Injection Height Perturbation– Sensitivity and Comparative Test for GEOS-Chem CO Model

Hannah Guo

Email: hannahulu.guo@mail.utoronto.ca

May 1st, 2024

Abstract

This study investigates the sensitivity of the GEOS-Chem chemical transport model to variations in injection heights of biomass burning emissions, utilizing carbon monoxide (CO) as the primary trace gas. Employing emissions data from the Global Fire Assimilation System (GFAS) and observational data from the Total Carbon Column Observing Network (TCCON), the study adjusts injection heights from 1500 meters to 7000 meters to assess their impact on model outputs. Despite these perturbations, only a minor improvement in the correlation coefficient (from 0.60 to 0.63) was observed, indicating a low sensitivity of the model to changes in injection height within this range.Future directions include enhancing vertical distribution modeling within GEOS-Chem, increasing model resolution, and expanding the scope of comparative analyses with additional observational datasets. This study contributes to our understanding of atmospheric modeling limitations and points towards potential areas for improvement in predicting the impacts of biomass burning on air quality and climate.

1 Introduction

Biomass burning refers to the combustion of living or once-living biological material. It was traditionally believed to primarily occur in tropical regions; however, satellite imagery has revealed a global distribution of biomass burning events. Biomass burning occurs wherever vegetation is abundant, with boreal forests serving as major sources.

This phenomenon can be triggered by natural processes, such as lightning, or human-induced activities. In the tropics, the majority of biomass burning events are anthropogenic, whereas natural causes are more prevalent in extratropical regions.

Sources of carbon monoxide (CO) include fossil fuel combustion, biomass burning, vegetation, oceans, and the oxidation of methane and other hydrocarbons. The estimates for these sources vary widely, but fossil fuel combustion and biomass burning are substantial contributors. This paper focuses exclusively on biomass emissions.

GEOS-Chem is a chemical transport model characterized by a horizontal resolution of 2^{o} latitude by 2.5^{o} longitude. It is driven by assimilated meteorology provided by NASA's Global Modeling and Assimilation Office. The model incorporates biomass burning emissions data from the Global Fire Assimilation System (GFAS), as detailed by Kaiser et al. (2012). GFAS assigns predetermined emission factors for various types of vegetation and materials, which may be burning. These factors are critical estimates of the amount of each pollutant released per kilogram of biomass burned and vary according to the type of biomass and the combustion conditions.

While other members of the research group are optimizing these emission factors through inverse modeling—assuming other variables remain constant—it is important to note that the GEOS-Chem model relies on estimations to determine emissions. Conventionally, all fires are injected at a specific altitude within the model. Therefore, this study aims to investigate how the model's results are affected by perturbations to the injection height within the troposphere. Specifically, we are interested in British Columbia biomass emissions in August 2018.

2 Methods

2.1 Model Configuration and Setup

This study utilized GEOS-Chem version 14.2.2 for carbon simulation, employing the default GFAS data files. We adjusted the fire emission injection heights in the model from the standard 1500 meters up to 7000 meters. This adjustment involved creating four modified GFAS files in addition to the one default file, thus enabling a range of scenarios to assess the impact of varying injection heights.

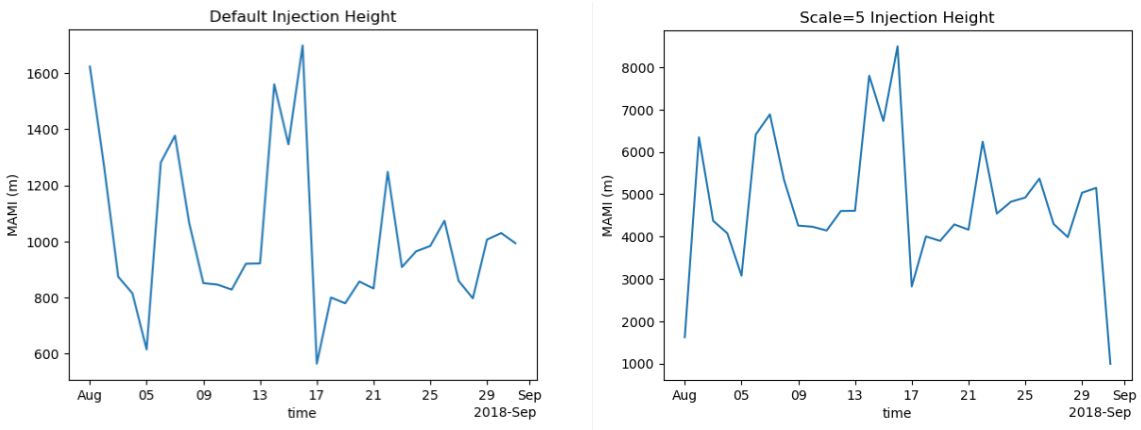

Figure 1: Injection Height Plots

The configuration of GEOS-Chem was modified to focus on the atmospheric conditions of August 2018. The model was set to run continuously throughout the month to capture the full cycle of emissions and atmospheric interactions. The primary modifications involved setting the appropriate date range in the GEOS-Chem configuration files and initiating the model run to generate the output data.

2.2 Data Collection for Sensitivity Analysis

For the purposes of sensitivity testing, observational data were sourced from the Total Carbon Column Observing Network (TCCON). TCCON utilizes ground-based Fourier Transform Spectrometers to measure the concentrations of greenhouse gases in the Earth's atmosphere. We are specifically looking at the time series data in East Trout Lake. This data (presented in Figure 2) is pivotal for calibrating and validating the accuracy of satellite sensors and was instrumental in providing a real-world comparative measure against our model's output.

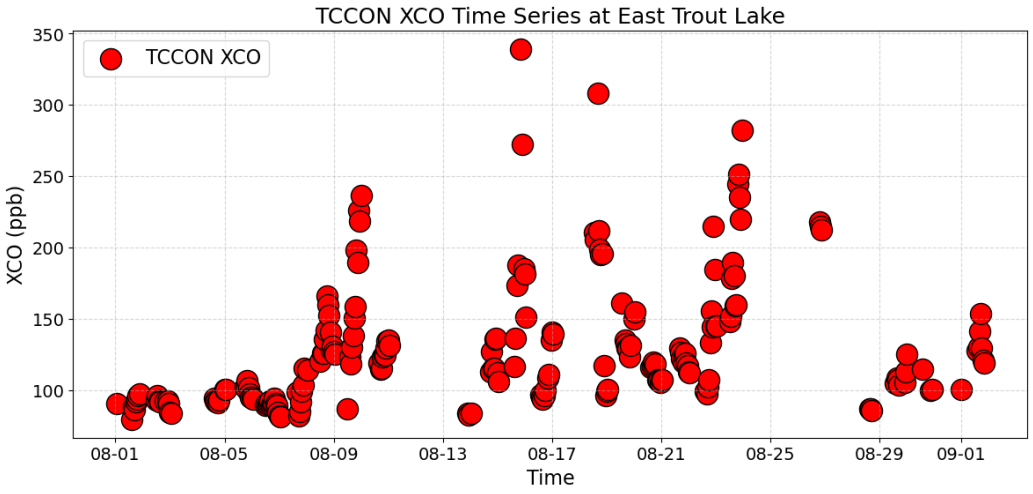

Figure 2: TCCON Measurement of CO at East Trout Lake

A comparative analysis was conducted to determine the statistical correlations between the carbon monoxide data produced by GEOS-Chem and the measurements recorded by TCCON. This analysis is crucial to understand the sensitivity of the model to changes in injection heights and to validate the model's performance against empirical atmospheric data.

3 Results

3.1 TCCON Data vs. GEOS-Chem Model

Upon comparing the CO outputs from GEOS-Chem with measurements from TCCON, a significant underestimation of CO concentrations by the GEOS-Chem model was observed relative to the actual measurements recorded by TCCON. This discrepancy highlights a consistent underestimation across the simulation scenarios.

The outputs for the five different injection heights tested (from 1500 meters to 7000 meters) revealed no significant increase in the accuracy of GEOS-Chem's CO measurements. Despite varying the injection heights, the model's performance did not show noticeable improvement in aligning with the TCCON data. There are four distinct peaks in all five plots– August 9th, 15th, 19th, and 24th.

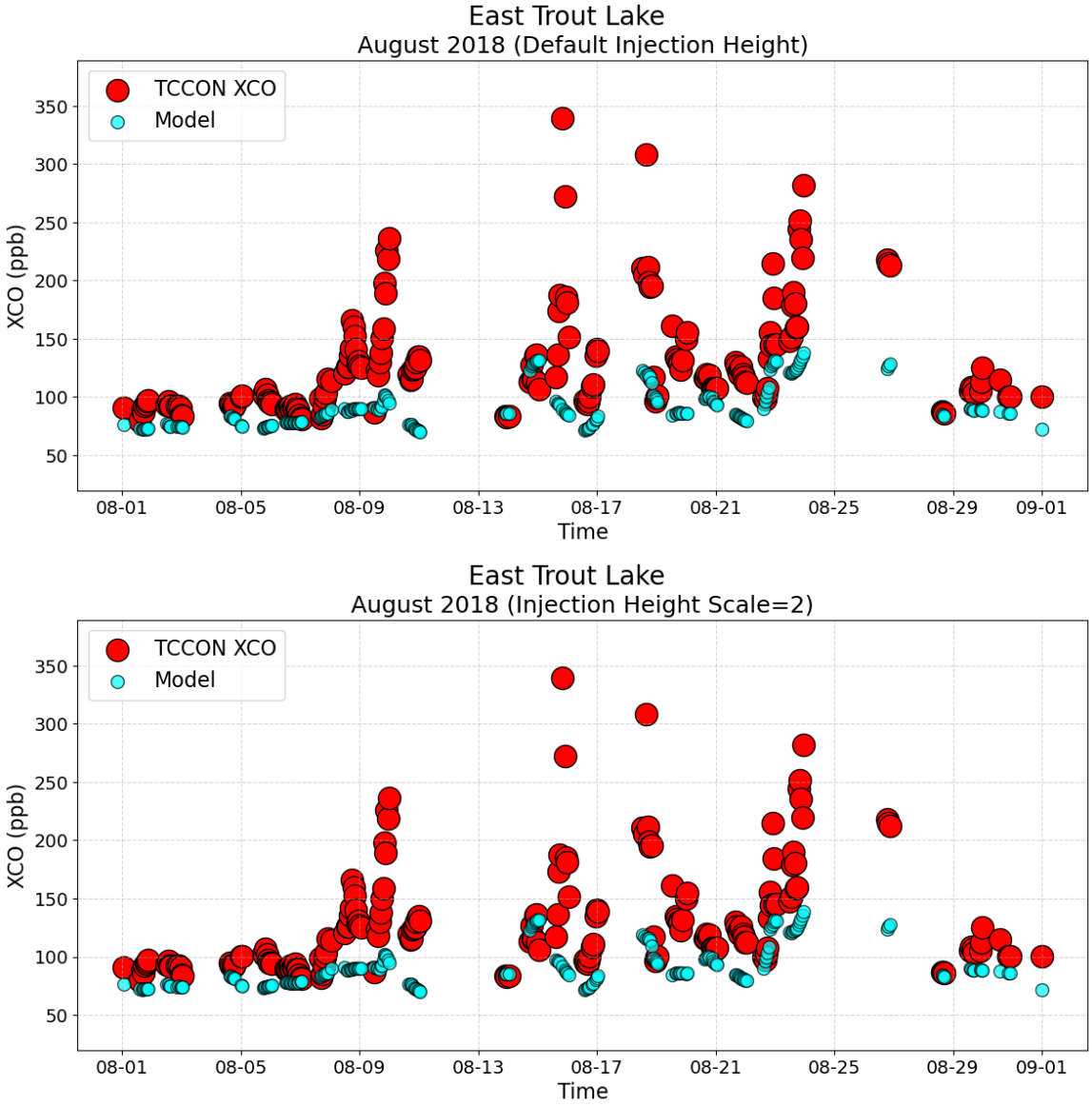

Figure 3: Plots with GEOS-Chem results vs. TCCON measurements

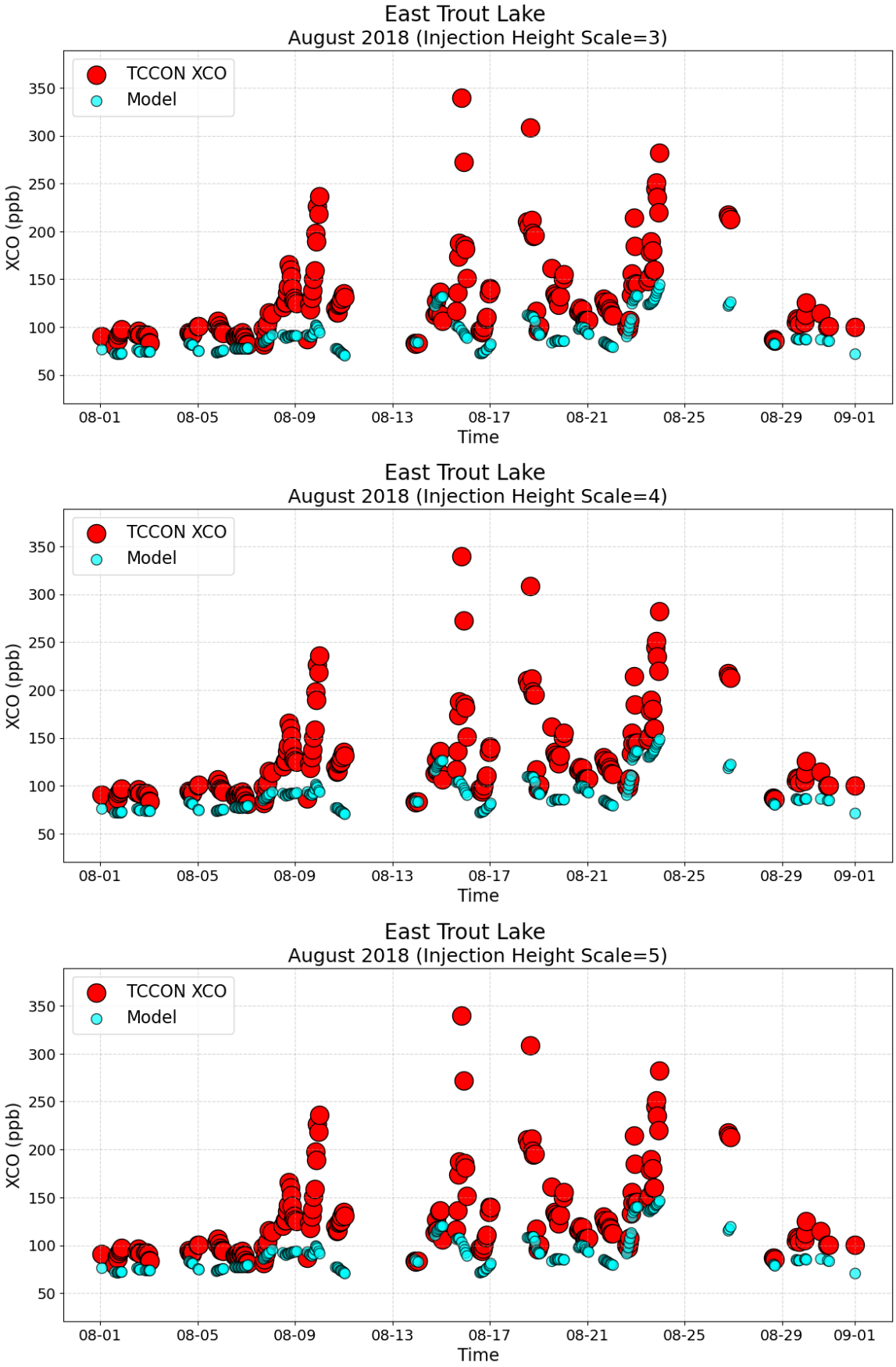

Figure 4: Plots with GEOS-Chem results vs. TCCON measurements cont'd

3.2 Correlation

Considering the observed discrepancies in the plots comparing GEOS-Chem output with TCCON measurements, it was essential to quantify the correlation to assess the sensitivity of the model to injection height perturbations. To achieve this, we employed the statistical correlation coefficient R. This coefficient indicates the degree of linear relationship between the modeled CO concentrations and the actual measurements from TCCON. A value of R closer to 1 would suggest a strong positive correlation, indicating better alignment between GEOS-Chem outputs and TCCON measurements.

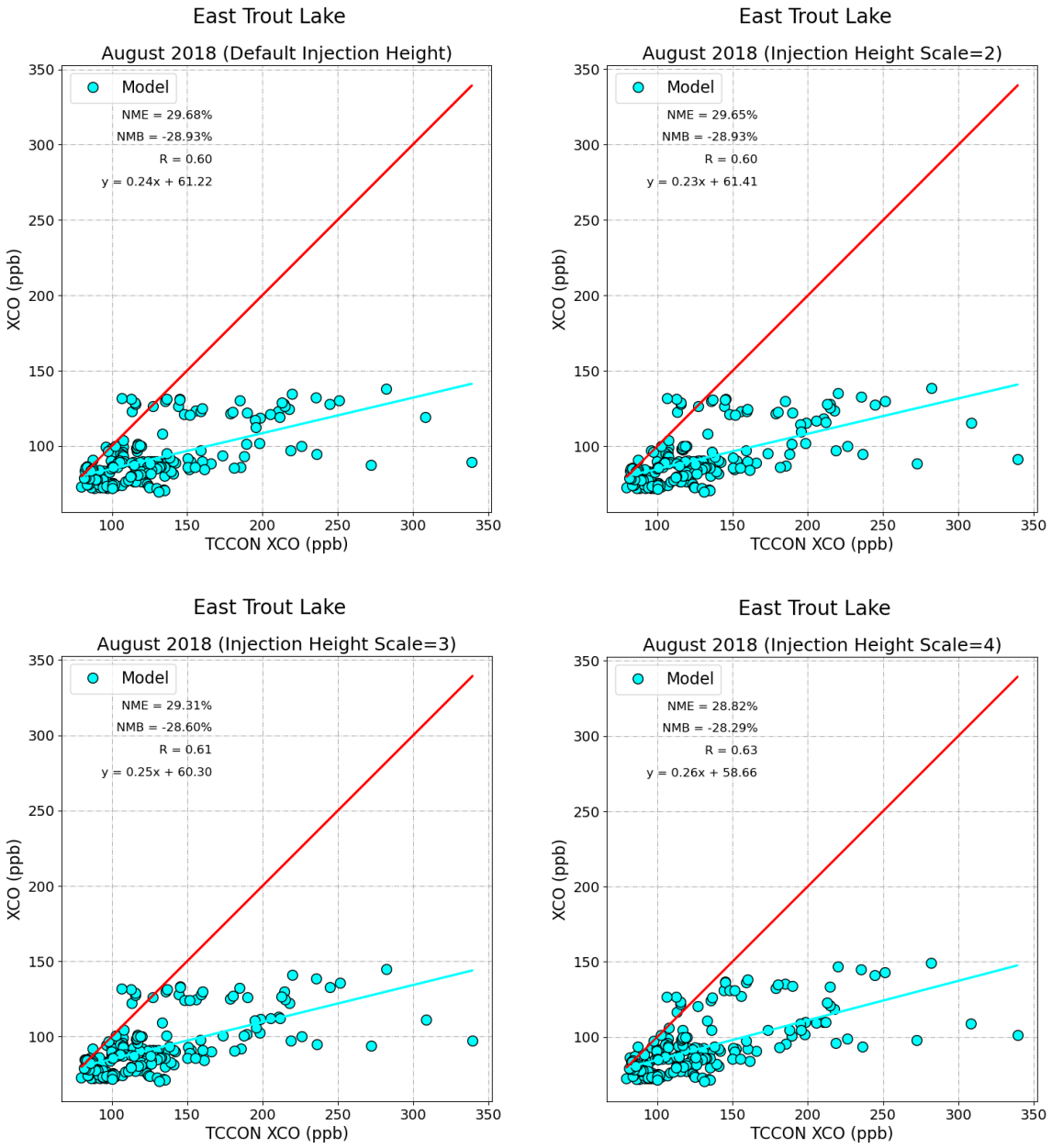

Figure 5: Correlation Plots between GEOS-Chem model outputs and TCCON measurements

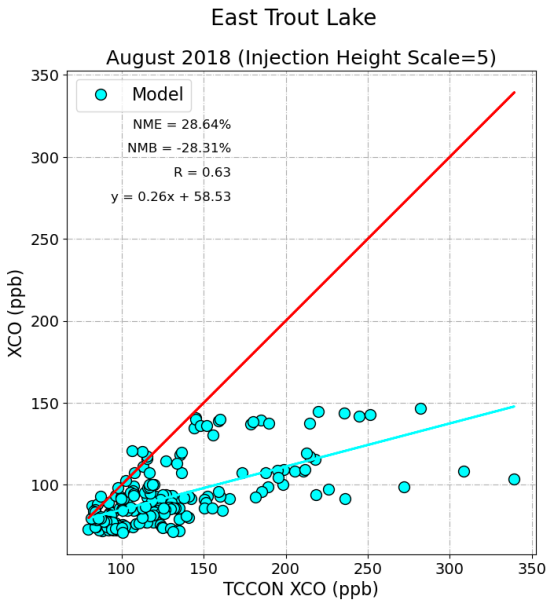

Figure 6: Correlation Plots between GEOS-Chem model outputs and TCCON measurements (cont'd)

4 Discussion

4.1 Sensitivity Test

From the outset, it is evident that the correlation coefficient R in Figure 6 showed a moderate increase, moving from 0.60 to 0.63 after adjusting the injection heights. This slight enhancement in the correlation value indicates a marginal improvement in the model's alignment with TCCON measurements. However, the small magnitude of this change, only 0.03 points, suggests that the GEOS-Chem model exhibits low sensitivity to changes in injection height. In practical terms, this implies that altering the altitude at which biomass burning emissions are injected into the model does not significantly impact the accuracy of the simulated CO concentrations. The limited response suggest a better way to estimate the vertical profile is needed.

4.2 Interpreting Discrepancies in CO Measurements

Initial Observations from TCCON Measurements** Firstly, it is important to recognize that TCCON measures atmospheric CO by observing the sun from the ground. The CO concentrations reported by TCCON encompass contributions from all injection heights across the atmospheric column. This broad integrative measurement approach is critical for understanding the full scope of atmospheric CO.

Although biomass burning emissions significantly contribute to atmospheric CO levels, other sources also play a role. These include fossil fuel combustion, industrial activities, and natural processes, which can contribute to the CO levels detected by TCCON. Given that our simulations specifically focus on biomass burning emissions injected at predetermined altitudes, some level of underestimation in our model outputs compared to TCCON data is expected.

Referring back to the earlier discussion in the Results section, particularly regarding the four peaks observed on specific dates, we conducted a backward trajectory analysis of air parcels, specifically the peak on August 24th. This analysis helps trace the origins of air masses detected at East Trout Lake:

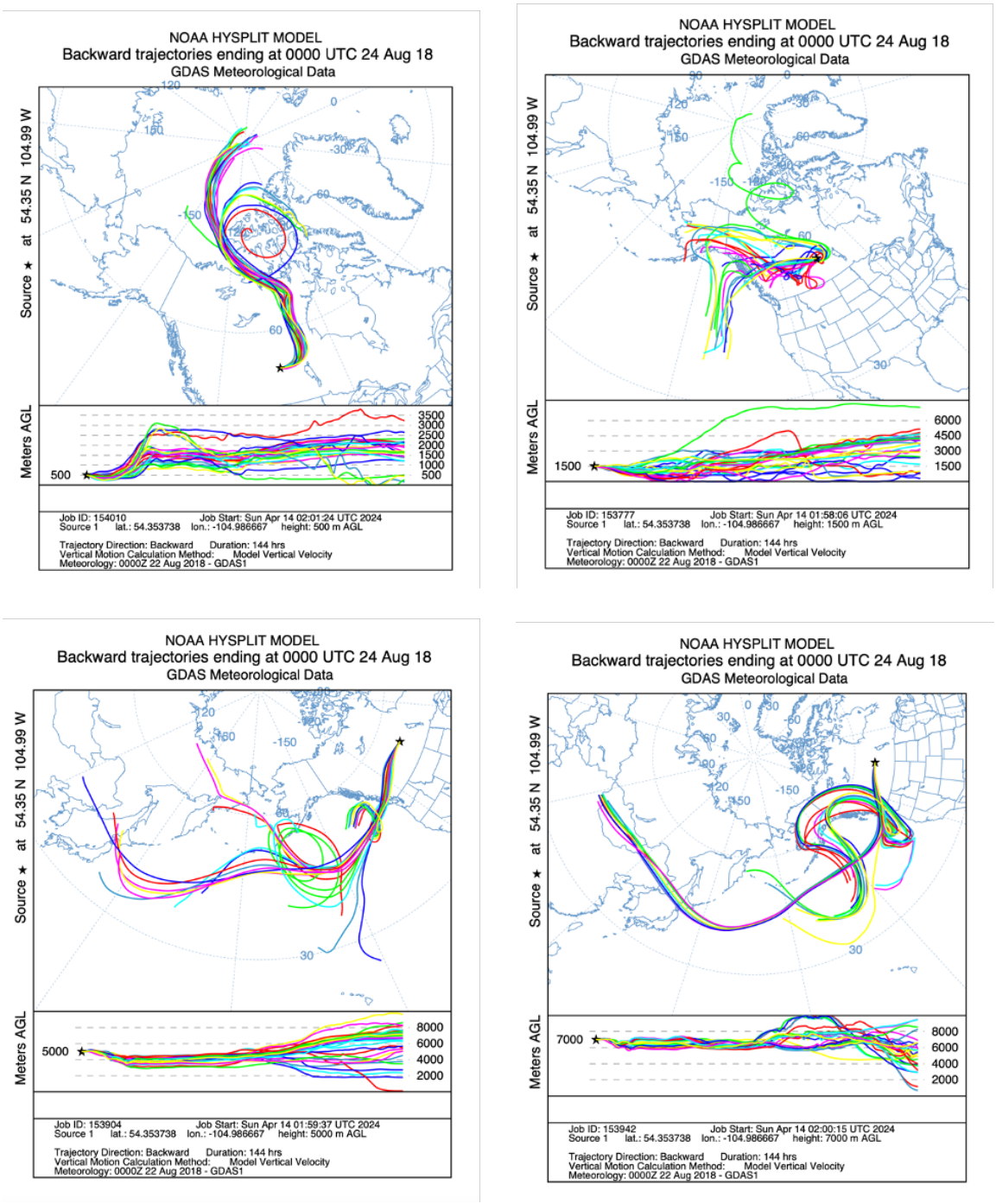

Figure 7: Six Day Back Trajectories of Air Parcels at East Trout Lake on August 24th

For low altitude trajectories (500m), air parcels primarily originated from the north. For higher altitude trajectories (1500m, 5000m, and 7000m), the origins of air parcels consistently shift to broader and more distant sources. The altitudes of 5000m and 7000m are situated in the mid-to-upper troposphere, significantly above the planetary boundary layer. Notably, air parcels in the mid- to upper troposphere originated from British Columbia, tracing further back to Siberia and northeastern China. The results are expected because at higher altitudes, atmospheric conditions are more influenced by upper-air patterns and less by direct surface processes.

These findings illustrate that the GEOS-Chem model, in its current configuration, captures only a fraction of the actual CO transported. The complexity of air parcel trajectories and the diversity of CO sources necessitate a more sophisticated approach to modeling vertical distribution. Enhancing the model to better account for these dynamics is essential for improving the accuracy of GEOS-Chem's predictions of CO concentrations.

5 Future Directions

A critical objective for advancing our research is the development of a more sophisticated model to enhance the accuracy of vertical distribution estimates. This improvement is informed by similar efforts in other research areas, such as studies on particulate matter like PM 2.5 from fires, which offer insights applicable to carbon monoxide modeling. Implementing GEOS-Chem High Performance (GCHP), which provides higher spatial resolution, could refine our simulations significantly, enabling a more detailed and nuanced representation of atmospheric processes.

Further, broadening the scope of our comparisons by integrating alternative datasets on CO concentrations from East Trout Lake and other locations could provide a comprehensive validation of our model's accuracy. Expanding the geographic and temporal scope of our analysis to include different locations and time frames, such as other months and years beyond August 2018, would allow us to assess seasonal variations and long-term trends, enhancing the model's robustness and applicability.

6 Conclusion

This study explored the impact of varying injection heights on the GEOS-Chem model's CO output, using GFAS for emissions input. Our findings reveal a consistent underestimation of CO levels by GEOS-Chem compared to observations from TCCON. Despite adjustments to the injection heights from 1500 meters to 7000 meters, the model showed only marginal improvements in correlation with TCCON data, with the correlation coefficient (R) increasing slightly from 0.60 to 0.63.

The analysis indicates that the model exhibits low sensitivity to changes in injection height within the tested range. This suggests that other factors, possibly including the accuracy of emission factors and the representation of transport processes in the model, may play more significant roles in influencing model accuracy.

Future work should focus on refining the vertical distribution modeling within GEOS-Chem, potentially incorporating more sophisticated models and extending the analysis to include a broader range of environmental conditions and geographic locations. Enhancing the model's resolution and expanding comparative analyses with different datasets could also provide deeper insights into the discrepancies observed and improve the model's predictive capabilities.

In conclusion, while this study has highlighted the limitations of the current modeling approach with respect to injection height sensitivity, it also suggests the need for significant improvements in atmospheric modeling of biomass burning emissions. By addressing these challenges, researchers can better predict the environmental and health impacts of such emissions, contributing to more effective policy-making and mitigation strategies.

References

[1] Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.-J., Razinger, M., Schultz, M. G., Suttie, M., & van der Werf, G. R. (2012). *Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power.* Biogeosciences, 9(1), 527-554. https://doi.org/10.5194/bg-9-527-2012

[2] Ma, Y., Zhu, Y., Liu, B., Li, H., Jin, S., Zhang, Y., Fan, R., & Gong, W. (2021). *Estimation of the vertical distribution of particulate matter (PM2.5) concentration and its transport flux from lidar measurements based on machine learning algorithms.* Atmospheric Chemistry and Physics, 21(24), 17003–17016. https://doi.org/10.5194/acp-21-17003-2021

[3] 2018 CO Measurement. https://www.canada.ca/en/environment-climate-change/services/national-pollutant-release-inventory/tools-resources-data/carbon-monoxide.html

[4] What is biomass burning. https://eospso.nasa.gov/sites/default/files/publications/BiomassBurn_final_508_0.pdf

[5] Air Parcel Backtrace Trajectory. https://www.ready.noaa.gov/hypub-bin/trajsrcm.pl

[6] TCCON Information. http://www.tccon.caltech.edu