Responses to the Reviewers' Comments

We would like to thank the editor and two anonymous reviewers for their helpful comments and suggestions. All authors have read the revised manuscript and agreed with the submission in its revised form.
Reviewers' comments are in black color, our responses are in blue color, and our corresponding revisions in the manuscript are in red color.

Response to the Reviewer #1

General Comments:

BVOCs are important precursors to ozone and secondary organic aerosols in the atmosphere. In this manuscript, the authors focused on a comprehensive analysis of trends in BVOC emissions from 2001-2020 on a regional to global scales and identified the contribution of various driving factors to these trends. The manuscript is well written, and I suggested the acceptance after addressing the comments below.

Response: We thank the reviewer for the encouraging comments. We have revised the manuscript following your comments.

1. The authors used a newer version of MEGAN. Could the authors elaborate the major advancement compared to previous versions such as MEGAN 2.1?

Response: Thank you. Following your comment, we have added the following text for the major advancement in the new MEGANv3.2 compared to MEGANv2.1:

in Section 2.1 "MEGANv3.2":

"Specifically, while MEGANv2.1 uses a look-up table of emission factors for the 15 PFTs corresponding to the biological emission classes (see Table 2 in Guenther et al. (2012)), MEGANv3.2 uses the so-called Emission Factor Processor, to estimate the landscape average emission factors, which are based on the following three databases: (1) Growth form datasets for four PFTs: tree, shrub, grass, and crops; (2) Ecotype datasets: composed of a mix of emission-specific tree species/grass associated with specific emission capacities; and (3) Updated tree species/grass datasets corresponding to the biogenic emission classes. These updates can distinguish the differences in vegetation emission factors in regions with the same PFT but with varying plant species. The new version also considers the additional stress factors of emissions by using the simple threshold function, including high/low temperature, strong wind, and heavy O_3 pollution."

2. Are the observations only in 2013? The seasonal variations of isoprene flux in MEGAN appears to be very small, which seems to be quite different from the observations. Any explanations?

Response: Yes, the observations are only in 2013. The magnitude of seasonal variations of the modeled isoprene flux is small compared to the observations. We have added the explanations for the small seasonal variations in simulated isoprene flux in Section 3.1.1 "Spatial distribution of BVOC emissions":

"The large bias in the seasonal variation of isoprene fluxes in MEGANv3.2 may be due to a lack of representation of the isoprene emission capacity of tree species at different leaf ages (Alves et al., 2018). Additionally, the model bias arises from a lack of realistic representations of leaf phenology, canopy structure, soil moisture feedbacks, and variation in isoprene emissions due to the complex biodiversity in the Amazon region."

3. Line 274: These discrepancies are mainly ascribed to the differences in vegetation emission factors between the two versions of MEGAN. Could the authors add some explanations the emission factors from which vegetation are more accurate?

Response: Thank you for the comment. We have added some explanation and discussion of the accuracy of the vegetation emission factors for MEGANv3.2 and MEGANv2.1 in Section 3.1.1 "Spatial distribution of BVOC emissions":

"Note that MEGANv2.1 only utilizes fixed emission factors corresponding to the PFTs, but the PFT is insufficient to characterize the emission factors, e.g., tree species with the same PFT may have very different BVOC emission rates. MEGANv3.2 further considers differences in emission factors for tree species with the same PFTs. Thus, the vegetation emission factors in MEGANv3.2 are more accurately represented. However, we note that the uncertainties associated with emission factors are still large due to the limited observational data (Guenther et al., 2020)."

4. Line 367: Could the authors explain why for monoterpene emissions, only the effects of vegetation and meteorological factors are considered?

Response: Thank for your comment. We have added the reasons why for monoterpene emissions in the model only the effects of vegetation and meteorological factors are considered in Section 3.2 "Trends of BVOC emissions":

"Different from isoprene emissions, there is no statistically significant effect of CO_2 concentration on monoterpene emissions as suggested by previous studies (Malik et al., 2019, 2023). Therefore, monoterpene emissions in MEGANv3.2 only consider the effects of vegetation and meteorological factors and show a significantly positive trend of 0.34% yr^{-1} globally (Fig. S2)."

References

Alves, E. G., Tóta, J., Turnipseed, A., Guenther, A. B., Vega Bustillos, J. O. W., Santana, R. A., Cirino, G. G., Tavares, J. V., Lopes, A. P., Nelson, B. W., de Souza, R. A., Gu, D., Stavrakou, T., Adams, D. K., Wu, J., Saleska, S., and Manzi, A. O.: Leaf phenology as one important driver of seasonal changes in isoprene emissions in central Amazonia, Biogeosciences, 15, 4019-4032, 10.5194/bg-15-4019-2018, 2018.

Guenther, A., Jiang, X., Shah, T., Huang, L., Kemball-Cook, S., and Yarwood, G.: Model of Emissions of Gases and Aerosol from Nature Version 3 (MEGAN3) for Estimating Biogenic Emissions, in: Springer Proceedings in Complexity, Springer, Cham, 187–192, https://doi.org/10.1007/978-3-030-22055-6_29, 2020.

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471-1492, 10.5194/gmd-5-1471-2012, 2012.

Malik, T. G., Gajbhiye, T., and Pandey, S. K.: Some insights into composition and monoterpene emission rates from selected dominant tropical tree species of Central India: Plant-specific seasonal variations, Ecological Research, 34, 821-834, 10.1111/1440-1703.12058, 2019.

Malik, T. G., Sahu, L. K., Gupta, M., Mir, B. A., Gajbhiye, T., Dubey, R., Clavijo McCormick, A., and Pandey, S. K.: Environmental Factors Affecting Monoterpene Emissions from Terrestrial Vegetation, Plants, 12, 3146, https://doi.org/10.3390/plants12173146, 2023.

Response to the Reviewer #2

General Comments:

This is a study of great relevance to the atmospheric pollution modeling community. The trends presented and the sensitivity of MEGAN 3.2 to various parameters and its geographical distribution are of great interest to all of us who model both emissions and air quality. It provides interesting insights into how BVOC emissions can change at specific regions and highlights the significant impact of land-use changes and global warming.

Response: We thank the reviewer for the encouraging comments.

I would like to ask the authors if they have reviewed or analyzed the uncertainty associated with the new emission factors used in MEGAN. Have they utilized those with the highest confidence index (denoted as 'J' in the code)? Or do they consider it worthwhile to address these factors or their spatial distribution in the future? Are these emission factors the default values in MEGAN for tree, shrub, grass, and crop categories?

Response: Thank you for your comments and questions. In fact, MEGANv3.2 provides an open-source and expandable database of species-specific emission factors. The model code uses these emission factors by default, and there is no option to set a confidence index (denoted as 'J' in the code). Therefore, in this study, we did not carry out sensitivity analyses directly for the uncertainty associated with the new emission factors, but instead used ground- and satellite-based observations, and previous simulation results to evaluate our modeled BVOC emission fluxes.

Currently, most of the tree emission factors provided by MEGANv3.2 come from observations in the United States as well as from numerous literature data. Therefore, there is an urgent need to conduct observations in other hotspot regions around the globe in the future. This point has been emphasized in the Discussion section.

These emission factors are not the default values in MEGAN for tree, shrub, grass, and crop categories. Compared to MEGANv2.1, MEGANv3.2 can distinguish the differences in vegetation emission factors in regions with the same PFTs but with varying plant species. We have added a detailed explanation of the MEGANv3.2 emission factor methodology in the model introduction section.

Text about the MEGANv3.2 emission factor calculation methodology has been added in Section 2.1 "MEGANv3.2":

"Specifically, while MEGANv2.1 uses a look-up table of emission factors for the 15 PFTs corresponding to the biological emission classes (see Table 2 in Guenther et al. (2012)), MEGANv3.2 uses the so-called Emission Factor Processor, to estimate the landscape average emission factors, which are based on the following three databases: (1) Growth form datasets for four PFTs: tree, shrub, grass, and crops; (2) Ecotype datasets: composed of a mix of emission-specific tree species/grass associated with specific emission capacities; and (3) Updated tree species/grass datasets corresponding to the biogenic emission classes. These updates can distinguish the differences in vegetation emission factors in regions with the same PFT but with varying plant species. The new version also considers the additional stress factors of emissions by using the simple threshold function, including high/low temperature, strong wind, and heavy O3 pollution."

Was there any anomaly in the reference year of 2001 that could potentially bias the study in specific regions? Did the authors find any unexpected anomalies that they did not anticipate?

Response: Thank you for your comments. Since there are significant inter-annual variations in the drivers (vegetation, meteorology, and CO_2) affecting BVOC emissions in some specific regions. The selection of the reference year may lead to differences in the modeled BVOC emissions, primarily affecting the magnitude rather than the sign of the absolute trends. However, this study focuses on the relative trends in BVOC emissions. Differences in the reference year have little effect on the magnitude and sign of our estimation results.

We have added the following discussion of the impact of the reference year selection on our results in Section 4 "Discussion":

"Note that the selection of the reference year (i.e., year 2001 in Table 1) may cause variations in simulated BVOC emissions, mostly affecting the magnitude rather than the sign of the absolute trends. Since this study focuses on the relative trends in BVOC emissions (i.e., ratio of absolute trend to multi-year means), differences in the reference year have little effect on the magnitude and sign of our estimation results."

Possible issues I have detected:

- In line 70, based on my reading of the rest of the manuscript, shouldn't the range '0.04-0.33% yr^{-1}' be negative?

Response: Sorry for the ambiguity of this sentence, we've corrected it.

"… and pointed out that land cover changes from 2001 to 2016 mitigate the isoprene emissions ranging from -0.33% to -0.04% yr^{-1}"

- Please review the use of capitalization for the acronyms 'LAI' and 'VCF' in both the text and figure captions.

Response: Thank you for your comment. We have reviewed and corrected the use of capitalization for the acronyms 'LAI' and 'VCF' in both the text and figure captions.

- In line 545, it should be corrected with "activity factors".

Response: Done. Thank you.

References

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471-1492, 10.5194/gmd-5-1471-2012, 2012.