

Author's Response to the Interactive Comments on “Assessment of WRF-GHG Model Simulations during the CAFE-Brazil Campaign in Amazonia”

We thank the anonymous reviewer for their constructive and valuable comments, which helped us improve the clarity and focus of the manuscript. Below, we address each point raised.

Reviewer Comment 1: Clarity of scientific focus and main message

“The manuscript contains many valuable analyses, but the central take-home messages are sometimes diluted by the volume of material. Early in the Introduction (end of Section 1), explicitly state 3–4 core hypotheses or questions can be helpful. For example: To what extent are CO₂ and CH₄ mismatches dominated by transport vs. flux errors? Does kilometer-scale resolution meaningfully improve GHG simulations in Amazonia under convective conditions?”

Author Response:

We thank the reviewer for this suggestion. We agree that stating the scientific questions explicitly at the end of the Introduction helps orient the reader.

We have revised the end of Section 1 to include the following three guiding questions:

(1) To what extent do atmospheric transport errors versus wetland flux uncertainties explain the observed–simulated mismatches in CH₄ mole fractions at ATTO? (2) How do large-scale wind regime misrepresentation and boundary-layer dynamics interact to modulate CH₄ transport biases at a tall tower site in central Amazonia? (3) Can regionally adapted biogenic flux parameterizations improve the representation of CO₂ net ecosystem exchange and CH₄ mole fractions in kilometer-scale WRF-GHG simulations over Amazonia?

We did not include the questions proposed by the reviewer, related to the role of kilometer-scale resolution, because this is only partially addressed in this study, as we do not perform a direct resolution sensitivity experiment.

Changes in the manuscript:

Three guiding questions have been added at the end of Section 1 (line [75] of the revised manuscript).

Text to add:

These objectives are guided by three core scientific questions: (1) To what extent do atmospheric transport errors versus wetland flux uncertainties explain the observed–simulated mismatches in CH₄ mole fractions at ATTO? (2) How do large-scale wind regime misrepresentation and boundary-layer dynamics interact to modulate CH₄ transport biases at a tall tower site in central Amazonia? (3) Can regionally adapted biogenic flux parameterizations improve the representation of CO₂ net ecosystem exchange and CH₄ mole fractions in kilometer-scale WRF-GHG simulations over Amazonia?

Reviewer Comment 2: Transport versus flux attribution

“A recurring theme is that meteorological biases dominate tracer errors, particularly for CH₄. While this is plausible and supported by evidence, the attribution is sometimes qualitative. Where possible, quantify transport sensitivity more explicitly, for example by showing tracer simulations with identical fluxes but different wind/PBL configurations (even if only briefly in the Supplement), or by explicitly stating how much of the CH₄ bias at ATTO can be explained by wind-direction errors during key events.”

Author Response:

We thank the reviewer for this suggestion. To quantify the contribution of transport errors to the CH₄ bias at ATTO, we performed a Spearman correlation analysis between the absolute CH₄ bias and three transport variables: wind direction error, wind speed error, and PBL height error, for all daytime events (N = 123).

Wind direction errors show no significant correlation with CH₄ bias ($r = -0.06$, $R^2 < 0.01$, $p = 0.53$), consistent with **Figure 1c**, where CH₄ residuals are nearly identical regardless of whether the modeled wind regime matches the observed one. Wind regime misclassification is therefore not a meaningful predictor of CH₄ bias magnitude.

In contrast, wind speed errors ($r = -0.34$, $R^2 = 0.11$, $p < 0.001$) and PBL height errors ($r = -0.39$, $R^2 = 0.16$, $p < 0.001$) are both statistically significant. The negative correlations indicate that underestimation of wind speed or PBL height reduces near-surface CH₄ dilution, producing larger positive biases. Partial correlations confirm that these predictors contribute independently ($r_{\text{partial}} = -0.33$ and -0.38 , respectively). Together, the three variables explain 14% of the total CH₄ bias variance (multiple regression $R^2 = 0.14$). The Southeast (SE) regime shows the strongest dependence ($r = -0.43$ for wind speed, $r = -0.41$ for PBL height).

The remaining ~86% of unexplained variance, along with the large CH₄ residuals observed even under correctly classified SE→SE transitions (**Figure 1b**), suggests that uncertainties in wetland fluxes are the dominant source of bias. This interpretation is further supported by polar plots (**Figure 2**), where

the largest CH₄ overestimation occurs under easterly winds — the direction most associated with upwind wetland sources — despite no systematic wind direction error in these cases.

Thus, while transport errors, particularly wind speed and PBL height underestimation, contribute modestly to CH₄ bias, improving wetland flux estimates is likely to have a larger impact on reducing model-observation discrepancies at ATTO.

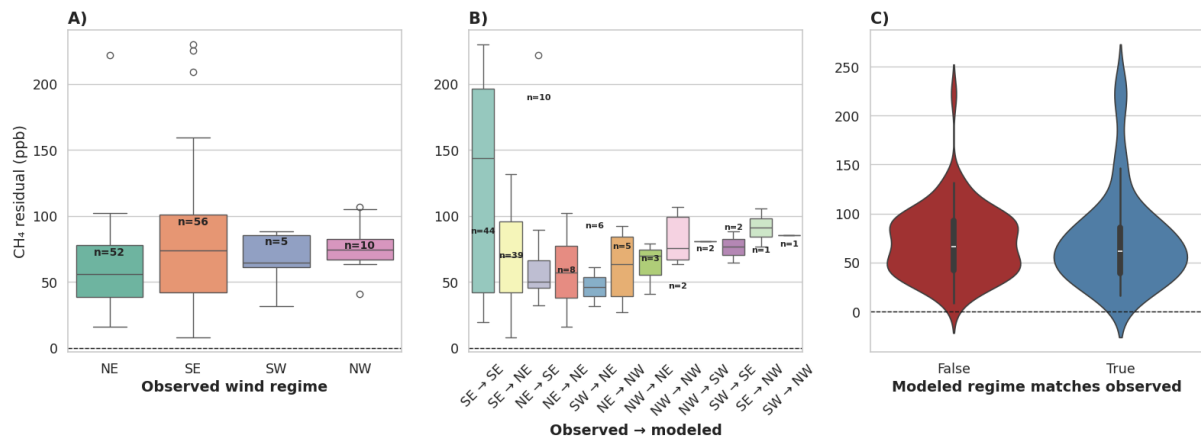


Figure 1. CH₄ residual [ppb] as a function of wind regime classification at ATTO during January 2023. (A) Box plots of CH₄ residuals grouped by observed wind regime (NE, SE, SW, NW) for daytime period (N=123). (B) CH₄ residuals grouped by observed-to-modeled wind regime transitions, showing cases where the model correctly reproduces the regime (e.g., SE→SE) and cases where it does not (e.g., SE→NE). (C) Violin plots comparing CH₄ residuals for events where the modeled wind regime matches the observed (True) versus events where it does not (False), for the daytime period. The dashed horizontal line indicates zero residual. The simulated CH₄ concentration is from the Kaplan model.

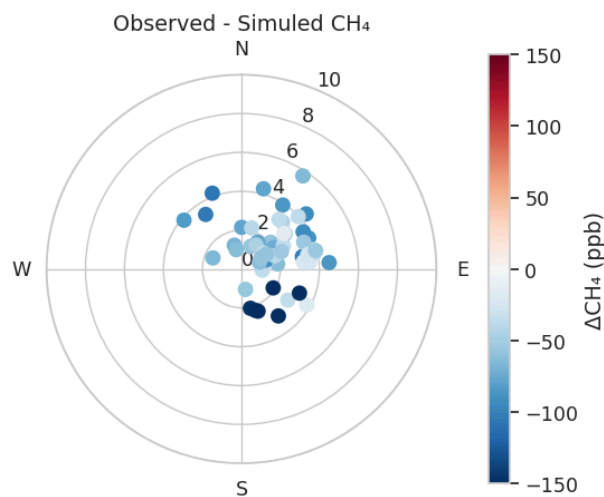


Figure 2. Polar plot of the difference in CH₄ mole fractions ($\Delta\text{CH}_4 = \text{observed} - \text{simulated}$, ppb) as a function of wind direction and wind speed at ATTO during January 2023 for the daytime period. Each point represents an hourly mean, with radial distance indicating wind speed (m s^{-1}) and color indicating the CH₄ difference. Positive values (warm colors) indicate that observations exceed model simulations, whereas negative values (cool colors) indicate model overestimation. The largest negative residuals occur under easterly wind conditions (approximately 80°–120°), suggesting a systematic model overestimation associated with air masses transported from wetland source regions upwind of ATTO.

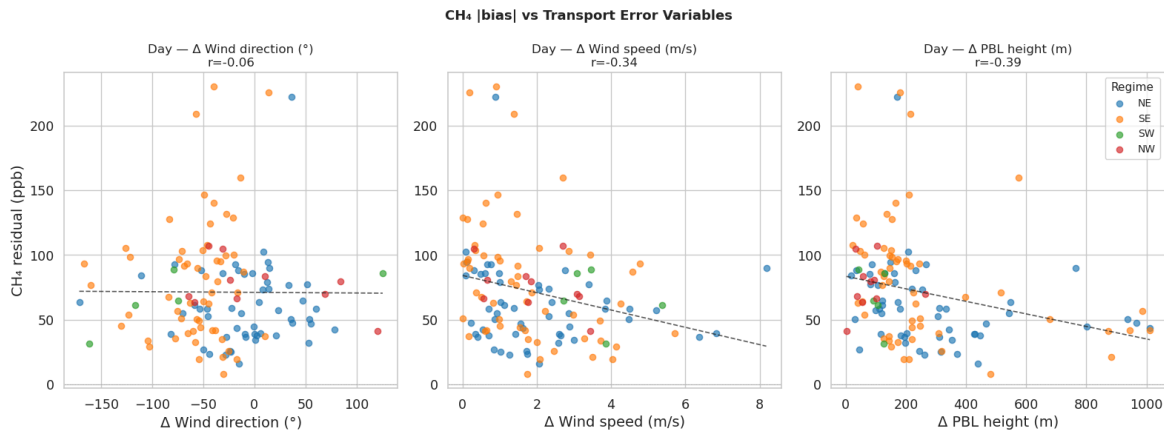


Figure 3. Correlation between daily CH₄ residual and transport error variables: wind direction difference (left), wind speed difference (center), and planetary boundary layer (PBL) height difference (right). Points are colored by transport regime (NE, SE, SW, NW). Dashed lines indicate linear regression fits, and r denotes the Pearson correlation coefficient for each variable.

Changes in the manuscript:

The quantitative transport attribution analysis has been incorporated into Sections 5 and 6 of the revised manuscript. Figures 1, 2, and 3 have been added as Figures S16, S17, and S18 in the supplementary manuscript.

Current text to be added (Section 5: line 430):

After the following paragraph: *"This highlights key differences between observed and simulated wind patterns. "*

And before: *"To further investigate the contribution of advection.."*

Text to add:

*To systematically quantify the contribution of transport errors to the CH₄ bias at ATTO, we performed a Spearman correlation analysis between the absolute CH₄ bias and three transport variables: wind direction error, wind speed error, and PBL height error, for all daytime events ($N = 123$): wind direction error, wind speed error, and PBL height error. Wind direction errors show no significant correlation with CH₄ bias ($r = -0.06$, $R^2 < 0.01$, $p = 0.53$), consistent with **Fig. S16c**, where CH₄ residuals are nearly identical regardless of whether the modeled wind regime matches the observed one. Wind regime misclassification is therefore not a meaningful predictor of CH₄ bias magnitude. In contrast, wind speed errors ($r = -0.34$, $R^2 = 0.11$, $p < 0.001$) and PBL height errors ($r = -0.39$, $R^2 = 0.16$, $p < 0.001$) are both statistically significant. The negative correlations indicate that underestimation of wind speed or PBL height reduces near-surface CH₄ dilution, producing larger positive biases. Partial correlations confirm that these predictors contribute independently ($r_{\text{partial}} = -0.33$ and -0.38 ,*

respectively). Together, the three variables explain 14% of the total CH₄ bias variance (multiple regression $R^2 = 0.14$). The Southeast (SE) regime shows the strongest dependence ($r = -0.43$ for wind speed, $r = -0.41$ for PBL height). The remaining ~86% of unexplained variance, along with the large CH₄ residuals observed even under correctly classified SE→SE transitions (**Fig. S16b**), suggests that uncertainties in wetland fluxes are the dominant source of bias. This interpretation is further supported by polar plots (**Fig. S17**), where the largest CH₄ overestimation occurs under easterly winds — the direction most associated with upwind wetland sources — despite no systematic wind direction error in these cases. Thus, while transport errors, particularly wind speed and PBL height underestimation, contribute modestly to CH₄ bias, improving wetland flux estimates is likely to have a larger impact on reducing model-observation discrepancies at ATTO.

Current text to be replaced (Section 6: line 538-541):

"For CH₄, simulated concentrations were largely controlled by background concentration and atmospheric transport, with local emissions playing a secondary role at ATTO. The simulations produced an artificial diurnal cycle driven by PBL dynamics, in contrast to the nearly constant observed concentrations, highlighting deficiencies in the representation of boundary-layer transport (particularly horizontal mixing), which compromise the concentrations observed at ATTO. Among the flux models, Kaplan strongly overestimated CH₄, whereas CAMS-Inversion and WetCHARTs showed better agreement with both surface and aircraft observations. Aircraft observations from the CAFE-Brazil campaign further demonstrate that WetCHARTs and CAMS-Inversion better capture the spatial variability of CH₄."

Replace with:

For CH₄, transport errors in wind speed and PBL height contribute modestly but significantly to the bias at ATTO, jointly explaining 14% of total CH₄ bias variance, while wetland flux uncertainties emerge as the dominant source of model-observation discrepancies. Among the flux models, Kaplan strongly overestimated CH₄, whereas CAMS-Inversion and WetCHARTs showed better agreement with both surface and aircraft observations. Aircraft observations from the CAFE-Brazil campaign further demonstrate that WetCHARTs and CAMS-Inversion better capture the spatial variability of CH₄.

Reviewer Comment 3: Interpretation of CH₄ diurnal cycle at ATTO

"The manuscript notes that the observed CH₄ signal at ATTO shows minimal diurnal variability, while simulations show a pronounced cycle driven by PBL dynamics. However, the discussion sometimes implies that this is primarily a model failure. Is it possible that this can be a combination of

alternative factors, such as weak local sources, tall tower sampling above canopy, and persistent regional background dominance?”

Author Response:

We thank the reviewer for this comment. The flat diurnal CH₄ cycle observed at ATTO during the wet season is best explained by these two factors. The absence of strong local CH₄ sources in the immediate tower footprint: ATTO is surrounded by upland terra firme forest, which is not a significant CH₄ source (Botía et al., 2020). The nearest wetland source — the Uatumã River — produces detectable signals primarily under specific nocturnal atmospheric conditions characterized by strong thermal stratification and low wind speeds from the SE (Botía et al., 2020). These conditions are less frequent during the wet season daytime. Second, the spatial heterogeneity of regional wetland emissions, which are distributed across large inundated areas upwind of ATTO, results in a well-mixed regional signal with limited temporal structure at the hourly scale. Whether Amazon wetland emissions themselves exhibit a diurnal cycle is poorly constrained observationally — diffusive fluxes from tropical wetlands have been reported to show little diurnal variation (Teh et al., 2017), and the dominant transport pathways do not necessarily respond to diurnal atmospheric forcing (Bastviken et al., 2024). We therefore could interpret the flat diurnal signal as the absence of sources, but also as the absence of a diurnal structure in those regional sources, combined with the lack of strong local emitters.

Changes in the manuscript:

Section 5 has been revised to reflect this more precise interpretation (lines [402-404]). Language that could be misread as implying model failure as the primary cause of the flat diurnal cycle has been removed.

Current text to be replaced (Section 5, lines ~402-404):

"This result occurs because the ATTO plateau has no strong sources, and the simulated diurnal cycle is not associated with biogenic emissions but with incorrect transport. All simulations overestimated the observed CH₄, with CAMS-Inversion (blue triangles) providing the best agreement, showing the lowest mean bias compared to the other inventories. Kaplan (red stars) consistently produced concentrations exceeding 2100 ppb, likely due to an overestimation of wetland emissions (Fig. S12). "

Replace with:

This result reflects the absence of strong local CH₄ sources in the immediate tower footprint: ATTO is surrounded by upland terra firme forest, which is not a significant CH₄ source (Botía et al., 2020).

The nearest wetland source — the Uatumã River — produces detectable signals primarily under specific nocturnal atmospheric conditions characterized by strong thermal stratification and low wind speeds from the SE (Botia et al., 2020). These conditions are less frequent during the wet season daytime. Second, the spatial heterogeneity of regional wetland emissions, which are distributed across large inundated areas upwind of ATTO, results in a well-mixed regional signal with limited temporal structure at the hourly scale. Whether Amazon wetland emissions themselves exhibit a diurnal cycle is poorly constrained observationally — diffusive fluxes from tropical wetlands have been reported to show little diurnal variation (Teh et al., 2017), and the dominant transport pathways do not necessarily respond to diurnal atmospheric forcing (Bastviken et al., 2024).

Current text to be replaced (Section 6: line 544-545):

"These results are consistent with other recent methane modeling studies, which also emphasize the need for better representation of atmospheric transport and wetland emissions in the Amazon."

Replace with:

The flat observed diurnal CH₄ cycle at ATTO reflects the absence of diurnal modulation in regional wetland emissions and the lack of strong local sources, rather than model failure, a distinction with direct implications for flux attribution in tall tower studies over Amazonia.

The following comment was added to the main text, clarifying these aspects

Reviewer Comment 4: A few grammatical issues. Below are some examples

- Line 111: "trace gases"
- Line 134: "initial conditions"
- Line 262: "gases"
- Line 449: "This does not mean"

Author Response:

We thank the reviewer for carefully identifying these grammatical inconsistencies. The suggested corrections have been implemented throughout the revised manuscript, and the text was additionally proofread to improve clarity and consistency.

Reviewer Comment 5:

"Considering increasing font size in some figures, such as Figures 3, 4, 6, and 8. Ensuring colorblind-safe palettes."

Author Response:

We thank the reviewer for this suggestion. The font sizes in Figures 3, 4, 6, and 8 have been increased to improve readability. In addition, color palettes were revised where necessary to ensure better accessibility and colorblind-safe visualization.

Reviewer Comment 6:

“Be consistent when referring to “background,” “boundary conditions,” and “large-scale concentration.” Clarify that “background tracer” refers to prescribed CAMS concentrations or model large-scale concentrations.”

Author Response:

We thank the reviewer for pointing out this terminology inconsistency. The manuscript has been revised to use these terms more consistently throughout the text. We now explicitly clarify that “background tracer” refers to the prescribed large-scale concentrations from CAMS boundary conditions used in the simulations.

Reference

Bastviken, D., Treat, C. C., Pangala, S. R., Gauci, V., Enrich-Prast, A., Karlson, M., Gålfalk, M., Romano, M. B., and Sawakuchi, H. O.: The importance of plants for methane emission at the ecosystem scale, *Aquatic Botany*, 184, 103596, <https://doi.org/10.1016/j.aquabot.2022.103596>, 2023.

Teh, Y. A., Wayne, M., Berrio, J.-C., Boom, A., and Page, S. E.: Seasonal variability in methane and nitrous oxide fluxes from tropical peatlands in the western Amazon basin, *Biogeosciences*, 14, 3669–3683, <https://doi.org/10.5194/bg-14-3669-2017>, 2017.