Response to the comments and resubmission of the manuscript "amt-2019-127"

Response to the comments of referee #1 for the open discussion of the manuscript "amt-2019-127"

We would like to thank Referee #1 for the comments that have helped improve the manuscript. The reviewer comments are in italic followed by our replies in normal text.

Major comments:

Comment 1 ("Title"): *First of all, the title of the paper needs to be revised to better represent the main contents of the manuscript. For example, this work focuses exclusively on the AMS and IC methods, although there are other techniques available for HMS quantification. Also, the current title reads as if the method targets a range of sulfur containing compounds, but in reality it is primarily for HMS.*

The title has been revised to: "Measurement techniques of identifying and quantifying Hydroxymethanesulfonate in cloud water and particulate matter"

Comment 2 ("IC method information"): *Secondary, more analytical details on the IC method are necessary. Information such as eluent composition, flow rate, column length, column temperature etc should be reported. For the quotation of detection limit in uM (e.g. page 7, line 14), the injection volume also matters. As this paper intends to present an improved IC method for HMS quantification, general aspects for evaluating and QA/QC an analytical method, such as calibrations curve, method precision (through repetitive analysis) and accuracy (through e.g. recovery analysis), and method robustness are important to be presented and discussed. It is also necessary to discuss the limitations and potential artifacts with the improved IC methods more thoroughly. For example, the stability of HMS is pH dependent. Loss of HMS is more severe at higher pH. The pH of the IC mobile phase is basic for eluent using sodium carbonate. The effect of HMS destruction during IC separating should be evaluated. Other issues such as the stability of the standard solution and potential loss of HMS in samples during storage are also important to discuss.*

The eluent composition and flow rate are presented in Section 2.2.2 page 6 lines 1-2 of the revised manuscript. We have added the column and compartment temperature, delivery speed and delivery sample volume on page 6 lines 2-3: "The column and compartment temperatures were both 25°C and the delivery speed and delivery sample volume for the analysis were 4 mL/min and 4 mL."

Information regarding the calibration curves, detection limit, accuracy, precision and robustness of our method have been added in the revised manuscript on page 7 and 8 lines 37-39 and 1-5, respectively: "The detection limits were determined by conducting sample runs of different concentrations. The concentration, C, for which the IC could not provide a clear peak was identified and samples runs were conducted for concentrations C+n, where n=0.2 mM. The concentration for which the baseline and the peak were clearly distinguishable was defined and 6 runs were conducted for this specific concentration to verify it. The uncertainty was determined, <1%, considering 99% confidence interval therefore it was concluded that for the system used in this work the lowest corresponding concentration, for which a measurable peak was efficiently detected, is the detection limit. Standards were

prepared before each experiment to ensure their stability and avoid possible decomposition if stored for a prolonged period of time.", page 7 lines 23-24: "Each sample analysis was conducted 4 times with individual sample preparation before each analysis. The area of the peaks was almost identical for sulfate and HMS in all 4 runs, with a difference only of 0.06 and 0.08 mM, respectively.", page 9 lines 3-8: "The eluent is also a technical aspect that differs between the two columns. The AS12A is an anion carbonate column, thus the eluent is neutral with respect to the pH, whereas the AS22 column is an anion hydroxide column, thus the eluent is basic with respect to pH. The stability of HMS has a strong pH dependence as it dissociates at high pH. The use of a neutral pH eluent avoids HMS decomposition during analysis. The majority of columns with alkyl quaternary ammonium functional group require neutral pH eluent, which also results in efficient separation of sulfur species." The pH of the eluent used for the AS12A was measured ~7.

The limitations of the method are presented in page 7 lines 30-32: "HMS and bisulfite/sulfite were not able to be separated as they had the same retention time in this case as well (Fig. 4). The efficiency and the clear separation of the peaks that the column provides allows for quantification of HMS when bisulfite/sulfite are not present." and page 8 lines 20-24: "If the concentrations are at lower levels, corresponding to $\lesssim$30 μM of HMS, value experimentally estimated under laboratory conditions, which is equivalent to $\lesssim 2\ \mu g \cdot m^{-3}$, assuming filter collection of ambient samples with sampling rate of ~80 $L \cdot min$, sampling time of ~6 hr and extraction volume of 20 mL, an aliquot of which, 4mL, is used for sample analysis, and sulfate is of equal or higher concentration, the peaks corresponding to HMS and sulfate have lower area signals and will be treated as one peak. For pH=12 the peaks could not be distinguished."

Minor comments:

Comment 1 ("Page 2 line 2"): *HSO3- can dissociate at pH < 6.*

We have clarified our statement on the revised manuscript in page 2 line 3: "In cloud and fog water, SO_2 reacts with water producing bisulfite (HSO_3^-), when 3<pH<6, which further dissociates to form sulfite (SO_3^{2-}) when pH>6."

Comment 2 ("Page 3 line 12"): *define RSMS and ATOFMS.*

We have defined the acronyms RSMS and ATOFMS in the revised manuscript in page 3 lines 15-16: "(rapid single-particle mass spectrometer: RSMS, aerosol time-of-flight mass spectrometer: ATOFMS)"

Comment 3 ("Page 7 line 6"): *what is 4x200nm corresponding to?*

The statement 4x200 nm has a typo, it should be mm, and corresponds to diameter and length of the column. It has been corrected in all parts of the revised manuscript that it is mentioned. Page 7 lines 14 and 27: "(diameter=4 mm and length=250 mm of the column)" and "(diameter=4 mm and length=200 mm of the column)".

Response to the comments of referee #2 for the open discussion of the manuscript "amt-2019-127"

We would like to thank the Referee #2 for the comments that have helped improve the manuscript. The reviewer comments are in italics followed by our replies in normal text.

It is unfortunate that the authors decided not to test the AG18-AS18 columns used in the URG AIM-IC. I understand that testing a new column would require additional laboratory work, but I really believe it would significantly extend the usefulness of the manuscript, as the AIM-IC is being used by many researchers in China. In the reviewer response, the authors note that they expect that the columns "will not allow efficient separation of HMS and sulfate", but this is highly qualitative and likely depends on the eluent and run conditions. I urge the authors to reconsider adding the AG18-AS18 column testing to their work here.

Regarding the use of the AG18-AS18 columns: The separation efficiency of liquid chromatography columns is largely based on their functional groups. The conditions, temperature, sample volume and flow rate of the AG18-AS18 columns are the same as the AG22-AS22 columns according to technical specification of the AS18 column found in the manufacturer's website. Therefore, they will not affect the efficiency. Based on the functional groups of the AG18-AS18 columns we do not expect efficient separation due to the hydrophobicity of the analytical column and its functional group. In addition, the common eluent used is KOH. We chose the use of columns that require neutral eluent to avoid possible decomposition of HMS during the analysis which can be rapid at elevated pH.

Major comments:

Comment 1 ("Title"): *The goal of this work, as stated through the paper, is to examine methods for the measurement of HMS in PM. Therefore, I suggest that the authors revise the title of their manuscript to specifically mention HMS and PM, rather than fog and cloud water.*

The title has been revised to: "Measurement techniques of identifying and quantifying Hydroxymethanesulfonate in cloud water and particulate matter"

Comment 2 ("Page 7, Line 19 and Page 8, Lines 5-6"): *The authors state "this method may result in noisy spectra for concentrations below 1 ppb" when discussing ESI-MS, but the paper cited (Chapman et al.) is from 1990. The signal/noise will depend on the mass analyzer used, in addition to the ionization method, and there have been great advances in mass analyzers and associated sensitivities over the past 30 years. Similarly, the LOD for the ESI-MS method is quoted as _100 ug/m3, but again, I expect this would have changed significantly over the time since publication. Therefore, these statements should be qualified, and rather future work should be motivated here to examine current sensitivities on ESI-MS instruments.*

We agree with the referee on the comment that there have been important advances in mass analyzers, and it is possible that the concentration and LOD mentioned might be improved. However, the Chapman et al. (1990) paper is, to our knowledge, the main study that describes the use of ESI-MS for the identification and quantification of HMS. Therefore, we believe that reporting lower LODs from more recent studies that do not consider HMS will not be accurate for the purpose of this study. We have included a statement emphasizing that due to improvements in the instrumentation over time such LODs might be improved.

The statement is in page 3 lines 29-33 on the revised manuscript: “Chapman et al. (1990) conducted an exploratory study reporting that the quantitative detection limit for HMS can be in the order of 100 $\mu g \cdot m^{-3}$, for typical sampling conditions, using an ESI-MS. Since 1990 there have been advances in the ESI-MS technology that could possibly result in lower detection limits. However, to our knowledge, these technological changes have not yet provided quantitative evidence of lower detection limits with respect to HMS analysis.”

Comment 3 (“Page 8, Line 11-12”): *In reviewing Whiteaker et al (2003, Atmos. Environ.) based on the reviewer response, this paper does not cite a lack of sensitivity by the ATOFMS for detecting HMS, making the statement on Line 11 misleading. Rather, Whiteaker et al. discuss the matrix effects of ammonium and sodium, which impact the peak area detected; I cannot find evidence in this manuscript that the LOD for HMS would be high, indicating a lack of sensitivity, and no comparison is provided to other techniques. Therefore, I suggest the authors remove the phrase “and lack of sensitivity” and instead suggest in the paper that a study of the sensitivity of single-particle mass spectrometry instruments to HMS is an area of future work needed (as eluded to now on Page 7,Lines 37-38).*

We would like to thank the referee #2 for the comment. The sentence aims to provide a general statement for single-particle mass spectrometry and along with the work of Whiteaker and Prather (2003), the studies of Neubauer at al. (1996 and 1997) are cited. In the work of Neubauer et al. (1996 and 1997) it is stated that the assigned ion peak for HMS is “only observed from particles that contain a strong acid or proton donor” and that particles of a specific range were able to be examined. We have remove the statement “and lack of sensitivity” as we agree with the referee that these limitations can fall within the area matrix effects. We also agree on the necessity of stating that the sensitivity of these instruments with respect to HMS requires more detailed study in the future and we have included that statement on the revised manuscript.

The statement is in page 4 lines 26-27: “The sensitivity challenges of these methods with respect to HMS quantification yield the necessity of further study.”

Comment 4 (“Page 7, Line 6-8”): *PALMS is a single-particle mass spectrometry instrument. Please correct here. Please also note that the single-particle mass spec papers listed here do not represent a complete list, as implied. Either include “e.g.” in front of the literature list, or conduct a more thorough literature search. Similarly, Section 1.2 describes each of the single-particle mass spectrometry studies listed here, but again, this is only a subset of published work on the subject, which is not reflected in the summaries presented. I’d encourage the authors to consider in Section 1.2 to conduct a more thorough literature search, and rather than describing each paper one-by-one, include a brief overview/summary of the observations.*

We have corrected the phrase by including “single-particle”. We included the single-particle mass spectrometry papers that have been used for identification and/or quantification of HMS. We clarify that in the manuscript in the relevant section which is in page 3 line 11: “A variety of technical methods have been used to detect HMS,…”.

Comment 5 (“Page 11, Line 12-14”): *The addition of the IC LODs and explanation of conversion to ambient mass concentration is very useful. However, please clarify how the LODs were determined and what they refer to, as there as multiple methods and definitions used in chromatography for LODs.*

The LODs were determined by conducting sample runs of different concentrations. The concentration, C, for which the IC could not provide a clear peak was identified and samples runs were conducted for concentrations C+n, where n=0.2 mM. The concentration for which the baseline and the peak were clearly distinguishable was defined and 6 runs were conducted for this specific concentration to verify it. We wanted 99% confidence interval therefore we calculated the standard deviation to also determine the uncertainty. The uncertainty was very low <1% therefore we concluded that for our system the lowest corresponding concentration, for which a measurable peak was efficiently detected, is the LOD. We have added this information in pages 7 and 8 lines 38-39 and 1-3, respectively: "The detection limits were determined by conducting sample runs of different concentrations. The concentration, C, for which the IC could not provide a clear peak was identified and samples runs were conducted for concentrations C+n, where n=0.2 mM. The concentration for which the baseline and the peak were clearly distinguishable was defined and 6 runs were conducted for this specific concentration to verify it. The uncertainty was determined, <1%, considering 99% confidence interval therefore it was concluded that for the system used in this work the lowest corresponding concentration, for which a measurable peak was efficiently detected, is the detection limit."

Comment 6 ("Page 11, Line 24-27"): *I am confused at why a significant underestimation occurred when the elevated baseline was used. How was this determined? Was a calibration curve obtained and then a known concentration run to check? What is "significant" in this case? Please clarify.*

We have clarified this information in the manuscript in page 8 and lines 17-20: "When this was applied a significant underestimation of the concentration, ≳15% of HMS with 4% uncertainty, of the compounds was observed, therefore the software automatic separation was selected to be used. The percentages of HMS and sulfate were obtained considering the software separation of the peaks and the underestimation was determined by obtaining the calibration curves for sulfate and HMS and examining known concentrations.". A calibration curve was obtained for all the examined compounds and a variety of know sample concentrations were tested. In all the cases we concluded that there was an underestimation of up to 15% of HMS, with 4% uncertainty, when the AS22 column was used, which is a significant underestimation.

Comment 7 ("Section 3.2"): *What are the uncertainties in the percentages reported? Is reporting to one decimal place appropriate? Where the samples run in triplicate?*

Each analysis was conducted 4 times with individual sample preparation before each analysis. For example, when we examined 2mM of HMS and 2mM of sulfate we prepared 4 different samples and analyzed them with IC. The area of the peaks was almost identical for sulfate and HMS in all 4 runs, with a difference only of 0.06 and 0.08 mM, respectively. Therefore, we concluded that it is accurate to report one decimal point.

Comment 8 ("Section 4"): *Add a statement of the required concentration needed to distinguish HMS and sulfate (discussed on page 11), as this seems like it will significantly impact the recommendation of the necessary mass loading for ambient samples.*

We have added that the required concentration needed to distinguish HMS and sulfate under the described conditions is >2 $\mu g \cdot m^{-3}$ of HMS and that sulfate concentration has to be lower than HMS. The statement is in page 9 lines 25-26: "Using an IC system, the detection limit of quantifying HMS and sulfate is 0.8 μM and 0.2 μM, respectively, and the required concentration needed to

distinguish HMS and sulfate was determined to be >2 $\mu g \cdot m^{-3}$ of HMS and the sulfate concentration has to be lower concentration than that of HMS.".

Additional comments:

Comment 1 ("Section 1.1"): *While the pivotal work of Munger et al 1986 (Science) is cited later in the manuscript, it would be highly valuable and most appropriate for this to be cited in the first paragraph of Section 1.1, as it sets the stage for the entirety of this work.*

In the revised manuscript we now cite Munger et al. (1986) in the first paragraph of the section where the HMS formation is mentioned. Page 1 line 29: "Hydroxymethanesulfonate (HMS; $HOCH_2SO_3^-$) is the product of the aqueous-phase reaction between dissolved sulfur dioxide (SO_2) and formaldehyde (HCHO) and is considered an important compound in cloud and fog water (Munger et al., 1986; Dixon and Aasen, 1999; Whiteaker and Prather, 2003).".

Comment 2 ("Page 2, Line 16-20"): *Please provide references for these statements.*

These statements refer to a response to a previous comment by the reviewer: "Metrohm MARGA uses a polystyrene/divinylbenzene copolymer with quaternary ammonium groups as functional group for separation of sulfite, sulfate and thiosulfate. Due to the fact that we are using the Dionex IC-5000+ IC model with adjustments in order to have a good separation of HMS and sulfate, compatibility issues might be encountered if we use a Metrohm column. It is possible that if the column used has polystyrene/divinylbenzene copolymer with alkyl quaternary ammonium group as functional group the separation of HMS and sulfate can be achieved, however we can not confidently make that statement. Unfortunately, we do not have access to this system for evaluation.". The statements results of discussion with technicians from Thermo Scientific, technical documents provided from Metrohm and experimental observations we obtained from ongoing projects.

Comment 3 ("Page 6, Line 27-28"): *Rephrase statement "…measurements of HMS have mainly been conducted of fog and cloud water only" as there have been many ambient PM measurements of HMS by single-particle mass spectrometry.*

We have rephrased the sentence according to the reviewer's recommendation. Page 2 lines 31-33: "Measurement of sulfate in ambient PM is common, whereas measurements of HMS have mainly been conducted for fog and cloud water. Studies reporting the presence of HMS in ambient PM using single-particle mass spectrometry have also been conducted (Neubauer et al., 1996; Neubauer et al., 1997; Whiteaker and Prather, 2003; Lee et al., 2003; Dall'Osto et al., 2009).".

Comment 4 ("Page 6, Line 30-32"): *This statement is confusing as written. Please clarify.*

We have clarified the statement in the revised manuscript. Page 2 lines 36-38: "Moreover, for MS, cations can be observed simultaneously in addition to sulfur-containing ions, whereas for IC a specified IC column with high sensitivity for sulfur-containing ions has to be used to identify them."

All acronyms have been specified in the revised manuscript.

Comment 5 and 6 ("Page 7, Line 29-30" and "Page 7, Line 35"): *Single-particle mass spectrometers have several lasers. Please correct "operating laser" to "desorption/ionization laser".*
Matrix effects are inherent to the laser desorption/ionization process and have nothing to do with the inlet design, pump configuration, and reflectron. Rather matrix effects are associated with the competition in ion formation. Please correct here.

We have revised according to the reviewer's recommendation. Page 4 line 4 and line 10: "desorption/ionization laser at 266 nm" and "have been optimized to overcome sensitivity issues by improving the inlet design".

Comment 7 ("Section 1.2"): *This section should describe the previous work of Gilardoni et al (2016, PNAS), who showed the AMS mass spectrum of HMS only. I realize that this paper is cited, but it would be useful for it to be described in the introduction to set the stage for how the current work builds upon this previous work.*

We have included more information of the work of Gilardoni et al (2016) in the section 1.2. Page 4 lines 8-9: "Gilardoni et al. (2016) provided the spectrum of HMS using standard samples. During that study HMS was used as a tracer of aqueous chemistry.".

Comment 8 ("Page 7, Line 13"): *Consider replacing "RSMS, PALMS, AToFMS" with "Single-particle Mass Spectrometry" as these are simply three of many types of single-particle mass spectrometers.*

We have revised according to the reviewer's recommendation. Page 3 line 21: "1.2 Previous work identifying HMS using Single-particle Mass Spectrometry, Capillary Electrophoresis and reverse-phase HPLC".

Comment 10 ("Page 7, Line 29"): *Correct "AToFMS" to "ATOFMS".*

We have changed the "AToFMS" to "ATOFMS" in the manuscript.

Comment 11 ("Page 8, Line 5-6"): *Please move these sentences the first paragraph of Section 1.2, where ESI-MS is discussed.*

We have moved these sentences as suggested in page 3 lines 29-33 in the revised manuscript.

Comment 12 ("Page 8, Line 6-7"): *Please clarify this sentence. Song et al. (2018) did detect HMS by SPAMS, even though the opposite seems to be stated in this sentence, with the opposite statement then in the following sentence.*

We have clarified this sentence in the revised manuscript. The study by Song et al. 2019 (published) stated that the detection limit using AMS and SPMS could be lower than the detection limit reported by Chapman et al. (1990). In addition, the authors state that the SPMS data revealed that approximately 10% of HMS-containing particles in the total particles counts during haze events but they could not provide a quantitative measure particle as HMS, possibly due to fragmentation. Therefore, even though in that study HMS was able to be identified and it is stated that the detection limit could be lower than reported in the past, no quantitative information could be retrieved. Page 4 lines 20-21: "Although it was stated that the detection limit could possibly be lower using AMS and SPMS (Song et al., 2019) than the concentration reported by Chapman et al. (1990), 100 $\mu g \cdot m^{-3}$ using ESI-MS,, such

lower levels of HMS were not able to be detected using these methods. In their study, Song at al. (2019) were able to identify HMS as a component of SOA but they could not quantify it, likely for the reasons outlined below in this work.".

Comment 13 ("Page 9, Line 17"): *Can you provide references here for the common use of this column?*

The main reference is the technical report of the column provided by the manufacturer. The specific column, based on our experience, and the information provided by the manufacturer is the most common column for inorganic analysis.

Comment 14 ("Page 10, Line 7"): *Please clarify "other species" here.*

The phrase "the other species" refers to the other sulfur-containing compounds presented in Figure 1; sodium bisulfite, sodium sulfate and ammonium sulfate. We have clarified in the revised manuscript in page 6 lines 26-27 in the revised manuscript: "other species (sodium bisulfite, sodium sulfate and ammonium sulfate)".

Comment 15 ("Page 10, Line 14"): *Fix reference formatting here.*

The reference formatting has been corrected in the revised manuscript.

Comment 16 ("Section 3.2"): *Some of this section repeats the methods and could be condensed.*

In the experimental section general information is provided however, in the section 3.2 we present more detailed information for each examined column pair.

Comment 17 ("Page 13, Line 1"): *I'm confused by the statement "Applications of both IC and AMS methods to the same ambient samples in the future" as isn't a finding of this work that the AMS is unable to distinguish between HMS and sulfate. Also, I'm confused because I thought these samples were not available for analysis based on the reviewer response. Please clarify.*

We have clarified this sentence as our intent was to point out that it would be useful to use the methods we describe in this work to analyze the ambient samples, or similar samples from severe haze events and specifically samples from similar conditions of the work of Wang et al. (2014). Page 10 line 1 in the revised manuscript: "Applications of both IC and AMS methods to the same ambient samples from similar conditions of the January 2013 haze event".

Response to the comments of referee #3 for the open discussion of the manuscript "amt-2019-127"

We would like to thank Referee #3 for the comments that have helped improve the manuscript. The reviewer comments are in italic followed by our replies in normal text.

Comment 1 (“Title”): *The title as it stands now is very broad. Maybe it could be phrased a bit more specfific ? Wouldn’t it make sense to clearly mention HMS ?*

The title has been revised to: “Measurement techniques of identifying and quantifying Hydroxymethanesulfonate in cloud water and particulate matter”

Comment 2 (“Introduction”): *It covers quite some aspects, but at times there could be some more coverage. Maybe the authors can check again, HMS has been discussed a bit more often.*

Information regarding the formation, chemistry and field measurements of HMS is presented throughout the introduction. As HMS is an important compound discussed in this work we provide information in all the paragraphs of the introduction.

Comment 3 (“Page 3 Section 1.2”): *I find it starngethat here the very successlfully applied CE (capillary electrophoretic) separation and determination is not described. This is a mayor flaw and needs to be corrected. See Scheinhardt et al ., but especially references therein, Kramberger et al.*

We have added a description of the CE method in page 4 lines 34-40: “Scheinhardt et al. (2014) provided evidence of identification of HMS during two field campaigns conducted in nine sites in Germany. Capillary electrophoresis (CE) was used resulting in efficient separation of HMS from other compounds when a voltage of -30 kV followed by hydrodynamic sample injection with 750 mbars was applied. Quantification was achieved through indirect UV detection at 260 nm wavelength and time resolution of 20 Hz. The detection limit of HMS was reported equal to 6-7 $ng \cdot m^{-3}$ and higher concentrations were observed during winter time. The method resulted successful quantification of HMS in concentration ≥18-21 $ng \cdot m^{-3}$. Concentrations in the range of 6-18 $ng \cdot m^{-3}$ were reported, however this range was characterized as less reliable in the study. (Scheinhardt et al., 2014)”

Comment 4 (“Page 5 line 29”): *For MSA you should possibly reference Huang, Shan, et al. "Latitudinal and seasonal distribution of particulate MSA over the Atlantic using a validated quantification method with HR-ToF-AMS." Environmental science & technology 51.1 (2016): 418-426.*

The citation of the recommended work has been added to the revised manuscript in page 6 line 11: “(Phinney et al., 2006; Huang et al., 2016; Chen et al., 2019)”.

Comment 5 (“Page 6 Section 3.1”): *Maybe it would be good to carry the conclusion of this section into the abstract: It is very difficult if not even impossible to identify or even quantify HMS through AMS only.*

The conclusion of Section 3.1 is presented in the abstract in page 1 lines 18-22: “In cases where the dominant sulfur-containing species are ammonium sulfate or HMS, differences in AMS fragmentation patterns can be used to identify HMS. However, the AMS quantification of HMS in complex ambient mixtures containing multiple inorganic and organic sulfur species is challenging due to the lack of unique organic fragments and variability of fractional contributions of $H_xSO_y^+$ ions as a function of matrix.”

Comment 6 ("HPLC"): *Also, the HPLC method presented here does not fully convince. Please give numbers of merit for it and compare to all existing offline analytical techniques. Could you discuss wether AMS paralleled by filter sampling and CE analysis wouldn't be a valuable option? In this view, the discussion at the end of the paper should be widened.*

Information and concentration ranges according to the study of Zuo and Chen (2003) are presented in page 4 lines 33-39. The study provides evidence of separation and quantification of HMS, sulfate and sulfite and the reported numbers that are relevant to the separation of these species are included in the manuscript. The present work does not aim to provide a literature review of the techniques that have been used to identify HMS thus Section 1.2 serves as a short discussion of methods previously used. The AMS coupled with CE analysis is an interesting option however since CE is not used in the present work, we could not comment on the efficiency of such a method. According to our finding AMS identification quantification of HMS is challenging. As pointed out by the referee #3, CE has successfully been used for the identification and quantification of HMS, however it is uncertain that the combination of the two system, AMS and CE, would result in better results.

Measurement techniques of identifying and quantifying Hydroxymethanesulfonate in cloud water and particulate matter.

Commented [DE1]: Title change
Major comment 1 from referee #1
Major comment 1 from referee #2
Comment 1 from referee #3

Eleni Dovrou[1], Christopher Y. Lim[2], Manjula R. Canagaratna[3], Jesse H. Kroll[2], Douglas R. Worsnop[3], and Frank N. Keutsch[1,4,5]

[1]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[2]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02138, USA
[3]Center for Aerosol and Cloud Chemistry, Aerodyne Research, Inc., Billerica, MA 02138, USA
[4]Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138, USA
[5]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA

Correspondence to: Eleni Dovrou (edovrou@g.harvard.edu)

Abstract. Oxidation of sulfur dioxide (SO_2) in the gas phase and in cloud and fog water leads to the formation of sulfate that contributes to ambient particulate matter (PM). For severe haze events with low light conditions, current models underestimate the levels of sulfate formation which occurs exclusively via the oxidation of sulfur dioxide. We show here that measurement techniques commonly used in the field to analyse PM composition can fail to efficiently separate sulfur-containing species resulting in possible misidentification of compounds. Hydroxymethanesulfonate (HMS), a sulfur(IV) species that can be present in fog and cloud water, has been largely neglected in both chemical models and field measurements of PM composition. As HMS is formed without oxidation it represents a pathway for SO_2 to contribute to PM under low light conditions. In this work, we evaluate two techniques for specific quantification of HMS and sulfate in PM, Ion Chromatography (IC) and Aerosol Mass Spectrometry (AMS). In cases where the dominant sulfur-containing species are ammonium sulfate or HMS, differences in AMS fragmentation patterns can be used to identify HMS. However, the AMS quantification of HMS in complex ambient mixtures containing multiple inorganic and organic sulfur species is challenging due to the lack of unique organic fragments and variability of fractional contributions of $H_xSO_y^+$ ions as a function of matrix. We describe an improved IC method that provides efficient separation of sulfate and HMS and thus allows identification and quantification of both. The results of this work provide a technical description of the efficiency

and limitations of these techniques as well as a method that enables further studies of the contribution and role of S(IV) versus S(VI) species to PM under low light atmospheric conditions.

1 Introduction

1.1 Sulfur species in cloud and fog water

Hydroxymethanesulfonate (HMS; $\mathbf{HOCH_2SO_3^-}$) is the product of the aqueous-phase reaction between dissolved sulfur dioxide ($\mathbf{SO_2}$) and formaldehyde (HCHO) and is considered an important compound in cloud and fog water (Munger et al., 1986; Dixon and Aasen, 1999; Whiteaker and Prather, 2003). HMS is very stable at low pH (pH<6) and is resistant towards oxidation by hydrogen peroxide and ozone; however, it can be oxidized by hydroxyl radicals (Kok et al., 1986; Martin et al., 1989; Chapman et al., 1990). HMS formation results in acidification of the cloud droplets and can contribute significantly to aerosol mass and aerosol sulfur concentration at low pH where it is stable (Dixon and Aasen, 1999). HMS can be retained in aerosol particles after cloud evaporation if the pH is greater than 4.

In cloud and fog water, SO_2 reacts with water producing bisulfite (HSO_3^-), when 3<pH<6, which further dissociates to form sulfite (SO_3^{2-}) when pH>6. Bisulfite and sulfite can be oxidized rapidly by several species such as the hydroxyl radical (OH), ozone (O_3), oxygen (O_2) and hydrogen peroxide (H_2O_2) (Hegg and Hobbs, 1982; Lind et al., 1987; Shen et al., 2012), thus S(IV) species are not expected in PM in significant amounts. Formation of HMS is favourable at high levels of sulfur dioxide and formaldehyde, low levels of oxidants like OH, H_2O_2 and O_3 (Hegg and Hobbs, 1982; Lind et al., 1987), and cloud and fog pH in the range of approximately 4-6 (Munger et al., 1984; Munger et al., 1986). Oxidation of dissolved sulfur dioxide by O_3 is significant for pH values greater than 4 and oxidation by H_2O_2 is considered to be the dominant pathway for the formation of sulfate in cloud and fog water. During haze events oxidant concentrations have been reported to be low resulting in low oxidation rates whereas formaldehyde and sulfur dioxide concentrations have been reported to be high (Ji et al., 2014; Rao et al., 2016; Wang et al., 2016). Therefore, the formation of HMS is favourable under these conditions.

Model simulations under low light conditions in regions with slow photochemistry, such as polluted cities in China and India, underestimate sulfate (SO_4^{2-}) concentrations measured in the field using ion chromatography (IC) (Wang et al., 2016), indicating that there is either a missing source of SO_4^{2-} in the model or other sulfur-containing species are misidentified as SO_4^{2-} by IC. During 2009 and 2010 two field campaigns were conducted in Germany (Scheinhardt et al., 2014) reporting the presence of HMS in particles produced in urban areas. HMS concentrations were highest during winter time in particles with 0.42-1.2 µm diameter size range, although concentrations were low, most likely as not all conditions conductive to HMS formation were met, i.e., there were low light conditions but also low formaldehyde and SO_2 concentrations. In January 2013 an extreme winter haze event was recorded over Northern China which resulted in high levels of sulfate measured by IC compared to periods observed before and after the event. The GEOS-Chem chemical transport model (GEOS-Chem CTM) was not able to reproduce the observed SO_4^{2-} concentrations during the haze events despite good performance during other periods, as it under-predicted SO_4^{2-} concentrations by a factor of 4 during the haze periods. Specifically, the model estimated SO_4^{2-} concentrations to be similar for haze and non-haze periods. This suggests that there might be a significant, missing source of SO_4^{2-} (Wang et al., 2014). Wang at al. (2014) suggested that a new heterogeneous pathway of SO_4^{2-} formation could explain the missing SO_4^{2-}. Moch et al. (2018) suggested the contribution of HMS to explain the high observed SO_4^{2-} concentrations during these low light haze events with slow

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photochemistry. In order to distinguish the two hypotheses, i.e., condensed-phase reactions producing sulfate or contribution from HMS, measurement techniques that allow quantitative speciated measurements of HMS and sulfate are needed.

Measurement of sulfate in ambient PM is common, whereas measurements of HMS have mainly been conducted for fog and cloud water ~~only~~. Studies reporting the presence of HMS in ambient PM using single-particle mass spectrometry have also been conducted (Neubauer et al., 1996; Neubauer et al., 1997; Whiteaker and Prather, 2003; Lee et al., 2003; Dall'Osto et al., 2009). Two main methods have been used, ion chromatography (IC) and mass spectrometry (MS). For IC a characteristic elution time is used for identification of different ions, including sulfate. For MS the detailed mass spectrum, especially differences in fragmentation patterns, can provide a means to differentiate, in this case, different sulfur-containing species. Moreover, for MS, cations can be observed simultaneously in addition to sulfur-containing ions, whereas for IC a specified IC column with high sensitivity for sulfur-containing ions has to be used to identify them. In order to distinguish HMS from sulfate using IC or MS, the elution times or the mass spectra and fragmentation patterns, respectively, have to be distinct. (Munger et al., 1986; Chapman et al., 1990; Neubauer et al., 1996; Neubauer et al., 1997; Dixon and Aasen, 1999; Zuo and Chen, 2003; Lee et al., 2003; Whiteaker and Prather, 2003; Dall'Osto et al., 2009)

Sulfate is traditionally measured using IC, but for measurements of PM little attention has been given to the effect of HMS in PM on sulfate measurements. An IC system with alkanol quaternary ammonium analytical column is widely used to separate the main inorganic ions, i.e. SO_4^{2-}, NO_3^-, Cl^- and Br^- (Hegg and Hobbs, 1982; Wang et al., 2005; Shen et al., 2012). Single-particle mass spectrometry (SPMS) and the Aerodyne aerosol mass spectrometer (AMS) have been used to detect sulfate (Jimenez, 2003; Murphy et al., 2006; Ji et al., 2014). SPMS and AMS are used for on-line and off-line analysis. During the on-line analysis ambient air is sampled through an inlet to the instrument. For offline analysis, filters collect particles from ambient air, the collected material is extracted into water and after additional dilution the extracts are atomized for analysis via SPMS or AMS.

A variety of technical methods have been used to detect HMS, mainly IC using specific columns (Munger et al., 1986; Dixon and Aasen, 1999), reverse-phase ion-pair high performance liquid chromatography (HPLC) (Zuo and Chen, 2003), electrospray ionization-tandem mass spectrometry (ESI-MS) (Chapman et al., 1990), single-particle analysis by laser mass spectrometry (PALMS) (Lee et al., 2003) and single-particle mass spectrometry (rapid single-particle mass spectrometer: RSMS, aerosol time-of-flight mass spectrometer: ATOFMS) (Neubauer et al., 1996; Neubauer et al., 1997; Whiteaker and Prather, 2003; Dall'Osto et al., 2009). In this work we present an IC method specifically developed to identify and quantify HMS and we discuss the ability of the AMS to identify and quantify HMS in the presence of sulfate and different cations, to evaluate the matrix effects, under laboratory conditions. In addition, we compare these methods with the technical methods used in previous work.

1.2 Previous work identifying HMS using Single-particle Mass Spectrometry, Capillary Electrophoresis and reverse-phase HPLC

Mass spectrometry has been used in the past to identify HMS. Chapman et al. (1990) reported its identification by using an electrospray ionization mass spectrometer (ESI-MS). The characteristic *m/z* ratio was determined to be *m/z*=111 ($HOCH_2SO_3^-$); to determine a distinct dissociation pattern for HMS the collision-induced dissociation spectrum showed that the *m/z*=80 (SO_3^-) and *m/z*=81 (HSO_3^-) can be used as characteristic fragment ions for HMS detection. To quantify HMS, *m/z*=81 (HSO_3^-) was used as its corresponding peak was larger than the *m/z*=80 (SO_3^-) and it showed linear relationship between concentration and ion signal in

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the ESI-MS. However, this method may result in noisy spectra for concentrations below 1 ppb, and as discussed later *m/z*=81 (HSO_3^-) is not specific to HMS, but rather requires use of tandem mass spectrometry. Chapman et al. (1990) conducted an exploratory study reporting that the quantitative detection limit for HMS can be on the order of 100 $\mu g \cdot m^{-3}$, for typical sampling conditions, using an ESI-MS. Since 1990 there have been advances in the ESI-MS technology that likely result in lower detection limits. However, to our knowledge, these technological changes have not yet provided quantitative evidence of lower detection limits with respect to HMS analysis.

Neubauer et al. (1996, 1997) explored the possibility of separating sulfur-species, including HMS, by the use of rapid single-particle mass spectrometer (RSMS) in aerosols. Particles are vaporized and ionized by a pulsed laser (248 nm) and analysis is completed by a reflectron time-of-flight mass analyzer. In contrast to ESI-MS, RSMS did not show an *m/z* ratio of 111 ($HOCH_2SO_3^-$) and the dominant signal was *m/z*=64 (SO_2^+) when dry particles were analysed. The *m/z*=111 ($HOCH_2SO_3^-$) ion was observed only in the case of acidic aqueous particles. The single particle mass spectrometer provides a wider dynamic range and shorter analysis time compared to ESI-MS however the quantification can be challenging in aqueous matrices due to interference from compounds, such as $(NH_4)_2SO_4$ and methyl sulfonic acid (MSA), present in the sample (Neubauer et al., 1996, Neubauer et al., 1997). Whiteaker and Prather (2003) used a single-particle aerosol time-of-flight mass spectrometer (ATOFMS), with desorption/ionization laser at 266 nm, to identify HMS in ambient particles and droplets as a tracer for fog processing. In that work, even though the *m/z*=111 ion was observed in some cases when HMS sodium salt was mixed with ammonium sulfate, the identification of HMS in ambient samples was difficult and resulted in uncertainties in the quantification (Whiteaker and Prather, 2003). During a fog event in London, Dall'Osto et al. (2009) also reported the presence of HMS using an ATOFMS. The *m/z*=111 ($HOCH_2SO_3^-$) and *m/z*=81 (HSO_3^-) ions were identified as markers of HMS. Gilardoni et al. (2016) provided the spectrum of HMS using standard samples. During that study HMS was used as a tracer of aqueous chemistry. Single-particle mass spectrometers have been optimized to overcome ~~matrix effects~~ sensitivity issues by improving the inlet design, reducing the pump configuration, applying a dual-polarity grid-less reflection design and removing secondary coating of aerosols prior to the analysis (Pratt et al., 2009; Hatch et al., 2014). Such changes can result in higher sensitivity (Pratt et al., 2009; Pratt and Prather, 2012; Hatch et al., 2014). The effect of these optimizations on the sensitivity to HMS has not been reported.

Lee et al. (2003) conducted a field campaign measuring the chemical composition of aerosols with 0.35-2.5 μM diameter during the 1999 Atlanta Supersite Project. Using a PALMS instrument they identified HMS via the *m/z*=111 ($HOCH_2SO_3^-$) ion. Methylsulfate ($CH_3OSO_3^-$) was also identified by the *m/z*=111 ion, however the authors concluded that due to the low acid concentrations in the particles and high temperatures in Atlanta, the *m/z*=111 ion could not be assigned to methylsulfate (Lee et al., 2003). ~~Chapman et al. (1990) conducted an exploratory study reporting that the quantitative detection limit for HMS can be in the order of 100 $\mu g \cdot m^3$, for typical sampling conditions, using an ESI-MS.~~ Although it was stated that the detection limit could possibly be lower using AMS and SPMS (Song et al., 2019) than the concentration reported by Chapman et al. (1990), 100 $\mu g \cdot m^{-3}$ using ESI-MS,, such lower levels of HMS were not able to be detected using these methods. In their study, Song at al. (2019) were able to identify HMS as a component of SOA but they could not quantify it, likely for the reasons outlined below in this work.

Overall, quantification of HMS using single-particle MS methods is challenging due to matrix effects ~~and lack of sensitivity~~ in ambient samples (Neubauer et al., 1996; Neubauer et al., 1997; Whiteaker and Prather, 2003). The sensitivity challenges of these methods with respect to HMS quantification yield the necessity of further study. Aerosol mass spectroscopy (AMS) was used in this work to investigate the ability to identify and quantify HMS and will be described in detail below. However, all mass

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spectrometry techniques share the challenge that the majority of the fragments, such as SO_3^- and HSO_3^-, are common to different sulfur-containing species, including organic compounds potentially in the measured PM(Ge et al., 2012; Canagaratna et al., 2015; Gilardoni et al., 2016; Song et al., 2019), and that the ratios can depend on other compounds present in PM, such as ammonium and other cations.

Scheinhardt et al. (2014) provided evidence of identification of HMS during two field campaigns conducted in nine sites in Germany using capillary electrophoresis (CE). CE achieved efficient separation of HMS from other compounds using a voltage of -30 kV and hydrodynamic sample injection with 750 mbars was applied. Quantification was achieved through indirect UV detection at 260 nm wavelength and a measurement rate of 20 Hz. The detection limit of HMS was reported as 6-7 $ng \cdot m^{-3}$ and concentrations above this were observed during winter time. The method resulted in successful quantification of HMS in concentrations $\geq$ 18-21 $ng \cdot m^{-3}$. Concentrations in the range of 6-18 $ng \cdot m^{-3}$ were reported, however this range was characterized as less reliable in the study. (Scheinhardt et al., 2014)

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Reverse-phase ion-pair HPLC has successfully been used to separate sulfur-species (Zuo and Chen, 2003). A cetylpyridium-coated C_{18} column was used for efficient separation of the sulfur-spieces and the detection was achieved by indirect UV light absorption. Zuo and Chen (2003) reported the separation and quantification of sulfite, sulfate and HMS at the concentration range of 19-430 μM, 6.7-430 μM and 3.8-430 μM, respectively. This work provides evidence that ion-exchange chromatography can be an efficient method for separation of sulfur-species. Even though mass spectrometry has been widely used for analysis of sulfur-species (Neubauer et al., 1996; Neubauer et al., 1997; Whiteaker and Prather, 2003), there is indication that chromatography methods could provide efficient separation of these species (Zuo and Chen, 2003).

2 Experimental

2.1 Chemicals and sample preparation

The sodium salt of HMS (Na-HMS) was purchased from Sigma Aldrich (purity 95%). Sodium sulfate (Na_2SO_4) and sodium metabisulfite ($Na_2S_2O_5$) were purchased from Sigma Aldrich (purity ≥99% in both cases) and used to prepare standards and reference solutions. Sodium metabisulfite was used as a source of bisulfite in the samples as it dissociates rapidly in water to form bisulfite. All solutions were prepared by using filtered Milli-Q water. The samples were analysed at 25 ºC in the pH range of 3 to 12. Six types of samples were prepared to examine all the possible combinations of sulfur-containing species. Solutions containing only sodium sulfate, sodium bisulfite/sulfite, Na-HMS and combinations of Na-HMS with sodium bisulfite/sulfite, Na-HMS with sodium sulfate, and all three sulfur-containing species were prepared and analysed. Hydrogen chloride and sodium hydroxide were used to control the pH of the samples.

2.2 Sample analysis

2.2.1 Aerosol Mass Spectrometry analysis

The Aerodyne high-resolution time-of-flight aerosol mass spectrometer (HR-ToF-AMS) (DeCarlo et al., 2006) was used to determine the mass spectral signatures of Na-HMS, sodium sulfate and bisulfite. The mass spectra of sodium sulfate, sodium bisulfite and sodium HMS were examined, and the concentration of each solution in the atomizer was 10 mM. The pH of the sample solutions was 6. In addition, solutions containing 20% sulfate and 80% Na-HMS, 40% sulfate and 60% HMS, 60% sulfate and 40% Na-HMS, 80% sulfate and 20% Na-HMS were analysed to evaluate the ability of distinguishing the two species at varying

sulfate to Na-HMS ratios. A reference spectrum of ammonium sulfate was also used to investigate the matrix effect. The solutions were atomized by a particle generator (TSI 3076) and subsequently dried before sampled by the AMS. The AMS heater was set in standard operating temperature of 600 °C. The flow was controlled using an atomizer and the mobility particle diameter was selected at 100.0 nm using an electrostatic classifier (TSI 3082).

2.2.2 Ion Chromatography analysis

A Dionex ICS-5000+ Ion Chromatography (IC) system was used to analyse the samples. Two pairs of guard and analytical columns were used. The AG12A-AS12A and the AG22-AS22 pairs (Dionex Ionpac) were selected in order to examine peak separation when columns with different internal coatings (functional groups) are used. The AG22-AS22 column pair was selected due to the fast analysis of inorganic ions that it provides and its general use for main inorganic anion analysis; it is a standard column used for measurement of anions in PM via IC. In addition, the AG12A-AS12A column pair was selected due to its ability to efficiently separate sulfur species. Both column pairs were selected because of the functional group of the analytical column, the hydrophobicity and their efficiency compared to other commercially available columns. The mobile phase during the experiments was 4.5 mM:0.8 mM sodium carbonate: sodium bicarbonate with flow rate 1 $mL \cdot min^{-1}$. The column and compartment temperatures were both 25ºC and the delivery speed and delivery sample volume for the analysis were 4 mL/min and 4 mL. The sample analysis time was 30 min with HMS, bisulfite and sulfate having retention times in the range of 14-16 min.

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3 Results and discussion

3.1 AMS spectra

Samples of sodium bisulfite, sulfate and Na-HMS were analysed individually using the HR-ToF-AMS in order to determine the mass spectral signatures of these compounds (Fig. 1). For Na-HMS organic ions CHO^+ (*m/z*=29.00) and CH_2O^+ (*m/z*=30.01) are observed. However, these organic ions are observed from many organic species (Canagaratna et al., 2015) and are not specific signatures of HMS. In contrast, methanesulfonic acid (MSA) has been shown to have unique marker ions that contain carbon and sulfur, such as $CH_3SO_2^+$ (*m/z*=78.99) and $CH_3SO_3^+$ (*m/z*=94.98) (Phinney et al., 2006; Huang et al., 2016; Chen et al., 2019). The unique fragmentation of MSA is attributed to the carbon-sulfur (C-S) bond. Chen et al. (2019) also reported that a variety of organic sulfate-containing compounds, that have a C-S bond can be distinguished from inorganic sulfate-containing compounds using AMS due to differences in the fragmentation patterns. In contrast, HMS has a sulfur-carbon-oxygen (S-C-O) bond pattern resulting in lower stability of the molecule. The C-S bond of MSA can be retained after ionization whereas the S-C-O bonds of HMS fragment either from desorption or ionization resulting in the unique marker ions of MSA and lack of specific ions for HMS.

Commented [DE21]: Addition of Huang et al. (2016) citation
Comment 4 referee #3

The dominant sulfur-containing $H_xSO_y^+$ ions observed for all samples used in this study were SO^+ (*m/z*=47.97) and SO_2^+ (*m/z*=63.96). Other weaker ions observed in some of the samples include SO_3^+ (*m/z*=79.96), HSO_3^+ (*m/z*=80.96) and $H_2SO_4^+$ (*m/z*=97.97). The fractional contributions of each of these ions relative to the sum of all the $H_xSO_y^+$ is shown in Table 1. The *m/z*=111 ($HOCH_2SO_3^-$), which has been previously assigned as the characteristic parent ion of HMS, is not observed in the AMS spectra due to fragmentation from electron-impact ionization and/or thermal decomposition. As shown in Table 1 and Figure 1, the difference between HMS spectra and those from the other species is the absence of signals corresponding to SO_3^+, HSO_3^+ and $H_2SO_4^+$ for HMS, which are minor fragment ions for the other species. In previous work the fractional contributions of SO^+ and SO_2^+ ions have been used as indicators of the presence of HMS in ambient samples (Ge et al., 2012; Gilardoni et al., 2016; Song et al., 2019). However, as shown in Figure 1, SO^+ and SO_2^+ ions are also the two major fragments of the other species (sodium

bisulfite, sodium sulfate and ammonium sulfate), and thus their presence and fractional contributions cannot be used as unique indicators for HMS. For example, as shown in Table 1, the fractional contributions of SO^+ and SO_2^+ ions in Na-HMS, $NaHSO_3$ and Na_2SO_4 spectra are very similar, making distinction challenging. Figure 2 and Table 1 demonstrate that the only clear distinction is a minor fragment from Na_2SO_4, SO_3^+. However, comparison of the mass-spectra of $(NH_4)_2SO_4$ and Na_2SO_4 reveal that the relative intensity of SO_3^+ depends strongly on the matrix, in this case the cation, as it is three times as large for $(NH_4)_2SO_4$ compared to Na_2SO_4. As seen in Table 1, the fractional contributions of the other $H_xSO_y^+$ fragment ions also depend on the cation. Ammonium sulfate has ion signals at HSO_3^+ and $H_2SO_4^+$ that are not present in any of the other species, but Farmer at al. (~~Farmer et al.,~~ 2010) have shown that organosulfate esters such as the trihydroxy sulfate ester of isoprene can also yield SO_3^+, HSO_3^+ and $H_2SO_4^+$ ions with relative intensities that are very similar to those observed in ammonium sulfate. In summary, these results show that the lack of truly unique fragments in the HMS spectrum makes identification and quantification of HMS concentrations from AMS spectra challenging, at least when analysing complex ambient samples that contain interfering sulfur-species such as inorganic sulfates, organic sulfates and inorganic bisulfite species. The most accurate quantification of HMS concentrations is likely to be derived from samples that are dominated by HMS. Chen et al. (2019) reported the difficulty in distinction of sulfur-species due to similarities in fragmentation patterns, which supports the conclusion of this work. The detection of different sulfur organic compounds with AMS is challenging as the fragmentation patterns only have subtle differences and are sensitive to matrix effects.

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3.2 IC chromatographs

The AG22-AS22 column pair was used to examine the ability to separate HMS and sulfate as well as bisulfite/sulfite and sulfate ions. The AS22 analytical column has the same functional group, alkanol quaternary ammonium, as columns used in previous work for identification of HMS and for ambient analysis during haze events (Munger et al., 1986; Dixon and Aasen, 1999; Wang et al., 2005; Cao et al., 2014; Cheng et al., 2016). The AS22 analytical column provides a direct comparison to this class of columns. The analytical columns can also be classified with respect to the eluent. The types of columns used in previous studies were the Dionex Ionpac AS11, AS11-HC and AS4A where the AS11 and AS11-HC are anion hydroxide columns and the AS4A is an anion carbonate column. The AS22 analytical column (diameter=4 mm and length=250 mm of the column) is also classified as an anion carbonate column. Anion hydroxide columns are columns that require a strong base eluent to maintain their sensitivity. In contrast, anion carbonate columns need a neutral eluent.

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Six samples containing either only sulfate, bisulfite/sulfite, HMS, combination of HMS with bisulfite/sulfite, HMS with sulfate and all three sulfur-containing species were analysed using the AG22-AS22 column pair in a pH range of 3-12. At pH 3-6 the dissolved sulfur dioxide will be in the form of bisulfite (HSO_3^-) and at pH>6 it will be in the form of sulfite (SO_3^{2-}). The three pH values of solution examined were pH=3, 6 and 12 whereas the eluent pH was ~7. In all cases sulfate and HMS or sulfate and bisulfite/sulfite were not clearly separated (Fig. 3, a and b). In addition, HMS and bisulfite/sulfite had the same retention time indicating that their separation is not possible in this system. Each sample analysis was conducted 4 times with individual sample preparation before each analysis. The area of the peaks was almost identical for sulfate and HMS in all 4 runs, with a difference only of 0.06 and 0.08 mM, respectively.

Commented [DE25]: Addition of information regarding the IC analysis
Major comment 2 referee #1

In order to examine the possibility of separating sulfate and HMS we used the AG12A-AS12A column pair. The AS12A analytical column has an alkyl quaternary ammonium functional group. The AS12A analytical column (diameter=4 mm and length=200 mm

of the column) is an anion carbonate column, with respect to the eluent, used to analyse inorganic compounds and has the ability to separate sulfur species. The same samples were analysed under the same conditions and the column achieved efficient separation of sulfate and HMS and also sulfate and bisulfite/sulfite (Fig. 3, c and d). HMS and bisulfite/sulfite were not able to be separated as they had the same retention time in this case as well (Fig. 4). The efficiency and the clear separation of the peaks that the column provides allows for quantification of HMS when bisulfite/sulfite are not present.

Calibration standards were prepared and analysed to determine the retention times (Fig. 5). Each sample was a single component sample containing only one of the sulfur-species. The detection limit of sulfate and HMS was experimentally determined as 0.2 μM and 0.8 μM. The equivalent $ng \cdot m^{-3}$, assuming filter collection of ambient samples with sampling rate of ~80 $L \cdot min$, sampling time of ~6 hr and extraction volume of 20 mL, are ~13 $ng \cdot m^{-3}$ and ~62 $ng \cdot m^{-3}$. The detection limits were determined by conducting sample runs of different concentrations. The concentration, C, for which the IC could not provide a clear peak was identified and samples runs were conducted for concentrations C+n, where n=0.2 mM. The concentration for which the baseline and the peak were clearly distinguishable was defined and 6 runs were conducted for this specific concentration to verify it. The uncertainty was determined, <1%, considering 99% confidence interval therefore it was concluded that for the system used in this work the lowest corresponding concentration, for which a measurable peak was efficiently detected, is the detection limit. Standards were prepared before each experiment to ensure their stability and avoid possible decomposition if stored for a prolonged period of time. The retention time of sulfate was 14.2-15.2 min for the system with the AS22 column and 10.8-11.2 min for the system with the AS12A column. The retention time of HMS was 14.8-15.2 min and 8.8-9.2 min, respectively. Interestingly, for the HMS and bisulfite individual samples a small amount of sulfate was produced, corresponding to 0.4% of the total signal due to oxidation from oxygen.

Comparing the results from the two column pairs, it was determined that for the AS22 analytical column the HMS peak appears slightly after the sulfate peak whereas for the AS12A analytical column the HMS peak appears before the sulfate peak. Using the AS12A analytical column, sulfate represents 55.2% of the total area signal and HMS 44.8% when a sample of 2 mM of HMS and 2 mM of sulfate was analysed. In contrast, for the AS22 analytical column the area signal of sulfate was 63.6% and HMS was 31.8% for both pH=3 and 6. The peaks were connected and there was no baseline separation thus the software automatically separated the peaks by a vertical line at the minimum point between them. The software allows for determination of the baseline which could result in quantification of the compounds by elevating the baseline to the minimum point between the connected peaks and disregarding the area below. When this was applied a significant underestimation of the concentration, ≳15% of HMS with 4% uncertainty, of the compounds was observed, therefore the software automatic separation was selected to be used. The percentages of HMS and sulfate were obtained considering the software separation of the peaks and the underestimation was determined by obtaining the calibration curves for sulfate and HMS and examining known concentrations. If the concentrations are at lower levels, corresponding to ≲30 μM of HMS, value experimentally estimated under laboratory conditions, which is equivalent to ≲2 $\mu g \cdot m^{-3}$, assuming filter collection of ambient samples with sampling rate of ~80 $L \cdot min$, sampling time of ~6 hr and extraction volume of 20 mL, an aliquot of which, 4mL, is used for sample analysis, and sulfate is of equal or higher concentration, the peaks corresponding to HMS and sulfate have lower area signals and will be treated as one peak. For pH=12 the peaks could not be distinguished. Therefore, when the AS22 analytical column was used the sulfate area signal was increased by 8.4% and the HMS area signal was decreased by 13% compared to the case of the AS12A column was used.

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Commented [DE27]: Clarification of LOD determination
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Commented [DE28]: Standard sample preparation statement
Major comment 2 referee #1

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Major comment 5 referee #2

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Considering the intensity of HMS and sulfate for the AS12A in the mixed sample, the intensity of the sulfate and HMS peaks was 26.2 μS·min and 21.3 μS·min, respectively, which is the same when HMS and sulfate samples were analysed individually. In contrast, in the case of the AS22, the intensity of the HMS and sulfate peaks was 13.7 μS·min and 30.2 μS·min, respectively. However, when samples containing only HMS and only sulfate were analysed the intensity was 9.3 μS·min and 33.9 μS·min, respectively. Thus, the intensity of the peak of HMS in the sample that contained both HMS and sulfate was 4.4 μS·min higher compared to the sample that had only HMS. The sulfate peak intensity was 3.7 μS·min lower in the sample that contained both HMS and sulfate compared to the sample that had only sulfate. Thus, the area signal of the sulfate increased but the intensity of the peak was decreased, and the reverse phenomenon was observed for HMS. Considering both the signal contribution and the intensity of the compounds, the results indicate that amounts of both compounds are probably incorporated in both peaks and since we have an increase in the area of sulfate it is more likely that some of HMS is attributed to sulfate in this analysis.

The AS22 and AS12A columns have different technical characteristics (Table 2). The difference in the retention times is due to the functional groups (internal coating) of the columns and thus their ability to separate ions. Sulfate is more polar than bisulfite/sulfite, therefore it is expected to have a stronger binding on the stationary phase (functional group) which results in a longer retention time. HMS and bisulfite/sulfite are not separated as they have very similar polarity. In addition, the AS22 analytical column is longer than the AS12A analytical column, which affects the retention time of the examined compounds. The eluent is also a technical aspect that differs between the two columns. The AS12A is an anion carbonate column, thus the eluent is neutral with respect to the pH, whereas the AS22 column is an anion hydroxide column, thus the eluent is basic with respect to pH. The stability of HMS has a strong pH dependence as it dissociates at high pH values. Therefore, the use of a neutral pH eluent allows to avoid HMS decomposition during analysis. The majority of columns with alkyl quaternary ammonium functional group require neutral pH eluent, which results in efficient separation of sulfur species.

Commented [DE31]: Clarification of eluent pH dependence on the IC analysis
Major comment 2 referee #1

Another factor that can affect the retention time of the compounds is the hydrophobicity of the stationary phase of the column. The AS22 analytical column has ultralow hydrophobicity whereas the AS12A analytical column has medium hydrophobicity resulting in more efficient separation of species within a single family. An ultralow hydrophobicity results in faster retention for non-polar compounds and will cause polar substances of the matrix to accumulate in the column, possible leading to undesirable effects such as misidentification of compounds and shifted retention times. Non-polar compounds will be transferred down the column more readily whereas polar compounds, such as sulfate and bisulfite/sulfite, might not be eluted efficiently by the eluent resulting in unrealistic retention times and peak shapes in the chromatograph. This factor can possibly explain the longer retention time of HMS compared to sulfate when the AS22 column is used, as sulfate has higher polarity than HMS.

4 Conclusion

This study investigates techniques used to identify and quantify HMS and sulfate in PM that contains both species. Two main methods were examined, IC and AMS. HMS and sulfate can be efficiently separated and quantified using an IC system with an analytical column that has an alkyl quaternary ammonium functional group (i.e. AS12A). However, using a column with alkanol quaternary ammonium functional groups (i.e. AS22) quantification of sulfate and HMS is challenging as the peaks are not separated efficiently and they may be identified as one species, typically sulfate. Hence, HMS could possibly be mistaken as sulfate in field measurements. Using an IC system, the detection limit of quantifying HMS and sulfate is 0.8 μM and 0.2 μM, respectively, and the required concentration needed to distinguish HMS and sulfate was determined to be >2 $\mu g \cdot m^{-3}$ of HMS and the sulfate

concentration has to be lower concentration than that of HMS. These sulfur-species can also be distinguished using a variety of mass spectrometry instrumentation if the HMS concentration is high compared to that of other sulfur species present in the analysed sample. However, the fragments that are used for HMS quantification are common to other sulfur-species and are subject to interference from organosulfates and inorganic sulfates. Moreover, this interference can vary with the matrix, in particular cations present in the sample (i.e. Na_2SO_4 versus $(NH_4)_2SO_4$).

Commented [DE32]: Addition of statement regarding the concentration required to separate HMS and sulfate
Major comment 8 referee #2

The results obtained in this study may help explain the case of January 2013 haze event in Northern China (Wang et al., 2014) where models under-predicted sulfate levels compared to observations. During the study of the 2013 haze events, field measurements, analysed using an alkanol quaternary ammonium column, showed 70-90% increased sulfate concentrations compared to the model simulations (Wang at al., 2014), and one explanation that has been proposed is that HMS was quantified as sulfate. Similarly, AMS measurements may have identified HMS as sulfate as explained above. This is also consistent with the explanation provided by Moch at al. (2018) and Song at al. (2019).

Applications of both IC and AMS methods to ~~the same~~ ambient samples from similar conditions of the January 2013 haze event in the future will provide an opportunity to characterize the efficiency of identification and quantification of HMS and sulfate in complex mixtures and the degree to which non-oxidative reactions of SO_2 contribute to ambient PM, especially for low light conditions associated with severe haze events. If HMS is not suspected to be present in field samples, it can be overlooked and possibly misidentified as sulfate.

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Additional comment 17 referee #2

Author contributions. FNK initially conceived of the work. ED developed the specific ion chromatography method described in this work, performed the experiments and analysed the data. CYL and ED conducted the aerosol mass spectrometry experiments and CYL, ED and MRC analysed the data. ED prepared the manuscript with contributions from CYL, MRC, JHK, DRW and FNK.

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

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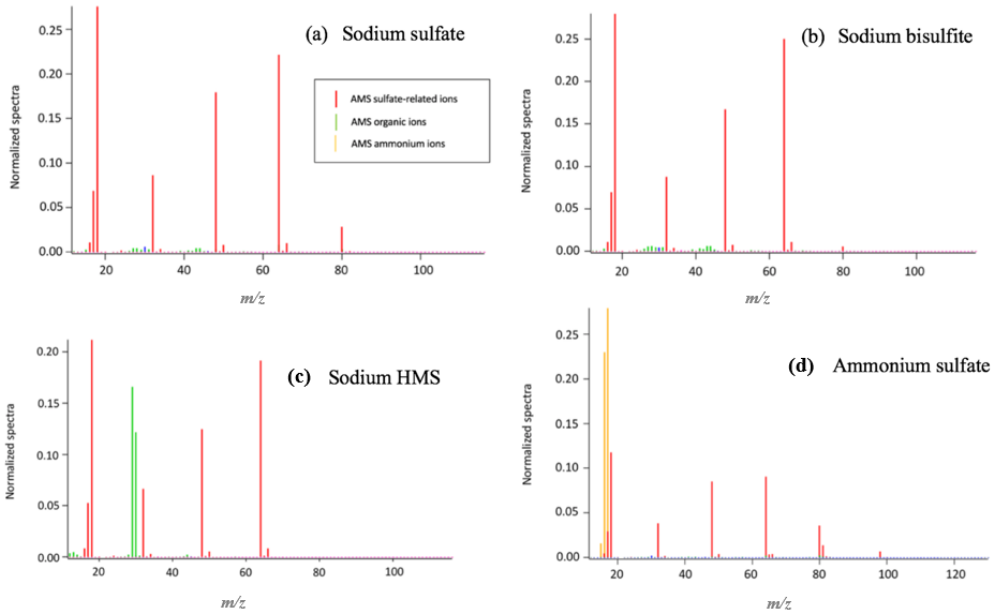

Figure 1: Samples analysis using the HR-ToF-AMS. (a) Sodium sulfate fragmentation. The main peaks are SO^+(*m/z*=48) and SO_2^+ (*m/z*=64). (b) Sodium bisulfite fragmentation. The spectrum is similar to the sodium sulfate spectrum indicating that their distinction is not possible. (c) Sodium HMS fragmentation. The main differences which allow the distinction among HMS, bisulfite and sulfate is the presence of the organic ions and the absence of the SO_3^+ ion (*m/z*=79.96) in the HMS spectrum. (d) Ammonium sulfate fragmentation was used as reference. Similar to (a), (b) and (c) the main ions are SO^+(*m/z*=48) and SO_2^+ (*m/z*=64). Ammonium sulfate is also distinguished from HMS due to the presence of the SO_3^+ ion (*m/z*=79.96), HSO_3^+ ion (*m/z*=80.96) and $H_2SO_4^+$ ion (*m/z*=97.97). The pH of all samples was 6 and the temperature 25 ºC.

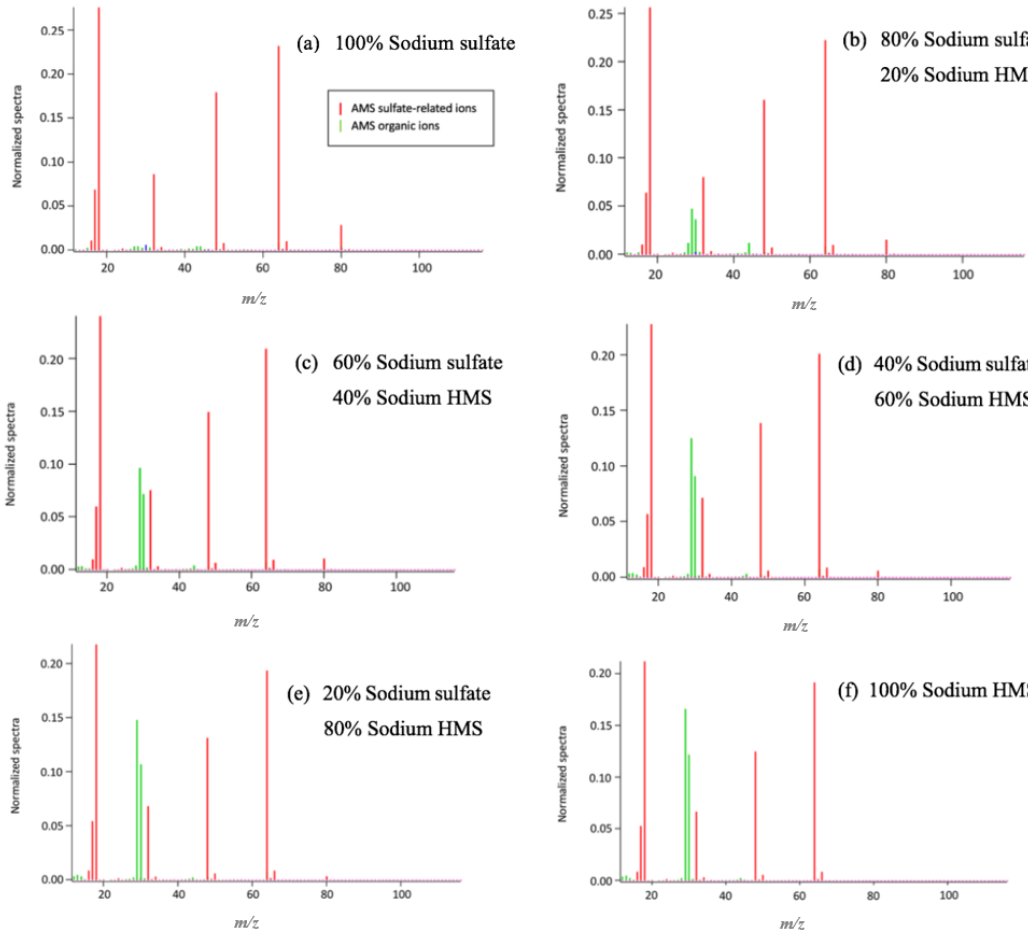

Figure 2: HR-ToF-AMS analysis of aqueous samples containing sodium sulfate and sodium HMS. (a) 10 mM (concentration in the atomizer) of sodium sulfate was analysed to obtain its signature based on its fragmentation. (b) A sample containing 80% sodium sulfate and 20% sodium HMS was analysed. (c) The sample was prepared with 60% of sodium sulfate and 40% of HMS. Consecutively, (d) presents the fragmentation of a sample with 40% sodium sulfate and 60% sodium HMS, (e) 20% sodium sulfate and 80% sodium HMS and (f) the fragmentation of 10 mM HMS sample. Increase of the concentration of HMS results in the increase of the organic ions and the decrease of the SO_3^+ ion (*m/z*=79.96). The dominant ions, SO^+(*m/z*=47.97) and SO_2^+ (*m/z*=63.96), seem to remain constant. The pH of all samples was 6 and the temperature 25 ºC.

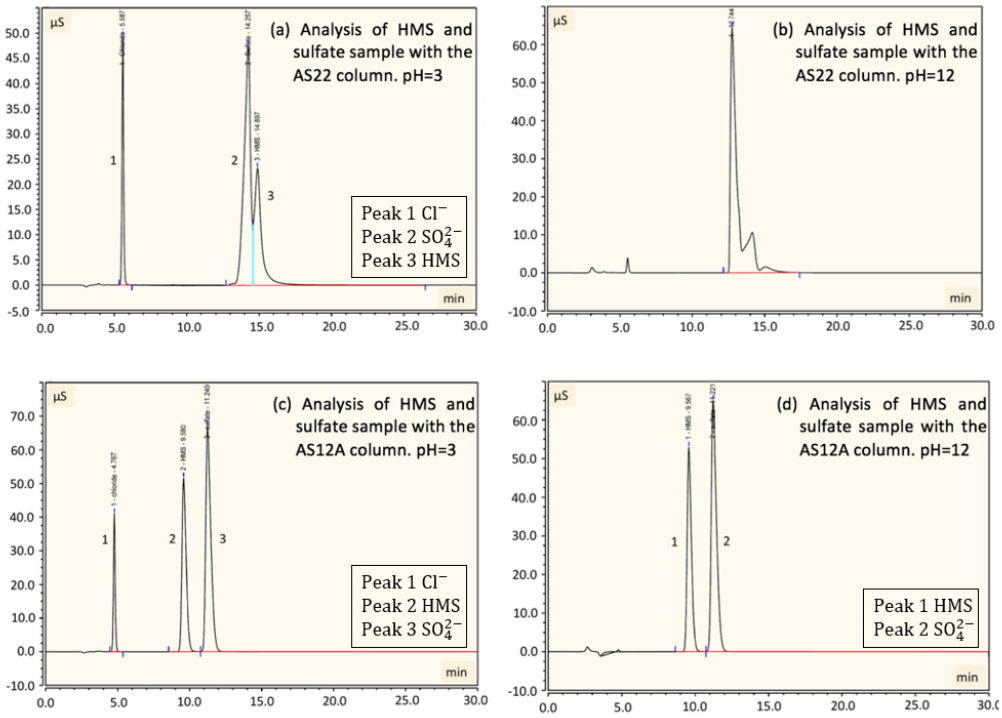

Figure 3: Detection and separation of sulfate and HMS using two ion chromatography systems. The first system, corresponding to (a) and (b), had an AG22 guard column and AS22 analytical column (alkanol quaternary ammonium functional group) and the second system, corresponding to (c) and (d), had an AG12A guard column and an AS12A analytical column (alkyl quaternary ammonium functional group). (a) A sample of 2 mM of HMS and 2 mM of sulfate at pH=3 was analysed using the AG22-AS22 column pair. Peak 1 represents the chloride at 5.6 min, as HCl was used to acidify the solution, peak 2 represents the sulfate at 14.3 min and peak 3 represents the HMS at 14.9 min. The separation of sulfate and HMS is not efficient. (b) The same analysis was performed at pH=12 indicating that the column fails to provide clear peaks in basic pH. The analysis was repeated using the AG12A-AS12A column pair in acidic (pH=3, (c)) and basic (pH=12 (d)) conditions. (c) Peak 1 represents the chloride at 4.8 min, peak 2 represents the HMS at 9.6 min and peak 3 represents the sulfate at 11.2 min. (d) Peak 1 represents the HMS at 9.6 min and peak 2 represents the sulfate at 11.2 min. The results indicate that the column separates efficiently the two species in both the cases of pH=3 and pH=12.

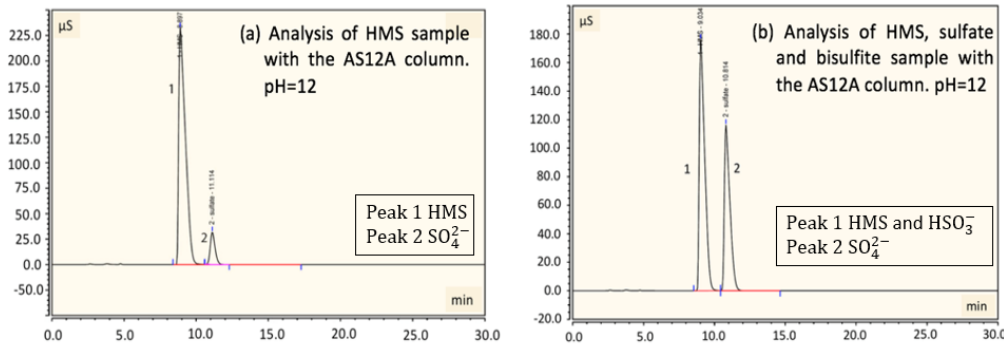

Figure 4: Detection and separation of HMS and sulfate using an ion chromatography system with AS12A analytical column and AG12A guard column. (a) A sample of 2 mM of HMS at pH=12 was analysed. A small amount of sulfate is produced due to oxidation by oxygen. The column separates efficiently HMS and sulfate. Peak 1 represents the HMS at 9.6 min and peak 2 represents the sulfate at 11.2 min. (b) A sample of 2 mM of HMS, 2 mM of sulfate and 4 mM of bisulfite at pH=12 was analysed. Peak 1 represents the HMS at 9.0 min and peak 2 represents the sulfate at 10.8 min. The separation of sulfate and HMS is efficient; however, separation of bisulfite and HMS was not possible. Samples were examined at pH=3 and 6 as well with similar separation efficiency as the aforementioned samples.

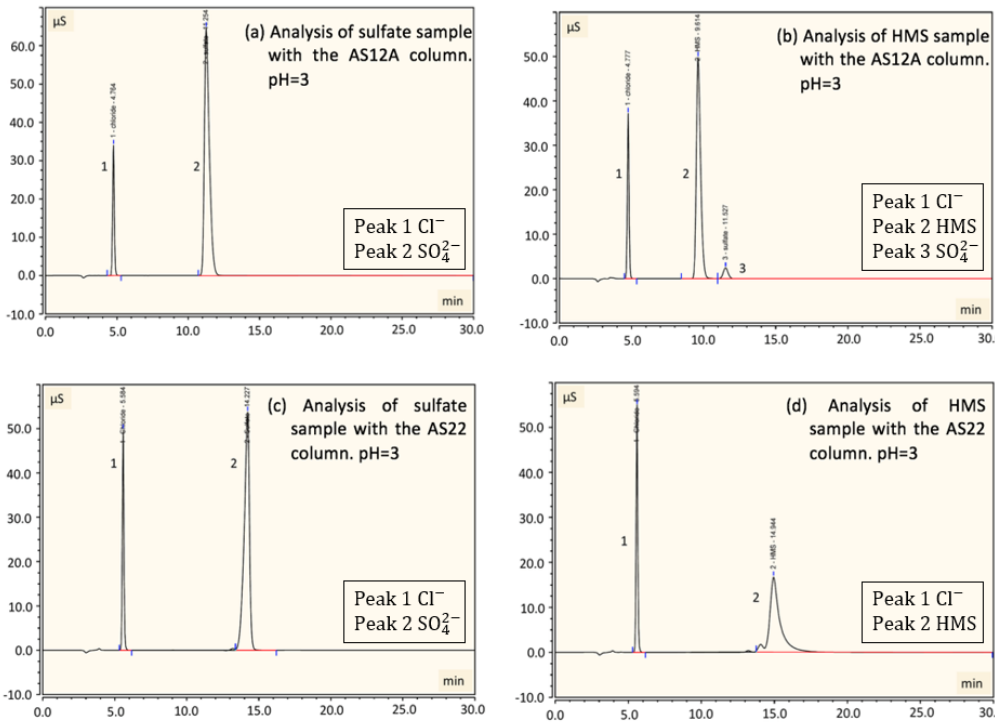

Figure 5: Sample analysis of sulfate and HMS using two ion chromatography systems. The first system, corresponding to (a) and (b), had an AG12A guard column and an AS12A analytical column (alkyl quaternary ammonium functional group) and the second system, corresponding to (c) and (d), had an AG22 guard column and AS22 analytical column (alkanol quaternary ammonium functional group). The pH was acidic (pH=3) and all samples were in room temperature (25 ºC). (a) A sample of 2 mM of sulfate was analysed using the AG12A-AS12A column pair. Peak 1 represents the chloride at 4.8 min, as HCl was used to acidify the solution, and peak 2 represents the sulfate at 11.3 min. (b) A sample of 2 mM of HMS was analysed using the AG12A-AS12A column pair. Similarly, peak 1 represents the chloride at 4.8 min and peak 2 represents the HMS at 9.6 min. Interestingly, a 0.4% of HMS is oxidized by oxygen, resulting on the production of sulfate (peak 3). (c) A sample of 2 mM of sulfate was analysed using the AG22-AS22 column pair. Peak 1 represents the chloride at 5.6 min and peak 2 represents the sulfate at 14.2 min. (d) A sample of 2 mM of HMS was analysed using the AG22-AS22 column pair. Similarly, peak 1 represents the chloride at 5.6 min and peak 2 represents the HMS at 14.9 min. Both systems provide efficient identification of sulfate and the chromatographs represent sulfate with a smooth shaped peak. In addition, both systems identify HMS; however, the system with the AG22-AS22 column pair indicates that the quantification of HMS might not be possible due to the discontinuous shape of the peak.

Table 1: Fractional contributions of SO^+, SO_2^+, SO_3^+, HSO_3^+ and $H_2SO_4^+$ to the sum of their intensities in AMS spectra.

Sample	SO^+ fraction (m/z=47.97)	SO_2^+ fraction (m/z=63.96)	SO_3^+ fraction (m/z=79.96)	HSO_3^+ fraction (m/z=80.96)	$H_2SO_4^+$ fraction (m/z=97.97)
Sodium sulfate (Na_2SO_4)	42%	56%	2%	0%	0%
Sodium bisulfite ($NaHSO_3$)	38%	62%	0%	0%	0%
Na-HMS	40%	60%	0%	0%	0%
Ammonium sulfate ($(NH_4)_2SO_4$)	45%	46%	6%	2%	1%
80% Na_2SO_4 and 20% NaHMS	42%	57%	1%	0%	0%
60% Na_2SO_4 and 40% Na-HMS	42%	57%	1%	0%	0%
40% Na_2SO_4 and 60% Na-HMS	35%	65%	0%	0%	0%
20% Na_2SO_4 and 80% Na-HMS	40%	60%	0%	0%	0%

5 **Table 2: Technical characteristics of the columns used for the ion chromatography analysis.**

Analytical column	Guard column	Functional group	Eluent classification	Analytical column diameter (mm)	Analytical column length (mm)	Hydrophobicity
AS22	AG22	Alkanol quaternary ammonium	Anion carbonate	4	250	Ultralow
AS12A	AG12A	Alkyl quaternary ammonium	Anion carbonate	4	200	Medium