CAMS Service Evolution

D5.2 Uncertainties in Isoprene CAMS-GLOB-BIO emissions at the grid cell level

Due date of deliverable	June 30th 2025
Submission date	June 30th 2025
File Name	CAMEO-D5-2-V2.0
Work Package /Task	WP5, Task 5.2
Organisation Responsible of Deliverable	Charles University
Author name(s)	Katerina Sindelarova
Revision number	2.0
Status	Issued
Dissemination Level	Public

Funded by the European Union

The CAMEO project (grant agreement No 101082125) is funded by the European Union.
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1 Executive Summary

The deliverable report describes a methodology for uncertainty estimation of isoprene emissions from vegetation and the results that were obtained. The novelty of this approach is a predefined, consistent approach to the emission uncertainty estimation, as this has not been done before. At the same time, this work should be regarded as a first step of such uncertainty estimation, acknowledging the relative simplicity and limitation of the chosen approach. The emission uncertainty was estimated for two distinct years which had a different climatology, and which are covered by the formaldehyde observations from the TROPOMI satellite instrument. The emission uncertainty is an important information for the emission dataset users as well as a required input to the inversion modelling system that uses remotely sensed measurements of formaldehyde to constrain the isoprene emissions.

The CAMS-GLOB-BIOv3.1 isoprene emission inventory developed under the Copernicus Atmosphere Monitoring Service (CAMS) was considered as a reference. Uncertainty of isoprene emissions was estimated based on uncertainty of selected variables that drive the isoprene emissions – leaf area index, meteorology (temperature and solar radiation) and emission potentials. Upper and lower limits of these variables were defined and then used in the emission model MEGAN (Model of Emissions of Gases and Aerosols from Nature), which is the same model used to calculate CAMS-GLOB-BIO dataset, to obtain upper and lower estimates of isoprene emission reflecting the variation of emission model inputs.

The result are monthly mean isoprene emission estimates for the years 2019 and 2022 on a global grid with horizontal spatial resolution of 0.25º x 0.25º. Each model grid cell is assigned with a mean isoprene emission from the CAMS-GLOB-BIOv3.1 dataset and an upper and lower limit isoprene emission value that represent the uncertainty range. The upper and lower limits are minimum and maximum values from the 8 MEGAN model runs, i.e. runs with upper and lower values for leaf area index, temperature, solar radiation, and isoprene emission potentials, selected per grid cell. In addition, the results of individual model runs are provided as well, so that the users can study the impact of uncertainty of input parameters separately or calculate standard deviation or relative error of the emissions, depending on their needs. As a side product, the upper and lower limit values of selected input variables are provided as well. This data may be useful for applications of online biogenic VOC modules embedded in the air quality models.

The obtained isoprene emission data show that the emission potential is the parameter that causes the largest levels of uncertainty. On global average the annual mean relative error of isoprene emission estimates is -57% and +38% in 2019, and -56% and +39% in 2022, with larger relative error values on regional level. The isoprene uncertainty data identify regions where our knowledge about isoprene emissions may be improved e.g. by surface flux measurements or by remote sensing data, especially by improving the emission potential information.

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2 Introduction

2.1 Background

The Earth's biosphere is a source of thousands of different volatile organic compounds (VOCs) that are being emitted into the atmosphere. These compounds have a very short lifetime and play a key role in the formation of the surface ozone and secondary organic aerosol, thus impacting the air quality and the Earth-Atmosphere energy balance. Vegetation is a source of about 90% of the total VOC emissions into the atmosphere from the Earth's surface, with isoprene being the most abundant species accounting for about 70% of the global biogenic VOC (BVOC) emission total when expressed in units of carbon (Guenther et al., 2012; Sindelarova et., 2014).

There exists a long list of studies that focus on isoprene flux measurements at different scales (leaf level to regional), bottom-up and top-down model systems for estimation of isoprene emissions and furthermore, remote sensing data of isoprene concentration that became available recently (Wells et al., 2020). However, it is very difficult to capture the spatial and temporal diversity of vegetation, together with a detailed enough description of the emission potentials of individual vegetation types and its dependence on environmental conditions, namely temperature and solar radiation, but also other factors that impact the plants condition such as soil moisture, ambient air composition, biotic stress. Current estimates of isoprene emissions therefore differ in the methodology that is being used to estimate the emission fluxes and in input data that are being used. These known factors, and possibly some unknown that we are not considering yet in the isoprene emission modelling, imply level of uncertainty that in this case can be relatively high. From the comparison of different isoprene emission datasets, Sindelarova et al. (2014) estimate the global isoprene uncertainty to be factor of 2-3, with even larger differences on regional scale.

The presumably large uncertainty of isoprene emissions motivated the effort in CAMEO to estimate its uncertainty in a consistent and predefined way. The emission uncertainty by itself is a valuable information for the emission users, but furthermore it is a necessary input information for the inversion modelling systems that are being used to constrain isoprene emissions with formaldehyde observations (e.g. Palmer et al., 2006; Millet et al., 2008, Stavrakou et al., 2009; Kaiser et al., 2018; Oomen et al., 2024).

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverables

The objective of this deliverable was to provide global gridded estimates of uncertainty of the biogenic isoprene emissions for two distinct years.

2.2.2 Work performed in this deliverable

In this deliverable the work as planned in the Description of Action (DoA, WP5 T5.2) was performed. The uncertainty of isoprene CAMS-GLOB-BIO emissions was estimated on a global grid for two selected years.

2.2.3 Deviations and counter measures

No deviations have been encountered.

2.2.4 CAMEO Project Partners:

ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
Met Norway	METEOROLOGISK INSTITUTT
BSC	BARCELONA SUPERCOMPUTING CENTER-CENTRO NACIONAL DE SUPERCOMPUTACION
KNMI	KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT-KNMi
SMHI	SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT
BIRA-IASB	INSTITUT ROYAL D'AERONOMIE SPATIALEDE BELGIQUE
HYGEOS	HYGEOS SARL
FMI	ILMATIETEEN LAITOS
DLR	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV
ARMINES	ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPPEMENT DES METHODES ET PROCESSUS INDUSTRIELS
CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
GRASP-SAS	GENERALIZED RETRIEVAL OF ATMOSPHERE AND SURFACE PROPERTIES EN ABREGE GRASP
CU	UNIVERZITA KARLOVA
CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
MF	METEO-FRANCE
TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO
INERIS	INSTITUT NATIONAL DE L ENVIRONNEMENT INDUSTRIEL ET DES RISQUES - INERIS
IOS-PIB	INSTYTUT OCHRONY SRODOWISKA - PANSTWOWY INSTYTUT BADAWCZY
FZJ	FORSCHUNGSZENTRUM JULICH GMBH
AU	AARHUS UNIVERSITET
ENEA	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

3 Methodology of uncertainty estimation

Given the prevalence of isoprene in the biogenic VOC (BVOC) emissions and due to the fact, that it is a species the most studied in the emission flux measurement campaigns and atmospheric concentration measurements in observational networks, isoprene is a species that the current work within the CAMEO project is focused on. The proposed methodology for estimation of uncertainty for isoprene emissions can be seen as a first step to assigning BVOC emissions with uncertainty levels and could be applied to other BVOC species in the future.

In CAMEO we aim to assign the isoprene emission data that are being developed under the CAMS project with uncertainty intervals based on the uncertainty of selected parameters that are being used to estimate the emissions. A long-term global dataset of biogenic emissions that is being developed under the CAMS project is called CAMS-GLOB-BIO (Sindelarova et al., 2022). It consists of monthly mean and monthly averaged daily profiles of emissions for 25 BVOC species on a global grid with horizontal spatial resolution of 0.25° x 0.25°.

CAMEO is using the CAMS-GLOB-BIOv3.1 isoprene emissions that have been calculated by the MEGANv2.1 model (Model of Emissions of Gases and Aerosols from Nature, Guenther et al., 2006; 2012). The emission model calculates an isoprene emission flux F (μg grid cell^{-1} h^{-1}) from a grid cell as follows:

$$F = \gamma \cdot EP \cdot S \quad (1)$$

where γ is a dimensionless factor that accounts for dependence of emissions on environmental factors (temperature, solar radiation, ambient CO_2 concentration, leaf area index, leaf age, etc.), EP (μg m^{-2} h^{-1}) is an emission potential of a grid cell, i.e. a unit emission under standard environmental conditions and S is a grid cell surface area (m^2).

The MEGAN model was driven by the ERA5 meteorological reanalysis (Hersbach et al., 2020), processed data of Leaf Area Index (LAI) from MODIS5 satellite instrument (Yuan et al., 2011) and a land cover description by plant functional types from the Community Land Model (CLM4, Lawrence and Chase, 2007). For more details on the MEGANv2.1 set up please see Sindelarova et al. (2022).

There are many possible ways how to estimate the uncertainty of the isoprene emissions including different emission models, variations of sources for input data, combining perturbations in driving factors, etc. In CAMEO, a first step approach was selected to fix the emission model to MEGANv2.1, i.e. the same emission model that calculates the mean CAMS-GLOB-BIO emissions and estimate the isoprene uncertainty based on the uncertainty of selected input model parameters. For the following model variables: leaf area index, temperature, solar radiation and emission potentials, a maximum and minimum values were estimated based on available data. These maximum and minimum values were then applied in the MEGANv2.1 model to obtain isoprene emissions reflecting this input parameter uncertainty. This exercise was performed for two different years, 2019 and 2022. The selection of these two years was motivated by two requirements. The uncertainty needed to be estimated for the years when TROPOMI (Tropospheric Monitoring Instrument) formaldehyde observations are available. Formaldehyde is the main oxidation product of isoprene and is used by the inversion modelling system to constrain the isoprene emissions. At the same time the selected years should represent different climatological conditions. The climatological conditions could be defined in different ways. In the context of biogenic emissions, the focus was given to the El Niño – Southern oscillation conditions as this phenomenon strongly affects emissions in the tropical regions, esp. of South America. It has been shown by different studies (e.g. Müller et al., 2008; Sindelarova et al., 2014) that the BVOC emissions significantly increase during the El Niño phase, as the temperature over South America increases, and on the other hand emissions tent to decrease during the La Niña phase, which relates to the temperature decrease. According to the data from NOAA Climate Prediction Center (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), moderate El Niño took place in 2019 and moderate La Niña took place in 2022. Moderate years were selected rather than extreme ones to provide information that could be representative for a longer period.

The following sections describe in detail methodology of how the uncertainty of selected input parameters was obtained and present isoprene estimates by the MEGANv2.1 model when uncertainty intervals of these inputs were applied.

3.1 Uncertainty of the Leaf Area Index

Leaf Area Index (LAI, $m^2.m^{-2}$) is defined as a one-sided green area of the leaf per unit of ground surface. It is a key parameter for isoprene emission estimation as it describes the amount of biomass in the vegetation canopy, and it simulates the vegetation seasonal cycle throughout the year. The mean CAMS-GLOB-BIOv3.1 emissions are simulated with LAI processed from the MODIS5 observations by Yuan et al. (2011). These LAI data were averaged to obtain monthly values and represent a mean LAI for each model grid cell. To account for the vegetated area only, the MODIS LAIs were divided by the fraction of the grid cell covered by the vegetation, as recommended by Guenther et al. (2006).

The study of Fang et al. (2021) estimated uncertainty of MODIS LAI product by analysing the quality flags and indicators embedded in the MODIS product, to identify temporal anomalies. They develop a spatially and temporally distributed map with mean relative error (RE) of MODIS LAI. The monthly mean maps with LAI relative error for the years 2019 and 2022 were used to create minimum and maximum LAI estimates for the MEGAN simulations for these two years. The minimum LAI estimate was calculated as (mean LAI – mean LAI * RE LAI), while the maximum LAI estimate was calculated as (mean LAI + mean LAI * RE LAI). Fig. 1 presents the spatial distribution of the annual mean LAI from MODIS together with the annual mean LAI relative error. The map with LAI relative error shows that the highest uncertainty of LAI is usually in areas with sparse vegetation, e.g. central Australia and sub-Saharan Africa (more than 50%).

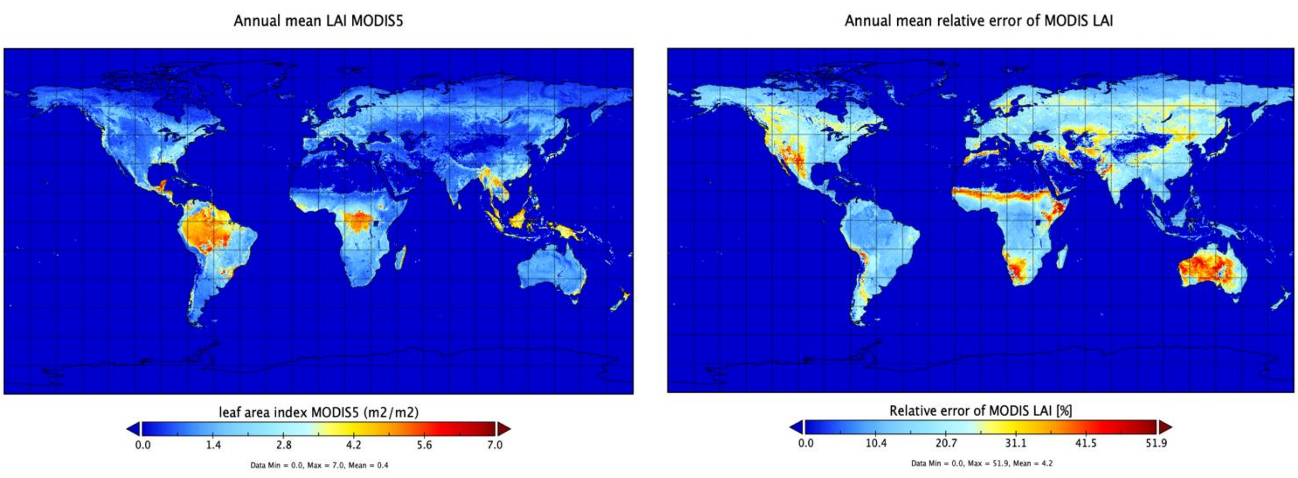

Fig.1 *Annual mean Leaf Area Index from the MODIS5 instrument (left) and annual LAI relative error as provided by Fang et al. (2021).*

3.2 Uncertainty of the meteorological inputs

Meteorological conditions are an important driver of the isoprene emissions. Laboratory studies have shown that there is a relationship between leaf temperature and solar radiation and the isoprene emissions from plants (Guenther et al., 1991, 1993). Isoprene is formed inside the plant during the photosynthesis process. Its production is linked to the photosynthetically active radiation (PAR), which is a portion of visible light with wavelengths between 400 and 700 nm. The isoprene emissions exponentially increase with increasing leaf temperature until a saturation point at about 40ºC after which the emissions decrease with further temperature increase. The relationship between isoprene emission and light intensity is almost linear again until a saturation point after which the emission rates remain constant with increasing light intensity. These dependencies of isoprene emission on meteorological conditions are defined by the emission activity factors γ in the MEGAN model and their description can be found in Guenther et al. (2012).

The CAMS-GLOB-BIO dataset is calculated using the ERA5 meteorological reanalysis. The ERA5 dataset unfortunately does not provide Photosynthetically Active Radiation parameter. Therefore, PAR is being calculated from the downward solar radiation at the surface divided by a factor of 2.2 as suggested by literature (e.g. Jacovides et al., 2003). The MEGAN model is therefore driven by monthly averaged daily profiles of downward solar radiation, 2m air temperature, 10m wind speed, air pressure and humidity.

Isoprene emissions are sensitive to temperature and light values and variations between different meteorological inputs can therefore significantly impact modelled isoprene emission rates. The uncertainty of ERA5 temperature and solar radiation was estimated from the results of the ERA5 ensemble runs. The ERA5 dataset provides mean and spread values for each variable obtained from a 10-member meteorological ensemble. The spread represents standard deviation. The difference between the mean and spread values was used to calculate a relative error for each variable. The 3-hourly data were interpolated and processed to obtain a monthly mean daily profiles (24 h values) of relative error for temperature and solar radiation, on a global 0.25º x 0.25º grid. These relative errors (RE) were then applied to meteorological inputs from ERA5 which are being used to calculate the CAMS-GLOB-BIO dataset. The upper estimate of ERA5 temperature was calculated as (TEMP + TEMP * RE) and lower estimate of ERA5 temperature was calculated as (TEMP – TEMP * RE). Similar approach was used for upper and lower estimate of solar radiation. These upper and lower values were then used in the MEGAN model to simulate the impact of variation of meteorological parameters on isoprene emission flux.

3.3 Uncertainty of the emission potential

The emission from a unit of surface under standardized environmental conditions is defined as an emission potential (EP, $\mu g\ m^{-2}\ h^{-1}$). The standard conditions at a leaf level are usually defined as PAR flux equal to 1000 $\mu mol\ m^{-2}\ s^{-1}$ and leaf temperature of 303 K. The MEGANv2.1 model calculates with emission potential values at a canopy level, for which the definition of the standard conditions is more complex. It includes the standard canopy LAI equal to 5 $m^2\ m^{-2}$, defined portion of growing, mature and old leaves, standard air temperature of 303 K, air humidity of 14 g kg^{-1}, wind speed equal to 3 m s^{-1} and distinct PAR conditions for sunlit and shaded leaves. For detailed description please see Guenther et al. (2012).

Emission potential is a crucial parameter in BVOC modelling as it defines the initial information about the emission which is then varied by the model depending on the seasonal cycle and meteorological conditions. Emission potential depends on the vegetation composition present at the surface. In this work we distinguish between emission potential and emission factor. Emission potential is used for a value that is assigned to the whole grid cell, while emission factor is assigned to a vegetation type, either single tree species or a more generalised vegetation type category (e.g. forest type, shrub, grass). Emission potential of a model grid cell is a result of combination of vegetation types present in the grid cell and emission factors assigned to this vegetation type. The level of precision of emission potential value depends on the level of detail of the vegetation description, ideally in the detail of single tree species. However, it is difficult to obtain such detailed information about land cover on a global scale. Furthermore, the assignment with emission factors depends on the availability of the information from literature. Emission factors are being measured at different spatial scales which imply the level of detail they represent. Emission factors measured at leaf level at laboratory or field campaigns describe emission from specific plant, canopy scale measurements from high towers above forest canopy can cover emissions from a specific forest type and aircraft measurements can describe emissions from a specific region. Preparation of the emission potential map for the emission model is therefore a balance between the available detail of the vegetation description and assignment of the vegetation type or category with appropriate emission factor.

In the MEGAN model there exist two options how to define the emission potential of the modelled domain. The model can work either with a detailed EP map provided by the user or it can calculate the emission potential map from a land cover map and predefined emission factors defined in the look-up tables. The MEGAN model uses 16 Plant Functional Types (PFTs) from the CLM4 model (Lawrence and Chase, 2007) to describe the land cover composition. These PFT classes distinguish between evergreen and deciduous, broadleaf and needleleaf forests, at different climate bands (boreal, temperate and tropical), as well as several shrub and grass classes. Each of these classes are assigned with an emission factor in the MEGAN model look-up table. The model then calculates the emission potential of each grid cell as a PFT fraction multiplied by appropriate emission factor, summed through all PFT classes present in the grid cell.

The advantage of detailed EP maps provided by the user is that it can include a detailed information of land cover and emission factors in specific parts of the world, where this information is available and be less precise in regions where the land cover description is more general. The description of the global vegetation by only 16 PFT classes, where the forest categories broadly describe the phenology of the leaves but are not able to cover the diversity of single tree species, is rather inaccurate but may be necessary due to lack of data.

The importance of emission potential values for isoprene emission estimation, yet the difficulty in setting its value for specific locations, makes the EP a factor that has large influence on the final emissions but is connected to high uncertainty. In order to estimate the possible lower and upper EP values on a grid cell level, several MEGAN model suitable EP maps were collected. These EP maps are either detailed maps created based on detailed vegetation description, or EP maps calculated by the MEGAN model based on different land cover inputs and emission factors from the look-up tables. Comparison of spatial distribution of the isoprene EP values from these 6 EP maps is presented in Figure 2. And their short description is given in Table 1.

The *EFMAP* is a default detailed isoprene EP map that is available together with the MEGAN model code (Guenther et al., 2012). It was built on detailed land cover in regions where this information was available (e.g. US) and includes information from the BVOC measurement campaign (esp. in the Amazon). The *EFMAP with EU update* is a MEGAN default detailed EP map which was updated in Europe with detailed land cover and single-tree species specific emission factors that were collected for the EMEP model (Sindelarova et al., 2022). The rest of the EP maps was calculated from the combination of global PFT maps and assigned emission factor. The *EP PFTs* is an EP map calculated using the CLM4 land cover map (Guenther et al., 2012), *EP MEGANv3* was calculated using the land cover and emission factor database from a newly released MEGANv3 model (https://bai.ess.uci.edu/megan/data-and-code). The map *EP PFTs ESA-CCI* was calculated based on land cover from ESA-CCI (ESA, 2017) which was converted to MEGAN PFT classes by the CCI-LC user tool v4.3 (Poulter et al., 2015). And finally, the *EP PFTs ESA Harper* map was created based on the ESA-CCI land cover processed by Harper et al. (2023).

These 6 EP maps were overlayed on top of each other and for each grid cell a minimum and maximum EP value was selected to create an upper and lower estimate of EP map. Fig. 3 presents the data source which is responsible for the minimum and maximum EP value in each grid cell. The maps show that overall, the EP values from *PFTs ESA-CCI Harper* are usually the lowest and the values from *EFMAPs* are often the highest, but many regional differences occur, e.g. *EFMAPS with EU update* provides the lower EP estimates in northern Europe.

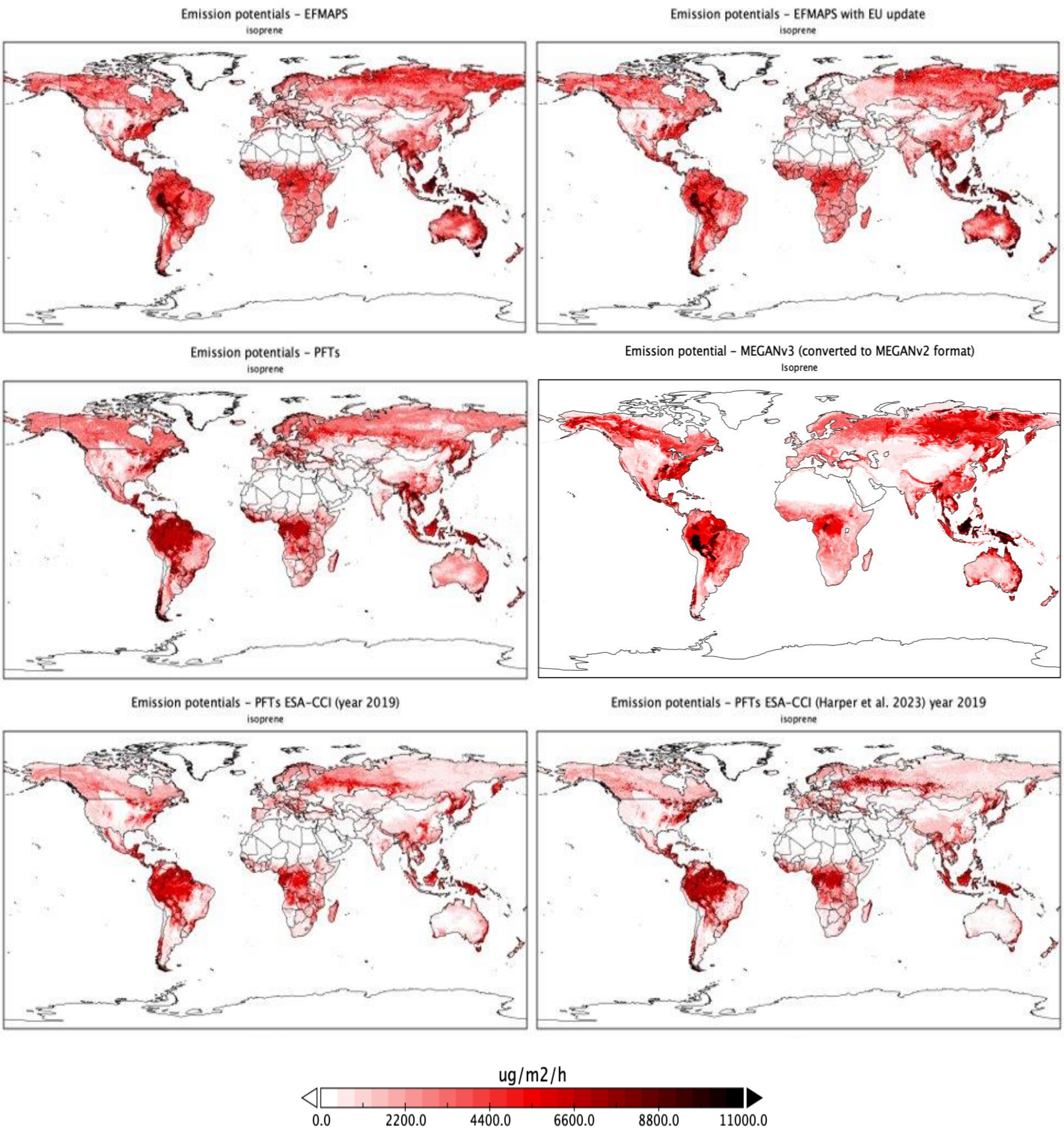

Fig. 2. *Comparison of isoprene emission potential maps for the MEGANv2.1 model.*

Table 1. *List of isoprene emission potential maps presented in Fig. 2.*

EP map	description	reference
EFMAP	MEGANv2.1 default map	*Guenther et al. (2012)*
EFMAP with EU update	MEGANv2.1 default map with updates in Europe	*Sindelarova et al. (2022)*
EP PFTs	EP calculated from CLM4 PFT	*Guenther et al. (2012)*
EP MEGANv3	EP map created by the MEGANv3 model	*MEGANv3*
EP PFTs ESA-CCI	EP calculated from ESA-CCI PFTs	*Sindelarova et al. (2022)*
EP PFTs ESA Harper	EP calculated from ESA-CCI PFTs from Harper et al. (2023)	*Harper et al. (2023)*

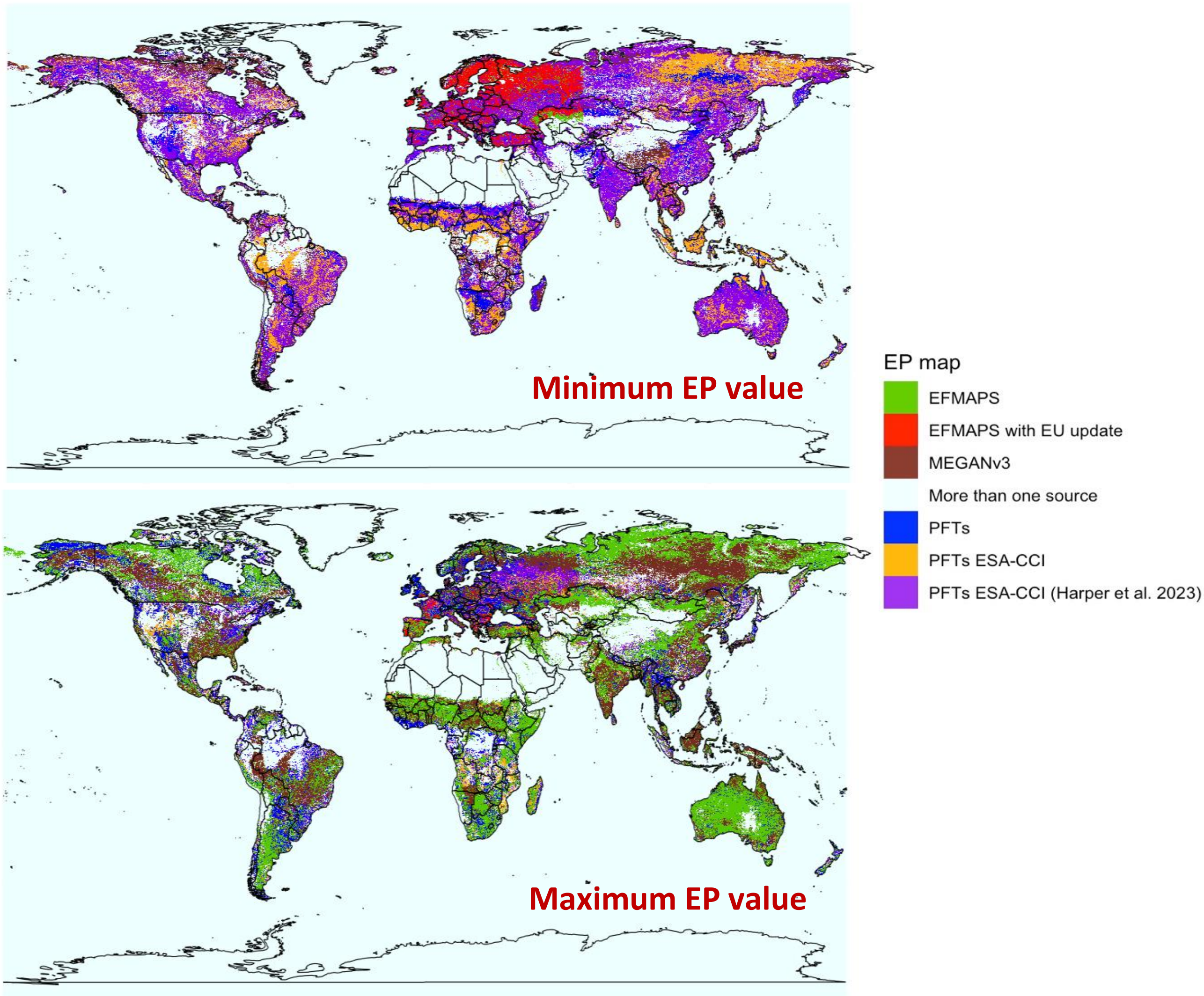

Fig. 3*. Description of EP maps responsible for minimum (top) and maximum (bottom) EP value estimates in each modelled grid cell.*

4 Uncertainty of the resulting isoprene emissions

The upper and lower estimates of LAI, temperature, solar radiation, and emission potentials described in previous sections were used individually as inputs to the MEGAN model to estimate isoprene emissions. The MEGAN model runs were performed for the years 2019 and 2022 which have a distinct climatology, and which are covered by the TROPOMI formaldehyde observations. The MEGAN model runs were performed a global grid with 0.25º x 0.25º horizontal spatial resolution on a monthly mean basis, i.e. same as the reference CAMS-GLOB-BIO isoprene estimates.

As a result, each grid cell of the model domain is assigned with a reference isoprene emission from the CAMS-GLOB-BIO dataset and 8 other isoprene estimates calculated with upper and lower values for the 4 selected input parameters. As indicated in the CAMEO project proposal, the final product of this task are monthly mean global gridded files where each grid cell includes mean isoprene emissions from the CAMS-GLOB-BIOv3.1 dataset and a minimum and maximum value selected from the 8 sensitivity emission model runs reflecting the uncertainty of the input data. The spread between minimum and maximum isoprene emission rate represents the uncertainty estimate of isoprene emission in individual grid cell.

Furthermore, the outputs of individual MEGAN model runs will be available as well. The users may then study isoprene uncertainty due to uncertainty of selected input parameters separately or can use the set of runs to calculate standard deviation or relative error of isoprene emissions with respect to the reference CAMS-GLOB-BIO, depending on the user needs or application.

In addition to the uncertainty of isoprene emissions, the uncertainty estimates for selected input parameters will be provided. These gridded datafiles with monthly mean upper and lower estimates of LAI, temperature, solar radiation, and emission potential can be used for isoprene uncertainty estimation in e.g. online BVOC modules that are embedded inside air quality models.

The comparison isoprene global monthly total emissions from the reference dataset CAMS-GLOB-BIOv3.1 with the CAMEO sensitivity runs is presented in Fig. 4., for both 2019 and 2022. In this context the emission uncertainty is defined as the difference between the reference isoprene emissions and the maximum and minimum value from the 8 sensitivity runs. The global mean relative error calculated from this difference equals to -57% and +38% in 2019, and -56% and +39% in 2022. On regional level the differences can be even higher. The isoprene annual totals were calculated over the regions defined within the GlobEmission project (*https://www.globemission.eu*). The spatial extent of the regions is presented in Fig. 5. The global and regional annual totals for the mean (CAMS-GLOB-BIOv3.1), CAMEO minimum and maximum isoprene emissions in 2019 and 2022 are listed in Table 2. Fig.6 shows annual profiles of isoprene emissions from the CAMS-GLOB-BIOv3.1 and from the individual CAMEO sensitivity runs plotted for selected regions. Each plot is assigned with a relative error value calculated from the difference between the CAMEO minimum and maximum estimates and the reference annual total, respectively. The spatial distribution of the annual mean isoprene emissions in CAMS-GLOB-BIOv3.1 is shown in Fig.7 together with the spatial distribution of the absolute difference between the CAMEO minimum and maximum isoprene and the reference, respectively. Fig. 6 and Fig. 7 present results for 2019 only since the plots for 2022 look very similar.

The plots clearly show that the uncertainty of emission potential maps is responsible for the highest uncertainty of the isoprene emissions globally as well as in all the regions. On global scale, the second most important parameter in the sense of contribution to the isoprene uncertainty is solar radiation, followed by temperature and then LAI. However, the importance of these variables differs on regional level. For example, in North Africa and Middle East the uncertainty due to LAI is high because the relative error in this sparsely vegetated area is also high.

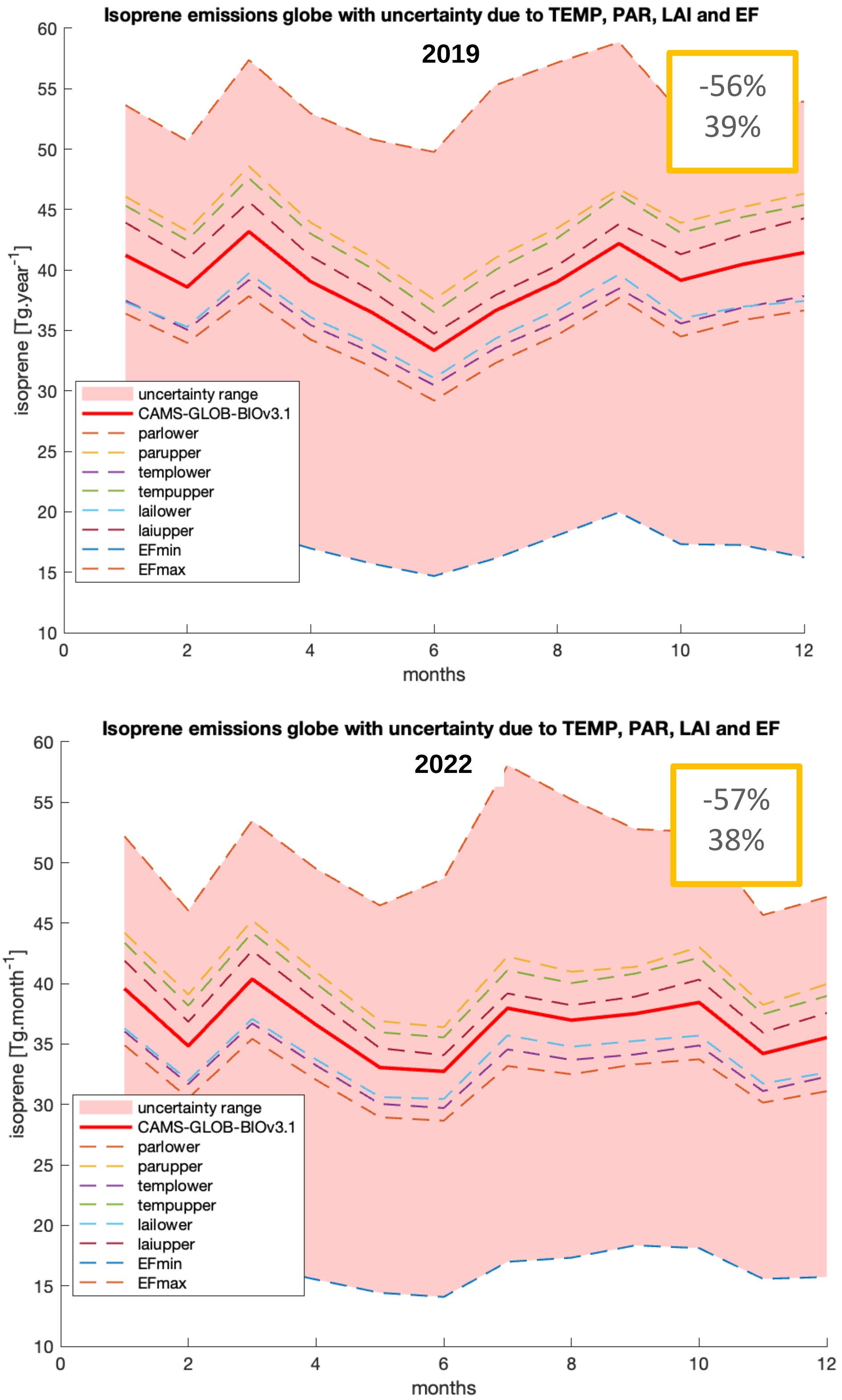

Fig. 4*. Comparison of global monthly total isoprene emissions from the reference CAMS-GLOB-BIOv3.1 and CAMEO runs driven by the upper and lower limits of solar radiation (par), temperature (temp), leaf area index (lai) and emission potential (EF) for the year 2019 (top) and 2022 (bottom). The numbers in the yellow box indicate the annual total relative difference between the minimum and maximum isoprene estimates and the reference CAMS-GLOB-BIOv3.1, resp.*

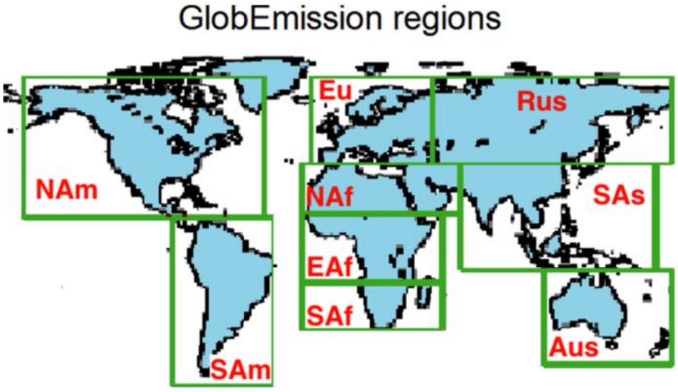

Fig. 5. *Geographical extent of the regions from Fig.5, adapted from the GlobEmission project (https://www.globemission.eu). The regions are the following: NAm – North America, SAm – South America, Eu – Europe, NAf – North Africa, EAf – East Africa, SAf – South Africa, Rus – Russia, SAs – Southeast Asia, Aus – Australia.*

Table 2. *Isoprene annual totals calculated over the GlobEmission regions and for the whole globe, for the mean dataset (CAMS-GLOB-BIOv3.1), CAMEO minimum and maximum isoprene estimates in 2019 and 2022.*

Isoprene annual total emissions / Tg. y^{-1}

	2019			**2022**		
	minimum	*mean*	*maximum*	*minimum*	*mean*	*maximum*
North America	13.0	34.4	52.6	12.2	33.4	51.4
South America	91.6	152.0	216.8	89.7	145.5	207.5
Europe	1.1	3.9	11.2	1.3	4.4	13.0
North Africa	0.4	6.2	8.8	0.4	6.2	9.0
East Africa	47.7	101.9	135.0	46.4	99.2	131.4
South Africa	6.0	18.0	22.3	5.0	14.3	17.9
Russia	2.2	7.1	12.9	2.4	7.6	13.8
Southeast Asia	33.6	84.0	117.3	31.4	77.7	108.8
Australia	7.6	65.0	73.6	6.0	51	57.7
globe	202.8	470.8	647.2	194.5	437.9	607.9

In regions that are usually the most studied for BVOC emissions, such as the South and North America, Southeast Asia, the isoprene uncertainty levels are similar as the global mean. The large uncertainty in regions such as Australia, Europe, Africa, Russia, identify parts of the world where especially the information about isoprene emission potential is not well known and where improvements in our knowledge with more measurements or with help of remote sensing would improve the isoprene emission estimates. The high positive relative error in Europe (+187%) is caused by the fact, that the reference CAMS-GLOB-BIOv3.1 uses the updated emission potential values based on detailed land cover and emission factor information from the EMEP model. This EP map with EU updates happens to be on the lower end of all the compared EP maps. Therefore, the upper limit EP simulations are this much higher than the reference CAMS-GLOB-BIO.

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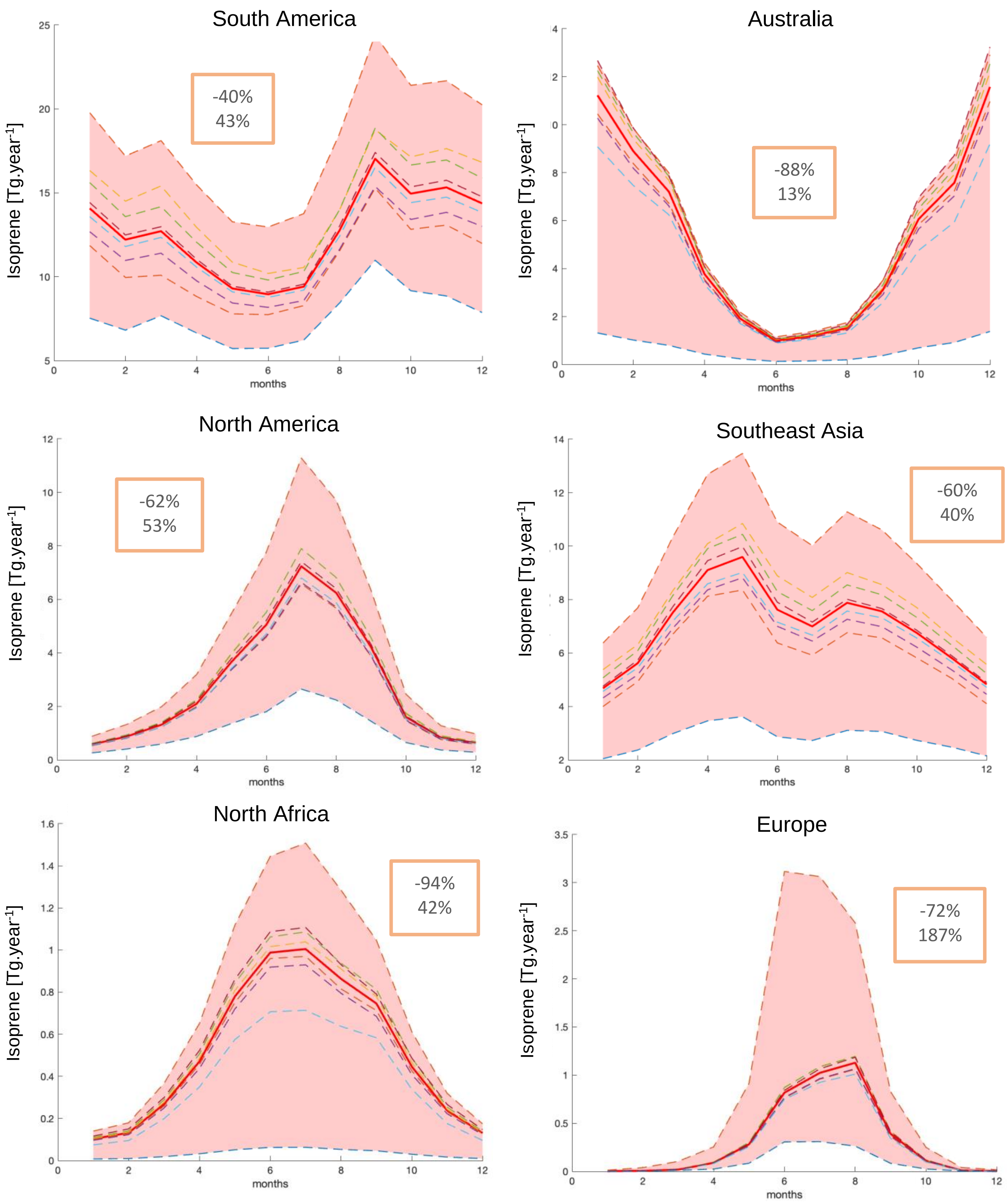

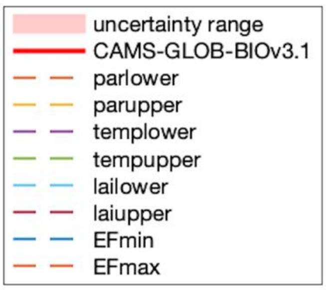

Fig. 6. *Comparison of regional monthly total isoprene emissions from the reference CAMS-GLOB-BIOv3.1 and CAMEO runs driven by the upper and lower limits of solar radiation (par), temperature (temp), leaf area index (lai) and emission potential (EF). The numbers in the yellow box indicate the annual total relative difference between the minimum and maximum isoprene estimates and the reference CAMS-GLOB-BIOv3.1, resp. Spatial extent of each region is defined in Fig. 5.*

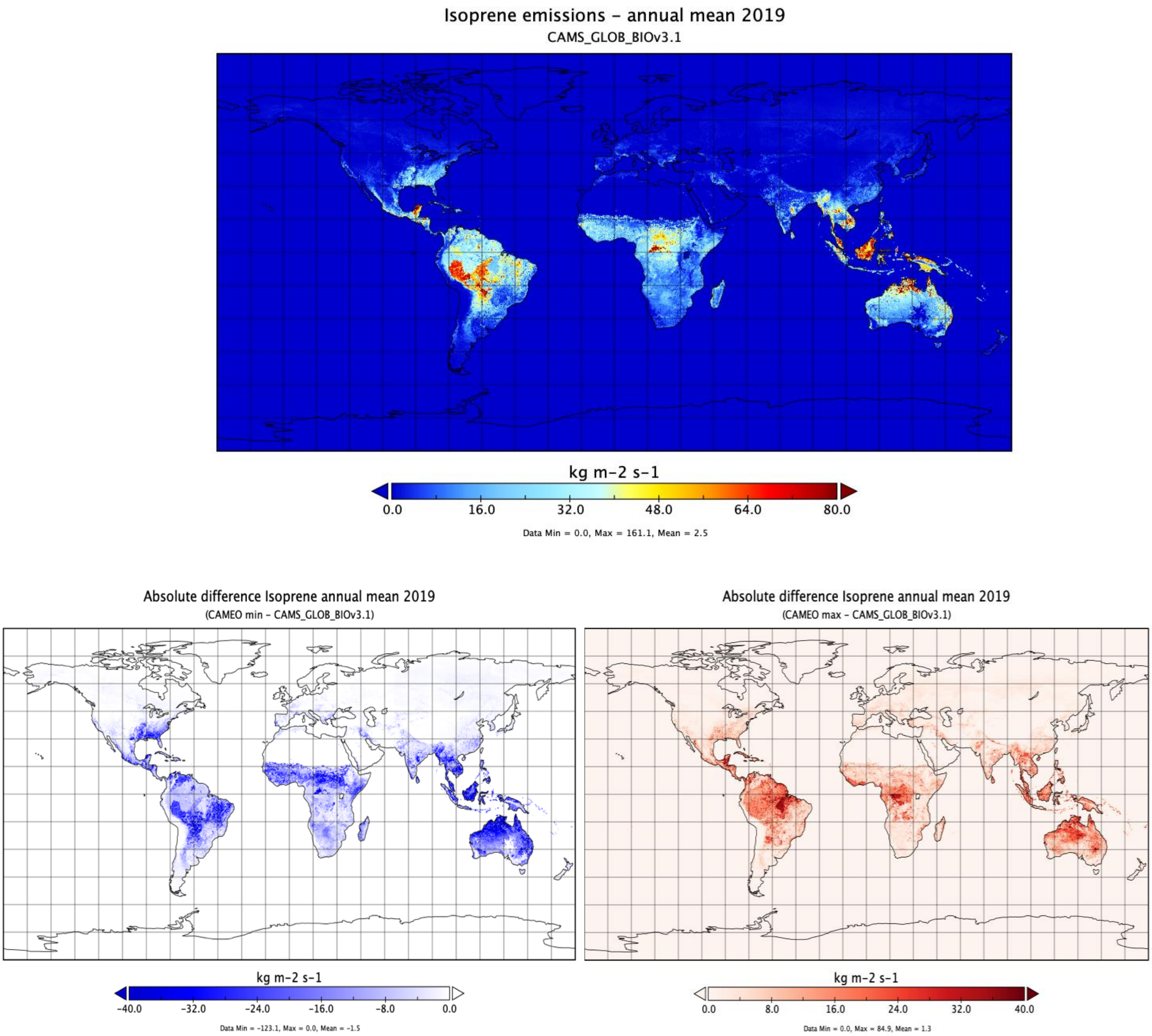

***Fig. 7**. Spatial distribution of the annual mean isoprene CAMS-GLOB-BIOv3.1 (top), the absolute difference between the CAMEO minimum estimate and the reference (bottom left) and the absolute difference between CAMEO maximum estimates and the reference emissions (bottom right) in 2019.*

The global monthly CAMEO uncertainty estimates of isoprene emissions were compared to isoprene data from other available emission studies. The comparison is presented in Fig. 8. All the datasets do not provide emissions up to the year 2019, so the plot shows CAMEO upper and lower limit values for the year 2019, but the rest of the isoprene emission totals refer to the year 2009 which was common for all the other datasets. A short description of the inventories from Fig. 8 is given in Table 3. Most of the datasets were calculated by the MEGAN-like model system, except for GUESS estimated by a process-based model LPJ-GUESS and ORCHIDEE calculated with a dynamic land surface model. The datasets differ in input data that were used for emission estimation, there is quite large diversity in driving meteorological data. Most of the datasets are so called ‘bottom-up’, but for two datasets named IASB-TD the isoprene emissions were constrained by the satellite observations of formaldehyde (OMI or GOME-2) using an inversion modelling system inside the MEGAN-MOHYCAN model. The appropriate references to datasets are provided in Table 3. Fig. 8 shows that the span between different isoprene emission inventories falls within the uncertainty range of isoprene emissions estimated within CAMEO.

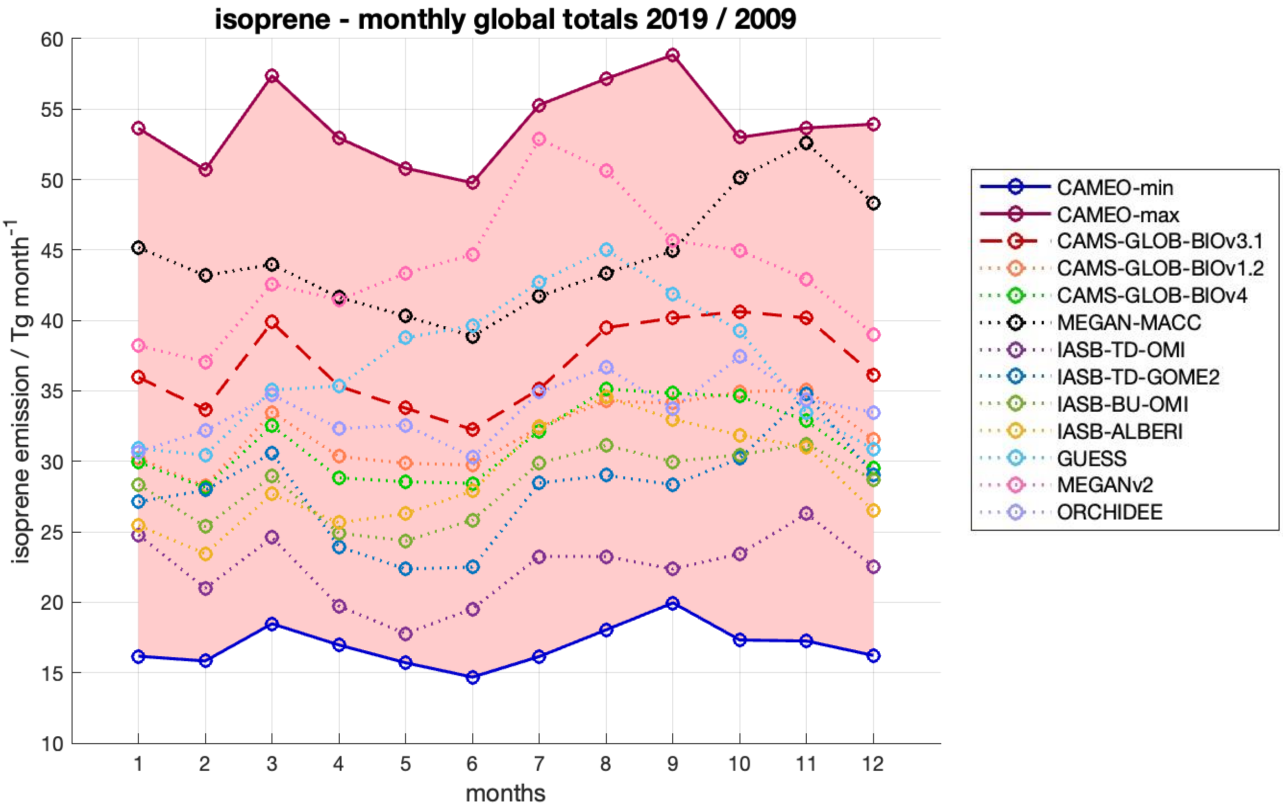

Fig. 8. *Comparison of isoprene global monthly totals of the reference CAMS-GLOB-BIOv3.1 (dashed red line), CAMEO minimum and maximum (solid lines) and other available isoprene emission datasets (dotted lines).*

Table 3. *List of isoprene emission datasets presented in Fig. 8 including basic details on the emission model set up and dataset reference.*

dataset	model	meteorology	inversion	reference
CAMS-GLOB-BIOv3.1	MEGANv2.1	ERA5	-	Sindelarova et al. (2022)
CAMS-GLOB-BIOv1.2	MEGANv2.1	ERA-Interim	-	Sindelarova et al. (2022)
CAMS-GLOB-BIOv4.0	MEGANv2.1	ERA5		CAMS report D3.1.1._2024
MEGAN-MACC	MEGANv2.1	MERRA/MERRA2	-	Sindelarova et al. (2014)

IASB-TD-OMI	MEGAN-MOHYCAN	ERA-Interim	OMI	Stavrakou et al. (2015)
IASB-TD-GOME2	MEGAN-MOHYCAN	ERA-Interim	GOME2	Stavrakou et al. (2014)
IASB-BU-OMI	MEGAN-MOHYCAN	ERA-Interim	-	Stavrakou et al. (2015)
IASB-ALBERI	MEGAN-MOHYCAN	ERA-Interim	-	Opacka et al. (2021)
GUESS	LPJ-GUESS	CRU	-	Arneth et al. (2007)
MEGANv2	MEGANv2.0	NCEP	-	Guenther et al. (2006)
ORCHIDEE	ORCHIDEE	CRU	-	Messina et al. (2016)

5 Conclusion

This report provides a first step approach to estimation of uncertainty of global isoprene emissions. The methodology relies on an emission model and varies the emission driving factors. The uncertainty was first estimated for the selected input variables and was then propagated through the emission model to the resulting isoprene emissions.

The parameter that brings the largest uncertainty to the final emissions is isoprene emission potential (EP). It defines emission rates under standard environmental conditions and depends on the vegetation composition of the modelled location and on emission factors assigned to the vegetation. The detailed enough vegetation description is often difficult to obtain, which causes large discrepancies in EP estimates and therefore in isoprene emissions. The estimates of isoprene relative error in this work show that in regions that are often studied and for which there exist data of detailed land cover and emission potential measurements, such as the Amazon, North America, Southeast Asia, the isoprene uncertainty is lower when compared to parts of the world where the data is lacking, e.g. parts of Africa, Australia, Siberia, even Europe. It gives an indication of locations where the additional measurements or use of remote sensing data would improve the quality of isoprene estimates.

The report shows that isoprene estimates from previous studies fall within the CAMEO uncertainty range which gives some level of reassurance to the validity of CAMEO results. However, one should keep in mind that due to the limited amount of input data, especially isoprene emission potential maps, the presented studies are not fully independent.

This project task's product of global gridded maps with monthly mean estimates of isoprene uncertainty represented as a range or isoprene upper and lower estimates along with the mean isoprene emission in each grid cell can be used to demonstrate the reliability of the emissions to the data users. Furthermore, the uncertainty gridded maps are one of the input variables to the model inversion system which constrains the isoprene emissions with formaldehyde observations.

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Appendix 1

Data availability

The gridded netCDF files with monthly averaged isoprene mean (CAMS-GLOB-BIOv3.1), minimum and maximum values for the years 2019 and 2022 are available for download from the following cloud folder.

The gridded netCDF files with mean, upper and lower limit values of the input variables to the emission model, i.e. 2m temperature, photosynthetically active radiation, leaf area index and isoprene emission potential, are available for download at the same location.

https://owncloud.cesnet.cz/index.php/s/39qAiQRFIknW7HY

Document History

Version	Author(s)	Date	Changes
1.0	Katerina Sindelarova	June 9th	Initial version
2.0	Katerina Sindelarova	30/6/25	Updated after internal review comments.

Internal Review History

Internal Reviewers	Date	Comments
Marion Schroedter-Homscheidt (DLR) and Philippe Ciais (CEA)	June 2025	Comments and suggestions