, J. and Ran, L.: Surface Flux Modeling for Air Quality Applications, Atmosphere, 2, 271-302, 2011.

Ran, L., Pleim, J., Gilliam, R., Binkowski, F. S., Hogrefe, C., and Band, L.: Improved meteorology from an updated WRF/CMAQ modeling system with MODIS vegetation and albedo, Journal of Geophysical Research: Atmospheres, 121, 2393-2415, https://doi.org/10.1002/2015JD024406, 2016.