The Variation on the Atmospheric Concentrations of Biogenic Carbonyl Compounds and their Removal Processes in the Northern Forest at Moshiri, Hokkaido Island in Japan

1, 2, *, ** Sou Matsunaga, 1 Michihiro Mochida and 1 Kimitaka Kawamura

1 Institute of Low Temperature Science, Hokkaido University, N19 W8, Kita-Ku, Sapporo, Hokkaido, 060-0819, Japan

2 Graduate School of Environmental Earth Science, Hokkaido University, N10 W5, Kita-Ku, Sapporo, Hokkaido, 060-0810, Japan

*Present address: Atmospheric Chemistry Division, National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO 80303, U.S.A.

**Present affiliation: Applied Chemistry Division, Faculty of Engineering, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

Corresponding Author: Sou Matsunaga (e-mail: smatsu@ucar.edu)

Fax: +1-303-497-1477
Abstract

Biogenic aldehydes, hydroxycarbonyls and dicarbonyls in gas and particle phases were collected with an annular denuder sampling system (ADSS) in a Quercus Crispula and Picea Glehnii Mast mixed forest. Eighty samples were collected from 22 to 29 August, 2002. The size distributions of aerosols were also observed concurrently with a scanning mobility particle sizer (SMPS). The gaseous concentrations of these carbonyl compounds ranged from the detection limit (approximately 1 pptv) to 154 pptv (630 ng m\(^{-3}\), 4-oxopentanal), and the particulate concentrations ranged from the detection limit (approximately 3 ng m\(^{-3}\)) to 200 ng m\(^{-3}\) (4-oxopentanal). Although the production processes of these compounds are different from each other, the temporal variations of the gaseous concentrations were quite similar. In addition, the variation was also similar to that of the ambient temperature. Furthermore, gas-to-particle conversion was suggested to be an important removal process of these compounds. We could evaluate the importance of the gas-to-particle conversion as a removal process of the gaseous species by an ADSS measurement. In addition, the results of our experiment indicated that the conversion includes two processes. The first is an adsorption onto the aerosols which have already existed in the atmosphere. The next is dissolution into the water phases in the aerosols. The latter process was particular to water soluble compounds. The measurement allowed us to identify the most likely removal processes of biogenic semi-volatile organic compounds (SOCs). In this paper, we discuss about these processes of semi-volatile and biogenic carbonyls in the forest atmosphere.

Index Terms: annular denuder, adsorption, vaporization, semi-volatile, isoprene oxidation products, gas-to-particle conversion
1. Introduction

Plants and microbes in the forest are known to produce many organic compounds, and a part of them can be vaporized to the atmosphere. The compounds include isoprene, monoterpenes, 2-methyl-3-buten-2-ol (232MBO) [Hewitt and Street, 1992; Kesselmeier and Staudt, 1999; Isebrands et al., 1999; Serca et al., 2001]. These organics react with oxidants such as OH, ozone and NO$_3$ in the air and/or on plant surfaces [Atkinson et al., 1989; Atkinson, 1990]. However, we have so far little knowledge of emission and removal processes of these organic compounds.

Most products of these atmospheric reactions contain oxygen atoms in their molecule, and these oxygenated compounds often have lower vapor pressures than that of their precursors. Organic compounds that have low vapor pressures tend to condense into liquid or solid. This condensation includes gas-to-particle conversion of semi-volatile organic compounds (SOCs) in the atmosphere. The gas-to-particle conversion of biogenic SOCs produces new aerosols in the forest atmosphere [Kavouras et al., 1998; Kavouras et al., 1999]. Furthermore, these biogenic SOCs can also grow the aerosols via their uptake onto the aerosols that are already in the atmosphere [Jang and Kamens, 2001; Matsunaga et al., 2003; Jang et al., 2003; Matsunaga et al., accepted to Chemosphere]. Because aerosols reflect and scatter solar radiation, thus, they are known to have an important role on the global climate [Andreae and Cruzten, 1997]. The optical properties of aerosols are known to depend on their mass and composition. Thus, the gas-to-particle conversion of gaseous SOCs is important not only as a removal process of gaseous SOCs but also as a factor which changes the optical properties of the atmosphere.
There are a number of studies about emission processes and rates of biogenic volatile organic compounds (BVOCs) [Hewitt and Street, 1992; Yokouchi, 1994; Guenther et al., 1995; Isebrands et al., 1999; Guenther, 1999; Serca et al., 2001]. These studies have led to the development of modeling studies. Owing to the studies, the emission rates and its diurnal variation of major BVOCs such as isoprene, monoterpenes and 232MBO can now be modeled well. In addition, there are also many studies on the degradation rates of BVOCs as well [Tuazon and Atkinson, 1989; Tuazon and Atkinson, 1990; Atkinson, 1989; Ferronato et al., 1998]. Thus, it seems to be possible to estimate the diurnal variations of their oxidation products (mostly biogenic SOCs) from the emission rates and degradation rates of their precursors. However, there are few studies that describe the diurnal variations of the biogenic SOCs including the oxidation products of BVOCs. Thus, it is still unknown whether the actual concentrations of the oxidation products of BVOCs are in agreement with those estimated from emission rates and degradation rates of their precursors.

In the past two decades, the sampling methods for the SOCs in both gas and particle phases have been advanced. In the beginning, they were mainly developed for assessment of air pollution in urban areas. Because anthropogenic SOCs contain harmful compounds such as polycyclic aromatic hydrocarbons (PAHs), they have been known as important air pollutants [Simoneit et al., 1991; Gundel et al., 1995]. In addition, the anthropogenic SOCs can be converted into fine particles whose diameter is less than 2.5 μm. These particles are called as PM$_{2.5}$ and they can go into the inner part of the human lung, and cause more serious injury than that of larger particles. Therefore, many sampling techniques for anthropogenic SOCs have been developed. The annular denuder sampling system (ADSS) is one of these techniques. Denuders were developed to remove the gaseous compounds in the sample air, because gaseous compounds can act as a positive artifact of the aerosol sampling. Possanzini and co-workers [1983] have developed a sampling system that is
based on denuder tubes. A similar system was also developed, the system can collect the semi-volatile PAHs in both gas and particle phases [Gundel et al., 1995]. A denuder tube can selectively collect gaseous compounds in the sample air onto its inner walls, which are coated with adsorbent or collection reagent, and particles can go through the denuder tube. This is based on the difference of diffusion velocity between gases and particles, gases can collide and be collected onto the inner walls within the time of passage, and however, particles can not collide to the wall there is in the condition of a laminar flow. Particles that have gone through the denuder tube are collected onto the filter that is connected at the latter part of the tube. Thus, the ADSS can separately collect atmospheric SOCs in both gas and particle phases.

In this study, we measured the concentrations of biogenic SOCs with the ADSS in the northern forest in Hokkaido Island, Japan. Our sampling method is based on a benzylhydroxyl oxime derivatization [Matsunaga and Kawamura, 2000], by which atmospheric semi-volatile carbonyls can be measured with a high sensitivity. The SOCs that we have measured include glycolaldehyde (GAL), hydroxyacetone (HAC), methylglyoxal, n-nonanal, n-decanal, 4-oxopentanal (4-OPA) and other carbonyl compounds. Although all of these compounds have high vapor pressures [Makar, 2001], they abundantly exist in the aerosols [Matsunaga et al., 2003; Matsunaga et al., accepted to Chemosphere]. Because there have been few reports that described diurnal variation of these SOCs in the forest atmosphere, there is little information about the emission processes of the biogenic SOCs and their removal processes. We will describe these processes that are based on the results obtained from the observation using ADSS and SMPS observations.
2. Experimental

2.1 Sampling Site

The sampling site is in the Uryu Experimental Forest of Hokkaido University (N 44° 21’, E 142° 15’, approximately 200 km north of Sapporo, rural area). Gas and aerosol samples were collected from August 22nd to 29th, 2002. The experimental forest is a mixed forest dominated by Quercus Crispula and Picea Glehnii Mast. The sampling site is located approximately 1 km inside of the nearest forest boundary.

2.2 Annular Denuder Sampling System (ADSS)

Atmospheric SOCs were collected with the ADSS. An outline of the system is presented in Fig. 1. The ADSS consists of an air inlet, cyclone, reaction tube, 1st denuder tube, filter pack, backup denuder tube and a diaphragm pump. The sample air is mixed with NO at the air inlet, resulting in the concentration of NO in the sample air to be of 2 ppmv. This procedure is to destroy the atmospheric oxidants in the sample air such as OH, ozone and NO₃ [Mochida et al., 2003]. The sample air goes through the cyclone (URG-2000-30EH, URG Corp., Chapel Hill, NC, U.S.A.), where particles larger than about 4 - 5 µm are removed at the flow rate of 10 L min⁻¹. The Teflon reaction tube provides time for destroying the atmospheric oxidants. The 1st denuder tube (URG-2000-30×242-3CSS, URG Corp.) is a multi channel annular denuder, and the distances between each inner wall are 1 mm and 1.5 mm. Its inner diameter and length are 30 mm and 242 mm, respectively.

The denuder tube was coated with a purified O-benzylhydroxylammoniumchloride (BHA, first grade, Wako, Osaka, Japan) in a methanol solution as a collection reagent. The denuder tubes were dried with a purified air flow before the sampling. In order to enhance
the collection efficiency of samples, an adsorbent (XAD-7, SUPELCO, Bellefonte, PA, U.S.A.) was mixed with the solution of BHA. The XAD-7 was pounded to a fine powder and cleaned with water, methanol and dichloromethane prior to being mixed with the solution. The concentrations of BHA and XAD-7 were 5% and 3% (w/w) in the solution, respectively.

Gaseous carbonyls in the sample air are immediately derivatized to its benzylhydroxyl oximes (BH oximes) on the inner walls of the 1st denuder tube, and trapped. Particulate compounds go through the 1st denuder and are trapped on a 47 mm quartz fiber filter installed in the Teflon filter pack (URG-2000-30FG, URG Corp.). Some of the compounds trapped on the filter can re-evaporate, and they are trapped by a backup denuder tube. The same collection reagent as the 1st denuder tube was used for the backup denuder tube. In this study, the compounds collected in the 1st denuder tube are regarded as gaseous compounds, and the sum of the compounds collected on the filter and backup denuder are the amount of particulate compounds. NOx contained in the exhaust is removed by a NOx trap cell that contains approximately 500 g of Purafill (Al2O3 pellets coated with KMnO4, Nitta, Osaka, Japan). The exhaust is released at approximately 10 m away from the ADSS and other instruments.

2.3 Diffusion Mobility Analyzer (SMPS) and Weather Conditions

The number concentration and size distribution of the aerosols were determined with the SMPS (TSI Model 3936, TSI Inc., Shoreview, MN, U.S.A.). The SMPS can determine the size and number of the aerosols whose diameter are 10 - 400 nm. The time resolution of SMPS analysis was approximately 280 seconds, and we used the 1 hour average of the number concentration and size distribution of the aerosols. The SMPS analysis was conducted from 25 to 29 of August
Temperature, relative humidity, wind speed and wind direction were measured at 1.5 m, 3.5 m and 10 m above the ground. Because the sensor for the ambient temperature at 3.5 m above the ground was close to the sampling apparatus and is possibly affected by the heat from the instruments, the temperature measured at 1.5 m above the ground is presented here. Global light intensity (~2880 nm) was also measured with MS-43F (EIKO, Japan). The height of the canopy level was approximately 15 m at the sampling site.

2.4 Sampling Procedure of the ADSS

The ADSS was placed at approximately 3.5 m above the ground, and the sampling was conducted from August 22 to 29. The flow rate of the sample air and sampling time were 10 L min⁻¹ and 3.5 hours, respectively. We changed the denuders and filters every 4 hours. To avoid contamination, the ADSS was turned off automatically for 30 minutes. Therefore, the air samples were collected at 00:15-03:45, 04:15-07:45, 08:15-11:45, 12:15-15:45, 16:15-19:45 and 20:15-23:45 (local time). The compounds collected in the denuders were immediately extracted with approximately 10 mL of methanol and stored in 10 mL glass centrifuge tubes with Teflon lined caps. The quartz fiber filters with aerosol samples were stored in 150 mL glass bottles. These extracts and filters were stored in a freezer at approximately -20°C prior to analysis.

2.5 Sample Treatment for the Carbonyl Compounds Collected with the ADSS

To remove the adsorbent in the extracts from the denuder tubes, the extracts were separated by a centrifuge separator and were filtered with cleaned quartz fiber wool, and placed into 25 mL pear flasks. Approximately 3 mL of methanol was added to the adsorbent that remained in the centrifuge tube, and the remaining adsorbent was extracted by ultrasonication for 5 minutes. After the ultrasonication, the methanol was also placed
into the pear flasks. These procedures were repeated three times. Aerosol samples on the quartz fiber filters were extracted with approximately 5 mL of methanol by the ultrasonication. The extract was filtered and was combined with the extract from the backup denuder of the same sample. The extraction for the filters was also repeated three times. These extracts were stored at room temperature within 24 hours, which allowed the carbonyl compounds collected on the filters to react with the excess BHA in the extracts from the backup denuders.

The extracts in the pear flask were concentrated to approximately 0.5 mL using a rotary evaporator, and 10 mL of ethyl acetate was added. A 7 mL of pure water purified with Milli-Q SP TOC (Millipore Corp., Billerica, MA, U.S.A.) and a 1 mL of 8M hydrochloric acid were added. The mixture was shaken for about 1 minute, and the water phase with excess BHA was removed and purified water and the hydrochloric acid were added to the ethyl acetate in the flask. This procedure was conducted once more, and to remove hydrochloric acid in the ethyl acetate by adding purified water to the solution. After the shaking, the water phase was removed from the mixture, and the ethyl acetate phase was replaced into a 50 mL pear flask. The solution in the 50 mL pear flask was concentrated to less than 0.5 mL and was placed into a 1.5 mL glass vial with a Teflon lined cap. The ethyl acetate in the solution was vaporized nearly to dryness with a gentle argon flow, and 30 µL of N,O-bis(trimethylsilyl)-acetamide (BSTFA, SUPELCO) was added to trimethylsilylation (TMS) of hydroxyl (-OH) functional group. The scheme of the derivatization is shown in Fig. 2. The mixture of the solution and TMS reagent was stored for more than 2 hours at 60°C. After the TMS reaction, the TMS reagent was also vaporized nearly to dryness and 50 µL of n-hexane was added to the remaining solution. Finally, 2 µL of the solution was injected into a GC/FID. The details of the sample treatment for carbonyl compounds have been described in Matsunaga and Kawamura...
All of the glass ware used for sampling and analysis were baked for 3 hours at 450°C before use. All of the solvents used in the procedures were special grade and purchased from Wako, and they were re-distilled before use.

2.6 GC analysis

A capillary GC (Carlo Erba GC6000) equipped with a cold on-column injector, fused silica DB-1701 capillary column (J&W Scientific, 0.32 mm i.d. × 60 m length, 0.25 μm film thickness) and an FID detector (280 °C) was used for the analysis of the derivatives of the carbonyls. The column oven temperature was programmed from 70 °C to 75 °C at 40 °C min⁻¹, then to 150 °C at 15 °C min⁻¹, and to 280 °C at 5 °C min⁻¹ (the final time was 15 min.). Peaks of the derivatives were identified by the comparison of the retention time to that of the derivatives of authentic standards. The authentic standards were purchased from Wako except for 4-OPA, which was synthesized by the ozonolysis of 6-methyl-5-hepten-2-one (Tokyo Kasei, Tokyo, Japan) and evaluated with GC/MS. GAL, HAC, nonanal, decanal, glyoxal and methylglyoxal and 4-OPA were quantified in this study. Since the purity of the standard of 4-OPA is not known, the amount of 4-OPA was calculated with the area of methylglyoxal, and was corrected with its carbon number. The collection efficiency of each gaseous compound described in this study was more than 90%. Formation of the particulate compounds on the filters was also checked, and the artifact on the filters was found to be negligible. Details of the sampling method and the results of more examinations for the sampling system are under preparation for a contribution by Matsunaga and co-workers. The detection limit of the ADSS sampling is 3-5 ng m⁻³ (both gas and particle phases). Estimated errors in the determination of gaseous and particulate compounds were ∼±10% and ∼±15% at 5-25 pptv, respectively. The
concentration values reported in the manuscript are the remainder after subtracting the blank values.

3. Results and Discussion

3.1 Variation of the concentrations of the Gaseous SOCs

The first half of the experiment was mostly cloudy and partly rainy, the ambient temperature was generally low (minimum: 8.6°C). The latter half was warmer than the first half and had partly clear skies. August 26th and 27th were clear sky days, and a heavy rain was observed on the 28th. Table 1 presents the maximum, minimum, average and median of the gaseous concentrations of the compounds which have been collected in this experiment. The concentrations of the gaseous SOCs varied more than a factor of 20 within a day. Their concentrations were generally high at noontime and decreased at nighttime. The SOCs discussed in this study are produced from several production processes, their structure and production schemes are shown in Fig. 3. GAL, HAC and methylglyoxal are oxidation products of isoprene [Tuazon and Atkinson, 1989; Tuazon and Atkinson, 1990; Atkinson, 1989]. GAL is also an oxidation product of 232MBO [Ferronato et al., 1998]. Methylglyoxal may also have other sources. Nonanal and decanal are probably emitted from vegetation and microbial processes [Kesselmeier and Staudt, 1999; Matsunaga et al., 2003]. 4-OPA is known to be produced by a particular process. This is an oxidation product of the organic compounds that exist on the surfaces of plants, such as squalene [Fruekilde et al., 1998; Matsunaga et al., accepted to Chemosphere]. 4-OPA is also produced by the oxidation of 6-methyl-5-hepten-2-one (6-MHO), which is directly vaporized from the vegetation via the oxidation of its precursors on the vegetation surfaces [Fruekilde et al.,]
Fig. 4 shows the variation of the gaseous concentrations of HAC, nonanal and 4-OPA. Although their production processes are each differ, the temporal variations were quite similar and correlated with that of the ambient temperature. This suggests at least two possibilities. First, the increase of the gaseous concentrations of the SOCs is affected by vaporization from their reservoir. Secondly, their emission and/or production rates are controlled by the ambient temperature or a factor that has a similar variation to that of correlated with temperature (e.g. light intensity).

Fig. 5a-c show the relationship between sum of the concentrations of these SOCs (GAL, HAC, nonanal, decanal and 4-OPA) and the ambient temperature at the site. The gaseous concentration increases with the increase in the ambient temperature (see Fig. 5a). In the contrast, the particulate concentrations did not so increase with the temperature (see Fig. 5b). The increase in the sum of the concentrations in both gaseous and particulate phase with the temperature suggests rising a relationship with direct emission and/or production (see Fig. 5c). Other SOCs measured in this study also has shown a similar pattern. Although the possibility that the direct emission and/or photochemical production rates of these SOCs correlate with the ambient temperature still remains, the differences of the production processes of the SOCs suggest that the concentrations were not controlled only by their source intensities.

There are several possibilities that can explain the rapid decrease in the concentrations of the gaseous SOCs during afternoon. They are 1: Adsorption onto the surfaces of plants and/or soil, 2: Gas-to-particle conversion, 3: Decrease of the source emission from their sources and/or decrease of their production rate, 4: Precipitation scavenging, 5: Degradation by the atmospheric oxidants and 6: Transportation out of the forest. As seen in Fig. 4, several wet precipitation events were observed, but the gaseous
SOCs did not decrease at 12:00-16:00 of the 24th, 08:00-12:00 of the 25th and 04:00-08:00 of the 28th. Thus, wet precipitation scavenging (possibility 4) probably does not effectively remove the gaseous SOCs. The atmospheric degradations of the SOCs (possibility 5) are also not fast enough to explain the variations. For example, the degradation of GAL can explain only less than 10% of the decrease in the concentration from 14:00 to 18:00 on August 27th [Bacher et al., 2001; Matsunaga et al., 2003]. For the possibility 6, the removal of the SOCs by vertical convection is not responsible for the diurnal variation patterns of the gaseous SOCs, since the concentrations had a maximum during noontime when the convection is greatest. If the vertical convection determines the variation patterns of the SOCs, the maximum should be at nighttime. In addition, the variations of gaseous SOCs did not agree with those of the particulate SOCs. If the variations of the SOCs were controlled by the vertical convection, they should show same pattern. Therefore, it is most likely that the diurnal variation patterns of the gaseous SOCs are controlled by their emission intensities and removal processes except for 4, 5 and 6 mentioned above. We will discuss about the possibilities 1 and 2 mentioned above as the controlling factors of the variations of these SOCs. The possibility 3 still remains. Because, we did not measure the emission rates of the SOCs and their precursors, we cannot identify the main removal process of the gaseous SOCs. However, we can discuss about the important factors that are effective to control the diurnal variation of the gaseous SOCs such as possibilities 1 and 2.

3.2 Adsorption of the SOCs onto the Plant Surfaces

As described above, we suggest that the vaporization to and removal from the atmosphere is one of major controlling factors of the concentrations of the SOCs. The most likely reservoir that can absorb and release the SOCs are the plant surfaces and/or soil [Welke et al., 1998]. Hornbuckle and Eisenreich [1996] have reported that the
concentrations of gaseous poly chlorinated biphenyls (PCBs) can be explained by the ambient temperature from the results of the experiment at the forest. They suggested that the concentrations of gaseous PCBs were controlled by the vaporization from the plant surfaces (because the ground of their sampling site was covered with lichens, thus, there was no exposed soil.) and the removal from the atmosphere. Because PCBs are fully anthropogenic compounds, they could ignore the direct emissions of PCBs and obtain such a simple conclusion. Our results also demonstrate some similarities with their results, and the SOCs which we measured are also semi-volatile and sticky as PCBs. In addition, because fogs were observed almost everyday in the forest, the lifetime of the aerosol particles may be short (about one day). Thus, the aerosols are probably not an important reservoir because of their short lifetime. However, the removal of the aerosols from the atmosphere promotes the adsorption of the SOCs onto the surfaces such as plant and soil. Although the possibility that all of the sources of the SOCs depend on the temperature still remains, it is still more likely that the vaporization and removal control the gaseous concentrations of the SOCs. To evaluate this hypothesis, we analyzed the extracts from leaves of the predominant species (Quercus Crispula and Picea Glehnii Mast) in the forest, and detected all of the SOCs, which were measured in this experiment, in the extracts. Thus, the leaves of the predominant species may work as a reservoir for the SOCs, although the possibility that the plants are the primary source of the SOCs can not be eliminated.

3.3 Gas-to-Particle Conversion of the SOCs

Table 2 shows the maximum, minimum, average and median of the particulate concentrations and the partition ratios (particle / (gas + particle)). The concentrations of particulate SOCs are comparable to those of gaseous SOCs. This indicates that the gas-to-particle conversion is also an important removal process of the gaseous SOCs. There is a
difference in the gas-to-particle conversion between water soluble compounds and insoluble compounds. Fig. 6a and b shows the partition ratios of the SOCs (GAL, HAC, nonanal and decanal). Fig. 6c shows the relative humidity (3.5 m above the ground) and the aerosol number concentration obtained with the SMPS (10–400 nm) at the sampling site. A large increase in aerosol concentrations was observed during the term 1 in Fig. 6a-c (shaded). In this term, the partition ratios of all of the SOCs rapidly increased. This indicates that the SOCs were converted into aerosols by the uptake onto the aerosol particles that had already been present in the atmosphere. In addition, the uptake onto small particles (< 10 nm) leads to growth of the small particles to larger than 10 nm. Similar phenomenon was also observed in the term 3 in Fig. 6a-c and a previous experiment on August 14, 2001 [Matsunaga et al., 2003]. Other SOCs also showed the increase with the same timing as the SOCs mentioned above (data not shown). Therefore, the uptake onto the aerosols is probably a common gas-to-particle conversion process for all SOCs.

On the other hand, the term 2 in Fig. 6a-c indicates the term when the relative humidity raised to 100%. In this term, although the aerosol concentration did not increase, the partition ratios of GAL and HAC increased. In contrast, nonanal and decanal did not show an increase during the term 2. The Henry’s Law constants of nonanal and decanal are lower than 1 (mol kg\(^{-1}\) atm\(^{-1}\)). These increases were particular to water soluble compounds whose Henry’s Law constant are larger than 10000 (mol kg\(^{-1}\) atm\(^{-1}\)) such as GAL, HAC, 4-oxopentanal, glyoxal and methylglyoxal. This suggests that the increase in the partition ratio was induced by the dissolution of the water soluble SOCs into the water phase in the aerosols. Therefore, the dissolution into the water phase in the aerosols is important as a gas-to-particle conversion process only for the water soluble SOCs. The relative humidity was also 100% from 18:00 of Aug. 28th to 12:00 of 29th, however, the partition ratio did not increase. In this term, the horizontal wind speed was relatively high (the average and
median of the wind speed during the sampling except for this term were 0.06 m s\(^{-1}\) and 0 m s\(^{-1}\), respectively.). This may be possibly because to the high wind speed (0.1-1.02 m s\(^{-1}\), average: 0.44 m s\(^{-1}\), median: 0.45 m s\(^{-1}\)) and high relative humidity activated the adsorption and deposition of the aerosols, and decreased the aerosols in the forest atmosphere.

4. Conclusion

Biogenic semi-volatile organic compounds (SOCs) such as glycolaldehyde, hydroxyacetone, n-nonanal, n-decanal, 4-oxopentanal, glyoxal and methylglyoxal in both gas and particle phases have been measured in northern forest on the Hokkaido Island in Japan. Their gaseous concentrations on fine days showed a clear diurnal variation. Although they have different production processes, all gaseous concentrations were strongly correlated with the ambient temperature. This suggests that the gaseous concentrations of the SOCs are not controlled only by their production rates. In addition, we found that gas-to-particle conversion is important as a removal process of the gaseous SOCs. Because we have measured the concentrations of the SOCs in both gaseous and particulate phases, this study could make an evaluation of the importance of gas-to-particle conversion as a removal process of the gaseous SOCs. We also found a difference in the gas-to-particle conversion between water soluble compounds and insoluble compounds. Water soluble compounds can be converted into aerosols not only by the uptake onto the aerosols but also by the dissolution into the water phase in the aerosols. Because, there are few reports described about these SOCs in both gaseous and particulate phases, the measurement of the SOCs with the ADSS and aerosol analysis with the SMPS provided us important information about the removal processes of biogenic SOCs. Furthermore, our data indicate that plants and soils are likely to be reservoirs for these SOCs. They may be
stored on plants or soil. Depending on the actual temperature and their partition between air and reservoirs, SOCs can be released or deposited. In order to evaluate the effect of the plant surfaces as a reservoir of the biogenic SOCs, other experiments such as bag enclosure measurements are needed in the future.

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Figure 1  The outline of the annular denuder sampling system (ADSS).

Figure 2  Schemes of the benzylhydroxyl oxime (BH oxime) derivatization. The details of the analytical method are described in Matsunaga and Kawamura [2000].

Figure 3  The production processes of the semi-volatile organic compounds (SOCs) that were measured in this study.

Figure 4  The concentrations of hydroxyacetone (blue circles), n-nonanal (red squares) and 4-oxopentanal (green diamonds) in the gas phase. The ambient temperature (black dashed line) and precipitation rate (sky blue solid line, 1 hour average) are also shown.

Figure 5  The relationship between the concentrations of the SOCs (glycolaldehyde, hydroxyacetone, n-nonanal, n-decanal and 4-oxopentanal) and the ambient temperature. (a) Sum of the gaseous concentrations. (b) Sum of the particulate concentrations. (c) Sum of the gaseous and particulate concentrations.

Figure 6  (a) The partition ratios (particle / (gas + particle)) of glycolaldehyde (blue circles and solid line) and hydroxyacetone (red squares). (b) The partition ratios of n-nonanal (blue circles) and n-decanal (red squares). (c) The relative humidity (blue dashed line) and the aerosol number concentration (10-400 nm, gray solid line) at the sampling site. The shaded term 1 indicates the term that the aerosol number concentration was rapidly increased. The shaded term 2 indicates the term that the relative humidity was reached to 100%. The shaded term 3 indicates the term that the phenomenon similar to the term 1 was observed.
B+C = Particle Phase
A = Gas Phase

C: Backup Denuder (To collect compounds vaporized from the former filter)
B: Quartz Fiber Filter (To collect compounds in the particle phase)
A: 1st Denuder (To collect compounds in the gas phase)

Reaction Tube (To titrate atmospheric oxidants by the reaction with NO)
Cyclone

Figure 1 (Matsunaga et al.)
Carbonyls (e.g. n-nonanal)

Hydroxycarbonyls (e.g. glycolaldehyde)

BHA (on the inner walls of the denuders)

Derivatives injected into GC

Figure 2 (Matsunaga et al.)
isoprene → 2-methyl-3-buten-2-one → hydroxyacetone

methylglyoxal

glycolaldehyde

Vegetation etc. → n-nonanal

vaporization and/or direct emission → n-decanal

Squalene and homologous compounds → 6-methyl-5-hepten-2-one → 4-oxopentanal (4-OPA)

Figure 3 (Matsunaga et al.)
Figure 4 (Matsunaga et al.)

The diagram illustrates the gaseous concentrations of hydroxyacetone (gas), n-nonanal (gas), 4-oxopentanal (gas), precipitation, ambient temperature, and wet precipitation over a period from 08/23 to 08/29. The gaseous concentrations are measured in ng m\(^{-3}\).
Figure 5 (Matsunaga et al.)

Concentrations (ng m$^{-3}$)

(a) Gas

(b) Particle

(c) Gas + Particle
Figure 6 (Matsunaga et al.)

(a) Partition Ratio (% of particle / (gas + particle))

(b) Partition Ratio (% of particle / (gas + particle))

(c) Relative Humidity (%) and Number Concentration of Aerosols
Table 1  The maximum, minimum, average and median of the gaseous concentrations of the SOC

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<th>Maximum (ng m(^{-3}))</th>
<th>Minimum (pptv)</th>
<th>Average (ng m(^{-3}))</th>
<th>Median (pptv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>glycolaldehyde</td>
<td>283 (116)</td>
<td>10 (4)</td>
<td>72 (30)</td>
<td>40 (17)</td>
</tr>
<tr>
<td>hydroxyacetone</td>
<td>201 (67)</td>
<td>9 (3)</td>
<td>48 (16)</td>
<td>34 (11)</td>
</tr>
<tr>
<td>n-nonanal</td>
<td>295 (51)</td>
<td>15 (3)</td>
<td>102 (18)</td>
<td>79 (14)</td>
</tr>
<tr>
<td>n-decanal</td>
<td>163 (26)</td>
<td>*</td>
<td>44 (7)</td>
<td>41 (6)</td>
</tr>
<tr>
<td>glyoxal</td>
<td>154 (65)</td>
<td>*</td>
<td>42 (18)</td>
<td>32 (14)</td>
</tr>
<tr>
<td>methylglyoxal</td>
<td>257 (88)</td>
<td>12 (4)</td>
<td>83 (28)</td>
<td>66 (23)</td>
</tr>
<tr>
<td>4-oxopentanal</td>
<td>625 (153)</td>
<td>*</td>
<td>150 (37)</td>
<td>109 (27)</td>
</tr>
</tbody>
</table>

*: Below the detection limit (3~5 ng m\(^{-3}\))
Table 2  The maximum, minimum, average and median of the particulate concentrations and the gas-particle partition ratios (particle / (gas + particle)).

<table>
<thead>
<tr>
<th></th>
<th>Particulate concentrations (ng m⁻³)</th>
<th>Partition ratios (P/(G+P)%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>glycolaldehyde</td>
<td>76</td>
<td>*</td>
</tr>
<tr>
<td>hydroxyacetone</td>
<td>89</td>
<td>*</td>
</tr>
<tr>
<td>n-nonanal</td>
<td>119</td>
<td>*</td>
</tr>
<tr>
<td>n-decanal</td>
<td>81</td>
<td>*</td>
</tr>
<tr>
<td>glyoxal</td>
<td>91</td>
<td>*</td>
</tr>
<tr>
<td>methylglyoxal</td>
<td>188</td>
<td>*</td>
</tr>
<tr>
<td>4-oxopentanal</td>
<td>196</td>
<td>*</td>
</tr>
</tbody>
</table>

*: The particulate concentration was below the detection limit (3~5 ng m⁻³)