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A biogenic volatile organic compounds emission inventory for Yunnan Province

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Abstract: The first detailed inventory for volatile organic compounds(VOC) emissions from vegetation over Yunnan Province, China was presented. The spatially and temporally resolved inventory was developed based on a geographic information system(GIS), remote sensing(RS) data and field measurement data, such as digitized land-use data, normalized difference vegetation index(NDVI) and temperature data from direct real-time measurement. The inventory has a spatial resolution of 5 km × 5 km and a time resolution of 1 h. Urban, agriculture, and natural land-use distributions in Yunnan Province were combined with biomass factors for each land-use category to produce a spatially resolved biomass inventory. A biogenic emission inventory was developed by combining the biomass inventory with hourly emission rates for tree, shrub and ground cover species of the study area. Correcting for environmental factors, including light intensity and temperature, a value of 1.1×10^{12} gC for total annual biogenic VOC emissions from Yunnan Province, including 6.1×10^{11} gC for isoprene, 2.1×10^{11} gC for monoterpenes, and 2.6×10^{11} gC for OVOC was obtained. The highest VOC emissions occurred in the northwestern, southwestern and north region of Yunnan Province. Some uncertainties were also discussed in this study.

Keywords: biogenic VOC; isoprene; monoterpene; emissions inventory; Yunnan Province

Introduction

Volatile organic compounds(VOC) are very important to the chemical composition of ambient atmosphere. Ozone is formed through the photochemical reactions of VOC of both anthropogenic and biogenic origin with oxides of nitrogen (NOx), and development of effective air quality control strategies within urban areas requires an accurate determination of the emission inventories of both of these precursors(Benjamin, 1997).

To assess the impact of reactive VOC on local, regional and global ozone formation and its possible impact on the annual temperature increase, accurate estimates of biogenic VOC emissions are necessary. The total inventory of VOC being emitted into the atmosphere from anthropogenic sources has been understood especially from mobile sources, however, the inventory of biogenic VOC emissions from vegetation is not well understood. Although the production and emission of biogenic VOC from vegetation has been recognized since the early 1960s(Went, 1960; Rasmussen, 1972), the approximately magnitude of these emissions was not characterized until studies(Zimmerman, 1979; Winer, 1983; Chameides, 1988; Pierce, 1990; Lamb, 1993; Geron, 1995) demonstrated that biogenic hydrocarbons can, in many cases, be a significant contribution to the overall VOC inventory in both rural and urban areas (Benjamin, 1997).

In the past several years, reports on the emission pattern and quality of VOC emission from plant species have increased. Guenther *et al*.(Guenther, 1995) demonstrated that the biogenic emissions of VOC accounted for more than 90% global VOC emissions and forests are the main source of biogenic emission of 1150 Tg/a. However, such reports in China are limited(Zhang, 2000). We have investigated VOC emissions from plants in north China since the early 1990s (Li, 1994; Bai, 1994; 1995), however study on south China, especially tropical or subtropical regions in China has never conducted before. In this study, the study site is Yunnan Province, China. Situated on the Yunnan-Guizhou Plateau, Yunnan Province, China, covers an area of 380000 km^2(latitude 21—29°N, longitude 97.5—106°E). Within a tropical-subtropical area, the Province has its unique climate character. Considering the special geographical distribution, unique climate character and large areas of vegetations in Yunnan Province, the study on the biogenic VOC emissions in Yunnan should be of great importance to the atmospheric environment in this region. In this study, with the biomass inventory, data of normalized emission factors, temperature and photosynthetic active radiation(PAR), a spatially and temporally resolved inventory of biogenic VOC emissions in Yunnan Province has been developed. And the results of this study will be the potential implications for oxidant modeling and for NOx and VOC controls in Yunnan Province. The results will also make us better understand the role of biogenic VOC in regional tropospheric chemistry.

1 Methodology

1.1 Introduction of the methodology

The specific methodology used in this study is similar to that described in previously(Wang, 2003) and is summarized here. In present study, a simplified modeling was used to integrate a variety of land-use, leaf biomass, species emission factor, temperature, and light intensity database to produce a spatially and temporally resolved biogenic VOC emission inventory of Yunnan Province. The biogenic VOC emissions of a particular day or month could be estimated. The annual emissions can be calculated by integrating the results of the twelve monthly emissions together.

1.2 Description of the algorithm

We have estimated biogenic emissions of VOC only from plant foliage, since VOC emissions from other sources are very uncertain but probably represent less than a few percent of total emissions(Guenther, 1995; Zimmerman, 1979). We have grouped biogenic VOC into three categories: isoprene, monoterpenes, and other VOC(OVOC). All data sets have been merged into a common grid system with a resolution of 1 km × 1 km. The daily total emission estimated temperature and PAR data(24 h) is extrapolated to a monthly estimate. Considering three categories of VOC, we have different algorithms: CHL algorithm for isoprene since isoprene is temperature and light dependent, DST algorithm for monoterpenes and OVOC since monoterpenes emissions are

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dependent only on temperature and we assume that OVOC emissions are dependent only on temperature too. The two algorithms are described in detail in the following sections.

1.2.1 CHL algorithm

Isoprene emissions were estimated using the Global Biosphere Emissions and International System (GLOBEIS) (Guenther, 1999). GLOBEIS is a flexible modeling framework that estimates foliar emissions as

$$\text{Emission}[E] = [\varepsilon] \times [D_p\ D_f] \times [\gamma_P \gamma_T \gamma_A] \times [\rho]. \quad (1)$$

Where ε is a landscape average emission capacity; D_p is the annual peak foliar density; D_f is the fraction of foliage present at a particular time of a year; the emission activity factors γ_P, γ_T and γ_A account for the influence of PAR, temperature, and leaf age, respectively, and ρ is an escape efficiency that represents the fraction of the isoprene emitted by the canopy that is released into the above canopy atmosphere. For some particular reasons such as some data shortage of leaf density D_p and D_f, we neglect the influence of leaf age($\gamma_A = 1$) and simplify γ_P and γ_T with a simple canopy model. And we assume that the escape efficiency $[\rho]$ is 0.95. Following the recommendations of Guenther *et al*. (Guenther, 1993), we estimate the influence of light and temperature on isoprene emission as $\gamma_P \times \gamma_T$, where light dependence is defined by

$$\gamma_P = (\alpha C_L Q)/(1 + \alpha^2 Q^2)^{1/2}. \quad (2)$$

Where Q is the flux of PAR (μmol/($m^2 \cdot s$), α = 0.0027 and C_L = 1.006 are empirical coefficients. Temperature dependence is described by

$$\gamma_T = \exp[C_{T1}(T - Ts)/RTsT] / \{1 + \exp[C_{T2}(T - T_M)/R\,Ts\,T]\}. \quad (3)$$

Where T is the leaf temperature(K), Ts is the leaf temperature at a standard condition(e.g., 303 K), R is a gas constant(8.314 J/(K·mol)), and C_{T1} (95000 J/mol), C_{T2} (230000 J/mol), and T_M (314 K) are empirical coefficients.

The algorithm in our present study is also simpler than that of Guenther *et al*. (Guenther, 2000). We assign that the hourly average temperature of Yunnan represents the hourly leaf temperature of all vegetations in Yunnan. And we assign the PAR of Kunming represents the hourly PAR of all plants in Yunnan. Moreover, the result with adopting the new and complicated algorithm mentioned by Guenther *et al*. (Guenther, 2000) is not very distinctly better because regions where over 80% of the difference is due to the species or land-cover estimates.

1.2.2 DST algorithm

$$\text{Emission}[E] = [\varepsilon] \times [D_p\ D_f] \times [\gamma_T] \times [\rho]. \quad (4)$$

The variations in Equation (4) are the same as those in Equation (1). Since monoterpene emissions are only dependent on the influence of temperature, we describe the relationship between temperature and monoterpene emission rate as

$$Y_t = \exp[\beta \times (T - Ts)]. \quad (5)$$

Where $\beta(0.09\ K^{-1})$ is an empirical coefficients, T is the leaf temperature(K), and Ts is the leaf temperature at a standard condition(e.g., 303 K).

2 Description of the input data

2.1 Land-use database

We characterized Yunnan Province land-cover distributions using a land-cover distribution map (The vegetation map of China, 1:4000000, resolution 4 km). Land-cover characteristics were estimated using plant species composition data compiled on a county scale for Yunnan Province and then distributed spatially with a 5 km × 5 km resolution(190 × 190 grid cells) using land-cover distribution map and the software PC ArcInfo3.5. In the 1:400000 land-use distribution map, the forests of Yunnan Province were divided into 28 different types, including 10 types of coniferous forests, 4 types of deciduous forests, 5 types of shrub, 3 types of grassland and 5 types of fruit trees and crop (Table 1). The value of the area for different vegetation types in each grid can be obtained and used as input data for the next step of our estimation.

2.2 Biomass database

The biomass database refers to the foliar density of each type of the plants. The value of annual peak foliar density (D_p) can be estimated by direct measurement. The value of the fraction of foliage present at a particular time of a year (D_f) derives from the remote sensing data. The annual peak foliar densityf D_p for the main types vegetation in Yunnan Province were derived from previous study (Hu, 2000; Wang, 2001). The ratio of the foliage D_f for typical vegetation of Yunnan Province present at a specific time of year to the foliage during the year was estimated by using the monthly normalized difference vegetation index(*NDVI*) data derived from remote sensing (NOAA 14th Satellite). The monthly average foliar density(D_m) of each type of the plants can be estimated in regard to the data of D_p and D_f. The brief method is described in the following section. The vegetation index, global vegetation index(*GVI*) used in our analysis is directly related to *NDVI* as *GVI* = 100 × (1 + *NDVI*)(Guenther, 1995). We estimated the monthly average foliar density(D_m) in each grid cell using equations similar to those used by present study (Guenther, 1995). We assumed that D_m is negligible when the monthly average *GVI* (G) is less than a set amount(G_2),

$$D_m = 0 \qquad G < G_2, \quad (6)$$

and increases exponentially with higher *GVI*,

$$D_m = D_p\{\exp[\ln(2)((G - G_2)/(G_{max} - G_2))]\} \qquad G > G_2, \quad (7)$$

where G_{max} is the maximum monthly average *GVI* estimate during the year. We have set G_2, the *GVI* at which foliage is negligible, to 110 for wooded areas and 102 for all other ecosystem types(Guenther, 1995).

2.3 Species emission factor database

Having obtained biomass distribution, we complied a database of isoprene and monoterpene emission rate factors for the 28 kinds of vegetation categories in the study area. Emission rate factors were determined either from field measurement, for those vegetation categories which were directly measured, or were assigned based on the taxonomic relationships or vegetation class for the plants which had never been experimentally measured. Of the 28 vegetation categories emission rate factors used in the present study, 3 were measured directly(Klinger, 2002). Of the remaining 25 vegetation categories, 3 were assigned emission rates based on previous study (Wang, 2001), and the remaining vegetation categories derived from previous study (Hu, 2000). We assume that the emission rate factor of other VOC is 1.5 μgC/(g·h). Calculating with the value of D_p for these vegetation categories. Then we obtained the database of isoprene and monoterpene emission rate factors(μgC/(g·h)) of 28 vegetation categories in Yunnan Province(Table 1).

Table 1 The isoprene and monoterpene emission rate factors of the 28 vegetation types in Yunnan Province

Vegetation types	D_p, g/m^2	Isoprene, μgC/(g·h)	Monoterpenes, μgC/(g·h)	OVOC, μgC/(g·h)	References
Pinus armandii	670	0	0.39	1.5	Klinger, 2002
Pinus yunnanensis and *Pinus kesiya* var. *langbianensis*	450	1	3	1.5	Wang, 2001
Subtropical and tropical *pinus* forests	1410	0.1	3	1.5	Wang, 2001
Tsuga, *Abies* and *Picea* forest	1625	1	3	1.5	Wang, 2001
Pinus Koraiensis forest	1380	60	0.2	1.5	Wang, 2001
Ulmus and *Platycarya* forest	285	0.1	0.2	1.5	Wang, 2001
Quercus and *Tsuga deciduous* forest	710	60	0.2	1.5	Wang, 2001
Castanopsis and *Pasania* mixed forest	710	34	0.2	1.5	Wang, 2001
Castanopsis, *Cinnamomum campora* and *Schima superba*	860	34	0.2	1.5	Wang, 2001
Tropical *Castanopsis*, *Cinnamomum Campora* and *Thwaceae* mixed forest	510	34	0.65	1.5	Wang, 2001
Quercus aquifolioides	615	34	0.2	1.5	Wang, 2001
Limestone monsoon forest	515	34	0.65	1.5	Wang, 2001
Lateritic soil monsoon forest	440	34	0.65	1.5	Wang, 2001
Tropical rainforest	1325	34	0.65	1.5	Wang, 2001
Rhododentron and *Vaccinium*	210	0	0	1.5	Klinger, 2002
Melastoma candidum shrub	255	8	0.65	1.5	Wang, 2001
Platycarya strobilacea, *Zanthoxylum Planispinum* and *Rosa* shrub	425	8	0.65	1.5	Wang, 2001
Ficus, *Alchornea*, *Boehmeria*, *Micromelum integerrimum* shrub	425	8	0.65	1.5	Wang, 2001
Rhododentron	315	0	0	1.5	Klinger, 2002
Dasiphora glabra var. *veitchii* shrub	455	6	0.2	1.5	Wang, 2001
Heteropogon contortus, *Cymbopogon Citrates* grassland	105.2	0.5	0.2	1.5	Hu, 2000
Herb, *Kobresia*, weed meadow	105.2	0.5	0.2	1.5	Hu, 2000
Kobresia meadow	105.2	0.5	0.2	1.5	Hu, 2000
Crop and fruit Ⅰ	800	0.1	0.1	1.5	Wang, 2001
Crop and fruit Ⅱ	800	0.1	0.1	1.5	Wang, 2001
Crop and fruit Ⅲ	800	0.1	0.1	1.5	Wang, 2001
Crop and fruit Ⅳ	1000	0.1	0.1	1.5	Wang, 2001
Crop and fruit Ⅴ	1000	0.1	0.1	1.5	Wang, 2001

2.4 Correction of the emission rate factors for environmental factors

Given the recognized dependence of biogenic VOC emissions on environmental factors (Guenther, 1995), most important temperature and light intensity in the present study, emission factors were corrected on a diurnal and monthly basis for variations in these two factors. Here is the brief description.

2.4.1 Temperature database

The temperature database is applied to the correction of isoprene, monoterpenes and OVOC emissions. The temperature data used in our present study derived from the direct measurement by NCEP (National Center for Environmental Prediction, NCEP). The temperature measurement was taken every six hours. We assumed the hourly temperature decreased or increased with a steady speed within the six hours. Then 24 hourly temperature data can be obtained for everyday of a year.

2.4.2 Light intensity database

Due to the absence of data sources of PAR, we calculated the PAR above Kunming (102.7°E, 25.07°N) using the correlation between the solar zenith angle and the solar radiation (Equation 9). These data were higher than the measured PAR since we assumed that it was sunny in Kunming throughout a year.

$$A = a \times \exp(-b \times ((1+c)/(\cos Z \times \cos Z + c))^{1/2}). \quad (8)$$

Where A is PAR (photons cm^2/s), Z is the solar zenith angle in Kunming, a, b and c are empirical coefficients.

3 Results and discussion

3.1 VOC emission estimates for Yunnan Province

Biogenic emissions of three kinds of VOC in Yunnan Province were computed using the above model, parameterized and modified using the model input values of the above database of biomass, emission rate factors, temperature and PAR. The model results provided the emissions for a particular day, a particular month or the year of 2002. These results gave annual VOC emissions for Yunnan Province of 6.1×10^{11} gC as isoprene (57%), 2.1×10^{11} gC as monoterpenes (19%), and 2.6×10^{11} gC as OVOCs (24%). Model results of VOC monthly and annual emissions from Yunnan Province are given in Table 2.

Table 2 Estimation of biogenic VOC emissions in Yunnan Province ($\times 10^9$gC)

	Isoprene	Monoterpenes	OVOC	Total VOC
Jan.	13.5	5.2	7.9	26.6
Feb.	12.5	3.5	6.0	22.0
Mar.	37.9	9.7	14.8	62.5
Apr.	47.6	9.7	15.5	72.8
May	17.4	4.9	8.3	30.5
Jun.	88.0	28.2	35.4	152
Jul.	80.9	30.6	36.1	148
Aug.	96.9	34.3	41.0	172
Sep.	89.7	28.2	35.2	153
Oct.	60.2	22.8	28.3	111
Nov.	35.9	16.8	19.8	72.5
Dec.	26.1	11.4	14.2	51.7
Annual.	607	205	263	1074
Annual percentage, %	57	19	24	100

Compared with the biogenic VOC emissions from Yunnan Province in Klinger *et al*. (Klinger, 2002), the isoprene annual emissions of 6.1×10^{11} gC found here are higher than that estimated by Klinger *et al*. (Klinger, 2002) of 3.8×10^{11} gC (Table 2). And the monoterpene annual emissions of 2.0×10^{11} gC found here are lower than that estimated by Klinger *et al*. (2002) of 2.9×10^{11} gC. The OVOC annual emissions of 2.6×10^{11} gC found here are also lower than that estimated by Klinger *et al*. (2002) of 7.5×10^{11} gC. The total VOC emissions estimated by this study 1.1×10^{12} gC is lower than the result of 1.4×10^{12} gC estimated by Klinger *et al*. (2002), this may be ascribed to the differences in model input values such as emission factors, biomass, vegetation composition, temperature and PAR. Considering the model we used is also different from Klinger *et al*. (2002), the model results here are similar to Klinger *et al*. (2002) in some cases.

The results found here were also compared with the model results of Guenther *et al*. (Guenther, 1995). The emissions from Yunnan Province were calculated by the following way: $E_B = E_C \times A_B / A_C$, where E_B is the emission of Yunnan Province, E_C is the emission of China, A_B is the vegetation area of Yunnan Province (368935 km^2), and A_C is the vegetation area of China (7729400 km^2). The results calculated in this way gave us the annual biogenic VOC emissions from Yunnan Province of 7.2×10^{11} gC as isoprene, 2.1×10^{11} gC as monoterpenes, and 4.3×10^{11} gC as OVOC. These results are also higher than our results.

This discrepancy between our results and those of Klinger *et al*. and Guenther *et al*. is mainly due to the land-cover data we used is very different. Guenther *et al*. (Guenther, 2000) reported regions where over 80% of the difference is due to the species or land-cover estimates. The land-cover should be the key factor that made these emission differences.

3.2 Temporal and spatial characteristics of VOC emissions

The model results in this study showed that the monthly emissions of Yunnan Province are very different (Table 2 and Fig.1). Table 2 shows that the isoprene emission in February is very low. Considering isoprene emissions are dependent on both temperature and light intensity, this result should be ascribed to the low temperature, the less sunlight, and the less biomass of leaves of deciduous trees in Yunnan Province in February, which are high isoprene emission sources. So in February, the isoprene emission from vegetation of Yunnan Province hit its low point at 1.3×10^{10} gC. Accordingly, in August, when temperature is high, sunlight is strong enough, and the foliar biomass is the largest, the isoprene emission hit its high point at 9.7×10^{10} gC. The isoprene emissions estimated here in April and October fluctuated between this maximum (9.7×10^{10} gC) and minimum (1.3×10^{10} gC). The same pattern happened on the emissions of monoterpenes. The monoterpene emissions in April (9.7×10^{9} gC) and October (2.3×10^{10} gC) fluctuated between this maximum (3.1×10^{10} gC) in July and minimum (3.5×10^{9} gC) in February. The same pattern also happened on the emissions of OVOC. The OVOC emissions in April (1.6×10^{10} gC) and October (2.8×10^{10} gC) fluctuated between this maximum (4.1×10^{10} g) in August and minimum (6.0×10^{9} g) in February. Since we assumed that the emission rate factor of OVOC for all kinds of vegetation category is 1.5 (μgC/(g·h) without considering the influence of temperature and PAR, this result can be ascribed by the fact that in August the foliar biomass reach the highest.

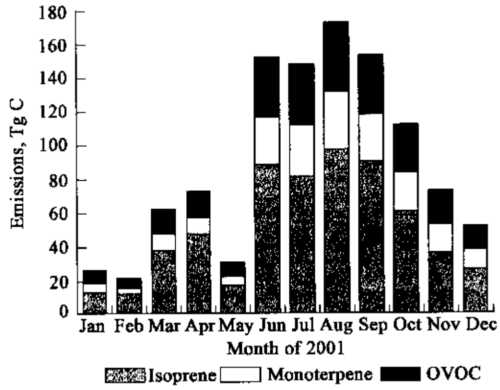

Fig.1 The monthly biogenic VOC emissions in Yunnan Province

Fig.1 described the biogenic VOC emissions of different months. The figure revealed marked differences in VOC emissions of different seasons. The results showed that in summer (June, July and August) the emissions reached its high point and in winter (October, November and December) the emissions reached its low point. The difference of monthly biogenic VOC emissions is very distinct. However the minimum monthly biogenic VOC emissions in Yunnan is more than 20 TgC due to the large areas of evergreen forests in this province of China.

Fig.2a, 2b, 2c and 2d show the distribution across Yunnan Province of modeled annual emissions of isoprene, monoterpenes, OVOC, and total VOC, respectively. These figures revealed marked differences in distributions of VOC from region to region in Yunnan Province. We found here the highest total VOC emissions occurred in the northwestern, southwestern and south region of Yunnan Province, where high VOC emitters of coniferous and deciduous forests are the main vegetation types in these regions. The lowest total VOC emissions occurred in middle and north region of Yunnan Province, where the main vegetation types are low VOC emitters of shrubs and grassland. In regard to isoprene, the highest emissions occurred in the southwestern and south region of Yunnan, where there are large areas of tropical rainforests and subtropical deciduous forests. Since in the northwestern region of Yunnan the main vegetation types are coniferous forests (*Pinus*, *Tsuga* and *Abies* etc.), which are mainly emitting monoterpenes, the isoprene emissions in this region are very low and monoterpene emissions are very high. So the highest monoterpene emissions occurred in the northwestern region of Yunnan, followed by the southwestern, south and southeastern region of Yunnan. The highest other VOC emissions occurred in the northwestern and southwestern region of Yunnan, where there are vegetation types with large biomass, since the emission rates of other VOC for all vegetation types are assigned to be 1.5 μgC/(g·h). In a word, the high VOC emissions occurred in three main areas in Yunnan, including the northwestern region, the southwestern region and the south region.

3.3 Biogenic VOC emissions from five different vegetation categories in Yunnan

Table 3, Table 4 and Fig.3 show the contribution to the biogenic VOC emissions of five vegetation categories in

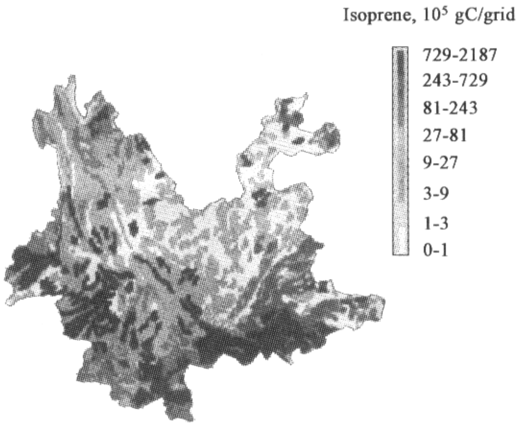

Fig.2a Spatial distribution of biogenic isoprene emissions in Yunnan Province for the year 2001

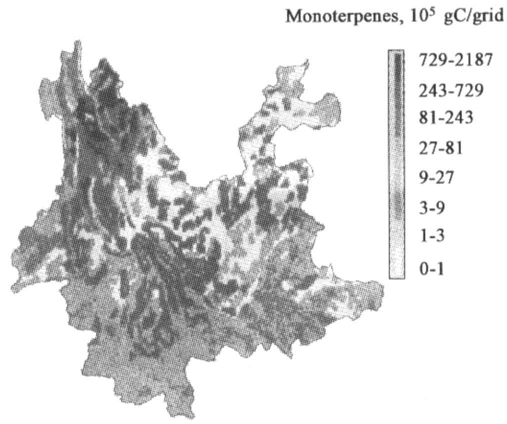

Fig.2b Spatial distribution of biogenic monoterpene emissions in Yunnan Province for the year of 2001

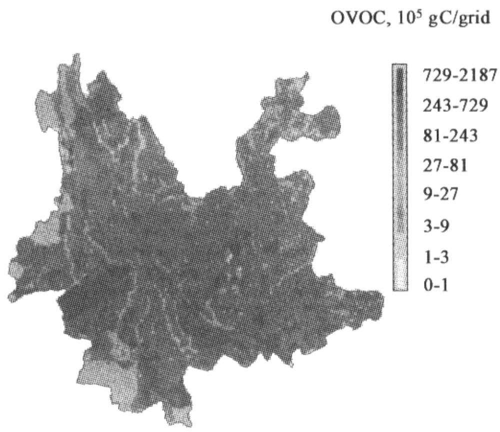

Fig.2c Spatial distribution of biogenic OVOC emissions in Yunnan Province for the year of 2001

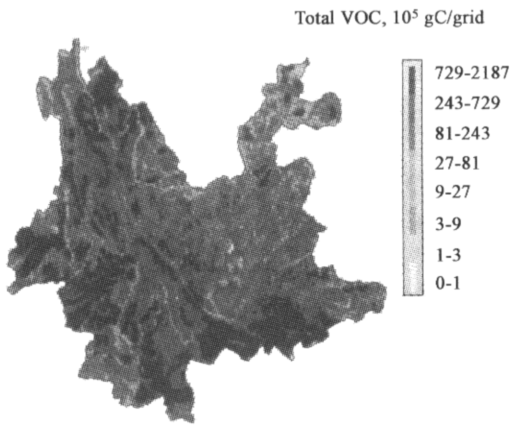

Fig.2d Spatial distribution of biogenic total VOC emissions in Yunnan Provice for the year of 2001

Yunnan Province including coniferous forest, deciduous forest, shrub, grassland and fruit trees and crop. The results gave total VOC emissions of 2.8×10^{11} gC from coniferous forest(26% of the total emissions of all vegetation), 6.4×10^{11} gC from deciduous forest (59%), 1.2×10^{11} gC from shrub(11%), 5.4×10^9 gC from grassland(0.5%) and 3.8×10^{10} gC from fruit trees and crop(3.5%)(Table 3). The percentage of vegetation area for deciduous forest is only 28%, however the VOC emissions from the deciduous forest account for 59% of the total VOC emissions from the five vegetation categories. The percentage of vegetation area for the forests in Yunnan Province is only 49% (deciduous forest + coniferous forest), and the VOC emissions from them account for 70% of the total biogenic VOC emissions. In regard to isoprene, the deciduous forest is the most important emission source(5.5×10^{11} gC and 84.4% of the total annual isoprene emission), followed by shrub (4.2×10^{10} gC and 7.0%), coniferous forest(1.8×10^{10} gC and 3.0%)(Table 4). The grassland and fruit trees and crop hardly emitted isoprene. The coniferous forest is the most important source of monoterpene emissions(1.7×10^{11} gC and 84.4% of the total annual monoterpene emissions), followed by the deciduous forest(1.9×10^{10} gC and 9.2%), shrub (1.0×10^{10} gC and 5.1%), fruit trees and crop(2.3×10^9 gC and 1.1%) (Table 4). The grassland hardly emitted monoterpenes. The coniferous forest is also the most important source of OVOC emissions (8.7×10^{10} gC and 32.9% of the total annual OVOC emissions), followed by the deciduous forest(7.4×10^{10} gC and 28.3%), shrub(6.3×10^{10} gC and 23.8%), fruit trees and crop(3.5×10^{10} gC and 13.1%), and grassland(4.3×10^9 gC and 1.6%).

Table 3 Biogenic VOC emissions from five categories of vegetation types ($\times 10^9$ gC)

Vegetation category	Areas, $\times 10^3$ km^2	Isoprene	Monoterpenes	OVOC	Total VOC
Coniferous forest	103.6	18.3	173.1	86.6	278
Deciduous forest	78.4	545	18.9	74.4	638
Shrub	141.3	42.4	10.4	62.7	116
Grassland	23.7	0.5	0.6	4.3	5.4
Fruit trees and crop	22.0	0.8	2.3	34.5	37.5
Total vegetation	369	607	205	263	1074

3.4 VOC emissions from Yunnan Province

Compared with the biogenic emissions from vegetations in China calculated by Klinger *et al*. (Klinger, 2002), the percentage of the biogenic emissions from vegetations in Yunnan could be calculated. The results are listed in Table 5. Considering the vegetation area of Yunnan accounts for 4.77% of the total vegetation area of China, the percentage of isoprene emissions (14.9%), monoterpene emissions (5.7%) and total VOC emissions(5.19%) of Yunnan are very high. The result of the substantially high isoprene emissions could be ascribed to the large area of rainforests

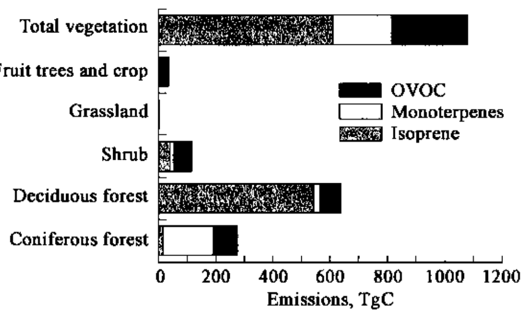

Fig.3 Comparison of emissions from five different cateories

and subtropical deciduous and evergreen broadleaved forests in Yunnan, which are high isoprene emitters. Accordingly, the large area of coniferous forests in Yunnan caused the high monoterpenes emissions.

Table 4 Proportion of the VOC emissions listed by five categories of vegetation types

Vegetation category	Areas[2], %	Isoprene[1], %	Monoterpenes[1], %	OVOC[1], %	Total VOC[2], %
Coniferous forest	28.1	3.0	84.4	32.9	25.9
Deciduous forest	21.2	89.8	9.2	28.3	59.4
Shrub	38.3	7.0	5.1	23.8	10.8
Grassland	6.4	0.1	0.3	1.6	0.5
Fruit trees and crop	6.0	0.1	1.1	13.1	3.5
Total vegetation	100	100	100	100	100

Notes: 1. Proportion of three kinds of VOC emitted by each vegetation category; 2. proportion of the five vegetation categories

Table 5 Comparison of the biogenic VOC emissions over Yunnan and China

	Yunnan[1]	China[2]	Percentage, %
Vegetation area, km^2	368935	7729400	4.77
Isoprene emissions, $\times 10^{11}$ gC	6.1	41	14.9
Monoterpenes emissions, $\times 10^{11}$ gC	2.0	35	5.7
OVOC emissions, $\times 10^{11}$ gC	2.6	130	2.0
Total VOC emissions, $\times 10^{11}$ gC	10.7	206	5.19

Notes: 1. Estimated in this study; 2. estimated by Klinger *et al*. (Klinger, 2002)

In a word, the biogenic VOC emissions in Yunnan Province are very high. This result can be interpreted by the distribution of vegetation types in Yunnan Province. However, earlier studies indicated that release of some VOC from diverse plants was found to be enhanced under SO_2 exposure, anaerobic conditions, or general air pollution conditions(Kesselmeier, 1999). In China, the air pollution of SO_2 and O_3 are very serious in recent years, and it may be responsible for the large VOC emissions form the tree species (Zhang, 2000). Since both the percentage of total VOC from vegetations in Yunnan and the total emissions are high, the investigation of the VOC emissions in Yunnan Province should be put more notice. The investigation of the biogenic VOC emissions in Yunnan from different vegetation succession of the ecosystem could be of great help to the correlation between the VOC emissions and the vegetation evolution. Meanwhile the establishment and the improvement of the correlation between the vegetation evolution and the atmospheric environment could be very helpful to the study of regional and global atmoshperic chemistry.

4 Uncertainties and research priorities

4.1 Uncertainties

By addressing the following five areas of uncertainty, the present study represents an uncertainty over 100%. The major uncertainties of these findings arise from observational errors in plot measurements and from inaccuracies of key assumptions used in the extrapolation.

Due to the absence of the data sources of Td, fshade and fsun, which are indispensable for the canopy model, the algorithm in our present study is simpler than that of Guenther *et al*. (Guenther, 2000) without using the canopy model. This shortcoming will cause higher isoprene emissions.

Uncertainty in the VOC emission potential assigned for a given species can occur from species misidentification, from inaccurate determinations of VOC emission, and from an unrealized discrepancy between assigned versus actual emission potentials. Such a discrepancy can result from assigning unmeasured species of a given genus the same emission potential as the measured species. Error from misidentification is likely quite low as botanical experts were employed for all identifications.

The temperature data used in our model calculation are not distributed in each grids of our map. We assign the average temperature of Yunnan Province to the temperature of everywhere in Yunnan.

The PAR data used in our present study are not derived from direct real-time measurement, however they are derived from our calculation. And we ignore the cloud and other meteorological factors which will affect the light intensity in Yunnan.

The uncertainties of biogenic VOC emissions are also important factors. It is estimated by Guenther (Guenther, 2000) that the uncertainties of biogenic VOC emissions in North America is 300%. The range of uncertainties is large enough that it can change from 50% when we estimate the regional biogenic VOC emissions in summer to 1000% when we estimate the biogenic OVOC emissions. It is very hard to assess the uncertainties exactly because of the lack of data we have (Guenther, 2000).

4.2 Research priorities

Given the uncertainties addressed above, there will be some research priorities to make a more reliable estimation for biogenic VOC over Yunnan Province. Guenther *et al*. (Guenther, 1995) inferred that a more reliable emission estimate for natural VOC (NVOC) should rely on (1) accurate estimates of sources types and densities; (2) accurate VOC emission factors for each source type; (3) an understanding of how changes in drivers such as temperature, light intensity, and moisture influence emissions of NVOC; and (4) estimates of driving variables for each grid and time step. Considering our present data sources and possibilities, some research priorities are addressed below.

4.2.1 Vegetation types and densities

In the present study, the vegetation of Yunnan Province can be grouped into 28 types. Some of them could be grouped into several more accurate parts. The Institute of Botany, the Chinese Academy of Sciences will publish a 1 : 1000000 digital vegetation map of China soon. If we apply the data sources, the estimation of our study will be much better.

4.2.2 VOC emission factors

In the present study, many of the 28 vegetation types emission factors were assigned based on the taxonomic relationships or determined from other literatures. If more species emission rate factors are identified by field measurement, the input data will be more creditable.

4.2.3 More accurate data sources of temperature and

light intensity

In the present study, we assumed the hourly average temperature of Yunnan Province represents the leaf temperature of all vegetations due to the limited date. And the PAR data are not derived from the field measurement. If we compile more data sources of temperature and PAR of many meteorology stations of Yunnan Province, we can improve the precision of our input data.

However, the present study of estimating the biogenic volatile organic compounds emissions is still very important regardless of the large uncertainties. Given the fact that this is the first time to develop an inventory of BVOC for Yunnan Province, the present study will be very helpful for our further research in the atmospheric environment in Yunnan Province.

5 Conclusions

The biogenic VOC emissions inventory in Yunnan Province estimated 1.1×10^{12} gC for the year of 2001, including isoprene emissions at 6.1×10^{11} gC, monoterpene emissions at 2.1×10^{11} gC and other VOC at 2.6×10^{11} gC. Isoprene emissions account for 57% and monoterpene emissions account for 19%. The results found here were lower than the model results of Klinger *et al*. (Klinger, 2002) and Guenther *et al*. (Guenther, 1995), this discrepancy is mainly due to the land-cover data we used were very different. The biogenic VOC emissions in Yunnan Province were very high, and they take an important role in the photochemical process in the ambient atmosphere of Yunnan Province for the high emissions of NOx. The major uncertainties of the findings in this study arise from observational errors in plot measurements and from inaccuracies of key assumptions used in the extrapolation.

References:

Bai Y H, Li J L, Zhang B X *et al*., 1994. The quantitative determination of hydrocarbon emitted from woods and vegetations over Beijing area [J]. Research of Environmental Sciences, 7(2): 49—54.

Bai Y H, Li J G, Liang B S *et al*., 1995. Relative factor of hydrocarbon emission from popular tree[J]. Environmental Chemistry, 14(2): 118—123.

Benjamin M T, Sudol M, Bloch L *et al*., 1996. Low-emitting urban forests: A taxonomic methodology for assigning isoprene and monoterpene emission rates [J]. Atmospheric Environment, 30: 1437—1452.

Benjamin M T, Sudol M, Vorsatz D *et al*., 1997. A spatially and temporally resolved biogenic hydrocarbon emissions inventory for the California south coast air basin[J]. Atmospheric Environment, 31: 3087—3100.

Benjamin M T, Winer A M, 1998. Estimating the ozone-forming potential of urban trees and shrubs[J]. Atmospheric Environment, 32: 53—68.

Chameides W L, Lindsay R W, Richardson J *et al*., 1988. The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study [J]. Science, 241: 1473—1475.

Chen L Z, 1997. Study on the function of temperate forestry eco-system [M]. Beijing: Sciences Press.

Feng Z W, Wang X K, Wu G, 1999. The biomass and productivity of Chinese forestry eco-system[M]. Beijing: Science Press.

Geron C, Guenther A, Pierce T, 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States[J]. Journal of Geophysical Research, 99: 12773—12792.

Geron C D, Pierce T E, Guenther A B, 1995. Reassessment of biogenic organic compound emissions in the Atlanta area[J]. Atmospheric Environment, 29: 1569—1578.

Guenther A, Zimmerman P, Harley P *et al*., 1993. Isoprene and monoterpene emission rate variability: Model evaluation and sensitivity analysis[J]. Journal of Geophysical Research, 98: 12609—12617.

Guenther A, Greenberg J, Harley P *et al*., 1996. Leaf, branch, stand and landscape scale measurements of volatile organic compound fluxes from U.S. woodlands[J]. Tree Physiology, 16: 17—24.

Guenther A, Zimmerman P, Harley P *et al*., 1993. Isoprene and monoterpene emission rate variability: Model evaluation and sensitivity analysis[J]. Journal of Geophysical Research, 98: 12609—12617.

Guenther A, Hewitt C, Erickson D *et al*., 1995. A global model of natural volatile organic compound emissions[J]. Journal of Geophysical Research, 100: 8873—8892.

Guenther A, Baugh B, Brasseur G *et al*., 1999. Isoprene emission estimates and uncertainties for the Central African EXPRESSO study domain[J]. Journal of Geophysical Research, 104: 30625—30639.

Guenther A, Geron C, Pierce T *et al*., 2000. Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America[M]. Atmospheric Environment, 34: 2205—2230.

Hu Y T, 2000. Study on regional air quality and its impact factors[D]. Peking University. Ph.D thesis. 30—50.

Kesselmeier J, Staudt M, 1999. Biogenic volatile organic compounds(VOC): an overview on emission, physiology and ecology[J]. J Atmos Chem, 33: 23—88.

Klinger L F, Li Q J, van Meter A, 2002. Assessment of volatile organic compound emissions from ecosystems of China[J]. Journal of Geophysical Research, 107(D21): 4603—4624.

König G, Brunda M, Puxbanm H *et al*., 1995. Relative contribution of oxygenated hydrocarbons to the total biogenic VOC emissions of selected mid-European agriculture and natural plant species[J]. Atmospheric Environment, 29: 861—874.

Lamb B, Gay D, Westberg H *et al*., 1993. A biogenic hydrocarbon emission inventory for the US using a simple forest canopy model [J]. Atmospheric Environment, 27: 1673—1690.

Li J L, Bai Y H, Hu J X *et al*., 1994. Diurnal variation in the concentration of terpenes and it's emission rate measurement from oil pine [J]. China Environmental Science, 14(3): 165—169.

Pierce T E, Lamb B K, Van Meter A R, 1990. Development of a biogenic emissions inventory system for regional scale air pollution models[C]. Proc. 83rd air waste management association annual meeting. Air and Waste Mange Assoc. Pittsburgh, Penn. 90—94

Rasmussen R A, 1972. What do hydrocarbons from trees contribute to air pollution? [J]. J Air Poll Control Ass, 22: 537.

Simpson D, Winiwarter W, Börjesson G *et al*., 1999. Inventorying emissions from nature in Europe[J]. Journal of Geophysical Research, 104: 8113—8152.

Wang Q G, 2001. Biogenic emissions of VOC and NOx in China and their impacts on tropospheric ozone[J]. Ph.D thesis. Chinese Academy of Sciences. 50—62.

Wang W M *et al*., 1986. The atlas of agricultural and regional planning for Yunnan Province[M]. Beijing: Press of Surveying and Mapping. 65—66

Wang Z H, Bai Y H, Zhang S Y, 2003. A biogenic volatile organic compounds emission inventory for Beijing[J]. Atmospheric Environment, 37: 3771—3782.

Went F W, 1960. Blue hazes in the atmosphere[J]. Nature, 187: 641—643.

Winer A M, Fitz D R, Miller P R, 1983. Investigation of the role of natural hydrocarbons in photochemical smog formation in California Air Resources Board[M]. California: Statewide Air Pollution Research Center, University of California Riverside.

Yu Y X, 1990. Brochure of microorganisms-test in environmental engineering [M]. Beijing: Chinese Environmental Science Press. 353.

Zhang X S, Mu Y J, Song W Z *et al*., 2000. Seasonal variations of isoprene emissions from deciduous trees[J]. Atmospheric Environment, 34: 3027—3032.

Zimmerman P R, 1979. Natural sources of ozone in Houston: natural organics [C]. In: Proc specialty conf on ozone/oxidants—interactions with the total environment. Pittsburgh, PA: Air Pollution Control Association.

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