Review of "Modeling the Drought Stress Impact on Summertime Biogenic Isoprene Emissions in South Korea" by Jeong et al.

This manuscript by Jeong et al. examines the impact of drought stress on biogenic isoprene emissions in South Korea using satellite formaldehyde (HCHO) data and the GEOS-Chem model with MEGAN2.1. The authors found that while OMI satellite data showed a 5.4% increase in HCHO under drought conditions, the model predicted a much higher 20.23% increase, indicating an overestimation of isoprene emissions. When the authors tested existing drought stress algorithms—originally developed for the Southeastern United States—they failed to correct this overestimation. To address this issue, they applied an Iterative Finite Difference Mass Balance (IFDMB) method, which reduced isoprene emissions by 60% under drought conditions and brought the modeled HCHO increase (10.71%) closer to observations. Finally, they proposed an empirical equation for adjusting isoprene emissions in South Korea as a function of surface temperature. Overall, this manuscript is well-written and well-organized, aligning with the journal's scope. However, I have concerns regarding certain aspects of the methodology. I recommend the manuscript for publication after substantial revisions.

→ We sincerely appreciate the reviewer who gave the constructive comments to improve the manuscript. Their comments are reproduced below followed by our responses in blue. The corresponding edits in the manuscript are highlighted with red color.

Research Scope

• The true goal of the study is unclear. While the authors claim to examine the impact of drought stress, they primarily test existing drought stress algorithms without conducting an in-depth investigation into the actual effects of drought stress. The improved results stem from the IFDMB method, suggesting that the study may be more focused on an observation-constrained emissions inversion application rather than the direct impact of drought stress. At this point, it is unclear whether the model bias is due to drought stress, inherent issues in the model algorithm, or biases in the model input (e.g., temperature). Additionally, discrepancies appear to exist even under normal conditions.

→ The true goal of this study is to improve the simulation of isoprene emissions under the drought conditions in South Korea. As presented in the new Table 1 in the revised manuscript, the biases of the mean HCHO column in the standard GEOS-Chem increased by 16.07 % under the drought conditions compared to the normal conditions. In addition, the spatial correlation between the HCHO columns from OMI and the standard GEOS-Chem decreased under the drought conditions compared to the normal conditions (please refer to the response to the reviewer's comment below). The main reason for the worsening performance of GEOS-Chem under drought conditions was that the standard GEOS-Chem did not have the ecophysiology module to simulate the soil parameter (β_t in Section 2.4), and thus it cannot simulate the impact of drought stress on the isoprene emissions. As two existing drought stress algorithms for GEOS-Chem were found to be ineffective in South Korea (Table 1), we estimated isoprene emissions by using the IFDMB method and provided the empirical equations to improve the simulation of isoprene emissions. Therefore, we believe that the IFDMB was used as a tool to achieve the true goal of this study: the improvement of the simulation of isoprene emissions in GEOS-Chem under the drought conditions in South Korea.

Table 1: The mean HCHO column bias (relative bias) of GEOS-Chem simulations under the normal condition and drought condition in South Korean region.

Unit: 10^{16} molec. cm^{-2}	Standard GEOS-Chem	WD	JD
Normal	0.22 (19.82 %)	0.18 (16.22 %)	0.13 (11.71 %)
Drought	0.42 (35.89 %)	0.36 (30.77 %)	0.26 (22.22 %)

Model & Data Quality Validation

• Basic model performance evaluation is required. Since the main objective of this study is to assess the impact of drought stress on biogenic emissions estimation, the model must demonstrate reasonable performance in terms of intensity and spatial distribution. Without this, it is difficult to determine the true source of uncertainty.

→ We agreed with the reviewer. The model we used was substantially evaluated with the KORUS-AQ field campaign data as stated in the paper (Park et al., 2021). In the new Figure S5a, we showed the scatter plot between the OMI HCHO column and the GEOS-Chem HCHO column under the normal conditions in South Korea. Although GEOS-Chem HCHO column showed some biases in intensity, the slope for the regression line was 0.90 and the correlation between the two was 0.58 (statistically significant at a 99% confidence level based on the Student's t test). It indicates that GEOS-Chem has reasonable performance in terms of the HCHO spatial distribution. However, the correlation was 0.32 under the drought conditions (the new Fig. S5b), indicating that the worsening performance of GEOS-Chem under the drought conditions. We added the following sentences in the revised manuscript.

"The spatial correlation between the OMI HCHO column and the standard GEOS-Chem under the normal condition was 0.58 (Fig. S5a), which was statistically significant at a 99% confidence level based on the Student's *t*-test. It indicates that the GEOS-Chem has reasonable performance in terms of spatial distribution of the HCHO column under the normal condition. However, the lower spatial correlation between two (0.32) was found under the drought condition (Fig. S5b), which consistently indicated the worsening performance of GEOS-Chem under the drought condition."

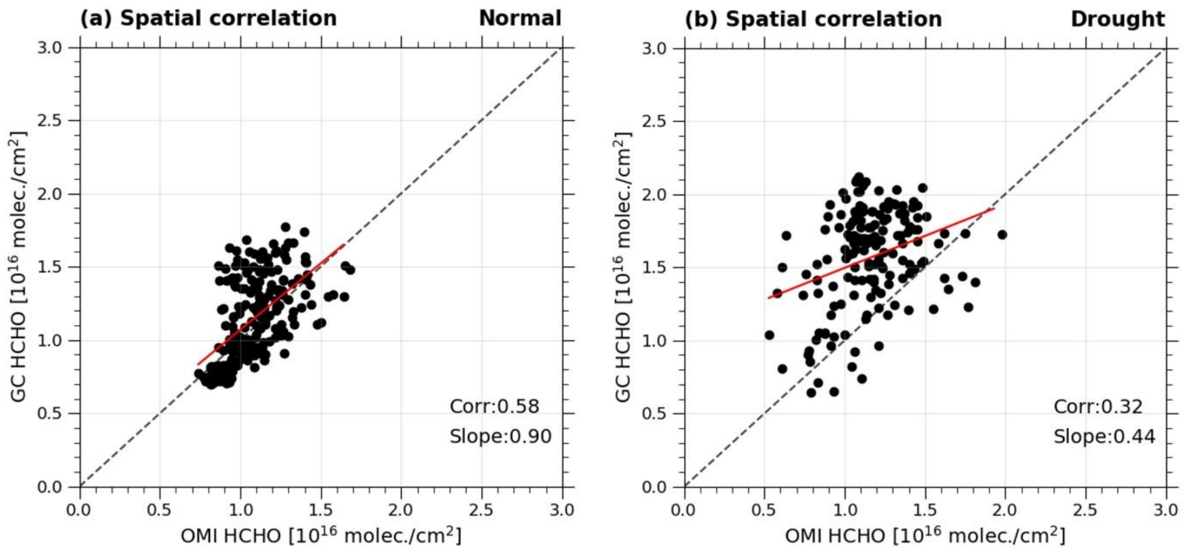

Figure S5: (a) Scatterplot of the OMI HCHO column and the GEOS-Chem HCHO column under the normal conditions in South Korea. Each dot denotes HCHO column value at each grid point in South Korea. The gray dashed line denotes 1:1 line and the red line denotes linear regression line. The slope for the regression line is shown at the right side of the panel with the correlation coefficient (Corr.) between two HCHO columns. (b) Same as a but for the drought conditions.

• The quality of the dataset should be carefully examined. There are several discrepancies that are difficult to understand. In Figures 2a and 2b, OMI HCHO shows a slight increase from normal to drought conditions. However, there is a notable decrease over the Taebaek Mountains, which raises concerns. Can the authors explain this? Otherwise, this may indicate potential quality issues in the satellite data or the drought-day selection process.

→ As stated in the manuscript, the Level 3 OMI HCHO dataset used in this study (OMHCHOd) is the dataset in which bad HCHO retrievals are already filtered out. As this dataset has been widely used in other studies (e.g., Wasti and Wang, 2022), we believe that there are no quality issues in the satellite data. The reason why there was a notable HCHO decrease over the Taebaek Mountains under the drought conditions (all category combined) might be that the HCHO over the Taebaek Mountains increased only under the extreme drought category as shown in the new Figure S4 in the revised manuscript. We added the following sentences in the revised manuscript:

"For example, the OMI HCHO column over the northeastern parts of South Korea (Taebaek Mountains), which showed a decrease under the drought condition (Figs. 2a-c), showed an increase only under the extreme drought category (Fig. S4)."

• Separation of normal and drought conditions is not clearly defined. Was this classification determined on a weekly basis, or was it based on specific drought years (e.g., 2016, 2017, and 2018)? If the latter, what years were used as the baseline for normal conditions?

→ We defined the normal and drought conditions on a weekly basis. As shown in Figure S1, the normal weeks and drought weeks could be defined in each summer (Dot denotes drought week). This calculation was done in every grid cell based on the DEDI at the corresponding grid cell. Given this, all analyses in this study were conducted on a weekly basis. To clarify, we added the following sentences in the manuscript:

"For each grid point, therefore, the normal (DEDI > -0.49) and drought (DEDI ≤ -0.49) conditions were defined based on a weekly basis using DEDI during three summers (2016 – 2018)."

IFDMB Method

• The application of IFDMB should be reviewed more carefully. In this study, the authors attempt to adjust biogenic isoprene emissions using OMI HCHO column density. However, unlike primary pollutants, HCHO is a secondary pollutant formed through the oxidation of VOCs. In the current model simulation, the contribution of anthropogenic VOC precursors is as significant as that of biogenic isoprene, as evidenced by the simulated HCHO spatial distribution (compare Figures 2d and 3a). The spatial distributions of HCHO from the model and OMI do not appear to be consistent, which warrants further review. As the authors stated in the manuscript, the IFDMB method does not account for the spatial transport of precursors. If the locations of emissions do not align with the locations of high HCHO concentrations, how can this method be justified?

→ This comment is associated with the reviewer's comment below. Please refer to our response to the reviewer's comment below.

• Provide the spatial distribution of anthropogenic and biogenic VOC (or isoprene) emissions from the model. The authors need to justify the application of the IFDMB method, which uses observed HCHO to adjust biogenic isoprene emissions exclusively.

→ The spatial distributions of anthropogenic VOC (AVOC) are presented in the new Figure S8 and those of biogenic isoprene emissions are presented in the original Figures 3b-c. The AVOC emissions were localized over northwestern and southeastern parts of South Korea where major metropolitan areas are located while isoprene emissions were distributed over most of South Korea. Also, AVOC emissions were consistent throughout the normal and drought conditions (Fig. S8 and Fig. 3a), which means that changes in HCHO under the drought conditions were caused by the changes in isoprene emissions. However, the assumption behind the application of IFDMB method is that anthropogenic VOC emissions used in this study are correct, at least with much higher accuracy than isoprene emissions, which is the main caveat in this study. However, the impact of AVOC emissions may be localized and spatially distinct from that of isoprene emissions. We added the following sentences in the revised manuscript.

"The assumption behind the application of IFDMB method was that AVOC emissions used in this study were correct, at least with much higher accuracy than isoprene emissions, which is the main caveat in this study. However, AVOC emissions were localized over the northwestern and southeastern parts of South Korea where major metropolitan areas are located (Fig. S8) while isoprene emissions were distributed over most of South Korea (Figs. 3b-c). Also, AVOC emissions were consistent throughout the normal and drought conditions (Fig. S8 and Fig. 3a), which means that changes in HCHO under the drought condition were caused by the changes in isoprene emissions. Therefore, the impact of AVOC emissions may be localized and spatially distinct from that of isoprene emissions."

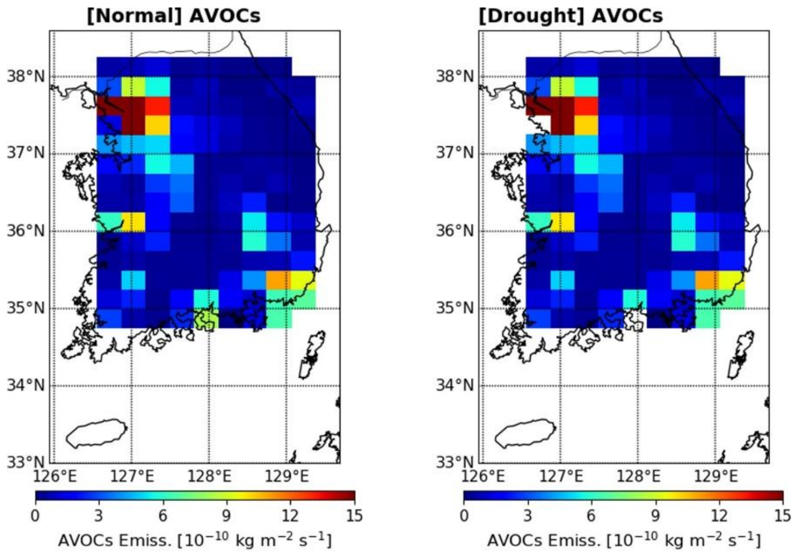

Figure S8: The spatial distribution of anthropogenic VOC (AVOC) emissions under normal condition (left) and drought condition (right).

• Figures 6 and 7 should be updated. These figures are confusing and misleading, as they present concentration and bias together. Please provide separate panels for concentrations (model and observations) and biases.

→ We have changed the original Figures 6/7 to the new scatter plot between the model and the observation (Figure 6 below). Also, we added statistical metrics such as R^2, RMSE, NMB in each panel in the new Figure 6. We also revised the manuscript with the new Figure 6 as below:

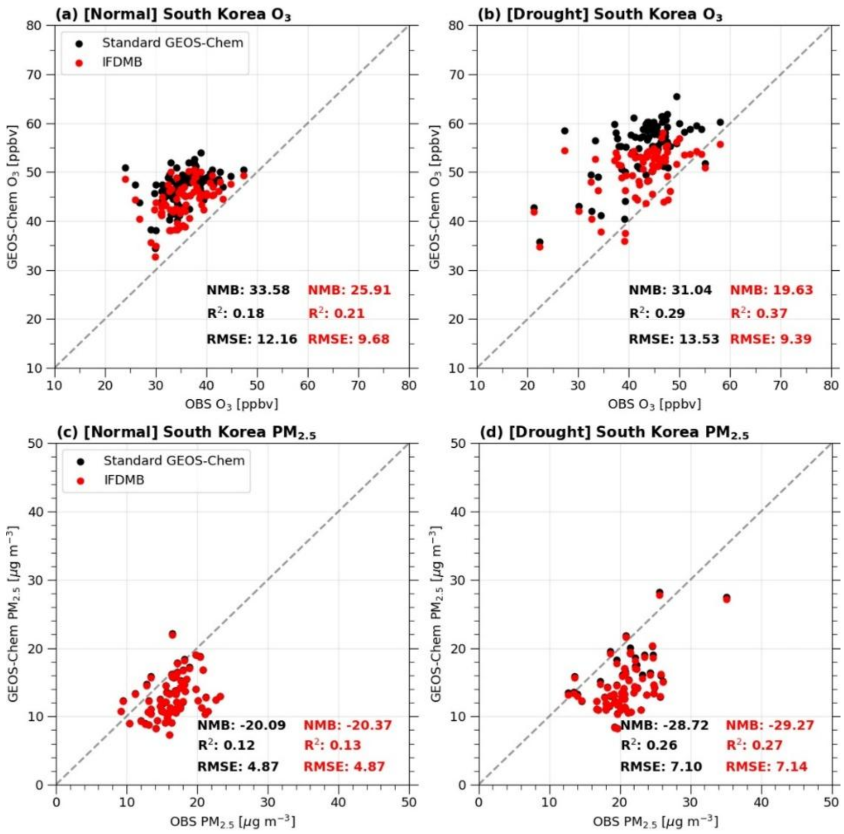

Figure 6. The scatter plot for the observed O_3 and the simulated O_3 under (a) the normal and (b) drought conditions. Black and red dots denote standard GEOS-Chem and IFDMB, respectively. Normalized mean bias (NMB), coefficient of determination (R^2), and root mean square error (RMSE) for the standard GEOS-Chem (black) and IFDMB (red) are presented in each panel. The gray dotted line is 1:1 line. (c-d) Same as a-b but for $PM_{2.5}$.

"Figures 6a-b show scatter plots of daytime (7am – 6pm) mean O_3 concentrations between the surface observations and the model outputs (black for standard GEOS-Chem and red for IFDMB) under the normal condition and the drought condition. Under the normal condition (Fig. 6a), the mean O_3 concentrations in South Korea were 35.50 ppbv and 46.90 ppbv in the observation and the standard GEOS-Chem, respectively. The standard GEOS-Chem had positive O_3 biases in most of the measurement sites, which was indicated by the normalized mean biases (NMB) of 33.58 %. After using posterior isoprene emissions estimated by the IFDMB, the modeled O_3 concentrations decreased in most of the South Korean region. The mean O_3 concentrations in the IFDMB were 44.23 ppbv under the normal condition, indicating that the mean O_3 concentrations were reduced by 2.66 ppbv (5.67 %) with respect to the standard GEOS-Chem by applying IFDMB. As a result, the NMB in IFDMB was 25.91 % under the normal condition, which was reduced by 7.67 % compared to the standard GEOS-Chem. Other metrics such as coefficient of determination (R^2) and root mean square error (RMSE) also show improvement in IFDMB compared to the standard GEOS-Chem (Fig. 6a). Under the drought condition (Fig. 6b), the mean observed O_3 concentrations in South Korea was 43.15 ppbv, which was higher than those under the normal condition. The increase in O_3 concentrations under the drought condition was consistent with the expectation of a VOC-limited regime in response to increasing HCHO yet no change in NO_2 under the drought condition as seen by OMI (Fig. S7d). The mean O_3 concentrations in the standard GEOS-Chem was 55.42 ppbv under the drought condition with the NMB of 31.04 %. In IFDMB, the mean O_3 concentrations was 50.47 ppbv under the drought condition, which was reduced by 4.95 ppbv (8.93 %) with respect to the standard GEOS-Chem. This is consistent with the VOC-limited regime where the reduction in isoprene emissions by the IFDMB leads to reduced ozone concentrations. The NMB in the IFDMB was 19.63 % under the drought condition, reduced by 11.41 % compared to the standard GEOS-Chem. As under the normal condition, the improvement was also indicated by higher R^2 and lower RMSE. Thus, the modeled O_3 concentration was found to be improved by applying the IFDMB method for better isoprene emissions modeling.

Figures 6c-d show scatter plots of daytime (7am – 6pm) mean $PM_{2.5}$ concentrations between the surface observations and the model outputs (black for standard GEOS-Chem and red for IFDMB) under the normal condition and the drought condition. Under the normal condition (Fig. 6c), the mean $PM_{2.5}$ concentrations were 16.41 $\mu g/m^3$ and 12.42 $\mu g/m^3$ in the observation and the standard GEOS-Chem, respectively. The standard GEOS-Chem had negative $PM_{2.5}$ biases in most of the measurement sites except for the Seoul metropolitan area. The NMB for the standard GEOS-Chem was -20.09 %. In IFDMB, contrary to ozone, the changes in $PM_{2.5}$ concentration were not significant as indicated by the NMB, R^2, and RMSE. Such insignificant changes in $PM_{2.5}$ in IFDMB were also found under the drought condition (Fig. 6d)."

• Clarify the data processing in Figure 8a–d. Please elaborate on how the data were processed and explain what each point represents. If possible, please provide the raw data points before binning in 0.2 K intervals.

→ Thanks for the reviewer's careful comment. The original Figure 8 was revised to Figure 7 in the revised manuscript. Each dot in the Figures 7a-b represents isoprene emission value in the standard GEOS-Chem versus that in IFDMB at each grid point in South Korea. The isoprene emission value was divided by LAI value at the corresponding grid point to consider the different vegetation coverage. The surface temperature value at the corresponding grid was also overlaid at each dot. Each dot in Figures 7c-d represents γ_{SM_OMI} value (Eq. 6) at the corresponding surface temperature. We revised the caption for Figure 7 in the revised manuscript for a clear explanation and added the new figure (Fig. S9) to provide the raw data points before binning in 0.2 K interval in Figs. 8c-d.

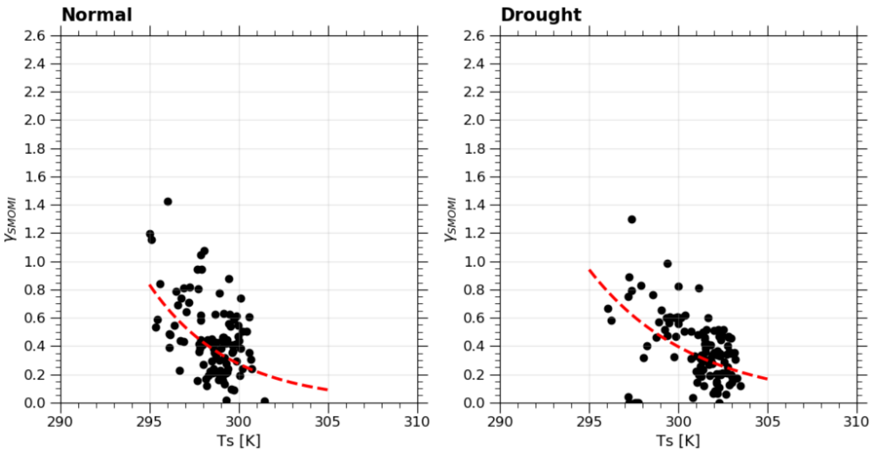

Figure S9: γ_{SM_OMI} with respect to the surface temperatures in (c) the normal and (d) the drought conditions. The red dotted lines indicate the fitted lines.