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Sensitivity of isoprene emission estimates to the time resolution of input climate data

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Abstract

We evaluate the effect of varying the temporal resolution of the input climate data on isoprene emission estimates generated by the community emissions model MEGAN (Model of Emissions of Gases and Aerosols from Nature). The estimated total global annual emissions of isoprene is reduced from 766 $Tg\,y^{-1}$ for hourly input data to 746 $Tg\,y^{-1}$ (a reduction of 3%) for daily average input data and 711 $Tg\,y^{-1}$ (down 7%) for monthly average input data. The impact on a local scale can be more significant with reductions of up to 65% for some locations when using monthly average data. If the daily and monthly average temperature data are used without the imposition of a diurnal cycle the global emissions estimates fall by 27–32%, and local annual emissions by up to 77%. A similar pattern emerges if hourly isoprene fluxes are considered. Given the importance of land-atmosphere interactions in the Earth system and the low computational cost of the MEGAN algorithms, we recommend that chemistry-climate models and the new generation of Earth system models input biogenic emissions at the highest temporal resolution possible.

1 Introduction

Isoprene, C_5H_8, is one of a class of chemicals known collectively as volatile organic compounds. It is not only the most abundant of these in the atmosphere, with total annual emissions believed to be equal to that of methane (Guenther et al., 1995), but it is also one of the most reactive, with an atmospheric lifetime of around 1.5 h with respect to the OH and NO_3 radicals (Atkinson and Arey, 2001).

Isoprene emissions are predominantly of biogenic origin (e.g. Guenther et al., 1995; Laothawornkitkul et al., 2009), leading to high mixing ratios of isoprene in the lower troposphere over vegetated land. Once released into the boundary layer, isoprene rapidly undergoes a series of photochemically initiated reactions, particularly in NO_x rich atmospheres, such as exist over large areas of the industrialised world. These

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reactions culminate in the production and destruction of tropospheric or ground-level ozone (Atkinson and Arey, 2001), a key atmospheric pollutant as well as a long-lived greenhouse gas.

In order to fully understand and predict the occurrence of ground-level ozone, it is necessary to reliably quantify emissions of all volatile organic compounds, and particularly of isoprene (e.g. Chameides et al., 1988), on both global and highly-resolved local scales. Estimates of both global and regional isoprene emissions have been generated since the mid-1990s (e.g. Guenther et al., 1995; Simpson et al., 1999). Both the algorithms and the input datasets have been improved since then and with global emission estimates converging towards a value of around 450–600 $\mathrm{Tg\,y^{-1}}$ (Arneth et al., 2008), the next goal is to incorporate these emission models into atmospheric and Earth system models to allow the impact of emissions on atmospheric chemistry and climate to be properly evaluated.

Although research is underway to develop global-scale process-based models of isoprene emissions (e.g. Grote and Niinemets, 2008), the majority of studies into emissions are carried out with the empirical algorithms developed by Guenther et al. (1995), hereafter referred to as the G95 algorithms, and subsequently refined into MEGAN, the Model of Emissions of Gases and Aerosols from Nature (Guenther et al., 2006). In both G95 and MEGAN, the algorithms estimate the flux of isoprene, F, in $\mu\mathrm{g\,m^{-2}\,h^{-1}}$, using

$$\mathrm{F}=\epsilon\times D\times\gamma \quad (1)$$

where ϵ is the base emission rate of isoprene from a particular plant species at standard conditions of 30°C and 1000 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ of photosynthetically active radiation (PAR), D is the foliar density or leaf area index in $\mathrm{m^2\,m^{-2}}$, and γ represents a dimensionless activity factor that adjusts the emission rate according to the current growth environment of the plant. γ reflects the effect of current and historical temperature and PAR, the leaf age and the soil moisture on isoprene flux. These activity factors and their derivations are fully described by Guenther et al. (1995, 2006) so no further details are given here.

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Numerous studies have been conducted to evaluate the sensitivity of the MEGAN emissions estimates to variations in, for example, land cover (e.g. Wiedinmyer et al., 2006), climate (e.g. Lathiere et al., 2006; Muller et al., 2008), and leaf area index (e.g. Smiatek and Bogacki, 2005). The most comprehensive analysis was reported in the original MEGAN paper (Guenther et al., 2006) in which total annual global isoprene emissions were computed for different climate and vegetation data sets. This demonstrated that isoprene emissions estimates from the MEGAN model could vary between 500 $\mathrm{Tg\,y^{-1}}$ and 750 $\mathrm{Tg\,y^{-1}}$ simply due to realistic variations in input data.

To date, none of these studies have addressed the fact that many of the climate data sources have different temporal resolutions. For example, in the MEGAN paper (Guenther et al., 2006), half of the weather datasets used provided 6-hourly values of temperature and PAR, while the others gave monthly mean values. While the values were all used to generate hourly data to drive the model, there are inherent assumptions in any method of interpolating between available data points which, given the non-linearity of the response of isoprene emissions to temperature and PAR (e.g. Monson et al., 1992; Guenther et al., 1991, 1993), will have an impact on the results. Indeed, Wang et al. (1998) suggested that their method of interpolating input temperature data resulted in a 20% increase in total global annual isoprene emissions. In the case of the monthly averaged data there is a loss of extreme values which will affect studies on the impacts of isoprene on climate.

Here, we evaluate the effect that the use of averaged climate data has on estimates of isoprene emissions generated by MEGAN, as well as the impact of altering the time interval at which the model is called within an atmospheric or Earth system model, by using the same climate data for each model run but varying the temporal resolution of that data as supplied to the model.

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2 Method

The study was conducted using the latest community version of the Model of Emissions of Gases and Aerosols from Nature, MEGAN v2.04, (NCAR 2007). MEGAN v2.04 implements the empirical isoprene emissions algorithms described as MEGAN-EZ by Guenther et al. (2006), but neglecting the impact of soil moisture.

2.1 Input data

The model requires input datasets of vegetation and climate variables. MEGAN v2.04 can be run on any spatial resolution over any geographical domain. For the purposes of this study, the model was run globally on a 0.5° by 0.5° regular grid over the course of a year. For each grid cell within the model domain the total flux of isoprene is calculated as the sum of the emissions from each plant functional type (PFT) within that cell.

The vegetation datasets comprise land cover, base emission rates and leaf area index. These input files, as described by Guenther et al. (2006), were all supplied by the National Center for Atmospheric Research (http://cdp.ucar.edu/), thus allowing comparisons to be made between the results of this study and emissions estimates previously generated with the full MEGAN algorithms.

The land cover datafile, version 2.0, gives the distribution of vegetation in terms of the fraction of a grid cell covered by each of the six plant functional types used for isoprene emissions in MEGAN v2.04. The global gridded map of base emission rates of isoprene by plant functional type, version 2.0, is currently the best resolved data for isoprene, with the emission factors varying with both plant functional type and geographical location. The map gives emission rates at standard conditions of 30°C and 1000 μmol m^{-2} s^{-1} (NCAR, 2007). NCAR's leaf area index database, version 2.0, contains a gridded map giving the average leaf area per unit vegetated ground area (m^2 per 1000 m^2) for each grid cell for each month of the year (NCAR, 2007).

MEGAN v2.04 also requires input values of the air temperature at 1.5 m above the surface and the short-wave radiation flux reaching the surface (NCAR, 2007). We

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used the UK Meteorological Office Unified Model, the UM, as the input climate model as this forms the basis of the UK community Earth system model, QESM. The values of temperature and short-wave radiation were generated by the UM for a year at current climatic conditions following a three month spin up period. UM output is provided at one hour intervals on a 2.5° by 3.75° global grid so the data were regridded to a 0.5° by 0.5° grid. However, owing to the computational cost of the radiation scheme within the UM, short wave radiation is only sampled at every third time step. This has implications for running MEGAN within a fully coupled Earth system model. This study is therefore also designed to determine the impact on estimates of isoprene emissions of driving MEGAN at 3-hourly, as opposed to hourly, intervals.

The UM output was also used to generate daily and monthly average values of temperature and short-wave radiation, to allow the study to be conducted using exactly the same original data for each run. Hence any differences in results can be entirely attributed to the difference in temporal resolution of the data.

2.2 Model runs

The only difference between the model runs is the temporal resolution of the input climate data. The original hourly and 3-hourly data from the UM were combined to drive MEGAN on an hourly time step, in which case the radiation data was converted to provide hourly values either by repeat sampling of the 3-hourly data or by interpolation between successive values, or a 3-hourly time step, in which case the hourly temperature data was either averaged over the time step or sampled at the time of the radiation data.

The daily average temperature and radiation data were converted to hourly data values by imposing a diurnal cycle in the form of a sinusoidal function. The MEGAN algorithms were then used at hourly intervals to generate emissions estimates using these values either together or in conjunction with the original temperature or radiation input data as described above. This simple sensitivity analysis allowed us to determine the goodness of fit between the applied diurnal cycle and the original data. The daily

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average temperature data were also used without the application of a diurnal cycle by repeat sampling of the average value. The monthly average data were used in the same way.

Table 1 shows the combinations of input data for each run performed, together with the global annual total isoprene emissions estimate. In addition hourly (or 3-hourly where appropriate) fluxes were also calculated for each run to allow an evaluation of the effect of varying the temporal resolution of the input data on instantaneous flux estimates that would be required for use with chemistry and climate models to simulate changes in air quality and atmospheric composition caused by the emissions of isoprene. The fluxes for each hour were also averaged over a month to generate an "average" 24 h period for each month to allow comparison with the hourly flux estimates obtained from monthly average input data.

3 Results

The estimates of total global annual isoprene emissions are reduced, in some cases markedly, as the temporal resolution of the input data decreases. Table 1 shows the estimates obtained by driving MEGAN at hourly time steps with input climate data with different resolutions. Using daily averaged data with a diurnal cycle applied results in a reduction of around 3% in the estimate of total global annual emissions; using monthly averaged data decreases the estimate by 7%. Table 1 shows the effect of reducing the number of times MEGAN is called over a 24 h period. Switching from an hourly to a 3 hourly time step also reduces the calculated total global annual emissions by about 3–4%. This has implications for how MEGAN should be used within a coupled Earth system model.

The percentage differences shown in Table 1 are for the total annual global emissions and are thus averaged across the world. Figure 1 shows that on a regional basis, there is large variability in the impact, with the percentage differences for monthly averaged input data ranging from −65% in eastern parts of the Americas and central Asia to +5%

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in coastal areas of SE Asia. It can be seen that while the differences are far smaller if MEGAN is run 3 hourly, the largest changes in estimated emissions in this case occur in the tropics where emissions of isoprene are highest.

Hourly fluxes of isoprene also show more variability than suggested by the overall percentage differences given in Table 1. Figure 2 shows that the instantaneous fluxes generated using daily averaged data with an imposed diurnal cycle are lower than those obtained from hourly input data for this location and time, by as much as 40% for some grid cells. Although the monthly average data appears to reproduce the emissions better, the two are not directly comparable as the daily averaged data shows the emissions for 15 January while the monthly average data is displaying the results of an average day in January. When compared with the average January day produced by averaging the emissions generated in Run 1 throughout January, it becomes apparent how poorly the monthly averaged data reproduces the emissions at this time.

If a diurnal cycle is not applied to daily or monthly average input data, the calculated flux of isoprene is reduced to such an extent that the results cannot be considered robust. The estimates obtained from this method are given in Table 1, which shows that isoprene emissions are under-estimated by 27–32% when compared with estimates from hourly data. This represents estimates between 20 and 25% lower than using averaged data with a diurnal cycle imposed. On a local basis, the reduction is as great as 77% for the boreal forests of Northern Europe in Runs 17 and 18 which use monthly averaged data.

The sensitivity studies conducted to assess the effect of using different temperature and radiation input files demonstrate that the diurnal cycle has been effective in capturing the general shape of the original data. Comparison of Runs 9 and 10 with Run 3 or Run 11 with Run 1 suggests that while daily averaged radiation data can be used to accurately recreate the radiation globally over the course of a year, the temperature profile is not as well captured. These differences occur because the process of averaging the original data removes the hour-to-hour, and in the case of monthly averaged data the day-to-day, variability of the temperature and radiation data. Even with the

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application of a diurnal cycle, this variability is not perfectly reproduced by the diurnal cycle which tends to produce smooth profiles for the data. The temperature cycle appears less accurate because the full 24 h period must be recreated while emissions only occur during daylight hours. Hence while the average temperature may be maintained, the balance between daytime and night time temperatures may not be. The loss of variability is more pronounced when monthly data is used with emissions reduced by a further 3–4% in both cases.

For the purposes of the atmospheric or Earth system models, the differences between the total global annual emissions estimates obtained from calling MEGAN hourly or 3 hourly with the original UM hourly temperature and 3 hourly radiation data are slight, with total global annual emissions for the interpolated hourly run, Run 2, only varying by −0.3 to +2.2% from the sampled hourly run, Run 1. The discrepancies in total annual emissions estimates obtained from the 3 hourly runs are greater with Run 5 varying by −9.7 to +1.7%, as shown in Fig. 1, and Run 6 by −10.0 and +0.7% in comparison with Run 1. The differences between instantaneous (hourly) fluxes generated by the two hourly runs are negligible for most times of day and location with discrepancies mainly occurring at the start and end of the day when emissions are low. However, as Fig. 2 shows there are more significant differences locally when instantaneous fluxes generated by the 3 hourly runs are considered with Run 5 showing that the fluxes are higher by up to 10% over part of Amazonia during the early afternoon (LT) when emissions are high. This suggests that MEGAN should be called at every time step of the Earth System model, hourly in the case of QESM, to improve robustness of results.

4 Conclusions

Our analysis shows that previously published estimates for total global annual isoprene emissions obtained from the G95 or MEGAN algorithms are too low by between 3 and 32% due to the coarse temporal resolution of the input data that was used. From this

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we conclude that the highest possible temporal resolution of input climate data should be used when calculating isoprene emissions using the MEGAN model. If hourly data are not available, for example when performing studies of historical emissions or to investigate future scenarios when the emissions are to be used in conjunction with datasets of anthropogenic emissions (Lamarque et al., 2009), then total global annual emissions estimates should be adjusted to an hourly result to ensure comparability between studies. Table 2 shows the effect of such an adjustment on the estimates from previous studies. It suggests that the impact of factors such as land cover, climate and land use change may be more significant than previously thought, as the range of emissions has increased markedly.

Our results clearly indicate that daily or monthly averaged climate data should not be used without the imposition of a diurnal cycle, even if the purpose of the study is to generate daily or monthly average emissions estimates. We have found that the results obtained in this way do not give reliable estimates of isoprene emissions with an overall global under-estimate of 25–30% and results locally varying between an increase of 5% and a decrease of 70%.

For local and regional studies in particular, data of a high temporal resolution should be used as our study shows that local discrepancies in isoprene flux are much higher than the overall percentage differences on a global scale. These differences are more pronounced the coarser the resolution of the original data, even with the imposition of a diurnal cycle onto averaged data. For example, using hourly data regenerated from daily averaged data under-estimates total global annual isoprene emissions by 3%, but on a local basis the discrepancies range from 15% under-estimate to 9% over-estimate when compared with the original data. The fluctuations in hourly fluxes are even more pronounced with an under-estimate of 40% for one region of Amazonia for early afternoon (LT) on 15 January.

For the purposes of atmospheric and Earth system modelling, these large differences in both instantaneous and total fluxes on a local scale may have a significant impact on both chemistry and climate. Given the low computational cost of the MEGAN

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algorithms, together with non-linearity of chemistry and climate responses to changes in isoprene fluxes, we recommend that MEGAN is called as often as is computationally feasible within an atmospheric or Earth system model, following a cost benefit analysis to determine the optimal time resolution, and ideally at every time step.

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Table 1. Total global annual isoprene emissions, in Tg y^{-1} for each run performed together with full description of input data used. Where daily and monthly average data have been converted to hourly data, this has been done by applying a diurnal cycle. The percentage difference shown is in relation to Run 1, which uses the original UM output temperature and radiation data, and is used as a baseline case.

Run No.	Temperature input data	Radiation input data	Isoprene	% diff
(a)	Hourly input:			
1	Hourly	3 hourly→hourly by sampling	766	0
2	Hourly	3 hourly→hourly by interpolation	773	+1
3	Daily→hourly	Daily→ hourly	746	−3
4	Monthly→hourly	Monthly→hourly	711	−7
(b)	3 hourly input:			
5	Hourly→3 hourly by sampling	3 hourly	744	−3
6	Hourly→3 hourly by averaging	3 hourly	737	−4
(c)	Average temperature input:			
7	Daily average	Daily→hourly	557	−27
8	Monthly average	Monthly→hourly	536	−30
(d)	Hourly input sensitivity study:			
9	Daily→hourly	3 hourly→hourly by sampling	741	−3
10	Daily→hourly	3 hourly→hourly via interpolation	749	−2
11	Hourly	Daily→hourly	770	0
12	Monthly→hourly	3 hourly→hourly by sampling	706	−8
13	Monthly→hourly	3 hourly→hourly by interpolation	712	−7
14	Hourly	Daily→hourly	740	−3
(e)	Average temp sensitivity study:			
15	Daily average	3 hourly→hourly by sampling	547	−29
16	Daily average	3 hourly→hourly by interpolation	555	−27
17	Monthly average	3 hourly→hourly by sampling	524	−32
18	Monthly average	3 hourly→hourly by interpolation	532	−31

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Table 2. The effect of the temporal resolution of the input data on the estimate of total global annual isoprene emissions in Tg y^{-1}.

Study	Input climatology	Isoprene	% Bias	Adjusted Isoprene
Guenther et al. (1995)	Monthly→hourly	570	−7	613
Wang and Shallcross (2000)	ECMWF 6 hourly	601	−4	626
Potter et al. (2001)[a]	Monthly average	634	−7 to −32	682 to 925
Naik et al. (2004)[a]	CRU monthly average	515	−7 to −32	554 to 752
Tao and Jain (2005)[a]	Monthly average	681	−7 to −32	732 to 994
Lathiere et al. (2006)	ISLSCP-II 3 hourly	521	−3	537
Muller et al. (2008)[b]	ERA 6 hourly→hourly	410	−3 to 0	410 to 423
Guenther et al. (2006)[b]	NCEP-DOE→hourly	600	−3 to 0	600 to 619
Guenther et al. (2006)	HadCM1 monthly→hourly	690	−7	742

[a] It is not clear from this study how the monthly average data were used to drive the emissions algorithms. This is reflected in the ranges given for the bias of the results and the adjusted total emissions.

[b] The effect of driving the algorithms with hourly data derived from original 6 hourly data is assumed to lie between using original hourly data and hourly data derived from original daily average data. This is reflected in the ranges given for the bias of the results and the adjusted total emissions.

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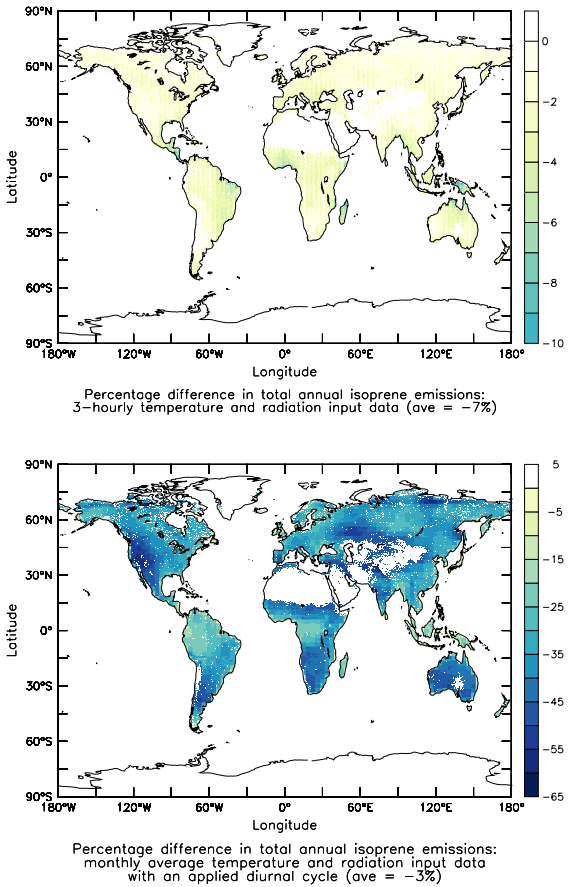

Fig. 1. The percentage difference in global total isoprene emissions in comparison with estimates for hourly temperature and repeat sampled radiation for 3 hourly radiation and sampled temperature data (top) and monthly average data with an applied diurnal cycle (bottom). The figure below each plot indicates the average percentage difference in total global annual isoprene emissions.

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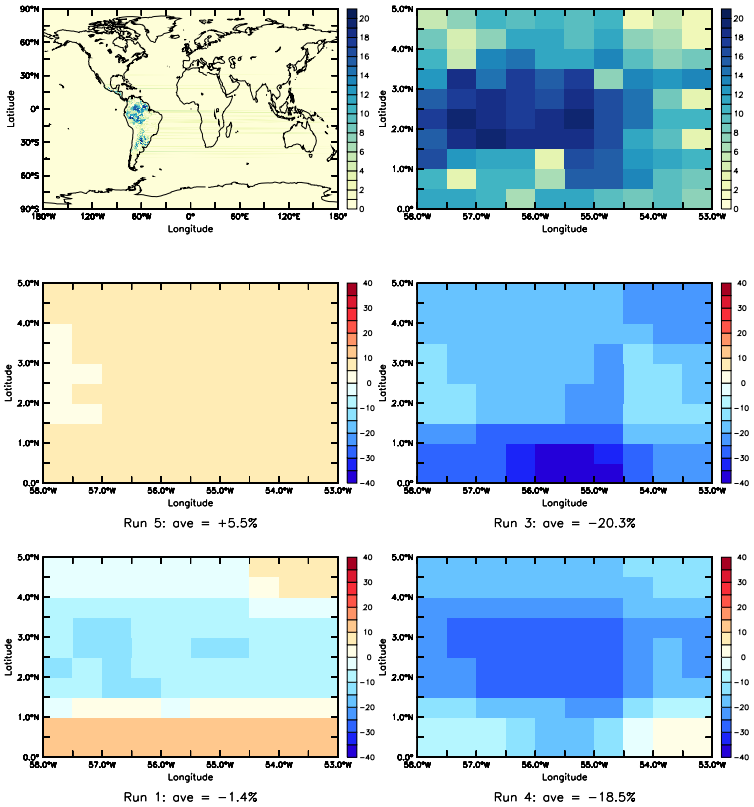

Fig. 2. Analysis for 15 January of the instantaneous isoprene flux (in $mg\,m^{-2}\,h^{-1}$) for a high emitting region of the Amazon (58 to 53 W and 0 to 5 N) at 19:30 (UTC) in comparison with estimates for hourly temperature and repeat sampled radiation (top row). The middle row shows the percentage differences of estimates using 3 hourly data (left) and daily average input data with a diurnal cycle applied (right). The bottom row shows the percentage differences of estimates for the same time on an average day in January for the original hourly run (left) and monthly average input data with an applied diurnal cycle (right). The figure below each plot indicates the average percentage difference for the region shown.

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