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Diurnal variations and vertical gradients of biogenic volatile and semi-volatile organic compounds at the Tomakomai larch forest station in Japan

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Abstract

Volatile and semi-volatile organic compounds (VOCs and SVOCs) in the atmosphere control oxidative capacity of air and formation of organic aerosols. To investigate sources, variations and fluxes of VOCs and SVOCs in the forest atmosphere, samples were collected in a larch forest at different heights in Tomakomai, Japan, from 3 to 5 September 2003 and were analyzed for VOCs (isoprene and α -pinene) and SVOCs (n-nonanal, n-decanal, glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal) using GC-FID and GC-MS. Isoprene (8–851 pptv) showed a diurnal variation with a maximum in daytime, whereas diurnal pattern was indistinct for α -pinene (6–145 pptv). SVOCs showed diurnal variations similar to isoprene, suggesting their origin to be biogenic. Denuder samplings of SVOCs demonstrated that up to 60% of SVOCs were present in aerosol particles. n-Nonanal and n-decanal were more abundant at lower altitude, suggesting their primary emissions from vegetations. In contrast, other four SVOCs showed an opposite or no trend and are considered as oxidation products of biogenic precursors such as isoprene. The averaged upward fluxes of isoprene and α -pinene were obtained to be 34.8 and 9.8 $\text{ng m}^{-2} \text{s}^{-1}$, respectively. Magnitudes of SVOC fluxes were comparable to those of α -pinene, indicating that SVOCs affect budgets of organic gases/aerosols over the forest.

1. Introduction

In the lower troposphere, volatile organic compounds (VOCs) play an important role in a number of chemical processes including formation/decomposition of O₃ and other oxidants (Fehsenfeld et al., 1992) as well as secondary formation of organic aerosols. Emissions of biogenic VOCs are suggested to be one order of magnitude larger than those of anthropogenic VOCs on global scale. Forest can act as a major source of biogenic VOCs, being dominated by isoprene (C₅H₈) and monoterpenes (C₁₀H₁₆; e.g., α-pinene). The emissions of VOCs from forests not only control oxidative capacity of ambient air, but also affect the air quality of the urban and semi-urban environments as well as remote atmosphere by the transport followed by a mixing with anthropogenic nitrogen oxides (NO_x).

Some organics that are produced photochemically from biogenic VOCs and/or emitted directly from vegetation and microbial processes have semi-volatile characteristics (Kavouras et al., 1999; Matsunaga et al., 2004). These semi-volatile organic compounds (SVOCs) are oxygenated, bearing carbonyl, hydroxyl, and carboxyl groups in their chemical structures. The oxygenated compounds are in many cases less volatile than their precursors and are potentially partitioned in gas phase and aerosol particles. Further, the biogenic SVOCs may participate in a new particle formation in the forest atmosphere (Kavouras et al., 1998). Such a process may play an important role in the earth climate system, because organic aerosol particles are hygroscopic and can act as efficient cloud condensation nuclei (Novakov and Penner, 1993).

To better understand the role of atmospheric organic compounds of biogenic origin, we need to obtain critical information including their emissions and transformation/degradation processes, as well as the budgets of the compounds between the forest and the atmosphere. But so far, such studies are limited and temporal variations of biogenic VOCs and SVOCs were rarely measured simultaneously over the forest canopy.

Moreover, information on the emissions/fluxes of oxygenated SVOCs between the forest and the atmosphere are very scarce, being in contrast to biogenic VOCs. In this study, we conducted 3-day observation to determine the concentrations of two VOC (isoprene and α -pinene) and six SVOC components (n-nonanal, n-decanal, glycolaldehyde, hydroxyacetone, glyoxal, and methylglyoxal) at two different heights using a 42 m high research tower in a Japanese larch forest in Hokkaido, Japan. Isoprene and α -pinene are dominant hydrocarbons emitted from forest plants, whereas the six SVOCs studied are major bi-functional carbonyls in the forest atmosphere (Matsunaga et al., 2003, 2004). Here we present diurnal variations and vertical profiles of VOCs and SVOCs. Further, fluxes of VOCs and SVOCs were calculated using a modified gradient method. The results are discussed in terms of photochemical degradation and production as well as secondary formation of organic aerosols.

2. Experiment

2.1. Sampling site

VOCs and SVOCs were sampled on a research tower (height, 42 m) of Tomakomai Flux Research Site (42°44' N, 141°31'E; elevation 140 m) in Japan during September 3-5, 2003. The schematic of the sampling site is presented in Fig. 1. This site is located within a plantation area (117 ha) dominated by a larch species of *Larix kaempferi* Sarg (Hirano et al., 2003). Larch is a dominant species of boreal forests in the northern part of East Asia, including Siberia. This site is characterized by a canopy height of 15 m on average, tree age of 45 years old and a good tree health condition. The fetch and the slope of the ground are 300-800 m and 1-2°, respectively, both of which are suitable for flux measurements. Air samplings for quantification of VOCs and SVOCs were carried out at heights of 22 and 38 m of the tower, which are equivalent to ca. 7 and 23 m above the canopy. During the sampling

period, weather condition was fine except for the period of after 1 pm on September 5 when it started to rain. Meteorological data including air temperature, wind speed/direction, humidity and photosynthetically active photon flux density (PPFD) were also collected on the tower. During the sampling period, air temperature and wind speed at a height of 27 m ranged from 12 to 23 °C and from 0.47 to 6.8 m s⁻¹, respectively.

2.2. Sampling methods for VOCs and SVOCs

Table 1 presents a sampling schedule of VOCs and SVOCs during this study. VOC samples were collected in 6 L canisters (Silico Can, Restek) that were pre-cleaned twice in a laboratory by purging helium at about 80 °C and pumped in vacuum prior to use. At heights of 22 and 38 m, sample air was drawn in the canister at a flow rate of 500 mL min⁻¹ through a bellows pump (Iwaki air pump type BA) and a thermal mass flow controller (STEC PAC-D2). Silico-steel tubings (GL Science, 1/4 inch) were used for sampling lines to minimize a potential adsorptive loss of VOCs in the lines. At a height of 8 m, on the other hand, air was collected in the canisters instantly without any flow control. A PTFE membrane filter was placed at the sampling inlet to remove aerosol particles. Ozone scrubber was not used because test samplings showed no significant decrease in concentrations of isoprene and α -pinene during the storage of 5 min to 1 week after sample collections.

Annular denuder sampling system was used to collect SVOCs in both gas phase and particles. Details of this method are described elsewhere (Matsunaga et al., 2003, 2004). Briefly, SVOC sampling system consists of cyclone-inlet (URG-2000-30EU), reaction tube, multi channel front annular denuder (URG-2000-30 x 242-3CSS), quartz filter, and a back-up denuder and a diaphragm pump. Based on the difference in diffusion rates of gas and particles, the front denuder collects volatile compounds and the filter and backup denuder collect particulate compounds. The inner walls of the denuders were coated with a collection reagent

of 5% O-benzylhydroxylamine hydrochloride ($C_6H_5CH_2ONH_2 \cdot HCl$; BHA-HCl) and 3% XAD-7. Gas phase carbonyls that contact with the reagents and immediately react with them are retained on the denuder walls in the form of BHA-oximes. To remove oxidants in air, nitrogen monoxide (NO) was mixed with the sample air at the inlet, resulting in the NO concentration in the sample air to be 2 ppmv. A model calculation of gas-phase chemical reactions has shown that this method effectively removes OH and NO_3 , as well as O_3 (Mochida et al., 2003). Pump exhaust was passed through a NO trap (Nitta Corporation) to avoid contamination of ambient air with high NO_x . Sample air was sucked at a constant flow rate of $10 L min^{-1}$ for 3 hours. After sampling, SVOCs collected on denuders were immediately extracted with 10 ml methanol and the extracts were stored in centrifugal tubes at $-20^\circ C$ prior to analysis. Particulate SVOCs collected on filters were also stored at $-20^\circ C$ in clean glass vials (50 ml) with a Teflon-lined cap.

2.3. Analytical methods for VOCs and SVOCs

VOCs were analyzed by GC-MS and all the analyses were completed within two weeks after the sample collection. Using an automated concentration system (DKK GAS-30) and a diaphragm pump, VOC sample air in the canister was transferred to an absorption column (1/8 inch) containing 150 mg of Tenax TA at $45 ml min^{-1}$ for 10 min at room temperature. Tenax TA column was heated to $280^\circ C$ for 15 min and the VOCs trapped were transferred to a capillary GC column. Desorbed VOCs were then trapped at the inlet of capillary column at $-150^\circ C$ using a cryofocusing unit (DKK GAS-2BCF) and then heated to $180^\circ C$ to transfer VOCs to a GC-MS system (GC: Hewlett Packard HP 6890, MS: HP 5973). A CP-Sill 8CB column (60 m \times 0.25 mm id \times 0.25 μm film thickness) was used with the GC oven temperature programmed from $30^\circ C$ (5 min) to $250^\circ C$ (10 min) at $20^\circ C min^{-1}$. Post run was conducted at $320^\circ C$ for 5 min to clean up the GC column. Helium was used as a

carrier gas at a flow rate of 2 ml min⁻¹. Stainless steel tubes of the sampling lines were heated to 100 °C to reduce absorption of VOCs on lines.

The mass spectrometer with an electron impact ionization source was operated at a selective-ion monitoring mode. Monitoring ions of m/z 67 and 72 were used for quantification of isoprene and m/z 93, 121, and 136 were for α -pinene. Standard VOC mixture (Taiyotoyosanso Corp.) containing 10 hydrocarbon species of 20 ppbv was analyzed by the GC-MS at different dilution ratios, and a linearity of the GC-MS response to the sample amount was confirmed ($R^2 \geq 0.99$). This standard was analyzed once a day for calibration before the atmospheric sample analysis.

SVOCs were analyzed as follows. First, the methanol extracts from the denuder were centrifuged to remove remaining XAD-7 particles. The filter samples were extracted with methanol and were combined to the extracts from the backup denuders which contain BHA-HCl reagent. This allows the carbonyls on the filter to be derivatized to BHA-oximes. The extracts were concentrated in a pear shaped flask (50 ml) using a rotary evaporator down to 0.5 ml, to which 10ml of ethyl acetate, 7 ml of pure water and 1 ml of 8 N hydrochloric acid were added. After the shaking of pear shape flask, the aqueous layer was removed. The ethyl acetate layer was concentrated to ca. 0.5 ml and transferred to 1.5 ml glass vial, to which 50 μ l of Sylon BFT (BSTFA:TMCS = 99:1, Supelco Corporation) was added after dryness. The vial was heated at 60 °C for 60 min for derivatization. The solvents were then evaporated under a gentle Argon stream and the derivatives were dissolved in 50 μ l of n-hexane. By the procedure above, carbonyl groups of compounds to be quantified are derivatized to oximes whereas hydroxyl and carboxyl groups are derivatized to trimethylsilyl ethers and esters, respectively (Figure 2).

SVOC-derivatives were quantified using a capillary GC-FID (Carlo Erba HRGC MEGA 2 series, column; DB-1701, 60 m \times 0.32mm(I.D.) \times 0.25 μ m). The GC oven

temperature was programmed from 70 to 150 °C at 20 °C min⁻¹ and then to 280 °C (10 min) at 4 °C min⁻¹. More details of SVOC analysis were described elsewhere (Matsunaga and Kawamura, 2000; Matsunaga et al., 2004).

As described above, concentrations of six SVOCs (n-nonanal, n-decanal, glycolaldehyde, hydroxyacetone, glyoxal, and methylglyoxal), which have been found in high concentrations in the forest (Matsunaga et al., 2003, 2004), are presented in this paper. As an oxidation product of α -pinene, pinonic acid was quantified by this method, but its concentration was in most cases below the detection limit (4 ng m⁻³). Although dimmers of α -pinene oxidation products have recently been reported (Tolocka et al., 2004), identification/quantification of such compounds were not attempted in this study. Field blanks of SVOCs correspond to 1.3-30 ng m⁻³ depending on compounds. They were used to correct SVOC concentrations. In the case of VOCs, blanks levels are low enough and thus neglected for calculations of VOC concentrations. Precisions (reproducibility) of SVOC analysis ranged from 2 to 14 %, whereas those of VOCs were from 6 to 8 %.

2.4. Calculations of vertical fluxes of VOCs and SVOCs

VOC and SVOC fluxes were calculated by a modified gradient method. Briefly, a VOC flux F_s (ng m⁻² s⁻¹) was calculated from the following equation:

$$F_s = -K \frac{\Delta c}{\Delta z} \quad (1)$$

where K (m² s⁻¹) is an eddy diffusion coefficient. Δc (ng m⁻³) is a difference in the VOC and SVOC concentrations between two sampling heights of 22 and 38 m. Δz (m) is the difference in sampling heights (38 - 22 = 16 m). Eddy diffusion coefficient K was obtained from the following equation assuming that eddy diffusion coefficients for heat and mass are identical:

$$\rho C_p \overline{w'T'} = \rho C_p \times K \times \frac{\Delta T}{\Delta z_T} \quad (2)$$

where $\rho C_p \overline{w'T'}$ is a sensible heat flux (W m^{-2}), which was obtained by the eddy covariance method using the data measured by a three-dimensional sonic anemometer-thermometer at 27 m of the tower (Hirano et al., 2003). ρ and C_p are a density (g m^{-3}) and an isopiestic specific heat ($\text{J g}^{-1} \text{K}^{-1}$) of air, respectively. ΔT is a difference in air temperature (K) at heights of 22 and 32 m, and Δz_T is 10 m. K was not obtained accurately when ΔT was so small. Such situation occasionally happened at night and early morning, and the K values were eliminated for such cases from the analysis of data.

3. Results and discussion

3.1. Diurnal variations of VOCs

Mixing ratios of isoprene and α -pinene at heights of 8, 22, and 38 m are presented in Fig. 3 together with air temperature and PPFD. Mixing ratios of isoprene both at 22m and 38m increased with an increase of PPFD and air temperature, showing a maximum in midday. The maximum concentrations of isoprene during the sampling periods were 851 and 700 pptv at heights of 22 and 38 m, respectively. Its nighttime concentrations were on the other hand very low, down to 23 and 13 pptv at heights of 22 and 38 m, respectively. Concentrations of isoprene positively correlated with PPFD ($R^2 = 0.75$ at 22 m) and air temperature ($R^2 = 0.52$ at 22 m), being consistent with the theory that biogenic isoprene emission is mainly controlled by leaf temperature and light intensity (Guenther et al., 1993). Concentrations of α -pinene were approximately one order of magnitude lower than those of isoprene, and the maximum concentrations of α -pinene at heights of 22 and 38 m were 145 and 94 pptv, respectively. In the case of α -pinene, the diurnal variations at both heights were less clear than those of isoprene. This may be related to the differences in the emission mechanism between isoprene

and α -pinene; α -pinene emission is not so sensitive as isoprene to the PPF (Kesselmeier and Staudt, 1999).

At a height of 8 m, concentrations of VOCs were obtained twice a day (see Table 1). Being similar to the cases of 22 and 38 m, diurnal patterns of isoprene (range: 8-503 pptv) and α -pinene (range: 33-93 pptv) at the 8 m height were also different; isoprene showed a clear diurnal pattern whereas α -pinene stayed almost unchanged throughout day and night.

3.2. Diurnal variations of SVOCs

Concentrations of six SVOCs (gas + particle) at heights of 22 and 38 m are presented in Fig 4. All the SVOCs showed diurnal variations with maxima in daytime. If SVOCs are directly emitted from the forest, it is reasonable that they show diurnal patterns with maxima in daytime, because their emission may positively correlate to ambient temperature and/or PPF like isoprene. On the other hand, if the SVOCs are secondarily formed, they may also show daytime maxima because photochemical processes and emissions of biogenic precursors are enhanced in daytime. Therefore, the diurnal variations of SVOCs are consistent with the characteristic of VOCs of biogenic origin. Because glycolaldehyde and hydroxyacetone (Fig 4c and d) are known as two major oxidation products of isoprene with methylvinylketone and methacrolein being as intermediates (Finlayson-Pitts and Pitts, 2000), our results suggest that isoprene oxidation significantly controls the abundances of SVOCs at the sampling site. Actually, glycolaldehyde and hydroxyacetone (Figs. 4c and d) showed a co-variation with isoprene (Fig. 3a), suggesting that isoprene oxidation is a significant process to control the SVOC distributions. Glyoxal and methylglyoxal (Figs. 4e and f) are also known to be the oxidation products of isoprene. They showed a similar temporal variation with isoprene, implying the contribution of isoprene oxidation to their abundance. Glyoxal and methylglyoxal may also be produced in part from other biogenic precursors

because their carbon structures are simple bearing only carbonyl groups, which are most typical functional groups being introduced as a result of atmospheric oxidation.

As presented in Fig. 4, significant differences in concentrations of SVOCs at two sampling heights were shown for some samples. For instance, concentrations of n-nonanal and n-decanal (Figs. 4a and b) at a height of 22 m were generally significantly higher than those at 38 m. On the other hand, the differences are less significant for other four carbonyls, glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal. This point will be discussed in more detail below.

Table 2 summarizes concentration ranges and means of SVOCs as well as those of VOCs.

3.3 Gas/particle partitioning of SVOCs

Attributing the SVOCs collected by the front denuder to be originally in gas phase and those on the filter and backup denuder to be in particles, the gas/particle partitioning of SVOCs can be obtained. As reported previously (Matsunaga et al., 2003; 2004), results from denuder sampling suggests a presence of SVOCs in aerosol particles. Ranges and means of the ratios of [particle]/[gas + particle] during the sampling period are calculated with a correction of measured collection efficiency of denuders for SVOCs. The results are summarized in Table 3. The mean ratios ranged from 0.4 to 24 % for six SVOCs, which are within the range reported in previous studies (Matsunaga et al., 2003; 2004).

Such high abundances of particulate carbonyls are surprising, taking into account the fact that boiling points of some carbonyls compounds (e.g, glyoxal) are even lower than water. However, recent laboratory studies have suggested an unexpected enhancement of particle formation due to volatile carbonyl compounds (Jang et al., 2002). They attributed the presence of carbonyl in particles to be originated from chemical reactions in particles, such as

formation of acetals. Further, reactions of semi-volatile carbonyl compounds to form aerosol particles via polymerization have been observed by chamber studies (Kalberer et al., 2004; Liggio et al., 2005). These mechanisms possibly explain the unexpectedly large abundance of SVOCs in aerosol particles as observed in this study. But so far, it is not known whether the carbonyls as a unit of polymers in aerosol particles can be detected by the method used in this study. Polymerization is potentially an important process for the formation of biogenic aerosols, and further studies are required to better understand the gas/particle partitioning of SVOCs.

3.4 Vertical gradients of VOCs and SVOCs and their implications for the emission and formation processes

In addition to the diurnal variation of VOCs and SVOCs, their vertical gradients may provide information on their origins. Fig. 5 presents differences in VOC and SVOC concentrations at two heights of 22 and 38 m by:

$$L = \log_{10} \frac{[C_{38}]}{[C_{22}]} \quad (3)$$

where C_{38} and C_{22} are the concentrations of compounds at heights of 38 and 22 m, respectively. If there is no vertical gradient observed, L is equal to zero. Apparently, in the cases of isoprene, α -pinene, n-nonanal, and n-decanal, negative L values are more frequently observed than positive L values (Fig. 5). In contrast, frequency of positive L values is similar to or more than that of negative L values for glycolaldehyde, hydroxyacetone, glyoxal, and methylglyoxal.

To evaluate whether or not the averaged L values are significantly different from zero and have systematic trends, t-test was applied for eight organic compounds studied (Table 4). By 10% two-sided t-test, averages of the ratios for the first four compounds, isoprene,

α -pinene, n-nonanal and n-decanal, are confirmed to be significantly lower than zero. This indicates that their main sources are present in the forest below the canopy level. It has been well known that isoprene and α -pinene are major biogenic VOCs emitted from vegetations. A significant emission of nonanal and decanal from vegetation and microbial processes has been suggested (Kesselmeier and Staudt, 1999), being consistent with the vertical gradients of these two aldehydes measured in this study. This also indicates that a possible secondary formation of n-nonanal and n-decanal (*e.g.*, oxidation of aliphatic compounds) is relatively minor compared to the direct emission from vegetations. It should be noted that concentrations of n-nonanal obtained in this study is potentially biased because omega-9 unsaturated fatty acids attached to filters and denuders during the atmospheric sampling possibly decompose to form n-nonanal via ozonolysis in a course of extraction and analysis of SVOCs (Fruekilde et al., 1998). On the other hand, this is not the case for n-decanal because of the absence of biological unsaturated fatty acids containing a double bond at omega-10 position.

On the other hand, different trend was observed in the vertical distributions of glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal (Fig. 5). In the case of glyoxal and methylglyoxal, downward flux was significant on average basis. On the other hand, mean fluxes of glycolaldehyde and hydroxyacetone were not significantly different from zero. This result suggests that possible primary emissions of these four carbonyls from vegetations are, even if present, less important than other sources. Since diurnal variations of these compounds that are similar to isoprene suggest a biogenic origin, secondary formation from biogenic precursors by photochemical oxidation are their most likely sources. Isoprene is known to produce glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal via O_3 and OH radical reactions (Finlayson-Pitts and Pitts, 2000). Hence isoprene may contribute substantially to the concentrations of these four carbonyls.

To confirm that secondary formation from isoprene does not lead to negative L values, time scales for the production of these four compounds from isoprene were calculated using a box model. In this model, both 1st oxidation products (*i.e.*, methylvinylketone and hydroxyacetone) and 2nd oxidation products (*i.e.*, glyoxal, methylglyoxal and methacrolein) were included. Concentrations of isoprene-reaction products with O_3 and OH were calculated using the maximum O_3 concentration measured at the site (ca. 40 ppbv), and OH concentration fixed to be 1×10^7 molecules cm^{-3} , and reaction rate constants for O_3 and OH (Paulson et al., 1992; Paulson and Seinfeld, 1992). Photolysis rates were calculated based on the latitude at the site and the solar zenith angle at noon. Time evolutions of the concentrations of carbonyls were obtained by solving the differential equations numerically with a 4th-order Runge-Kutta scheme (Jain, 1984).

Calculated temporal evolution of the concentrations of isoprene and the degradation products, and their formation rates, are presented in Fig. 6. The results indicate that at least several tens of minutes are necessary in order that glyoxal, methylglyoxal, glycolaldehyde, and hydroxyacetone can be produced from isoprene. On the other hand, a residence time of air below the sampling tower in daytime was calculated to be on the order of minutes from the diffusion coefficients as well as air volume below the sampling heights. Thus, SVOCs (glyoxal, methylglyoxal, glycolaldehyde, and hydroxyacetone) are produced not only below the sampling height (22-38 m) in the forest, but also above it. This results in a uniform vertical distribution of SVOCs. The reasons of positive L values observed for glyoxal and methylglyoxal may be caused by dry deposition on leaves, enhanced photochemical formation above the canopy due to enhanced light intensity and oxidant concentrations, or their transport into the forest from the outside. From the dataset in this study, however, it is difficult to specify which process is responsible for vertical gradients of glyoxal and methylglyoxal.

3.5 Fluxes of VOCs and SVOCs over the forest

Based on the modified gradient method described in the experimental section, vertical fluxes of VOCs and SVOCs were calculated from the differences in the concentrations at heights of 22 and 38 m. Table 5 summarizes mean fluxes for VOCs and SVOCs obtained in this study. The mean fluxes of isoprene and α -pinene during the sampling were 34.8 and 9.8 $\text{ng m}^{-2} \text{s}^{-1}$, respectively. To our knowledge, no flux measurements of VOCs over a larch forest have been conducted. However, for instance, the magnitudes of our isoprene fluxes are comparable to the values 40.5-183 $\text{ng m}^{-2} \text{s}^{-1}$ reported over a sitka spruce forest in southwestern Scotland (Beverland et al., 1996) with similar daytime maximum air temperature (<15 – 19 °C). On the other hand, α -pinene fluxes obtained in our study are much lower than those reported in the southwestern Scotland (24.7-156 $\text{ng m}^{-2} \text{s}^{-1}$).

Being similar to the vertical profiles of SVOCs shown in Fig. 5, SVOC fluxes can be separated into two groups. Mean fluxes of n-nonanal and n-decanal are positive (upward) on average (Table 5). In contrast, fluxes of other SVOCs, that is, glycolaldehyde, hydroxyacetone, glyoxal, and methylglyoxal, are rather unclear if their uncertainty (one standard deviation) was considered. As discussed above, these SVOCs may not be emitted from the forests significantly, rather they are likely produced above/below the canopy by the photochemical oxidation of their precursors such as isoprene and, to a lesser extent, α -pinene. Sum of the mean fluxes of n-nonanal and n-decanal is 8.3 $\text{ng m}^{-2} \text{s}^{-1}$, whereas that of glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal fluxes is -18.4 $\text{ng m}^{-2} \text{s}^{-1}$. The summed flux of n-nonanal and n-decanal is nearly equal to the α -pinene flux, meaning that supply of n-nonanal and n-decanal from vegetation to the atmosphere is significant at this site.

The large positive (upward) and negative (downward) fluxes of SVOCs imply its

potential importance to the budget of organic gases and aerosols in the interface between the forest and the atmosphere. As SVOCs are more polar and thus are stickier than VOCs, adsorptive loss on leaves and stems and their re-evaporation in daytime may control, at least in part, their vertical fluxes. This adsorption/evaporation process possibly enhances the diurnal behavior of the SVOCs, in particular bi-functional carbonyls that are produced by the oxidation of isoprene. Further studies are required to better understand the atmospheric behavior of SVOCs and the importance of their fluxes, particularly in terms of the formation of biogenic aerosols.

4. Summary and conclusions

Diurnal distributions and vertical gradient of two VOCs (isoprene and α -pinene) and six SVOCs (n-nonanal, n-decanal, glyoxal, methylglyoxal, glycolaldehyde, and hydroxyacetone) were studied over the larch forest in Hokkaido, Japan. Diurnal patterns of six SVOCs with a maximum in daytime suggest that they are mainly of biogenic origin. Substantial presence of SVOCs in aerosol particles is suggested by denuder samplings, being consistent with previous studies. A significant decrease in the concentrations at higher altitude was observed for n-nonanal and n-decanal, suggesting that they are mainly released directly from the vegetations. On the other hand, other four SVOCs (glyoxal, methylglyoxal, glycolaldehyde, and hydroxyacetone) that are known as oxidation products of isoprene show on average no- or opposite trends in vertical distributions. This indicates that direct emissions of these four carbonyls from vegetations are minor and that bi-functional carbonyls are mainly produced by photochemical oxidation of biogenic organic compounds emitted to the air. Calculations of the VOC and SVOC fluxes have revealed that emission of SVOCs are substantial in comparison to VOCs, suggesting that SVOCs are important components to better understand the budget of organic gases and aerosols in the forest atmosphere.

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Figure captions

Fig. 1. Schematic representation of the research forest and the tower (sampling site).

Fig. 2. Two-step derivatization of bi-functional carbonyl compounds used in this study. An example for hydroxyacetone is presented.

Fig. 3. Concentrations of VOCs (isoprene and α -pinene) at heights of 8 m (cross), 22 m (open circle), and 38 m (solid square) above the ground level. Air temperature and PPFD at a height of 27 m are superimposed on the figure.

Fig. 4. Concentrations of six SVOCs (n-nonanal, n-decanal, glycolaldehyde, hydroxyacetone, glyoxal and methylglyoxal,) at heights of 22 m (open circle) and 38 m (solid square) above the ground level. Air temperature and PPFD at 27 m are superimposed on the figure.

Fig. 5. Vertical gradients of VOCs and SVOCs represented by $L = \log_{10}([\text{Concentrations at 38 m}]/[\text{Concentrations at 22 m}])$. The raw data points, means, and one-standard deviations are presented by horizontal lines, open circles, and solid vertical bars, respectively. The values whose concentrations at one of two heights were lower than their errors originating from blank subtractions are not included here because of a large uncertainty in L .

Fig. 6. Result from a box model calculation of photochemical oxidation of isoprene. Initial concentration of isoprene is 2.5×10^{11} molecule cm^{-3} . (a) Time profiles of VOC and

SVOC concentrations after introduction of isoprene to the system. (b) Formation rates of VOCs and SVOCs as a function of time.

Table 1. Start Time of VOC and SVOC samplings

Date	Height	VOCs	SVOCs
3 September	22, 38m	9:00, 12:15, 16:45, 20:00	8:00, 12:20, 16:30, 22:00
	8m	13:00	—
4 September	22, 38m	0:00, 6:10, 9:30, 13:00, 16:30, 19:00	5:30, 9:00, 12:30, 16:00, 22:00
	8m	0:00, 13:15	—
5 September	22, 38m	6:00, 10:00, 13:00	5:30, 9:00, 12:30
	8m	0:00, 13:15	—

Table 2. Concentrations of VOCs and SVOCs at heights of 22, 38 and 8 m

		22 m			38 m			8 m		
		n ^a	Range	Mean	n ^a	Range	Mean	n ^a	Range	Mean
<i>VOCs (pptv)</i>	isoprene	14	23-851	225	14	13-700	163	5	8-503	219
	α-pinene	14	24-145	67	14	6-94	43	5	33-93	70
<i>SVOCs (ng m⁻³)</i>	n-nonanal	11	13-106	60	12	≤7-76	37	—	—	—
	n-decanal	11	≤9-92	56	12	9-68	35	—	—	—
	glycolaldehyde	11	18-432	203	12	62-668	226	—	—	—
	hydroxyacetone	11	≤13-267	126	12	≤13-358	134	—	—	—
	glyoxal	11	26-106	60	12	30-136	66	—	—	—
	methylglyoxal	11	36-271	155	12	64-415	174	—	—	—

^aNumber of samples.

Table 3. Collection efficiency of denuders and Ratios of particle/(gas + particle) (%) determined from the denuder and filter analysis

Compounds	C E ^a	22 m			38 m		
		n ^b	Range ^c	Mean ^c	n ^b	Range ^c	Mean ^c
n-nonanal	0.95 ± 0.07	11	0-57	21	11	0-32	16
n-decanal	0.91 ± 0.12	10	0-55	23	12	0-57	24
glycolaldehyde	1.00 ± 0.00	11	0-45	15	12	2-38	17
hydroxyacetone	0.85 ± 0.12	9	0-27	7	11	0-51	15
glyoxal	0.81 ± 0.03	11	0-43	10	12	0-18	8
methylglyoxal	0.71 ± 0.20	11	0-42	5	12	0-4	0.4

^a Collection efficiency (CE) of denuders that was calculated by $1-(C_1/C_2)$ where C_1 and C_2 are concentrations of SVOCs collected by first and second denuders, respectively, in the absence of filters. Averages of two experiments are presented. Potential artifacts by attachment of particles on denuders are not considered. ^b Number of samples. Samples whose concentrations (gas + particles) were less than blank levels were omitted. ^c Ratios of gas/(gas + particle) after a correction of CE. The zero value means that the SVOC concentration in particles after a correction of CE is calculated to be ≤ 0 .

Table 4. Results of two-sided t-test for the null hypothesis $\log(C_{38}/C_{22}) = 0$

Compounds		n ^a	t ^b	$P(T < t)$ ^c	10 % two-sided t-test ^d
VOCs	isoprene	14	-3.34	0.53 %	rejected
	α-pinene	14	-3.39	0.48 %	rejected
SVOCs	n-nonanal	11	-2.12	6.0 %	rejected
	n-decanal	11	-6.06	0.019 %	rejected
	glycolaldehyde	11	1.41	19 %	not rejected
	hydroxyacetone	10	-0.37	72 %	not rejected
	glyoxal	11	2.79	1.9 %	rejected
	methylglyoxal	9	1.90	8.6 %	rejected

^a Number of samples subjected to the t-test. ^b $t = (\bar{L} - 0) \sqrt{V/n}$, where \bar{L} and V are mean and

variance of $\log(C_{38}/C_{22})$, respectively. ^c Limit of probability that null hypothesis is

rejected by 10 % two-sided t-test. ^d “rejected” means that the $\log(C_{38}/C_{22})$ is significantly

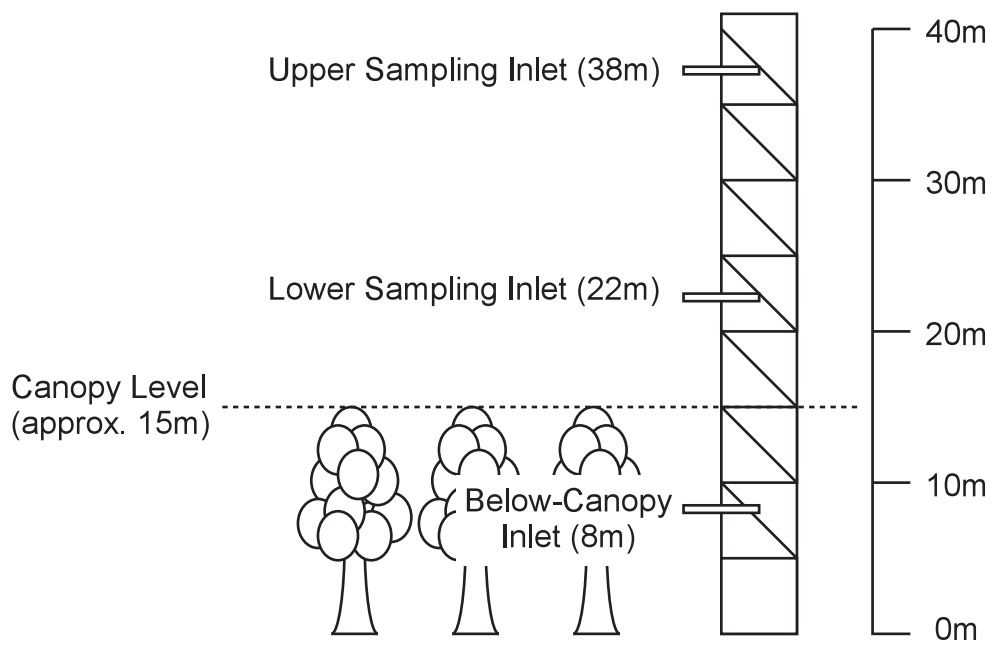
different from zero by 10% two-sided t-test.

Table 5. *Mean vertical fluxes ($\text{ng m}^{-2} \text{s}^{-1}$) of VOCs and SVOCs studied*

Compounds	Mean ($\pm 1\sigma$)^a
<i>VOCs</i>	
isoprene	34.8 ± 80.8
α -pinene	9.8 ± 9.0
<i>SVOCs</i>	
n-nonanal	3.8 ± 7.1
n-decanal	4.4 ± 4.0
glycolaldehyde	-6.9 ± 22.1
hydroxyacetone	1.1 ± 11.0
glyoxal	-3.5 ± 8.8
methylglyoxal	-9.0 ± 22.7

^a Positive values correspond to upward flux.

Fig. 1 Ieda et al.



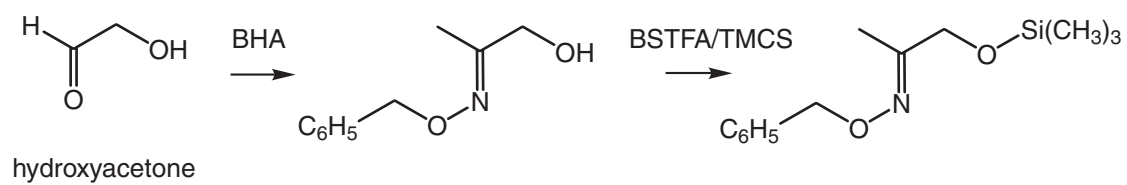


Fig. 3 Ieda et al.

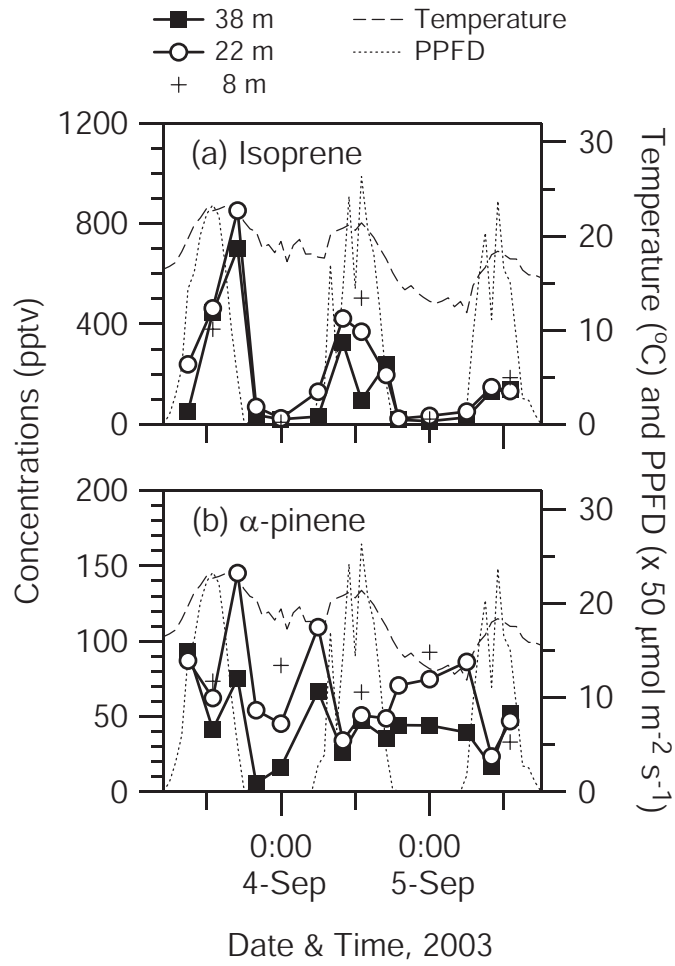


Fig. 4 Ieda et al.

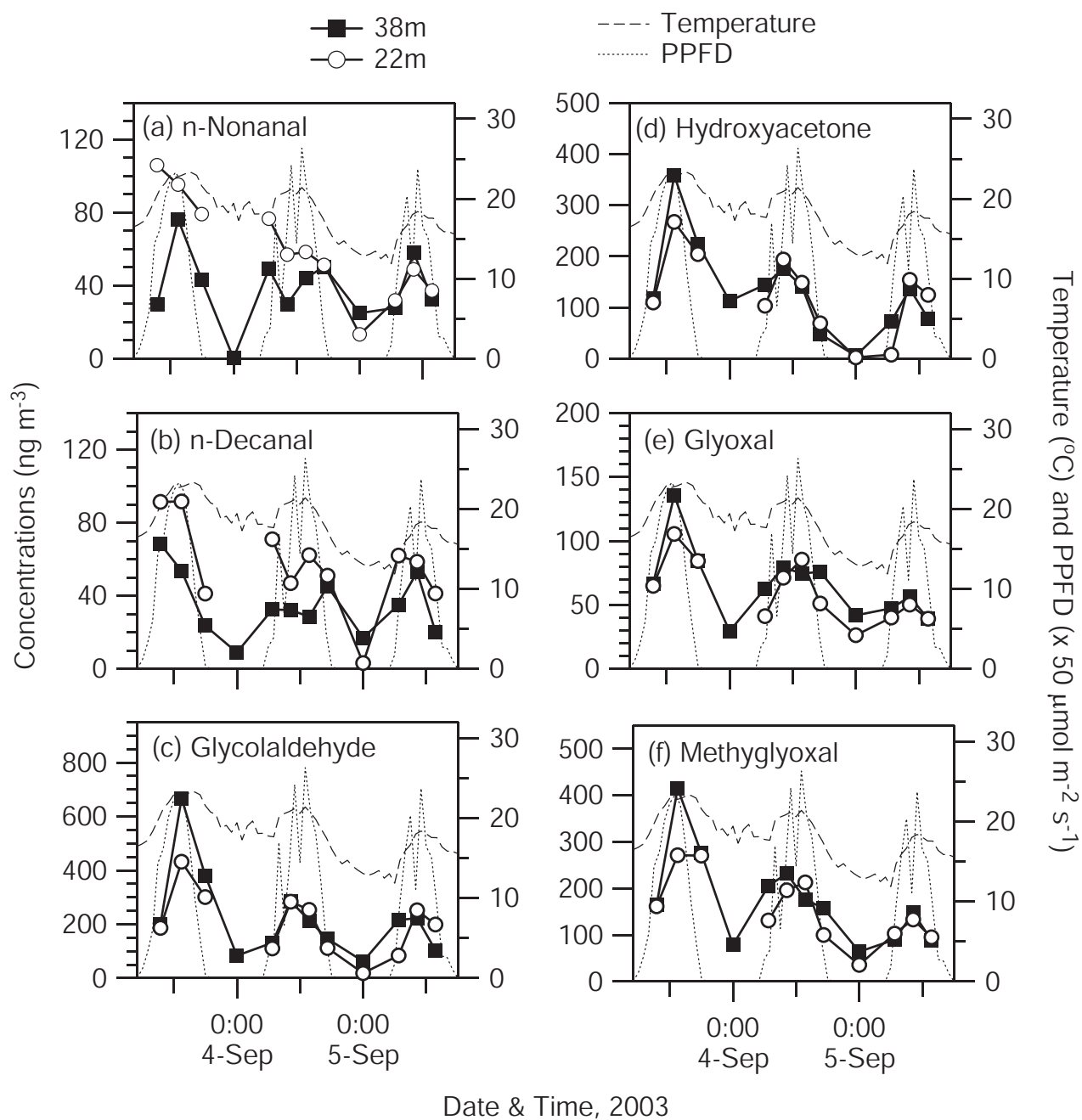


Fig.5 Ieda et al.

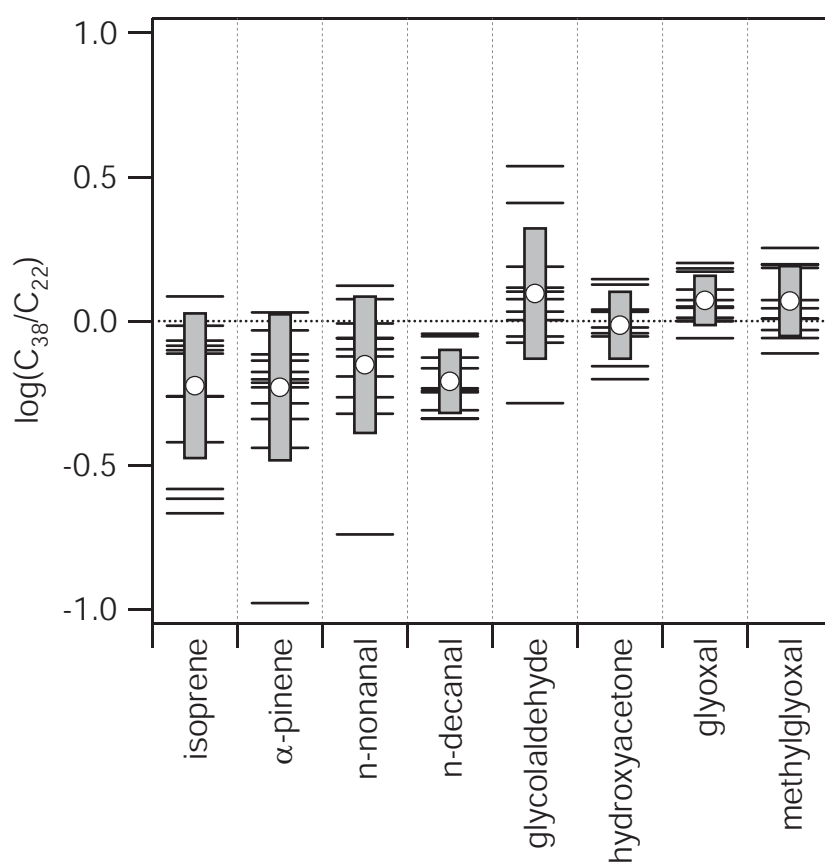


Fig. 6 Ieda et al.

