

We thank reviewer #1 for taking the time to review our manuscript and for giving us constructive feedback on how to improve the manuscript. We address the five main comments below.

Comment 1

1. *The manuscript clearly presents two new BVOC emission datasets, but it did not state how these datasets advance beyond existing ones (e.g., CAMS-GLOB-BIO, MEGAN-MACC) in terms of process representation, especially regarding dynamic vegetation and soil moisture effects. A more direct comparison of methodological improvements and their impacts on emission estimates would strengthen the introduction or conclusions.*

Response

We agree with reviewer 1 and thank them for their comment. We are in complete agreement that this is relevant material to add to the paper. Moreover, when we created the concept of the SURFEX-MEGAN3.0 emissions we had the methodology of the CAMS-GLOB-BIO emissions, and its earlier iterations, in mind. We specifically tried to make some incremental improvements to the methodology. Specifically, we attempted to improve these aspects:

- **The satellite LAI data source.** We selected the Copernicus Land Monitoring Service (CLMS) LAI products in place of MODIS LAI. CLMS LAI products show consistently better accuracy (Sanchez-Zapero et al., 2018), precision, uncertainty, and temporal and spatial correlation than their MODIS counterparts.
- **Using a phenological vegetation model (Calvet et al., 1998) coupled with multi-layer diffusion-based soil moisture model in SURFEX (Decharme et al., 2019).** This meant that we could use the daily simulated and assimilated LAI values from SURFEX rather than monthly mean LAI values as was used in MEGAN-MACC and CAMS-GLOB-BIOv3.1.
- **Using a data assimilation approach.** A data assimilation approach combining satellite LAI data with a model offers the best of both worlds from both satellite observations and models. The observations offer more accurate, precise, and realistic estimate of the true LAI state, the model offers spatially and temporally contiguous fields with no data gaps, and the assimilation algorithm acts to smooth out and reduce uncertainties achieving an optimised estimation of the true LAI state.
- **Soil moisture effects.** The multi-layer (14 in this case) diffusion model for soil moisture is able to represent soil moisture accurately (Decharme et al., 2019; Blyverket et al., 2019). When this model is further improved by assimilation of LAI data, this improves the model's representation of evapotranspiration, which then indirectly improves the estimation of soil moisture (Albergel et al., 2017).
- **The spatial resolution.** A higher spatial resolution at $0.1^\circ \times 0.1^\circ$ compared to $0.5^\circ \times 0.66^\circ$ and $0.25^\circ \times 0.25^\circ$ in the case of MEGAN-MACC and CAMS-GLOB-BIOv3.1, respectively. Besides simply providing BVOC emissions at higher resolution, the spatial resolution is particularly important when representing land surface processes due to the heterogeneity of the land surface.
- **The temporal resolution.** The SURFEX-MEGAN emissions were produced with a temporal resolution of 1-hour. The MEGAN-MACC and CAMS-GLOB-BIOv3.1 emissions have a quasi 1-hour temporal resolution by combining the monthly mean emissions with a mean diurnal variability for the emissions for any particular month.
- **The meteorological data.** Besides the impact on the spatial resolution, this point is most relevant in comparison to MEGAN-MACC that used MERRA.

We have added this text to the introduction expanding on the listed incremental improvements to highlight the aspects noted above:

“We outline below advancements relative to previous work on BVOC emissions in the context of CAMS and European air quality (i.e., Sindelarova et al., 2014 and Sindelarova et al., 2022):

- i) Using a phenological vegetation model (Calvet et al., 1998) within SURFEX allows us to estimate LAI on a daily basis instead of only on a monthly mean basis as in the case of (Sindelarova et al., 2014 and Sindelarova et al., 2022).
- ii) A data assimilation approach combining satellite LAI data with a model offers the best of both worlds from both satellite observations and models. The observations offer a more accurate, precise, and realistic estimate of the true LAI state, the model offers spatially and temporally contiguous fields with no data gaps, and the assimilation algorithm acts to smooth out and reduce uncertainties achieving an optimised estimation of the true LAI state.
- iii) Using Copernicus Land Monitoring Service (CLMS) LAI products in place of MODIS LAI. CLMS LAI products show consistently better accuracy, precision, uncertainty, and temporal and spatial correlation than their MODIS counterparts when evaluated against independent observations (Sánchez-Zapero et al., 2018).
- iv) The multi-layer (14 in this case) diffusion model for soil moisture is able to represent soil moisture accurately (Decharme et al., 2019; Blyverket et al., 2019). When this model is further improved by assimilation of LAI data, this improves the model’s representation of evapotranspiration, which then indirectly improves the estimation of soil moisture (Albergel et al., 2017).
- v) A higher spatial resolution at $0.1^\circ \times 0.1^\circ$ compared to $0.5^\circ \times 0.66^\circ$ and $0.25^\circ \times 0.25^\circ$ in the case of MEGAN-MACC (Sindelarova et al., 2014) and CAMS-GLOB-BIOv3.1 (Sindelarova et al., 2022), respectively. Besides simply providing BVOC emissions at higher resolution, the spatial resolution is particularly important when representing land surface processes due to the heterogeneity of the land surface.
- vi) The emissions we present were produced with a temporal resolution of 1-hour. The MEGAN-MACC and CAMS-GLOB-BIOv3.1 emissions have a quasi-1-hour temporal resolution by combining the monthly mean emissions with a mean diurnal variability for the emissions for any particular month.
- vii) Using the state-of-the-art land cover maps over Europe, ECOCLIMAP-II (Faroux et al., 2013), which contain specific adaptations of the CORINE land cover to European conditions.
- viii) Updated MEGAN version to v3.0 (Guenther et al., 2020; Zhang et al., 2021). Many existing publicly available BVOC emission datasets and examples of applications in the literature use MEGAN 2.1.”

We have also added some additional discussion to the conclusions relevant to the expanded list of improvements:

References

Blyverket, J., Hamer, P. D., Bertino, L., Albergel, C., Fairbairn, D., & Lahoz, W. A. (2019). An evaluation of the EnKF vs. EnOI and the assimilation of SMAP, SMOS and ESA CCI soil moisture data over the contiguous US. *Remote Sensing*, 11(5), 478.

Calvet, J. C., Noilhan, J., Roujean, J. L., Bessemoulin, P., Cabelguenne, M., Olioso, A., & Wigneron, J. P. (1998). An interactive vegetation SVAT model tested against data from six contrasting sites. *Agricultural and Forest Meteorology*, 92(2), 73-95.

Decharme, B., Delire, C., Minvielle, M., Colin, J., Vergnes, J. P., Alias, A., ... & Voldoire, A. (2019). Recent changes in the ISBA-CTRIP land surface system for use in the CNRM-CM6 climate model and in global off-line hydrological applications. *Journal of Advances in Modeling Earth Systems*, 11(5), 1207-1252.

Sanchez-Zapero, J., Fuster, B., Camacho, F., Quality Assessment Report, (LAI, FAPAR, FCOVER, Collection 300 M, Version 1). Copernicus Land Monitoring Service. <https://land.copernicus.eu/en/technical-library/quality-assessment-report-leaf-area-index-333-m-version-1/>

Comment 2

2. *While the evaluation using ambient isoprene concentrations is valuable, the lack of direct comparison with eddy covariance or other flux measurements of BVOCs is a limitation. The authors should acknowledge this and discuss plans or possibilities for such evaluations in future work.*

Response

We thank the reviewer for this comment. We agree that this limitation should be made clearer in the manuscript. We would also like to note that, to our knowledge, the eddy covariance flux measurements of isoprene are only available as part of short-term measurement campaigns, which diminishes their usefulness for evaluating a multi-year emission dataset.

We have added this text to the discussion of the BVOC observations:

“We have not included a comparison between our emissions and eddy covariance flux observations of isoprene. This is a limitation of this work that prevents an evaluation of the magnitude of the emissions and of the observed variability in emissions. One reason for this is that such observations are only available as part of short-term campaigns, which limits their usefulness for evaluating multiyear emission datasets.”

In the time between the submission of this manuscript, the completion of the review, and our subsequent response, an article was published citing the preprint showing a spatially wider comparison between the emissions and isoprene, albeit for a 1-week, Europe-wide observation campaign. We have therefore added this text to the manuscript:

“The SURFEX-MEGAN3.0 open-loop emissions were evaluated in a recent study detailing a Europe-wide 1-week measurement campaign focused on VOCs (Aas et al., 2025). This evaluation showed that the SURFEX-MEGAN3.0 open-loop emissions correlated well with observed isoprene concentrations at roughly half of the sites included in the study, albeit for a short time period.”

We have also added text to the conclusions section in a paragraph where we discuss other limitations. We direct readers to see response to comment 5 below, which discusses limitations more generally.

Comment 3

3. *Although LAI assimilation could improve LAI estimates to some extents, its impact on total isoprene emissions might be modest. The authors should elaborate on why this is the case and whether this suggests that LAI assimilation is more critical for certain regions or compounds.*

Response

We thank the reviewer for their comment. We address their comments in two parts. First, on the question of modest impacts on isoprene emissions. It is true that the impact on the Europe-wide totals averaged on monthly timescales is very limited. This is likely due to taking averages over large spatial areas leading to cancelling out of positive and negative LAI assimilation increments. It is also true that the maps showing the monthly and annual mean differences between the analysis and open loop emissions are quite low in absolute terms. Part of this is likely because of the temporal averaging, which, again, likely has the effect of cancelling the positive and negative increments out for particular grid cells over time. If we were to look at shorter time scales, we would see larger differences in the emissions between the two datasets. Lastly, but not least, the ISBA-a-gs model is quite skillful already for natural vegetation types when driven by good quality meteorological forcing and has been well validated for such cases (Delire et al., 2020). Thus, the open-loop model can capture the vegetation phenology and LAI in absolute terms quite well already. This has the effect of reducing the opportunity for the LAI assimilation step to make large improvements to the open-loop.

We have added this text to the manuscript to address the reviewer's comment:

"The impacts of the LAI assimilation on total and the monthly mean isoprene emissions appear modest for four reasons. First, the total isoprene emissions are subject to both temporal and spatial averaging, which leads to an effect whereby positive and negative assimilation increments cancel out over time and space leading to only small deviations from the open-loop. Second, the monthly mean emission maps are subject to temporal averaging that will over time lead to cancelling out of positive and negative LAI increments in time.

Beyond these purely statistical reasons, a third reason is that the underlying vegetation model in SURFEX, ISBA-a-gas, is quite skillful already at representing natural vegetation types when driven by good quality meteorological forcing and has been well validated in such cases (Delire et al., 2020). When the base model starts out with a good estimate of the observed state, this reduces the opportunity for the LAI assimilation step to make large improvements to the estimated state variable. Indeed, this effect was seen when using SURFEX to estimate soil moisture over the continental United States (Blyverket et al., 2019)."

Blyverket, J., Hamer, P. D., Bertino, L., Albergel, C., Fairbairn, D., & Lahoz, W. A. (2019). An evaluation of the EnKF vs. EnOI and the assimilation of SMAP, SMOS and ESA CCI soil moisture data over the contiguous US. *Remote Sensing*, 11(5), 478.

Delire, C., Séférian R., Decharme B., Alkama R., Calvet J.-C., Carrer D., Gibelin A.-L., Joetzjer E., Morel X., Rocher M., Tzanos D.: The global land carbon cycle simulated with ISBA-CTRIP: improvements over the last decade, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001886, <https://doi.org/10.1029/2019MS001886>, 2020.

Second, we address the question of whether LAI assimilation is more critical for certain regions. The underlying vegetation model in SURFEX, ISBA-a-gs, is not a crop model. It is designed to simulate natural vegetation types. This means that it does not simulate ploughing, seeding/planting, and harvesting, only includes simple prescriptive irrigation processes, and does it simulate which cultivars are being planted, which can all impact the LAI simulation in significant ways. The LAI assimilation offers an approach that can therefore correct LAI over regions with large proportions of crop cover. Indeed, this has been demonstrated in previous applications of the SURFEX model (see for example Albergel et al., 2017, Rojas-Munoz et al., 2023, and Jarlan et al., 2023 articles below). It should be noted that crops are not usually the largest source of isoprene. Thus, this may offer an explanation for why the impact on isoprene emissions of the assimilation step is limited.

Albergel, C., Munier, S., Leroux, D. J., Dewaele, H., Fairbairn, D., Barbu, A. L., Gelati, E., Dorigo, W., Faroux, S., Meurey, C., Le Moigne, P., Decharme, B., Mahfouf, J.-F., and Calvet, J.-C.: Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX_v8.0: LDAS-Monde assessment over the Euro-Mediterranean area, *Geosci. Model Dev.*, 10, 3889–3912, <https://doi.org/10.5194/gmd-10-3889-2017>, 2017.

Rojas-Munoz, O., Calvet, J. C., Bonan, B., Baghdadi, N., Meurey, C., Napoly, A., ... & Zribi, M. (2023). Soil moisture monitoring at kilometer scale: assimilation of sentinel-1 products in ISBA. *Remote Sensing*, 15(17), 4329.

Jarlan, J., Albergel, C., Bonan, B., Calvet, J.-C., de Rosnay, P., Ottlé, C., and Peylin, P.: Assimilation de données de télédétection pour le suivi des surfaces continentales in *Inversion et assimilation de données de télédétection*, 45-95, ISTE Editions, <https://doi.org/10.51926/ISTE.9142.ch2>, 2023

We have added this text to the manuscript to address this comment:

“A fourth reason is that the ISBA-a-gs vegetation model is not a crop model and is designed to simulate natural vegetation types. It lacks the means to simulate cultivation processes such as ploughing, seeding, and harvesting, and only includes a prescriptive irrigation process. This means that the open-loop model typically has much larger errors in its representation of the true vegetation state. This means that the LAI assimilation offers an opportunity to correct LAI over regions with large proportions of crop cover. Indeed, this has been demonstrated in previous applications of the SURFEX model (see for example Albergel et al., 2017, Rojas-Munoz et al., 2023, and Jarlan et al., 2023 articles below). Furthermore, it should be noted that crops are not usually the largest source of isoprene. Thus, this may offer an explanation for why the impact on isoprene emissions of the assimilation step is limited.”

Comment 4

4. *The manuscript mentions using MEGAN EFP with updated land cover but does not fully address potential biases from emission factors, especially given their significant contribution to uncertainty. The authors should discuss on how emission factors were validated or constrained for the European domain.*

Response

We agree with the reviewer that this is a relevant point to raise. We also agree with the reviewer that emission factors (EFs) are a significant contribution to the overall uncertainty in the emissions over Europe. This has been discussed in several papers (e.g. Simpson et al., 1999, Keenan et al., 2009, Rinne et al., 2009, Oderbolz et al., 2013, or Sindelarova et al., 2022) and future efforts are required to improve this area. However, it is important to note that the main purpose of this manuscript is not to evaluate the emission factors (EFs) used in MEGAN3, but rather to demonstrate the use of SURFEX and

assimilated LAI to calculate the emissions. We believe it is beyond the scope of this paper to try to do a full validation or to constrain the EFs that we used. As a general comment, it is hard to do specific validation of EFs due to the lack of direct measurement at the grid scale of our emission inventories and the underlying PFT data. It would require at least one other manuscript to address this topic with sufficient detail to properly address and highlight the important issues.

The best we can do here is to provide comparison of the EFs used to compile the SURFEX-MEGAN emissions, and those used in two of the prominent inventories that we compare against: CAMS-GLOB-BIOv3.0 (MEGAN2.1) and CAMS-GLOB-BIO3.1 (EMEP). This will give some information on the uncertainties in our emissions. Furthermore, it provides the first step towards motivating and identifying the further investigations that are needed for future studies. We carried out a comparison between the emission factors (EFs) used in the CAMS-GLOB-BIO datasets and those used to create the SURFEX-MEGAN emissions as part of background research for the paper. We have, therefore, now added figures showing the emission factors from CAMS-GLOB-BIO3.0 and 3.1 to the supplement. We also add some interpretation to this comparison to the manuscript (Sect. 3.3.2) that takes into account the findings from Sindelarova et al. (2022) that indicated that changes from the MEGANv2.1 to EMEP EFs led to reductions in the overall magnitude between the CAMS-GLOB-BIOv3.0 and CAMS-GLOB-BIOv3.1 emissions.

“The emission factors used in the different emission inventories contribute another important source of uncertainty and likely also play an additional role in explaining the differences in their magnitude. It is well established that uncertainties in emission factors are an important contributor to the overall uncertainty in emissions (Simpson et al., 1999, Keenan et al., 2009, Rinne et al., 2009, Oderbolz et al., 2013). Sindelarova et al. (2022) found that changing from the MEGANv2.1 to the EMEP emission factors, respectively, accounted for the higher estimated emissions over Europe of CAMS-GLOB-BIOv3.0 compared to CAMS-GLOB-BIOv3.1.

We compare the emission factors in this study (see Figure 7) to the emission factors for the CAMS-GLOB-BIOv3.0 and v3.1 emission inventories (Sindelarova et al., 2022) over Europe (see the supplement with CAMS-GLOB-BIOv3.0 in Figure S21 and CAMS-GLOB-BIOv3.1 in Figure S22). Due to differences in approach, it is not possible to compare the absolute magnitude of the emission factors shown in Figure 7 compared to those in Figures S21 and S22. This is because a different set of standard conditions were used by CAMS-GLOB-BIO from those used by SURFEX-MEGAN3.0. Furthermore, CAMS-GLOB-BIO, which is built on MEGAN2.1, uses a canopy-level approach instead of the leaf-level approach used in SURFEX-MEGAN3.0. Thus, the CAMS-GLOB-BIO emission factors include a multiplication by a standard LAI value of 5 m².m⁻² for 3.0 and by a monthly climatological LAI derived from Yuan et al. (2011) for 3.1, whereas LAI is only treated within the activity factor calculations in SURFEX-MEGAN3.0.

Comparing Figures 7, S21, and S22, we determine that the SURFEX-MEGAN3.0/MEGAN EFP emission factors are more similar in their spatial distribution to those from CAMS-GLOB-BIOv3.0/MEGANv2.1 than the CAMS-GLOB-BIOv3.1/EMEP-based emission factors. The spatial patterns of the EMEP-based emission factors show much more heterogeneity than the MEGAN3.0 emission factors and show both maxima and minima in different regions. The EMEP-based emission factors show specific regions that have much higher relative values associated with broadleaf species in southern Europe on the one hand and areas that have relatively much lower values in central Europe and mountainous regions on the other. The MEGAN2.1 emission factors used in CAMS-GLOB-BIOv3.0 are more spatially smooth with less heterogeneity, which is a point of similarity with SURFEX-MEGAN3.0. The MEGAN2.1 emission factors do show peak values similar regions, e.g., mountainous regions like the Pyrenees, Alps, Balkans, and Carpathians, but differ by showing peaks in Russia, northern Norway, and Galicia.

Sindelarova et al. (2022) determined that the increased heterogeneity of the EMEP-based emission factors, particularly the large regions in Europe with relatively low values, contributed to the lower emissions that they calculated for CAMS-GLOB-BIOv3.1 compared to CAMS-GLOB-BIOv3.0. Following the same logic, and given the differences we see comparing SURFEX-MEGAN3.0 to the more heterogeneous EMEP-based emission factors, we attribute the higher SURFEX-MEGAN3.0 emissions compared to the CAMS-GLOB-BIOv3.1 emissions to be largely due to the effect of the emission factors.”

And also in the conclusions:

“Part of the difference in the absolute magnitude in the SURFEX-MEGAN3.0 and CAMS-GLOB-BIOv3.1 emissions was attributed to the difference in emission factors used to calculate both emission inventories. With the SURFEX-MEGAN3.0 emission factors generally having an effect that increased the isoprene emissions relative to those from CAMS-GLOB-BIOv3.1. This highlights the need for more study on emission factors in Europe and for us to update the emission factors in future work related to specific emitting vegetation species.”

In addition, we provide some details on ongoing research being done within two EU projects connected with CAMS (CAMS2-61,CAMAERA), which itself has identified challenges that limit progress on this specific topic.

“Work to evaluate and improve the European EFs in both EMEP and CAMS-GLOB-BIO is underway in other EU projects (CAMAERA, <https://camaera-project.eu/>, last access: 6 February 2026 and the continuation of CAMS2-61, Denier van der Gon, 2025), and any improvements can be incorporated in future applications of SURFEX-MEGAN3.”

References

Denier van der Gon: 2025, Documentation of CAMS emission inventory products, Denier van der Gon, H., Gauss, M., and Granier, C. (eds), CAMS261_2021SC1 – Product documentation, Copernicus Atmosphere Monitoring Service, 1 pp., <https://doi.org/10.24380/uag-0svt>, 2025.

Keenan, T., Niinemets, Ue., Sabate, S., Gracia, C., and Penuelas, J.: Process based inventory of isoprenoid emissions from European forests: model comparisons, current knowledge and uncertainties, *Atmos. Chem. Physics*, 9, 4053–4076, 2009.

Oderbolz, D. C., Aksoyoglu, S., Keller, J., Barmpadimos, I., Steinbrecher, R., Skjoth, C. A., Plass-Duelmer, C., and Prevot, A. S. H.: A comprehensive emission inventory of biogenic volatile organic compounds in Europe: improved seasonality and land-cover, *Atmos. Chem. Physics*, 13, 1689–1712, <https://doi.org/10.5194/acp-13-1689-2013>, 2013.

Rinne, J., Back, J., and Hakola, H.: Biogenic volatile organic compound emissions from the Eurasian taiga: current knowledge and future directions, *Boreal Environment Research*, 14, 807–826, 2009.

Wells, K. C., Millet, D. B., Payne, V. H., Vigouroux, C., Aquino, C. A. B., De Mazière, M., de Gouw, J. A., Graus, M., Kurosu, T., Warneke, C., and Wisthaler, A.: Next-Generation Isoprene Measurements From Space: Detecting Daily Variability at High Resolution, *J. Geophys. Res.*, 127, e2021JD036181, <https://doi.org/https://doi.org/10.1029/2021JD036181>, 2022.

Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., ... & Öquist, M. G. (1999). Inventorying emissions from nature in Europe. *Journal of Geophysical Research: Atmospheres*, 104(D7), 8113-8152.

Comment 5

5. *The study shows many limitations. The authors should add more descriptions about the limitations in the discussions or conclusions.*

Response

We agree with the reviewer's comment. We have added a paragraph to the conclusions section that addresses limitations on the following topics: emission factors, the lack of flux tower measurement comparisons, limitations on the consistency of land cover datasets, using grid-level LAI to drive MEGAN rather than PFT-specific LAI, the necessary tradeoff between high resolution meteorological forecast versus coarser resolution reanalysis, and the lack of tests in an atmospheric model to compare to observations.

"We now address the various limitations of our work. First, we did not include a comparison with flux tower measurements nor did we test our emissions in an atmospheric model to simulate atmospheric concentrations of isoprene and secondary chemical species. Both would be valuable ways to extend our work in the future. There were also a series of methodological choices that affected the uncertainties of the presented emissions that could be addressed via sensitivity tests and form the basis of future work. For instance, we only used a single set of emission factors to calculate the emissions, and given their associated uncertainties, it would be worthwhile to investigate this further and test other emission factors in the future. We used the grid-averaged LAI output from SURFEX, but it would be worthwhile to test using the PFT-specific LAI values and then calculate the emissions separately for each PFT within each grid cell, e.g., following the approach of Oumami et al. (2024). Lastly, it would be worthwhile to test the trade-off of using coarser resolution meteorological reanalysis versus higher resolution meteorological forecast. We evaluated that the latter would be advantageous when designing this study but testing the former would help to evaluate that hypothesis further."

We have also added this text to the discussion of land use datasets:

"One further limitation of our work was the inconsistency between the land use datasets used in the SURFEX land surface model and the MEGAN EFP tool for calculating emission factors. This inconsistency should be corrected in future work following the example of Oumami et al. (2024) and Sindelarova et al. (2022)."