Sensitivity of global biogenic isoprenoid emissions to climate variability and atmospheric CO_2

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[1] Isoprenoids (isoprene and monoterpenes) are the most dominant class of biogenic volatile organic compounds (BVOCs) and have been shown to significantly affect global tropospheric chemistry and composition, climate, and the global carbon cycle. In this study we assess the sensitivity of biogenic isoprene and monoterpene emissions to combined and isolated fluctuations in observed global climate and atmospheric carbon dioxide (CO_2) concentration during the period 1971–1990. We integrate surface emission algorithms within the framework of a dynamic global ecosystem model, the Integrated Biospheric Simulator (IBIS), to simulate biogenic fluxes of isoprenoids as a component of the climate-vegetation dynamics. IBIS predicts global land surface isoprene emissions of 454 Tg C and monoterpenes of 72 Tg C annually and captures the spatial and temporal patterns well. The combined fluctuations in climate and atmospheric CO_2 during 1971–1990 caused significant interannual and seasonal variability in global biogenic isoprenoid fluxes that was somewhat related to the El Niño-Southern Oscillation. Furthermore, an increasing trend in the simulated emissions was seen during this period that is attributed partly to the warming trend and partly to CO_2 fertilization effect. The isolated effect of increasing CO_2 during this period was to steadily increase emissions as a result of increases in foliar biomass. These fluctuations in biogenic emissions could have significant impacts on regional and global atmospheric chemistry and the global carbon budget. *INDEX TERMS:* 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* isoprenoid, interannual variability, atmospheric CO_2

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1. Introduction

[2] Approximately 90% of the total nonmethane volatile organic compounds (VOCs) emitted into the atmosphere globally comes from terrestrial vegetation [*Guenther et al.*, 1995] (hereinafter referred to as G95). These biogenic VOCs (BVOCs) include isoprenoids (isoprene, monoterpenes, and sesquiterpenes), alkanes, alkenes, carbonyls, alcohols, esters, ethers, and acids [*Fehsenfeld et al.*, 1992; *Kesselmeier and Staudt*, 1999]. The annual emission of BVOCs is estimated to be about 1.2 Pg (10^{12} g) of carbon [G95]. Isoprenoids are the dominant class of BVOCs with respect to both their emission activity and their capacity to influence atmospheric composition [G95; *Monson and Holland*, 2001]. In this study, isoprenoids represents isoprene and monoterpenes since we do not consider sesquiterpenes.

[3] BVOCs play a significant role in determining the local, regional, and global atmospheric composition. They react with hydroxyl radical (OH), ozone (O_3), and nitrate radical (NO_3) in the atmosphere, resulting in the formation of organic species, such as, carbon monoxide (CO), peroxy radicals, alkoxy radicals, and carbonyl compounds, that can enhance concentrations of O_3 and other oxidants in environments rich in nitrogen oxides (NO_x) [*Went*, 1960; *Rasmussen*, 1972; *Chameides et al.*, 1988; *Fehsenfeld et al.*, 1992; *Houweling et al.*, 1998]. Reactions of BVOCs with OH can also lead to enhanced levels of atmospheric methane (CH_4), a key greenhouse gas, as OH is the major sink for CH_4. For example, *Poisson et al.* [2000] predicted a 15% increase in

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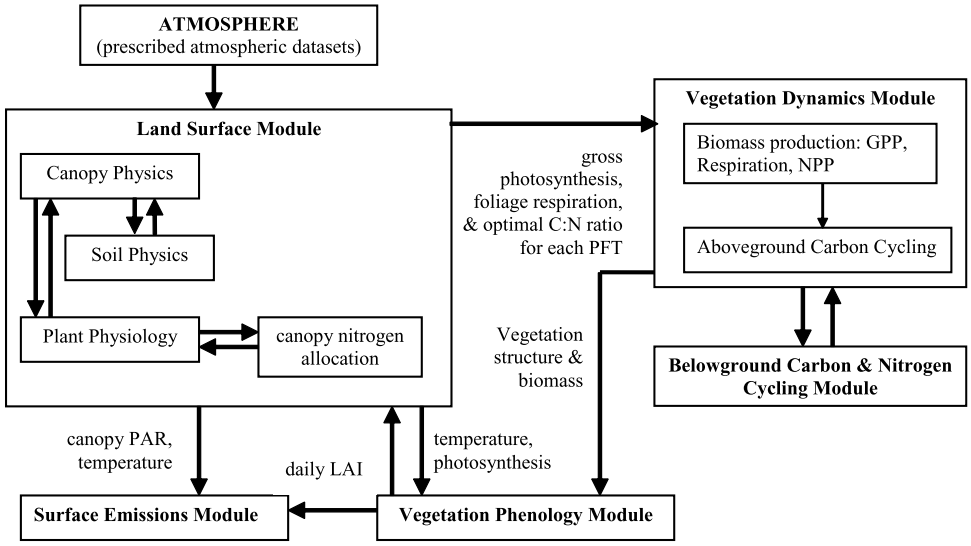

Figure 1. Schematic of IBIS adapted from *Kucharik et al.* [2000].

the tropospheric lifetime of CH_4 as a result of a BVOC-induced 20% reduction in the global OH concentration. Field measurements and laboratory studies have also confirmed significant secondary organic aerosol formation from BVOC emissions, suggesting an indirect influence of BVOCs on the radiation balance of the Earth [*Hoffmann et al.*, 1997; *Griffin et al.*, 1999].

[4] BVOCs play a key role in the global carbon budget and cycling, as most organic compounds are oxidized to carbon dioxide (CO_2) in the atmosphere. Current research efforts are directed toward investigating and accounting for each carbon flux into and out of the terrestrial biosphere to reduce uncertainties in the attribution of the net residual carbon sink into the terrestrial biosphere [*Malhi*, 2002; *Kesselmeier et al.*, 2002a; *Guenther*, 2002]. *Kesselmeier et al.* [2002a] inferred that the amount of carbon emitted by plants as BVOC accounts for up to 2% of the net primary productivity (NPP), where NPP is the annual increment of carbon in land plants represented by the difference between photosynthesis and plant respiration. *Guenther* [2002] noted that the predicted annual global BVOC emissions of about 1.2 Pg C would result in the annual production of approximately 1.0 Pg C as CO_2 per year. He further argued that, since BVOCs are expected to respond differently to changes in climate, atmospheric CO_2 concentration, and land cover, an accurate understanding of future changes in the global carbon cycle will require the inclusion of these trace gases in carbon budget studies.

[5] BVOC emissions from ecosystems are highly species-specific and are sensitive to a number of environmental factors, including temperature, sunlight, water and nitrogen availability, ambient concentrations of pollutants (O_3 and SO_2), and other stresses [*Lerdau et al.*, 1997; *Kesselmeier and Staudt*, 1999; *Fuentes et al.*, 2000]. Of significant importance is the temperature dependence of isoprene and monoterpenes emissions, which suggests that global increases in temperature will augment their emissions from ecosystems [*Constable et al.*, 1999]. This increase may result in increasing levels of tropospheric pollutants and greenhouse gases, as described earlier. Similarly, elevated levels of atmospheric CO_2 may increase the foliar biomass in unmanaged ecosystems that is available to produce BVOCs, and therefore, emissions will increase proportionally. This inference, however, is unfounded for commercial agriforest species that have been shown to reduce isoprene emissions despite concurrent increases in both photosynthesis and biomass accumulation [*Rosenstiel et al.*, 2003].

[6] Algorithms that describe the influence of temperature and sunlight on biogenic isoprenoid emissions using ecosystem-specific base emission rates exist and have been recently incorporated in global and regional ecosystem models [*Baldocchi et al.*, 1999; *Wang and Shallcross*, 2000; *Potter et al.*, 2001]. Inclusion of surface emission algorithms within the framework of dynamic ecosystem models provides a capability for investigating both short and long term changes in emissions due to climate, disturbance, and land-use induced changes in ecosystem structure and distribution.

[7] Understanding the feedbacks between BVOC fluxes, atmospheric chemistry, the global carbon cycle and climate requires the assessment of the impact of global scale environmental changes on BVOC emissions from ecosystems to the atmosphere [*Fuentes et al.*, 2001; *Guenther*, 2002]. Therefore, in this study, we investigate the effect of climate variations, coupled with increases in atmospheric CO_2 on global BVOC emissions during the 20-year period from 1971–1990. We use a dynamic global vegetation model to examine the interannual trend and spatial variability of biogenic isoprenoid emissions and their relationship to climate and CO_2 perturbation.

2. Methods

2.1. Model Description

[8] We used an updated version of the Integrated Biospheric Simulator (IBIS 2.5) [*Foley et al.*, 1996; *Kucharik et al.*, 2000] to simulate the biogenic emissions of isoprene and monoterpenes. IBIS is a dynamic global vegetation model that simulates the interactions of the terrestrial biosphere with the atmosphere through land surface and hydrological processes, canopy physiology, vegetation dynamics, and terrestrial carbon balance within a single integrated framework (Figure 1).

[9] The land surface module of IBIS simulates the energy, water, carbon, and momentum balance of the soil-vegetation-atmosphere system. It represents two types of vegetation canopies: lower (grasses and shrubs) and upper (trees), and six soil layers to simulate soil physics. Canopy radiation transfer is simulated using the two-stream approximation following the approach of *Sellers et al.* [1986] and *Bonan* [1995]. Photosynthesis, respiration and stomatal conductance are simulated using mechanistic approaches within the soil-vegetation-atmosphere transfer scheme, allowing for explicit coupling between vegetation canopies and the atmosphere. IBIS uses a natural vegetation map with 15 ecosystem types or biomes [*Ramankutty and Foley*, 1999] and each of these biomes consist of a unique combination of 12 plant functional types (PFTs). The geographical distribution of each PFT is determined by climatic constraints [*Kucharik et al.*, 2000]. The relative abundance of the 12 PFTs in each grid cell changes in time according to their ability to photosynthesize and use water. The vegetation dynamics module predicts the transient changes in leaf area index (LAI) and biomass for the 12 PFTs, based on annual carbon balance. IBIS simulates these biophysical and biogeochemical processes at timescales ranging from 60 min to a year.

[10] Measurement and laboratory studies show that isoprene and monoterpene emissions are highly sensitive to temperature. Isoprene emissions show a temperature maximum and subsequent reduction at higher temperatures [*Guenther et al.*, 1991, 1993; *Monson et al.*, 1994], while monoterpene emissions increase exponentially with increasing temperature [*Tingey et al.*, 1980, 1991; *Guenther et al.*, 1991]. In addition, isoprene emissions are extremely light-dependent with noticeably different emissions among shaded and sunlit leaves [*Harley et al.*, 1996], and no emissions under dark conditions [*Guenther et al.*, 1991; *Tingey et al.*, 1979]. Monoterpene emissions from most plants are regarded as light-independent. There are, however, exceptions to the influence of these environmental factors on isoprene and monoterpene emissions. For example, isoprene emissions from CAM (Crassulacean Acid Metabolism) plants may be light-independent [*Lerdau and Keller*, 1997], and monoterpene emissions from some plant species have been found to be light-dependent [*Bertin et al.*, 1997].

[11] Within the IBIS framework, we incorporated isoprenoid emission algorithms that describe the short-term influences of temperature and light on emissions (Figure 1). These empirical emission algorithms, based on field measurements and laboratory experiments, were initially proposed by *Guenther et al.* [1991, 1993], and further developed for a global natural volatile organic compound emissions inventory for the International Global Atmospheric Chemistry Project (IGAC) [G95]. Isoprenoid emissions from plant canopies are estimated as follows:

$$F = \varepsilon F_d \gamma_T \gamma_L \rho, \tag{1}$$

where F is the emission flux (μg C m^{-2} h^{-1}), ε is the ecosystem-specific emission factor (μg C g^{-1} h^{-1}) at a standard leaf temperature (T_s) of 303.15 K and standard photosynthetically active radiation (PAR) flux of 1000 μmol m^{-2} s^{-1}, F_d is the foliar biomass density (g dry weight m^{-2}), γ_T and γ_L are dimensionless scalars that describe the response of emissions to diurnal variations in leaf temperature and incident sunlight (for isoprene only), and ρ is an escape efficiency factor that represents the fraction of gas emitted by the canopy that is released into the above-canopy atmosphere. For isoprene emissions, temperature and light dependence factors are given by

$$\gamma_T = \frac{\exp\left(\frac{C_{T1}(T - T_s)}{RT_sT}\right)}{0.961 + \exp\left(\frac{C_{T2}(T - T_M)}{RT_sT}\right)} \tag{2}$$

and

$$\gamma_L = \frac{\alpha C_{L1} PAR}{\sqrt{1 + \alpha^2 PAR^2}}, \tag{3}$$

where R (8.314 J K^{-1} mol^{-1}) is the gas constant, C_{T1} (95000 J mol^{-1}), C_{T2} (230000 J mol^{-1}), T_m (314 K), α (0.0027), and C_{L1} (1.066) are empirical coefficients derived from measurements [*Guenther*, 1997]. For monoterpene emissions, temperature dependence factor is given by

$$\gamma_T = \exp(\beta^*(T - T_s)), \tag{4}$$

where β is an empirical coefficient equal to 0.09 K^{-1} [*Guenther et al.*, 1993] and $\gamma_L = 1$.

[12] At each grid cell, emissions are predicted every 60 min using canopy variables supplied by IBIS. Daily foliar density is estimated by dividing the LAI for each PFT by its specific leaf area [*Foley et al.*, 1996]. γ_T is calculated using IBIS simulated hourly leaf temperature for trees (upper canopy), and grasses and shrubs (lower canopy). γ_L is calculated for sunlit and shaded leaves for each canopy layer. We assume a globally uniform value of $\rho = 1$ in the absence of estimates from field measurements. This should be regarded as an upper limit since canopy chemistry and physics may reduce the fraction of VOCs released into the free atmosphere [*Guenther et al.*, 1999].

[13] Base emission factors are defined as the rate of emission per unit foliar biomass expected from a plant species under a given set of environmental conditions [*Guenther*, 1997]. They vary significantly for different plant species and are influenced by nutrient status, soil moisture content, and foliage developmental stage [*Fuentes et al.*, 2000, and references therein]. A robust modeling scheme to predict global VOC emissions would require taking into account the influence of these factors on ε and the heterogeneity in plant species. Limited field measurements, however, restrict the assignment of ε for a wide variety of plant species on a global scale. As described above, IBIS uses a combination of 12 PFTs to define a biome on each grid cell. This approach deals with the issue of species variability to some extent. Therefore we assigned ε for the 12 PFTs based on G95 recommendations (Table 1). We assigned an isoprene emission factor of 0.0 for grasses contrary to recommendations of G95, as several measurement studies have since shown that grasses are not a major emitter of isoprene (see http://www.es.lancs.ac.uk/cnhgroup/download.html).

2.2. Simulations

[14] Initially, IBIS was driven in the dynamic mode to an equilibrium state using a monthly mean climatological data set of temperature, precipitation, relative humidity, and cloud

Table 1. Plant Functional Types and Their Specific Leaf Area Defined in IBIS and Emission Factors (ε) for Isoprene and Monoterpenes Based on *Guenther et al.* [1995][a]

Plant Functional Type	Isoprene, μg C g^{-1} hr^{-1}	Monoterpenes, μg C g^{-1} hr^{-1}	Specific Leaf Area, m^2 kg^{-1}
	Trees		
Tropical broadleaf evergreen tree	24.0	0.4	25.0
Tropical broadleaf drought-deciduous tree	45.0	1.2	25.0
Warm-temperate broadleaf evergreen tree	24.0	0.8	25.0
Temperate conifer evergreen tree	16.0	2.4	12.5
Temperate broadleaf cold-deciduous tree	45.0	0.8	25.0
Boreal conifer evergreen tree	8.0	2.4	12.5
Boreal broadleaf cold-deciduous tree	45.0	0.8	25.0
Boreal conifer cold-deciduous tree	8.0	2.4	25.0
	Shrubs and Grasses		
Evergreen shrub	16.0	0.8	12.5
Deciduous shrub	16.0	0.8	25.0
Warm grass	0.0	1.2	20.0
Cool grass	0.0	0.8	20.0

[a]Isoprene emission factors for warm and cool grasses have been assigned a value of 0.0 based on other studies that show that grasses are not a major emitter of isoprene.

cover for the 1961–1990 period. This data set, compiled by *New et al.* [1999], is referred to as CRU05 hereafter. The model was run at a resolution of 2° longitude by 2° latitude. The simulation was initialized with an "observed" potential vegetation map [*Ramankutty and Foley*, 1999] that represents vegetation that would exist in the absence of human activities. Therefore croplands are not included in this vegetation map. A constant atmospheric CO_2 concentration of 333.4 ppm (parts per million), which is the mean for the thirty-year period 1961–1990 [*Keeling and Whorf*, 2003], was used. IBIS was run for 300 years to arrive at a near equilibrium state. Beginning from this initial equilibrium state, the following simulations were performed for the 1961 to 1990 period:

[15] 1. CON: Control using CRU05 mean 1961–1990 climatology.

[16] 2. CLIM: Climate only, using transient changes in climate data (monthly climate anomalies relative to 1961–1990 from *New et al.* [2000]).

[17] 3. CO2: CO_2 only, using transient atmospheric CO_2 concentrations from *Keeling and Whorf* [2003].

[18] 4. CLIM_CO2: Transient changes in both climate and CO_2 concentration.

[19] CON was aimed at simulating ecosystem attributes resulting from mean climate and a constant atmospheric CO_2 for the thirty-year period from 1961 to 1990. We only use years 1971–1990 for our analysis of simulations CLIM, CO2 and CLIM_CO2 to let the carbon pools adjust to the different climatic conditions and CO_2 level. The CO2 simulation, for instance, is initialized with the results of the CON simulation that was performed with an atmospheric CO_2 level of 333.4 ppmv. However, the observed CO_2 concentration for 1961 used in the CO2 simulation is only 317 ppmv. In the following section, we first evaluate IBIS's ability to simulate biogenic emissions using results from CON, and then, using results from the three simulations we investigate the inter-annual and spatial variations in isoprenoid emissions in response to the past 20 year climate variability and increasing atmospheric CO_2.

3. Results and Discussions

3.1. Control Simulation

[20] IBIS simulates the ecosystem attributes (NPP, biomass, vegetation structure and distribution) for the mean 1961–1990 climatology reasonably well. Simulated global total NPP (56.5 Pg C/yr) and vegetation biomass (622 Pg C/yr) fall within the range of other estimates and measurements at 45–60 Pg C/yr and 500–950 Pg C/yr, respectively [*Kucharik et al.*, 2000; *Cramer et al.*, 2001]. As discussed in the work of *Delire et al.* [2003], IBIS simulates the distribution of vegetation types or biomes fairly well (Figure 2). The vegetation type for a grid cell is calculated using a combination of rules based on climate and the LAI of the different PFTs in that grid cell. For example, a grid cell would be classified as a temperate deciduous forest if the calculated LAI for temperate broadleaf cold deciduous

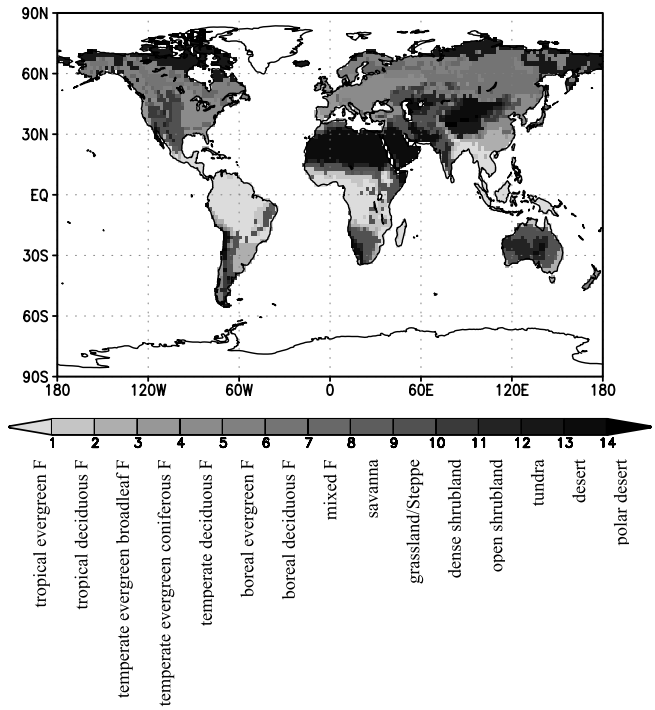

Figure 2. Distribution of potential vegetation ecosystems simulated by IBIS driven by 1961–1990 mean CRU05 climate (simulation CON). See color version of this figure at back of this issue.

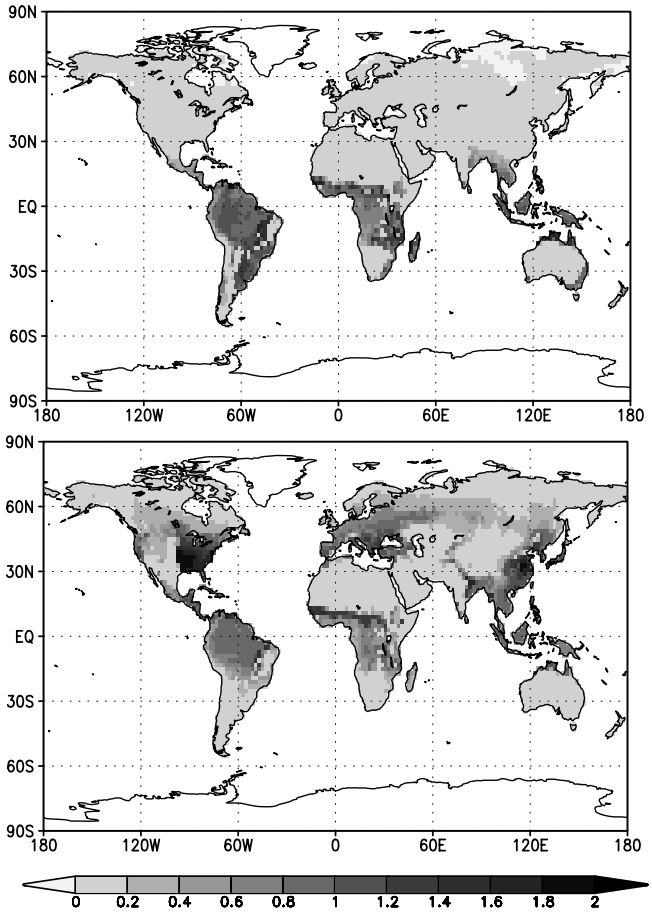

Figure 3. Global distribution of isoprene emission rates (g C m^{-2} $month^{-1}$) simulated by IBIS driven by the 1961–1990 mean CRU05 climate for (top) January and (bottom) July (simulation CON). See color version of this figure at back of this issue.

trees was the highest in that grid cell and if the total LAI of the upper canopy was greater than 1.5. The same grid cell would be classified as a savanna if the total LAI was smaller than 1.5 or as a tundra if the annual 5°C growing-degree-days (GDD5) was lower than 350.

[21] The global distribution of simulated isoprenoid fluxes is explained by the vegetation distribution simulated by IBIS. The major characteristics of today's potential vegetation are well represented, including tropical evergreen forests surrounded by deciduous forests and savannas in the tropics, grasslands and shrublands in the western United States and Australia, South Africa and South America, temperate deciduous forests in the eastern United States and China, and boreal forests in Canada and north-central Eurasia. There are, however, a few inconsistencies in the model results, such as, the lack of extensive savannas. Widespread temperate evergreen forests in Argentina and tropical deciduous forests in Africa and South America are included in the simulation at the expense of savannas. We note that IBIS fails to represent savannas accurately because the existence of these ecosystems depends on disturbances, such as fires and extreme weather events, which are poorly represented in IBIS [*Delire et al.*, 2003, 2002]. The simulation of savannas also depends on climate variability which is not present in the CON simulation. These deviations in vegetation distribution are reflected in the simulated isoprenoid emissions.

[22] The simulated spatial and temporal distribution of global isoprene and monoterpene emissions for January and July (Figures 3 and 4) are in reasonable agreement with the distribution simulated by G95. In the tropics, evergreen forests emit isoprenoids throughout the year, while deciduous forests show some seasonal variability consistent with the annual cycle of leaf display. Prominent seasonal variation in emissions in the extra-tropics is related to variations in temperature and foliar densities. In January, the simulated isoprene emissions are high for southern parts of South America and Africa, because IBIS simulates extensive temperate evergreen and tropical deciduous forests in these regions. Particularly high isoprene emission rates are simulated for southeast United States and east China during the summer time because a high emission factor is assigned to the dominant PFT, temperate broadleaf deciduous tree, in these regions. Similarly, peak monoterpene fluxes are simulated for southeast United States originating from temperate coniferous forests. We note that these emission estimates

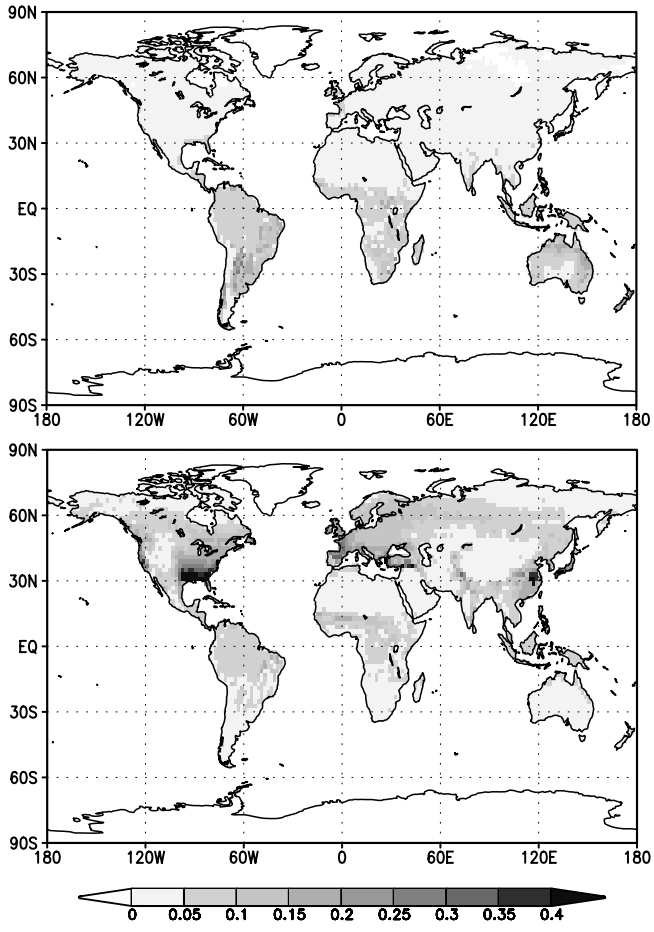

Figure 4. Global distribution of monoterpene emission rates (g C m^{-2} $month^{-1}$) simulated by IBIS driven by the 1961–1990 mean CRU05 climate for (top) January and (bottom) July. See color version of this figure at back of this issue.

Table 2. IBIS Simulated Estimates of Isoprene and Monoterpene Emissions for Mean 1961–1990 CRU Climatology[a]

IBIS Biomes	Land Area, 10^6 km^2	Average Emission, g C m^{-2} yr^{-1}		Isoprene, Tg C yr^{-1}	Monoterpene, Tg C yr^{-1}
		Isoprene	Monoterpene		
Tropical evergreen F.	23.8	9.40 (13.64)	0.70 (3.11)	223.45	16.73
Tropical deciduous F.	6.11	12.68 (13.15)	1.01 (1.41)	77.52	6.16
Temperate evergreen broadleaf F.	7.77	5.16 (4.30)	0.75 (0.92)	40.14	5.84
Temperate evergreen conifer F.	3.13	4.41 (3.68)	1.66 (3.68)	13.80	5.21
Temperate deciduous F.	10.10	4.25 (4.08)	0.73 (0.42)	43.11	7.44
Boreal evergreen F.	11.10	0.63 (0.52)	0.43 (0.68)	7.01	4.74
Boreal deciduous F.	8.45	0.70 (1.49)	0.23 (0.27)	5.89	1.96
Mixed forest/woodland	3.64	2.31 (2.77)	0.760 (0.67)	8.40	2.77
Savanna	3.46	4.05 (7.20)	0.69 (1.90)	14.00	2.38
Grassland/steppe	18.20	0.38 (4.35)	0.80 (1.07)	7.00	14.59
Dense shrubland	3.73	1.76 (3.29)	0.179 (0.92)	6.58	0.67
Open shrubland	7.74	0.236 (0.61)	0.247 (0.09)	1.83	1.91
Tundra	9.24	0.16 (0.14)	0.05 (0.05)	1.53	0.46
Desert	17.60	0.18 (0.76)	0.055 (0.09)	3.10	0.97
Polar/desert/rock/ice (minus Antarctica and Greenland)	0.82	0.062	0.006	0.05	0.01
Total	134.9			453.6	71.8

[a]Values in parenthesis are average fluxes estimated from *Guenther et al.* [1995] overlaid on IBIS biome distribution.

are for natural vegetation cover and do not account for land cover changes as a result of human activities. Conversion of forested land to croplands has been shown to reduce biogenic VOC emissions [*Steiner et al.*, 2002] and would need to be included for better emission estimates.

[23] Simulated isoprenoid fluxes for each biome resulting from the mean climate for the 1961–1990 period are shown in Table 2. IBIS captures the ecosystem-wise distribution of isoprenoid surface fluxes fairly well. Forests and savanna ecosystems account for more than 80% of the global total isoprenoid emissions estimated by IBIS, which is in agreement with the estimates of G95 and *Potter et al.* [2001]. Almost 70% of the global total biogenic isoprene emissions simulated by IBIS come from tropical ecosystems (tropical rain forests, tropical deciduous and savanna), followed by temperate forests. Besides forests, grasslands are also a significant source of monoterpenes. Generally, average isoprenoid emission rates in these ecosystems are within 30% of values reported by G95 (Table 2). There are, however, notable differences in IBIS simulated emissions as compared to values reported by G95. IBIS simulated isoprene emissions for grasslands, and savannas are particularly lower than G95 estimates. In this study, we have assumed an emission factor of 0.0 for grass PFTs based on measurements that conclude that grasses are not a major emitter of isoprene (see http://www.es.lancs.ac.uk/cnhgroup/download.html). Therefore IBIS simulated isoprene emissions for grasslands and savanna are substantially lower than G95 estimates. They are not zero because of the emissions from the nongrass PFTs in the ecosystem. Monoterpene emissions for tropical forests and temperate evergreen conifer forests are particularly low compared with G95 estimates.

[24] Based on the simulated ecosystem attributes, IBIS calculates an annual global isoprenoid flux of 525.4 Tg C for the period 1961–1990, of which, 453.6 Tg C are emitted as isoprene and 71.8 Tg C as monoterpenes. G95 estimate these fluxes as 503 and 127 Tg C. Our estimated global isoprene flux is lower than G95 estimates primarily because we have not included grasslands as a major emitter of isoprene. According to G95, grasslands emit 91.7 Tg C of isoprene. Subtracting this amount from their global total flux of 503 Tg C yields a total isoprene emission flux of 411.3 Tg C. Our estimated total isoprene flux of 453.6 Tg C is within 10% of this value. Global isoprene emissions estimated by similar modeling studies of *Levis et al.* [2003], *Potter et al.* [2001], *Wang and Shallcross* [2000] are 507, 559, and 530 Tg C, respectively. *Levis et al.* [2003] report global monoterpene fluxes of 33 Tg C in their model simulation.

[25] IBIS simulated isoprenoid fluxes are lower compared with G95 mainly due to differences in the temporal resolution of meteorological parameters, and the simulated vegetation cover and associated LAIs. IBIS calculates emissions every hour, while G95 used monthly averaged meteorological quantities to calculate fluxes using the same emission algorithms. The higher temporal resolution of IBIS possibly leads to lower emission rates as demonstrated by *Steiner et al.* [2002]. Furthermore, since emissions are directly proportional to foliar biomass (equation 1), the lower IBIS simulated foliar biomasses compared with those used in G95 result in lower emissions.

[26] Although several field measurements of isoprenoid (especially isoprene) fluxes from a variety of vegetation types have been made, an absolute comparison of IBIS simulated isoprenoid emissions with field measurements is difficult. This is because the meteorological conditions, foliar biomass, and the spatial and temporal resolution at the time of measurements do not necessarily correspond with the conditions used in the model. Nonetheless, an approximate comparison of simulated isoprenoid fluxes with landscape level observations shows that the agreement between model estimates and measurements is within the uncertainty level of the methodology. For example, *Isebrands et al.* [1999] measured isoprene emissions of 1.89 mg C m^{-2} hr^{-1} from mixed hardwood forests of northern Wisconsin in July which is comparable to our model estimates of 1.19 mg C m^{-2} hr^{-1}. *Rinne et al.* [2002] observed 1–2 mg C m^{-2} hr^{-1} of isoprene and 0.2 mg C m^{-2} hr^{-1} of monoterpene fluxes above the Amazonian rain forest in July which is comparable to our model estimates of 1.3 mg C m^{-2} hr^{-1} and 0.1 mg C m^{-2} hr^{-1} of isoprene and monoterpene fluxes, respectively.

3.2. Effect of Variations in Climate and Atmospheric CO_2

[27] We investigate the isolated and combined effects of climate variations and increasing atmospheric CO_2 concentration on global isoprenoid emissions using results from the three simulations: CLIM for the climate effect only, CO2 for the CO_2 effect only, and CLIM_CO2 for the combined effects of climate and CO_2. Like the control simulation, vegetation distribution is allowed to respond to variations in climate and CO_2 concentration in these simulations. In the period 1971–1990, biogenic isoprenoid emissions respond to a global warming of about 0.3°C/decade and a 28 ppm increase in atmospheric CO_2 concentration, among other environmental changes. They also respond to variations in climate like the 1983 El Niño event.

[28] Monthly anomalies in isoprenoid emissions and NPP from their mean monthly values for the three simulations CLIM, CO2, and CLIM_CO2 are shown in Figure 5. Isoprenoid emissions from simulation CLIM_CO2 present pronounced fluctuations from their mean monthly values and a positive trend over the 1971–1990 period (Figures 5a and 5b). Global isoprene and monoterpene emissions increase by 1.3 TgC yr^{-1} ($r^2 = 0.50$) and 0.28 TgC yr^{-1} ($r^2 = 0.32$), respectively. When responding to increasing atmospheric CO_2 only, isoprene emissions increase by 1.0 TgC yr^{-1} ($r^2 = 0.99$) and monoterpene by 0.25 TgC yr^{-1} ($r^2 = 0.98$). Variations in climate alone (simulation CLIM) do not result in an overall increase in isoprenoid emissions. Increases in temperature and atmospheric CO_2, however, interact positively to enhance isoprenoid emissions, as the increasing trend in emissions is larger for simulation CLIM_CO2 than for simulation CO2. The positive trend in emissions is due to the enhanced accumulation of biomass following the increasing in atmospheric CO_2 concentration. This CO_2 fertilization effect can be clearly seen in the monthly anomalies of global NPP for the CO2 simulation where NPP increases by 0.22 PgC yr^{-1} ($r^2 = 0.99$) (Figure 5c). While in agreement with *Levis et al.* [2000], this increase in NPP as a result of CO_2 fertilization should be regarded as an upper limit as mineral nutrient limitations (for example, availability of nitrogen) on photosynthesis and plant growth were not considered in this study.

[29] On an interannual basis, modeled isoprene and monoterpene emissions for the CLIM_CO2 vary with an interannual coefficient of variation of 2.5% and 4.1%, respectively, in the period 1971–1990 in response to the combined variations in climate and atmospheric CO_2. This is comparable to the 3.4% variation in modeled NPP for the same period for CLIM_CO2 simulation. Most of the interannual variation is due to the climate and is largely related to the variability in the El Niño-Southern Oscillation (ENSO) affecting the tropics. This is not surprising since most of the isoprenoid emissions originate from the tropical vegetation types (Table 2). The lower than average emissions in 1971–1972, 1974–1975, 1984–1985, and 1988–1989 correspond to La Niña years while the higher than average emissions in 1973, 1977, 1983 and 1987 correspond to El Niño years (Figure 5). The correlation coefficient between annual emissions and a Southern Oscillation Index (SOI), based on the sea level pressure difference between Tahiti and Darwin for 1971–1990, is −0.54 ($p < 0.05$) for isoprene and −0.24 ($p < 0.3$) for monoterpenes in the CLIM simulation and slightly higher (−0.55, $p < 0.05$ and −0.33, $p < 0.1$) in the CLIM_CO2 simulation. Correlation with ENSO is lower for monoterpenes because the extra-tropical regions contribute more to their global emissions.

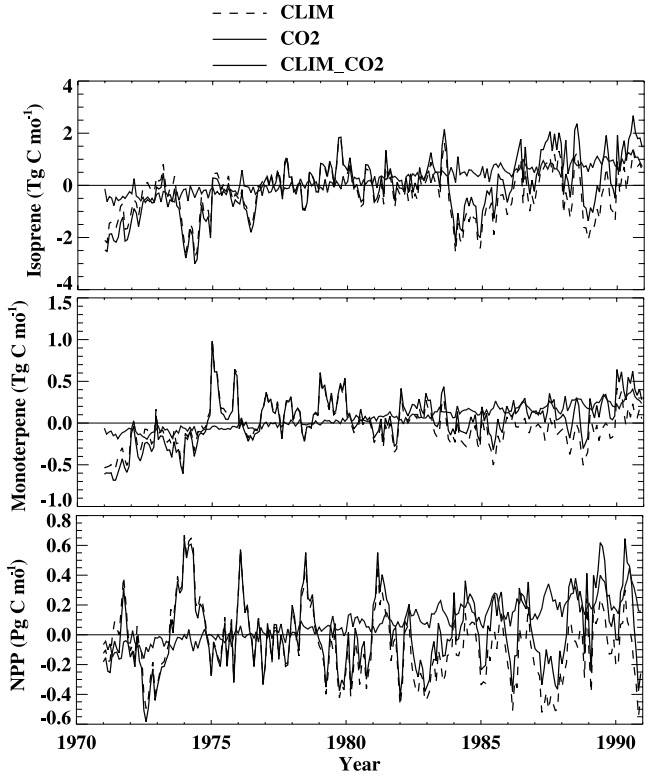

Figure 5. The monthly anomalies of global (top) isoprene and (middle) monoterpene emissions and (bottom) net primary productivity calculated as deviations from the average seasonal cycle for CLIM, CO2, and CLIM_CO2 simulations. See color version of this figure at back of this issue.

[30] El Niño events are characterized by warmer and drier conditions in the tropics, while the climate during La Niña is generally wetter and cooler. Isoprenoid emissions depend highly on temperature and PAR (in the case of isoprene) and are thus likely to depend on the temperature and cloudiness variations associated with ENSO. To our knowledge, there is no long-term measurement of isoprenoid emissions in the tropics so that the relationship with ENSO cannot be tested. There is, however, anecdotal evidence from *Kesselmeier et al.* [2002b] on a forest site in the Amazon basin showing that emissions are higher at the end of the dry season and lower at the end of the wet season. During El Niño the wet season is drier and warmer in the Amazon basin and during La Niña both the wet and dry seasons are cooler [*Foley et al.*, 2002]. It seems, thus, logical that emissions are higher during El Niño and lower during La Niña. The effect of ENSO variability is also seen on the global NPP (Figure 5c), with reduced and increased assimilation of carbon during El Niño years and La Niña years, respectively. This behavior is similar to other models [*McGuire et al.*, 2001] and is coherent with results from inverse models applied to atmospheric CO_2 measurements [*Bousquet et al.*, 2000].

[31] An analysis of the impact of combined and isolated effect of climate variability and atmospheric CO_2 changes on individual biomes shows that they differ in their magnitude of interannual variation (Figure 6). Biome-wise standard deviations about the annual mean emissions for the three simulations clearly indicate that the emissions for CLIM and CLIM_CO2 simulations have the highest variability as compared to that for CO2 simulation, suggesting that the interannual variability is mostly driven by climate variations. For most biomes, the interannual variation in isoprenoid emissions for CLIM_CO2 is slightly higher than that for CLIM, indicating that CO_2 fertilization enhances the amplitude of variability (consistent with the observation made earlier). The year-to-year variations in emissions are highest for biomes that are significant isoprenoid emitters, for example, tropical forests, and temperate forests.

[32] Tropical ecosystems (tropical evergreen and deciduous forests, and savanna) account for approximately 70% of the estimated global isoprene emissions and their interannual deviations for both CLIM and CLIM_CO2 simulations are almost twice that of northern ecosystems. These variations in isoprene emissions for tropical ecosystems are largely driven by changes in annual rainfall patterns that impact cloud cover and vegetation cover. In the northern ecosystems (temperate and boreal forests), variability in isoprene emissions is mostly driven by interannual temperature fluctuations. For monoterpene fluxes, the model predicted interannual variability is not dominant in any one ecosystem. Interannual variability in the tropical ecosystems is comparable to that in northern ecosystems. Variation in monoterpene emissions is mainly driven by year-to-year changes in temperature since the modeled emissions are dependent on only one climatic factor, i.e., temperature. Therefore, given that temperatures are fairly constant in the tropics, the fluctuations in monoterpene emissions in tropical ecosystems are rather small.

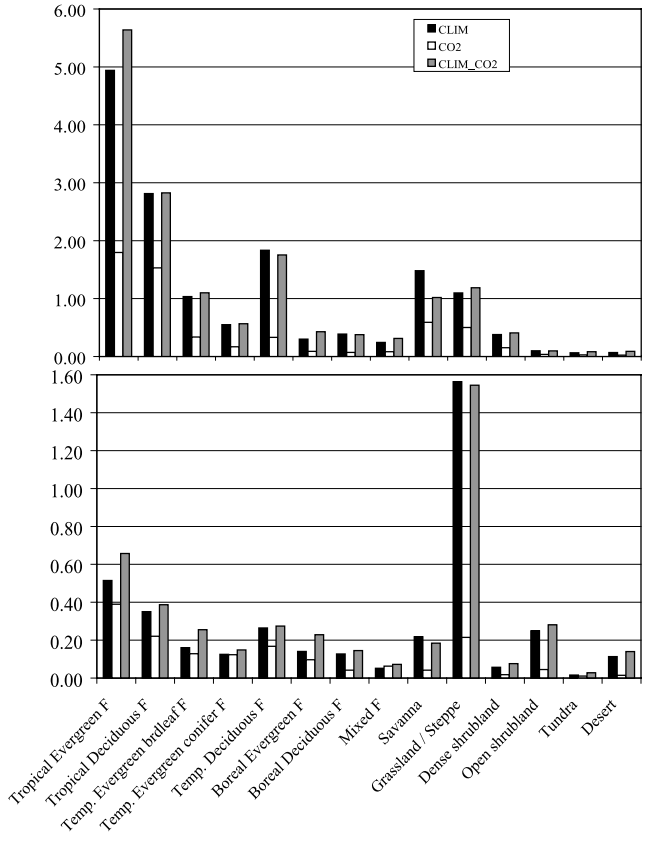

Figure 6. Interannual variations in (top) isoprene and (bottom) monoterpene emissions expressed as standard deviation for IBIS biomes for CLIM, CO2, and CLIM_CO2 simulations.

4. Conclusions and Discussion

[33] We incorporated a surface emissions module within the framework of a dynamic vegetation model, IBIS, to simulate biogenic isoprenoid emissions as a component of the climate-vegetation dynamics, and used this model to assess the sensitivity of global biogenic isoprenoid emissions to combined and isolated variations in climate and atmospheric CO_2 concentration during the period 1971 to 1990. Our model results showed that isoprenoid emissions are extremely sensitive to variations in climatic variables, particularly, temperature and precipitation. Increasing atmospheric CO_2 concentration enhanced the amplitude of interannual variability and induced an increasing trend in isoprenoid emissions as a result of CO_2 fertilization during the period 1971–1990. The combined variations in climate and atmospheric CO_2 from 1971 to 1990 caused significant seasonal (17–25%) and interannual (2–4%) variability in the simulated global isoprenoid fluxes with an increasing trend during this time period. The interannual variability was largely related to the ENSO variability; El Niño years resulting in higher than average emissions and La Niña years in lower than average. The tropical ecosystems accounted for most of the interannual variations in the simulated isoprene emissions, while no dominant ecosystem contributed to the variability in monoterpene emissions in our model simulations.

[34] The isoprenoid emission rates simulated by IBIS are based on the current understanding of the large-scale patterns in emissions for various ecosystems. The predicted spatial and temporal distributions of global emissions closely follow climate patterns and vegetation distribution, and are generally in agreement with previous model estimates. We, however, note that uncertainties associated with modeled emission estimates range from a factor of three to five [G95] because of the large variability among plant species within vegetation types. Biogenic surface fluxes in general, and specifically isoprene, are vegetation species dependant. Small changes in vegetation species abundance (not accounted for in climate-ecosystem models) can yield large changes in biogenic emissions in certain cases. Changes in temperature and moisture and changes in vegetation leaf biomass might then be less significant than changes in the abundance of specific vegetation species with respect to their impacts on BVOC emissions. Therefore climate-ecosystem models need to include species-specific plant succession to model accurately the changes in BVOC emissions. Furthermore, emission algorithms that simulate the biochemical pathway of BVOC synthesis in plants can better explain the influence of increasing atmospheric CO_2 on emission capacity of plants [*Rosenstiel et al.*, 2003].

[35] In addition, human land cover changes that may further reduce global isoprenoid emissions [*Kesselmeier and Staudt*, 1999] have not been included in this study. Therefore our emission estimates should be interpreted cautiously.

[36] The long-term climate variability in global isoprenoid emissions may be investigated using satellite observations. Recently, *Abbot et al.* [2003] investigated the seasonal and interannual variability of North American isoprene emissions using satellite observations of formaldehyde (HCHO). They observed that the interannual variability in HCHO over the southeastern United States roughly follows the surface air temperature and is consistent with the temperature dependence of isoprene emissions. Our results for isoprene variability in the temperate forests over the United States are consistent with these observations. Therefore long-term satellite measurements have the potential to provide an estimate of the variability in global isoprenoid emissions and can be used for refining global emission models such as described in this study.

[37] The interannual variability in NPP of terrestrial ecosystems to fluctuations in climate and atmospheric CO_2 from 1971 to 1990 is estimated to be 3.4%. This estimate is comparable to a recent estimate of 2.1% by *Cao et al.* [2002] for a 17-year period (1981–1998). As predicted by IBIS, the interannual variability in isoprenoid emissions is comparable to the variability in the NPP of terrestrial ecosystems due to changes in climate and atmospheric CO2, implying their importance in understanding future changes in the global carbon cycle. Although carbon emitted as isoprenoids accounts for approximately 1.0% of the global NPP simulated by IBIS, the predicted year to year variations in emissions are expected to contribute significantly to the net ecosystem carbon flux and therefore global carbon budget [*Guenther*, 2002, *Kesselmeier et al.*, 2002a].

[38] The sensitivity of isoprenoid emissions to climate variations and atmospheric CO_2 will have implications on local to regional air quality. Warmer and drier years with higher isoprenoid emissions will cause increased levels of tropospheric ozone resulting in health impacts. Therefore appropriate air pollution control strategies that take into account the sensitivity of BVOC emissions to climate change are required.

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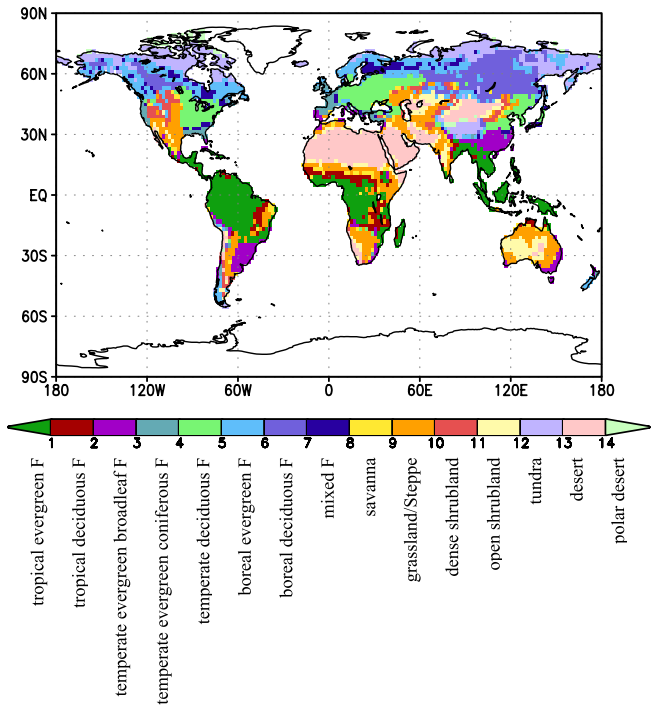

Figure 2. Distribution of potential vegetation ecosystems simulated by IBIS driven by 1961–1990 mean CRU05 climate (simulation CON).

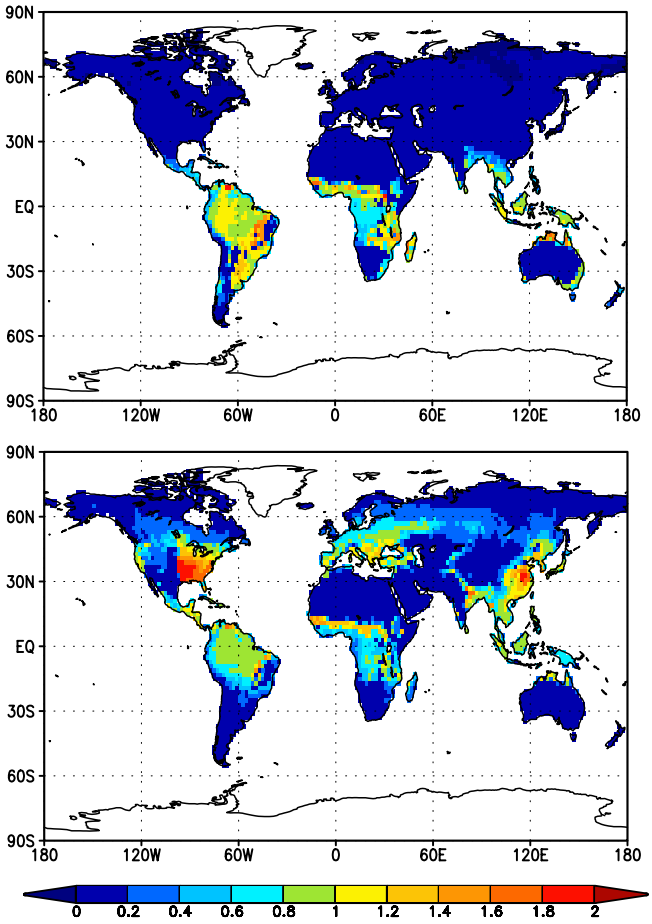

Figure 3. Global distribution of isoprene emission rates (g C m^{-2} $month^{-1}$) simulated by IBIS driven by the 1961–1990 mean CRU05 climate for (top) January and (bottom) July (simulation CON).

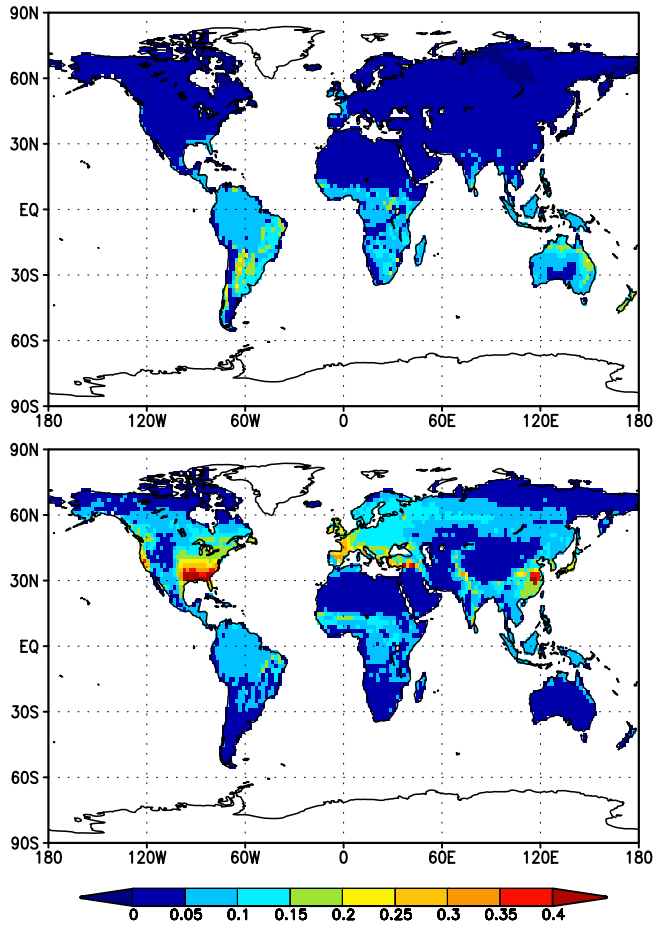

Figure 4. Global distribution of monoterpene emission rates (g C m^{-2} $month^{-1}$) simulated by IBIS driven by the 1961–1990 mean CRU05 climate for (top) January and (bottom) July.

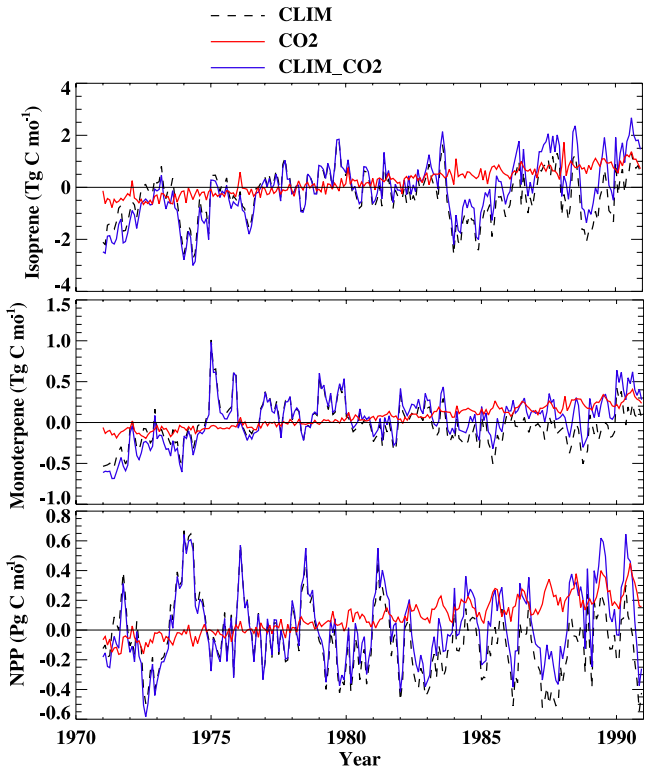

Figure 5. The monthly anomalies of global (top) isoprene and (middle) monoterpene emissions and (bottom) net primary productivity calculated as deviations from the average seasonal cycle for CLIM, CO2, and CLIM_CO2 simulations.