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Improved land cover and emission factors for modeling biogenic volatile organic compounds emissions from Hong Kong

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ABSTRACT

This paper describes a study of local biogenic volatile organic compounds (BVOC) emissions from the Hong Kong Special Administrative Region (HKSAR). An improved land cover and emission factor database was developed to estimate Hong Kong emissions using MEGAN, a BVOC emission model developed by Guenther et al. (2006). Field surveys of plant species composition and laboratory measurements of emission factors were combined with other data to improve existing land cover and emission factor data. The BVOC emissions from Hong Kong were calculated for 12 consecutive years from 1995 to 2006. For the year 2006, the total annual BVOC emissions were determined to be 12,400 metric tons or 9.82×10^9 g C (BVOC carbon). Isoprene emission accounts for 72%, monoterpene emissions account for 8%, and other VOCs emissions account for the remaining 20%. As expected, seasonal variation results in a higher emission in the summer and a lower emission in the winter, with emission predominantly in day time. A high emission of isoprene occurs for regions, such as Lowest Forest-NT North, dominated by broadleaf trees. The spatial variation of total BVOC is similar to the isoprene spatial variation due to its high contribution. The year to year variability in emissions due to weather was small over the twelve-year period (−1.4%, 2006 to 1995 trendline), but an increasing trend in the annual variation due to an increase in forest land cover can be observed (+7%, 2006 to 1995 trendline). The results of this study demonstrate the importance of accurate land cover inputs for biogenic emission models and indicate that land cover change should be considered for these models.

1. Introduction

Volatile Organic Compounds (VOCs) in the troposphere react photochemically with oxides of nitrogen (NO_x) in the presence of solar radiation to form smog which contains various secondary air pollutants such as ozone and peroxyacetyl nitrate (PAN). This smog causes adverse impact on human health, plants and agricultural products. Atmospheric VOCs come from two sources, anthropogenic and natural sources. Petrochemical plants, motor vehicles, and industrial/commercial use of paints, thinners and dry cleaning solvents are some examples of anthropogenic sources while vegetation (trees, grasses and marshes) is an important source of natural biogenic VOC. These biogenic sources emit a significant amount of VOCs into our atmosphere with a composition, including isoprene and terpenes, which is considerably more reactive than anthropogenic VOCs. Biogenic VOC studies enhance our knowledge of biogenic emissions and the production of secondary air pollutants. They also provide useful inputs for air quality modeling and provide information for the government to develop effective environmental strategies associated with large scale tree planting and urban greening programs.

BVOC emission modeling is a multi-disciplinary research topic, which involves knowledge in botanical science, scientific computing, atmospheric science, and geography. The topic is an important and growing area of research that has been studied and reviewed in the literature by many researchers. Fuentes et al. (2000) reviewed the science of biosynthesis, transport, and chemical transportation of hydrocarbons emitted by the terrestrial biosphere and examined the integration of biogenic hydrocarbon kinetics and atmospheric physics into quantitative modeling systems. Kesselmeier and Staudt (1999) reviewed the knowledge of biogenic emission of some VOCs and discussed biosynthesis, emission inventories, relations between emission and plant physiology and temperature, radiation, and ecophysiological functions. An extended summary of standard emission factors with data related to plant genus and species is included for isoprene and monoterpenes in the paper.

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Hewitt and Street (1992) compiled an extensive database of emissions of non-methane hydrocarbons from plants and Benjamin et al. (1996) describes a methodology for assigning biogenic emission rates based on taxonomic relationships.

Benjamin and Winer (1998) proposed a method for estimating the O_3-forming potential of tree and shrub species due to their BVOC emissions, which acts as a good reference for air quality modelers. Daily isoprene and monoterpene emission rates of individual tree and shrub species are calculated based on their biomass factors, isoprene and monoterpene emission factors. They are then multiplied by the maximum incremental reactivities (MIRs) to arrive at an O_3-forming potential. Careful selection of tree and shrub species of lower ozone-forming potential for tree planting programs could reduce ground-level O_3 formation, especially in urban areas polluted with nitrogen oxides. With the use of an atmospheric chemistry model (CiTTyCAT) Donovan et al. (2005) quantified the effects of trees on urban air quality. The model considers the chemical composition of an air parcel subjected to photochemistry, emission, deposition, and mixing from the free troposphere (Evans et al., 2000; Emmerson et al., 2004).

BVOC emission models are useful tools for estimating BVOC emission inventories and have been applied to many cities in the world. The Global Biogenic Emission Inventory System (GloBEIS) developed by Guenther et al. (1999, 2000) is an example of a model used to estimate biogenic VOC emissions for regulatory modeling. Wang et al. (2003) describes a similar approach that was used to develop a biogenic VOC emission inventory for Beijing. The spatially resolved inventory was developed based on GIS and remote sensing including the use of a normalized difference vegetation index (NDVI). Guenther et al. (1999) used GloBEIS to compute annual emission of isoprene, monoterpenes, and other VOCs from Central Africa. Later, Guenther et al. (2000), using the same model, estimated the emissions of non-methane VOCs, carbon monoxides, and nitrogen oxides from natural sources from North America while Simon et al. (2001) estimated the BVOC emission from a French forest ecosystem. Symeonidis et al. (2008) developed a system for estimating biogenic non-methane VOCs emissions based on the GloBEIS model and used this to estimate the biogenic emissions from the Balkan Peninsula in Europe. Song et al. (2008) compared modeled results from GloBEIS with observed isoprene concentrations from ground and aircraft measurements in southeast Texas and found good agreement for diurnal isoprene patterns.

The Model of Emissions of Gases and Aerosols from Nature (MEGAN), described by Guenther et al. (2006), is a global model with a resolution that is suitable for regional modeling. MEGAN has been applied to many studies including the estimation of emission fluxes and OH reaction potential of BVOCs from a mixed northern hardwood forest. MEGAN has been used to estimate both branch-level emissions of individual tree species and whole-canopy fluxes of isoprene, monoterpenes, and sesquiterpenes at specific locations (e.g. Ortega et al., 2007) and regional to global scale studies (e.g. Heald et al., 2009). Recently, Sakulyanontvittaya et al. (2008) used MEGAN version 2.02 to estimate emissions of BVOCs across the United States with a focus on monoterpenes and sesquiterpenes in particular. Some emission factors are provided in their paper based on recent laboratory measurements. When compared to the Biogenic Emission Inventory System (BEIS 3.0), MEGAN was found to estimate higher isoprene but lower monoterpene emissions for the period between July 2001 and January 2002 (Sakulyanontvittaya et al., 2008).

Recent satellite imaging and remote sensing studies have provided approaches that could be useful in obtaining land cover data for use in BVOC emission modeling. Darvishsefat et al. (2004) conducted a comparison of Spot-5 and Landsat-7 satellite images for mapping a forest area in northern Iran. They concluded that Spot-5 data could be more appropriate than Landsat-7 data for forest mapping and updating for one particular map scale. A national land cover database for the United States was generated by Homer et al. (2007) based on remote sensing from Landsat-5 and Landsat-7 satellite images. Yang et al. (2001) conducted mapping of tropical forest vegetation for the Yunnan province in the southwestern part of China using Landsat TM satellite data. Leff et al. (2004) synthesized satellite-derived land cover data and agricultural census data to produce global data sets of the distribution of 18 major crops across the world. Huete et al. (2006) analyzed Amazon vegetation phenology with Moderate Resolution Imaging Spectroradiometer (MODIS) satellite measurements from 2000 to 2005. The MODIS Enhanced Vegetation Index (EVI) was found to increase by 25% with sunlight during the dry season across Amazon forests, opposite to ecosystem model predictions. This finding suggests there is an incomplete understanding of either ecosystem functioning, the affect of humidity on satellite-derived LAI data, or both.

In 2004, the Environmental Protection Department (EPD) of the HKSAR Government commissioned the University of Hong Kong (HKU) to study the BVOC emissions in Hong Kong. This was the first study to conduct BVOC emission factor and land cover measurements in Hong Kong. In this study, the emission rates of isoprene and monoterpene of thirteen local tree species were determined by an enclosure measurement method (Tsui et al., 2009). BVOC emission estimates were established using the GloBEIS emission model driven by detailed land use, tree distribution and hourly meteorological data. The study was continued by the present team in November 2007 to further investigate the BVOC emissions in Hong Kong using high-resolution satellite images and the improved emission model MEGAN.

The objectives of the study are to adapt the MEGAN model to the Hong Kong environment, and to enhance the modeling of BVOC emissions over previous study by using improved biomass and tree survey data, additional laboratory measurement results, and using satellite images with appropriate resolution. The ultimate aim is to develop a more accurate BVOC emission inventory and assess the major uncertainties.

2. Determination of VOC emission rates of typical plant species

2.1. Laboratory measurement

In the previous study, isoprene emission rates of 13 plant species were determined by a static enclosure measurement approach. For this study, the VOC emission rate measurements were conducted on ten additional plant species, which were identified as potential high VOC emitters by Tsui et al. (2009).

The experiment was divided into two phases: adaptation period and enclosure period. A glass chamber used to enclose the target leaves was housed in a controlled environment chamber. The temperature of the enclosure was maintained with a variation of less than 1 °C. Light was supplied by two white light sources situated on the left and right sides of the enclosure to ensure even irradiation. Light intensity was measured by a photometer, and temperature inside the chamber was monitored by a temperature probe. During the adaptation period, a branch of seedling selected for study was enclosed in the glass chamber for 2–3 h under a standard condition of 30 °C and 1000 PAR for adaptation. That followed the enclosure period during which the seedling was enclosed for 1 h in a continuous flow-through system. A solid-phase microextraction sampler equipped with carboxen/polydimethylsiloxane (CAR/PDMS) fiber (Supelco, MO, US) was inserted

into the glass chamber for sampling BVOC emissions from the plant studied throughout the 1-h enclosure period. Measurement of BVOC emissions of each plant species was conducted in triplicate.

2.2. Sample analysis

BVOC emissions from plants were analyzed with an HP5890 GC–FID (Hewlett Packard Inc, Avondale, PA, US) equipped with a DB5-MS capillary column (Agilent, CA, US) with 30 m length and 0.25 mm i.d. The injection port and detector temperatures were set at 250 °C and 280 °C, respectively. The SPME fiber carrying VOCs sampled from the emissions of the studied plant was desorbed at the injection port for 5 min. Oven temperature was programmed with an initial temperature set at 30 °C and held for 2 min. It was then increased to 70 °C at 10 °C min^{-1}, held for 5 min and increased to 80 °C at 10 °C min^{-1}. Finally, the oven temperature was increased to 200 °C at 25 °C min^{-1}. Nitrogen was used as the carrier gas throughout the measurement.

The SPME-GC system was calibrated using a standard gas mixture prior to analysis (Scientific and Technical Gases Limited, Staffordshire, UK), which was composed of the following 10 major BVOC species commonly emitted by plants: isoprene, methanol, ethanol, acetone, 1,8-cineole, ρ-cymene, D-limonene, linalool, α-pinene, and β-pinene at 10 ppm. The mixture was balanced by nitrogen. The VOC standard was diluted with nitrogen using a dynamic gas calibrator to 5 concentrations: 1 ppm, 0.2 ppm, 0.1 ppm, 0.06 ppm and 0.03 ppm for constructing a 6-point calibration curve. Retention time detected from analysis of the standard gas mixture was used for identification of VOC emissions from plants.

The identities of BVOC species detected from the 10 plant species by GC–FID were confirmed by GC–MS analysis. An HP6890 GC–MS (Hewlett Packard Inc, Avondale, PA, US), was equipped with the same capillary column as the GC–FID used for analyzing BVOC emissions from the 10 studied species. The oven program used for the GC–MS was identical to that used in the GC–FID analysis described above. Other BVOC species emitted from the studied plant species that were not included in the VOC standard mixture were also identified by the GC–MS analysis. However, quantitative analyses for these BVOC species were not possible due to the lack of complementary standards for calibration.

Control experiments were conducted before every enclosure measurement by sampling and analyzing clean air from a zero air generator (Sabio Engineering Inc.) that flowed through the empty glass chamber. Any background emissions detected were deducted from the measurement results.

2.3. Result of laboratory measurement

The BVOC emissions results of the 10 target species are shown in Table 1 and compared with literature values. Since BVOC measurements conducted in the Asia Pacific region are limited, there was no literature value available to compare with 5 of the studied species (i.e. *Baeckea frutescens*, *Lophostemon confertus*, *Cinnamomum parthenoxylon*, *Cratoxylum cochinchinense*, *Litsea rotundifolia*). BVOC emission rates measured in this study were generally comparable to the rates reported by other researchers except *Aporusa dioica* and *Syzygium jambos* for which the literature values are much higher than the laboratory values. The measurement approaches used for the literature values were similar to that of the present study and the reason for the large differences in reported emission rates is not known but possible reasons are discussed below.

For the laboratory measurements conducted for this study, the measured isoprene emission factors for a few plant species were lower than values reported in the literature (e.g. *S. jambos*). This is similar to what was found in a previous study (Tsui et al., 2009). Possible reasons for the discrepancy between the measured and literature emission factors include immature leaves, genetic differences between plants from different regions, and that greenhouse grown plants tend to be exposed to lower than ambient light levels and this results in lower isoprene emission rates. However, it should also be noted that the literature values for *Aporusa* and *Syzygium* listed in Table 1 were extracted from screening studies of Baker et al. (2005) and Klinger et al. (2000) which consisted of one or a few measurements on each species. These studies were intended as an initial screening effort and may not be representative of the average value for a plant species.

In contrast to isoprene, enclosure measurements are more likely to identify a low/negligible monoterpene emitter as a high monoterpene emitter rather than identifying a high monoterpene

Table 1
BVOC emissions of the 10 target species measured by GC–FID and GC–MS.

Plant species	BVOC species emitted	Emission rate (μg BVOC g^{-1} h^{-1})	Other BVOC species detected by GC–MS	Literature value (μg BVOC g^{-1} h^{-1})	Reference
Baeckea frutescens	Isoprene	0.1 ± 0.01	α-Phellandrene	N/A	N/A
	Limonene	1.83 ± 0.11			
Schima superba	Isoprene	0.11 ± 0.07	Nil	0	Baker et al., 2005
	Limonene	0.2 ± 0.03		0	
Lophostemon confertus	Isoprene	0.07 ± 0.01	Nil	N/A	N/A
	Limonene	0.41 ± 0.14			
Cinnamomum parthenoxylon	Isoprene	0.05 ± 0.001	Camphene	N/A	N/A
	Limonene	0.74 ± 0.18	beta-Cymene		
			Camphor		
			Caryophyllene		
Aporusa dioica	Isoprene	0.11 ± 0.005	Nil	3.39	Baker et al., 2005
	Limonene	0.12 ± 0.02		2.26	Baker et al., 2005
Schefflera heptaphylla	Isoprene	0.01 ± 0.005	α-Phellandrene	0	Baker et al., 2005
	α-Pinene	0.11 ± 0.01	β-Phellandrene	0	
	β-Pinene	0.16 ± 0.03	ρ-Cymene	0	
	Limonene	0.14 ± 0.07		0	
Cratoxylum cochinchinense	Isoprene	2.07 ± 0.19	Nil	N/A	N/A
	Limonene	1.04 ± 0.18			
Litsea rotundifolia	Isoprene	0.02 ± 0.002	Nil	N/A	N/A
Syzygium jambos	Isoprene	0.02 ± 0.002	Nil	119	Klinger et al., 2002
	Limonene	0.29 ± 0.05		N/A	N/A
Gordonia axillaris	Nil	N/A	1-Hexanol, 2-ethyl	No BVOC emission detected	Baker et al., 2005

Remark: N/A = Not applicable/no literature value available.

emitter as a low/negligible monoterpene emitter. This is because some plants store monoterpenes in structures that are damaged during the enclosure process. The high literature value for *Schima superba* is an example of a very high value that was likely caused by disturbance. The lower value measured for *S. superba* may also reflect the local genotype and environment and is therefore adopted in the present study.

3. BVOC emission modeling

The MEGAN model was applied for BVOC emission modeling in this study. The following sections describe the model and preparation of the necessary driving variables.

3.1. Model description

The MEGAN model was used to calculate hourly emission rates per grid for 20 chemical species and categories at each grid cell including isoprene, methyl-butenol, myrcene, sabinene, limonene, 3-carene, ocimene, β-pinene, α-pinene, farnesene, β-caryophyllene, methanol, acetone, acetaldehyde, formaldehyde, methane, nitrogen oxides, other monoterpenes, other sesquiterpenes, carbon monoxide and other VOC. The net emission rate of each VOC species (mg compound m^{-2} earth surface h^{-1}) from terrestrial ecosystems into the above-canopy atmosphere at a specific location and time is described by the following equation (Guenther et al., 2006):

$$\text{Emission} = [\varepsilon][\gamma][\rho] \quad (1)$$

3.1.1. Emission factor ε

ε (mg m^{-2} h^{-1}) is an emission factor which represents the emission of a compound into the canopy at a standard condition. This factor is specified by the user at each grid cell for each VOC species based on land cover data and field survey data analysis as described in Sections 3.2 and 3.4, respectively. MEGAN uses a canopy-scale emission factor rather than a leaf-scale factor. The canopy-scale emission factors are based on extrapolation from leaf and branch-scale emission measurements to the canopy-scale level using a canopy environment model as mentioned in Section 3.2.4.

3.1.2. Emission activity factor γ

The emission activity factor γ accounts for emission changes due to deviations from the standard condition (Guenther et al., 2006). It is a product of a set of non-dimensional emission activity factors.

$$\gamma = \gamma_{CE} \cdot \gamma_{age} \cdot \gamma_{SM} \quad (2)$$

where γ_{CE} is the variation in emission due to LAI, light, temperature, humidity and wind conditions; γ_{age} is the variation due to leaf age; and γ_{SM} is the variation due to changes in soil moisture.

Note that for the current study, γ_{CE} is a function of temperature, solar radiation, and LAI. It is computed based on the weather data as described in Section 3.3 and the LAI data as described in Section 3.2.4. γ_{age} is calculated with a leaf age algorithm that assigns different emission activities to new, growing, mature, and old leaves (Guenther et al., 2006; Sakulyanontvittaya et al., 2008). There is observational evidence that moderate (or intermittent) drought can increase the isoprene emission while extended drought will decrease isoprene emissions (Guenther et al., 2006). Most of the species-level emission studies were conducted under normal condition without drought. As Hong Kong did not have any serious drought during the study period, it is reckoned that normal soil moisture existed, which did not impose any significant effect on the BVOC emissions in the present study. Also note that different VOC species (isoprene, monoterpenes, sesquiterpenes) have different temperature- and light-dependence factors and algorithms (Kesselmeier and Staudt, 1999; Sakulyanontvittaya et al., 2008) and this can be represented in MEGAN. The parameterized canopy environment emission activity (PCEEA) algorithm was used (Guenther et al., 2006). As a result, the growth environment temperature is accounted for by using the monthly mean temperature.

Lastly, the ρ in equation (1) is a factor that accounts for the production and loss of emission within plant canopies. This parameter is not modeled in this study and is set to one. This will have little impact on the modeling results as mentioned by Sakulyanontvittaya et al. (2008). The algorithms to compute the factors γ_{CE} and γ_{age} are described in detail by Guenther et al. (2006) and Sakulyanontvittaya et al. (2008).

3.2. Information required for emission factors determination

3.2.1. Land cover data

The habitat map from the HKSAR government report "2006 Terrestrial Habitat Mapping and Ranking Based on Conservation Value" (SDD, 2006) provided the land cover data for the present study. The map is based on remote sensing analysis of two SPOT-5 satellite images, which classifies the Hong Kong land area into 24 habitat classes (Table 2). The map was selected because it was derived from high-resolution satellite images and has been ground-truthed using aerial photos and field surveys.

The use of multiple land cover data was not possible due to the unavailability of continuous data over the past twelve-year period. Fig. 1 shows the adjustment of final results for other years due to temporal change in land cover according to the land cover data of SDU studies (Leung et al., 2008a).

3.2.2. Plant-functional types (PFT)

Among the 24 habitat classes, 10 of them were selected as plant-functional types (PFTs) as follows: Feng Shui Forest; Montane Forest; Lowland Forest; Mixed Shrubland; Shrubby Grassland; Grassland; Plantation/Mixed Forest; Mangrove; Golf Course/Urban

Table 2
Area and percentage distribution of the habitat classes (SDD, 2006).

Category	Area (ha)	Percentage of total area (%)
1 Feng Shui Forest	211	0.19
2 Montane Forest	110	0.10
3 Lowland Forest	12,622	11.29
4 Mixed Shrubland	27,941	25.00
5 Shrubby Grassland	22,305	19.95
6 Grassland	15,440	13.81
7 Plantation/Mixed Forest	926	0.83
8 Mangrove	457	0.41
9 Golf Course/Urban Park	1158	1.04
10 Cultivation	6301	5.64
11 Seagrass Bed	7	0.01
12 Sandy Shore	211	0.19
13 Rural Industrial Storage	1044	0.93
14 Rocky Shore	90.6	0.08
15 Quarry	246	0.22
16 Other Urban	13,936	12.47
17 Natural Watercourse	861	0.77
18 Modified Watercourse	2820	2.52
19 Landfill	303	0.27
20 Intertidal Mudflat	746	0.67
21 Freshwater Brackish Wetland	897	0.80
22 Fishpond/Gei Wai	896	0.80
23 Bare Rock Soil	2030	1.82
24 Artificial Rocky Hard Shoreline	231	0.21

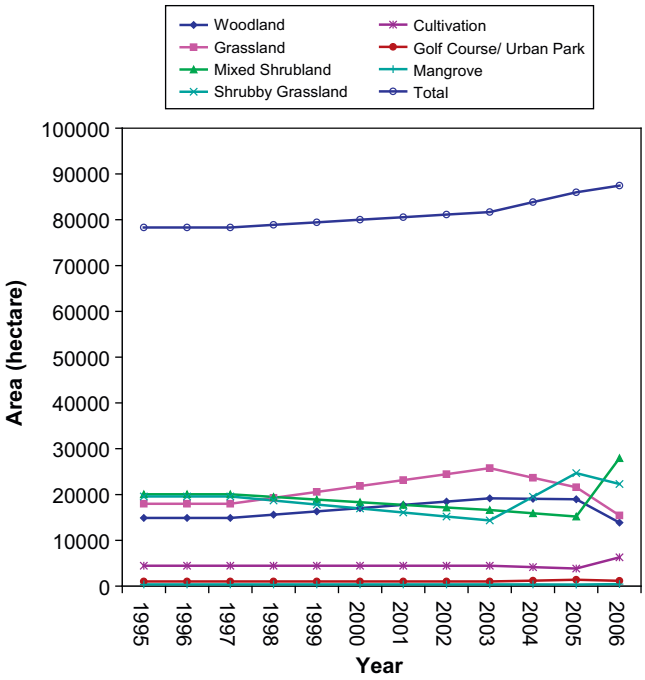

Fig. 1. Area figures (hectare) for adjustment of final results due to temporal changes in land cover.

Park; and Cultivation. These 10 PFTs comprise 78% of the total land area of Hong Kong. The remaining 14 habitat classes were grouped together as "others". They were not considered as PFTs since they are either non-vegetation classes or the contributed area is small, leading to negligible emission contributions.

Table 3
The plant-functional types identified in the present study.

Plant function types
1. Lowland Forest – NT North
2. Lowland Forest – NT North-West
3. Lowland Forest – NT East
4. Lowland Forest – Kowloon
5. Lowland Forest – HK Island
6. Lowland Forest – Islands
7. Mixed Shrubland – NT North
8. Mixed Shrubland – NT North-West
9. Mixed Shrubland – NT East
10. Mixed Shrubland – Kowloon
11. Mixed Shrubland – HK Island
12. Mixed Shrubland – Islands
13. Shrubby Grassland – NT North
14. Shrubby Grassland – NT North-West
15. Shrubby Grassland – NT East
16. Shrubby Grassland – Kowloon
17. Shrubby Grassland – HK Island
18. Shrubby Grassland – Islands
19. Grassland – NT North
20. Grassland – NT North-West
21. Grassland – NT East
22. Grassland – Kowloon
23. Grassland – HK Island
24. Grassland – Islands
25. Feng Shui Forest
26. Montane Forest
27. Plantation Mixed Forest
28. Mangrove
29. Golf Course Urban Park
30. Cultivation
31. Others

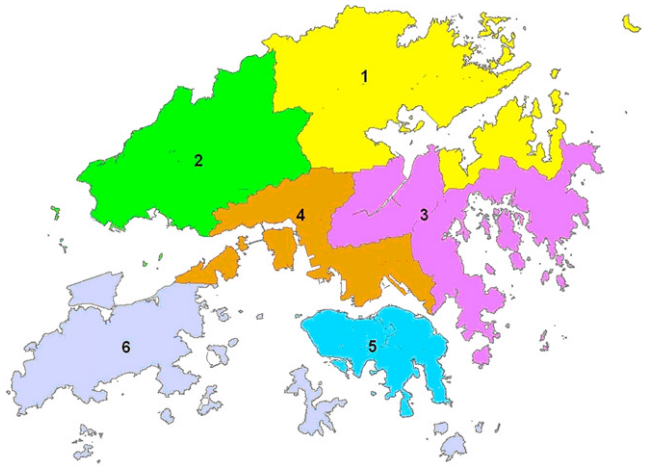

Fig. 2. Subdivision of Hong Kong into six sub-regions (1. NT North; 2. NT North-West; 3. NT East; 4. Kowloon; 5. HK Island; 6. Islands).

Furthermore, among the abovementioned 10 PFTs, 4 of them were considered as dominant PFTs by area. They are: Lowland Forest; Mixed Shrubland; Shrubby Grassland; and Grassland. These 4 PFTs contribute 70% of the total Hong Kong land area. These four area-dominant PFTs were further refined spatially as described in Section 3.2.3. The plant-functional types mentioned above are summarized in Table 3.

3.2.3. *Sub-regions*

In order to improve the spatial representation of emission factors, the Hong Kong land area was subdivided into six sub-regions as shown in Fig. 2. These six sub-regions are: New Territories (NT) North, New Territories North-West, New Territories East, Kowloon, Hong Kong Island, and Islands. The purpose of this division is to spatially refine some of the PFTs, especially the area-dominant ones. It is unnecessary to spatially refine the non-area-dominant PFTs due to their small area contributions. The sub-regions were setup by grouping regions of adjacent Hong Kong District Councils (Table 4). The selection of these sub-regions was determined by balancing the objective of characterizing the spatial variation of emission factors with the availability of tree survey locations. Sub-regions were chosen such that each had several field survey locations.

3.2.4. *Emission factors (EF) and leaf area index (LAI)*

Spatial variation of EFs (values for each grid cell) is required for input into the MEGAN program (EF Map). This information was estimated from the local PFT (at each grid cell) and the EFs representing each PFT class. The PFT-level EFs were obtained through tree data analysis as described in Section 3.5. The species-level EFs were obtained as described below. The species-level isoprene EFs were determined based on the laboratory measurements described

Table 4
Sub-regions and the District Councils.

Sub-region	District Councils
New Territories (NT) North	North, Tai Po
New Territories (NT) North-West	Yuen Long, Tuen Mun
New Territories (NT) East	Sha Tin, Sai Kung
Kowloon	Kowloon City, Kwun Tong, Sham Shui Po, Wong Tai Sin, Yau Tsim Mong, Tsuen Wan, Kwai Tsing
Hong Kong Island	Central & Western, Eastern, Southern, Wan Chai
Islands	Islands

in Section 2, literature values, or taxonomy. The species-level monoterpene EFs were determined based on laboratory measurements if available (i.e. for the 23 measured plant species in the previous and current studies). The species-level monoterpene EFs for the plant species not measured in the previous and current studies were determined based on vegetation types (broadleaf trees; needle-leaf trees; shrubs; or herbaceous cover) and default MEGAN emission factors as described in Section 3.1.1. The species-level EFs of other VOCs were determined based on vegetation types (broadleaf trees; needle-leaf trees; shrubs; or herbaceous cover) and default MEGAN emission factors. This applied to all PFTs with available field survey data.

Spatial variation of LAI was determined in a similar fashion as the local PFT (at each grid cell) and the LAI representing the PFT class. Two methods were considered to obtain LAI data: assignment of LAI values described above; and use of available LAI data from the MEGAN Community Data Portal (CDP) (http://acd.ucar.edu/~guenther/MEGAN/MEGAN.htm), which is based on MODIS satellite data (Guenther et al., 2006) and has a global coverage at about 1 km resolution. The two approaches were compared and numerical experiments show that the use of MEGAN-CDP LAI data leads to inadequate spatial results in mixed resolution (100 m versus 1 km and causes e.g. Lamma Island to produce no emission output due to inadequate LAI data). LAI values were determined for PFT classes as in the previous studies (Tsui et al., 2009) based on the approach of Geron et al. (1994). Note that the seasonal variation of LAI was not considered for this study.

Leaf Mass Density (LMD, g m^{-2}) was used to convert the leaf-scale species-level emission factors (in μg g^{-1} leaf dry weight h^{-1}) to canopy-scale species-level emission factors (in μg m^{-2} h^{-1}). This is performed using a simple extrapolation/canopy environment model to multiply the leaf mass density with the leaf-scale species-level emission factors and a factor to account for canopy environment conditions. This conversion was performed on the input data (pre-processing) and LMD is not required as an input into the MEGAN program.

3.2.5. *Modeling for compounds other than isoprene*

Default MEGAN emission factors were used for modeling monoterpenes (for the plant species not measured in the previous and current studies) and other VOCs. These emission factors were categorized into broadleaf trees, needle-leaf trees, shrubs, and herbaceous cover (denoted as “vegetation types” hereinafter). To obtain the spatial emission factors (at each grid cell), vegetation species representing a PFT were grouped into the vegetation types. This information was then combined with the reference MEGAN emission factors to obtain the spatial EFs (for each cell) for compounds other than isoprene.

3.3. *Weather data*

Hourly averages of air temperature and solar radiation were provided from the Hong Kong Observatory. The air temperature data from 22 weather stations were received and the averaged air

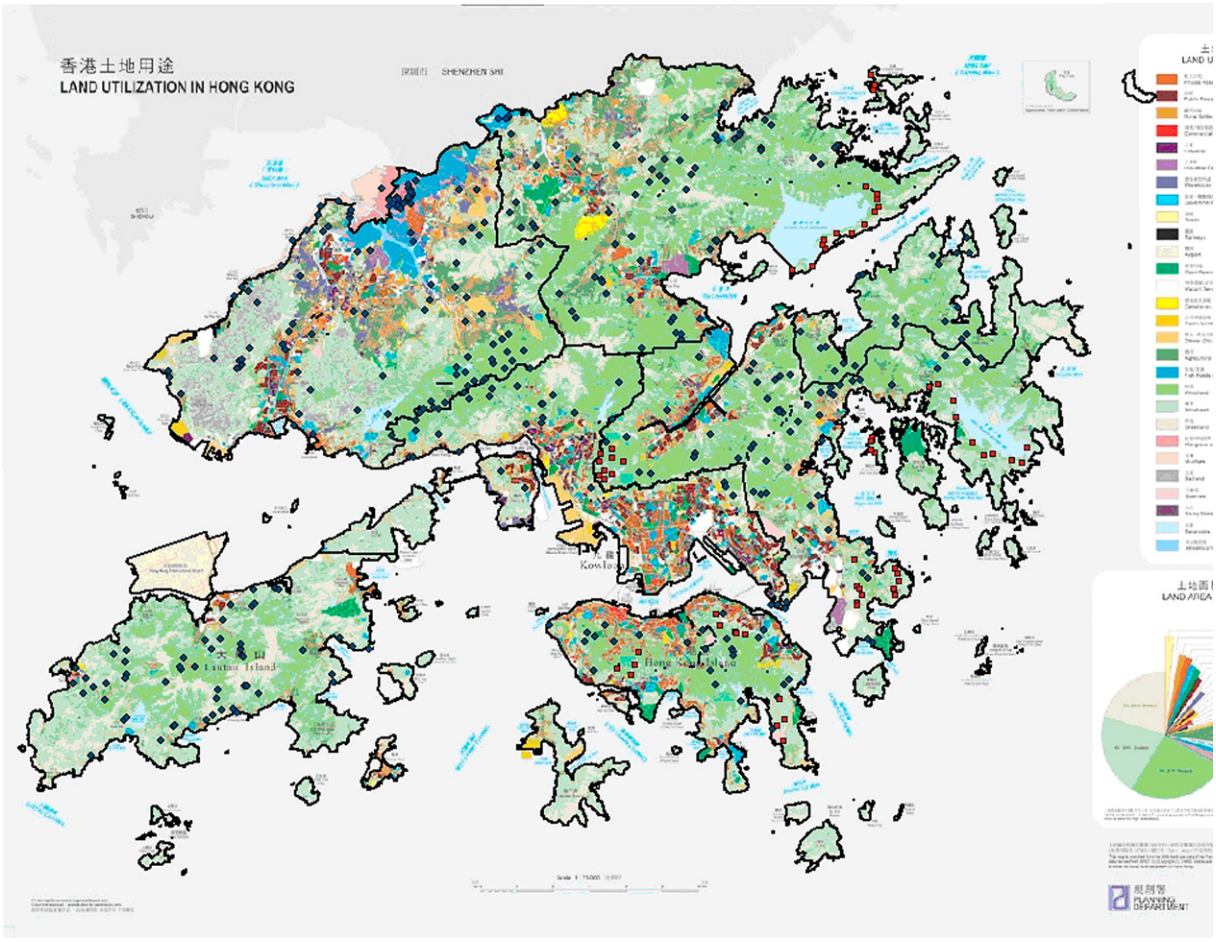

Fig. 3. Site locations of available field surveys (black dots: 370 sites from SDD study (SDD, 2006); red squares: 65 sites from previous study by HKU Department of Botany (Tsui et al., 2009); triangle: sites of the present study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature from these 22 weather stations from 1995 to 2006 were used together with the hourly solar radiation at the King's Park weather station over the same period for inputting into the MEGAN program. Wind speed and humidity are not required for input when using the PCEEA version of MEGAN (version 2.04).

3.4. Supplementary field surveys

Field surveys were conducted to supplement the available tree survey data. The available tree survey data includes data of 370 and 65 sites from previous studies conducted by SDD (2004) and HKU (Tsui et al., 2009), respectively. The site locations of all the above tree surveys are given in Fig. 3. A total of 61 additional tree surveys were conducted in order to ensure that the dominant PFTs (Lowland Forest, Mixed Shrubland, Shubby Grassland, and Grassland) had sufficient tree survey data in the six sub-regions (Table 4).

3.5. Tree data analysis

This section describes the methodology for analysis of field survey data. It describes the method for determining PFT-level EFs and LAI.

3.5.1. Collection of field survey data

In this project, field survey observations of species composition were collected from the following sources: the field survey data from 370 SDD sites (SDD, 2004); 65 sites from the previous study by the HKU Botany department (Tsui et al., 2009); and 61 sites from this study together with data from 9 tree planting programs by AFCD. Each observation included vegetation species composition and abundance.

3.5.2. Grouping of field survey data

The field survey data were grouped by PFT classes so that each class had several representative sites and plant species. This data was grouped based on the site location, its PFT classification from the habitat map, the on-site habitat classification and its sub-region and the location determined using GIS.

It should be noted that no field survey data were available for the Montane Forest and Golf course/Urban park sub-regions. To remedy this deficiency, the Montane Forest was represented by Lowland Forest, Golf Course was represented by Grassland while Urban Parks were neglected. The uncertainty associated with this approach is small since Montane Forest, Golf Course, and Urban park only contribute to 0.1%, 0.4%, and 0.6% of Hong Kong land, respectively.

3.5.3. Determination of PFT-level EFs and LAI

The PFT-level emission factors and LAIs were obtained by taking the arithmetic average, weighted by tree species composition, and the area-weighted average of herbaceous/grass cover. Area emission factors were determined for the PFT types based on their plant species abundance and coverage. These factors assume the same area per tree/shrub of surveyed sites.

For isoprene, the PFT-level EFs (in $\mu g\ m^{-2}\ h^{-1}$) were obtained by multiplying the canopy-scale species-level EFs (in $\mu g\ m^{-2}\ h^{-1}$) and the area fractions. For monoterpenes, the plant species were separated into two groups: those with monoterpene measurements, and those without monoterpene measurements. For the former group, the PFT-level EFs were obtained by multiplying the canopy-scale species-level EFs and the area emission factors. For the latter group, the vegetation species were categorized into vegetation types (broadleaf trees; needle-leaf trees; shrub; and herbaceous cover). The PFT-level EFs were obtained from the vegetation types, the area factors, and the vegetation type's emission factors as described. The total PFT-level EFs representing the PFT were obtained by summing the PFT-level EFs from the two groups. For other VOCs, the vegetation species were categorized into vegetation types (broadleaf trees; needle-leaf trees; shrub; and herbaceous cover). The LAI values were obtained by analysis of the plant species composition (of the PFTs) and their LAI values. A LAI value of 3 is assigned for pine, 5 for deciduous, and 7 for Abies, Picea and Pseudotsuga. Apart from that a LAI value of 4 is assigned for grass and shrub following the default value of GloBEIS. The PFT-level LAIs were obtained by multiplying the species-level LAIs and the area factors. The result of the PFT-level emission factors and LAI are shown elsewhere (Leung et al., 2008a).

3.6. Model domain

The grid employed in this paper has a size of 626 × 453 with 100 m resolution. This covers a rectangular region of 62.6 km × 45.3 km. The grid is aligned with the HK1980 grid system (Leung et al., 2008b).

4. Results

4.1. Grouping of compounds

The modeled chemical species were grouped into three categories: isoprene; monoterpenes (myrcene, sabinene, limonene,

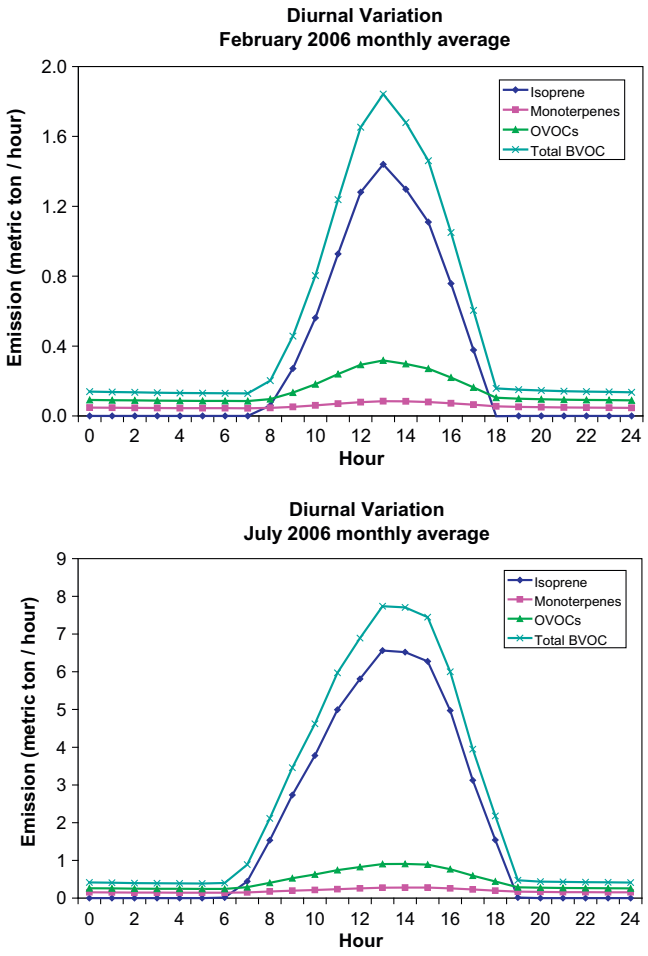

Fig. 4. Diurnal variation of BVOC emission in February and July 2006.

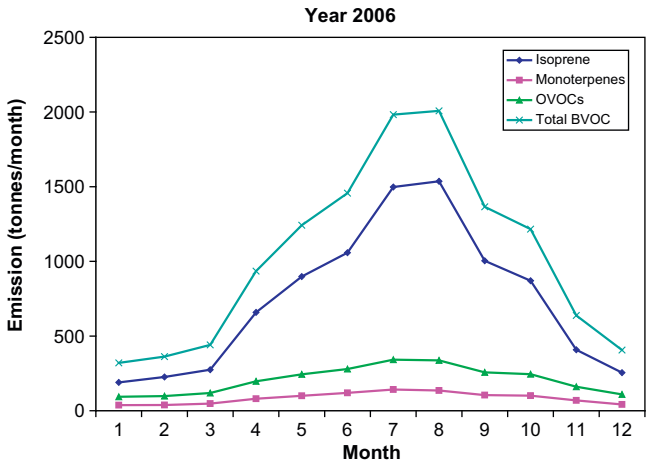

Fig. 5. Monthly BVOC emissions in 2006.

3-carene, ocimene, β-pinene, α-pinene, farnesene, β-caryophyllene, other monoterpenes, other sesquiterpenes); and other VOCs (methyl-butenol, methanol, acetone, acetaldehyde, formaldehyde). "Total BVOC" denotes the sum of contributions from isoprene, monoterpenes and other VOCs. It does not include contributions from methane, nitrogen oxides, and carbon monoxide, although the amounts of these gases were calculated by the model.

4.2. Diurnal variation

The monthly-averaged diurnal variation of BVOC emissions in February and July 2006 are shown in Fig. 4. The BVOC emission profile follows that of isoprene which is the main component of the BVOCs. The diurnal variation of isoprene emission mainly follows the solar radiation pattern with emissions that are high in day but very low at nighttime. Since there are different light-dependent factors for various compounds in the model, nighttime emission estimates were zero for isoprene but non-zero for monoterpenes and other VOCs.

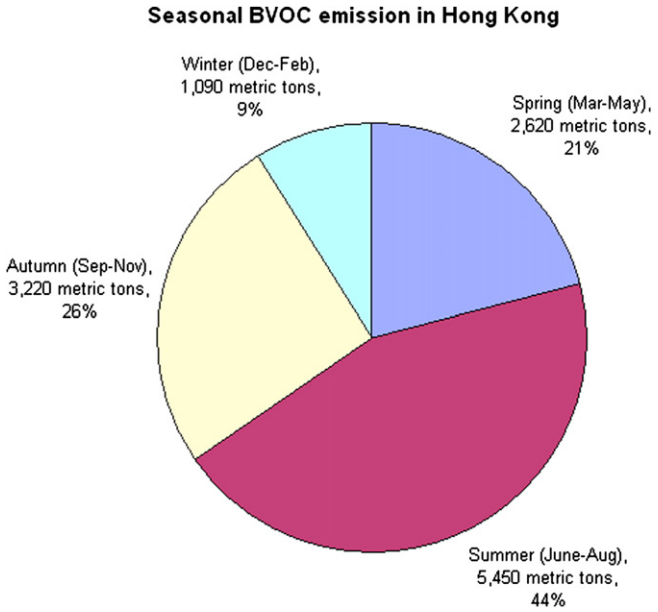

Fig. 6. Seasonal BVOC emissions in Hong Kong (2006).

4.3. Monthly and seasonal variation

Monthly BVOC emissions were computed with MEGAN for the years from 1995 to 2006 and that of 2006 is presented in Fig. 5. Similarly, the profile of the total BVOC emissions follows that of the

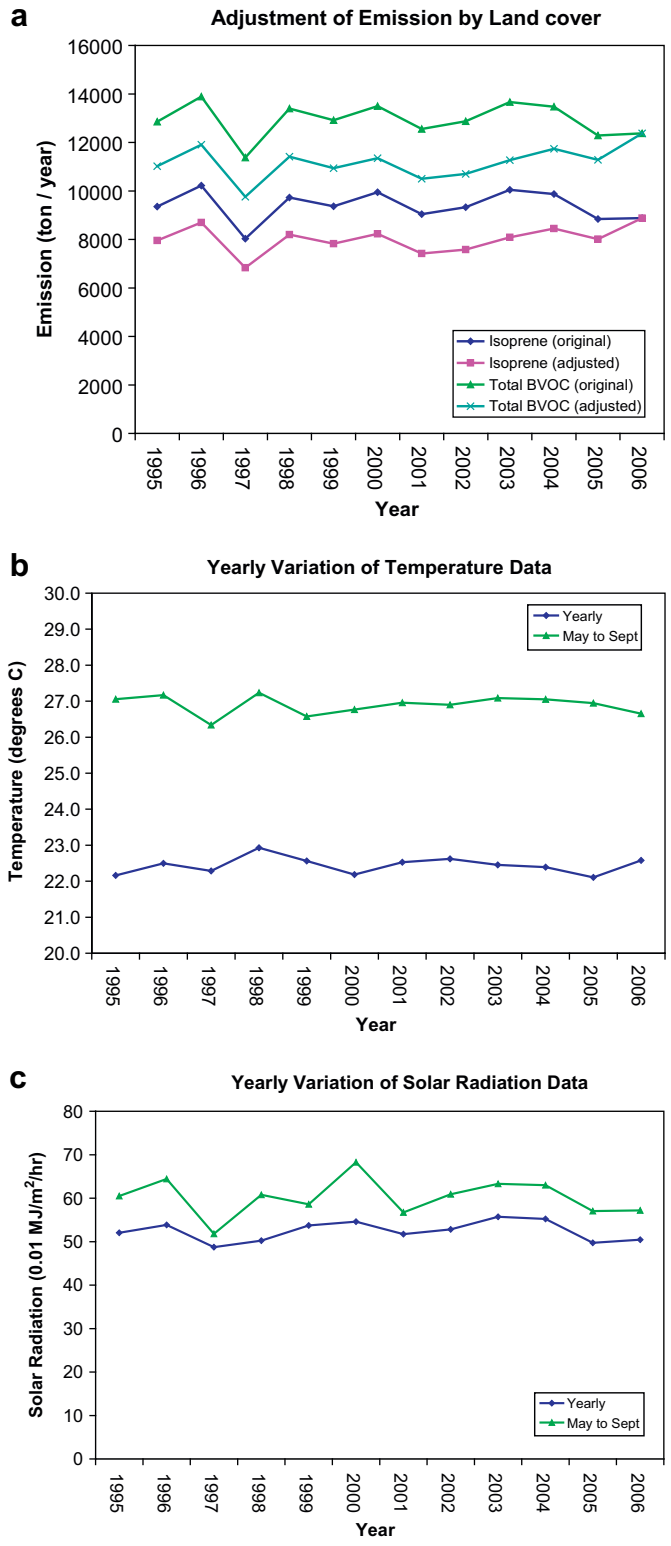

Fig. 7. a. Adjustment of emission results by land cover areas. b. Annual variation of temperature data. c. Annual variation of solar radiation data.

isoprene emission. The trends of isoprene, monoterpenes and other VOCs emissions all show an increase from the start of the year and reach the maximum in August which is the peak summer month of the year.

The seasonal variations in simulated BVOC emissions in Hong Kong in 2006 are shown in Fig. 6. As expected, maximum BVOC emissions occurred in the summer (June–August) (5450 metric tons, 44%) while minimum BVOC emissions occurred in the winter (December to February) (1090 metric tons, 9%). The large difference in BVOC emissions between summer and winter time (5-fold) is mainly due to the large temperature difference between these two seasons in Hong Kong (typically 20 °C).

4.4. Annual variation

Fig. 7a shows the annual emissions from 1995 to 2006 together with the variations in temperature (Fig. 7b) and solar radiation (Fig. 7c) over the same period. Temperature and solar radiation are the two driving forces for temporal BVOC emission variation and are highly correlated. For example, the drop in emission in the year 1997 can be explained by the corresponding decrease in both temperature and solar radiation in the summer of 1997. In the present study, only one habitat map of 2006 was used to provide land cover data. The use of multiple land cover data was not possible due to the unavailability of continuous data over the studied twelve-year period. Therefore, adjustment of final results for other years due to temporal change in land cover was estimated based on the reported figures of vegetation land cover areas for 1990–2006 from the government EPD (Leung et al., 2008a). Both the original and adjusted emissions for the twelve years are presented in Fig. 7a. For the year 2006, the total annual BVOC emissions in Hong Kong was estimated to be 12,400 metric tons (9.82×10^9 g C (BVOC carbon)), of which isoprene emission accounts for 72% (8880 metric tons/7.83×10^9 g C), monoterpene emissions account for 8% (1020 metric tons/0.90×10^9 g C), and OVOC emissions account for 20% (2480 metric tons/1.09×10^9 g C) of the total annual emissions.

4.5. Spatial variation

The spatial variation of BVOC emission from Hong Kong in 2006 is shown in Fig. 8. A high emission of isoprene can be observed in regions such as “Lowland Forest – NT North” (see Fig. 2 for definition) where emission factors have large values. The highest emission of isoprene (per area) was found in “Shrubby Grassland – Islands” although this PFT region has a relatively low area contribution. The spatial variation of total BVOC is similar to the isoprene spatial variation, since the contribution from isoprene is the highest (72% for year 2006). On the other hand, the spatial variation of monoterpenes and other VOC emissions are quite different from the isoprene spatial variation. High monoterpenes and other VOCs were observed in “mangrove” where emission factors have large values.

4.6. Result by PFT

The breakdown of BVOC emissions in 2006 by PFT is shown in Fig. 9. The top-five BVOC-emitting PFTs are “Mixed Shrubland – NT

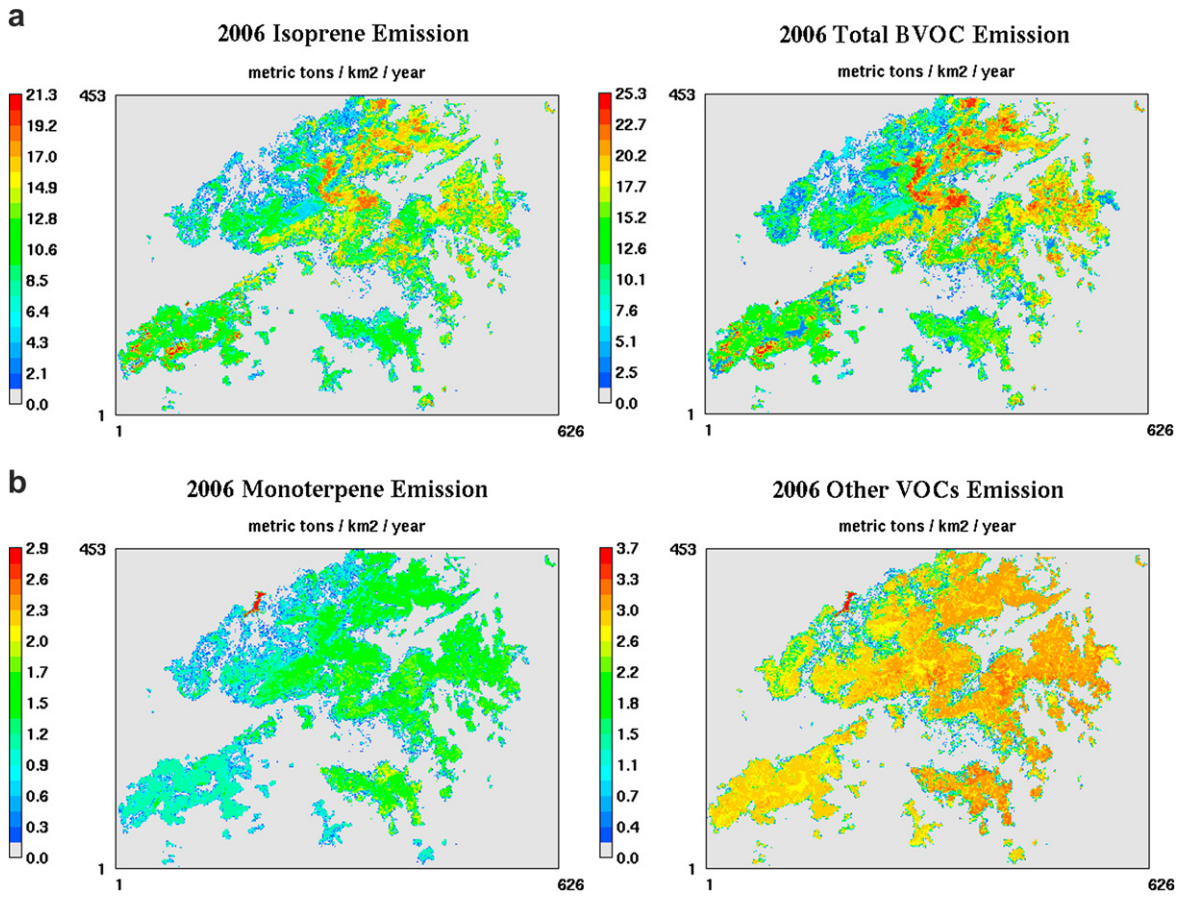

Fig. 8. a. Spatial variation of isoprene and Total BVOC emissions in 2006. b. Spatial variation of monoterpene and other VOC emissions in 2006.

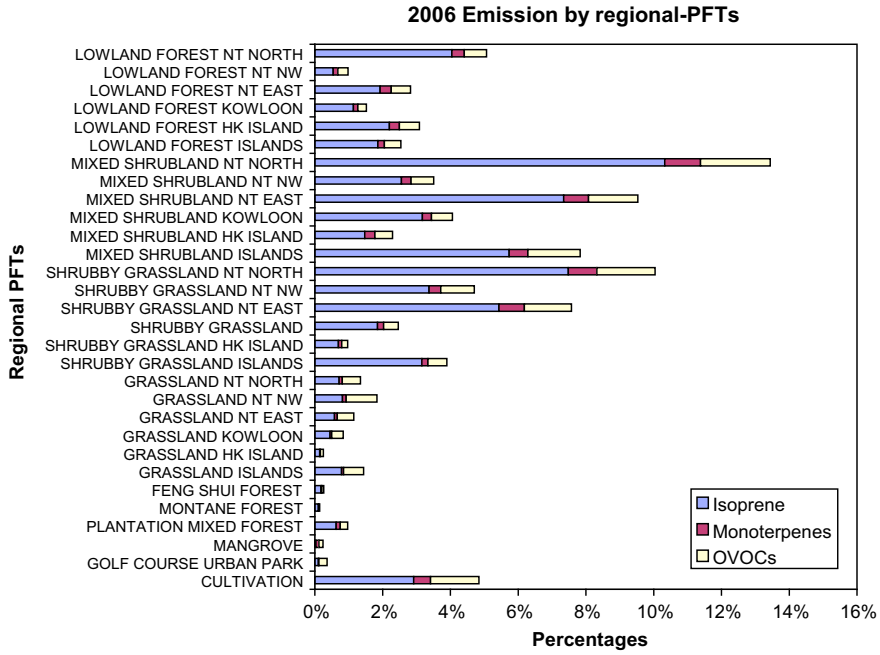

Fig. 9. 2006 Emission breakdown by PFTs.

North", "Mixed Shrubland – NT East", "Mixed Shrubland – Islands", "Shrubby Grassland – NT North", and "Shrubby Grassland – NT East". Note that a PFT region has a high emission contribution if it has a high emission factor (per area) and a large area contribution. For example, "Shrubby Grassland – Island" has a high emission factor (per area), but the total emission from this PFT is not as large as some other PFTs due to its relatively low area.

4.7. Comparison to other studies

Table 5 shows a comparison of the emission results between this study, using MEGAN, and the previous study, using GloBEIS, over the period of August 2004–July 2005 (Tsui et al., 2009). The results show higher isoprene emission (+104%) and lower monoterpenes (−65%) compared to previous study. The same weather data was used in the two studies and the response of emissions to temperature and solar radiation are similar in MEGAN and GloBEIS. The large differences in emissions calculated for the two studies are mainly caused by the extrapolation of field survey data and the methodology used to assign species-level emission factors. Sakulyanontvittaya et al. (2008) also found higher isoprene (+64%) and lower monoterpenes (−34%) using MEGAN compared to GloBEIS for a simulation in the United States in the summer.

Table 6 compares the total and area average BVOC emissions of Hong Kong with other cities and countries. It shows that total BVOC emissions in Hong Kong are much higher than the global area average emission estimated by Guenther et al. (2006) and higher than estimates for other Asian locations such as Beijing and Taiwan. As indicated in Table 7, the area average isoprene emission for Hong Kong is 40–110% higher than the global average.

5. Discussion

The number of plant species identified for this study is about 300. Most of the species come from the tree survey data of SDD (2006). The number of species included in the study of Tsui et al. (2009) was 148. The plant species diversity in Hong Kong is very high and the theoretical number of species is 3164, including native and introduced vegetation species and varieties (Hong Kong Herbarium http://www.hkherbarium.net/Herbarium/index.html). Obviously, there is a large gap between the theoretical number of species in Hong Kong and the surveyed number of species. Many of these plants are herbaceous species which are difficult to identify and include in field surveys. Additional field surveys are recommended not only to increase the number of species with quantified biogenic emissions but also to improve characterization of plant-species spatial distributions.

In this study, the monoterpenes emission is 65% less than the previous study using GloBESIS (Tsui et al., 2009). The 20 species were handled separately in the MEGAN model and have different light-dependent factors while the monoterpenes were treated as one group in GloBEIS but this does not contribute significantly to the difference in emissions. The cause is mainly due to the differences in emission factors and the difference in handling of monoterpenes and OVOCs between GloBEIS and MEGAN models and a similar result has been reported by Sakulyanontvittaya et al. (2008).

Table 5
Comparison of emission results between this study and previous study. (Figures in metric tons BVOC, bracketed figures in 10^9 g carbon).

	This study	Previous study Tsui et al. (2009)	% Change
Isoprene	7826 (6.90)	3838 (3.39)	+104%
Monoterpenes	892 (0.79)	2582 (2.27)	−65%
OVOCs	2311 (1.02)	3336 (1.89)	−31%
Total BVOC	11,029 (8.75)	9757 (7.89)	+13%

Table 6
Comparison of total BVOC emission with other studies.

Country/ region	Area (km^2)	Total BVOC (g C $year^{-1}$)	Area average (g C km^{-2} $year^{-1}$)	References
Hong Kong	1100	8.75×10^9	7.95×10^6	Current study
Beijing	14,500	1.60×10^{10}	1.10×10^6	Wang et al., 2003
China	9,600,000	2.05×10^{13}	2.14×10^6	Klinger et al., 2002
Taiwan	36,000	1.68×10^{11}	4.67×10^6	Chang et al., 2005
Global (land)	146,800,000	1.10×10^{15}	7.49×10^6	Guenther et al., 1995

Table 7
Comparison of isoprene emission with MEGAN 2006 study.

Country/ region	Area (km^2)	Isoprene (ton $year^{-1}$)	Area average (ton km^{-2} $year^{-1}$)	References
Hong Kong	1100	7826	7.1	Current study
Global (land)	146,800,000	$(500–750) \times 10^6$	3.4–5.1	Guenther et al., 2006

This study applied a species level approach for isoprene emission factors and PFT level approach for monoterpenes. The reason is that plant species tend to have high, low or negligible isoprene emission rates, whereas the variability of monoterpene emission rates within a species can be as much between species as they are within a PFT. The lack of suitable monoterpene emission rate measurements requires the assignment of an average value to PFTs as adopted in the present study. For isoprene, species-level emission factors, similar to Tsui et al. (2009), were used to compute average emission factors for plant-functional types. For monoterpenes, the plant species were categorized into broadleaf, needle leaf, shrub, and herbaceous, and emission factors were assigned based on the categories. In general, the default MEGAN 2.0 emission factors, described by Sakulyanontvittaya et al. (2008), were used. These factors are based on the recent Helmig et al. data (2007) as well as other data sets. Note that the use of the Helmig et al. data, which have considerably lower emission factors than most other data sets, would have led to lower monoterpene emissions and thus a bigger difference in comparison to Tsui et al. (2009). This is illustrated by the study of Sakulyanontvittaya et al. (2008). Further analysis has been done to compare the present results from MEGAN and those from the GloBESIS model (Tsui et al., 2009). It has been found that the difference is not caused by the weather data but mainly caused by the extrapolation of field survey data and by grouping of the plant species in the methodology, and the species-level emission factors. This finding is based on the following observations:

- There are three main inputs to the MEGAN program: LAI distributions, emission factor maps and weather data. Since the same period (August 2004–July 2005) was adopted for the simulation, the deviation due to weather variation was precluded. Similar LAI values were used in GloBEIS and MEGAN simulations. Hence, the difference is caused primarily by the emission factor map.
- The emission factor map depends on: the species-level emission factors and the plant-species spatial distribution approximation.
- The species-level emission factors in this project are nearly the same as those in the previous project except those 10 plant species selected for the present laboratory measurement.
- The plant-species spatial distribution depends on the extrapolation of field survey data and grouping of the plant species. In the present study, a plant-functional-type approach was used with satellite land cover information. In the previous project, information from satellite was not available and plants species was grouped by country parks. This leads to a difference in emission factor map between current (Leung et al., 2008a,b) and previous study (Tsui et al., 2009).

To summarize, the differences between the isoprene emissions estimated for this study and for the previous study is mainly due to the change in land cover data. The present study is considered to be more accurate due to the adaptation of an improved spatial distribution of plant species using a comprehensive habitat map, and incorporation of additional field survey (61 more field surveys) and more government tree planting data (9 AFCD tree planting programs).

6. Uncertainties

In this study, a number of factors affecting the accuracy of the modeling are identified as follows:

- A uniform vegetation species distribution was assumed within a PFT but there could be variation of species within a PFT. Nonetheless, the PFT approach is a fair approximation and is suitable for Hong Kong because of the heterogeneity of vegetation species.
- The vegetation species representing a PFT were sampled from a finite number of field surveys. There could be variation in locations of insufficient field survey data. The field survey data may deviate from the expected vegetation classes based on SDD's habitat map but is difficult to assess the degree of mismatch.
- The spatial emission results other than year 2006 were approximated by changes in land cover. The changes are unknown in several years and the trends were estimated.
- There are no available field survey data for Urban Park, Golf Course, and Montane Forest. However, the uncertainty is estimated to be less than 1% due to small area contributions. The emission from other unclassified habitat classes is not considered. The uncertainty is expected to be small since they are either non-vegetation classes or they have small area contributions.
- Some emission factors were determined by literature or taxonomy. There may be variation between local values and foreign measurements.
- Effects of wind speeds and humidity on leaf temperature are not currently modeled. They may lead to deviation in emissions which are very sensitive to leaf temperature. However, the uncertainty is expected to be small since the resulting errors are somewhat offset with underestimated leaf temperatures in parts of the canopy and overestimates in other parts.
- Different approaches were used to obtain emission factors for isoprene and monoterpene that lead to uncertainty in the modeling results.
- The PFT-level emission factors (and LAIs) were obtained by number average of plant species. This assumes each tree occupies the same area of land but there could be variation in reality.
- There are uncertainties in the LAI/LMD approximation. For instance, the seasonal changes of the LAI data were not currently modeled.

7. Recommendations

Although there were obvious improvements for the present study as compared to the previous one, the following areas of improvement are recommended:

- To conduct additional field surveys to increase the number of identified species. This can not only increase the number of identified species but also improve the plant-species spatial distribution approximation. Future tree planting information, if available, from governments such as AFCD and LCSD would also be beneficial to enrich the current tree species database.
- As found from the present study, some species, such as *S. jambos*, had a low emission value but is suspected to be an

isoprene emitter. It would be interesting to conduct additional studies to determine why some measured individuals did not emit isoprene. In addition to potential analytical problems, which can be minimized (at least for isoprene and most monoterpenes), there are inherent problems associated with the enclosure measurement process (e.g. disturbance, shaded leaves). We need a better understanding of this and it is an active area of research that includes comparisons of various enclosure techniques and evaluating them by comparing to above-canopy flux measurements.

- It is possible, alternatively, to use the LAI data from Community Data Portal (CDP) based on MODIS satellite data. However, the resolution is not good enough for the present application. It is recommended for future studies to refine the LAI data using high-resolution satellite data when there are more resources available.
- In the current version of MEGAN (version 2.04), a simple parameterized canopy environment model is used that does not consider the influence of wind speed and humidity on leaf temperature and other factors. The detailed canopy model provided as an option with MEGAN version 2.1 may provide a more reliable result.
- It is recommended to compare model emission results to above-canopy flux measurements if available. This provides a solid methodology to validate model emission results.
- An additional recommendation is to use a regional air quality model to conduct a sensitivity study to determine where the current BVOC emission uncertainties have the biggest impact on ozone or particles. Comparison of isoprene and other BVOC concentrations predicted by the model with field observations could be done to evaluate the model predictions.

8. Conclusions

Following the approach of Tsui et al. (2009), this work continued the development of a BVOC emission model for the estimation of biogenic VOC emissions from vegetation in the HKSAR. The improved Model of Emissions of Gases and Aerosols from Nature (MEGAN) developed by Guenther et al. (2006) was used. The spatial BVOC emission determination for Hong Kong was enhanced by using satellite images with a 10-m resolution. The emission factor map was produced using plant-species-level emission factors from laboratory measurements, literature, and taxonomy; plant-species spatial distribution approximated with the aid of satellite land cover information from the Sustainable Development Division of HKSAR; and data from available field surveys. A plant-functional-type approach was used, with spatial vegetation types grouped based on a habitat map derived from satellite information. Additional field surveys on 61 sites and 9 AFCD's tree planting program data were used to supplement the previous field survey database. Laboratory measurements were conducted for ten local plant species to supplement the local plant-species-level emission factors. The model was applied successfully to obtain BVOC estimations for a continuous twelve-year period from 1995 to 2006 with adjustment to take into account of temporal variation in the land cover. The estimated emissions differ considerably from the study of Tsui et al. (2009). Differences in model algorithms and weather data had a minimal impact on the difference in emissions, which were instead attributed to land cover and emission factors.

For the year 2006, the total annual BVOC emissions in Hong Kong was estimated to be 12,400 metric tons (9.82×10^9 g C (BVOC carbon)), in which emissions of isoprene, monoterpene and OVOC account for 72%, 8%, and 20%, respectively. The annual variation in emission due to weather over the twelve-year period (1995–2006) was found to be small, (−1.4%) but an increasing trend in the annual variation due to changes in the land cover can be observed (+7%). Recommendations for future studies are given, including additional field surveys, measurement technique improvements, refinement of LAI data, and extension to regional studies.

There are several advantages of urban vegetation cover such as carbon sequestration, and the reduction of ozone and particulate matter, as well as lowering urban temperature. There are also adverse effects of vegetation on air quality, depending on the types, amount and location of vegetation. Urban tree planting should be encouraged. However, simply planting more trees may not result in the expected improvement in air quality. Unplanned planting of high BVOC or allergenic pollen trees could adversely affect air quality of the environment. Thorough planning, which takes into account of every potential effect of a greening project, should be conducted before implementation. Moreover, efficient management should be followed to ensure the long-term contribution of trees in terms of carbon reservoirs and effective filters for pollutants, as well as to minimize BVOC emissions, carbon emissions due to decomposition, and allergenic pollen effects to the public.

Disclaimer

The content of this paper does not necessarily reflect the views and policies of the HKSAR Government, nor does mention of trade names or commercial products constitute an endorsement or recommendation of their use.

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