General Comments

Jeong et al. investigated the impact of drought on isoprene and air quality in South Korea using OMI formaldehyde (HCHO) observations and GEOS-Chem modeling. They validated two existing drought algorithms for isoprene emissions using OMI HCHO data. Furthermore, they constrained isoprene emissions during drought using an inverse modeling approach with OMI HCHO. The topic is within the scope of ACP, and the manuscript is well organized. However, I have some concerns about the methods and techniques that need to be addressed before it can be further evaluated.

→ 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.

1. Bias correction of the OMI HCHO product. The author used a single correction factor of 1.28, derived from the comparison of airborne HCHO measurements from KORUS-AQ, to adjust the OMI HCHO product (Zhu et al., 2020). However, other studies using measurements from airborne platforms, FTIR, and MAX-DOAS suggest a negative bias in the OMI HCHO product when HCHO levels are high and a positive bias when HCHO levels are low (Müller et al., 2024; De Smedt et al., 2021). This phenomenon is also indicated in the reference cited by the author to justify the correction factor used (Zhu et al., 2020). I would suggest that the author consider using a different correction approach (e.g., the method in Müller et al. (2024)) for comparison considering the uncertainties from the single field campaign.

→ We appreciate the reviewer's constructive comment. Responding to the reviewer's comments, we calculated the bias-corrected OMI HCHO column based on the method in Müller et al. (2024) and compared it to the originally corrected OMI HCHO column (following Zhu et al. (2020)) under both normal and drought conditions (Fig. S2 in the revised manuscript). The two corrected HCHO columns were highly correlated with a correlation slope close to 1, expect for a few low-value points deviating from the 1:1 regression line under normal conditions. This suggests a single correction factor adopted by the manuscript is acceptable. We added the following sentences and figure (Fig. S2) in the revised manuscript:

"We also compared this method to a different bias correction method suggested by Müller et al. (2024) and the results were shown in Figure S2. The two corrected HCHO columns were highly correlated with a regression slope close to one, except for a few HCHO points under normal condition. The corrected HCHO columns used in this study were 7-12% higher compared to those from Müller et al. (2024) under normal and drought conditions, respectively."

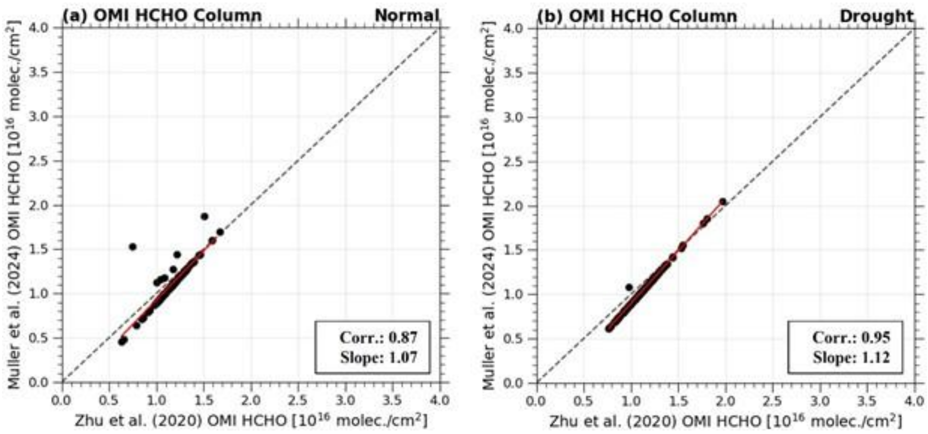

Figure S2: Scatterplot between two bias-corrected OMI HCHO columns following Zhu et al. (2020) and Müller et al. (2024) under (a) normal and (b) drought conditions. The method in Zhu et al. (2020) was used in this study. Each dot denotes HCHO column value at each grid point in South Korea. The gray dashed 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.

2. The impact of drought or water stress severity. The impact of water stress on isoprene emissions depends on the severity of the drought. In general, water stress can increase isoprene emissions by elevating leaf temperature through stomatal closure. However, as the drought becomes more severe, the carbon substrate supply for isoprene is cut off, leading to a decrease in emissions, as observed in field studies (Potosnak et al., 2014; Seco et al., 2015). However, the authors did not distinguish between different levels of drought severity. Therefore, I believe it is necessary to conduct an analysis based on a finer classification of drought levels.

→ We agree with the review on this point. Following Zhang et al. (2022), the DEDI drought severity can be broken down into five categories (Table S1 in the revised manuscript). Based on these five categories, we calculated the observed HCHO columns in each drought category (Figure S4 in the revised manuscript). The mean HCHO columns indeed tended to increase as the drought was stronger, which is consistent with Wasti and Wang (2022) showing the 2.97 % increase of the OMI HCHO column under the mild drought and 8.02 % in the extreme drought. However, as described in the paper, since our study period included only three summers the number of cases in each drought category was small, especially for severe and extreme categories, and thus we did not elaborate on the impact of drought severity. We added the following sentences, table (Table. S1), and figure (Fig. S4) in the revised manuscript to discuss the impact of drought severity.

"It is known that the impact of water stress on isoprene emissions depends on the severity of the drought (Potosnak et al., 2014; Seco et al., 2015; Wasti and Wang, 2022). To examine this impact, the DEDI was separated into five categories following Zhang et al. (2022): Normal/Wet, Incipient drought, Moderate drought, Severe drought, and Extreme drought (Table S1). Based on these five categories, we calculated the observed HCHO columns in each drought category (Fig. S4). While the domain-mean HCHO columns tended to increase as the drought became stronger, the signal is weak and not uniform by location. 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). This is probably because our study period included only three summers.

Given the small sampling size, we chose not to separate drought severity in the following analysis."

Table S1: Five drought categories by DEDI drought index

Drought category	Chance of occurrence	DEDI threshold (South Korea)
Extreme drought	2% or less	DEDI ≤ -2.02
Severe drought	2 – 10 %	-2.02 < DEDI ≤ -1.15
Moderate drought	10 – 20 %	-1.15 < DEDI ≤ -0.75
Incipient drought	20 – 30 %	-0.75 < DEDI ≤ -0.49
Normal/Wet	More than 30 %	-0.49 < DEDI

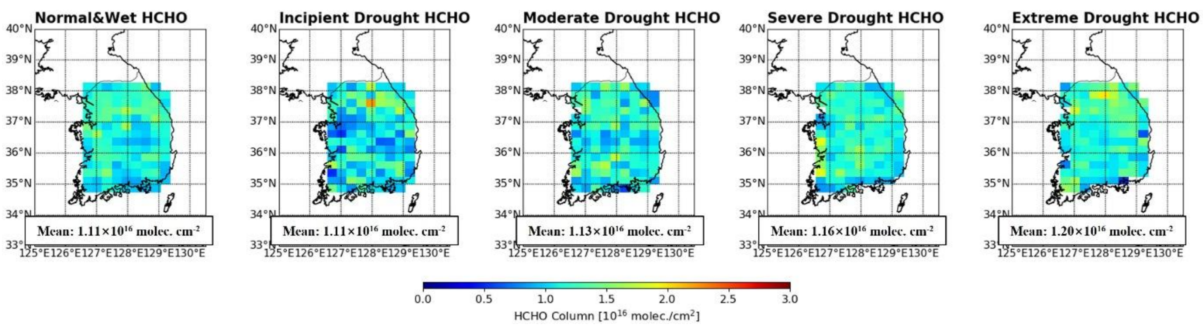

Figure S4: The OMI HCHO columns under five drought categories based on DEDI drought index.

3. The simulation of drought. Wang et al. (2022) demonstrated that the performance of drought simulations directly affects how well the model simulates the impact of drought on isoprene emissions. The authors used the soil moisture stress (βt) from the Hadley Centre Global Environment Model version 2–Earth System Model (HadGEM2-ES). However, they did not provide any information about the model's performance in capturing changes in soil moisture or water stress. Therefore, I would suggest validating the model's soil moisture or water stress simulations in the same scale of their comparison like weekly before analyzing the HCHO simulations.

→ Because of no available observations of soil moisture to validate the soil moisture stress (βt), we used the same approach as in Wang et al. (2022) to calibrate the soil moisture stress (βt) according to the drought index. In Figure S3 in the revised manuscript, we showed the distribution of calculated soil moisture stress (βt) under the normal and drought conditions based on DEDI drought index. Consistent with the Wang et al. (2022), we selected a threshold of βt below which it was under drought condition. This threshold was 0.64, which was 60% percentile of βt in the South Korea drought conditions. This value was used to turn on drought stress algorithms in GEOS-Chem.

4. Poor statistics. The only statistical analysis applied in the paper is the comparison of mean values, which is not sufficient for the audience to understand the analysis and the uncertainties behind these comparisons. I will provide more specific guidance on this part in my minor comments.

→ Thank you for the reviewer's constructive comment. We responded to this comment in the reviewer's specific minor comment below.

Minor comments.

Line 27: The estimation by Guenther et al., 2012 is suggesting that isoprene accounts for 50% of global BVOC emission. However, I also believe this number is quite uncertainty. So I would say 50-70% in a relatively safe way.

→ Good point. We revised the manuscript as below:

"BVOCs are emitted from terrestrial vegetations and 50–70 % of global BVOCs emissions are isoprene emissions (Pacifico et al., 2009; Sindelarova et al., 2014)."

Line 32: Stomatal conductance" and "photosynthesis rate" are two related terms, and I don't think the statement here is correct for explaining the drought impact on isoprene emissions. In addition, Seco et al. (2022) discusses the high temperature sensitivity of isoprene in the Arctic, so I have no clue why this reference is included here.

→ The Seco et al. reference was used to support the statement on the overall dependence of isoprene emissions on meteorological factors. We revised the manuscript as below:

"Isoprene emissions depend on not only physiological factors such as plant functional type, leaf area index, and leaf age, but also meteorological factors such as temperature, radiation, and soil moisture, which affect plant's physiology such as stomatal conductance, isoprene synthase activity, and carbon substrate supply (Ferracci et al., 2020; Guenther et al., 2012; Guenther et al., 2006; Potosnak et al., 2014; Seco et al., 2022)."

Line 104: Please provide the reference for the OMI HCHO dataset you used.

→ Added.

Table 1. Please provide the standard deviation of your model results as well as the OMI HCHO column concentration, and conduct a significance test for your mean comparison.

→ The original Table 1 changed to the mean HCHO column bias of GEOS-Chem simulations for better readability. Instead, we added the mean, standard deviation, and p-value based on Student's *t*-test in each figure (Figures 2-5).

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 %)

Line 195: I assume monoterpenes and sesquiterpenes are grouped into the lumped alkenes. As indicated in Figure S3, isoprene emissions are far higher than those of other terpenoids. Could you provide more vegetation information (e.g., broadleaf and conifer tree fractions) to explain this?

→ We updated the original Figure S3 to Figure S6 in the revised manuscript to include monoterpenes and sesquiterpenes (Figure below). As shown in Figure S6, isoprene emissions are much higher than monoterpenes and sesquiterpenes, which is consistent with the previous study (Jang et al., 2020; Kim et al., 2015). According to the Korea Forest Service (https://english.forest.go.kr/kfsweb/kfi/kfs/cms/cmsView.do?cmsId=FC_001679&mn=UENG_01_03#:~:text=Status%20of%20Forest%20in%20Korea&text=The%20forested%20area%20in%20Korea,times%20higher%20than%20in%201953), about 60% of forests in Korea consist of deciduous-leaved forests and mixed forests, and 36.9% are coniferous forests. As isoprene emissions are associated with broadleaf trees and monoterpene emissions are associated with conifer trees, higher isoprene emissions can be explained by these forest fractions. Also, oak trees (*Quercus mongolica, Quercus variabilis, and Quercus acutissima*), which are known to be major sources of high isoprene emissions, are dominant species in the deciduous-leaved forests (Lee et al., 2025) so this can explain high isoprene emission in South Korea. Responding to the reviewer's comment, we added the following sentences to the revised manuscript.

"The reason why isoprene emissions are higher than monoterpenes and sesquiterpenes is because of the type of forests in South Korea. According to the Korea Forest Service (https://english.forest.go.kr/kfsweb/kfi/kfs/cms/cmsView.do?cmsId=FC_001679&mn=UENG_01_03#:~:text=Status%20of%20Forest%20in%20Korea&text=The%20forested%20area%20in%20Korea,times%20higher%20than%20in%201953), about 60% of forests in Korea consist of deciduous-leaved forests (*Quercus mongolica, Quercus variabilis, and Quercus acutissima*) and mixed forests, and 36.9% are coniferous forests. The deciduous-leaved trees are well-known sources of biogenic isoprene."

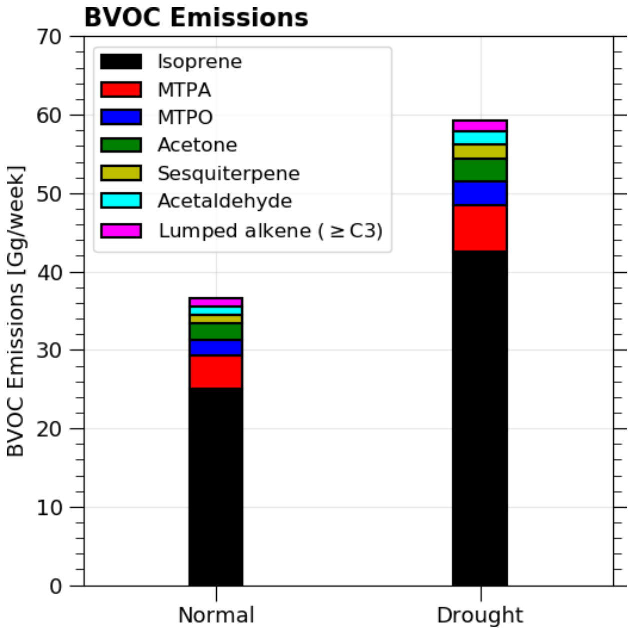

Figure S6: The total amounts of each BVOC emission under the normal and the drought conditions in South Korea in the standard GEOS-Chem. The each BVOCs emission include isoprene, MTPA (monoterpenes including α-pinene, β-pinene, sabinene, and carene), MTPO (monoterpenes including myrcene, ocimene, and other monoterpenes), acetone, sesquiterpene (farnesene, β-caryophyllene, and other sesquiterpene), acetaldehyde, and lumped alkene (≥ C3).

Figure 6/7 and ozone/PM2.5 validation: The comparison here is quite generic and lacks details. The authors compared the model with the in-situ measurements. The only comparison presented is the Mean Bias (difference in mean values). I think some scatter plots of the model and observations on a weekly scale could be useful to understand the change in model performance after improving the model emissions using the OMI satellite data. Besides the common statistical metrics like R^2, RMSE, ME, and MB, a significance test should be conducted to determine if the improvement in emissions is statistically significant.

→ The reviewer's point is well taken. We revised Figures 6/7 to show 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:

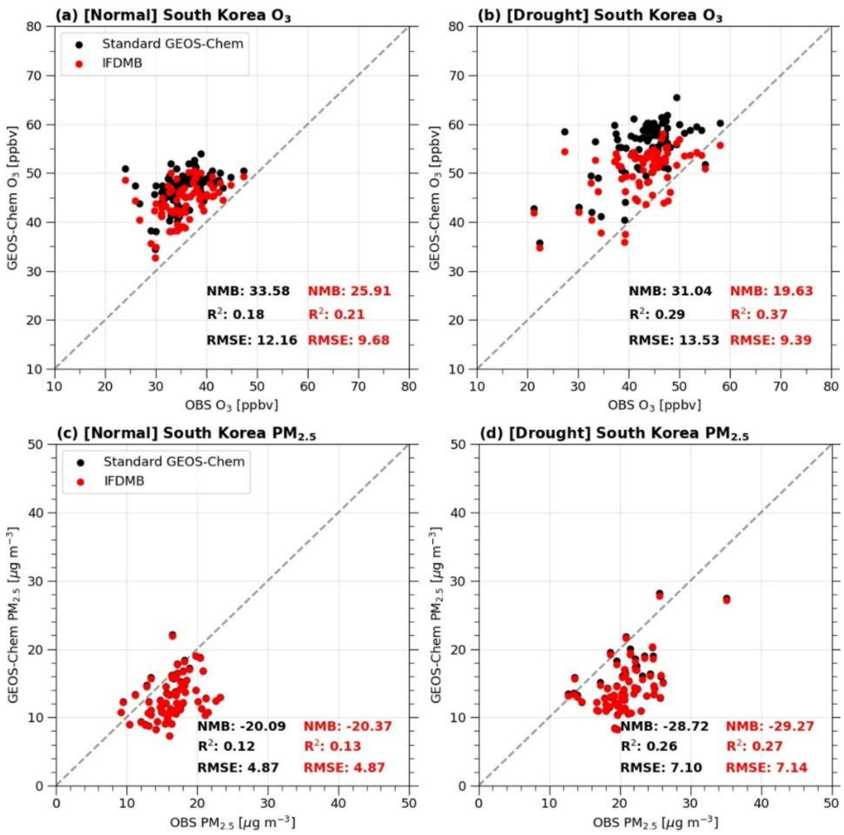

Figure 6. The scatter plot for the observed O_3 and the simulated O_3 under (a) the normal and (b) drought conditions. Black and red dots denote standard GEOS-Chem and IFDMB, respectively. Normalized mean bias (NMB), coefficient of determination (R^2), and root mean square error (RMSE) for the standard 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 μg/m^3 and 12.42 μg/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)."

Equation 7 and Figure 8. The analysis here is confusing. I think the authors are arguing that drought stress is the main driver of the isoprene emission bias. However, the analysis focuses on temperature. Although high temperatures often coincide with drought in many cases, there are two drivers of vegetation water stress: one is the high Vapor Pressure Deficit (VPD) caused by a dry and hot atmosphere, and the other is dry soil conditions, which determine the water supply for plants. Additionally, long-lasting droughts are mainly controlled by a lack of water. However, the equation and analysis here use the soil moisture parameter (βt) as the indicator of drought severity but use temperature as the input for addressing the isoprene emission bias. This raises the question: is the bias caused by drought, or temperature, or both?

→ We agree with the reviewer's point. We think that the isoprene emission biases were caused by both drought and temperature. First, the standard GEOS-Chem does not have the ecophysiology module, which means it cannot simulate soil moisture parameter (β_t) and thus the impact of the drought stress on the isoprene emissions. That's the main reason why the standard GEOS-Chem has significant biases in the drought conditions. In addition, we found that the isoprene emissions in standard GEOS-Chem were overestimated mainly in high temperatures in both normal and drought conditions (Fig. 7a). This is because the isoprene emissions in the standard GEOS-Chem have a factor for temperature (Section 2.4). Given these, we chose to use soil moisture parameter (β_t) to separate the normal and drought conditions in the model and then use surface temperature to adjust the model emissions in each condition. Responding to the reviewer's comment, we added the following clarification in the main text:

"This suggests that MEGAN2.1 implemented in the standard GEOS-Chem tends to overestimate isoprene emissions compared to those in the IFDMB in high surface temperatures under both normal and drought conditions. The isoprene emissions in the standard GEOS-Chem have a strong dependence on temperature (Section 2.4). This dependence may be overestimated in South Korea under high temperature conditions.

Given that a lack of ecophysiology module to simulate soil moisture (βt) was the main reason why the standard GEOS-Chem has significant biases in the drought condition, we constructed an equation to adjust MEGAN2.1 isoprene emissions by using soil moisture parameter (βt) to separate the normal and drought conditions in the model and using surface temperature to adjust MEGAN2.1 isoprene emissions in each condition."

Reference

De Smedt, I., Pinardi, G., Vigouroux, C., Compernolle, S., Bais, A., Benavent, N., Boersma, F., Chan, K. L., Donner, S., Eichmann, K. U., Hedelt, P., Hendrick, F., Irie, H., Kumar, V., Lambert, J. C., Langerock, B., Lerot, C., Liu, C., Loyola, D., Piters, A., Richter, A., Rivera Cárdenas, C., Romahn, F., Ryan, R. G., Sinha, V., Theys, N., Vlietinck, J., Wagner, T., Wang, T., Yu, H., and Van Roozendael, M.: Comparative assessment of TROPOMI and OMI formaldehyde observations and validation against MAX-DOAS network column measurements, Atmos. Chem. Phys., 21, 12561-12593, 10.5194/acp-21-12561-2021, 2021.

Müller, J. F., Stavrakou, T., Oomen, G. M., Opacka, B., De Smedt, I., Guenther, A., Vigouroux, C., Langerock, B., Aquino, C. A. B., Grutter, M., Hannigan, J., Hase, F., Kivi, R., Lutsch, E., Mahieu, E., Makarova, M., Metzger, J. M., Morino, I., Murata, I., Nagahama, T., Notholt, J., Ortega, I., Palm, M., Röhling, A., Stremme, W., Strong, K., Sussmann, R., Té, Y., and Fried, A.: Bias correction of OMI HCHO columns based on FTIR and aircraft measurements and impact on top-down emission estimates, Atmos. Chem. Phys., 24, 2207-2237, 10.5194/acp-24-2207-2024, 2024.

Potosnak, M. J., LeStourgeon, L., Pallardy, S. G., Hosman, K. P., Gu, L., Karl, T., Geron, C., and Guenther, A. B.: Observed and modeled ecosystem isoprene fluxes from an oak-dominated temperate forest and the influence of drought stress, Atmospheric Environment, 84, 314-322, https://doi.org/10.1016/j.atmosenv.2013.11.055, 2014.

Seco, R., Karl, T., Guenther, A., Hosman, K. P., Pallardy, S. G., Gu, L., Geron, C., Harley, P., and Kim, S.: Ecosystem-scale volatile organic compound fluxes during an extreme drought in a broadleaf temperate forest of the Missouri Ozarks (central USA), Global Change Biology, 21, 3657-3674, doi:10.1111/gcb.12980, 2015.

Seco, R., Holst, T., Davie-Martin, C. L., Simin, T., Guenther, A., Pirk, N., Rinne, J., and Rinnan, R.: Strong isoprene emission response to temperature in tundra vegetation, Proceedings of the National Academy of Sciences, 119, e2118014119, 10.1073/pnas.2118014119, 2022. Wang, H., Lu, X., Seco, R., Stavrakou, T., Karl, T., Jiang, X., Gu, L., and Guenther, A. B.: Modeling Isoprene Emission Response to Drought and Heatwaves Within MEGAN Using Evapotranspiration Data and by Coupling With the Community Land Model, Journal of Advances in Modeling Earth Systems, 14, e2022MS003174, https://doi.org/10.1029/2022MS003174, 2022.

Zhu, L., González Abad, G., Nowlan, C. R., Chan Miller, C., Chance, K., Apel, E. C., DiGangi, J. P., Fried, A., Hanisco, T. F., Hornbrook, R. S., Hu, L., Kaiser, J., Keutsch, F. N., Permar, W., St. Clair, J. M., and Wolfe, G. M.: Validation of satellite formaldehyde (HCHO) retrievals using observations from 12 aircraft campaigns, Atmos. Chem. Phys., 20, 12329-12345, 10.5194/acp-20-12329-2020, 2020.