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Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO_2 concentration, climate, and land use

J. Lathière,[1,2,3] C. N. Hewitt,[2] and D. J. Beerling[1]

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[1] We describe the development and analysis of a global model based on Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006) for estimating isoprene emissions from terrestrial vegetation. The sensitivity of calculated isoprene emissions to descriptors including leaf age, soil moisture, atmospheric CO_2 concentration, and regional variability of emission factors is analyzed. The validity of the results is evaluated by comparison with compilations of published field-based canopy-scale observations. Calculated isoprene emissions reproduce above-canopy flux measurements and the site-to-site variability across a wide range of latitudes, with the model explaining 60% of the variance. Although the model underestimates isoprene emissions, especially in northern latitude localities, this disagreement is significantly corrected when regional variability of emission factors for particular plant functional types is considered (r^2 = 0.78). At the global scale, we estimate a terrestrial biosphere isoprene flux of 413 TgC yr^{-1} using the present-day climate, atmospheric CO_2 concentration, and vegetation distribution, and this compares with other published estimates from global modeling studies of 402 to 660 TgC yr^{-1}. The validated model was used to calculate changes in isoprene emissions in response to atmospheric CO_2 increase, climate change, and land use change during the 20th century (1901–2002). Changes in all of these factors are found to impact significantly on isoprene emissions over the course of the 20th century. Between 1901 and 2002, we estimate that at the global scale, climate change was responsible for a 7% increase in isoprene emissions, and rising atmospheric CO_2 caused a 21% reduction. However, by the end of the 20th century (2002), anthropogenic cropland expansion has the largest impact reducing isoprene emissions by 15%. Overall, these factors combined to cause a 24% decrease in global isoprene emissions during the 20th century. It remains to be determined whether predicted 21st century warming and increased use of isoprene-emitting crops for biofuels (e.g., oil palm) will more than offset any future CO_2 suppression of isoprene emission rates.

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1. Introduction

[2] Isoprene (C_5H_8) is the most important reactive volatile organic compound in the Earth's atmosphere. It is synthesized by some plant species and because of its high volatility is emitted into the atmosphere from leaf mesophyll tissue. Its global emission rate is estimated to be in the range 440–660 TgC yr^{-1} [*Guenther et al.*, 1995, 2006], which is comparable to the estimated present-day flux of methane (CH_4) (375–450 TgC yr^{-1}) [*Houghton et al.*, 2001]. Although published estimates of isoprene emissions show relatively little variation, suggesting a degree of certainty and understanding, much remains to be explored on this topic [*Arneth et al.*, 2008].

[3] Isoprene is very reactive in the troposphere, with a chemical lifetime ranging from a few minutes to hours. Because its principal reaction is with the hydroxyl radical, which is itself the principal oxidant of methane, emissions of isoprene have an influence on the lifetime, and hence radiative forcing potential, of methane, the third most important "greenhouse gas" in the atmosphere [*Poisson et al.*, 2000]. Reactions of isoprene may also influence the production and removal of tropospheric ozone, an important air pollutant and greenhouse gas [*Kesselmeier and Staudt*,

[1]Department of Animal and Plant Sciences, University of Sheffield, Sheffield, UK.
[2]Lancaster Environment Centre, Lancaster University, Lancaster, UK.
[3]Now at Laboratoire des Sciences du Climat et de l'Environnement, IPSL, UVSQ, CEA, CNRS, Gif-sur-Yvette, France.

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1999], and may form secondary organic aerosols [*Kurpius and Goldstein*, 2003; *Claeys et al.*, 2004]. Hence global isoprene emissions can influence both air quality and climate.

[4] The main determinants of biogenic isoprene emission rates are plant type, leaf surface area, leaf temperature and flux of photosynthetically active radiation. However, other variables, including drought [*Fang et al.*, 1996], leaf age [*Kuzma and Fall*, 1993; *Kuhn et al.*, 2004], atmospheric CO_2 concentration [*Rosenstiel et al.*, 2003; *Possell et al.*, 2005] and ozone exposure [*Fares et al.*, 2006], can also influence emission rates [*Monson et al.*, 2007]. The high sensitivity of isoprene emissions to external factors, as well as their large temporal and geographical variation, make it challenging to study, model and validate fluxes from vegetation, especially at the global scale. Although difficult to achieve, it is important to understand and predict how isoprene emissions from vegetation have changed and will change in the future as conditions on the Earth's surface change [*Wang and Shallcross*, 2000; *Levis et al.*, 2003; *Sanderson et al.*, 2003; *Naik et al.*, 2004, *Lathière et al.*, 2006; *Guenther et al.*, 2006; *Arneth et al.*, 2007a].

[5] Here, we couple off-line the Sheffield Dynamic Global Vegetation Model (SDGVM) [*Woodward et al.*, 1995; *Beerling et al.*, 1997; *Beerling and Woodward*, 2001; *Woodward and Lomas*, 2004] with an isoprene emission model based on MEGAN (Model of Emissions of Gases and Aerosols from Nature) [*Guenther et al.*, 2006] to predict changes in emissions from the terrestrial biosphere in response to historical changes in CO_2, climate and land use. The SDGVM provides the global distribution of key plant functional types (PFTs) and terrestrial ecosystem properties (leaf area index, soil moisture, leaf age) required by the emission model which in turn predicts the flux of isoprene from the biosphere to the atmosphere from these attributes and climate. We evaluate the coupled model by comparing its predictions with above-canopy flux measurements previously reported for isoprene. We then investigate the sensitivity of isoprene emissions to environmental changes (atmospheric CO_2, climate and land use) during the course of the 20th century, isolating the relative effects of changing atmospheric CO_2 concentrations, climate and land use change on isoprene emissions from vegetation.

2. Model Description

[6] The Sheffield Dynamic Global Vegetation Model (SDGVM) [*Woodward et al.*, 1995; *Beerling et al.*, 1997; *Beerling and Woodward*, 2001; *Woodward and Lomas*, 2004] is driven with monthly inputs of temperature, precipitation and relative humidity, and an underlying map of soil texture. Depending on the climate and CO_2 concentration, the SDGVM calculates the potential distribution of C_3 and C_4 grasses, evergreen broad-leaved and needle-leaved trees, and deciduous broad-leaved and needle-leaved trees, and provides monthly canopy leaf area index and vegetation fraction for each PFT as well as soil moisture required by the emission model. The distribution of crops around the world is not explicitly included in this version of the SDGVM. Nevertheless, given large differences in emission factors between crops and other PFTs, as well as the dramatic expansion of crop area (from 8.4 million km^2 in the 1850s, to 15.7 million km^2 in the 1950s) [*Wang et al.*, 2006], it is necessary to account for the distribution and historical expansion of croplands when calculating BVOC emissions during the last century. We therefore combine the potential natural vegetation distribution calculated by the SDGVM with crop maps compiled by De Noblet-Ducoudré and Peterschmitt (personal communication, 2006), based on *Loveland et al.* [2000] and corrected for crops by *Ramankutty and Foley* [1999] and for anthropogenic grasses by *Goldewijk* [2001]. These maps are based on historical data and give unique information on the evolution of land use around the world, at high temporal resolution (1 year). We then decrease the fraction of natural vegetation proportionally to the area of crops and assume a leaf area index of 2 m^2 m^{-2} for crops over the year. Hence, we derive the distribution of each PFT and crops over the Earth's surface for each year since 1901 and this is used as input to the isoprene emission model.

[7] Our approach to calculating isoprene emissions largely follows the parameterized approach of *Guenther et al.* [2006]. The direct impacts of leaf age and soil moisture on isoprene emissions are also taken into account. Based on available isoprene emission measurements and empirical data, *Guenther et al.* [2006] compiled global maps of emission factors for six different ecosystems (broad-leaved trees, needle-leaved evergreen and deciduous trees, grasses, shrubs and crops), which gives the possibility of accounting for the variability of isoprene emission factors around the world, within a PFT. We therefore use those maps, but to ensure versatility in our implementation of the model, we also allow for the possibility of using the mean values for isoprene emission factors given by *Guenther et al.* [2006], of 12.6 mg (C) m^{-2} h^{-1} for broad-leaved trees, 2 mg (C) m^{-2} h^{-1} for evergreen needle-leaved trees, 0.7 mg (C) m^{-2} h^{-1} for deciduous needle-leaved trees, 0.09 mg (C) m^{-2} h^{-1} for crops and 0.5 mg (C) m^{-2} h^{-1} for grasses (both C_3 and C_4). A 4% loss of isoprene in the canopy is assumed [*Karl et al.*, 2004; *Guenther et al.*, 2006].

[8] Several experimental studies have examined the impact of atmospheric CO_2 concentrations on emission rates of organic compounds from plants. Although the response of monoterpenes and other VOC emissions to atmospheric CO_2 concentration remains unclear [*Loreto et al.*, 1996; *Constable et al.*, 1999; *Loreto et al.*, 2001; *Snow et al.*, 2003; *Baraldi et al.*, 2004; *Vuorinen et al.*, 2004], the effects on isoprene emissions are consistent. In laboratory and mesocosm experiments, and measurements made in the vicinity of naturally occurring springs at which CO_2 is emitted, causing an increase in ambient CO_2 concentration, isoprene emissions have been shown to decrease when plants are grown under elevated CO_2 concentrations [*Sharkey et al.*, 1991; *Rosenstiel et al.*, 2003; *Scholefield et al.*, 2004; *Possell et al.*, 2004; *Rapparini et al.*, 2004; *Pegoraro et al.*, 2005; *Possell et al.*, 2005]. The empirical function of *Possell et al.* [2005] is used to account for the decrease in isoprene emission capacity with increasing atmospheric CO_2 concentration (the so-called isoprene suppression effect), modified to a present-day CO_2 concentration of 366 ppm. The function is described by the equation

Table 1. Published Estimates of Global Biogenic Emissions of Isoprene From Terrestrial Vegetation

Source	Emission Estimates (TgC yr^{-1})	Difference in Emission Estimates From This Study (%)
This study; mean EF – potential with crops	413	Control
This study; mean EF – potential	471	+14%
Arneth et al. [2007b]	412	<1%
Guenther et al. [2006]; gridded EF	440 to 660	+6.5% to +60%
Lathière et al. [2006]	460	+11%
Lathière et al. [2005]; real	402	−3%
Lathière et al. [2005]; potential	502	+21.5%
Tao and Jain [2005]; gridded EF	601	+45.5%
Naik et al. [2004]	454	+10%
Levis et al. [2003]	507	+23%
Sanderson et al. [2003]	484	+17%
Adams et al. [2001]	495	+36%
Potter et al. [2001]	559	+35%
Wang and Shallcross [2000]	530	+28%
Guenther et al. [1995]	503	+22.5%
Range of estimates	402–660	
Mean of estimates	500 ± 57	

$[-0.0123 + (441.4795/CO_2) + (-1282.65/CO_2^2)]$, with emission rates normalized to 1 for the present day. Recent work by *Wilkinson et al.* [2009] demonstrated a very similar response of isoprene emissions to higher-than-current atmospheric CO_2 concentrations.

[9] The emission model is driven with monthly inputs of air temperature, downward radiation flux, leaf area index and vegetation fraction for each plant functional type (PFT), and soil moisture. We use a canopy radiation scheme based on *De Pury and Farquhar* [1997] to prescribe the diurnal variation in radiation flux and a monthly mean diurnal cycle of isoprene emissions is calculated with a time step of 1 h. Therefore our model does not represent the variability of emissions within a month. However, as our work focuses on the sensitivity of emissions to model parameters, and on their century-scale evolution, we believe that the most important factor is to take into account the diurnal variation of emissions, which our model does consider, using photosynthetically active radiation flux as a primary driver of isoprene emissions.

[10] We use two different sets of monthly climate data (temperature, radiation flux and precipitation). The first (UM) was provided by the Meteorological Office's Unified Model [*Johns et al.*, 1997; *Staniforth et al.*, 2005] for the present day at a spatial resolution of 2.5° latitude by 3.75° longitude. The second (Climate Research Unit (CRU)) is an observation-based 0.5° × 0.5° gridded climate data set for 1901 to 2002 [*Mitchell and Jones*, 2005].

3. Results and Discussion

3.1. Comparison of Predicted Fluxes With Previous Estimates

[11] Several studies modeling past, present-day or future BVOC emissions at the global scale have been published [*Guenther et al.*, 1995; *Wang and Shallcross*, 2000; *Adams et al.*, 2001; *Potter et al.*, 2001; *Levis et al.*, 2003; *Sanderson et al.*, 2003; *Naik et al.*, 2004; *Tao and Jain*, 2005; *Lathière et al.*, 2005; *Guenther et al.*, 2006; *Lathière et al.*, 2006; *Arneth et al.*, 2007b]. Most of these use algorithms from *Guenther et al.* [1995] or *Guenther et al.* [2006] to calculate BVOC emissions, with the exception of the work by *Arneth et al.* [2007b] which used a process-based approach [*Niinemets et al.*, 1999]. Several inputs related to climate and vegetation (plant distribution and leaf area index) are used to calculate emissions. In particular, the distribution of plant types can be either based on a prescribed map ("real" vegetation) or calculated using a vegetation model ("potential" vegetation), with the number of plant types varying from 5 to 26 among the references listed. Crops are not always considered.

[12] Using the present-day distribution of vegetation types generated by the SGDVM (no crop), a global isoprene emission flux of 471 TgC yr^{-1} is calculated using the UM climatology, which compares well with previous global emission estimates of 402–660 TgC yr^{-1} (Table 1). When the global "potential" vegetation cover generated by the SGDVM is modified by superimposing the actual present-day distribution of crops (from De Noblet-Ducoudré and Peterschmitt, personal communication, 2006), global isoprene emissions decrease to 413 TgC yr^{-1}. This value might therefore be considered as our current best estimate of actual global isoprene emissions from the terrestrial biosphere.

[13] Using a number of databases for climate (IIASA, CRU, MM5...) and terrestrial ecosystem (AVHRR, MODIS, SPOT...) properties, *Guenther et al.* [2006] calculate a global emission rate of isoprene ranging from 440 TgC yr^{-1} to 660 TgC yr^{-1}. This is 7% to 60% higher than the fluxes calculated here. Isoprene emission estimates calculated by other studies range from −3% to +46% of the estimates made here, varying from 402 TgC yr^{-1} [*Lathière et al.*, 2005] to 601 TgC yr^{-1} [*Tao and Jain*, 2005].

[14] Figure 1a shows the geographic distribution of predicted annual isoprene emissions, after imposing the crop mask. In common with previous studies, high isoprene emission rates are predicted in South America (Amazonia), central Africa and parts of tropical Asia, with annual emissions of up to 800 mgC m^{-2} d^{-1} [*Guenther et al.*, 1995; *Wang and Shallcross*, 2000; *Naik et al.*, 2004; *Tao and Jain*, 2005; *Lathière et al.*, 2006]. On a regional basis, the largest decrease in annual isoprene emissions resulting from the superposition of a crop mask occurs in the Northern Hemisphere, where crops gain over large areas (Figure 1b). On a regional scale, isoprene emissions reach 30 TgC yr^{-1} in North America when crops are considered, compared to 43 TgC yr^{-1} when they are excluded. In Europe, isoprene emissions decrease from 12 TgC yr^{-1} to 7 TgC yr^{-1} (almost −40%) after accounting for cropland distribution.

3.2. Comparison of Predicted and Measured Isoprene Fluxes

[15] We evaluated the canopy-scale emission estimates of isoprene calculated as described above against a selection of measurements taken from the literature of above-canopy emission fluxes made at various locations around the world

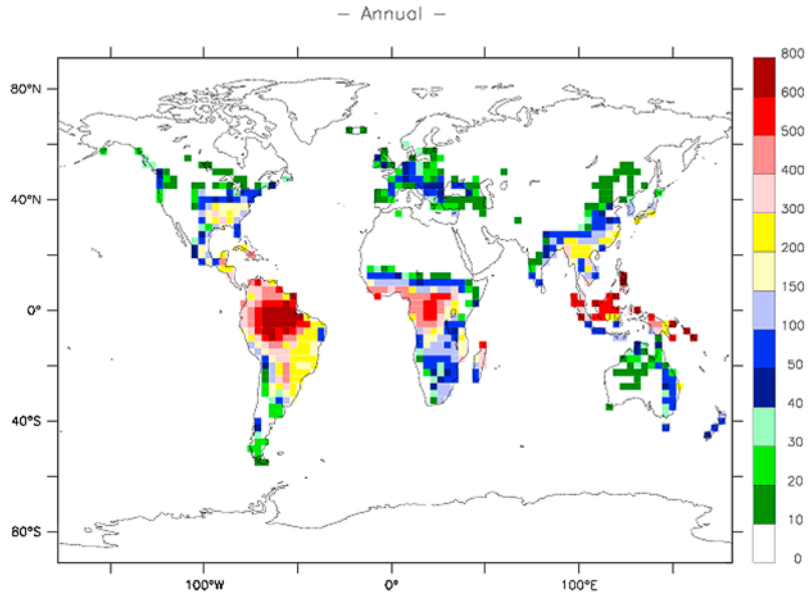

Figure 1a. Annual isoprene emissions in mgC m^{-2} d^{-1} calculated with mean emission factors and the Unified Model (UM) climatology, considering a potential present-day vegetation distribution for natural ecosystems and including crops.

(Table 2). The observational data comprised 20 mean fluxes, obtained at 12 different sites located between 2°S and 67°N and 105°W and 24°E, including tropical, temperate and boreal forests. The time averaging periods used in the model were adjusted to match the timescale of the canopy flux measurements. Emissions computed with both the CRU data sets and the UM climatology were evaluated, using both the isoprene emission function for the PFT predicted by the SDGVM at the measurement location ("matching" case) and the most dominant PFT given by the SDGVM for the grid cell in which the measurement location occurs ("dominant" case). The use of the two different climate data sets allows us to distinguish between possible errors associated with the climate model bias.

[16] Predicted isoprene emission rates generally agree with measurements (Figure 2). The combination of mean emission factors listed above for each PFT, "matching" PFTs and the UM climatology gives the best correlation between model predictions and measurements (r^2 = 0.62), while the worst correlation is obtained using the "dominant" PFTs and the CRU climate data (r^2 = 0.42). However, if the gridded emission factors of *Guenther et al.* [2006] are

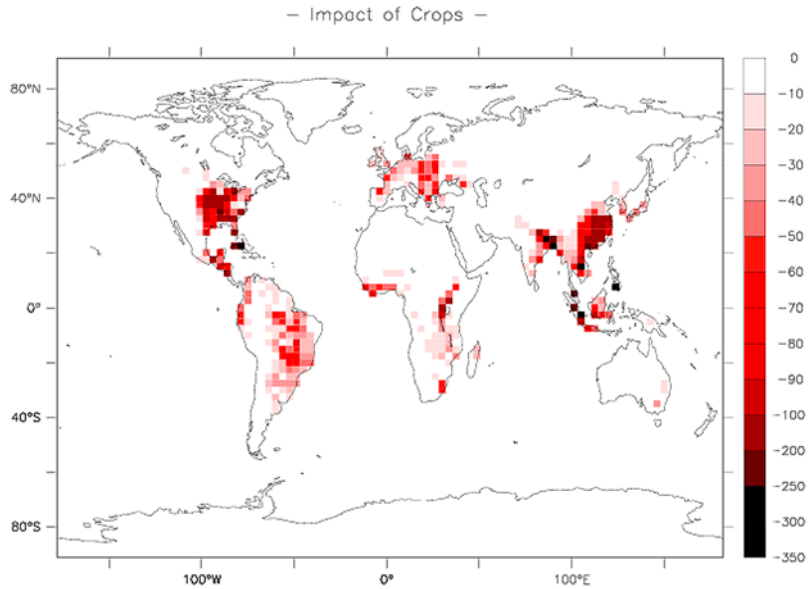

Figure 1b. Impact of crop extension on annual isoprene emissions in mgC m^{-2} d^{-1}.

Table 2. Summary of Canopy-Scale Isoprene Emission Measurements[a]

Site Number	Source	Location	Plant Species	Year	Measurement Technique	Period	Data: LAI (m^2 m^{-2})	Data: Flux (mgC m^{-2} h^{-1})
1a	*Guenther*	United States	*Quercus sp.,*	1992	Above	August mean	4.9[b]	4.2
1b	*et al.* [1996]	35.57N	*Liquidambar sp.*		canopy	August maximum		15.8
		to 84.17W	*and Nyssa sp.*		REA			
2a	*Geron et al.*	United States	*Quercus spp.,*	1994	Above	August–October	4.4–5.8	13.35
	[1997]	35.58N	*Liquidambar styraciflua,*		canopy	maximum		
2b		to 79.06W	*Liriodendron tulipifera*		REA	August–October		3.78
			and Acer rubrum			mean		
3a	*Guenther and*	United States	*Quercus spp, Liquidambar*	1996	Above	June maximum	6.3[b]	11
3b	*Hills* [1998]	35.58N	*styraciflua, Liriodendron*		canopy	June mean		6.2
		to 79.06W	*tulipifera and Acer rubrum*		EC			
4a	*Westberg et al.*	United States	*Populus tremuloides*	1998	Above	August maximum	6.77[b]	10.5
	[2001]	45.30N			canopy	warmest days		
4b		to 84.42W			EC	August maximum		1.8
						coolest days		
5	*Apel et al.*	United States	*Populus tremuloides*	1998	Above	August maximum	3.5	9
	[2002]	45.55N			canopy			
		to 84.71W			FIS			
6a	*Pattey et al.*	Canada	*Picea mariana,*	1994	Above	July maximum	4 [*Pattey et al.*,	4.58
	[1999]	53.98N	*Pinus banksiana and*		canopy		1997]	
6b		to 105.1W	*Larix laricina*		REA	September	3.9 [*Pattey et al.*,	1.67
						maximum	1997]	
7a	*Westberg et al.*	Canada	*Picea mariana*	1994	Above	May to September	3.7–4	3.3
	[2000]	53.98N			canopy	maximum	[*Pattey et al.*,	
		to 105.1W			REA		1997]	
7b			*Populus tremuloides*				3.08[b]	7.3
8a	*Rinne et al.*	Finland	*Betula pubescens,*	1996	Above	July mean	4.9[b]	0.013
8b	[2000]	67.58N	*Picea abies*		canopy	July maximum		0.1134
		to 24.14E			GT			
9	*Spirig et al.*	Germany	*Quercus robur, Quercus*	2003	Above	July maximum	3.5	4.8
	[2005]	50.55N	*rubra Betula pendula,*		canopy			
		to 6.24E	*Fagus sylvatica*		EC			
10	*Greenberg et al.*	Congo	Rain forest	1996	Above	November	(only one value in	1.35
	[1999]	4.24N			canopy	December	the database) 3.47[b]	
		to 18.31E			REA	maximum		
11a	*Kuhn et al.*	Brazil	Rain forest	2001	Above	July mean	4.6	2.1
11b	[2007]	2.35S			canopy	July maximum		5.4
		to 60.12W			REA			
12	*Geron et al.*	Costa Rica	*Pentaclethra*	1999	Above	October mean	8 (Model)	2.2
	[2002]	10.26N	*macrolaba*		canopy			
		to 83.59W			REA			

[a]REA, Relaxed Eddy Accumulation; EC, Eddy Covariance; GT, Gradient Technique; FIS, Fast Isoprene Sensor.
[b]LAI from the ORNL DAAC compilation database, choosing the best matching for each ecosystem, time period, and location used.

used instead of the mean values, the correlation between predicted and measured fluxes improves significantly (Figure 3) (r^2 = 0.78 with the UM climatology and r^2 = 0.72 with the CRU data sets, both using the "matching" PFTs). However, a key finding in this model evaluation is that modeled emissions underestimate observations, especially for vegetation in midlatitude and high-latitude locations.

3.3. Sensitivity of Emission Estimates to Model Parameters

[17] To assess the sensitivity of the predicted isoprene emission estimates to model variables (impact of CO_2 concentration, leaf age, soil moisture and mean values for emission factors) the model was run with and without inclusion of each parameter in turn. Every run included the impact of canopy loss. In doing so, we study the direct impacts of these parameters on isoprene emissions, not the indirect impacts that would arise from changes in LAI or vegetation distribution resulting from changes in soil moisture or atmospheric CO_2 concentration and that would then indirectly affect the emissions. Table 3 reports the resulting global isoprene emission fluxes and the difference between each run and the control run in which all parameters are considered. The present-day UM-simulated climatology and current atmospheric CO_2 concentration were used, as well as a potential vegetation distribution generated by the SGDVM, not accounting for crop distribution. For this control run, the global isoprene emission rate is 471 TgC yr^{-1}.

[18] Excluding the direct effects of leaf age or soil moisture on isoprene emissions, as parameterized in our model and described in section 2, only has a minor impact on global estimates, increasing emissions by 0.5% and 1%, respectively, compared to the control run. These impacts are significantly lower than those calculated by previous studies: 10% for leaf age [*Lathière et al.*, 2006] and 7% for soil moisture [*Guenther et al.*, 2006]. In our study, the distribu-

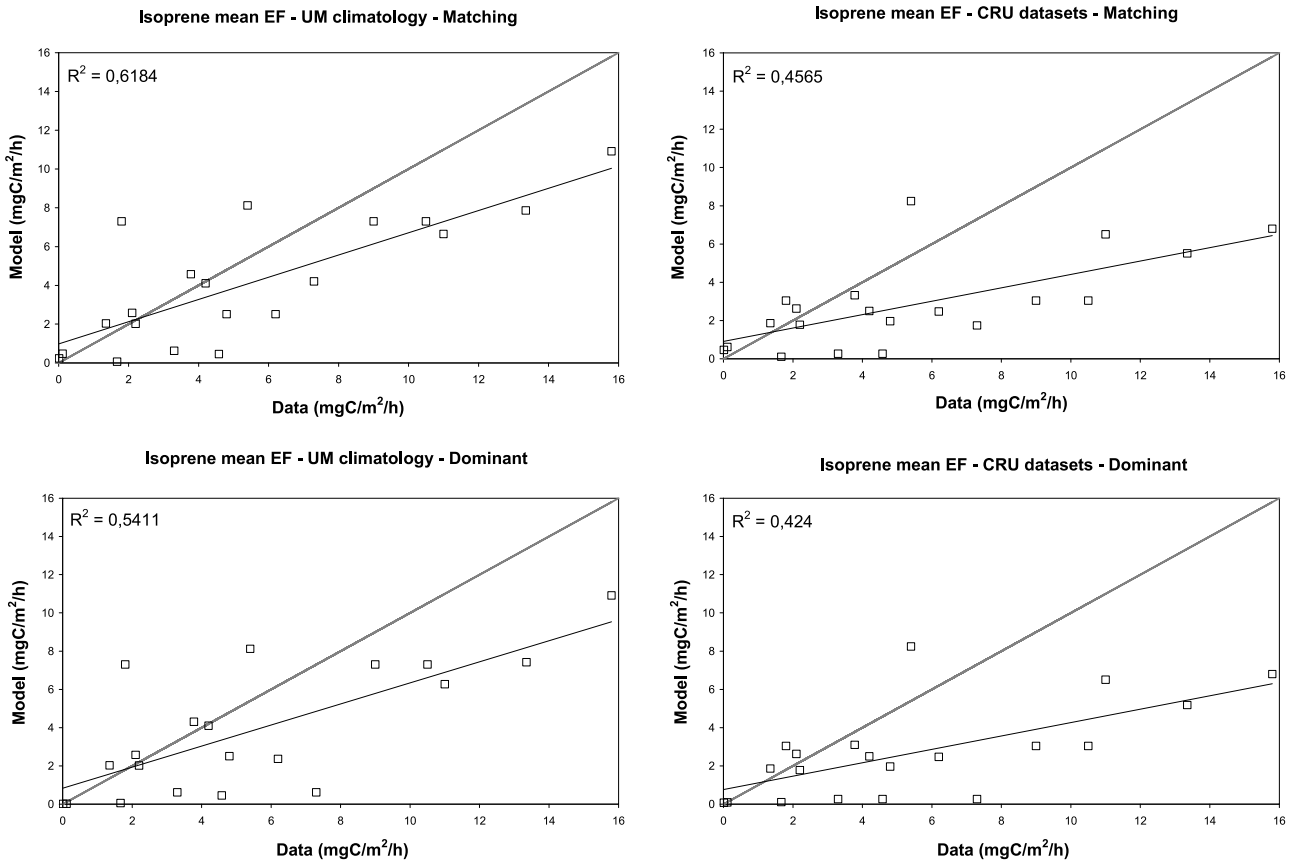

Figure 2. Isoprene model-data correlation for the present-day potential simulation using mean emission factors with climate conditions provided either by the (left) UM or (right) Climate Research Unit (CRU) data sets and considering either the matching or the dominant plant functional type (PFT).

tion of leaves in each age class is calculated based on the difference between the current and the previous month LAI provided by the SDGVM [*Guenther et al.*, 2006], whereas it is calculated online with a different vegetation model in *Lathière et al.* [2006]. Moreover, we used different values for isoprene emission efficiency for each leaf class based on *Guenther et al.* [2006]. Differences in sensitivity to the direct soil moisture effects on emissions may arise from the use of observations (NCEP-DOE reanalysis) data sets by *Guenther et al.* [2006] compared to our SDGVM calculated soil moisture regimes. However, our emissions are sensitive to regional variations in site water balance. In regions characterized by both high temperature and low rainfall for several months of the year, such as eastern Brazil, southern Africa or northern Australia, taking into account the direct impact of soil moisture on isoprene emissions can lead to a decrease in emissions of up to 10%, 20% and 30%, respectively.

[19] Sensitivity to atmospheric CO_2 concentrations, through the isoprene suppression effect, was assessed for a value of 560 ppmv, and global isoprene emissions from the terrestrial biosphere decreased by 35% compared with the present day (Table 3). However, this potential reduction may be offset in the future by a warmer climate [*Lathière et al.*, 2005; *Sanderson et al.*, 2003; *Monson et al.*, 2007; *Arneth et al.*, 2007a].

[20] Adopting gridded emission factor maps [*Guenther et al.*, 2006] to calculate isoprene emissions, instead of a single mean value for each PFT, decreases global isoprene emissions by 32% to 319 TgC yr^{-1}. The differences in annual isoprene emissions between these simulations also show marked regional differences (Figure 4) and are attributable to the different emission rates used. For example, the maps of *Guenther et al.* [2006] give values of 4 mgC m^{-2} h^{-1} in Amazonia, and 8–10 mgC m^{-2} h^{-1} in other parts of South America, central Africa and Asia for broad-leaved trees. In contrast, the PFT specific value for broad-leaved trees is higher at 13 mgC m^{-2} h^{-1}. In equatorial Africa, eastern Australia and Europe, the use of the *Guenther et al.* [2006] maps of emission factors, which reach up to 17 mg C m^{-2} h^{-1} for broad-leaved trees in those areas, leads to an increase in annual emissions varying from 10–50 mg C m^{-2} h^{-1}. Isoprene emissions in North America are affected both positively, with an increase in emissions on the east coast, and negatively, in central regions where emission decreases.

3.4. Evolution of Isoprene Emissions From the Terrestrial Biosphere Over the 20th Century

[21] To investigate the evolution of isoprene emissions during the 20th century, when atmospheric CO_2 concentra-

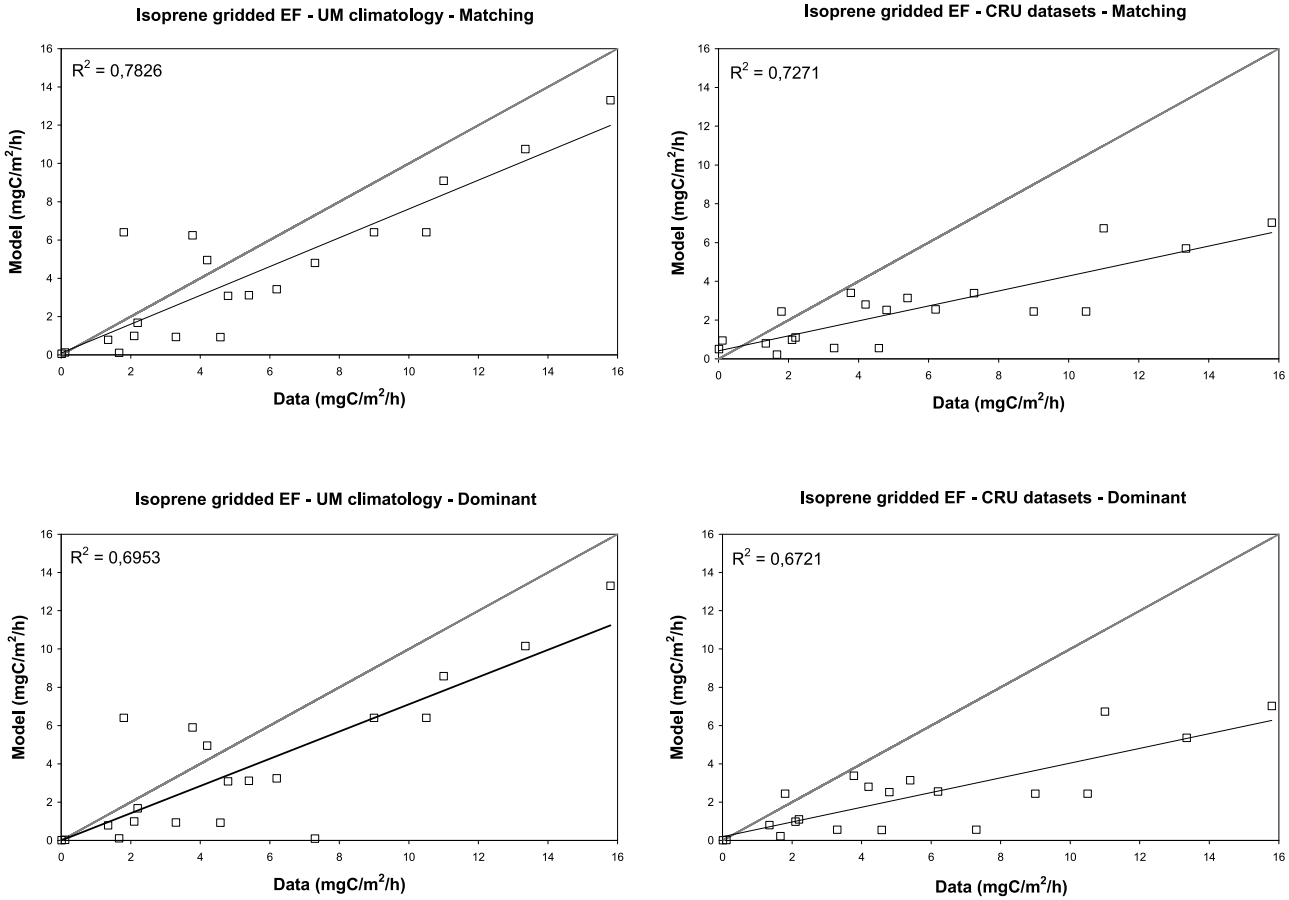

Figure 3. Isoprene model-data correlation for the present-day potential simulation using gridded emission factors with climate conditions provided either by the (left) UM or (right) CRU data sets and considering either the matching or the dominant PFT.

tion increased from 289 ppmv to 373 ppmv (+29%), we performed simulations using the CRU climate data sets from 1901 to 2002.

[22] Three century-long simulations were performed: the simulations CLIM + CO2 + issup and CLIM + CO2 + issup + CROPS consider the effects of changes in both climate and atmospheric CO_2 concentration, with and without the application of a crop mask, respectively. In these simulations, atmospheric CO_2 affects isoprene emissions both indirectly, through the CO_2 fertilization of terrestrial vegetation, and directly, through the suppression effect of isoprene emissions (issup). For comparison with CLIM + CO_2 + issup, we performed a further simulation ignoring isoprene suppression by CO_2 (CLIM + CO_2). For the simulations CLIM + CO_2 + issup and CLIM + CO_2, only the calculated "potential" vegetation distribution is considered (i.e., without application of a crop mask). The distribution of crops is taken into account in the simulation

Table 3. Sensitivity of Calculated Global Isoprene Emissions to Model Parameters and Simulation Conditions[a]

Input Data			Parameters Considered for Isoprene Emissions				Results for Isoprene
Vegetation Distribution	Climate	CO_2 Concentration	CO_2 Impact	Leaf Age	Soil Moisture	Mean EF Only	(TgC yr^{-1})
Potential present	Present	366	+	+	+	+	471
			+	–	+	+	473 (+0.5%)
			+	+	–	+	476 (+1%)
			+	+	+	–	319 (−32%)
		560	+	+	+	+	307 (−35%)
Potential present with crops	Present	366	+	+	+	+	413 (−12%)

[a]Change in emissions compared to the control run is specified in percent. Calculations accounting for all parameters (471 TgC yr^{-1}) are considered as the control. Canopy loss of isoprene is included in every run.

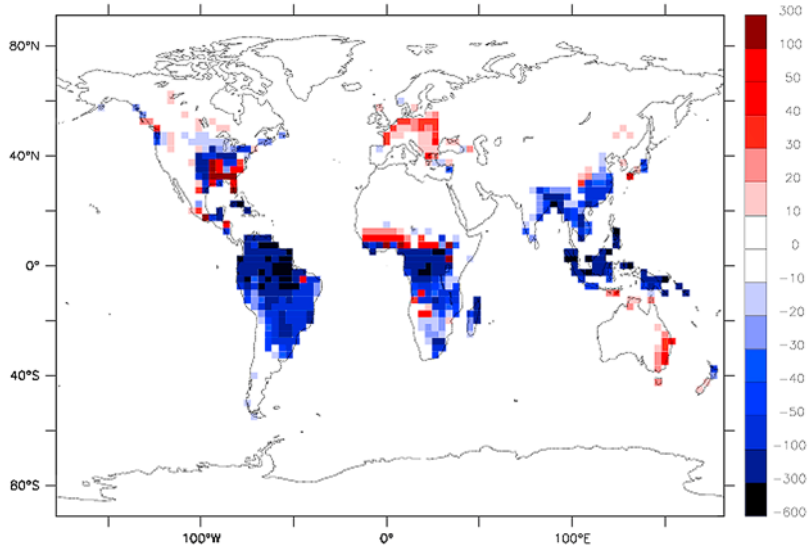

Figure 4. Impact of using gridded emissions factors compiled by *Guenther et al.* (2006] on annual biogenic emissions of isoprene. Difference in emissions between the run using maps of emission factors and the run using mean emission factors is illustrated in mgC m^{-2} d^{-1}.

CLIM + CO_2 + issup + CROPS. Figure 5 shows the global annual isoprene emissions calculated for the period 1901–2002 for these three simulations.

[23] In 1901, we estimate global isoprene emissions from the terrestrial biosphere of 657 TgC yr^{-1} from potential vegetation when CO_2 effects on isoprene emissions are included. This drops to 607 TgC yr^{-1} when some potential vegetation is replaced by crops. If the effects of CO_2 on isoprene emissions are excluded, we estimate total emissions are 520 TgC yr^{-1} in 1901. Accounting for both CO_2 and croplands is therefore critical. Our best estimate for global isoprene emissions for use in atmospheric chemistry simulations in 1901 is therefore 607 TgC yr^{-1}. At the end of the 20th century (2002), we estimate total isoprene emissions of 550 TgC yr^{-1} using potential vegetation, but accounting for cropland expansion reduces this value to

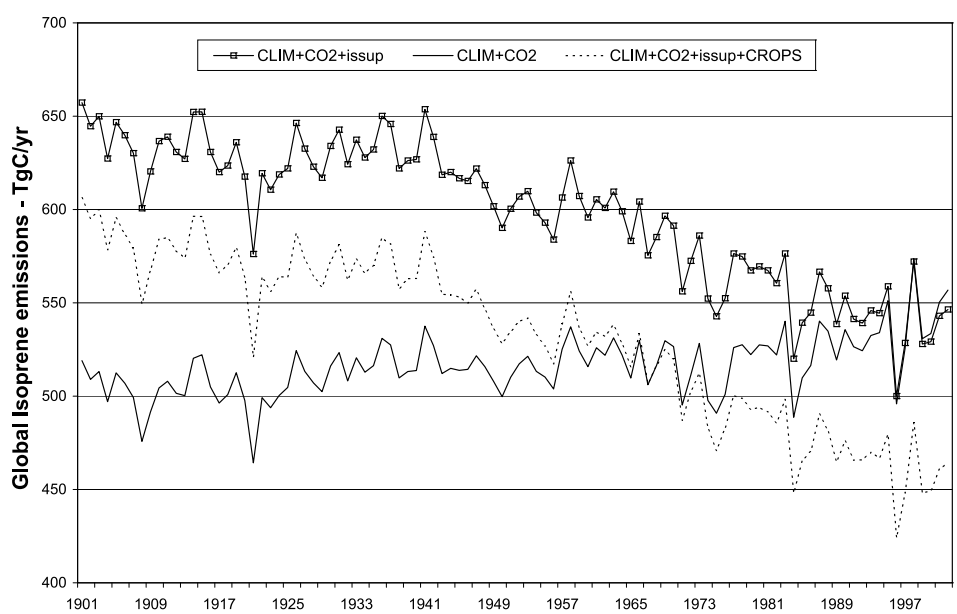

Figure 5. Global isoprene emissions given in TgC yr^{-1} over the 1901–2002 period for the runs CLIM + CO_2 + issup (squared black line), CLIM + CO_2 (black line), and CLIM + CO_2 + issup + CROPS (dashed line).

464 TgC yr^{-1}. Our results show that the impact of land use change on isoprene emissions doubles over the course of the 20th century, going from an 8% decrease in 1901 up to a 16% decrease in 2002. Over this period, agriculture expanded, primarily in the Northern Hemisphere, in regions of central and eastern Europe, and central part of North America. Consequently, it is mainly in these regions that isoprene emissions are affected by land use change. In the future, isoprene emissions from tropical and Southern Hemisphere regions, where large changes in crop surfaces and land management are expected, could in turns be significantly affected, with large potential consequences on tropospheric chemistry and air quality.

4. Conclusion

[24] The off-line coupling of the SGDVM vegetation model with an emission model based on *Guenther et al.* [2006] driven with suitable global climate data sets allows calculation of biogenic emissions of isoprene from the terrestrial vegetation. Our calculations include the impact of temperature and radiation, as well as the influence of soil moisture, leaf age, canopy loss and atmospheric CO_2 concentration on emission levels. Modeled isoprene emission rates reproduce above-canopy flux measurements and site-to-site variability, with the best correlation between model and data found by using the UM climatology and the matching plant functional type (r^2 = 0.62). There is a tendency for the model to underestimate isoprene emissions, especially in high-latitude regions, but this disagreement is reduced when the global maps of emission factors compiled by *Guenther et al.* [2006], integrating the regional variability of emission factor within a PFT, are used (r^2 = 0.78). Our analyses identified that the largest uncertainty lies in assigning emission factors to plant functional types and how these may vary across the land surface.

[25] Changes in climate, atmospheric CO_2 concentration and land use over the course of the 20th century had a significant impact on isoprene emissions from terrestrial vegetation, with the former leading to greater isoprene emissions and the latter two leading to lower isoprene emissions. Overall, a 24% decrease in global isoprene emissions was predicted for the 20th century. For the 21st century, our calculations suggest that these conflicting drivers on isoprene emission rates will continue as croplands expand and CO_2 concentrations and temperatures increase. However, the possible rapid expansion of biofuel production with high isoprene-emitting plant species (e.g., oil palm, willow and poplar) may reverse the trend by which conversion of land to food crops leads to lower isoprene emissions.

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D. J. Beerling, Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK.

C. N. Hewitt, Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK.

J. Lathière, Laboratoire des Sciences du Climat et de l'Environnement, IPSL, UVSQ, CEA, CNRS, F-91191 Gif-sur-Yvette, France. (juliette.lathiere@lsce.ipsl.fr)