Atmospheric
Measurement
Techniques

Open Access

Determination of atmospheric organosulfates using HILIC chromatography with MS detection

A. P. S. Hettiyadura[1], E. A. Stone[1], S. Kundu[1], Z. Baker[1], E. Geddes[2], K. Richards[2], and T. Humphry[2]

[1]Department of Chemistry, Chemistry Building, University of Iowa, Iowa City, IA 52242, USA
[2]Chemistry Department, Truman State University, Kirksville, MO 63501, USA

Correspondence to: E. A. Stone (betsy-stone@uiowa.edu)

Abstract. Measurements of organosulfates in ambient aerosols provide insight to the extent of secondary organic aerosol (SOA) formation from mixtures of biogenic gases and anthropogenic pollutants. Organosulfates have, however, proved analytically challenging to quantify, due to lack of authentic standards and the complex sample matrix in which organosulfates are observed. This study presents a sensitive and accurate new analytical method for the quantification of organosulfates based upon ultra-performance liquid chromatography (UPLC) with negative electrospray ionization mass spectrometry (MS) with the aid of synthesized organosulfate standards. The separation is based upon hydrophilic interaction liquid chromatography (HILIC) with an amide stationary phase that provides excellent retention of carboxy-organosulfates and isoprene-derived organosulfates. The method is validated using six model compounds: methyl sulfate, ethyl sulfate, benzyl sulfate, hydroxyacetone sulfate, lactic acid sulfate and glycolic acid sulfate. A straightforward protocol for synthesis of highly pure organosulfate potassium salts for use as quantification standards is presented. This method is used to evaluate the efficiency and precision of two methods of ambient $PM_{2.5}$ sample extraction. Spike recoveries averaged $98 \pm 8\%$ for extraction by ultra-sonication and $98 \pm 10\%$ for extraction by rotary shaking. Ultra-sonication was determined to be a better method due to its higher precision compared to rotary shaking. Analysis of ambient $PM_{2.5}$ samples collected on 10–11 July 2013 in Centreville, AL, USA during the Southeast Atmosphere Study (SAS) confirms the presence of hydroxyacetone sulfate in ambient aerosol for the first time. Lactic acid sulfate was the most abundant compound measured ($9.6–19\,ng\,m^{-3}$), followed by glycolic acid sulfate ($8–14\,ng\,m^{-3}$) and hydroxy-acetone sulfate ($2.7–5.8\,ng\,m^{-3}$). Trace amounts of methyl sulfate were detected, while ethyl sulfate and benzyl sulfate were not. Application of this HILIC separation method to ambient aerosol samples further demonstrates its utility in resolving additional biogenic organosulfates.

1   Introduction

On a large scale, particulate matter (PM) in the atmosphere impacts the earth's radiative balance directly by scattering and absorbing solar radiation (Jacobson et al., 2000) and indirectly by acting as cloud condensation nuclei (CCN) (Novakov and Penner, 1993). PM also contributes to negative human health outcomes, such as cardiovascular and respiratory diseases (Davidson et al., 2005). Knowledge of the chemical composition of PM can aid in the identification of PM sources and better management of air resources. SOA are formed in the atmosphere by reactions of gaseous precursors that yield products that partition to the particle phase. It remains one of the most poorly understood PM sources (Foley et al., 2010), in part because of its chemical complexity and the fact that it forms in complex environmental mixtures.

Atmospheric organosulfates are SOA compounds that contain a characteristic sulfate ester functional group (R-O-SO_3^-). It has been suggested that organosulfates are a significant component of fine particulate organic matter (Stone et al., 2012; Tolocka and Turpin, 2012; Frossard et al., 2011; Hawkins et al., 2010; Surratt et al., 2008; Shakya and Peltier, 2013). Laboratory chamber experiments have demonstrated that SOA formed from biogenic volatile organic compounds (VOCs, e.g., isoprene, 2-methyl-3-buten-

2-ol (MBO), monoterpenes, and sesquiterpenes) in the presence of oxidants and sulfuric acid, contain a large organosulfate component (Iinuma et al., 2009; Chan et al., 2011; Surratt et al., 2007b; Zhang et al., 2012a, b, 2014).

Due to the atmospheric abundance of organosulfates and their importance in SOA formation, analytical methods have been developed to detect them in ambient aerosol by a range of off-line and on-line instrumentation, including Fourier transform infrared spectroscopy (FTIR) (e.g., Hawkins and Russell, 2010; Maria et al., 2003), in situ single particle mass spectrometry (e.g., Farmer et al., 2010; Froyd et al., 2010), capillary electrophoresis (CE) (Yassine et al., 2012) and liquid chromatography (LC) coupled with negative electrospray ionization ((−) ESI) MS (e.g., Olson et al., 2011a; Surratt et al., 2008; Wang et al., 2013). ESI-MS is especially sensitive to the detection of organosulfates in the negative mode, because these compounds carry a negative charge (Surratt et al., 2007a; Romero and Oehme, 2005). High-resolution (HR) MS may be used to determine organosulfate exact masses, chemical formulas, structural characteristics, and abundance (Shalamzari et al., 2013; Laskin et al., 2009; Altieri et al., 2008; Zhao et al., 2013; Pratt et al., 2013; Staudt et al., 2014; Surratt et al., 2008; Tao et al., 2014). A major limitation in the quantification and speciation of organosulfates is the glaring lack of authentic quantification standards, which are needed for the calibration of the ESI-MS detector (Staudt et al., 2014).

Further, the chemical identification and quantification of organosulfates requires the analytical separation of target analytes from the inorganic aerosol matrix and from each other. Organosulfates are strongly acidic (Guthrie, 1978) and are consequently anionic and non-volatile in the environment. Hence, these cannot be separated using gas chromatographic techniques and must be approached using a condensed-phase separation process (e.g., liquid chromatography (LC) or capillary electrophoresis). Prior studies have applied reversed-phase LC to aqueous atmospheric samples that range from water-soluble and methanol-extractable aerosol components to fog water (Surratt et al., 2008; Cappiello et al., 2003; Stone et al., 2012). Reversed-phase separations that rely upon a non-polar stationary phase and polar mobile phase are successful in retaining higher-molecular weight, monoterpene-derived nitro-oxy organosulfates (e.g., $C_{10}H_{16}NSO_7^-$) (Gao et al., 2006; Surratt et al., 2007a) and aromatic organosulfates (e.g., $C_7H_7SO_4^-$) (Kundu et al., 2010; Staudt et al., 2014). However, this mode of LC separation is not optimized for lower-molecular weight and highly polar organosulfates; for example glycolic acid sulfate ($C_2H_3O_6S^-$) and 2-methyltetrol sulfate ($C_5H_{11}O_7S^-$) are retained less than 2.5 min and co-elute with numerous other organosulfates, small organic acids, polyols, and inorganic sulfate (Stone et al., 2012). Co-elution of analytes with other compounds may lead to negative biases in their ESI response due to competition for ionization (Reemtsma and These, 2003). Other modes of LC separation such as ion pairing with dibutylam-

monium acetate have shown better separation and retention of isoprene derived organosulfates (Wang et al., 2013), but has not been used quantitatively. HILIC is specifically designed to retain molecules with ionic and polar functional groups (Hemström and Irgum, 2006) and has shown promise in retaining carboxylic acid containing organosulfates, such as glycolic acid sulfate and lactic acid sulfate, which are among the most abundant atmospheric organosulfates quantified to date (Olson et al., 2011a).

The objective of this study was to develop an accurate and sensitive method for quantifying highly polar atmospherically relevant organosulfates using HILIC chromatography for separation and tandem mass spectrometry (MS/MS) for detection. Used in concert with commercially available and laboratory-prepared pure standards of the organosulfates, this combination enables the facile separation, identification, and quantification of highly polar, ionic, and nonvolatile organosulfates collected from the atmosphere. HILIC separation is achieved using an ethylene bridged hybrid (BEH) amide column. Organosulfates with aromatic, keto-, hydroxyl-, and carboxyl- functional groups are quantified with tandem quadrupole mass spectrometric detection (TQD) against calibration curves prepared from commercially available or synthesized standards. In addition to quantifying these compounds, the new method is shown to be efficient in the separation of other major organosulfates present in the southeastern United States, for which standards are not yet available. A highly efficient sample preparation protocol for the extraction and pre-concentration of organosulfates from fine particulate matter ($PM_{2.5}$) samples is reported, and the extraction efficiencies of ultra-sonication and rotary shaking are compared. Also reported here are the first measurements of hydroxyacetone sulfate in ambient $PM_{2.5}$, from samples that were collected in Centreville, AL.

2 Materials and methods

2.1 Chemicals, reagents, and general methods

Six organosulfate standards were used in method development, two of which were commercially available: methyl sulfate (sodium methyl sulfate, 99 %, Acros Organics) and ethyl sulfate (sodium ethyl sulfate, 96.31 %, Sigma–Aldrich). Lactic acid sulfate was prepared according to Olson et al. (2011a). Benzyl sulfate, hydroxyacetone sulfate, and glycolic acid sulfate were synthesized as described below. Acetonitrile (ACN) was purchased from Fisher Scientific (Optima[TM]) and ultra-pure water was prepared on-site (Thermo, BARNSTED EasyPure-II; 18.2 MΩ resistivity). All other reagents and solvents were obtained from Fisher Acros and used without further purification. Elemental analysis was conducted by Atlantic Microlab in Norcross, GA and nuclear magnetic resonance (NMR). spectra were col-

lected on a Bruker ARX-400 NMR spectrometer with a 5 mm broadband probe.

HR-MS analysis in the (−) ESI mode was performed on a micrOTOF spectrometer (Bruker Daltonics). The ESI conditions used include capillary voltage 2.6 kV (benzyl sulfate) and 2.8 kV (for other five standards), sample cone voltage 15 V (benzyl sulfate), 30 V (methyl sulfate, ethyl sulfate, lactic acid sulfate and glycolic acid sulfate) and 35 V (hydroxyacetone sulfate), desolvation temperature 350 °C, source temperature 110 °C, cone gas flow rate 30 L h^{-1}, and desolvation gas flow rates of 550–650 L h^{-1}. Data were collected from a mass range 40 to 400 with V geometry in reflectron mode. Signals below a threshold level (set at 5–18 % of the relative abundance) were filtered out. A small peptide (Val-Tyr-Val, m/z 378.2029, Sigma–Aldrich) was used for lock mass correction.

2.2 General procedure for the synthesis of organosulfates

Each sulfate ester standard was synthesized using a general method derived from that of Hoff et al. (2001). To synthesize a sulfate ester, 1 molar equivalent (eq) of the appropriate alcohol was added with stirring to 15 mL of dry pyridine in a round bottom flask under nitrogen. To that clear, colorless mixture, slightly more than 1 eq of pyridine sulfur trioxide complex was added at once and the resulting cloudy white mixture was stirred for 8 h, after which the solution was clear. The pyridine was removed via distillation under vacuum, and the resulting clear oil (the pyridinium salt of the ester), varying in color from colorless to slight yellow, was converted to the potassium form. The conversion to the potassium salt and the crystallization procedures varied among the esters.

2.2.1 Benzyl sulfate, potassium salt

To synthesize the potassium salt of benzyl sulfate, once the pyridine solvent had been removed via distillation under vacuum, the resulting clear yellow oil was dissolved in approximately 10 mL of distilled water and titrated with 1 M potassium hydroxide (KOH) until the pH was above 11. Then, 50 mL of ethanol (neat) was added to the remaining aqueous solution. The resulting solution (approximately 75 % ethanol) was heated to boil and quickly vacuum filtered to remove a small amount of stark white precipitate that gave no ^{1}H or ^{13}C NMR spectrum when analyzed. The mother liquor was then placed in a freezer (−5 °C) overnight. Potassium benzyl sulfate formed in the mother liquor as colorless needles that were collected by vacuum filtration and rinsed with cold 90 % ethanol. The needles proved to be analytically pure benzyl sulfate. Yield: 75 %; ^{1}H NMR (400 MHz, DMSO-d6): δ/ppm 4.84 (s, 2 H); 7.25–7.41 (m, 5 H). ^{13}C NMR (400 MHz, DMSO-d6): δ/ppm 8.45; 56.01; 67.54; 127.42; 127.59; 128.13; 137.56. HR-MS ((−) ESI) m/z (relative intensity, %): 187.0072 (81.75, $C_7H_7SO_4^-$),

95.9497 (100.00), 80.9636 (15.74). Analysis calculated for $C_7H_7SO_4^- K^+$: C 37.15, H 3.12, S 14.17. Found: C 36.64, H 2.93, S 14.10.

2.2.2 Hydroxyacetone sulfate, potassium salt

The isolation of the potassium salt of hydroxyacetone sulfate was accomplished using Dowex 50WX8-200 cation exchange resin that had been charged with potassium ions. The exchange was conducted by making a slurry with the pyridinium salt of the ester dissolved in water and approximately 80 equivalents of resin, using water to maintain a slurry. After filtration, the water was removed via rotary evaporation under vacuum at no more than 40 °C, and the resulting white solid was recrystallized from a boiling 80 % ethanol solution, including a hot filtration step as in the synthesis of benzyl sulfate. The potassium salt of hydroxyacetone sulfate formed as colorless needles that were collected by vacuum filtration and rinsed with cold 90 % ethanol. The needles proved to be analytically pure hydroxyacetone sulfate. Yield: 35 %; ^{1}H NMR (400 MHz, DMSO-d6): δ/ppm 2.10 (s, 3 H); 4.26 (s, 2 H). ^{13}C NMR (400 MHz, DMSO-d6): δ/ppm 26.47; 71.05; 206.39. HR-MS ((−) ESI) m/z (relative intensity, %): 152.9836 (21.94, $C_3H_5SO_5^-$), 96.9564 (96.86), 80.9609 (50.19), 79.9533 (100.00). Analysis calculated for $C_3H_5SO_5^- K^+$: C 18.74, H 2.62, S 16.68. Found: C 18.57, H 2.55, S 16.79.

2.2.3 Glycolic acid sulfate, potassium salt

The isolation of the potassium salt of glycolic acid sulfate was conducted in a similar manner to that of hydroxyacetone sulfate, except that after filtering off the cation exchange resin and rinsing, the water was reduced to about 10 mL via rotary evaporation at 40 °C, and then titrated to pH 2 using 3 M HCl, before sufficient ethanol was added to make an 80 % ethanol solution. The product was then crystallized from the boiling ethanolic solution as in the previous syntheses. The potassium salt of glycolic acid sulfate formed as colorless needles that were collected by vacuum filtration and rinsed with cold 90 % ethanol. The needles gave NMR and mass spectra consistent with glycolic acid sulfate, and gave elemental analysis results fitting approximately 50 % protonation of the carboxylic acid moiety. Yield: 45 %; ^{1}H NMR (400 MHz, DMSO-d6): δ/ppm 4.54 (s). ^{13}C NMR (400 MHz, DMSO-d6): δ/ppm 63.59; 172.20. HR-MS ((−) ESI) m/z (relative intensity): 154.9650 (10.00, $C_2H_3SO_6^-$), 96.9588 (100.00), 75.0076 (30.50). Analysis calculated for $C_2H_{2.5}SO_6^- K_{1.5}^+$: C 11.27, H 1.18, S 15.04. Found: C 11.58, H 1.18, S 15.13.

2.3 Collection of PM$_{2.5}$ in Centreville, AL

PM$_{2.5}$ was collected at the Southeastern Aerosol Research and Characterization (SEARCH) network site in Centreville, AL from 1 June to 15 July 2013 during the SAS

field study. Sample collection followed the daytime (08:00–19:00 LT) and nighttime (20:00–07:00 LT) schedule. A medium-volume sampler (URG Corporation) was used to collect particles with aerodynamic diameter less than 2.5 μm by way of a Teflon-coated aluminum cyclone operating at 92 Lpm. $PM_{2.5}$ was collected on quartz fiber filters (90 mm diameter, Pall Life Sciences) that were pre-baked at 550 °C for 18 h to remove organic material. Pre- and post-sampling flow rates were measured with a calibrated rotameter. All filters were handled using clean techniques, which included storage of filters in plastic petri dishes lined with pre-cleaned aluminum foil and manipulation with pre-cleaned stainless steel forceps. Post-sampling, filters were stored frozen in the dark. One field blank was collected for every five samples.

2.4 PM sample extraction and preparation

Sub-samples of $PM_{2.5}$ filter samples and field blanks (totaling 15 cm^2) were obtained using standardized filter punches of known area. These sub-samples were submerged in 10.0 mL of ACN and ultra-pure water (95 : 5, by volume) and extracted for 20 min by ultra-sonication (60 sonics min^{-1}, 5510, Branson) or an orbital-shaker (125 rpm, VWR). Extracts were filtered through polypropylene membrane syringe filters (0.45 μm pore size). Filtrates were reduced in volume to 500 μL under ultra-high purity nitrogen gas (5 psi) at 50 °C using an evaporation system (TurboVap® LV, Caliper Life Sciences). These were transferred to 1.5 mL vials and the solvent was blown to dryness using a micro-scale nitrogen evaporation system (Reacti-Therm III TS-18824 and Reacti-Vap I 18825, Thermo Scientific). Extracts were then re-constituted with ACN and ultra-pure water (95 : 5, by volume) to a final volume of 300 μL. To test the efficiency of extraction by ultra-sonication and rotary shaking (125 rpm, VWR Advanced Digital Shaker), a series of quality control samples were extracted by each method. These quality control samples consisted of four laboratory blanks (of 5.4 cm^2 quartz fiber filters) and seven spiked samples, for which standards were spiked on to blank quartz fiber filters to achieve a final concentration of 100 μg L^{-1}.

2.5 Separation and detection of organosulfates

Organosulfates were separated using a UPLC system (equipped with quaternary pump, autosampler, and thermostatted column compartment, ACQUITY UPLC, Waters, Milford, MA, USA). The separation was optimized using a BEH amide column (2.1 mm × 100 mm, 1.7 μm particle size; ACQUITY UPLC, Waters) equipped with a pre-column. The column was maintained at 35 °C and the mobile phase flow rate was 0.5 mL min^{-1}. A 5 μL injection volume was used for quantitative analysis of samples and standards. The optimized mobile phase A (organic) consisted of ammonium acetate buffer (10 mM, pH 9) in ACN and ultra-pure water (95 : 5, by volume) and mobile phase B (aqueous) consisted

of ammonium acetate buffer (10 mM, pH 9) in ultra-pure water. A solvent gradient was used to elute the analytes: mobile phase A was maintained at 100 % for 2 min, then decreased to 85 % from 2 to 4 min and held constant until 11 min, which was sufficient to elute the analytes. To re-equilibrate the column prior to the next injection, the solvent program was returned to 100 % mobile phase A from 11 to 11.5 min and was held constant until 14 min had passed. The wash solvent (needle wash) consisted of ACN and ultra-pure water (80 : 20, by volume).

Organosulfates were detected by a TQD MS (ACQUITY, Waters) equipped with an ESI source in the negative ion mode. The detector was operated in multiple reaction monitoring (MRM) mode, in which the deprotonated molecule was selected in the first quadrupole, fragmented in the second quadrupole and product ions were selected in the third quadrupole. Optimized MS conditions (cone voltages and collision energies) are provided in Table 1. Other ESI conditions include a capillary voltage of 2.7 kV, source temperature of 150 °C, desolvation temperature of 450 °C, cone gas (N$_2$) flow rate at 100 L h^{-1}, desolvation gas (N$_2$) flow rate at 900 L h^{-1} and collision gas (Ar) flow rate at 0.05 mL min^{-1}. All data were acquired and processed using MassLynx software (version 4.1). The linear range of each authentic standard was determined using a series of standard solutions at 0.500, 1.00, 25.0, 50.0, 100., 300. and 500. μg L^{-1} that were prepared in organic mobile phase. Reproducibility of the MS method was determined based on seven replicate injections of the 100 μg L^{-1} solution. The limit of detection (LOD, 3 × standard deviation) and the limit of quantification (LOQ, 10 × standard deviation) were obtained from multiple injections ($n = 10$) of the 25.0 μg L^{-1} solution.

3 Results and discussion

3.1 Synthesis of organosulfates standards

Benzyl sulfate, hydroxyacetone sulfate, and glycolic acid sulfate were synthesized and isolated as potassium salts for use as analytical standards. A straightforward, two-step approach to synthesis was used. The syntheses of the sulfate ester were accomplished with pyridine-sulfur trioxide as a sulfur source, since it is a solid that is more stable and substantially easier to handle than the common alternative, chlorosulfonic acid. Alcohols were converted to sulfate esters and first formed pyridinium salts, which are oils at room temperature. To convert the products to a solid, and weighable form, sulfate esters were converted to the potassium salts. The protocol used for this conversion was dictated by the stability of each ester to hydrolysis. For benzyl sulfate, the pyridinium salt was dissolved in water and titrated to pH > 10 using 1 M KOH in order to liberate pyridine and leave behind the potassium salt of the ester. When this process was tried with either of the carbonyl-containing sulfate esters, the result was com-

Table 1. MS parameters for MRM transitions of UPLC-MS/MS, linearity, coefficient of determination (R^2), limit of detection (LOD), limit of quantification (LOQ), and relative standard deviation (RSD) of seven replicate standard injections.

| Compound	Deprotonated molecule and m/z		Product ion and m/z		Cone voltage (V)	Collision energy (eV)	Retention time (min.)	Linear range ($\mu g\,L^{-1}$)	R^2	LOD ($\mu g\,L^{-1}$)	LOQ ($\mu g\,L^{-1}$)	RSD (%)
Methyl sulfate	$CH_3SO_4^-$	111	$SO_3^{-\cdot}$	80	36	18	0.88 ± 0.03	25.0–500	0.998	2.6	8.6	2.9
			$SO_4^{-\cdot}$	96		14						
Ethyl sulfate	$C_2H_5SO_4^-$	125	HSO_4^-	97	26	12	0.78 ± 0.03	25.0–500	0.998	3.4	11.2	2.5
Benzyl sulfate	$C_7H_7SO_4^-$	187	HSO_3^-	81	42	18	0.58 ± 0.02	25.0–300	0.995	3.9	13.2	3.0
			$SO_4^{-\cdot}$	96		20						
			$C_6H_5^-$	77		26						
Hydroxyacetone sulfate	$C_3H_5SO_5^-$	153	$SO_3^{-\cdot}$	80	32	18	0.66 ± 0.02	25.0–300	0.996	2.6	8.7	3.0
			HSO_4^-	97		20						
Glycolic acid sulfate	$C_2H_3SO_6^-$	155	$C_2H_3O_3^-$	75	26	18	7.84 ± 0.01	25.0–300	0.998	1.9	6.3	15.6
			HSO_4^-	97		14						
Lactic acid sulfate	$C_3H_5SO_6^-$	169	HSO_4^-	97	28	16	7.57 ± 0.02	25.0–300	0.995	3.9	13.0	5.9

plete hydrolysis of the sample before recrystallization occurred. Therefore, for hydroxyacetone sulfate and glycolic acid sulfate, Dowex cation-exchange resin was used to convert the pyridinium salt to the potassium salt. The potassium salts of all three esters crystallized as shiny white needles from hot 80–90 % ethanol.

The three sulfate ester potassium salts were examined for identity and purity using elemental analysis, MS, and ^{1}H and proton-decoupled ^{13}C NMR, using DMSO-d6 as the NMR solvent. For all three esters, NMR spectra were first taken of the pure, recrystallized substance, and then a portion of the starting alcohol was added to the NMR tube and spectra were taken again in order to ensure that none of the observed peaks were due to starting material. Potassium benzyl sulfate produces a ^{1}H NMR with two regions of peaks; a multiplet spanning from 7.25–7.33 ppm from the five closely spaced aromatic hydrogens, and a singlet at 4.77 ppm from the isolated methylene. The ^{13}C NMR spectrum contained three closely spaced peaks from the unsubstituted aromatic carbons between 127.4 and 128.1 ppm, a shorter quaternary aromatic carbon peak at 137.6 ppm, and a methylene carbon peak at 67.5 ppm. ^{1}H NMR spectrum of potassium hydroxyacetone sulfate consists of two singlets at 4.3 and 2.1 ppm from the methylene and methyl groups, respectively. In the ^{13}C NMR, the ketone carbon peak is at 206.4 ppm, the methylene at 71.8 ppm, and the methyl at 26.5 ppm. Potassium glycolic acid sulfate produces a very simple proton spectrum, having only a singlet methylene peak at 4.5 ppm. The acidic proton is not observed. The lack of an acidic proton peak is common, since rapid proton exchange in the presence of even a slight amount of water in the solvent causes the peak to broaden and shorten until it effectively disappears. The ^{13}C NMR of potassium glycolic acid sulfate is likewise simple, with only two peaks: the carboxylic acid carbon at 172.2 ppm, and the methylene carbon at 63.6 ppm.

The identity and purity of the three potassium sulfate ester salts were assessed by elemental analysis and MS. All three esters yielded elemental analyses that closely matched the expected values, with the elemental analysis of potassium glycolic acid sulfate fitting well for a sample that was roughly 50 % protonated. In addition, the high-resolution mass spectrum for each ester yielded a molecular peak that closely matched the expected molar mass, which is further discussed in Sect. 3.2.

3.2 MS/MS fragmentation and optimization

Product ion spectra given by methyl sulfate, ethyl sulfate, hydroxyacetone sulfate, glycolic acid sulfate and lactic acid sulfate under applied (−) ESI conditions are shown in Fig. 1. Formulas were assigned to deprotonated molecules and product ions using HR-MS/MS (with data provided in Table 1). Major sulfur-containing product ions included the sulfite ion radical ($SO_3^{-\cdot}$ at m/z 80) that forms from the homolytic cleavage of an O–S bond, the sulfate ion radical ($SO_4^{-\cdot}$ at m/z 96) that forms from the homolytic cleavage of a C–O bond, the bisulfite anion (HSO_3^- at m/z 81) that forms by hydrogen abstraction followed by the heterolytic cleavage of an O–S bond (Attygalle et al., 2001), and the bisulfate anion (HSO_4^- at m/z 97). The bisulfate anion has been postulated to form via a cyclic syn-elimination pathway in which a proton is abstracted from the C-2 position (Attygalle et al., 2001). Notably, the bisulfate anion is absent in the MS/MS spectrum of methyl sulfate, as there is no C-2 position. For hydroxyacetone sulfate, the proton in bisulfate anion likely comes from the C-3 position. In glycolic acid sulfate and lactic acid sulfate, the proton in the bisulfate anion may come from the carboxylic acid group (Shalamzari et al., 2013). Glycolic acid sulfate and lactic acid sulfate spectra contain glycolate ($C_2H_3O_3^-$, m/z 75) and methyl glycolate ions ($C_3H_5O_3^-$,
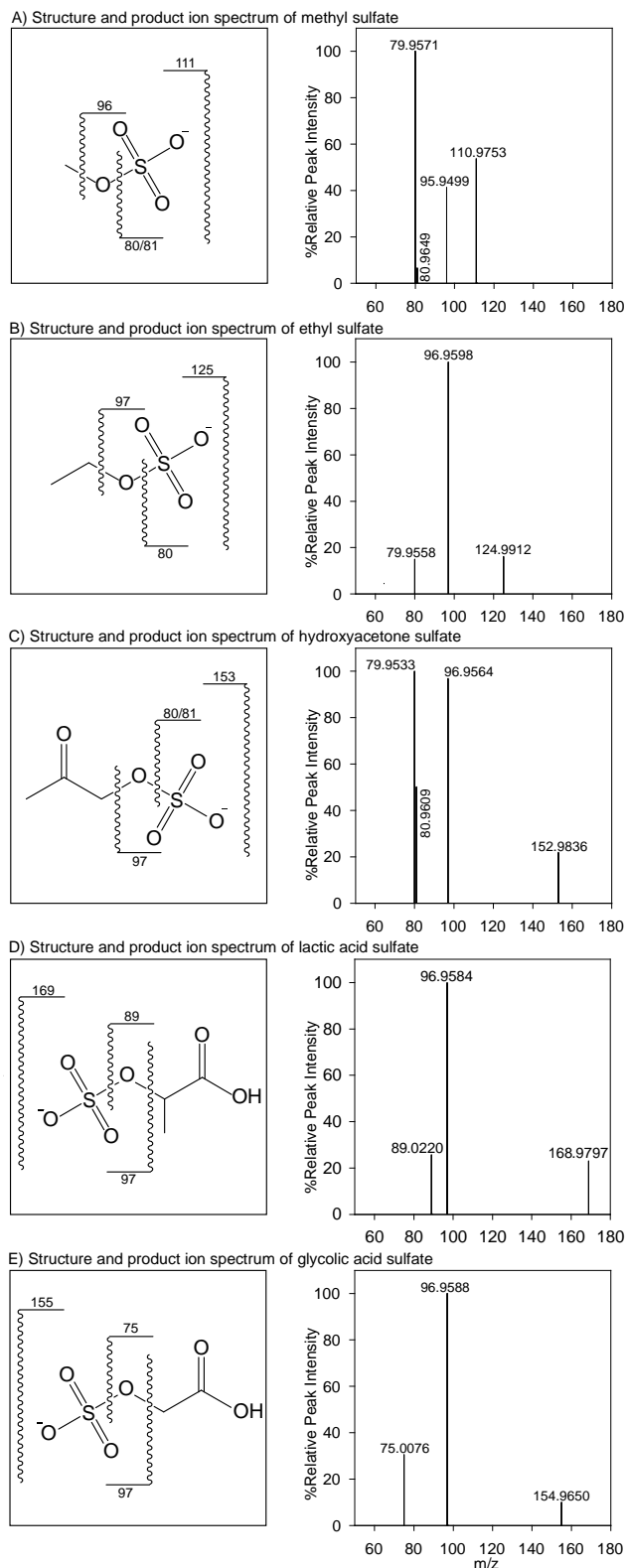
Figure 1. Product ion spectra of organosulfate standards generated by quadrupole time of flight (Q-TOF) MS/MS of a directly infused standard solution.

m/z 89), respectively, which form from neutral loss of SO_3 and are resonance stabilized. The MS/MS fragmentation of benzyl sulfate is discussed elsewhere (Attygalle et al., 2001; Kundu et al., 2013).

The MS/MS method was optimized for the detection of each analyte by molecular precursor and product ions. The source conditions (collision energy and cone voltage) used in MRM are given in Table 1. Two transitions were optimized for each analyte. Exceptions include benzyl sulfate, for which three transitions were used, as well as ethyl sulfate and lactic acid sulfate that relied upon a single transition. For quantitative analysis of organosulfates with more than one transition, the individual transition signals were summed.

3.3 HILIC separation

Analytes were separated on a BEH amide column that retains extremely polar compounds through ionic, hydrogen bonding, and dipole interactions. In HILIC chromatography, water in the mobile phase is adsorbed to the stationary phase, forming a hydrophilic layer (Strege, 1998) into which ions and polar compounds partition (Alpert, 2007). The delocalization of the amide nitrogen electrons to the carbonyl oxygen imparts a partial positive charge on the nitrogen atom, promoting strong dipolar interactions. In addition, the amide group imparts hydrogen bond donor and acceptor sites on the stationary phase, increasing retention of molecules capable of hydrogen bonding. Polar analytes are eluted from the column as the aqueous fraction of the mobile phase increases, shifting partitioning from the stationary to mobile phase (Grumbach et al., 2004, 2008).

Under the optimized conditions that provided the best resolution of analytes, the aqueous portion of the mobile phase increased 5–20 % and eluted the six organosulfate standards within 8 min (Table 1 and Fig. 2). The mobile phase was buffered to pH 9 with 10 mM ammonium acetate to maintain a consistent charge state on the stationary phase and analytes. However, the actual pH of the mobile phase may be 1–1.5 pH units closer to neutral due to the high organic content of the mobile phase (Espinosa et al., 2000; Canals et al., 2001). A slightly basic pH was selected to completely deprotonate carboxylic acid groups in glycolic acid sulfate and lactic acid sulfate.

The charge state of organosulfates plays a key role in their retention on the BEH amide column. At basic pH, glycolic acid sulfate and lactic acid sulfate are fully deprotonated; each carry a −2 charge, and are retained 7.84 and 7.57 min, respectively. Singly charged organosulfates – methyl sulfate, ethyl sulfate, benzyl sulfate, and hydroxyacetone sulfate – elute within the window of 0.58–0.88 min, and are baseline-resolved. The application of this separation protocol to ambient aerosol samples, and the resolution of isoprene and biogenic organosulfates signals, is discussed in Sect. 3.7.
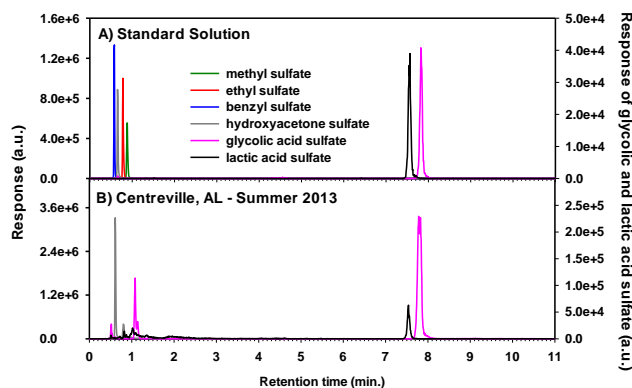
Figure 2. MRM chromatograms of **(a)** a mixed standard containing six organosulfates at $100 \, \mu g \, L^{-1}$ and **(b)** an ambient aerosol sample collected during the daytime on 10 July 2013 in Centreville, AL. Responses of glycolic acid sulfate and lactic acid sulfate are shown on the right axis.

3.4 Comparison of BEH amide and BEH HILIC retention

Preliminary studies in the separation development involved the use of a BEH HILIC column and are hereby compared to the optimized separation on the BEH amide column discussed in Sect. 3.3. On the BEH HILIC column, glycolic acid sulfate and lactic acid sulfate were retained for less than 2 min ($t_R < 2$ min), while benzyl sulfate, ethyl sulfate and methyl sulfate were co-eluted ($t_R < 0.6$ min). In comparison, longer retention times and baseline resolution were achieved on the BEH amide column (Table 1 and Fig. 2a). The increase in organosulfate retention results from the amide-functionalization of BEH particles, which introduces hydrogen bond donor and acceptor sites, strengthening the interaction with organosulfates, particularly those carrying carboxyl and hydroxyl functional groups. Because of the longer retention and better resolution of the six standard compounds used in method development, the BEH amide column was selected for further optimization and aerosol analysis.

3.5 Method validation

The goal of method development was to develop a robust and sensitive protocol for the quantification of organosulfates in ambient aerosol. Optimized UPLC and MS/MS conditions were applied to a series of authentic organosulfate standards, and produced highly linear calibration curves ($R^2 \geq 0.995$), as shown in Table 1. The linearity requirement was met for methyl sulfate and ethyl sulfate across concentration ranges of 25.0–$500 \, \mu g \, L^{-1}$, and for all other compounds across 25.0–$300 \, \mu g \, L^{-1}$. LOD and LOQ ranged 1.9–3.9 and 6.3–$13.2 \, \mu g \, L^{-1}$, respectively. The relative standard deviation (RSD) was 2.5–$3.0 \, \%$ for the first four compounds to elute, and increased to $16 \, \%$ for glycolic acid sulfate and $6 \, \%$

for lactic acid sulfate, which were retained longer on the column.

The precision and the sensitivity of this method make it well suited for the quantification of organosulfates in ambient aerosol. The extracted filter samples from Centreville each contained 18–$48 \, \mu g$ organic carbon and yielded methyl sulfate, hydroxyacetone sulfate, glycolic acid sulfate and lactic acid sulfate concentrations within the linear range of this method. For accurate quantitation of organosulfates by LC-MS, each analyte should be quantified against an analytical standard with the same structure to avoid significant biases (Staudt et al., 2014). When compared to prior studies that used matched quantification standards, the HILIC method proves to have comparable quantitative capabilities, with some notable differences. For example, the linear range obtained for lactic acid sulfate and glycolic acid sulfate in this study ranges 25.0–$300 \, \mu g \, L^{-1}$ compared to 5.0–$500 \, \mu g \, L^{-1}$ reported by Olson et al. (2011b) who utilized a bare-silica (an underivatized) HILIC column (Olson et al., 2011b). While the HILIC-amide based method is well-suited for retention of small polar organosulfates bearing carboxyl and hydroxyl groups, it does not perform as well for less-functionalized organosulfates. For example, benzyl sulfate eluted at 5.8 min on a reversed-phase UPLC column and when coupled with MS/MS detection had linear range of 0.1–$150 \, \mu g \, L^{-1}$ and LOD $0.35 \, \mu g \, L^{-1}$ (Kundu et al., 2013; Staudt et al., 2014); meanwhile, benzyl sulfate eluted in less than 1 min from a BEH amide column, and has a linear range of 25.0–$300 \, \mu g \, L^{-1}$ and LOD of $3.9 \, \mu g \, L^{-1}$. The higher LOD and linear range for benzyl sulfate in the current method is likely due to the use of ACN (bp $82 \, °C$) instead of methanol (bp $65 \, °C$), which does not de-solvate as readily in the ESI source. This example illustrates the complementarity of reversed-phase UPLC methods to the HILIC-based UPLC methods, with reversed-phase chromatography being better suited for aromatic and higher-molecular weight organosulfates and HILIC being better for more functionalized and polar organosulfates.

3.6 Optimization of extraction

Previous studies have shown that methanol converts carboxy-organosulfates to methyl esters and should be avoided in quantitative analysis of organosulfates (Olson et al., 2011a), meanwhile ACN is effective for extracting carboxylic acids in ambient aerosols (Kristensen and Glasius, 2011). In this study, ACN and ultra-pure water (95 : 5, by volume) were used as the extracting solvent. Two methods of extracting organosulfates from the filters were investigated: the commonly used methods such as ultra-sonication (Surratt et al., 2007a; Gao et al., 2006) and rotary shaking. Previous studies have observed formation of negative artifacts during ultra-sonication due to acoustic cavitation (Mutzel et al., 2013; Riesz et al., 1985). Rotary shaking, on the other hand is considered as a milder method of extraction.
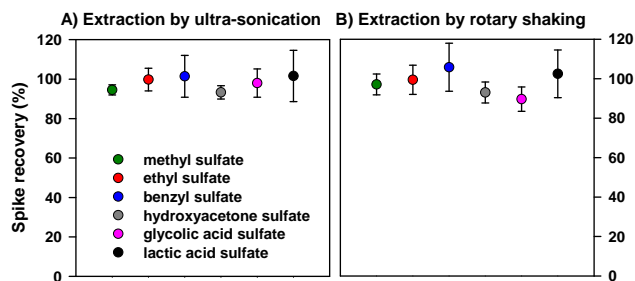
Figure 3. Comparison of spike recovery (%) ($100\,\mu g\,L^{-1}$, $n = 7$ each) extracted by **(a)** ultra-sonication and **(b)** rotary shaking.

Extraction by ultra-sonication and rotary shaking were determined to be efficient and reproducible methods for extracting organosulfates from filters. The results of seven replicate extractions of the six organosulfates in a standard solution are shown in Fig. 3. Overall, spike recoveries for ultra-sonication ranged 83–121 % and averaged ($\pm$ standard deviation) 98 ± 8 % and for rotary shaking ranged 79–122 % and averaged 98 ± 10 %. Both methods were found to be accurate within 100 ± 15 % for 95th percentile values and did not introduce artifacts into extraction. Although negative artifacts during ultra-sonication due to acoustic cavitation can be significant in highly aqueous extraction solvents (Riesz et al., 1985), it is expected that the lack of these negative artifacts in this study is due to either the use of an organic rich extraction solvent (ACN and ultra-pure water, 95 : 5, by volume) or the stability of organosulfates under these conditions. Ultra-sonication had the advantage of better precision, with narrower ranges of results and lower RSD (ultra-sonication, 8 %; rotary shaking, 10 %). Consequently, ultra-sonication was selected for the extraction of ambient aerosol samples from filter media.

3.7 Application to ambient aerosol

Concentrations of organosulfates quantified in ambient $PM_{2.5}$ from Centreville, AL are provided in Table 2 with analytical uncertainties. Lactic acid sulfate was the most abundant organosulfate measured, with 10 July daytime and 10–11 July nighttime concentrations of 19 ± 1 and $9.6 \pm 0.6\,ng\,m^{-3}$, respectively. Hydroxyacetone sulfate, quantified for the first time in this study, was the third-most abundant organosulfate measured at levels of 5.8 ± 0.2 and $2.7 \pm 0.1\,ng\,m^{-3}$, respectively. Methyl sulfate was observed at lower concentrations, and benzyl sulfate and ethyl sulfate were not detected. Glycolic acid sulfate concentrations reported in Olson et al. (2011a) across six locations ($1.9–11.3\,ng\,m^{-3}$) are in agreement with our results (8–$14\,ng\,m^{-3}$); however, the lactic acid sulfate concentration observed in Centreville is 5 times greater than the highest level of the lactic acid concentration previously reported in Olson et al. (2011a).

Table 2. Ambient concentrations of organosulfates with analytical uncertainties ($ng\,m^{-3}$) measured in $PM_{2.5}$ from Centreville, AL in 2013.

Compound	10 July – day (08:00–19:00 LT)	11 July – night (20:00–07:00 LT)
Methyl sulfate	0.70 ± 0.05	0.34 ± 0.04
Ethyl sulfate	BDL*	BDL*
Benzyl sulfate	BDL*	BDL*
Hydroxyacetone sulfate	5.8 ± 0.2	2.7 ± 0.1
Glycolic acid sulfate	14 ± 2	8 ± 1
Lactic acid sulfate	19 ± 1	9.6 ± 0.6

* BDL – below detection limit.

The UPLC method is also efficient at resolving other organosulfates present in atmospheric aerosols that are expected to have high atmospheric abundances due to their strong HR-MS signals. As shown in Fig. 4a, four major and two minor organosulfate signals with the formula $C_5H_{11}O_7S^-$ (m/z 215; calculated mass: 215.0225) are baseline-resolved. Peak retention times in minutes (and error in the observed m/z) are 1.40 ($-0.5\,mDa$), 1.74 ($0.5\,mDa$), 2.87 ($-0.3\,mDa$), 3.65 ($-1.8\,mDa$), 4.51 ($-0.2\,mDa$) and 4.81 ($0.1\,mDa$). HR-MS/MS spectra of these six peaks (Q-TOF) showed HSO_4^- as a product ion, confirming the presence of an aliphatic sulfate moiety. Prior studies have suggested that $C_5H_{11}O_7S^-$ corresponds to 2-methyltetrol sulfates derived from isoprene epoxides (IEPOX) (Gómez-Gónzalez et al., 2008; Surratt et al., 2008, 2010). Considering the ring-opening of the four IEPOX isomers elucidated by Paulot et al. (2009) and the regioselectivity of epoxide ring opening reaction, four major isomers of $C_5H_{11}O_7S^-$ (m/z 215) are expected to form (one example given in the inset of Fig. 4a, others are discussed in the Supplement and shown in Table S1). The two minor peaks are expected to be the minor products of the ring opening and proposed structures are given in Table S1. The separation of six isomers by this method is superior to reversed-phase chromatography, in which these IEPOX-derived organosulfate isomers co-elute in two peaks (Stone et al., 2012). The HILIC separation is also an improvement over ion pairing reversed-phase separation, which resolves only two peaks (Wang et al., 2013). The resolution of isomers is significant, because methyltetrol sulfates have generated the greatest organosulfate signal in prior field studies (Froyd et al., 2010; Lin et al., 2013) and may prove useful in elucidating different organosulfate formation pathways.

HILIC chromatography of atmospheric aerosol samples from Centreville, AL also reveals the presence of multiple isomers of major biogenic organosulfates. Figure 4b shows the extracted HR-MS ion chromatograms for $C_5H_9O_7S^-$ (m/z 213; calculated mass: 213.0069). Six major signals for $C_5H_9O_7S^-$ were observed with retention times of 1.10, 1.29, 1.58, 1.80, 2.07, and 2.23 min and errors $\leq 1.6\,mDa$, but
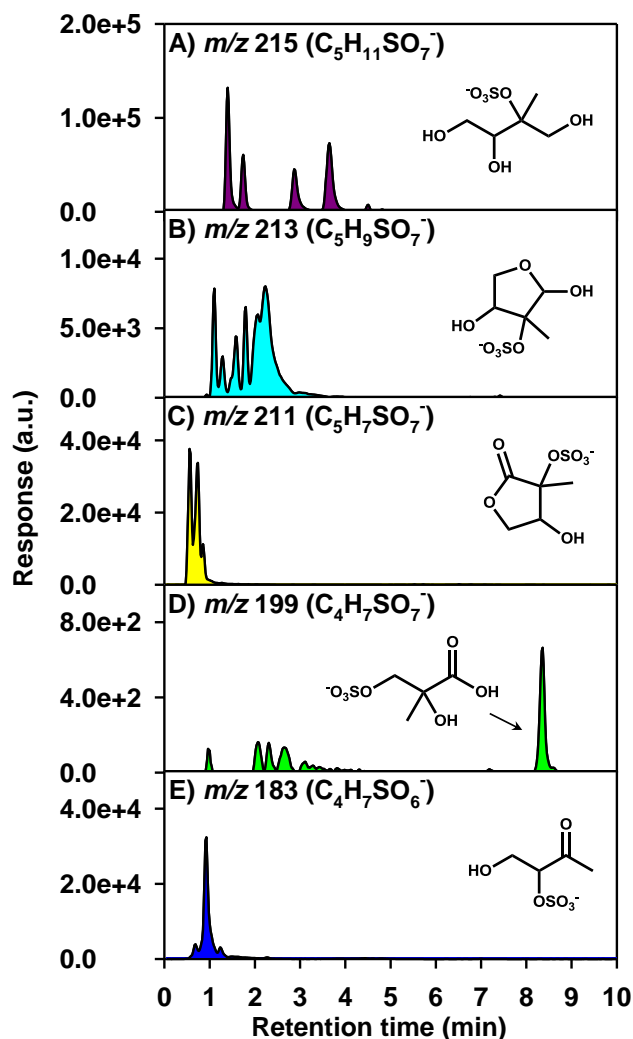
Figure 4. Extracted ion chromatograms and the proposed structures for organosulfates qualitatively identified in PM$_{2.5}$ collected during the daytime on 10 July 2013 in Centreville, AL using HR-MS: **(a)** $C_5H_{11}O_7S^-$ (m/z 215.0225), **(b)** $C_5H_9O_7S^-$ (m/z 213.0069), **(c)** $C_5H_7O_7S^-$ (m/z 210.9912), **(d)** $C_4H_7O_7S^-$ (m/z 198.9912), **(e)** $C_4H_7O_6S^-$ (m/z 182.9963) (smoothed 2 × 1; absolute window: ±0.01 Da).

were not baseline-resolved. Organosulfates with the formula $C_5H_9O_7S^-$ have previously been reported to form in chamber studies with isoprene as the precursor gas (Surratt et al., 2008) and suggested to have other VOC precursors such as 2-*E*-pentenal, a photolysis product of the green leaf volatile 3-*Z*-hexenal (Gómez-González et al., 2008). The short retention time of $C_5H_9O_7S^-$ on the BEH amide column indicates that this molecule does not contain a carboxylic acid group. The proposed structure for $C_5H_9O_7S^-$ shown in the inset of Fig. 4b, is an intramolecular hemiacetal that would form by the cyclization of a γ-hydroxyaldehyde that would result from the oxidation of a primary alcohol in the methyltetrol sulfate ($C_5H_{11}O_7S^-$) to an aldehyde, as detailed in

the Supplement and Table S2. The shorter retention times of $C_5H_9O_7S^-$ (m/z 213) compared to $C_5H_{11}O_7S^-$ (m/z 215) supports this structural assignment, in that the former has one less hydroxyl group than the latter, thus decreasing the strength of hydrogen-bonding interactions with the stationary phase and causing it to elute earlier.

In addition, the HILIC separation with HR-MS reveals multiple signals for $C_5H_7O_7S^-$ (m/z 211, calculated mass: 210.9912). Although the peaks are not resolved, three signals dominate with retention times of 0.56, 0.74, and 0.85 min, each with an error in the observed mass ≤ 1.5 mDa. Organosulfates with the formula $C_5H_7O_7S^-$ (m/z 211) have been shown to form in chamber studies with isoprene as the precursor gas (Surratt et al., 2008) and are related to the organosulfates with formulas $C_5H_9O_7S^-$ (m/z 213) and $C_5H_{11}O_7S^-$ (m/z 215), with an increase of one and two units of unsaturation, respectively. The proposed structure shown in the inset of Fig. 4c is a lactone that is postulated to form via the cyclization and dehydration of a γ-hydroxycarboxylic acid, which would be produced by the oxidation of a primary alcohol in the methyltetrol sulfate ($C_5H_{11}O_7S^-$, e.g., Fig. 4a) to a carboxylic acid, as discussed in the Supplement and shown in Fig. S3. Again, the order of elution of $C_5H_7O_7S^-$ (m/z 211), $C_5H_9O_7S^-$ (m/z 213) and $C_5H_{11}O_7S^-$ (m/z 215) supports the structural designation of a lactone, which has fewer hydroxyl groups through which it interacts with the BEH amide stationary phase, causing it to elute earlier.

Organosulfates with the formulas $C_4H_7O_7S^-$ (m/z 199, calculated mass: 198.9912) also separate into multiple peaks on the BEH amide column, revealing the presence of multiple isomers. As shown in Fig. 4d, $C_4H_7O_7S^-$ elutes in several peaks with retention times of 3.67, 3.81, 3.98, 7.19, and 8.36 min and error in the observed mass ≤ 2.7 mDa. Notably, the strongest signal obtained for $C_4H_7O_7S^-$ appears at 8.36 min; this retention time falls in the range of glycolic acid sulfate and lactic acid sulfate, and indicates the presence of a carboxylate group. Organosulfates with this formula have previously been identified as a sulfated isoprene photo-oxidation product (Gómez-González et al., 2008; Shalamzari et al., 2013). The proposed structure shown in the Fig. 4d inset is the sulfated form of 2-methylglyceric acid proposed by Gómez-González et al. (2008) and the early eluting peaks likely include the glycolic glycolate organosulfate proposed by Shalamzari et al. (2013). Organosulfates with the formulas $C_4H_7O_6S^-$ (m/z 183, calculated mass: 182.9963) elute in three peaks with retention times 0.67, 0.91, and 1.23 min as shown in Fig. 4e, with error in the observed mass ≤ 1.2 mDa. The isomers of $C_4H_7O_6S^-$ are expected to contain carbonyl, ether, ester or hydroxyl, but not carboxylate groups. This retention data are consistent with the structure of $C_4H_7O_6S^-$ proposed by by Shalamzari et al. (2013) and shown in the Fig. 4e inset, which is suggested to form from methyl vinyl ketone, an oxidation product of isoprene. The chromatograms in Fig. 4 demonstrate that the combination of HR-MS with HILIC chromatography reveals

the presence of multiple conformational isomers for major organosulfate signals that are primarily associated with isoprene. Absolute retention times on the BEH amide column can be used to determine the presence or absence of carboxylate groups and the relative retention times of similar compounds gives insights to the functional groups present.

4 Conclusions

A UPLC-MS/MS method for the quantification of atmospheric organosulfates was developed and validated for the purpose of evaluating the ambient concentrations of a variety of lower-molecular-weight organosulfates containing alkyl, benzyl, hydroxyl, carbonyl and carboxy functional groups. In addition to resolving the six model compounds used in method validation, the HILIC separation holds promise for the separation of organosulfates derived from isoprene and other biogenic VOC. In comparing the two procedures for preparing filter samples for organosulfates quantification, both sonication and rotary shaking were proven to be efficient, with ultra-sonication providing better precision, narrower rangers and lower RSD. Initial measurements indicate that hydroxyacetone sulfate is relatively abundant in $PM_{2.5}$, compared to the measured organosulfates. HILIC chromatography is a promising analytical technique for the separation of organosulfates from one another and the complex aerosol matrix. When coupled with authentic standard development and highly sensitive MS/MS detection, it provides an improved technique for the quantification and speciation of atmospheric organosulfates. Improved measurements of this class of compounds will advance the understanding of SOA precursors and formation mechanisms.

The Supplement related to this article is available online at doi:10.5194/amt-8-2347-2015-supplement.

References

Alpert, A. J.: Electrostatic repulsion hydrophilic interaction chromatography for isocratic separation of charged solutes and selective isolation of phosphopeptides, Anal. Chem., 80, 62–76, doi:10.1021/ac070997p, 2007.

Altieri, K. E., Seitzinger, S. P., Carlton, A. G., Turpin, B. J., Klein, G. C., and Marshall, A. G.: Oligomers formed through in-cloud methylglyoxal reactions: Chemical composition, properties, and mechanisms investigated by ultra-high resolution FT-ICR mass spectrometry, Atmos. Environ., 42, 1476–1490, doi:10.1016/j.atmosenv.2007.11.015, 2008.

Attygalle, A. B., Garcia-Rubio, S., Ta, J., and Meinwald, J.: Collisionally-induced dissociation mass spectra of organic sulfate anions, J. Chem. Soc. Perkin Trans., 2, 498–506, doi:10.1039/B009019K, 2001.

Canals, I., Oumada, F. Z., Rosés, M., and Bosch, E.: Retention of ionizable compounds on HPLC, 6. pH measurements with the glass electrode in methanol–water mixtures, J. Chromatogr. A, 911, 191–202, doi:10.1016/S0021-9673(00)01271-1, 2001.

Cappiello, A., De Simoni, E., Fiorucci, C., Mangani, F., Palma, P., Trufelli, H., Decesari, S., Facchini, M. C., and Fuzzi, S.: Molecular characterization of the water-soluble organic compounds in fogwater by ESI-MS/MS, Environ. Sci. Technol., 37, 1229–1240, 2003.

Chan, M. N., Surratt, J. D., Chan, A. W. H., Schilling, K., Offenberg, J. H., Lewandowski, M., Edney, E. O., Kleindienst, T. E., Jaoui, M., Edgerton, E. S., Tanner, R. L., Shaw, S. L., Zheng, M., Knipping, E. M., and Seinfeld, J. H.: Influence of aerosol acidity on the chemical composition of secondary organic aerosol from beta-caryophyllene, Atmos. Chem. Phys., 11, 1735-1751, doi:10.5194/acp-11-1735-2011, 2011.

Davidson, C. I., Phalen, R. F., and Solomon, P. A.: Airborne particulate matter and human health: A review, Aerosol Sci. Tech., 39, 737–749, doi:10.1080/02786820500191348, 2005.

Espinosa, S., Bosch, E., and Rosés, M.: Retention of ionizable compounds on HPLC. 5. pH scales and the retention of acids and bases with acetonitrile-water mobile phases, Anal. Chem., 72, 5193–5200, doi:10.1021/ac000591b 2000.

Farmer, D. K., Matsunaga, A., Docherty, K. S., Surratt, J. D., Seinfeld, J. H., Ziemann, P. J., and Jimenez, J. L.: Response of an aerosol mass spectrometer to organonitrates and organosulfates and implications for atmospheric chemistry, P. Natl. Acad. Sci. USA, 107, 6670–6675, doi:10.1073/pnas.0912340107, 2010.

Foley, K. M., Roselle, S. J., Appel, K. W., Bhave, P. V., Pleim, J. E., Otte, T. L., Mathur, R., Sarwar, G., Young, J. O., Gilliam, R. C., Nolte, C. G., Kelly, J. T., Gilliland, A. B., and Bash, J. O.: Incremental testing of the Community Multiscale Air Quality (CMAQ) modeling system version 4.7, Geosci. Model Dev., 3, 205–226, doi:10.5194/gmd-3-205-2010, 2010.

Frossard, A. A., Shaw, P. M., Russell, L. M., Kroll, J. H., Canagaratna, M. R., Worsnop, D. R., Quinn, P. K., and Bates, T. S.: Springtime Arctic haze contributions of submicron organic particles from European and Asian combustion sources, J. Geophys. Res.-Atmos., 116, D05205, doi:10.1029/2010jd015178, 2011.

Froyd, K. D., Murphy, S. M., Murphy, D. M., de Gouw, J. A., Eddingsaas, N. C., and Wennberg, P. O.: Contribution of isoprene-derived organosulfates to free tropospheric aerosol mass, P. Natl. Acad. Sci. USA, 107, 21360–21365, doi:10.1073/pnas.1012561107, 2010.

Gao, S., Surratt, J. D., Knipping, E. M., Edgerton, E. S., Shahgholi, M., and Seinfeld, J. H.: Characterization of polar organic components in fine aerosols in the southeastern United States: Identity, origin, and evolution, J. Geophys. Res.-Atmos., 111, D14314, doi:10.1029/2005jd006601, 2006.

Gómez-González, Y., Surratt, J. D., Cuyckens, F., Szmigielski, R., Vermeylen, R., Jaoui, M., Lewandowski, M., Offenberg, J. H., Kleindienst, T. E., Edney, E. O., Blockhuys, F., Van Alsenoy, C., Maenhaut, W., and Claeys, M.: Characterization of organosulfates from the photooxidation of isoprene and unsaturated fatty acids in ambient aerosol using liquid chromatography/(–) electrospray ionization mass spectrometry, J. Mass Spectrom., 43, 371–382, doi:10.1002/jms.1329, 2008.

Grumbach, E. S., Wagrowski-Diehl, D. M., Mazzeo, J. R., Alden, B., and Lraneta, P. C.: Hydrophilic interaction chromatography using silica columns for the retention of polar analytes and enhanced ESI-MS sensitivity, LC-GC N. Am., 22, 1010–1023, 2004.

Grumbach, E. S., Diehl, D. M., and Neue, U. D.: The application of novel 1.7 μm ethylene bridged hybrid particles for hydrophilic interaction chromatography, J. Sep. Sci., 31, 1511–1518, doi:10.1002/jssc.200700673, 2008.

Guthrie, J. P.: Hydrolysis of esters of oxy acids – pKa values for strong acids, Can. J. Chem.-Rev. Can. Chim., 56, 2342–2354, doi:10.1139/v78-385, 1978.

Hawkins, L. N. and Russell, L. M.: Oxidation of ketone groups in transported biomass burning aerosol from the 2008 Northern California lightning series fires, Atmos. Environ., 44, 4142-4154, doi:10.1016/j.atmosenv.2010.07.036, 2010.

Hawkins, L. N., Russell, L. M., Covert, D. S., Quinn, P. K., and Bates, T. S.: Carboxylic acids, sulfates, and organosulfates in processed continental organic aerosol over the southeast Pacific Ocean during VOCALS-REx 2008, J. Geophys. Res.-Atmos., 115, D13201, doi:10.1029/2009jd013276, 2010.

Hemström, P. and Irgum, K.: Hydrophilic interaction chromatography, J. Sep. Sci., 29, 1784–1821, doi:10.1002/jssc.200600199, 2006.

Hoff, R. H., Larsen, P., and Hengge, A. C.: Isotope effects and medium effects on sulfuryl transfer reactions, J. Am. Chem. Soc., 123, 9338–9344, doi:10.1021/ja0163974, 2001.

Iinuma, Y., Boge, O., Kahnt, A., and Herrmann, H.: Laboratory chamber studies on the formation of organosulfates from reactive uptake of monoterpene oxides, Phys. Chem. Chem. Phys., 11, 7985–7997, doi:10.1039/b904025k, 2009.

Jacobson, M. C., Hansson, H. C., Noone, K. J., and Charlson, R. J.: Organic atmospheric aerosols: Review and state of the science, Rev. Geophys., 38, 267–294, doi:10.1029/1998RG000045, 2000.

Kristensen, K. and Glasius, M.: Organosulfates and oxidation products from biogenic hydrocarbons in fine aerosols from a forest in North West Europe during spring, Atmos. Environ., 45, 4546–4556, doi:10.1016/j.atmosenv.2011.05.063, 2011.

Kundu, S., Kawamura, K., Andreae, T. W., Hoffer, A., and Andreae, M. O.: Diurnal variation in the water-soluble inorganic ions, organic carbon and isotopic compositions of total carbon and nitrogen in biomass burning aerosols from the LBA-SMOCC campaign in Rononia, Brazil, J. Aerosol Sci., 41, 118–133, 2010.

Kundu, S., Quraishi, T. A., Yu, G., Suarez, C., Keutsch, F. N., and Stone, E. A.: Evidence and quantitation of aromatic organosul-

fates in ambient aerosols in Lahore, Pakistan, Atmos. Chem. Phys., 13, 4865–4875, doi:10.5194/acp-13-4865-2013, 2013.

Laskin, A., Smith, J. S., and Laskin, J.: Molecular characterization of nitrogen-containing organic compounds in biomass burning aerosols using high-resolution mass spectrometry, Environ. Sci. Technol., 43, 3764–3771, doi:10.1021/es803456n, 2009.

Lin, Y. H., Knipping, E. M., Edgerton, E. S., Shaw, S. L., and Surratt, J. D.: Investigating the influences of SO_2 and NH_3 levels on isoprene-derived secondary organic aerosol formation using conditional sampling approaches, Atmos. Chem. Phys., 13, 8457–8470, doi:10.5194/acp-13-8457-2013, 2013.

Maria, S. F., Russell, L. M., Turpin, B. J., Porcja, R. J., Campos, T. L., Weber, R. J., and Huebert, B. J.: Source signatures of carbon monoxide and organic functional groups in Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) submicron aerosol types, J. Geophys. Res.-Atmos., 108, 8637, doi:10.1029/2003JD003703, 2003.

Mutzel, A., Rodigast, M., Iinuma, Y., Böge, O., and Herrmann, H.: An improved method for the quantification of SOA bound peroxides, Atmos. Environ., 67, 365–369, doi:10.1016/j.atmosenv.2012.11.012, 2013.

Novakov, T. and Penner, J. E.: Large contribution of organic aerosols to cloud-condensation-nuclei concentrations, Nature, 365, 823–826, 1993.

Olson, C. N., Galloway, M. M., Yu, G., Hedman, C. J., Lockett, M. R., Yoon, T., Stone, E. A., Smith, L. M., and Keutsch, F. N.: Hydroxycarboxylic acid-derived organosulfates: Synthesis, stability, and quantification in ambient aerosol, Environ. Sci. Technol., 45, 6468–6474, doi:10.1021/es201039p, 2011a.

Olson, C. N., Galloway, M. M., Yu, G., Hedman, C. J., Lockett, M. R., Yoon, T. P., Stone, E. A., Smith, L. M., and Keutsch, F. N.: Reply to comment on "Hydroxycarboxylic acid-derived organosulfates: Synthesis, stability and quantification in ambient aerosol", Environ. Sci. Technol., 45, 9111–9111, doi:10.1021/es203122z, 2011b.

Paulot, F., Crounse, J. D., Kjaergaard, H. G., Kürten, A., St. Clair, J. M., Seinfeld, J. H., and Wennberg, P. O.: Unexpected epoxide formation in the gas-phase photooxidation of isoprene, Science, 325, 730–733, doi:10.1126/science.1172910, 2009.

Pratt, K. A., Fiddler, M. N., Shepson, P. B., Carlton, A. G., and Surratt, J. D.: Organosulfates in cloud water above the Ozarks' isoprene source region, Atmos. Environ., 77, 231–238, doi:10.1016/j.atmosenv.2013.05.011, 2013.

Reemtsma, T. and These, A.: On-line coupling of size exclusion chromatography with electrospray ionization-tandem mass spectrometry for the analysis of aquatic fulvic and humic acids, Anal. Chem., 75, 1500–1507, 2003.

Riesz, P., Berdahl, D., and Christman, C. L.: Free radical generation by ultrasound in aqueous and nonaqueous solutions, Environ. Health Perspect., 64, 233–252, doi:10.2307/3430013, 1985.

Romero, F. and Oehme, M.: Organosulfates – a new component of humic-like substances in atmospheric aerosols?, J. Atmos. Chem., 52, 283–294, 2005.

Shakya, K. M. and Peltier, R. E.: Investigating missing sources of sulfur at Fairbanks, Alaska, Environ. Sci. Technol., 47, 9332–9338, doi:10.1021/es402020b, 2013.

Shalamzari, M. S., Ryabtsova, O., Kahnt, A., Vermeylen, R., Herent, M. F., Quetin-Leclercq, J., Van der Veken, P., Maenhaut, W., and Claeys, M.: Mass spectrometric characteriza-

tion of organosulfates related to secondary organic aerosol from isoprene, Rapid Commun. Mass Spectrom., 27, 784–794, doi:10.1002/rcm.6511, 2013.

Staudt, S., Kundu, S., He, X., Lehmler, H. J., Lin, Y. H., Cui, T. Q., Kristensen, K., Glasius, M., Zhang, X., Weber, R., Surratt, J. D., and Stone, E. A.: Aromatic organosulfates in atmospheric aerosols: Synthesis, characterization, and abundance, Atmos. Environ., 94, 366–373, doi:10.1016/j.atmosenv.2014.05.049, 2014.

Stone, E. A., Yang, L., Yu, L. E., and Rupakheti, M.: Characterization of organosulfates in atmospheric aerosols at four Asian locations, Atmos. Environ., 47, 323–329, 2012.

Strege, M. A.: Hydrophilic interaction chromatography-electrospray mass spectrometry analysis of polar compounds for natural product drug discovery, Anal. Chem., 70, 2439–2445, doi:10.1021/ac9802271, 1998.

Surratt, J. D., Kroll, J. H., Kleindienst, T. E., Edney, E. O., Claeys, M., Sorooshian, A., Ng, N. L., Offenberg, J. H., Lewandowski, M., Jaoui, M., Flagan, R. C., and Seinfeld, J. H.: Evidence for organosulfates in secondary organic aerosol, Environ. Sci. Technol., 41, 517–527, doi:10.1021/es062081q, 2007a.

Surratt, J. D., Lewandowski, M., Offenberg, J. H., Jaoui, M., Kleindienst, T. E., Edney, E. O., and Seinfeld, J. H.: Effect of acidity on secondary organic aerosol formation from isoprene, Environ. Sci. Technol., 41, 5363–5369, 2007b.

Surratt, J. D., Gomez-Gonzalez, Y., Chan, A. W. H., Vermeylen, R., Shahgholi, M., Kleindienst, T. E., Edney, E. O., Offenberg, J. H., Lewandowski, M., Jaoui, M., Maenhaut, W., Claeys, M., Flagan, R. C., and Seinfeld, J. H.: Organosulfate formation in biogenic secondary organic aerosol, J. Phys. Chem. A, 112, 8345–8378, doi:10.1021/jp802310p, 2008.

Surratt, J. D., Chan, A. W. H., Eddingsaas, N. C., Chan, M. N., Loza, C. L., Kwan, A. J., Hersey, S. P., Flagan, R. C., Wennberg, P. O., and Seinfeld, J. H.: Reactive intermediates revealed in secondary organic aerosol formation from isoprene, P. Natl. Acad. Sci. USA, 107, 6640–6645, doi:10.1073/pnas.0911114107, 2010.

Tao, S., Lu, X., Levac, N., Bateman, A. P., Nguyen, T. B., Bones, D. L., Nizkorodov, S. A., Laskin, J., Laskin, A., and Yang, X.: Molecular characterization of organosulfates in organic aerosols from Shanghai and Los Angeles urban areas by nanospray-desorption electrospray ionization high-resolution mass spectrometry, Environ. Sci. Technol., 48, 10993–11001, doi:10.1021/es5024674, 2014.

Tolocka, M. P. and Turpin, B.: Contribution of organosulfur compounds to organic aerosol mass, Environ. Sci. Technol., 46, 7978–7983, doi:10.1021/es300651v, 2012.

Wang, W., Safi Shalamzari, M., Maenhaut, W., and Claeys, M.: Ion-pairing liquid chromatography/negative ion mass spectrometry for improved analysis of polar isoprene-related organosulfates, Rapid Commun. Mass Spectrom., 27, 1585–1589, doi:10.1002/rcm.6603, 2013.

Yassine, M. M., Dabek-Zlotorzynska, E., Harir, M., and Schmitt-Kopplin, P.: Identification of weak and strong organic acids in atmospheric aerosols by capillary electrophoresis/mass spectrometry and ultra-high-resolution Fourier transform ion cyclotron resonance mass spectrometry, Anal. Chem., 84, 6586–6594, doi:10.1021/ac300798g, 2012.

Zhang, H. F., Lin, Y. H., Zhang, Z. F., Zhang, X. L., Shaw, S. L., Knipping, E. M., Weber, R. J., Gold, A., Kamens, R. M., and Surratt, J. D.: Secondary organic aerosol formation from methacrolein photooxidation: roles of NOx level, relative humidity and aerosol acidity, Environ. Chem., 9, 247–262, doi:10.1071/en12004, 2012a.

Zhang, H. F., Worton, D. R., Lewandowski, M., Ortega, J., Rubitschun, C. L., Park, J. H., Kristensen, K., Campuzano-Jost, P., Day, D. A., Jimenez, J. L., Jaoui, M., Offenberg, J. H., Kleindienst, T. E., Gilman, J., Kuster, W. C., de Gouw, J., Park, C., Schade, G. W., Frossard, A. A., Russell, L., Kaser, L., Jud, W., Hansel, A., Cappellin, L., Karl, T., Glasius, M., Guenther, A., Goldstein, A. H., Seinfeld, J. H., Gold, A., Kamens, R. M., and Surratt, J. D.: Organosulfates as tracers for secondary organic aerosol (SOA) formation from 2-methyl-3-buten-2-ol (MBO) in the atmosphere, Environ. Sci. Technol., 46, 9437–9446, doi:10.1021/es301648z, 2012b.

Zhang, H. F., Zhang, Z., Cui, T., Lin, Y.-H., Bhathela, N. A., Ortega, J., Worton, D. R., Goldstein, A. H., Guenther, A., Jimenez, J. L., Gold, A., and Surratt, J. D.: Secondary organic aerosol formation via 2-methyl-3-buten-2-ol photooxidation: Evidence of acid-catalyzed reactive uptake of epoxides, Environ. Sci. Tech. Lett., 1, 242–247, doi:10.1021/ez500055f, 2014.

Zhao, Y., Hallar, A. G., and Mazzoleni, L. R.: Atmospheric organic matter in clouds: exact masses and molecular formula identification using ultrahigh-resolution FT-ICR mass spectrometry, Atmos. Chem. Phys., 13, 12343–12362, doi:10.5194/acp-13-12343-2013, 2013.