Organic tracers of fine aerosol particles in central Alaska: summertime composition and sources

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Abstract

$PM_{2.5}$ aerosols were collected at Fairbanks (64.51°N and 147.51°W) in central Alaska during the summer of 2009 and analyzed for organic tracer compounds using gas chromatograph-mass spectrometer. The organic compounds were grouped into fourteen classes based on their functional groups and sources. Concentrations of total organics measured ranged from 113 to 1664 ng m^{-3} (ave. 535 ng m^{-3}). Anhydrosugars (ave. 186 ng m^{-3}) and *n*-alkanoic acids (ave. 185 ng m^{-3}) were two major classes among the 14 compound classes. The similar temporal trends and strong positive correlations among anhydrosugars and *n*-alkanoic acids demonstrated that biomass burning (BB) is the major source of organic aerosols (OAs) in central Alaska. The dominance of higher molecular weight *n*-alkanoic acids over lower molecular weight homologues and their carbon preference index (5.6-9.8) confirmed that they were mostly emitted from plant waxes during BB in central Alaska. The mass concentration ratios of levoglucosan to mannosan denoted that softwood is the main biomass burned. The rainfall event distinctly enhanced the levels of mannitol and arabitol due to the growth of fungi and active discharge of fungal spores in the subarctic region. Molecular compositions of biogenic secondary organic aerosol (BSOA) tracers inferred that isoprene is a crucial precursor of BSOA over central Alaska. Our results suggest forest fires and plant emissions to be the crucial factors controlling the levels and molecular composition of OAs in central Alaska. We propose that $PM_{2.5}$ laden with OAs derived in central Alaska may have a serious impact on the air quality and climate in the Arctic via long-range atmospheric transport.

Keywords: Primary organic aerosol, Secondary organic aerosol, Molecular composition, Biomass burning, Temporal trends, Central Alaska.

1 Introduction

Atmospheric aerosols can absorb and scatter solar radiation and alter the radiative forcing of the atmosphere (Seinfeld and Pandis, 1998; Wilkening et al., 2000). Fine aerosol particles have a diameter size close to the wavelengths of visible lights and thus are expected to have a stronger climatic impact than coarse particles (Kanakidou et al., 2005). They can also be transported far away from the source regions and thus their climatic and environmental effects are delocalized compared to the emission areas. Aerosol particles that are hydrophilic can act as cloud condensation nuclei (CCN) and have an indirect climatic effect through modification of cloud properties (Novakov and Penner, 1993; Novakov and Corrigan, 1996).

Organic aerosols (OAs) that are comprised of thousands of organic compounds contribute about 20 to 50% of total mass of fine particles in the continental mid-latitudinal atmosphere (Saxena and Hildemann, 1996) whereas it is around 90% in tropical forest areas (Crutzen and Andreae, 1990; Andreae and Rosenfeld, 2008). They are derived from anthropogenic and natural sources. They can alter the physical and chemical properties of atmospheric particles depending on the meteorological conditions. OAs are highlighted for the past decade because they are related to the changes of global and regional climate and chemical composition of the atmosphere as well as public health. Primary organic aerosols (POA) are directly emitted as particulate forms whereas secondary organic aerosols (SOA) refer to particulate organic matters that are transformed to aerosol-phase via gas-phase oxidation of organic precursors. Emissions of POA particles and SOA precursors can be released from numerous sources near the ground surface and subsequently mixed in the boundary layer and to a lesser extent in the free troposphere. The dry depositional removal of OAs mainly depends on the sizes of the aerosol particles.

The molecular composition of OAs can be used as tracer to better understand the sources and formation pathways. Advances were made during the last decade to better understand the formation of OAs and their precursors in the atmosphere. On a global scale, the emission of biogenic volatile organic compounds (VOCs) is one order of magnitude higher than that of anthropogenic VOCs (Seinfeld and Pandis, 1998). It is notable that biogenic VOCs are comprised of unsaturated hydrocarbons with double bonds and are more reactive towards the atmospheric oxidants such as hydroxyl (OH) radical and ozone (O_3) than anthropogenic VOCs that are largely comprised of aromatic hydrocarbons. This specific feature of biogenic VOCs further enhances their significance as a conceivable supplier to the global burden of OAs in the atmosphere. Laboratory and chamber experiments have also documented that biogenic VOCs are the potential precursor for SOA formation in the atmosphere (Kavouras et al., 1998; Jaoui et al., 2007).

Although early Arctic explores had noticed atmospheric haze (Nordenskiold, 1883), the remote Arctic atmosphere was believed to be extremely clean. Pilots flying over the North American Arctic in the 1950s observed widespread haze that could be seen every winter and early spring (Mitchell, 1957). It took until the 1970s for scientists to realize that the haze was air pollution transported from the middle latitudes (Barrie, 1986). Over the past three decades there has been much research on the climate consequences of this pollution that is also present in summer. Surface air temperature has increased more than the global average over the past few decades and is predicted to warm by about 5 °C over a large part of the Arctic by the end of the twenty-first century (IPCC, 2001). The arctic atmosphere is considered as a unique natural laboratory for photochemical reactions and transformations during the polar sunrise (Kawamura et al., 1996). Arctic atmosphere is influenced by marine-derived OAs from the Arctic Ocean as well as continentally derived OAs and their precursors from mid-latitudes in Eurasia or North America (Stohl et al., 2006; Law and Stohl, 2007).

Previous analyses have reported a substantial contribution of summertime boreal forest fires to the chemical composition of aerosol over the Arctic (Iziomon et al., 2006; Kaplan and New, 2006; Stohl et al., 2006). French et al. (2003) proposed that wildfire has contributed a substantial amount of carbon-based gas from 1950 to 1999 in the atmosphere of the boreal region of Alaska. Based on the modeling and in-situ observations of black carbon (BC) and soot during the FROSTFIRE campaign, Kim et al. (2005) revealed that BC and soot particles of 0.4 to 10 μm in radius can be transported to the Arctic and the whole area of Alaska in a very short time. The results of Kaplan and New (2006) delivered strong evidence that high-latitude ecosystems are sensitive to climate change due to the increase in concentrations of greenhouse gases. Iziomon et al. (2006) examined summertime aerosols based on column integrated and surface aerosol measurements at Borrow in the North Slope of Alaska between 1998 and 2003. They noticed high loadings of aerosols at least 8 days each summer and demonstrated that the pollution events with the highest aerosol loadings were associated with smoke from wildfires in northwest Canada. Stohl et al. (2006) explored the impact of boreal forest fire emissions on the light absorbing aerosol levels at the Barrow Arctic station. They proposed that boreal forest fires could result in elevated concentrations of light absorbing aerosols throughout the entire Arctic with an impact on the radiation transmission of the Arctic atmosphere. The results of Ward et al. (2012) based on Chemical Mass Balance modeling revealed that wood smoke was the major source of $PM_{2.5}$ particles mainly during the winter months at several locations in Fairbanks. Haque et al. (2016) found high contributions of isoprene oxidation products than monoterpene and sesquiterpene oxidation products to SOA formation in summer due to the more isoprene emissions and high levels of oxidants. They estimated isoprene-derived secondary organic carbon (SOC) approximately 5 times higher than SOA derived from monoterpene and nearly 2 times higher than sesquiterpene-derived SOA in central Alaska. Because climate change is generally proceeding fastest in the high latitudes (Serreze et al., 2000; Hinzman et al., 2005), there is an increasing demand for better understanding of the chemical compositions and sources of OAs in the Arctic atmosphere.

We have collected $PM_{2.5}$ samples during the summer of 2009 at Fairbanks in central Alaska. The samples were analyzed for several organic tracer compounds to characterize OAs in the North American subarctic region. This paper discusses the molecular compositions of various organic compound classes and the factors controlling temporal changes in their concentrations in central Alaska. We also discuss the sources of organic compounds detected and the secondary formation processes as well as atmospheric implications for the burden of OAs in the arctic and subarctic atmosphere.

2 Methodology

2.1 Description of sampling area

Alaska is located in a subarctic zone. Fairbanks is the largest city in central Alaska. It is situated in the central Tanana Valley connecting the Chena River near the Tanana River. The location of the sampling site in Fairbanks (64.51°N and 147.51°W) and its surroundings are shown in Figure 1. The altitude of the sampling location is 136 m above sea level. A total area of Fairbanks is nearly 85 km^2 with a population of 31,500. The sampling site is located at the downside of Fairbanks where a forest is very close to the campus of the University of Alaska Fairbanks. The highest levels of atmospheric aerosol burden in the United States have been recorded in Fairbanks (Ward et al., 2012). The National Emission Inventory database pointed out that forest fires and combustion of fossil fuels are the two critical sources of air pollution in Fairbanks (Shakya and Peltier, 2013; Ware et al., 2013).

2.2 Sample collection

Atmospheric particle samples of sizes less than 2.5 μm in diameter ($PM_{2.5}$) were collected on the rooftop of the International Arctic Research Center building of the University of Alaska Fairbanks during the summer season from June 5 to September 21 in 2009 when a forest fire was active in the region. The collection of samples was performed using a low-volume air sampler model URG-2000-39EH (USA) with a flow rate of 16.7 L min^{-1}. $PM_{2.5}$ particles were retained on a quartz fiber filter of 47 mm in diameter that was pre-combusted at 450 °C for 6 hours. The sampler was operated for three to several days to get enough aerosol particles on the filter to detect trace organic species with very low concentrations. We collected 13 samples (Alaska 01 to 13) and 3 field blanks during the campaign. The samples and field blank filters were individually placed in a pre-heated glass vial with a Teflon-lined screw cap. We stored the aerosol samples in a dark room at -20 °C to prevent the samples from microbial degradation and loss of semivolatile organic compounds.

2.3 Analysis of organic tracers

We analyzed the samples for organic compounds using a gas chromatograph-mass spectrometer (GC-MS) system: Hewlett-Packard (HP) model 6890 GC coupled to HP model 5973 mass-selective detector. A 5.0 cm^2 filter area of each aerosol sample was extracted with a 10 ml dichloromethane (CH_2Cl_2) and methanol (CH_3OH) mixture (2:1) through ultrasonication (10 min × 3). The solvent extracts were filtered through a Pasteur pipet packed with pre-combusted (450 °C for 6 hours) quartz wool to remove particles and filter debris. The extracts were concentrated by a rotary evaporator and then dried under a stream of pure nitrogen gas. The hydroxyl (OH) and carboxyl (COOH) groups of organic compounds in the extracts were derivatized to trimethylsilyl ethers and esters, respectively, by the reaction with 50 μl N,O-bis(trimethylsilyl)trifluoroacetamide including 1% trimethylsilyl chloride and 10 μl pyridine at 70 °C for 3 hours (Schauer et al., 1996; Simoneit et al., 2004a). *n*-Hexane containing 1.43 ng μl^{-1} of a C_{13} *n*-alkane internal standard (40 μl) was added into the derivatives before injection of the sample into a GC-MS.

The separation of compounds was performed on a 30 m long DB-5MS fused silica capillary column (0.25 mm inner diameter and 0.25 μm film thickness). Helium was used as a carrier gas at a flow rate of 1.0 ml min^{-1}. The GC oven temperature was programmed from 50 °C for 2 min to 120 °C at 30 °C min^{-1} and then 300 °C at 6 °C min^{-1} with a final isotherm hold at 300 °C for 16 min. The sample was injected on a splitless mode with the injector temperature of 280 °C. The mass detection was conducted at 70 eV on an electron ionization mode with a scan range of 50 to 650 Daltons. The organic compounds were determined by the comparison of the GC retention times and mass fragmentation patterns of a sample with those of authentic standards and National Institute of Standards and Technology library data. The mass spectral data were acquired and processed using HP Chemstation software. GC-MS relative response factor of each compound was calculated using authentic standards or surrogate compounds. The recoveries of authentic standards or surrogates were above 80% for target compounds. The data reported here were not corrected for recoveries. The relative standard deviation of the measurements based on duplicate analyses was within 10%. The field blank filters were analyzed by the procedure described above. The target compounds were not detected in the blank filters.

2.4 Meteorology and air mass trajectories

Figure 2 shows temporal changes of daily average meteorological parameters at the campaign site. The daily mean temperature was in a range of 2.0 to 33 °C with an average of 13.9 °C whereas the daily average relative humidity ranged from 19 to 99 % with a mean of 63 %. The mean wind speed was 5.2 km h^{-1} and the total rainfall was 122 mm during the sampling period. The 5-days air mass backward trajectories at the height of 500 m above the ground level were computed from Hybrid Single Particle Lagrangian Integrated Trajectory model (Draxler and Rolph, 2013). The air mass backward trajectories arriving over the observation site during the collection of aerosol samples is presented in Figure 3.

3 Results and discussion

3.1 Overview of the molecular composition of organic aerosols

A total of 96 organic compounds were detected in $PM_{2.5}$ samples collected at Fairbanks during the sampling period. We grouped them into fourteen compound classes as listed in Table 1 together with the mean concentrations and ranges. Figure 4 shows the chemical compositions of OAs in individual samples (Alaska 01 to 13). The levels of all the quantified organic compounds in Alaskan samples ranged from 113 to 1664 (ave. 535 ng m^{-3}) with the predominance of anhydrosugars (ave. 186 ng m^{-3}) and *n*-alkanoic acids (ave. 185 ng m^{-3}). Anhydrosugars are produced by pyrolysis of cellulose and hemicellulose followed by the subsequent emission to the atmosphere and are widely used as specific tracers of biomass burning (BB) (Simoneit et al., 1999; Sang et al., 2013). *n*-Alkanoic acids are derived directly from the surface of plant leaves and marine phytoplankton as well as BB and meat cooking (Kawamura and Gagosian, 1987; Rogge et al., 1993; Fine e al., 2001). Sugar alcohols were detected in ample amount in three samples collected during the end of the campaign. We also detected a substantial amount of isoprene-derived SOA tracers and *n*-alkanols in Alaskan samples while the concentrations of other compound classes are relatively low.

3.2 Anhydrosugars and lignin and resin products: tracers of biomass burning

The combustion of biopolymers including cellulose and hemicellulose as well as lignin and suberin produces several organic molecules that have been recognized as important source tracers of OAs. Anhydrosugars and lignin and resin acids are specific tracers of BB among the pyrolysis products of biopolymers (Simoneit et al., 1999). The pyrolysis of cellulose and hemicellulose produces anhydrosugars such as levoglucosan and its isomers mannosan and galactosan (Simoneit et al., 1999; Engling et al., 2009). Figure 5a presents molecular distributions of anhydrosugars in Alaskan $PM_{2.5}$ samples. Levoglucosan is the dominant anhydrosugar followed by mannosan and galactosan in Alaskan samples. Their concentrations ranged from 23 to 463 ng m^{-3} (ave. 125 ng m^{-3}), 4.1 to 180 ng m^{-3} (ave. 36 ng m^{-3}) and 3.5 to 106 ng m^{-3} (ave. 26 ng m^{-3}), respectively.

Because 90% of levoglucosan exist in the atmospheric particles with aerodynamic diameter less than 2 μm (Giannoni et al., 2012), it is reasonable to compare the levoglucosan concentrations of Alaskan $PM_{2.5}$ samples with those reported in PM_{10} and TSP during summer or BB season. We found that the concentration levels of levoglucosan in central Alaska are substantially higher than those from the Bering Sea (10 ng m^{-3}) and Arctic Ocean (5.2 ng m^{-3}) (Hu et al., 2013), Chichijima (0.24 ng m^{-3}) and Okinawa (0.57 ng m^{-3}) Islands in the western North Pacific (Verma et al., 2015; Zhu et al., 2015), Northern Japan (7.8 ng m^{-3}) (Agarwal et al., 2010), Mt. Everest (47.2 ng m^{-3}) (Cong et al., 2015). They are comparable to those reported at urban site Chennai in India (ave. 111 ng m^{-3}) (Fu et al., 2010) but lower than those reported at rural site Lumbini in Nepal (ave. 771 ng m^{-3}) (Wan et al., 2017), forest site Rondonia in Brazil (ave. 1180 ng m^{-3}) (Graham et al., 2002) and Chiang Mai in Thailand (ave. 1222 ng m^{-3}) (Thepnuan et al., 2019).

The emission strength of BB products and their long-range atmospheric transport influence the atmospheric levels of anhydrosugars. The backward trajectories reveal that air masses mostly came from the ocean during the campaign (Fig. 3). This result shows that anhydrosugars present in the Alaskan aerosols were mainly associated with the local and regional BB during the campaign. The higher level of levoglucosan in Fairbanks than other sites in the Arctic implies a possible effect of BB on the air quality and climate in the arctic region. Stocks et al. (2000) and Grell et al. (2011) proposed that the frequency of boreal forest fires recently increased in summer due to global warming. Figure 6a-c show the temporal trends of anhydrosugars in the Alaskan aerosols. The levels of anhydrosugars expressively alter during the campaign period. The lower levoglucosan levels were found at the beginning of the campaign whereas they became very high (241 to 463 ng m^{-3}) in 4-23 July (Fig. 6a). Another peak of levoglucosan was found in 30 July to 4 August (169 ng m^{-3}). The concentrations of levoglucosan decreased towards the end of the campaign (23 to 50 ng m^{-3}). Forest fires smokes were seen during 4-23 July and 30 July to 4 August over central Alaska. This observation demonstrates that levoglucosan levels became high due to the local forest fire in central Alaska. Mannosan and galactosan presented similar temporal variations with levoglucosan (Fig. 6b and c). The chemical reaction of anhydrosugars could also influence their concentrations in the atmosphere. Although previous studies have reported that levoglucosan can remain stable in the atmosphere for around 10 days with no substantial degradation (Fraser and Lakshmanan, 2000; Schkolnik and Rudich, 2006), recent findings (Hoffmann et al., 2009; Hennigan et al., 2010; Gensch et al., 2018) reported significant chemical reactivity of levoglucosan and have raised a question over the stability of levoglucosan in the atmosphere. Hennigan et al. (2010) carried out a smog chamber experiment and reported the lifetime of atmospheric levoglucosan to be 0.7 to 2.2 days when exposed to 1×10^6 molecules of OH cm^{-3}. This lifetime is within the range of 0.5 to 3.4 days predicted by Hoffmann et al. (2009) using the Spectral Aerosol Cloud Chemistry Interaction Model. Lai et al. (2014) found that the atmospheric lifetime of levoglucosan ranged from 1.2 to 3.9 days by the control experiment integrating OH in a flow reactor under different environmental conditions and different mixing states. Nevertheless, Bai et al. (2013) reported an atmospheric lifetime of levoglucosan to be 26 days under the different variables along with OH level of 2×10^6 molecules cm^{-3} that is much longer than other predictions.

It is notable from the above discussion that the degradation of levoglucosan is mostly induced by the oxidation reaction with OH radicals and photochemical aging during long-range transport. Therefore, the degradation of levoglucosan could be insignificant if the receptor site is close to the source region. As discussed previously, anhydrosugars detected in Alaskan aerosols during the campaign were originated from local and regional BB, we consider that the degradation of anhydrosugars may not be important to contribute the low levels of BB tracers in the samples collected at the beginning and end of the campaign. The low concentrations of anhydrosugars during the beginning and end of the campaign might be caused by the decreased emission rate of BB tracers due to lower BB activities in the source region. A wet deposition may another cause to lower the level of anhydrosugars in aerosol samples collected at the beginning and end of the campaign because we observed rainfall especially in 5 June to 3 July and 6 August to 17 September in Fairbanks (Fig. 2). Although the concentrations of both mannosan and galactosan are much lower than levoglucosan (Fig. 5a), we observed strong positive correlations (*r* = 0.94-0.97) among these tracers (Table 2).

This result indicates that they might have originated from similar types of biomass via the burning in central Alaska.

Levoglucosan (L) is largely produced by thermal decomposition of cellulose while mannosan (M) is mainly a pyrolysis product of hemicellulose (Simoneit et al., 1999). Klemm et al. (2005) investigated that hardwood contains almost 55 to 65 % of cellulose and 20 to 30 % of hemicellulose. Accordingly, in a laboratory chamber analysis, Schmidl et al. (2008) found the L/M ratios of nearly 2.5 to 3.9 for softwoods and around 14 to 15 for hardwoods burning. It is worth to use the L/M ratio to identify the relative contribution of biomass types: hardwood vs. softwood in central Alaska. The L/M ratios in Alaskan samples ranged from 2.2 to 6.8 (ave. 4.6), which are much lower than the ratios found in smoke samples derived from the burning of hardwoods but almost similar to the ratios found in samples derived from the burning of softwoods. The L/M ratios found in Alaskan aerosol samples are also much lower than the ratios reported for the samples derived from burning of rice straw (12.3 to 55.0) (Sheesley et al., 2003; Sullivan et al., 2008; Engling et al., 2009), cereal straw (55.7) (Zhang et al., 2007), wheat straw (12.7) and corn straw (19.5) (Cheng et al., 2013).

Fine et al. (2001, 2002, 2004) presented the concentrations of BB tracers in fine particles derived from the burning of several wood species collected from the United States. Bases on their data, we calculated the L/M ratios to be 3.4 to 6.7 for softwood burning and 10.7 to 83.4 for hardwood burning. Our values from the Alaskan aerosol (2.2 to 6.8) are well within the range of L/M ratios for softwood burning from the United States. The ratios in Alaskan aerosol samples are comparable to those for marine aerosols collected from the Arctic Ocean (ave. 3.5) (Fu et al., 2013), South China Sea (6.4) and western North Pacific (ave. 4.6) (Fu et al., 2011). Our values are also similar to those found in aerosol samples collected at Montana in the USA (4.6) (Ward et al., 2006), Vienna (4.1 to 6.4) and Salzburg (5.4 to 5.7) sites in Austria (Caseiro et al., 2009) and Moitinhos in Portugal (ave. 3.5) (Pio et al., 2008), where BB was dominated by burning of softwoods but lower than the ratios estimated in aerosol samples collected at Chennai in India (ave. 11.2) (Fu et al., 2010), Karachi in Pakistan (ave. 17.5) (Sahid et al., 2016), Lumbini in Nepal (ave. 15.1) (Wan et al., 2017), Morogoro in Tanzania (9 to 13) (Mkoma et al., 2013), Chiang Mai in Thailand (14.1 to 14.9) (Tsai et al., 2013) and Rondonia in Brazil (ave. 14.2) (Claeys et al., 2010), where hardwoods and crop residues were the major sources of biomass burning. Our results and above comparison imply that softwood is most likely biomass burned in central Alaska during the campaign.

Burning of lignin produces phenolic compounds such as 4-hydroxybenzoic (4-HBA), vanillic and syringic acids whereas dehydroabietic acid (DHAA) is a specific pyrolysis product of resin present in the bark surface and needle leaves and woody tissues of conifers (Simoneit et al., 1993). We detected 4-HBA and DHAA in the Alaskan aerosols although their concentrations were much lower than BB tracers produced from cellulose and hemicellulose burning (Fig. 5b). The concentrations of 4-HBA and vanillic acid ranged from 0.4 to 6.4 ng m^{-3} (ave. 1.7 ng m^{-3}) and 0.1 to 8.6 (ave. 1.8 ng m^{-3}), respectively whereas those of syringic acid ranged from 0.02 to 1.1 ng m^{-3} (ave. 0.2 ng m^{-3}). Shakya et al. (2011) and Myers-Pigg et al. (2016) reported that syringic to vanillic acid ratios for the burning of woody and non-woody angiosperm range from 0.1 to 2.4 whereas the ratios of softwood are 0.01 to 0.24. The concentration ratio of syringic to vanillic acid can therefore be used as a marker to distinguish the type of vegetation burned. We found that syringic to vanillic acid ratios in Fairbanks aerosols ranged from 0.02 to 0.5 (ave. 0.2), suggesting that softwood is more important biomass burned in central Alaska during the campaign. This conclusion is consistent with the observation on the L to M ratios as discussed above. The temporal variation of 4-HBA is very similar to that of anhydrosugars whereas vanillic and syringic acids presented rather similar temporal trends with DHAA in Alaskan aerosols (Fig. 6d-g). Simoneit et al. (1993) proposed that the emission of DHAA is different than those of lignin and cellulose burning products and therefore it is a more specific molecular marker of the burning of conifer trees. The concentrations of DHAA ranged between 0.9 and 19 ng m^{-3} (ave. 6.1 ng m^{-3}), which are higher than those of lignin pyrolysis products (Fig. 5b). This result suggests that the burning of conifer is a common source of OAs in central Alaska.

3.3 Lipids: tracers of leaf waxes and marine sources

Series of lipid class compounds, including *n*-alkanes (C_{21} to C_{33}), *n*-alkanols (C_8 to C_{30}) and *n*-alkanoic acids (C_{12} to C_{32}) were detected in Alaskan aerosols. *n*-Alkanoic acids are the major lipid class compounds in Alaskan aerosols (ave. 185 ng m^{-3}), which is several times higher than those of *n*-alkanols (ave. 46 ng m^{-3}) and *n*-alkanes (ave. 24 ng m^{-3}) (Table 1). Figure 7a-c show the average molecular distributions of lipid compounds in Alaskan aerosols. The molecular distribution of *n*-alkanes is characterized by an odd-carbon-number predominance with maxima at heptacosane (C_{27}: ave. 6.8 ng m^{-3}). Low molecular weight (LMW) *n*-alkanes are dominated in particles derived from fossil fuel combustion whereas those derived from leaf waxes are enriched with high molecular weight (HMW) *n*-alkanes (Rogge et al., 1993; Hays et al., 2005; Wang et al., 2009). A remarkable feature in the molecular signature of *n*-alkanes is the presence of only the HMW species (C_{21} to C_{33}) in

Alaskan aerosols. This molecular signature in the $PM_{2.5}$ samples suggests that leaf waxes are the major source of *n*-alkanes in central Alaska with no significant contribution from fossil fuel combustion. This feature is different from the result of marine aerosols collected over the Arctic Ocean (Fu et al., 2013), in which *n*-alkanes were mostly of fossil fuel origin. We conclude that fossil fuel combustion is not an important source of OAs over central Alaska during the summer campaign. This remark is consistent with the fact that the fossil fuel biomarkers such as hopanes and steranes (Ding et al., 2009; Wang et al., 2009) were not detected in the Alaskan samples. These results demonstrate that biogenic *n*-alkanes emitted from boreal forest fires largely overwhelmed fossil fuel combustion-derived *n*-alkanes in central Alaska.

The carbon preference index (CPI) is a powerful tool to characterize the anthropogenic versus biogenic sources of lipid compounds (Simoneit et al., 1991; Kawamura et al., 2003). The CPI value of *n*-alkanes in fossil fuel emission is usually close to unity while it is more than 5 for leaf waxes (Peltzer and Gagosian, 1989). The calculated CPI values of *n*-alkanes in the Alaskan aerosols are in the range of 5.2 to 9.9 with an average of 6.6. These values are significantly higher than those reported in urban aerosols from megacities in China (0.9 to 1.8) (Wang et al., 2006), India (1.2 to 2.3) (Fu et al., 2010) and Japan (1.1 to 2.8) (Kawamura et al., 1994), where aerosol particles were seriously affected by fossil fuel combustion. The broader range of CPI values was found in aerosol particle samples collected over Mt. Tai (1.1 to 8.0) (Fu et al., 2008) and the western North Pacific (1.8 to 15) (Kawamura et al., 2003), where the input of plant waxes overwhelms the contribution of fossil fuel combustion. Together with these assessments our results strongly infer that *n*-alkanes over the Alaskan atmosphere were mainly originated from plant leaf waxes. The wax covering the external surface of a plant leaf is composed of a mixture of long-chain aliphatic compounds. Kollattukudy (1976) investigated that odd carbon number *n*-alkanes (C_{25} to C_{33}) are one of the most abundant compound classes in the leaf wax. Simoneit et al. (1991) considered the excess of odd homologues minus the neighboring even homologues as the abundance of plant derived *n*-alkanes in atmospheric samples. The contribution of estimated plant-derived *n*-alkanes in total *n*-alkanes ranged from 53 to 70 % (ave. 61 %), implying that leaf wax is a major source of *n*-alkanes in the Alaskan aerosols.

The average molecular characteristics of *n*-alkanols and *n*-alkanoic acids displayed even-carbon-number predominance (Fig. 7b and c). *n*-Alkanols presented maxima at docosanol (C_{22}: ave. 9.2 ng m^{-3}) whereas *n*-alkanoic acids demonstrated a peak at tetracosanoic acid (C_{24}: ave. 63 ng m^{-3}). Microbes and marine phytoplankton are the sources of LMW *n*-alkanols and *n*-alkanoic acids while their HMW homologues are specifically derived from higher plant waxes (Kawamura et al., 2003; Wang and Kawamura, 2005). Simoneit (2002) has proposed that BB also emit a large extent of *n*-alkanols and *n*-alkanoic acids into the atmosphere. The average concentrations of HMW *n*-alkanols (C_{21} to C_{30}: 31 ng m^{-3}) and HMW *n*-alkanoic acids (C_{21} to C_{32}: 122 ng m^{-3}) are twice higher than those of LMW *n*-alkanols (C_8 to C_{20}: 15 ng m^{-3}) and LMW *n*-alkanoic acids (C_{12} to C_{20}: 58 ng m^{-3}) in the Alaskan aerosols. This result shows that locally derived plant waxes might be the source of HMW *n*-alkanols and *n*-alkanoic acids in central Alaska. The CPI values of *n*-alkanols and *n*-alkanoic acids are in the range of 3.0 to 10 (ave. 6.2) and 5.6 to 9.8 (ave. 7.9), respectively, suggesting a large contribution of plant waxes to lipid class compounds in central Alaskan aerosols.

The concentrations of *n*-alkanes and *n*-alkanols slightly decreased from June 05-12 to late June samples (June 25 to July 04) and then dramatically increased in July 04-06 sample (Fig. 6h and i). The concentration peaks of *n*-alkanes and *n*-alkanols were also observed in sample of July 14-23 whereas their concentrations constantly decreased from July 30 to the end of the campaign. The levels of *n*-alkanoic acids were low at the beginning of the campaign and then increased drastically in July 04-06 sample and remained high in two samples collected in July 06-23 (Fig. 6j). Concentrations of *n*-alkanoic acids decreased from July 30 to September 21. Fascinatingly, the temporal variations of lipid class compounds were similar to those of anhydrosugars (Fig. 6a-c and h-j). Figure 8a-c show the linear regression analysis of lipid compounds with levoglucosan. We found strong correlations (r = 0.90-0.96) of lipid compounds with levoglucosan in Alaskan aerosols. These results suggest that forest fires significantly control the atmospheric levels of lipids in central Alaska via the evaporative ablation of leaf-waxes of terrestrial plants.

We also detected unsaturated *n*-alkanoic acids in Alaskan aerosol samples. Oleic ($C_{18:1}$) and linoleic ($C_{18:2}$) acids are major constituents of the cell membranes in terrestrial plants. They released into the atmosphere directly from the leaf surface by wind action (Yokouchi and Ambe, 1986; Noureddini and Kanabur, 1999). Fine et al. (2001) and Hays et al. (2005) proposed that BB also emits significant amounts of $C_{18:1}$ and $C_{18:2}$ to the atmosphere. They are subjected to photochemical oxidation in the atmosphere. $C_{18:1}$ and $C_{18:2}$ are more reactive due to a double bond than $C_{18:0}$ in the atmosphere with oxidants such as OH radical and O_3. The ratio of $C_{18:1}$+$C_{18:2}$ to octadecanoic acid ($C_{18:0}$) is thus used as an indicator of photochemical processing of OAs (Kawamura and Gagosian, 1987). The ratios ranged from 0.03 to 0.3 with an average of 0.2 in Alaskan aerosols. Because average concentrations of $C_{18:1}$ (0.9 ng m^{-3}) and $C_{18:2}$ (0.5 ng m^{-3}) in Alaskan samples are significantly lower than that of $C_{18:0}$ (10 ng m^{-3}), $C_{18:1}$ and $C_{18:2}$ may be rapidly degraded in the atmosphere by photochemical oxidations.

3.4 Sugar compounds: tracers of primary biological particles

Nine sugar compounds were detected in Alaskan aerosol samples with five primary sugars and four sugar alcohols (Fig. 9). The concentrations of primary sugars were in the range of 0.3 to 44 ng m^{-3} (ave. 13 ng m^{-3}) whereas those of sugar alcohols ranged from 1.0 to 24 ng m^{-3} (ave. 14 ng m^{-3}). The concentrations of total sugar compounds ranged from 1.3 to 62 ng m^{-3} (27 ng m^{-3}), in which sugar alcohols comprised more fractions of total sugars (ave. 54.2 %) than that of primary sugars (ave. 45.8 %) in Alaskan aerosols. Primary sugars are abundantly present in vascular plants. They are produced during the photosynthetic process in leaves and then accumulated in growing plants (Medeiros et al., 2006). Figure 9a presents the average molecular distributions of primary sugars in Alaskan aerosols. Primary sugars are characterized by the predominance of glucose in Alaskan samples with the concentration range of 0.1 to 19 ng m^{-3} (ave. 6.8 ng m^{-3}) followed by trehalose (ave. 2.6 ng m^{-3}). Although sucrose (ave. 1.6 ng m^{-3}) and fructose (ave. 1.3 ng m^{-3}) are not abundant (Fig. 9a), glucose showed strong positive correlations with fructose (r = 0.91) and sucrose (r = 0.82) (Table 2). Fructose also presented a strong correlation with sucrose (r = 0.94) (Table 2). These correlations indicate their similar source and origin in the atmosphere of central Alaska.

Glucose and fructose are carbohydrates enriched in tree barks as well as branches and leaves (Medeiros et al., 2006; Li et al., 2016). They are present in plant nectars and fruits as well as pollen and fern spores (Baker et al., 1998; Graham et al., 2002). Dust and BB derived particles have also been reported as the major sources of glucose and fructose in the atmosphere (Nolte et al., 2001; Rogge et al., 2007). Sucrose is produced in plant leaves and distributed to several portions of the plant body (Jia et al., 2010). Sucrose has also been reported in airborne pollen grains produced from blooming plants (Pacini, 2000), surface soil and associated microbiota (Simoneit et al., 2004b) and dehydrated plant materials (Ma et al., 2009). We found that glucose shows moderate correlation (r = 0.48) with levoglucosan (Fig. 8d). Shafizadeh and Fu (1973) documented that glucose is a minor product of cellulose pyrolysis. The predominance of glucose among primary sugars together with a moderate correlation with levoglucosan suggests that pyrolysis of cellulose and hemicellulose is not the source of glucose in central Alaska. Pullman and Buchanan (2008) investigated that soluble carbohydrates such as glucose are a major component of conifers where it can be stored in a large amount as deposited or dissolved free molecules. The temporal trend of glucose showed a peak in the sample collected during July 14-23 (Fig. 6k). Interestingly, the same sample shows a high loading of DHAA that is a unique tracer of the burning of conifer trees (Fig. 6g). This result suggests that the burning of conifer plants is the source of glucose in central Alaska.

Trehalose is a well-known constituent of microbes and fungal spores as well as plant species and suspended soil particles (Graham et al., 2003; Medeiros et al., 2006). The levels of trehalose stayed constant from June 05 to July 14 and dramatically decreased in July 23 to August 08 and then increased towards the end of the campaign when rainfall occurs in central Alaska (Fig. 2 and Fig. 6m). This result shows that the major source of trehalose might be the fungi in the surface soil of central Alaska that was emitted after the rainfall event. Terrestrial plants and marine phytoplankton as well as soil dust particles and associated microorganisms release xylose into the atmosphere (Cowie and Hedges, 1984). Although xylose is a minor primary sugar in Alaskan aerosols (ave. 1.1 ng m^{-3}), its temporal trend is very similar to that of anhydrosugars (Fig. 6a-c and n). This result together with a strong positive correlation of xylose with levoglucosan (r = 0.92) implies its BB origin in central Alaska (Fig. 8g). This implication is similar to that of Sullivan et al. (2011), who documented that atmospheric levels of xylose in the Midwestern United States were attributed to BB emission.

Sugar alcohols presented the predominance of arabitol (ave. 6.6 ng m^{-3}) and mannitol (ave. 6.2 ng m^{-3}) (Fig. 9b). The concentration levels of erythritol (ave. 1.0 ng m^{-3}) and inositol (ave. 0.3 ng m^{-3}) are much lower than those of arabitol and mannitol in Alaskan aerosols. Arabitol and mannitol concentrations were high during the beginning and end of the campaign than those during the middle of the campaign (Fig. 6o and p). We found that arabitol and mannitol are strongly correlated (r = 0.95), implying their similar source in the Alaskan aerosols (Table 2). The major sources of arabitol and mannitol are airborne fungal spores (Pashynska et al., 2002; Bauer et al., 2008). Debris from mature leaves has also been proposed as a source of arabitol and mannitol in the forest areas (Pashynska et al., 2002; Zhang et al., 2010). Guasco et al. (2013) and Prather et al. (2013) proposed that bubble bursting of seawater contribute bacteria and dissolve organic species along with sea-salts to aerosol particles. We presume a negligible input of marine sources to sugar alcohols in Alaskan fine aerosol samples. Arabitol and mannitol were also detected in aerosol particles derived from BB (Fu et al., 2012; Yang et al., 2012; Nirmalkar et al., 2015). We found insignificant correlations of arabitol (r = 0.16) and mannitol (r = 0.27) with levoglucosan (Fig. 8h and i). This result suggests that BB is not an important source of arabitol and mannitol in the Alaskan aerosols.

The source of arabitol and mannitol might be fungi in the surface soil of Fairbanks whose activities were high during the campaign. Elbert et al. (2007) suggested that the active ejection of fungal spores demands water from the nearby atmosphere and release through osmotic pressure and surface tension effects. As shown in Figure 2 and Figures 6o and 6p, arabitol and mannitol concentrations in Alaskan samples are well connected with the rainfall event. We found that the levels of arabitol and mannitol are high during and after the rainfall. The rainfall increases the moisture contents in surface soil and thus fungal and microbial activities are enhanced in central Alaska. This study implies that the precipitation stimulates the release of fungal spores to increase the arabitol and mannitol levels in Alaskan samples. Gottwald et al. (1997), and Burch and Levetin (2002) reported that passive discharge of spores is enhanced under windy conditions. This consideration further implying that fungal spores are actively ejected in the atmosphere of central Alaska. Our finding is consistent with the result of Elbert et al. (2007) from Amazonia rainforest where the ambient fungal spores were controlled by the active discharge. It is noteworthy that primary sugar trehalose presented significant positive correlations with arabitol (r = 0.85) and mannitol (r = 0.74) (Table 2), documenting that trehalose is also be produced from surface soil under wet conditions in central Alaska.

3.5 Phthalate esters: tracers of plastic burning

Phthalates are widely used as a plasticizer in synthetic polymers and as a softener in polyvinylchloride (Thuren and Larsson, 1990; Wang et al., 2006). They can be emitted into the atmosphere by evaporation from polymers because they are not chemically bonded (Staples et al., 1997). The compositions of phthalate esters are the subject of scientific discussion and public concern due to their potential carcinogenic and endocrine disrupting properties (Sidhu et al., 2005; Swan et al., 2005). We detected four phthalate esters in Alaskan aerosols, including diethyl phthalate (DEP), dibutyl phthalate (DBP), diisobutyl phthalate (DiBP) and diethylhexyl phthalate (DEHP).

The ambient concentrations of total phthalate esters ranged from 0.4 to 6.6 ng m^{-3} (ave. 1.7 ng m^{-3}), which are slightly higher than those from the North Sea to the high Arctic (0.4 to 1.0 ng m^{-3}) (Xie et al., 2007), comparable to or slightly lower than those observed in the North Pacific (0.72 to 4.48 ng m^{-3}) (Atlas and Giam, 1981), Great Lakes (0.1 to 10 ng m^{-3}) (Eisenreich et al., 1981), Canadian High Arctic (0.28 to 11 ng m^{-3}) (Fu et al., 2009), but much lower than those reported in Sweden (0.5 to 127 ng m^{-3}) (Thuren and Larsson, 1990), mountainous aerosols (9.6 to 985 ng m^{-3}) (Fu et al., 2008) and urban aerosols from megacities in India and China (62 to 2200 ng m^{-3}) (Wang et al., 2006; Fu et al., 2010). Figure 10a shows the average molecular distributions of phthalate esters in Alaskan aerosols. We found DEP (ave. 0.8 ng m^{-3}) as a dominant phthalate followed by DBP and DEHP (ave. 0.4 ng m^{-3}), whereas DiBP was less abundant (ave. 0.2 ng m^{-3}). The predominance of DEP among phthalate esters in Alaskan aerosol is different than those found in marine aerosol from the Arctic Ocean (Xie et al., 2007; Fu et al., 2013) and urban aerosols from India and China (Wang et al., 2006; Fu et al., 2010), where DEHP was the dominant species. We found similar temporal variations with significant positive correlations among detected phthalate esters (r = 0.71-0.88) (Fig. 11a-d and Table 2), suggesting that they have similar sources in central Alaska.

3.6 Tracers of biogenic SOA

Significant progress has been made in the last decade to better understand SOA formation from BVOCs such as isoprene, monoterpenes and sesquiterpenes (Carlton et al., 2009; Ding et al., 2014; Jathar et al., 2014; Sarkar et al., 2017). SOA is a crucial component of the atmosphere that has an impact on the radiation budget directly by scattering sunlight and indirectly by acting as CCN (Kanakidou et al., 2005; Carlton et al., 2009). Isoprene has conjugated double bonds and thus it is more reactive towards oxidants such as O_3 and NO_x to result in various intermediates and stable products via a series of oxidative reactions in the atmosphere. We detected six organic compounds including 2-methylglyceric acid (2-MGA), three C_5-alkene triols and two 2-methyltetrols (2-MTLs) as isoprene-SOA tracers in the Alaskan aerosols. Their total concentrations ranged from 2.0 to 142 ng m^{-3} (ave. 41 ng m^{-3}), which are significantly higher than those reported over the North Pacific (0.11 to 0.48 ng m^{-3}) (Fu et al., 2011), Canadian High Arctic (ave. 0.30 ng m^{-3}) (Fu et al., 2009), North Pacific to Arctic (ave. 0.62 ng m^{-3}) (Ding et al., 2013), western North Pacific (0.05 to 7.22 ng m^{-3}) (Zhu et al., 2016), forest site in western Germany (ave. 20.5 ng m^{-3}) (Kourtchev et al., 2008a), and Mumbai in India (ave. 1.1 ng m^{-3}) (Fu et al., 2016) but lower than those in Mt. Changbai (22 to 280 ng m^{-3}) (Wang et al., 2008) and Mt. Fuji (ave. 69 ng m^{-3}) (Fu et al., 2014), Research Triangle Park in USA (19.9 to 384 ng m^{-3}) (Lewandowski et al., 2007) and several sites in China (8.65 to 554 ng m^{-3}) (Ding et al., 2014).

Molecular compositions of isoprene-SOA tracers are characterized by the predominance of C_5-alkene triols (ave. 20 ng m^{-3}) and 2-MTLs (ave. 19 ng m^{-3}) in Alaskan aerosols (Fig. 12). Surratt et al. (2010) proposed that C_5-alkene triols and 2-MTLs are higher generation products from the photooxidation of epoxydiols of isoprene under low-NO_x conditions. C_5-Alkene triols were strongly corrected with 2-MTLs (r = 0.97) in the Alaskan aerosols (Table 2). The abundant co-presence of C_5-alkene triols and 2-MTLs suggest their similar sources and formation pathways in central Alaska. 2-Methylerythritol (ave. 13 ng m^{-3}) is twice more abundant than 2-methylthreitol (ave. 5.9 ng m^{-3}), being similar to previous studies (Ion et al., 2005; Cahill et al., 2006). The concentration of 2-MGA is significantly lower (ave. 2.2 ng m^{-3}) than C_5-alkene triols and 2-MTLs (Fig. 12). Surratt et al. (2006) suggested that 2-MGA is produced by the oxidation of methacrolein and methacrylic acid and has been detected as an important gas-phase intermediate in the SOA formation from isoprene under high-NO_x conditions. Temporal variations of isoprene-SOA tracers were very similar to each other in Alaskan aerosols (Fig. 11e-g). Their concentrations increased in the sample of June 12-25 to July 06-14 and decreased in the sample of July 14-23 and July 23-30. They increased significantly in July 30 to August 04 sample and quickly reduced in August 04-08 sample and then remain comparable at the end of the campaign.

Four organic acids were identified as monoterpenes-SOA tracers in Alaskan aerosols. They include 3-hydroxyglutaric acid (3-HGA), pinonic acid (PNA), pinic acid (PA) and 3-methyl-1,2,3-butanetricarboxylic acid (3-MBTCA). Hallquist et al. (2009) suggested that these acids are produced by the oxidation of pinenes through reactions with OH radical and O_3. Their total concentrations ranged from 1.0 to 36 ng m^{-3} (ave. 9.2 ng m^{-3}), which are higher than those reported in the North Pacific (0.02 to 0.22 ng m^{-3}) (Fu et al., 2011), Canadian High Arctic (ave. 1.6 ng m^{-3}) (Fu et al., 2009), North Pacific to Arctic (ave. 0.05 ng m^{-3}) (Ding et al., 2013), western North Pacific (0.04 to 10.8 ng m^{-3}) (Zhu et al., 2016), and comparable to those reported at several sites in China (3.09 to 33.8) (Ding et al., 2014) but lower than those reported at Mt. Fuji in Japan (ave. 39 ng m^{-3}) (Fu et al., 2014), forest site in Germany (ave. 25.6 ng m^{-3}) (Kourtchev et al., 2008a) and Finland (11.1 to 217 ng m^{-3}) (Kourtchev et al., 2008b). PA is most abundant (ave. 3.4 ng m^{-3}) among monoterpene-SOA tracers followed by PNA (ave. 2.3 ng m^{-3}) (Fig. 12). The dominance of PA over PNA in summertime can be explained by the much lower vapor pressure of PA than that of PNA. However, this pattern is different from those found in summertime aerosols at the summit of Mt. Tai in China (Fu et al., 2008) and other sites in Europe (Kavouras and Stephanou, 2002) and North America (Cahill et al., 2006), in which PNA is more abundant than PA.

PA and PNA are the initial photooxidation products of monoterpenes that can further photooxidized to 3-MBTCA in the atmosphere (Gomez-Gonzalez et al., 2012). The concentration ratio (3-MBTCA to PA+PNA) can therefore be used to differentiate the fresh and photochemically processed monoterpene-SOA tracers in the atmosphere. We found the ratios to be 0.1 to 1.4 (ave. 0.5), demonstrating that monoterpene-SOA are mostly fresh in central Alaska. The ratios of 3-HGA to 3-MBTCA are mostly lower when they are produced from α-pinene as compared to β-pinene. Lewandowski et al. (2013) documented a major contribution of α-pinene to monoterpene-SOA tracers based on the 3-HGA/3-MBTCA ratio of about 1 in the southeastern United States than those observed in California (1.8 to 3.8). Ding et al. (2014) also suggested α-pinene as the major precursor in China based on the low ratios in Hefei (1.16) and Qianyanzhou (0.75). We found the ratios ranging from 0.5 to 2.0 in Alaskan aerosols (ave. 1.0), indicating that α-pinene mainly contributes to monoterpene-SOA tracers. 3-HGA and 3-MBTCA displayed somewhat similar temporal variations although the patterns are different from PA and PNA (Fig. 11h-k), which showed very similar variations in Alaskan aerosols.

Sesquiterpenes are BVOCs with high reactivity and relatively low vapor pressure (Duhl et al., 2008). β-Caryophyllene is dominant sesquiterpene. The ozonolysis or photooxidation of β-caryophyllene produces β-caryophyllinic acid in the atmosphere (Jaoui et al., 2007). Concentrations of β-caryophyllinic acid in Alaskan aerosols ranged from 0.1 to 3.4 ng m^{-3} (ave. 0.9 ng m^{-3}), which are higher than those from the Canadian High Arctic (ave. 0.12 ng m^{-3}) and Arctic Ocean (ave. 0.017 ng m^{-3}) (Fu et al., 2009; Fu et al., 2013) but lower than those reported in several sites in China (0.17 to 17.4 ng m^{-3}) (Ding et al., 2014) and Research Triangle Park in USA (5.9 to 25 ng m^{-3}) (Lewandowski et al., 2007). The temporal variation of β-caryophyllinic acid is very different than those of isoprene and monoterpene-SOA tracers detected in Alaskan aerosols (Fig. 11l). Akagi et al. (2011) reported that biogenic VOCs could also be emitted from biomass burning. Our result showed a high level of β-caryophyllinic acid in the samples that were affected by BB in central Alaska. Ciccioli et al. (2014) proposed that sesquiterpenes could be accumulated in leaves and wood because of low volatility and then abundantly emitted upon heating. The temporal trend variation of β-caryophyllinic acid is similar to those of anhydrosugars (Fig. 6a-c and 11l). Interestingly, we found a strong correlation (r = 0.98) of β-caryophyllinic acid with levoglucosan (Fig. 8j), again indicating that forest fire largely contributes to the formation of β-caryophyllinic acid in central Alaska.

3.7 Aromatic and polyacids: tracers of SOA

We detected benzoic acid in the Alaskan aerosol with the concentration range of 0.1 to 0.9 (ave. 0.3 ng m^{-3}). Benzoic acid is produced from several anthropogenic sources. It is a primary pollutant in the automobile emission and smokes derived from burning of biomass and biofuels (Rogge et al., 1993; Kawamura et al., 2002). It is also a secondary product of photochemical degradation of toluene emitted from anthropogenic sources (Suh et al., 2003).

It can play an important role to enhance the new particle formation in the atmosphere (Zhang et al., 2004). The temporal variation of benzoic acid is similar to anhydrosugars detected in Alaskan samples (Fig. 6a-c and 11m). We also found a strong positive correlation (r = 0.95) of benzoic acid with levoglucosan (Fig. 8k), demonstrating that BB is the source of benzoic acid in central Alaska.

Polyacids are also the secondary photooxidation products of atmospheric organic precursors (Wang et al., 2007; Fu et al., 2012). Concentrations of total polyacids ranged from 1.2 to 10 ng m^{-3} (ave. 3.3 ng m^{-3}), among which glyceric acid (ave. 1.6 ng m^{-3}) was dominant (Fig. 13). Significant positive correlations were found among all polyacids (r = 0.67-0.87) in Alaskan aerosols (Table 2). These results imply that polyacids may have similar sources or formation pathways in central Alaska. We found that polyacids showed no significant correlations with benzoic acid (r = 0.17-0.53), which is mostly of BB origin in Alaskan samples as discussed above (Table 2). These correlations and different temporal trends of benzoic acid and polyacids suggest that forest fires are not the main source of polyacids in the Alaskan samples (Fig. 11m-p). This remark is further supported by the insignificant correlations of polyacids with levoglucosan (r = 0.29-0.47) (Fig. 8l-n). Claeys et al. (2004) suggested that SOA tracer such as tartaric acid is produced by the photochemical oxidation of isoprene. Interestingly, significant positive correlations (r = 0.67-0.78) of polyacids were found with total isoprene-SOA tracers detected in Alaskan samples (Table 2), suggesting that they may be produced by photooxidation of isoprene in the Alaskan atmosphere.

3.8 Contributions of compound classes to aerosol organic carbon

The contributions of each compound class to organic carbon (OC) in the Alaskan aerosols are given in Table 3. BB tracers accounted for 1.35 to 8.35 % (ave. 4.40 %) of OC. The contribution of anhydrosugars to OC was substantially high (ave. 4.26 %) than that of lignin and resin acids (ave. 0.14 %). This value from Fairbanks is notably higher than those reported in aerosol samples collected from a round-the-world cruise (ave. 0.15 %) (Fu et al., 2011), Gosan Jeju Island in Korea (ave. 0.29 %), Sapporo (ave. 0.44 %) and Chichijima (ave. 0.06 %) in Japan (Simoneit et al., 2004a), and Chennai in India (ave. 0.59 %) (Fu et al., 2010). The lipid compound classes in Fairbanks samples accounted for 1.16 to 45.8 % (ave. 12.4 %) of OC. *n*-Alkanoic acids contributed on average 7.48 % (0.67 to 15.9 %), which is much higher than those estimated in samples of round-the-world cruise (ave. 0.82 %), Sapporo (ave. 0.62 %) and Chichijima (ave. 0.78 %) (Simoneit et al., 2004a; Fu et al., 2011). The tracers of primary biological aerosol particles accounted for on average 0.85 % (0.17 to 1.50 %), among which comparable contributions of primary sugars (ave. 0.39 %) and sugar alcohols (ave. 0.46

%) to OC were found in Alaskan aerosols. Plastic burning tracer accounted for 0.02 to 1.07 % of OC (ave. 0.14 %), which is lower than those from Sapporo (ave. 1.1 %) and Chichijima samples (ave. 1.2 %) (Simoneit et al., 2004a) and tropical samples from India (ave. 4.50 %) (Fu et al., 2010). Biogenic SOA tracers contributed 0.18 to 3.99 % of OC (ave. 1.66 %), among which the contribution of isoprene-derived SOA tracers was high (ave. 1.28 %) followed by monoterpene (ave. 0.34 %) and sesquiterpene (ave. 0.03 %) SOA tracers. Other SOA tracers that contribute very less to OC include polyacids (ave. 0.08 %) and aromatic acids (ave. 0.02 %).

With the consideration of water-soluble dicarboxylic acids and related polar compounds measured in the same sample sets as reported in Deshmukh et al. (2018), the total organic compounds identified in the Alaskan aerosols accounted for 6.37 to 59.2 % with a mean of 21.4 % of OC. This result indicates that a substantial portion of OAs studied in the Alaskan site can be identified at a molecular level.

4 Conclusions and implications

We identified 96 organic compounds in $PM_{2.5}$ samples collected at Fairbanks in central Alaska during the summer campaign in 2009. Concentrations of total organic compounds ranged from 113 to 1664 (ave. 535 ng m^{-3}). The most abundant compound classes in the Alaskan aerosol are anhydrosugars (ave. 186 ng m^{-3}) and *n*-alkanoic acids (ave. 185 ng m^{-3}). The temporal variations of anhydrosugars dramatically changed during the campaign, showing peaks during BB events. The similar temporal trends of lipids and strong correlations with levoglucosan demonstrated that local forest fires likely control the atmospheric levels of OAs in central Alaska. The concentration ratios of levoglucosan to mannosan (2.2 to 6.8) and syringic to vanillic acid (0.02 to 0.5) suggest that burning of softwood is common sources of OAs. The higher levels of HMW *n*-alkanoic acids and *n*-alkanols than their LMW homologues together with high CPI values of *n*-alkanes (5.2 to 9.9), *n*-alkanols (3.0 to 10) and *n*-alkanoic acids (5.6 to 9.8) further suggest that they were emitted by the thermal ablation of plant waxes during forest fire in central Alaska. The temporal patterns of mannitol and arabitol suggested that the rainfall play an important role to enhance their levels in central Alaska. The molecular compositions of phthalate esters displayed that diethyl phthalate is commonly used plasticizer in central Alaska. The molecular composition of biogenic SOA tracers with a predominance of isoprene-SOA tracers (ave. 41 ng m^{-3}) suggested that isoprene is a crucial precursor of SOA over central Alaska. Our results provide valuable information to better understand the compositions of OAs and their sources and formation pathways in the subarctic atmosphere.

The Arctic is a critical region on the Earth with a significant warming and high sensitivity to climate forcing due to a strong effect on an albedo-sea ice feedback system. Our results substantiated that forest fires and plant emissions are important factors controlling the organic chemical composition of fine aerosol particles in central Alaska. The results of Hegg et al. (2009) and Warneke et al. (2009) validate that BB causes a more efficient transport and deposition of BC aerosol in Arctic snow, causing a strong climate forcing in high latitudes. Based on in-situ measurements in the Arctic and a transport model of carbon monoxide (CO), Warneke et al. (2010) proposed that BB plumes transported to the Arctic in spring in 2008 were more than double the Arctic atmospheric burden in other seasons. Biogenic emissions from boreal forest largely increase during the summertime growing season. The year-round measurements conducted at Fairbanks by Haque et al. (2016) have shown that SOA derived from biogenic VOC emissions dominated organic chemical composition of total suspended particles during summer in central Alaska. The measurements of Ward et al. (2012) and Wang and Hopke (2014) demonstrate that Arctic air pollution could be so severe that the city of Fairbanks has been labeled as a serious nonattainment area by the United States Environmental Protection Agency.

It is worth therefore to note from the above discussion that the Fairbanks exemplifies many of the problems of pollution in the Arctic regions. The local and regional BB episodes in warmer season enhanced the atmospheric levels of OAs in central Alaska. Because residence time of fine particles is relatively long in the atmosphere, we propose that OAs of $PM_{2.5}$ at Fairbanks can be subjected to long-range transport to the Arctic causing a significant influence on the air quality and climate in the Arctic region. Although we studied the aerosol samples collected in 2009, further research is needed to characterize the seasonal and interannual trends of OAs using more recent aerosol samples to better evaluate their current impact in the Arctic atmosphere.

Data availability. The data set of this paper is given in Table S1 in the supplement file.

Author contributions. KK designed the research. YK collected the aerosol samples. DKD and MMH analyzed the samples for organic tracer compounds. DKD evaluated the data and wrote the paper under the supervision of KK. All authors contributed to discussing results and commenting on the paper.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Concentrations (ng m^{-3}) of organic tracer compound classes detected in $PM_{2.5}$ aerosols from central Alaska.

Compound classes	Minimum	Maximum	Mean	Median	S.D.[a]
Anhydrosugars	31	749	186	69	217
Lignin acids	0.5	15	3.8	2.2	4.2
Resin acid	0.9	19	6.1	5.1	4.7
n-Alkanes	0.5	77	24	21	23
n-Alkanols	5.3	119	46	29	38
n-Alkanoic acids	9.2	562	185	82	209
Primary sugars	0.3	44	13	12	11
Sugar alcohols	1.0	24	14	18	7.4
Phthalate esters	0.4	6.6	1.7	0.9	1.8
Aromatic acid	0.1	0.9	0.3	0.2	0.2
Polyacids	1.2	10	3.3	2.6	2.5
Isoprene oxidation products	2.0	142	41	20	43
Monoterpene oxidation products	1.0	36	9.2	7.0	8.7
Sesquiterpene oxidation products	0.1	3.4	0.9	0.3	1.0
Sum of all	113	1664	535	251	517

[a]Standard deviation

Table 2. Statistical summary for the linear regression among the organic tracers in $PM_{2.5}$ aerosols from central Alaska.

Linear regression	Correlation coefficient	P value	Significance of correlation at P value < 0.05
Levoglucosan vs. Mannosan	0.97	< 0.05	Significant
Levoglucosan vs. Galactosan	0.94	< 0.05	Significant
Mannosan vs. Galactosan	0.95	< 0.05	Significant
Glucose vs. Fructose	0.91	< 0.05	Significant
Glucose vs. Sucrose	0.82	< 0.05	Significant
Fructose vs. Sucrose	0.94	< 0.05	Significant
Arabitol vs. Mannitol	0.95	< 0.05	Significant
Trehalose vs. Arabitol	0.85	< 0.05	Significant
Trehalose vs. Mannitol	0.74	< 0.05	Significant
DEP[a] vs. DBP[b]	0.85	< 0.05	Significant
DEP[a] vs. DiBP[c]	0.87	< 0.05	Significant
DEP[a] vs. DEHP[d]	0.71	< 0.05	Significant
DBP[b] vs. DiBP[c]	0.81	< 0.05	Significant
DBP[b] vs. DEHP[d]	0.88	< 0.05	Significant
DiBP[c] vs. DEHP[d]	0.75	< 0.05	Significant
C_5-Alkene triols vs. 2-Methyltetrols	0.97	< 0.05	Significant
Glyceric acid vs. Tartaric acid	0.84	< 0.05	Significant
Glyceric acid vs. Citric acid	0.67	< 0.05	Significant
Tartaric acid vs. Citric acid	0.87	< 0.05	Significant
Benzoic acid vs. Glyceric acid	0.53	> 0.05	Not significant
Benzoic acid vs. Tartaric acid	0.39	> 0.05	Not significant
Benzoic acid vs. Citric acid	0.17	> 0.05	Not significant
Glyceric acid vs. isoprene SOA tracer	0.78	< 0.05	Significant
Tartaric acid vs. isoprene SOA tracer	0.75	< 0.05	Significant
Citric acid vs. isoprene SOA tracer	0.67	< 0.05	Significant

[a] Diethyl phthalate
[b] Dibutyl phthalate
[c] Diisobutyl phthalate
[d] Diethylhexyl phthalate

Table 3. Contributions (%) of individual organic compound classes to organic carbon (OC) in $PM_{2.5}$ aerosols from central Alaska.[a]

Compound classes	Minimum	Maximum	Mean	Median	Standard deviation
Biomass burning tracers					
Anhydrosugars	1.32	8.12	4.26	3.64	2.13
Lignin and resin acids[b]	0.03	0.51	0.14	0.11	0.13
Subtotal	1.35	8.35	4.40	3.71	2.24
Lipid compounds					
n-Alkanes	0.05	8.53	1.55	0.98	2.19
n-Alkanols	0.40	21.3	3.32	1.82	5.47
n-Alkanoic acids	0.67	15.9	7.48	6.71	4.80
Subtotal	1.16	45.8	12.4	9.20	11.3
Primary biological aerosols					
Primary sugars	0.05	0.85	0.39	0.50	0.26
Sugar alcohols	0.07	0.95	0.46	0.33	0.33
Subtotal	0.17	1.50	0.85	0.74	0.56
Phthalate esters	0.02	1.07	0.14	0.05	0.28
Aromatic acid	0.01	0.09	0.02	0.01	0.02
Polyacids	0.02	0.25	0.08	0.09	0.06
Biogenic SOA tracers					
Isoprene oxidation products	0.07	3.20	1.28	0.83	1.12
Monoterpene oxidation products	0.07	0.75	0.34	0.34	0.20
Sesquiterpene oxidation products	0.02	0.04	0.03	0.03	0.01
Subtotal	0.18	3.99	1.66	1.22	1.29
Dicarboxylic acids and related compounds[c]	1.15	2.97	1.90	1.87	0.58
Total detected organic compounds	6.37	59.2	21.4	16.9	13.8

[a] All the organic compounds quantified were converted to carbon contents and then divided by OC. See Deshmukh et al. (2018) for OC and dicarboxylic acids and related compounds. [b] The results of lignin and resin acids were combined due to the very low contribution of resin acid to OC.

Figure captions

Figure 1. The location of the sampling site at Fairbanks in central Alaska (64.51°N and 147.51°W) and its surrounding regions.

Figure 2. The daily average variations of meteorological parameters from 5 June to 21 September 2009 at observation site in central Alaska.

Figure 3. The air mass backward trajectories over the observation site during the collection of aerosol samples. The color scale shows the height of the air parcel.

Figure 4. Chemical compositions of organic compounds in $PM_{2.5}$ aerosols from central Alaska. The sample collection periods are June 5-12 (Alaska 01), June 12-25 (Alaska 02), June 25-July 04 (Alaska 03), July 04-06 (Alaska 04), July 06-14 (Alaska 05), July 14-23 (Alaska 06), July 23-30 (Alaska 07), July 30-August 04 (Alaska 08), August 04-08 (Alaska 09), August 08-25 (Alaska 10), August 25-31 (Alaska 11), August 31-September 10 (Alaska 12) and September 10-21 (Alaska 13) in 2009.

Figure 5. Molecular distributions of anhydrosugars and lignin and resin acids in $PM_{2.5}$ aerosols collected in central Alaska.

Figure 6. Temporal changes in the concentrations of biomass burning tracers and other organic compounds in the Alaskan aerosols.

Figure 7. Molecular distributions of lipid compounds in $PM_{2.5}$ aerosols collected in central Alaska. See Figure 5 for the description of the box-and-whisker diagram.

Figure 8. Correlations of organic compounds with a biomass burning tracer levoglucosan in the Alaskan aerosol samples.

Figure 9. Molecular distributions of primary sugars and sugar alcohols in $PM_{2.5}$ aerosols collected in central Alaska. See Figure 5 for the description of the box-and-whisker diagram.

Figure 10. Molecular distributions of phthalate esters in $PM_{2.5}$ aerosols collected in central Alaska. See Figure 5 for the description of the box-and-whisker diagram.

Figure 11. Temporal changes in the concentrations of phthalate esters and other organic compounds in the Alaskan aerosols.

Figure 12. Molecular distributions of biogenic secondary organic aerosol tracers in $PM_{2.5}$ aerosols collected in central Alaska. See Figure 5 for the description of the box-and-whisker diagram.

Figure 13. Molecular distributions of aromatic and polyacids in $PM_{2.5}$ aerosols collected in central Alaska. See Figure 5 for the description of the box-and-whisker diagram.

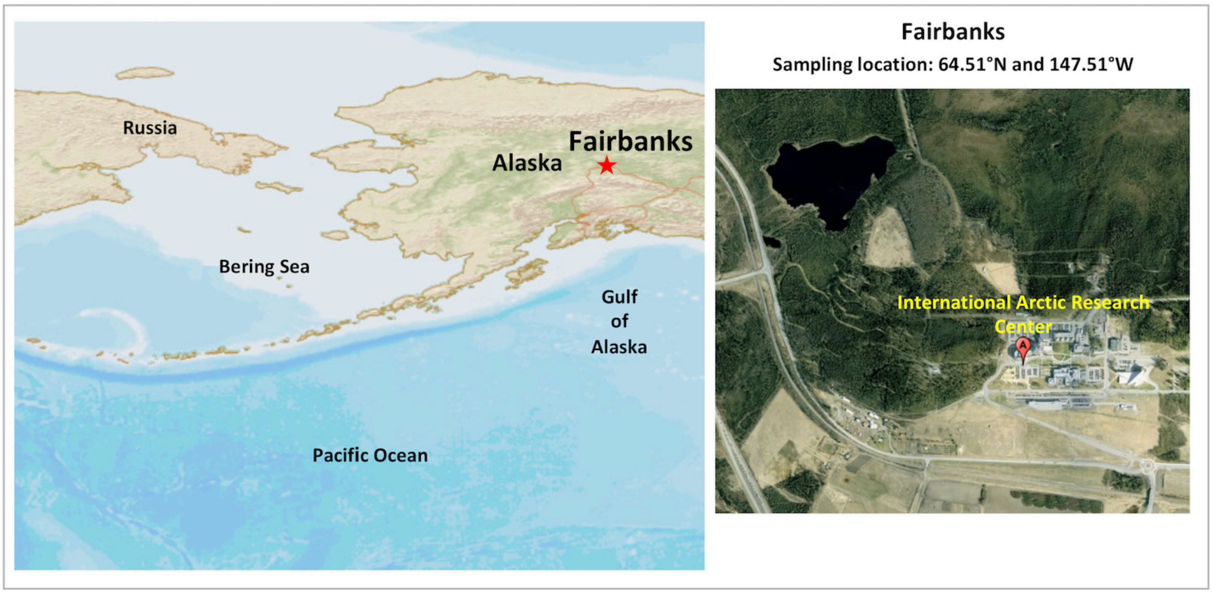
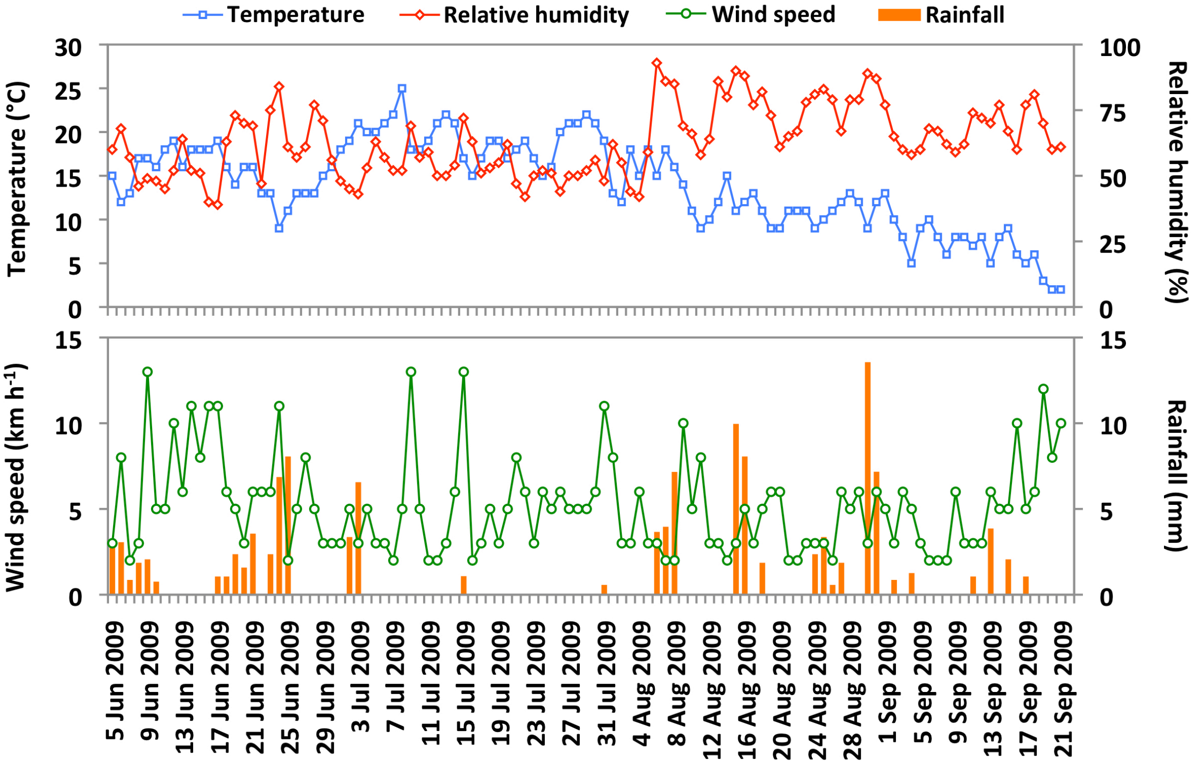


Figure 1



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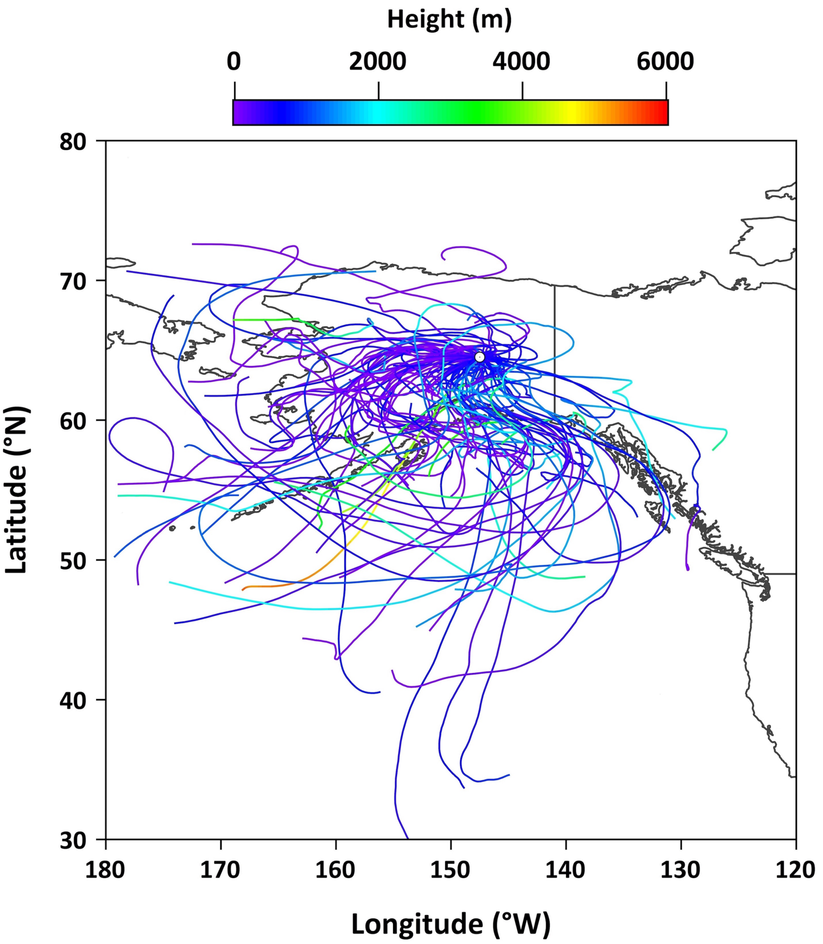
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Latitude (°N)
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120
Longitude (°W)

Figure 3

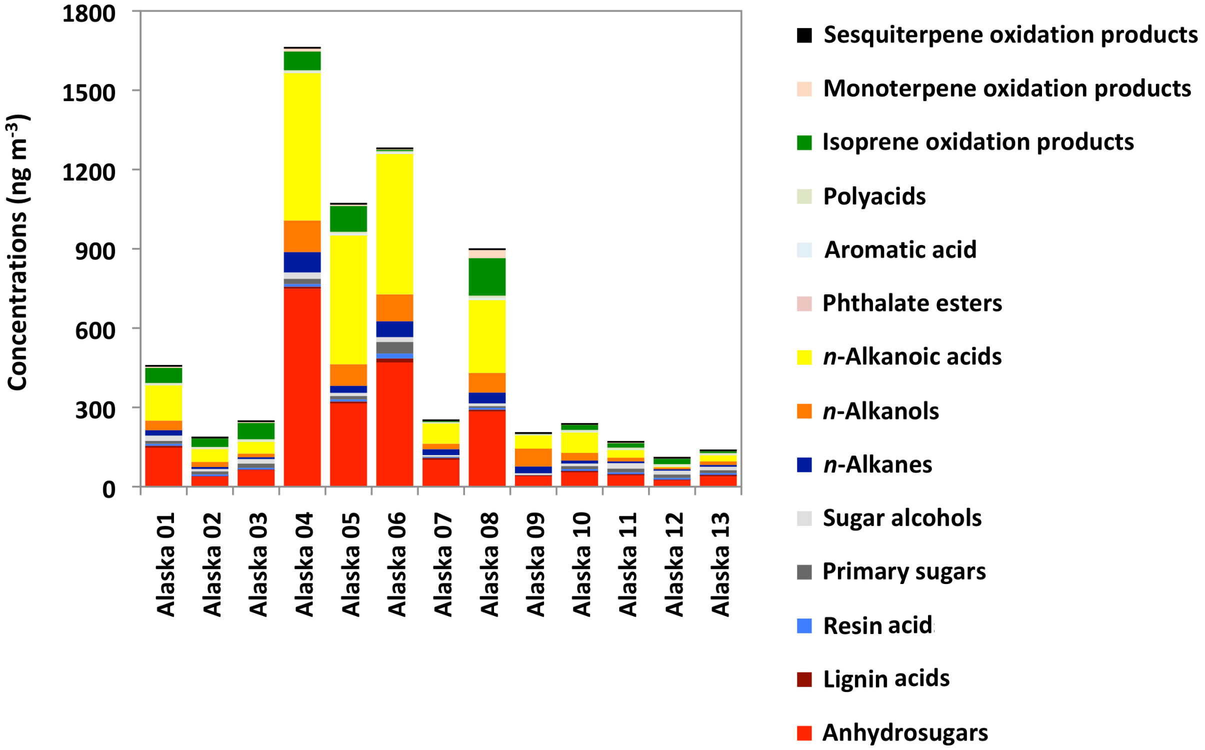


Figure 4

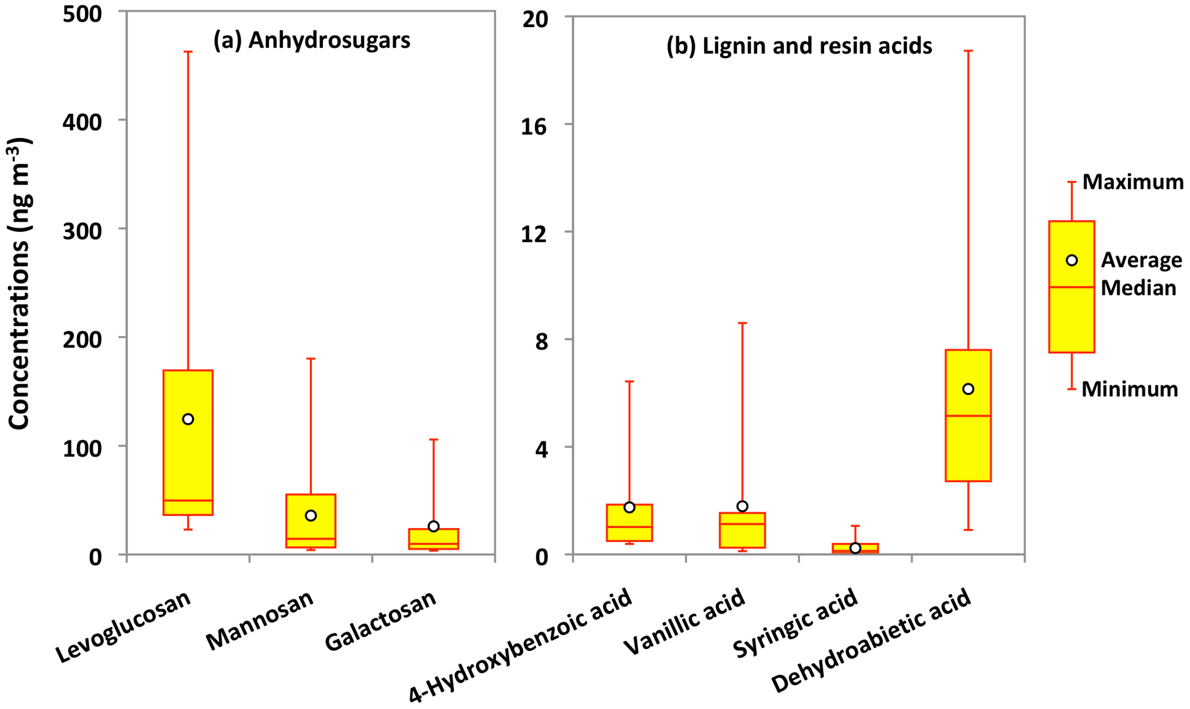


Figure 5

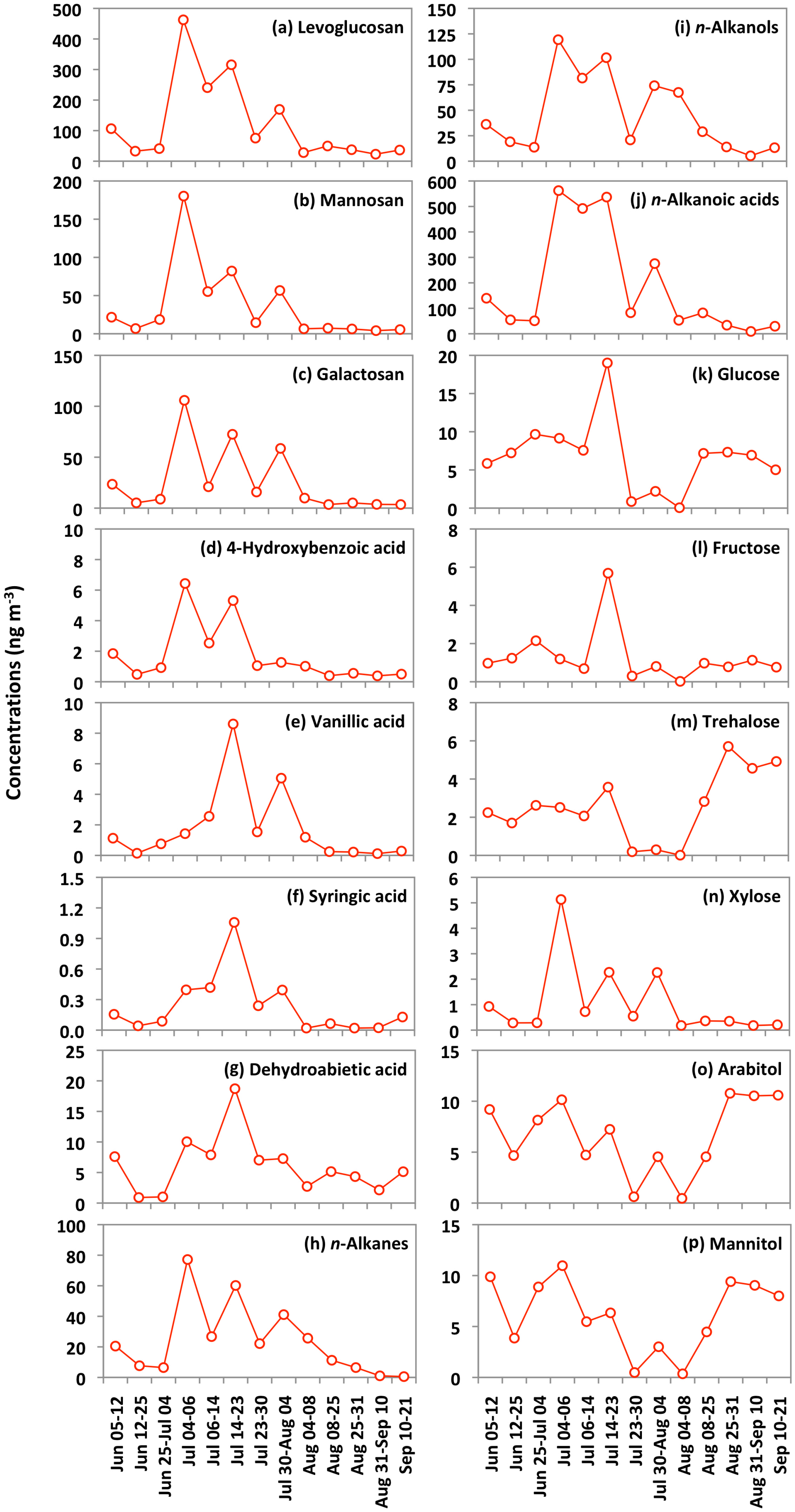
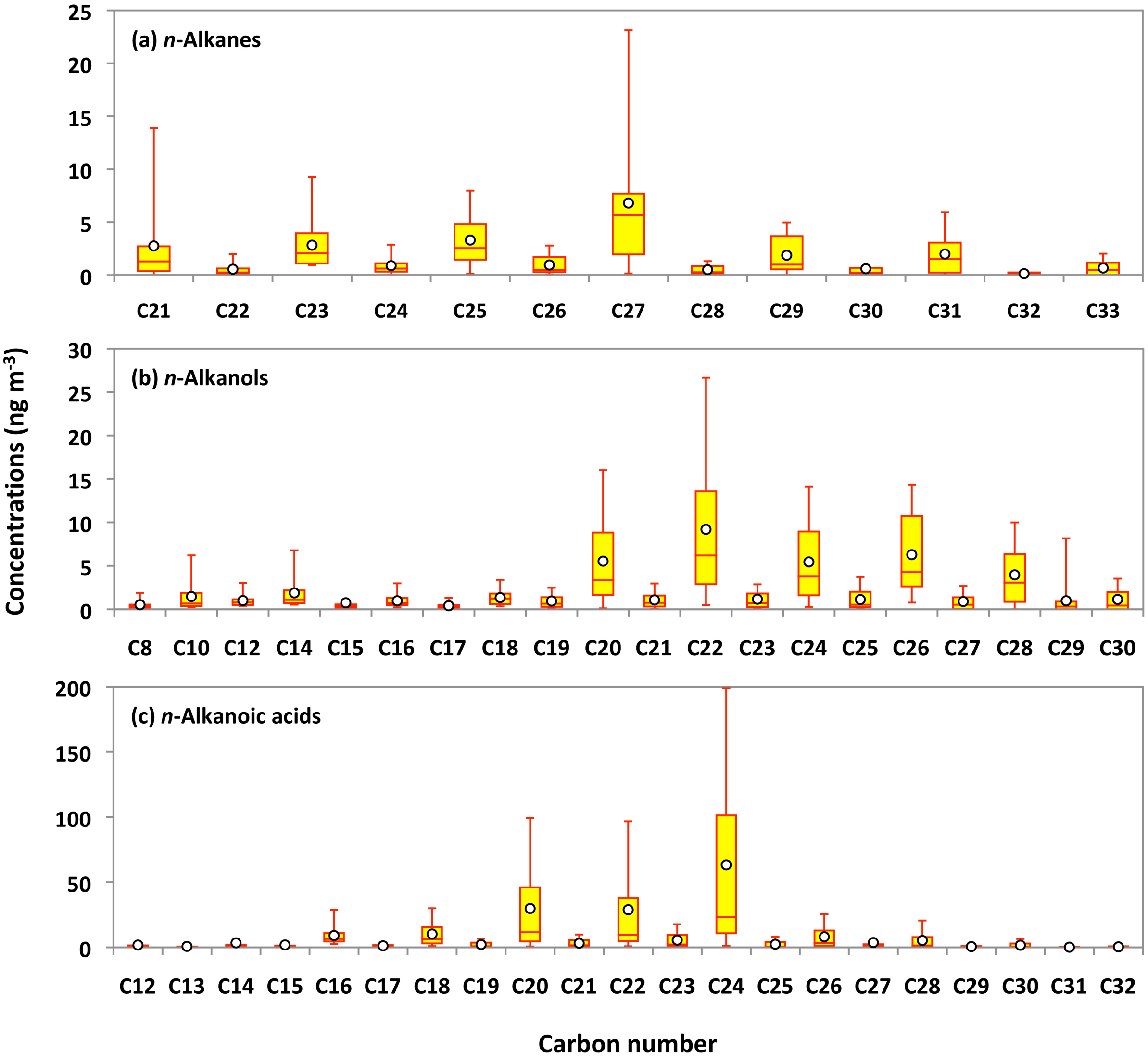

Concentrations (ng m^{-3})
(a) Levoglucosan
(b) Mannosan
(c) Galactosan
(d) 4-Hydroxybenzoic acid
(e) Vanillic acid
(f) Syringic acid
(g) Dehydroabietic acid
(h) *n*-Alkanes
(i) *n*-Alkanols
(j) *n*-Alkanoic acids
(k) Glucose
(l) Fructose
(m) Trehalose
(n) Xylose
(o) Arabitol
(p) Mannitol
Jun 05-12
Jun 12-25
Jun 25-Jul 04
Jul 04-06
Jul 06-14
Jul 14-23
Jul 23-30
Jul 30-Aug 04
Aug 04-08
Aug 08-25
Aug 25-31
Aug 31-Sep 10
Sep 10-21

Figure 6

1222



1223

1224 **Figure 7**

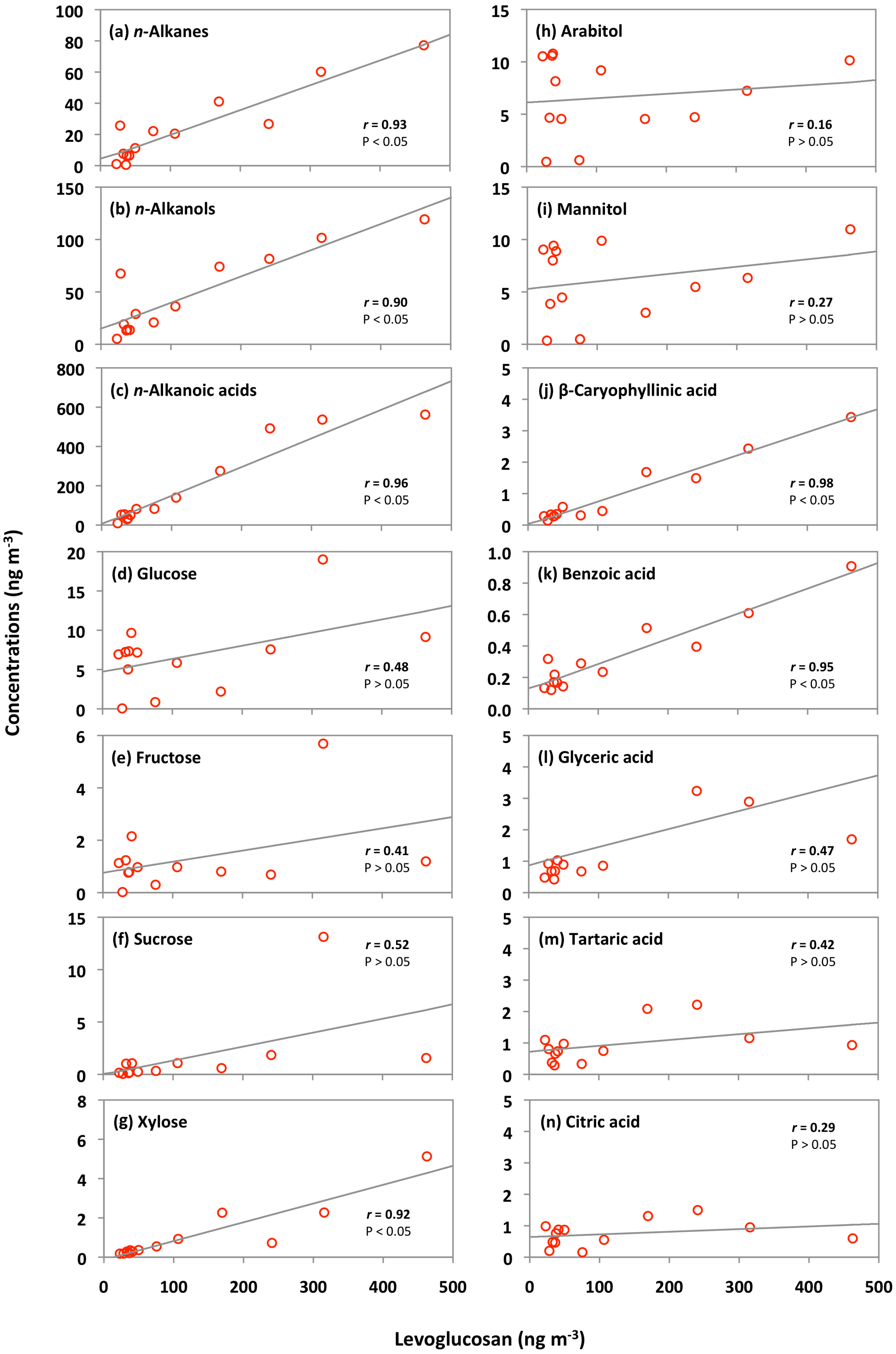
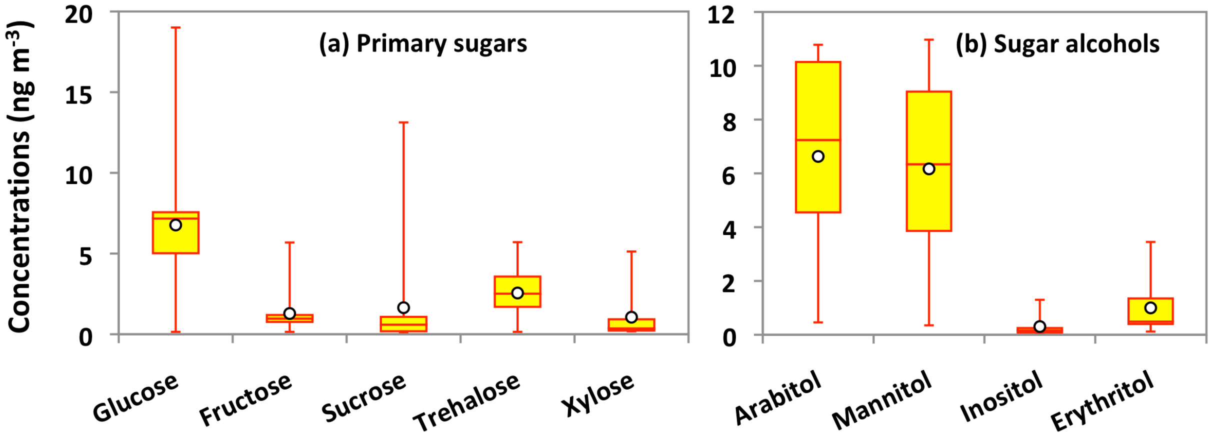
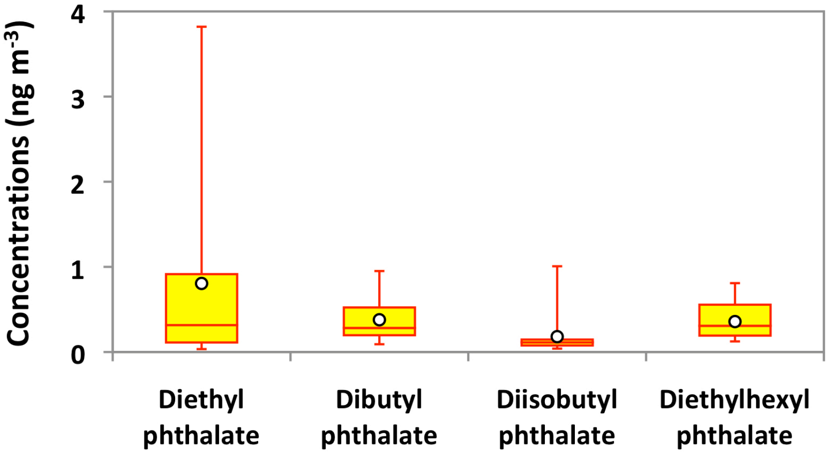

(a) n-Alkanes
r = 0.93
P < 0.05
(b) n-Alkanols
r = 0.90
P < 0.05
(c) n-Alkanoic acids
r = 0.96
P < 0.05
(d) Glucose
r = 0.48
P > 0.05
(e) Fructose
r = 0.41
P > 0.05
(f) Sucrose
r = 0.52
P > 0.05
(g) Xylose
r = 0.92
P < 0.05
(h) Arabitol
r = 0.16
P > 0.05
(i) Mannitol
r = 0.27
P > 0.05
(j) β-Caryophyllinic acid
r = 0.98
P < 0.05
(k) Benzoic acid
r = 0.95
P < 0.05
(l) Glyceric acid
r = 0.47
P > 0.05
(m) Tartaric acid
r = 0.42
P > 0.05
(n) Citric acid
r = 0.29
P > 0.05
Concentrations (ng m-3)
Levoglucosan (ng m-3)
0
100
200
300
400
500

Figure 8



1227

1228 **Figure 9**



1229

1230 **Figure 10**

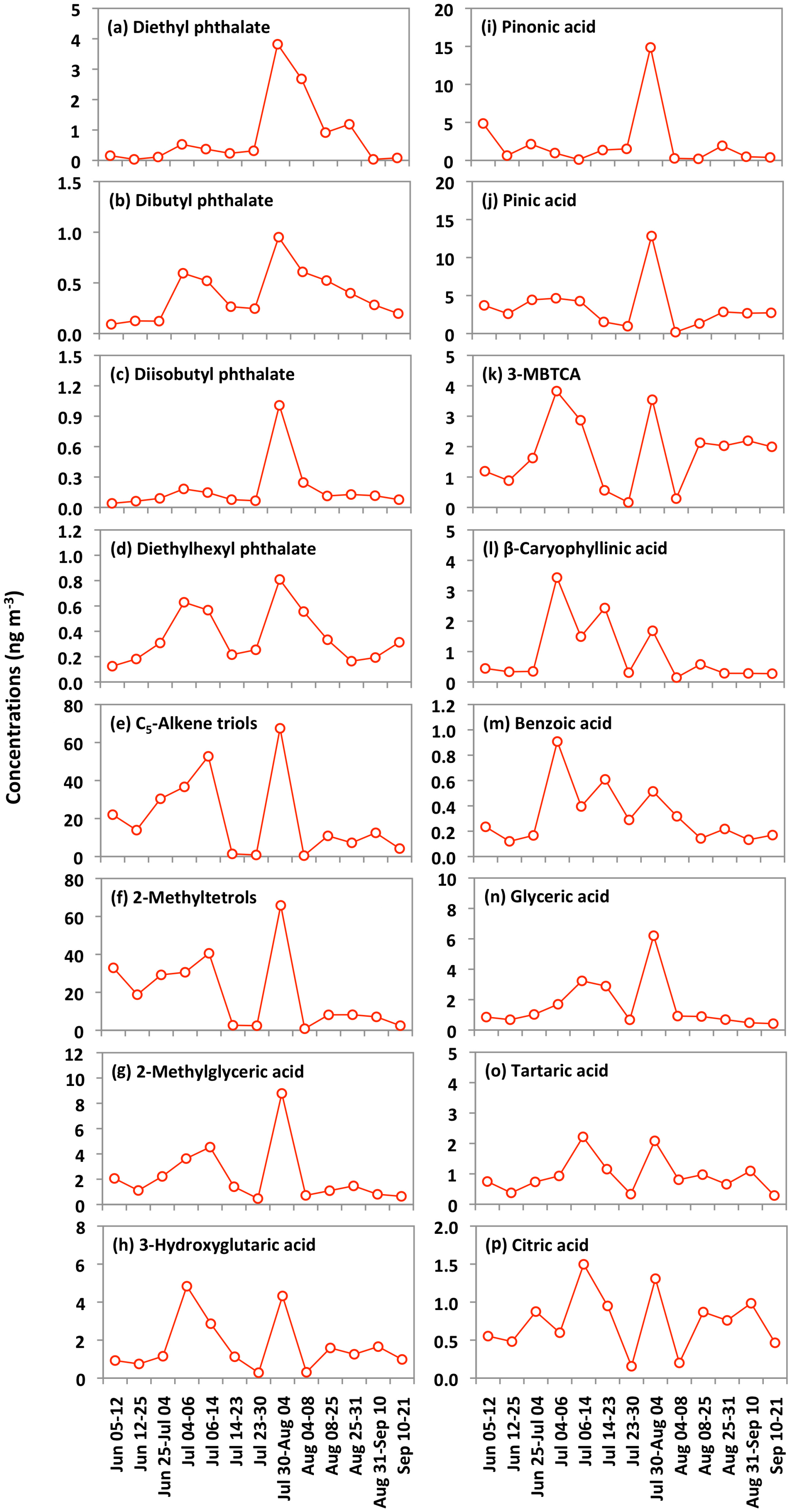

(a) Diethyl phthalate
(b) Dibutyl phthalate
(c) Diisobutyl phthalate
(d) Diethylhexyl phthalate
(e) C_5-Alkene triols
(f) 2-Methyltetrols
(g) 2-Methylglyceric acid
(h) 3-Hydroxyglutaric acid
(i) Pinonic acid
(j) Pinic acid
(k) 3-MBTCA
(l) β-Caryophyllinic acid
(m) Benzoic acid
(n) Glyceric acid
(o) Tartaric acid
(p) Citric acid
Concentrations (ng m^{-3})
Jun 05-12
Jun 12-25
Jun 25-Jul 04
Jul 04-06
Jul 06-14
Jul 14-23
Jul 23-30
Jul 30-Aug 04
Aug 04-08
Aug 08-25
Aug 25-31
Aug 31-Sep 10
Sep 10-21

Figure 11

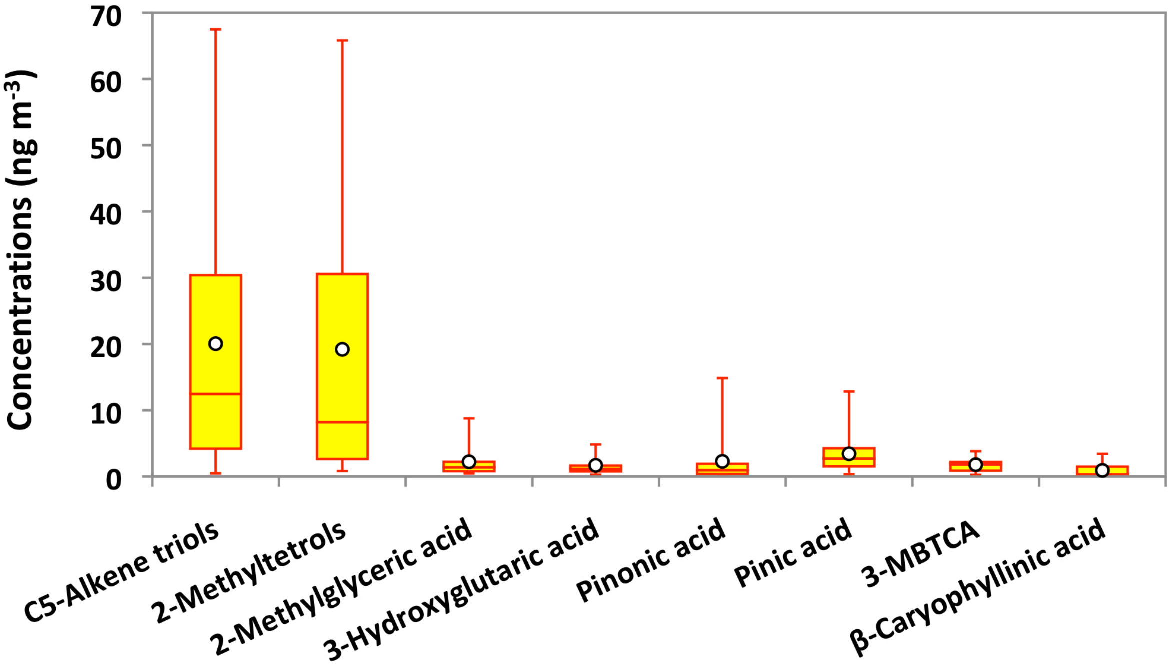


Figure 12

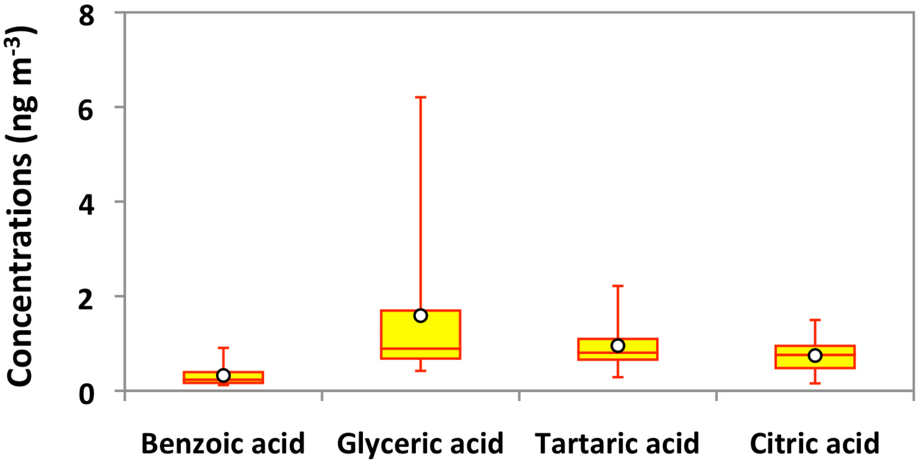


Figure 13