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Estimation of ambient BVOC emissions using remote sensing techniques

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ABSTRACT

The contribution of Biogenic Volatile Organic Compounds (BVOCs) to local air quality modelling is often ignored due to the difficulty of obtaining accurate spatial estimates of emissions. Yet their role in the formation of secondary aerosols and photochemical smog is thought to be significant, especially in hot tropical cities such as Hong Kong, which are situated downwind from dense forests. This paper evaluates Guenther et al.'s [Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T.E., Harley, P., Klinger, L., Lerdau, M., McKay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., Zimmerman, P., 1995. A global model of natural volatile organic compound emissions. Journal of Geophysical Research 100, 8873–8892] global model of BVOC emissions, for application at a spatially detailed level to Hong Kong's tropical forested landscape using high resolution remote sensing and ground data. The emission estimates are based on a landscape approach which assigns emission rates directly to ecosystem types not to individual species, since unlike in temperate regions where one or two single species may dominate over large regions, Hong Kong's vegetation is extremely diverse with up to 300 different species in one hectare. The resulting BVOC emission maps are suitable for direct input to regional and local air quality models giving 10 m raster output on an hourly basis over the whole of the Hong Kong territory, an area of 1100 km^2. Due to the spatially detailed mapping of isoprene emissions over the study area, it was possible to validate the model output using field data collected at a precise time and place by replicating those conditions in the model. The field measurement of emissions used for validating the model was based on a canister sampling technique, undertaken under different climatic conditions for Hong Kong's main ecosystem types in both urban and rural areas. The model-derived BVOC flux distributions appeared to be consistent with the field observations, indicating the robustness of the landscape modelling approach when applied to tropical forests at detailed level, as well as the promising role of remote sensing in BVOC mapping.

1. Introduction

Volatile organic compounds (VOCs) in the atmosphere react to form ozone and secondary aerosols by the photooxidation of volatile organic compounds (VOCs) in the presence of nitrogen oxides (NO_x). As such they contribute to air pollution, including photochemical smog in urban areas. Biogenic volatile organic compounds from vegetation also have significant impacts at global scale, on tropospheric chemistry, the carbon budget, and ozone formation, and contribute to global climate change. Biogenic VOCs (BVOCs) emitted from vegetation are more reactive than, and exceed anthropogenic VOCs on a global scale (Lamb et al., 1987; Zimmerman et al., 1988). Isoprene is by far the most common and most reactive of BVOC species, and over 90% of isoprene is emitted from forests (Lamb et al., 1987). There have been many attempts to quantify BVOC emissions from source regions by spatial modelling using environmental parameters (Guenther et al., 1995, 2006; Wang et al., 2003; Chen et al., 2009; Tsui et al., 2009). However, due to the wide variability in emissions between plant species, as well as a lack of detailed spatial data on plant biomass, such estimates have been subject to large uncertainties. Moreover, few models have been verified empirically by comparing the modelled estimates with field-measured emissions (eg. Wang et al., 2003; Tsui et al., 2009). The uncertainties in emission estimates are especially serious for tropical regions because most emission databases do not cover tropical species, yet tropical regions are estimated to contribute ca. 80% of annual isoprene emissions (Guenther et al., 2006). Only a few tropical species have been measured, but in Hong Kong, the natural vegetation of secondary, sub-tropical evergreen forest in late successional stage, is extremely diverse with up to 300 different tree species in one hectare (Dudgeon and Corlett, 2004).

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Further sources of uncertainty in BVOC mapping relate to environmental factors such as light and temperature which cause great variation in quantity of BVOCs emitted from a single plant (Gulden et al., 2007). Such variability commonly exceeds differences in emissions between different species (ibid). Since BVOCs are emitted from plant leaves, accurate knowledge of leaf biomass and its variation over space and time is a fundamental requirement for accurate spatial modelling. The complexity of tropical ecosystems creates great variation of both incident light, and temperature within an ecosystem, due to site variations in topography and plant canopy structure (Whitmore, 1984), and these cannot be accurately represented by the usual practice of applying a single value to a whole ecosystem.

BVOC emissions of landscapes are usually estimated by multiplying a standard emission rate for a particular vegetation (or ecosystem) type by the area covered by each vegetation type, accounting for leaf density and its seasonal changes, and correcting for the main environmental drivers, light and temperature. The standard emission rates have generally been assigned based on previous studies which measured BVOC emissions over vegetation canopies in major world ecosystems. However, although the tropics contribute over 80% of global isoprene emissions (Guenther et al., 2006), and isoprene comprises 44% of all BVOC emissions (Guenther et al., 1995), few estimates are from tropical regions. However, Geron et al.'s (1994) modelled estimates of isoprene emission rates for the eastern United States are 5–10 times higher than for models developed in other countries, suggesting low transferability. Thus accurate estimates of BVOC emissions from tropical landscapes are urgently required.

Remote sensing data and image processing techniques are now available which can permit improved estimates of BVOC emissions over large areas, and an example is given here for the Hong Kong territory, an area of 1100 km^2. In addition, 53 samples of ambient isoprene concentrations collected from different ecosystem types on 13 days during summer and winter are available for verification of the modelled estimates.

Current emission models are based on an emission rate ($mgC\,m^{-2}\,h^{-1}$) that is defined for standard conditions e.g. leaf temperature of 30 °C and photosynthetically active radiation (PAR) of 1000 $\mu mol\,m^{-2}\,s^{-1}$, and then adjusted for variable temperature and light conditions. Most isoprene is emitted under standard conditions (Geron et al., 2000), thus the standard, or base rate is critical in obtaining realistic estimates. Isoprene emission rates (E) are calculated using Equation (1) (Guenther et al., 1993, 1999).

$$E\left(\mathrm{mgC\,m^{-2}\,h^{-1}}\right) = \varepsilon D \gamma_t \gamma_p, \quad (1)$$

where ε is the isoprene emission capacity for a landscape ($\mu gC\,g$ (leaf dry weight)$^{-1}\,h^{-1}$); D is the foliar density (leaf dry matter m^{-2} of ground); γ_t is the coefficient representing the influence of temperature on emissions, and γ_p is the coefficient representing the influence of light intensity on emissions.

Ideally, emission factors should be based on species, but in highly diverse tropical forests this approach is not practical, therefore the values of ε for this study used an ecosystem approach, based on Guenther et al.'s (1995) database of emission capacities for major world ecosystem types. Their estimates were based on 22 field studies of BVOC emissions, although the authors recognized that values of ε for landscapes within an ecosystem may vary widely. The few data for the tropics were derived from Zimmmerman et al.'s (1998) estimates for Amazonia using a tethered balloon. Additionally, in many studies environmental parameters such as temperature and PAR flux (light intensity) are often based on monthly averages of radiation and temperature from local climate stations (Tsui et al., 2009), and foliar density from published tables (Wang et al., 2003; Gulden and Yang, 2006; Tsui et al., 2009). Such a bulk parameterization approach is suitable for input to generalized (eg. global and long term) emission and climate models. However it is unsuitable for air quality modelling and prediction over detailed urban areas such as Hong Kong, where BVOC emissions play an important role in the formation of photochemical smog, with great variations in time and space.

2. Objective

The objective is to demonstrate and evaluate a remote sensing methodology for obtaining spatially detailed BVOC concentrations over a large study area in the tropics. The basic BVOC emission model of Guenther et al. (1995) is tested using empirical and spatially detailed maps of temperature, foliar density, and photosynthetically active radiation (PAR) obtained by fieldwork combined with ASTER, SPOT and Landsat satellite images.

3. Methodology

The overall method of this study is to compute isoprene emissions using Equation (1) for the study area using remote sensing data, for all 53 field data collection times of ambient isoprene concentrations (Chen et al., 2009), and thereby to evaluate the model results from Equation (1) with the measured field data. Since the parameters for temperature (γ_t) foliar density (D), and PAR and (γ_p) are based on ASTER, SPOT and Landsat images data respectively, resampled to the highest resolution of 10 m for SPOT (see Section 3), the model output is in the form of raster data at 10 m spatial resolution. The temporal resolution of the model output is half-hourly, determined by the half-hourly temperature data from the Hong Kong Observatory's fixed stations.

3.1. Isoprene emission capacity (ε)

Isoprene emission capacity (ε) is based on 6 ecosystem types which are derived from a land use/land cover map at 10 m resolution. For the highest biomass class of mixed forest, isoprene emission rates for 10 local species, which together comprise 76% of the area of Hong Kong's forests, were available (Tsui et al., 2009). The average emission rate for these 10 dominant species, when individually weighted by area occupied is 18.14 $\mu gC\,g^{-1}\,h^{-1}$. For three other classes, agriculture, grassland and shrubland, standard rates from Guenther et al. (1995) were used. Fig. 1 shows the isoprene emission values for different ecosystems.

3.2. Foliar density (D)

Foliar density (D) of an ecosystem represents the total leaf mass carrying out metabolic processes and so is directly related to the ecosystem's capacity for BVOC emission. Previous studies have either used literature values devised in other areas to represent D (Wang et al., 2003; Gulden et al., 2006; Tsui et al., 2009; Zheng et al., 2010), or used an easily measured field variable such as Diameter at Breast Height (DBH) which is related in the literature to D. However, biases as large as 100% have been found using this foliage-stemwood approach (Marshall and Waring, 1986), since such allometric models do not take account of stand characteristics such as shade, stand density, age and site quality. Geron et al. (1994) used field DBH with published allometric models (Minckler and Gingrich, 1970) to derive tree crown width from DBH for their study area, since the DBH–crown width relationship is said to be independent of site quality. They then used other published allometric models (eg. Burton et al., 1991) to derive D from tree crown width. Not only are such models subject to propagated error due to

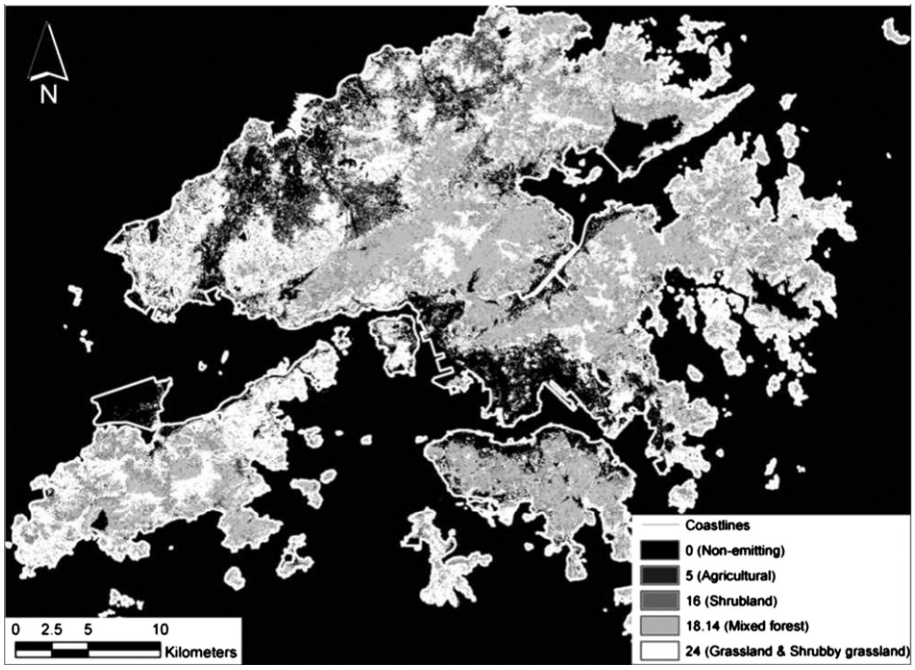

Fig. 1. Base isoprene emission capacities of Hong Kong ecosystems ($\mu gC\,g^{-1}\,h^{-1}$).

multiple parameter substitution, but they are also based on deciduous and non-tropical species eg. foliar densities of 700 g m^{-2} for Pinus and Acacia, 375 for Eucalyptus, Ilex and Quercus, and would not be suitable for our tropical study area in Hong Kong.

In this study, a site-specific allometric model for D (leaf dry matter in g m^{-2}) was established, based on current project work at the Hong Kong Polytechnic University, on carbon sequestration mapping of Hong Kong's vegetation (Nichol and Sarker, in press). Harvesting of 75 whole trees of dominant species was undertaken, where leaves were dried and weighed separately from woody parts, and the DBH was measured for each tree. Fig. 2a shows the correlation between leaf dry matter and grouped DBH ($r = 0.93$) for the 75 trees. These regression parameters were then used to convert 20 forest plots of 30 m diameter, within which the DBH of every tree had been measured, to leaf dry matter (g m^{-2}). Leaf dry matter was converted to D by dividing total plot leaf dry matter by total plot area (m^2). Fig. 2b shows the correlation between leaf dry matter of those plots and an image-derived vegetation index (RVI), of $r = 0.90$. Using this vegetation index from a SPOT image, foliar density was obtained for the whole study area at 10 m resolution.

3.3. The influence of light (Photosynthetically Active Radiation (PAR)) on emission activity according to Leaf Area Index (LAI)

The BVOC emission activity of PAR is dependent on both the amount of light (PAR) incident, as well as the area of leaf surface (LAI) receiving the light (Equation (2)) (Guenther et al., 1993, 1999).

$$\gamma_P = \frac{\alpha \cdot C_L \cdot Q}{\left(1 + \alpha^2 \cdot Q^2\right)^{\frac{1}{2}}} \tag{2}$$

where Q is the flux of PAR ($\mu mol\,m^{-2}\,s^{-1}$); $\alpha = 0.001 + 0.00085LAI$; $C_L = 1.42\exp(-0.3LAI)$.

In this study the PAR flux (Q) was measured in the field using a light meter. These PAR values are likely to represent the canopy in grassland and shrubland and for forest, observations were taken in small canopy gaps in order to represent as much as possible the top of canopy, and different levels below it. Summer time PAR values observed from fieldwork were between ~300 and ~1000 $\mu mol\,m^{-2}\,s^{-1}$ including both cloudy and sunny days, and lower values (~100–600 $\mu mol\,m^{-2}\,s^{-1}$) were observed in winter.

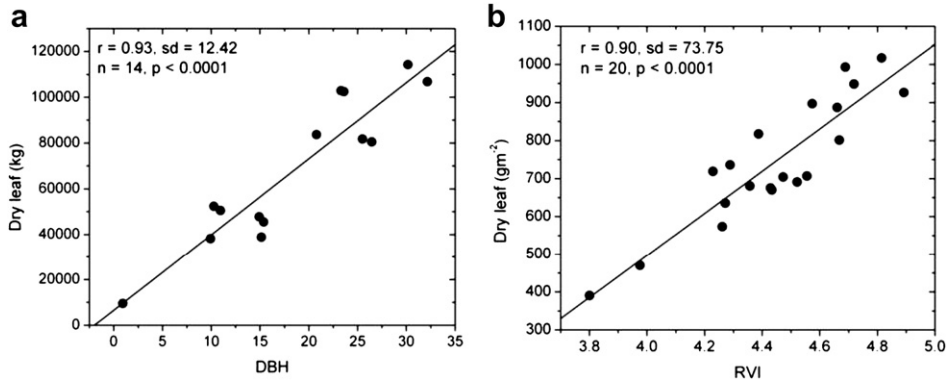

Fig. 2. a. Relationship between leaf dry weight and DBH for 75 trees; b. relationship between leaf dry weight and SPOT image Ratio Vegetation Index (RVI), from 20 forest plots.

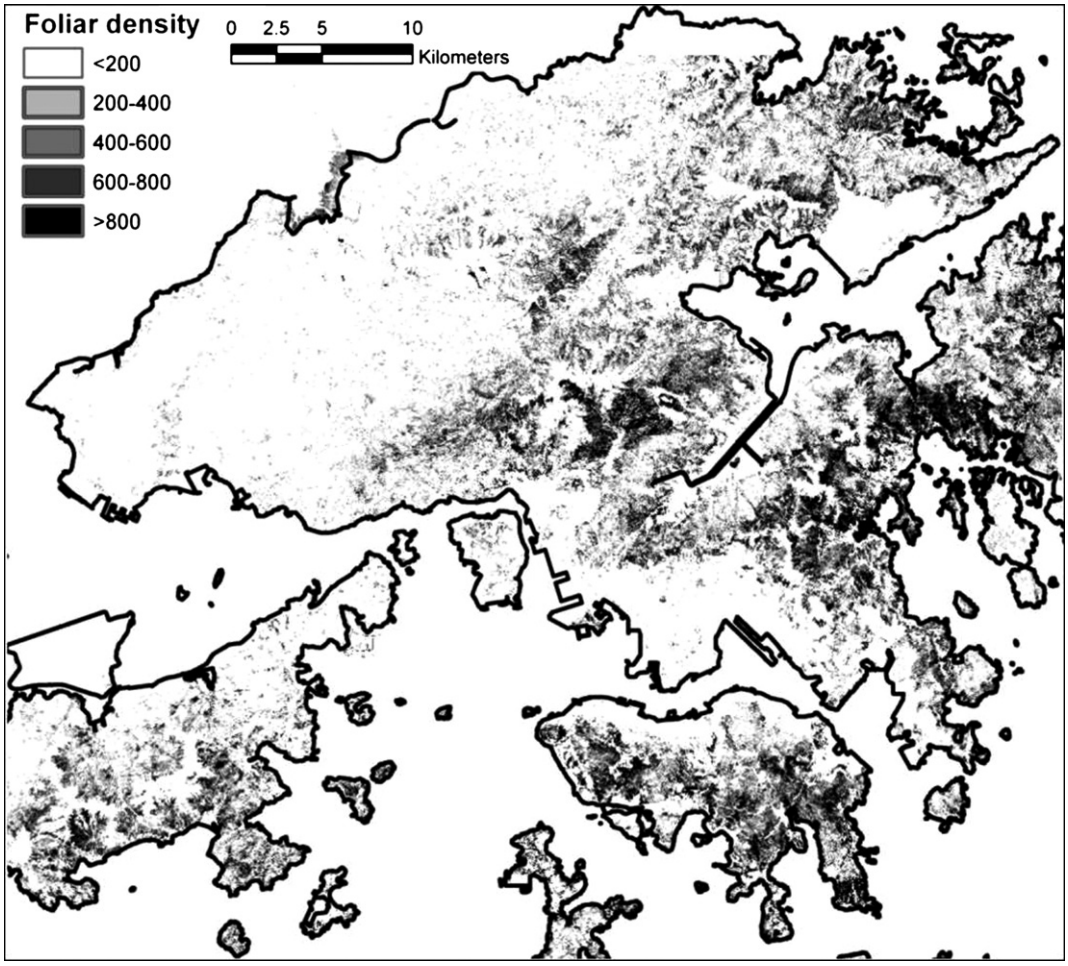

Fig. 3. Foliar density ($g\,m^{-2}$) based on field data and SPOT image at 10 m resolution.

For the parameter LAI, most previous studies have used literature values eg. 3 for Pinus, 5 for deciduous species (Gholz, 1986; Guenther et al., 1994), and 8.2 for tropical forest Alexandre (1981). In this study, an LAI image specific to the forested study area was produced from field data using a LAI-2000 Plant Canopy Analyzer during winter 2008, where the LAI of 11 forest plots of 30 m diameter was measured. These data values were regressed against an atmospheric and geometrically corrected Landsat image with 30 m resolution acquired in December 2006. The LAI image was produced using Equation (3), which employs the Ratio Vegetation Index (RVI) which had the highest correlation ($r = 0.83$) among several other indices with the field LAI values (Fig. 4a). The LAI image over Hong Kong is shown in Fig. 4b.

$$\mathrm{LAI} = -1.51 + (1.17 \cdot b_1) \tag{3}$$

where b_1 is RVI = Near Infra-red/Red.

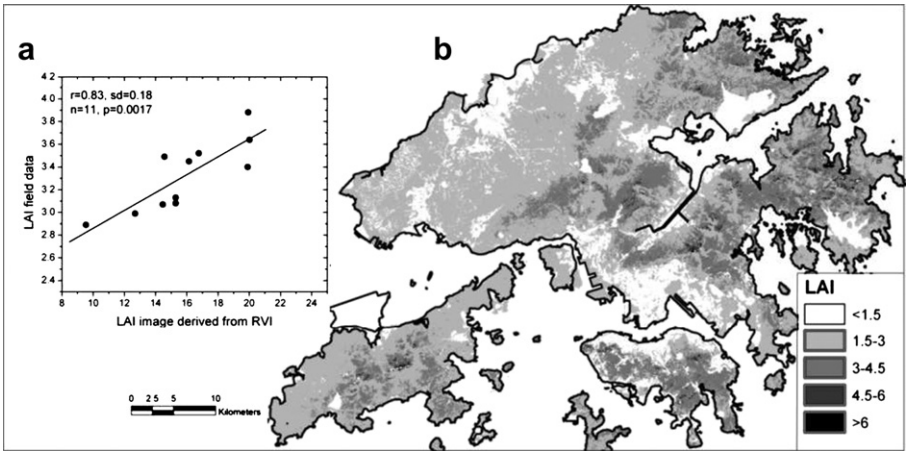

Fig. 4. a. Relationship between LAI field data and LAI image derived from RVI index; b. LAI image derived from RVI index.

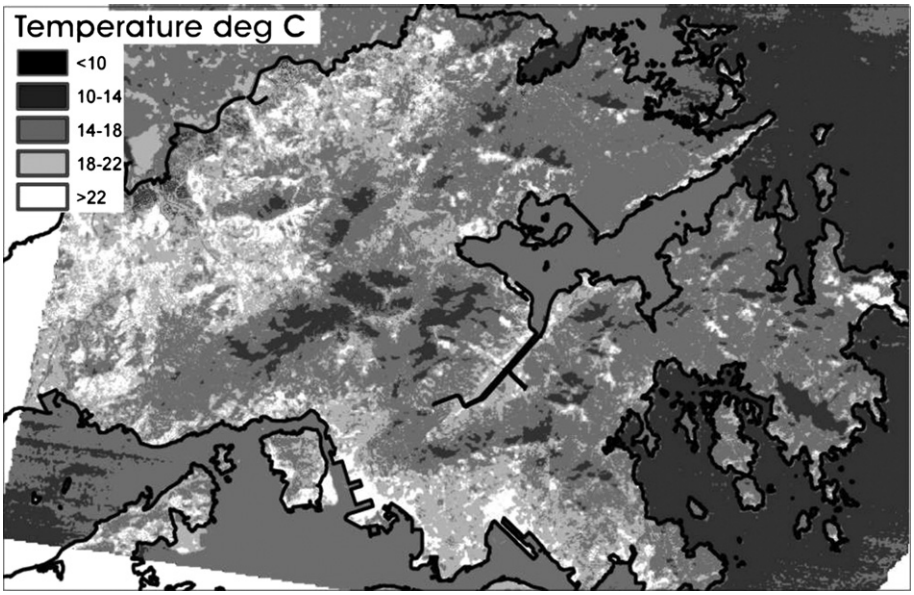

Fig. 5. Surface temperature image at 10 m resolution derived from ASTER thermal data corresponding to field data of 13 February 2007 (°C). For diurnal temperature variations, average half-hourly temperatures from 10 local climate stations are used to adjust image values.

3.4. The influence of temperature on emission activity

Current emission models are based on an emission factor defined for standard conditions represented by a temperature of 30 °C (303 K), and models are then adjusted for short-term temperature effects. BVOC flux is a function of foliar density, PAR and leaf surface temperature, but temperature appears to be the most important variable (Geron et al., 2000; Guenther et al., 2006). Therefore, data on spatial and temporal variations in the canopy temperature of a forest are essential. Temperature was calculated based on Equation (4) (Guenther et al., 1993, 1999)

$$\gamma_T = \frac{E_{opt} \cdot C_{T2} \cdot \exp(C_{T1} \cdot x)}{C_{T2} - C_{T1} \cdot (1 - \exp(C_{T2} \cdot x))} \quad (4)$$

where E_{opt} is the maximum normalized emission capacity (=1.9), C_{T1} and C_{T2} are the empirical coefficients for energy of activation and deactivation (=95 and =230 respectively), $x = ((1/T_{opt}) - (1/T))/R$, T is the current leaf surface temperature (in K), T_{opt} is the constant temperature (=312.5 K), and R is the gas constant (=0.00831).

This study adopted an empirical approach by deriving the current leaf surface temperature (T) from summer and winter satellite images acquired on 13 August 2008 and 31 January 2007. This is ideal, since thermal satellite data represent surface, as opposed to air temperature, which is used in most BVOC models, as air temperature is usually available from climate stations. The 90 m resolution thermal data were atmospherically corrected and enhanced to a resolution of 10 m using the emissivity modulation method (Nichol, 2009), and an accuracy (Mean Absolute Difference (MAD)) of within 1 °C has been observed for this conversion procedure. To adjust the images to the different dates and times of day of the field data, the images were regressed against half-hourly data from 10 local climate stations. The accuracy of this procedure is acceptable, since a daytime image has been shown to represent temperature distributions within +/−4 h of the image time (To et al., in press). The surface temperature images (Fig. 5) were then input to Equation (1) to compute the isoprene emission maps.

Finally, the isoprene fluxes (mgC g^{-1} h^{-1}) for Hong Kong were calculated for each field data collection time.

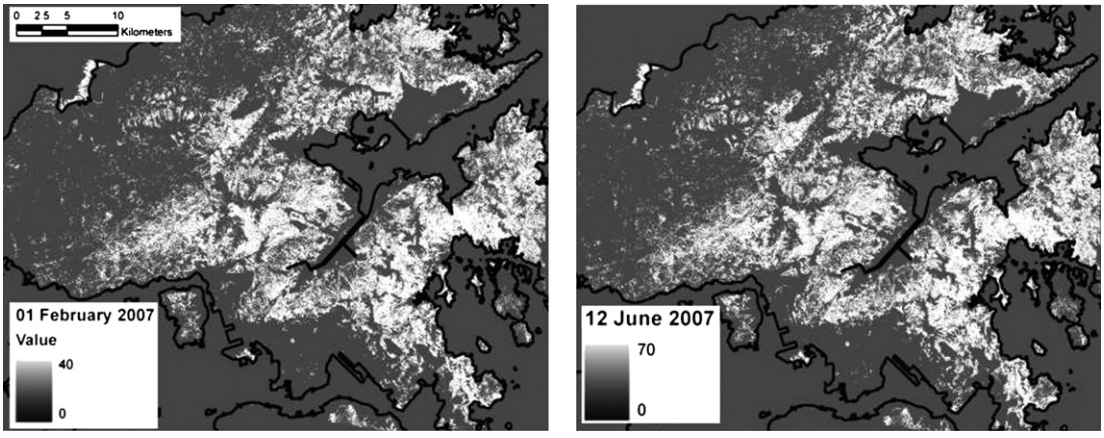

Fig. 6. Isoprene emissions on a. 1 February 2007 at 11 a.m. local time; b. 12 June 2007 at 3 p.m. local time (unit: mgC m^{-2} h^{-1}).

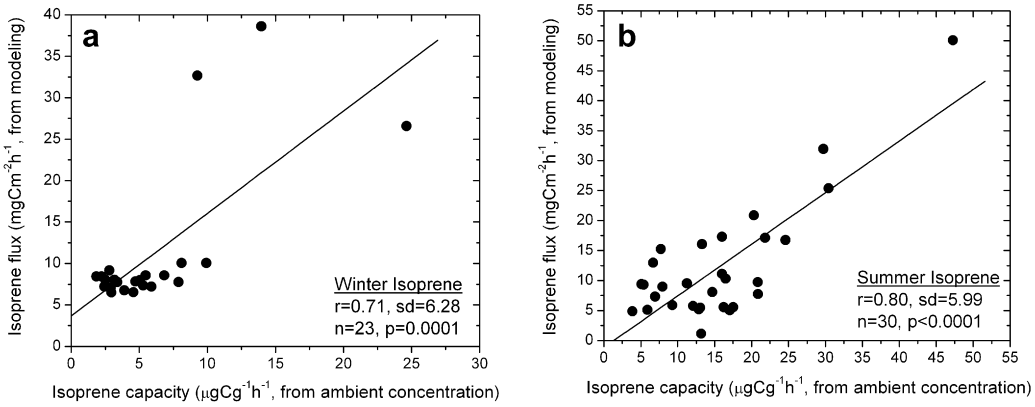

Fig. 7. Comparison between image-modelled isoprene flux with field concentration-derived isoprene capacity (sites pooled for forest, shrubland and grassland), a. winter; b. summer.

3.5. Field data collection: isoprene concentrations by canister sampling

Air samples were collected from representative sites of forest, shrubland and grassland within Hong Kong's country parks, which were identified using remote sensing, and located in the field by GPS with 1–2 m accuracy. A total of 53 samples on 13 days were obtained every one to two hours during both morning and afternoon and for both summer and winter, to account for different solar radiation conditions. The canisters were shipped to the Hong Kong Polytechnic University for chemical analysis by Gas Chromatography (GC) by the analytical system developed in the air laboratory. A full description is given in Chen et al. (2009).

For comparison of the field concentrations with the model outputs, we used a simple box model technique (with data on boundary layer height, and an estimate of isoprene lifetime) to estimate emission capacity (ε) from the ambient concentrations by adapting Wang et al.'s (2003) method for field conditions (Equation (5)). Since Wiedinmyer et al. (2005) show that the ratio of isoprene at 250 m above the ground (which tends to be similar to the boundary layer isoprene) ranges from 0.34 to 0.94 with an average of 0.66, concentrations measured near the surface were multiplied by 0.66. The derived "field emission capacity" from Equation (5) was then compared with the modelled emission rate produced for the times of the field data collections generated by the model (Fig. 7).

$$\varepsilon\left(\mu gC\ g^{-1}\ h^{-1}\right) = 40.9\,(C \cdot M \cdot V)/W \cdot t \qquad (5)$$

where 40.9 is the conversion factor from ppm to $\mu g\,m^{-3}$, C is the concentration (ppm), M is the molecular weight (ie. 68 for isoprene), V is the volume of the 1 m^2 air column (ie. boundary layer height · 1 m · 1 m), W is the dry weight of the square meter of leaf biomass at ground level (eg. 800 $g\,m^{-2}$ assumed for forest, from Fig. 3), and t is the isoprene lifetime of ca.1 h for tropical ecosystems (Karl et al., 2007; Lelieveld et al., 2008). The exact rate of uptake however, is subject to uncertainty since no site measurements of OH were collected at the same time as the field-measured isoprene concentrations.

Ayers and Gillett (1988) stated that the upward dispersal of pollutants from the surface in a strongly mixed boundary layer is 2 $m\,s^{-1}$. This would give only 20 min to reach our (average) boundary layer height of 600–700 m. So with an isoprene lifetime of one hour, and near to midday, the loss due mainly to chemical reactions would be balanced by an equal flux of isoprene from the surface. Thus for the box modelled conversion we have assumed the boundary layer to be homogeneous.

4. Results

Fig. 6 shows the modelled isoprene distributions over Hong Kong for a summer and a winter situation.

The values of foliar density (D) computed during this study from destructive sampling in sub-tropical evergreen secondary forest, are between 200 and 800 $g\,m^{-2}$, which appears reasonable, given that Alexandre (1981) quotes a range of 600–1100 $g\,m^{-2}$ from many studies in primary tropical rain forests. Our values are also somewhat lower than Geron et al.'s (1994) values for mature temperate deciduous and coniferous forests (375 $g\,m^{-2}$ and 700–1500 $g\,m^{-2}$ respectively), which were applied by Tsui et al. (2009) to Hong Kong. The LAI values from field measurement in this study, between 3 and 4, also appear considerably lower than the literature-derived values of 3–7 used by Tsui et al. (2009), probably because the literature values used assumed 100% canopy cover.

As expected, summer isoprene values, both from field concentrations as well as the modelled values were higher than for winter (Figs. 6 and 7) due to higher temperatures and higher PAR values in summer. The correlations between the field estimated isoprene emissions and modelled isoprene capacity values (Fig. 7) are significant at the 1% level for both summer and winter, but are higher in summer ($r = 0.80$) than in winter ($r = 0.71$). This fairly good agreement observed between the model results (emission rate) based on several physical and environmental parameters, and ambient field concentrations (emission capacity) in the study area, suggest that the basic emission model and emission capacities of Guenther et al. (1995) are robust, and applicable to tropical landscapes at a detailed level, and that remote sensing data can be used to estimate BVOC concentrations at detailed level for input to air quality modelling.

5. Conclusion

This study has demonstrated the application of a global BVOC emission model to a tropical landscape using high resolution remote sensing and site-specific field data. Unlike most previous BVOC modelling studies (Potter et al., 2001; Wang et al., 2003; Guenther et al., 2006; Tsui et al., 2009), the modelled results were validated using concentrations measured in the field, at precise locations and precise times corresponding to the computed model estimates. In view of the very large uncertainties noted in previous BVOC emission models and measurements (Geron et al., 1994; Guenther et al., 1995, 2006; Goldstein et al., 1998; Leung et al., 2010; Zheng et al., 2010; Rinne et al., 2002; Palmer et al., 2006), which Guenther et al. (1995, 2006) judge to be a factor of 3 or

higher, the results in this study indicate reasonable consistency between modelled and field-measured data, suggesting a promising role for remote sensing in obtaining detailed BVOC estimates over large study areas. For local air quality modelling where high temporal and spatial resolution is required, remote sensing appears to be the only feasible approach for tropical forested regions in view of their very high species, ecosystem and structural diversity. Although the forest in Hong Kong is evergreen, there is some leaf loss in the winter dry season, as the foliage retention period for tropical and sub-tropical evergreen forest is believed to be only 2 years (Liu et al., 2002). However this study assumed *D* and LAI to be constant for all seasons, which probably explains the lower correlation during winter.

Application to other study areas would require the collection of semi-permanent spatial data for the modelling, in the form of representative field data on leaf density and leaf area, along with temporal (eg. hourly) data from local climate stations. This would enable near-real time BVOC mapping for input to dynamic local air quality models, such as the Pollutants in the Atmosphere and their Transport over Hong Kong (PATH) model (Noonan et al., 2001), used by Hong Kong's Environmental Protection Department.

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