

## Response to Reviewers of:

**“Evaluation of the Chemical Composition of Gas and Particle Phase Products of Aromatic Oxidation” by Archit Mehra et al., 2020, submitted to ACP**

### General Response

We thank the reviewers for their comments, helping us to clarify ambiguities and further improve the manuscript. Referee #1 states that the manuscript provides potentially useful information however they have some concerns about how representative the experimental conditions are. Referee #2 feels the work is valuable as it identifies a series of missing highly oxidised products from current mechanisms.

### Overall Content and Scope

The manuscript aims to provide a detailed characterisation of product distributions from the oxidation of a range of aromatic VOCs. The manuscript did not aim to relate in any way the observed ion signal strengths to concentrations, yields or act as a surrogate for these. As such, the comparison with the master chemical mechanism was solely based upon potential products which could be formed, and the model simulation itself was not run as the purpose of this study was not to make any quantitative comparison with yields estimated by the MCM. We feel that both reviewers have slightly misunderstood this, which we recognise could be a reflection of the way in which the manuscript has been written. To address this, we have made changes to make the aims clearer and added explicit clarification that we do not link the ion signals observed directly to product yields.

### Anonymous Referee #1

#### Received and published: 10 April 2020

We thank the referee for their detailed and helpful comments that we have used to clarify and improve the manuscript. As is stated above the main comments have stemmed from misunderstanding that the paper was investigating yields and hence required us to be explicit about the relationship between ion signals and concentrations and also the actual experimental conditions associated with implementing an MCM model run. As we have stated above we were not seeking to do this in the paper and have clarified this in the paper explicitly to address future misinterpretation. We have carefully addressed the referee's well considered comments.

*This paper reports results of mass spectral analyses of gas- and particle-phase products formed in the reactions of several C9 alkylbenzenes and 1-methyl naphthalene with OH radicals in the presence and absence of NOx. The products are identified by mass and the atomic numbers corresponding to the masses, but other structural information is not provided. A large number of products are observed, with carbon numbers ranging from 2 to the number of carbons in the starting compound, and although the product distributions differ depending on the compound and NOx levels, the contributions of products that are unique to any given compound are relatively small. The product distributions are discussed in terms of extent of oxidation, whether the product is likely to be*

*from fragmentation or ring retaining (based on atom numbers), the extent to which the products are consistent with MCM, and how the product distributions compare with what is observed in the atmosphere.*

*This paper gives potentially useful information on products formed from aromatics, but I have some concerns about how representative the experiments are of atmospheric conditions and the correspondence between the ion signals and actual product yields.*

Comments relating to how representative the experiments are of atmospheric conditions have been addressed in detail below. The referee also comments on the correspondence between ion signals and actual product yields - as we have already stated above, this was not the aim of the study and we have added additional clarification of this within the manuscript.

*In addition, I think the presentation and discussion of the results could be improved, especially with regard to mechanistic implications. The major issues I see are discussed below, followed by a summary of other issues or suggestions.*

We have addressed these points in turn below.

### **Major comments**

*There should be more discussion of how their experimental system differs from the atmosphere, and also the extent of secondary reaction of products formed. Can the very low wavelength UV light they use to generate the radicals (and NOx) photolyse the reactants or products and cause products to be formed that would not be formed in the lower atmosphere or deplete products that otherwise be important?*

The potential of the low wavelength UV light used to generate radicals to photolyse the reactants has been determined through calculation of the potential non-OH fates of the VOCs in the experimental system. These have been determined for the VOCs for which photolysis data exists (1-methyl naphthalene, 1,3,5-trimethyl benzene and 1,2,4-trimethyl benzene). The photolysis yields from these species are minor under the conditions used in this study, with reaction with OH contributing 99.5 %, 98.3 %, 99.9 % of the fate of 1,3,5-trimethyl benzene, 1,2,4-trimethyl benzene and 1-methyl naphthalene, respectively. Sufficient literature data on the photolysis of propyl and isopropyl benzene is not available and thus these estimates cannot be produced. However, we anticipate that their loss, like that of the other substituted aromatics is also dominated by OH oxidation under the conditions operated in these experiments. On this basis we conclude that photolysis is not important for the reactions of aromatic VOC in this study. The referee also asks about the potential for non-representative product photolysis or non-OH depletion of products. As has been discussed at length in the recent extensive review by Peng & Jimenez, 2020 and in Peng et al. 2016, the effect of non-representative UV photolysis of products or intermediates is very difficult to fully characterise as quite simply there is scarcity of data available. We thus conclude that despite this shortcoming there is no substantial evidence for large mechanistic differences and OFRs provide a useful tool for studies of this type.

We have added the following into the methodology to clarify this:

“The use of non-tropospheric low wavelength UV light to generate radicals in OFR can result in the potential photolysis of reactants. However, operational conditions can be optimised to ensure OH loss is the dominant removal process of the VOC (Peng et al., 2016; Peng & Jimenez, 2020). In this study, under the conditions used > 98 % the loss of VOC can be attributed to reaction with OH. This is based on calculations under the relevant conditions for 1,3,5-trimethyl benzene, 1,2,4-trimethyl benzene and 1-methyl naphthalene for which photolysis rate data exist. The relevant photolysis data does not exist for propyl benzene and isopropyl benzene and thus, to the extent that results for the TMBs and methyl naphthalene are also applicable to propyl and isopropyl benzene, we anticipate that their loss is also dominated by OH oxidation. The photolysis of products or intermediates are more difficult to fully clarify, as discussed in Peng et al. (2020) and thus the practical approach taken here is to optimise the OH oxidation to ensure that OH loss is the dominant pathway for the VOCs themselves. ”

*They give an "OH exposure" number for their experiments and state that it is similar to "Chinese megacities", but they do not give the range of OH exposure numbers in Chinese cities or elsewhere or citations for them.*

We have added a reference to (Lu et al., 2019) and inserted the following sentence:

“For example, OH concentrations in Beijing can reach as high as  $\sim 1 \times 10^7$  molecules  $\text{cm}^{-3}$  (Bryant et al., 2019), an order of magnitude higher than the global average of  $\sim 1 \times 10^6$  molecules  $\text{cm}^{-3}$  (Lelieveld, Gromov, Pozzer, & Taraborrelli, 2016) which is used to relate OH exposure in an OFR to days of equivalent atmospheric oxidation (Lambe et al., 2015). This changes what would be 11 days of equivalent atmospheric oxidation in the OFR under global average OH concentrations to just over 1 day of oxidation in Beijing.”

*What is the fraction of initially present aromatic hydrocarbon that reacts during an experiment?*

As discussed above, this study was focused upon product distribution and not yields thus the fraction of aromatic hydrocarbon reacted has not been quantified, and is not required for interpretation of the results presented in this manuscript.

*Do they have an estimate of how much of observed products are from multi-generations of reaction?*

We have made a lower bound estimate of this and added the following to the paper:

“Molteni et al. (2018) suggested that ring-retaining products with ion formulas containing 4-6 more hydrogen atoms more than their parent hydrocarbon could be attributed to multiple-OH attacks. More recently, Tsiligiannis et al. (2019) has shown that  $\text{C}_9\text{H}_{14}\text{O}_2$  products from the oxidation of 1,3,5-trimethyl benzene have characteristics of second generation products owing to their enhanced contributions in experiments with higher OH exposures. Thus, in order to obtain a lower bound estimate of the contribution multi-generational OH attack, ions with 4-6 more hydrogen atoms than the parent hydrocarbon were classed as multi-generational products. Overall their contribution to signal is < 10 % in all experiments (Figure S5– S6).”

Added to supplement:

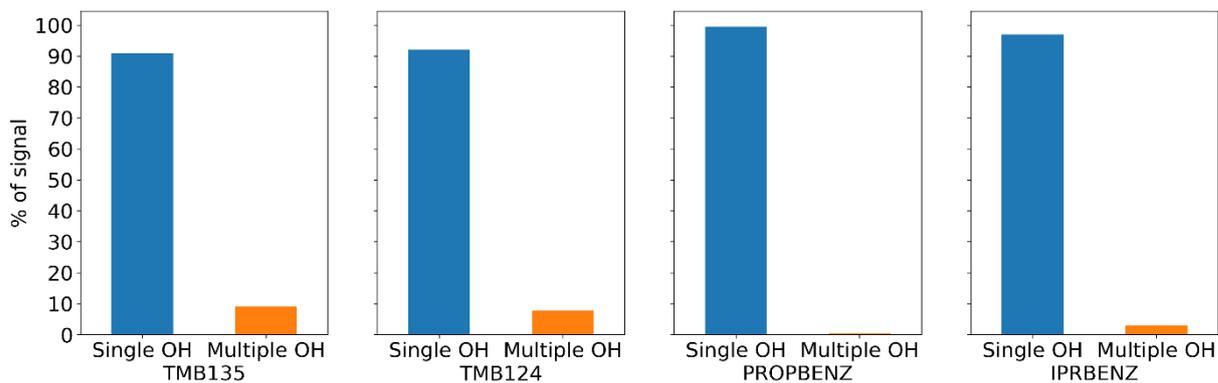


Figure S5 – Signal contribution from ions associated with multiple generations of reaction with OH under low-NO<sub>x</sub> conditions, defined as ions which contain > 4 hydrogen atoms more than the VOC precursor species (14 in all cases)

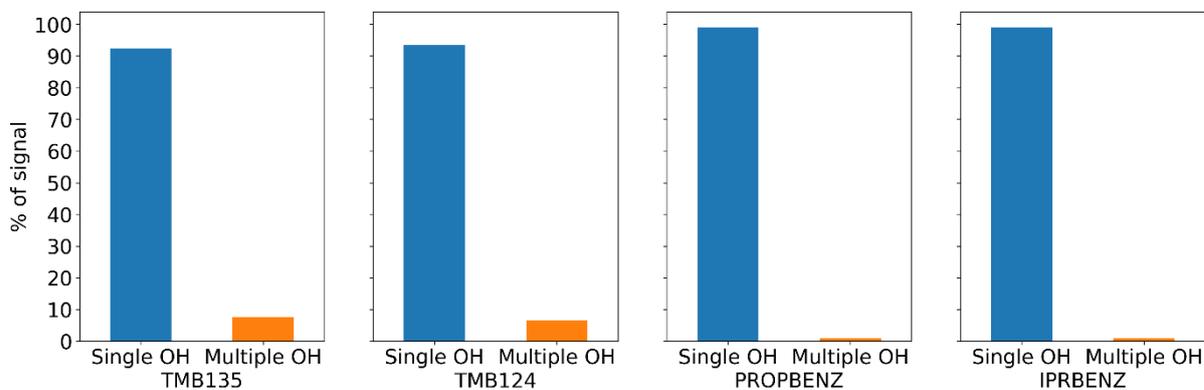


Figure S6 – Signal contribution from ions associated with multiple generations of reaction with OH under med-NO<sub>x</sub> conditions, defined as ions which contain > 4 hydrogen atoms more than the VOC precursor species (14 in all cases)

*Have they attempted to model their experimental conditions to obtain information about representativeness?*

The objective in this work was not to look at yield comparisons under different conditions, but rather understand the range of product distributions comparing those observed experimentally with those defined in the current version of the MCM, therefore no modelling was performed. Comparison with the MCM was with that of all potential products output in the subset mechanisms, and thus not related to any given experimental condition, but to act as a benchmark of current scientific understanding of the aromatic chemical mechanisms within the MCM.

*The major results are presented primarily as figures giving fractions of ion signals that have various characteristics, plus some summary information given in the text. The paper has a "Supplementary Data" (SD) section to give additional information, and ideally it should have the information that is summarized or shown*

*graphically in the text, so the reader can examine it in more detail, to either to verify the discussion in the paper or perhaps to gain other insights. The SD does have 20 tables giving the "top 20" product distributions for each of the 2 types of experiments with 2 analysis methods and 5 compounds, but it only has the information regarding the ion detected and true/false flags indicating whether it is common or unique among the compounds studied and whether it has the same molecular formula as a product predicted by MCM. That is not the most interesting information they could present. These tables should include at least the relative ion signal intensity, and ideally also the classifications as ring-scission, ring-retaining, HOM, DBE, and other classifications they discussed or summarized. Instead of just indicating that this may be predicted by MCM, they should give the name and structure of the products(s) corresponding to this molecular weight. This would make the tables much more interesting and greatly increase the value of this work and information content of the paper.*

Tables with this additional information have been included in a revised supplement. Structures have not, however been included as we feel these may be misleading as the mass spectrometry techniques used in this study cannot distinguish structures.

*The discussion of MCM and mechanistic implications could be improved. It is not surprising that MCM does not predict the full range of products they observe, especially HOM, because (1) the version of MCM that is currently online does not have autooxidation reactions that are now believed to be important, and (2) it employs lumping or reduction methods when it gets to 3+ generation products of the compounds represented. What might be more interesting would be high yield products that MCM predicts that they DO NOT observe. These should be listed, or it should be stated that there are no such products if that is in fact observed. One way to do this would be to run MCM to model the conditions of the experiments, summarize the yields predicted, and list these against the observed relative ion signals of products with the same molecular weight in the experiments. Are the products observed more consistent with the revised mechanisms predicted by Wang et al (2017)?*

The referee provides suggestions of how our discussion of MCM and mechanistic implications can be improved. We agree that it is not surprising that the MCM does not predict the full range of products, especially HOM and describe the comparison with MCM as a benchmark against which observations can be compared in 4.1.1. As the MCM itself was not run for these simulations, owing to the objectives of this study not being to describe yields but instead product distributions, the high products cannot be distinguished. We have, however include a list of the ions within the MCM that are not observed in these experiments in the supplement as suggested.

The closed shell products of C<sub>9</sub>H<sub>12</sub>O<sub>6</sub> and C<sub>9</sub>H<sub>12</sub>O<sub>8</sub> observed in Wang et al. 2017 are consistent with our observations from the aromatic systems. We have added this clarification in section 4.2.2.

*The tables in the SD indicate that no signals were observed for glyoxal (C<sub>2</sub>H<sub>2</sub>O<sub>2</sub>), which is known to be formed in significant yields from all products (and is predicted by MCM). Also, methyl glyoxal (C<sub>3</sub>H<sub>4</sub>O<sub>2</sub>) should also be seen as a product from the trimethylbenzenes and propyl glyoxal (C<sub>5</sub>H<sub>8</sub>O<sub>2</sub>) should be formed from propyl benzene. Does this method not work for alpha-dicarbonyls? If so, state this. Or are they all rapidly photolyzed away by the high UV in their system? This gives me some doubt about the credibility of the experimental system.*

Glyoxal explanation added:

“It should be noted that glyoxal, a major product from aromatic oxidation is detected by the Vocus as  $C_3H_3O_2^+$  which is dominated in these experiments by protonated acetone. The sensitivity of glyoxal in PTR is almost one tenth of that of acetone, and furthermore  $C_3H_3O_2^+$  can also be influenced by fragmentation, and thus is not included in the analysis herein (Pang et al., 2014; Stönnner, Derstroff, Klüpfel, Crowley, & Williams, 2017; Thalman et al., 2015).”

Methylglyoxal explanation added:

“It should be noted that this mass range omits methyl glyoxal, a dominant product of aromatic oxidation, which was observed by Vocus in all experiments.”

Propyl glyoxal is observed and already exists within the supplement of the paper as detected, except for propyl benzene in which it is observed but is not within the Top 20 dominant ions.

*It is stated that they did not correct for sensitivity of the ion signals to the actual concentrations in their analyses, apparently because of the complexities involved. However, since they are using the ion signal as a surrogate for the yields, it would be useful to estimate the uncertainty or potential for error when not making this correction.*

As previously outlined, we are not using the ion signal as surrogate for yields, as is suggested by the referee, and thus we cannot put uncertainty estimates upon a relationship we are not defining. We are aware of the significant uncertainties in relating ion signal to yields and thus have taken the approach of comparing product distributions in this manuscript. Thus, we deem it not necessary to estimate the error when correcting for sensitivities, when this data is not presenting the results as quantitative yields.

We have added a statement to the methodology to clarify this misunderstanding:

“It should be noted that we have not attempted to relate ion signals to yields and thus the comparison of ion signals in this study should not be assumed to be related to quantitative product yields derived from models such as those implementing mechanisms including the MCM. ”

## **Other Comments**

*The abstract should state what they mean by "product signal" and describe the analysis methods in a few words.*

Added:

“A time-of-flight chemical ionisation mass spectrometer (ToF-CIMS) with iodide-anion ionisation was used with a filter inlet for gases and aerosols (FIGAERO) for detection of products in the particle phase, while a Vocus proton transfer reaction mass spectrometer (Vocus-PTR-MS) was used for detection of products in the gas phase. The signal of product ions observed in the mass spectra were compared for the different precursors and experimental conditions. “

The statement in the abstract that the MCM "highlights" missing product pathways, but it is not clear from that statement if it is the MCM that is missing something (which is the case), or the experiments aren't finding something that MCM predicts (which may or may not be the case – see comments above – but is probably not what the authors meant to say).

Rephrased:

"Ions corresponding to products contained in the near explicit gas phase Master Chemical Mechanism (MCMv3.3.1) are utilised as a benchmark of current scientific understanding, and comparison of these with observations shows that the MCM is missing a range of highly oxidised products from its mechanism."

The observation that "A large proportion of the ring scission products observed in the particle phase are more oxidised than those previously reported" is significant and should be included in the abstract.

Thank you for noting this. The text in the abstract has been rephrased to include:

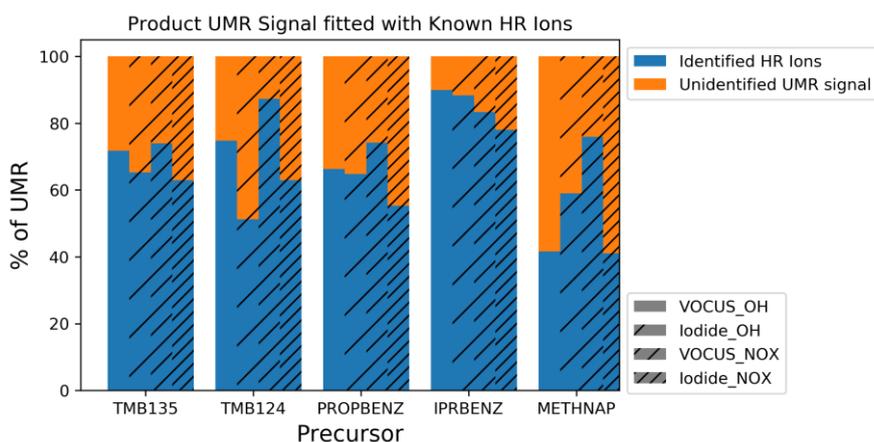
"In the particle phase, the bulk of product signal from all precursors comes from ring scission ions, a large proportion of which are more oxidised than previously reported and have undergone further oxidation to form highly oxygenated organic molecules (HOM)."

Was there only a single experiment of each of the 10 types listed on Table 1, or are the concentrations given there the averages of several experiments. If the latter, indicate the number of experiments?

Rephrased:

"VOC concentrations during single experiments for each precursor"

The legend on the top right on Figure 1 should be moved to where it doesn't get in the way of the data being shown.



The labels indicating the compounds on Figure 3 need to be larger and easier to read. Right now they are in a very tiny font hugging the axes and are hard to see.

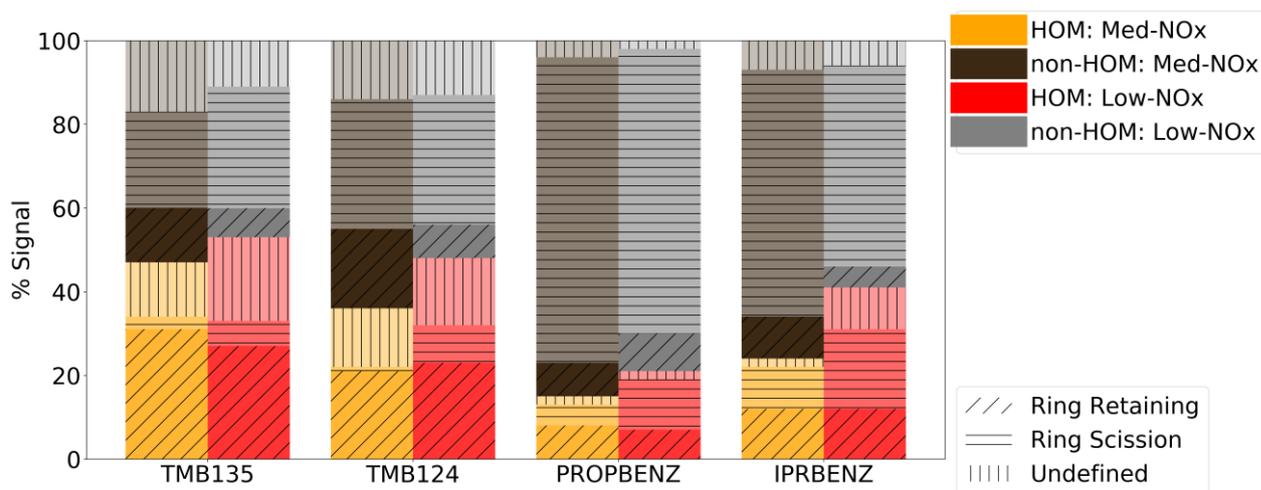
These have been amended.

Could they use a different color on Figure 3 to indicate N-containing ions?

As we state on lines 308-310 of the revised manuscript, specific N-containing ions have not been included in further analysis due to potential contributions from thermal decomposition, thus we feel it is not relevant to include these in the figure.

Table 2 would have more impact if it were shown as a bar-plot figure. It clearly shows *n*-propyl benzene as an outlier among the alkylbenzenes in terms of NO<sub>x</sub> effects. (I would have thought isopropyl benzene would be more likely the outlier, since the autooxidation proposed by Wang et al (2017) may be more important for this compound.) It might be useful to also include their estimates of ring-retaining and ring-scission fractions on this same table or figure, since there are also discussed in the text.

We would like to thank the reviewer for bringing our attention to this insightful figure, since not only has the new figure improved clarity, it has enabled us to find an error in the Table itself for the HOM contribution in the 1,3,5-trimethyl benzene experiments. This does not influence the conclusions of the manuscript itself as HOM from 1,3,5-trimethyl benzene was high in both the table and in the Figure now presented. An improved figure has now been included, which improves the mechanistic insights through combining the ring-retaining and ring-scission classifications with those of HOM and non-HOM to enable all key features of the systems to be observed. The detailed proportions have been amended accordingly through the text.



It is not clear what is the purpose of table 3, giving MCM branching ratios for various types of reactions, since they give no comparison of this with their data. If they can identify their products by the classifications on this

*table, why don't they give the relative amounts derived from their data? If not, why include this table and discussion?*

This table was presented to provide a context for the mechanistic discussions, however has now been removed.

The "Authors Contributions" section does not list all the authors.

As we have made clear in the author contributions, all authors contributed to discussions of the results and comments on the manuscript. We have included explicit reference where people had explicit role. We hope this is acceptable. We can list all authors under the contribution to the manuscript but we feel this would be less clear to read.

The supplement document does not identify the title, authors, and journal of the manuscript it goes with.

This has been added into the supplement.

## **Anonymous Referee #2**

### **Received and published: 16 April 2020**

We thank the referee for their comments which we have used to improve the manuscript. As is stated above, the main comments are relating to a misunderstanding that the paper was comparing yields derived from the MCM, and this has been clarified in the paper to address this. Below we address the referee's specific comments.

*Archit Mehra and co-workers conducted the evaluation of the chemical composition of gas and particle phase products of aromatic oxidation. Gas and particle phase composition are compared with the simulation results by Master Chemical Mechanism (MCMv3.3.1). This work highlights a series of missing highly oxidized products in the pathways. The work is therefore valuable in this regard. The article can be published once the authors have addressed the following points.*

*1. Line 31: "HOMs" Abbreviations should be given their full names when they first appear. Also, for Line 47 "SAPRC".*

Move full names from line 33 to line 31.

Inserted:

"the Statewide Air Pollution Research Center of the University of California in Riverside (SAPRC) mechanism" and (Carter, 1988) reference.

2. For the experiment of 1-methylnaphthalene: why the mixing ratio of VOCs is lower than other experiments? And for each VOCs, the experiments were conducted only once? If not, in all the experiments the mixing ratio of VOCs was controlled uniformly?

A lower VOC mixing ratio was required in this experiment to obtain appreciable SOA mass. The experiments were only conducted once.

Changed caption of Table 1:

“Table 1 - VOC concentrations during single experiments for each precursor”

Added explanation of different VOC concentrations:

“Their concentrations (Table 1) were optimised to obtain similar aerosol mass concentrations in the different experiments.”

3. Line 141: what is the “PFA”?

Line 141 Inserted: “perfluoroalkoxy alkane (PFA)”

4. Line 144: you should change the “N2” into “N<sub>2</sub>”, and you should check the paper to avoid the similar error.

Line 144 Inserted: “N<sub>2</sub>” subscripted. Checked all paper for N2 and replaced with “N<sub>2</sub>”

5. Figure 2: What is the ordinate?

Insert Y-Axis Label: “Ion Counts”

6. Figure 3, Figure 4: The quality of images needs to be improved.

Made axis labels clearer and larger in line with reviewer 1’s comments also.

7. Line 273: how to identify the C<sub>4</sub>H<sub>6</sub>O<sub>2</sub> and C<sub>4</sub>H<sub>8</sub>O<sub>3</sub>? Give the spectrum information.

Added to supplement as Figures S6-S7.

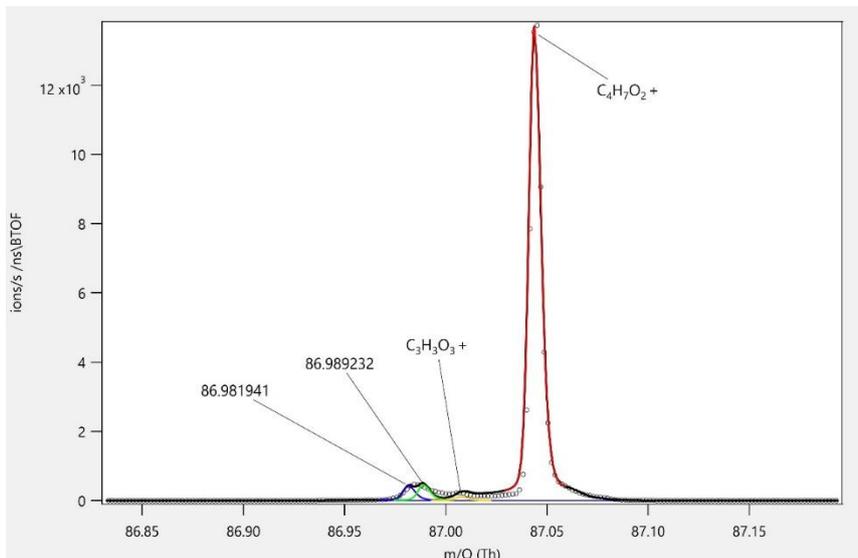


Figure S6 – High resolution peak fit of the ion  $C_4H_7O_3^+$  corresponding to  $C_4H_6O_3$  detected by Vocus

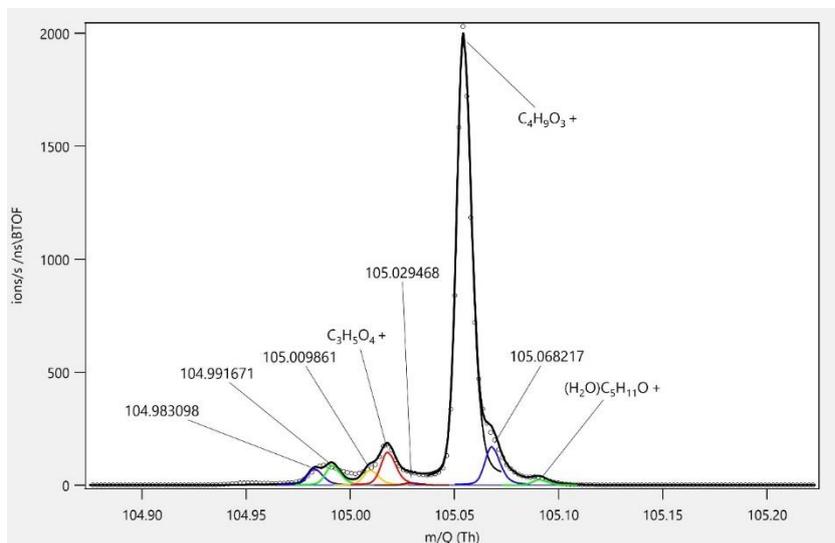


Figure S7– High resolution peak fit of the ion  $C_4H_9O_3^+$  corresponding to  $C_4H_8O_3$  detected by Vocus

8. Line 277-278: “with a small reduction in the fraction of C4 product ions and an increase in C2 product signal” what is the reason?

The ion contributing to this has been added to the discussion:

“Under medium- $NO_x$  conditions, the dominant gas phase ions are consistent with those produced under low- $NO_x$  conditions and the product signal shows a broadly similar distribution to the medium- $NO_x$  conditions, with a small reduction in the fraction of C4 product ions and an increase in C2 product **signal which can be attributed to an increase in  $C_2H_4O_3$ .**”

9. In this paper, are there any new mechanism that could optimize the MCM? When the missing highly oxidized products were considered in MCM, is there any difference between simulation and experiments?

The reviewer here has interpreted that the conditions in the OFR were modelled using the MCM mechanisms, which as highlighted above was not the case. A sentence of additional clarification is added:

“Note that models incorporating MCM chemistry were not run for any particular conditions for these comparisons, instead the potential products included in the detailed MCM aromatic chemical mechanisms were simply compared with the ions observed in this study.”

New mechanistic details which could optimise the MCM are described in a companion paper (Wang et al. 2020). This has been referenced the paper:

“A companion paper provides more detailed discussion of the mechanisms responsible for formation of the dominant oxidised products from these precursors (Wang et al., 2020) .

# Evaluation of the Chemical Composition of Gas and Particle Phase Products of Aromatic Oxidation

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## Abstract

Aromatic volatile organic compounds (VOC) are key anthropogenic pollutants emitted to the atmosphere and are important for both ozone and secondary organic aerosol (SOA) formation in urban areas. Recent studies have indicated that aromatic hydrocarbons may follow previously unknown oxidation chemistry pathways, including autoxidation that can lead to the formation of highly oxidised products. In this study we evaluate the gas and particle phase ions formed during the hydroxyl radical oxidation of substituted C<sub>9</sub>-aromatic isomers (1,3,5-trimethyl benzene, 1,2,4-trimethyl benzene, propyl benzene and isopropyl benzene) and a substituted polyaromatic hydrocarbon (1-methyl naphthalene) under low and medium NO<sub>x</sub> conditions.

A time-of-flight chemical ionisation mass spectrometer (ToF-CIMS) with iodide-anion ionisation was used with a filter inlet for gases and aerosols (FIGAERO) for detection of products in the particle phase, while a Vocus proton transfer reaction mass spectrometer (Vocus-PTR-MS) was used for detection of products in the gas phase. The signal of product ions observed in the mass spectra were compared for the different precursors and experimental conditions. The majority of mass spectral product signal in both gas and particle phases comes from ions which are common to all precursors, though signal distributions are distinct for different VOCs. Gas and particle phase composition are distinct from one another. Ions corresponding to products contained in the near explicit gas phase Master Chemical Mechanism (MCMv3.3.1) are utilised as a benchmark of current scientific understanding, and comparison of these with observations shows that the MCM is missing a range of highly oxidised products from its mechanism.

In the particle phase, the bulk of product signal from all precursors comes from ring scission ions, a large proportion of which are more oxidised than previously reported and have undergone further oxidation to form highly oxygenated organic molecules (HOM). Under perturbation of OH oxidation with increased NO<sub>x</sub>, the contribution of HOM ion signals to the particle phase signal remains elevated for more substituted aromatic precursors. Up to 43 % of product signal comes from ring-retaining ions including (HOMs); this is most important for the more substituted aromatics. Unique products are a minor component in these systems, and

many of the dominant ions have ion formulae concurrent with other systems, highlighting the challenges in utilising marker ions for SOA.

## 1 Introduction

45 Volatile Organic Compounds (VOCs) are emitted from both natural and anthropogenic sources and their oxidation in the troposphere is important for reactive chemistry leading to ozone (Atkinson, 2000; Derwent et al., 1998) and secondary organic aerosol (SOA) formation (Ziemann et al., 2012). This can have severe air quality, environmental and health impacts (Hallquist et al., 2009). Globally, VOCs such as isoprene have been estimated to be the largest contributors to SOA formation (Guenther et al., 1995; Simpson et al., 1999). However, in urban and industrialised areas, other sources of VOC become increasingly important (Borbon et al., 2013; Karl et al., 2009; Liu et al., 2008b; McDonald et al., 2018). Aromatics are one such class of VOC, which are emitted from fuel use, biomass burning, solvent use and industry (Corrêa and Arbilla, 2006; Liu et al., 2008a).

In the troposphere aromatic hydrocarbons primarily react with the hydroxyl radical (OH) (Calvert, 2002). Detailed mechanisms of aromatic oxidation have been generated previously from experimental work in simulation chambers (Calvert, 2002) and this chemistry has been included in chemical mechanisms such as the Master Chemical Mechanism (MCM: [mcm.york.ac.uk](http://mcm.york.ac.uk)) and the [Statewide Air Pollution Research Center of the University of California in Riverside \(SAPRC\) mechanism](#) whose primary goal is to describe ozone formation (Bloss et al., 2005; Carter, 1988; Carter and Heo, 2013; Metzger et al., 2008; Suh et al., 2003; Volkamer et al., 2002). The aromatic oxidation mechanism in the MCM has not been updated since 2005 (Jenkin et al., 2003, Bloss et al., 2005) and this can only be achieved once sufficient evidence of the rate, branching ratios and product distributions has been obtained. Explicit chemical mechanisms often lead to large discrepancies between modelled and measured SOA formation (Johnson et al., 2006; Khan et al., 2017; Volkamer et al., 2006), which may be associated with both uncertainty in the formation pathways of semi-volatile and low volatility species and a poor representation of aerosol volatility and partitioning.

65 SOA is made up of thousands of oxidised organic compounds which each exist at very low, often sub-ppt levels in the atmosphere (Hallquist et al., 2009). This makes measurement of generated products challenging even under controlled laboratory conditions. However, the increasing availability of high-resolution instrumentation that enable real time detection of thousands of molecules (Hallquist et al., 2009) has allowed more detailed chemical characterisation of the gas and particle phase VOC oxidation products. Chemical ionisation is extremely powerful in this area due to soft ionisation schemes, such as  $I^-$ ,  $NO_3^-$  and  $H_3O^+$ , that form clusters with the types of molecules that sit within atmospherically relevant oxidation ranges (Isaacman-Vanwertz et al., 2018; Isaacman-VanWertz et al., 2017). These techniques have enabled identification of many new oxidation products, thereby supporting more detailed mechanistic studies (Molteni et al., 2018; Wang et al., 2015).

Recent mechanistic studies have highlighted the importance of previously unknown pathways, such as autoxidation (Molteni et al., 2018; Wang et al., 2017) and multi-generational OH-attack (Garmash et al., 2020; Zaytsev et al., 2019), for the formation of highly oxygenated organic molecules (HOM) which may contribute to new particle formation (NPF) and rapid SOA formation and growth. Recent work has shown that autoxidation may play a major role on SOA formation at regional and global scales due to the potential for autoxidation of aromatics to continue to be favourable even under higher NO conditions (Crouse et al., 2013; Pye et al., 2019). Furthermore, reductions in  $NO_x$  in the US and Europe are enabling autoxidation to play an increasing role under urban conditions (Praske et al., 2018). In order to ascertain the importance of aromatic SOA, detailed laboratory characterisation of SOA composition and aromatic oxidation mechanisms for a broad suite of relevant aromatics is required alongside ambient measurements.

Gas phase chemistry and SOA formation has been well studied for the most ubiquitous aromatic VOCs; benzene and toluene (Bruns et al., 2016; Molteni et al., 2018; Ng et al., 2007; Suh et al., 2003; Volkamer et al., 2002). However, more recently the importance of substituted aromatic hydrocarbons in urban areas has been highlighted for both ozone and SOA formation (Kansal, 2009; Monod et al., 2001). Furthermore, substituted aromatics have high OH reactivities and aerosol mass yields (Odum et al., 1996) so despite existing at generally smaller concentrations than their less substituted homologues, reductions in their emissions may be essential to improving urban air quality (Von Schneidmesser et al., 2010). Uncertainty exists in the emission inventories

of C<sub>7</sub>-C<sub>9</sub> aromatics and this could be important when considering the differences between ozone and SOA formation in developed and developing megacities, particular with a lack of speciation of aromatics in fuels globally (Borbon et al., 2013). Recent work has begun to fill this gap in the chemical knowledge, and it can be seen that though other pollutants have been decreased in newer fuels, an increasing trend is observed in the levels of aromatics in cities such as Beijing (Peng et al., 2017). In urban environments, the impact of this is not easy to constrain, particularly as these emissions can have complex interactions with biogenic VOCs (Kari et al., 2019) impacting upon SOA composition and yields (McFiggans et al., 2019).

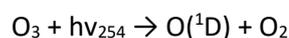
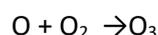
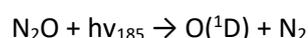
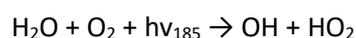
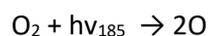
C<sub>9</sub> aromatics are of particular interest in urban areas, with major emissions sources including unburnt exhaust emissions (Corrêa and Arbilla, 2006; Na et al., 2005), evaporative losses (Miracolo et al., 2012; Rubin et al., 2006) and solvent use (Zhang et al., 2013). Another group of aromatics which are increasingly a focus of research are polyaromatic hydrocarbons (PAH) which can be emitted from vehicular emissions (Miguel, Kirchstetter and Harley, 1998) and biomass burning (Bruns et al., 2016). With < 50 % of SOA products identified (Hamilton et al., 2005; Sato et al., 2007), it is important to build up a detailed chemical insight in order to improve mechanistic understanding of which chemical pathways are leading to SOA formation (Atkinson and Arey, 2007). Previous studies of HOMs have focused on either very different precursors (Mentel et al., 2015) or a small range with limited comparison between isomers (Molteni et al., 2018).

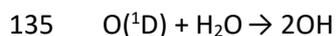
In this study we focus on the photochemical oxidation of substituted aromatic hydrocarbons which have recently been found to form HOMs through rapid intramolecular autoxidation reactions (Wang et al., 2017). Though VOCs are often arbitrarily grouped in models (Carter, 2000; Yarwood et al., 2005), recent work has found that the location, number and isomeric structure of substituent groups on the benzene ring can have implications on SOA yield, chemical composition and physical properties (Li et al., 2016). In this study we investigate a range of isomers of C<sub>9</sub>-aromatics to evaluate this effect in more detail. Of the aromatics studied in these experiments, molecular understanding of SOA products is most well developed for the trimethyl benzene isomers (Huang et al., 2014; Li and Wang, 2014; Sato et al., 2012, 2019). Though other aromatics have been studied, these have either lacked molecular level detail or focused on gas phase oxidation and lacked detailed characterisation of SOA (Chan et al., 2009; Li et al., 2016; Molteni et al., 2018; Ping, 2013). Here we present a detailed characterisation of the chemical composition of the oxidation products of a range of substituted aromatics (isomers of C<sub>3</sub>-substituted aromatics and a PAH): propyl benzene (PROP BENZ), isopropyl benzene (IPR BENZ), 1,3,5-trimethyl benzene (TMB135), 1,2,4-trimethyl benzene (TMB124), and a substituted PAH, 1-methyl naphthalene (METHNAP). We evaluate the trends in chemistry across different isomers under low and medium NO<sub>x</sub> conditions and discuss the relative importance of different oxidation pathways.

## 2 Methodology

### 2.1 Oxidation of VOCs

We conduct our experiments in an Aerodyne Potential Aerosol Mass (PAM) oxidation flow reactor (OFR) (Lambe et al., 2011) affording short experimental timescales and the ability to generate consistent and reproducible oxidation conditions. Aromatic VOCs were injected into a carrier gas of synthetic air through use of an automated syringe pump, either neat or diluted in carbon tetrachloride (CCl<sub>4</sub>). **Their concentrations (Table 1) were optimised to obtain similar aerosol mass concentrations in the different experiments.** In the OFR, OH, HO<sub>2</sub> and NO radicals were generated via O<sub>2</sub> + H<sub>2</sub>O + N<sub>2</sub>O photolysis at 254 and 185 nm via the following reactions:





140 All experiments were carried out at a temperature of 26 °C, relative humidity of 35 % and constant gas flow of 10 SLM through the OFR, including injection of ~3 % N<sub>2</sub>O at the inlet to generate NO in a subset of experiments (Lambe et al., 2017; Peng et al., 2018). At these conditions, the estimated OH exposure in the OFR were in the range of  $1.5 \times 10^{12}$  -  $1.7 \times 10^{12}$  molecules cm<sup>-3</sup> s<sup>-1</sup>. These elevated exposures are not attainable in conventional environmental chambers and may prove relevant for understanding photochemistry in urban areas with high oxidation capacities such as those observed in Chinese megacities (Lu et al., 2019; Tan et al., 2019). For example, OH concentrations in Beijing can reach as high as  $\sim 1 \times 10^7$  molecules cm<sup>-3</sup> (Bryant et al., 2019), an order of magnitude higher than the global average of  $\sim 1 \times 10^6$  molecules cm<sup>-3</sup> (Lelieveld et al., 2016) which is used to relate OH exposure in an OFR to days of equivalent atmospheric oxidation (Lambe et al., 2015). This changes what would be 11 days of equivalent atmospheric oxidation in the OFR under global average OH concentrations to just over 1 day of oxidation in Beijing.

150 In experiments where N<sub>2</sub>O was added to the OFR, the NO:HO<sub>2</sub> concentration ratio was approximately 0.5 as calculated using an adapted version of the OFR photochemical box model described in Li et al., 2015 and Peng et al., 2015. The use of non-tropospheric radiation to generate radicals in OFR can result in photolysis of reactants, however, operational conditions can be optimised to ensure OH loss is the dominant removal process of the VOC (Peng and Jimenez, 2020). In this study, under the conditions used > 98 % the loss of VOC can be attributed to reaction with OH. This is based on calculations under the relevant conditions for 1,3,5-trimethyl benzene, 1,2,4-trimethyl benzene and 1-methyl naphthalene for which photolysis rate data exist. The relevant photolysis data did not exist for propyl benzene and isopropyl benzene and thus, to the extent that results for TMB and methyl naphthalene are also applicable to propyl and isopropyl benzene, we anticipate that their loss is also dominated by OH oxidation. The photolysis of products or intermediates are extremely difficult to fully clarify, as discussed in Peng et al. (2020) and thus the practical approach taken here is to optimise the OH oxidation to ensure that OH loss is the dominant pathway for the VOCs themselves.

160 Between experiments the OFR was flushed with humidified synthetic air at full lamp power for 12-36 hours until the particle mass generated was reduced to background concentrations, measured by a scanning mobility particle sizer (SMPS) and an aerosol mass spectrometer (AMS). During this time the walls were cleaned of semi-volatiles and precursors, measured by I-CIMS and Vocus PTR-MS. Backgrounds were determined under lights off/on, with/without precursor injection conditions and spectra recorded with all of the instrumentation. The conditions discussed herein are low NO<sub>x</sub> ([NO] < 0.1 ppb) and medium NO<sub>x</sub> ([NO] > 1 ppb, [NO]: [HO<sub>2</sub>] = 0.5).

165

Precursor	isopropyl benzene		1-methyl naphthalene		propyl benzene		1,2,4-trimethylbenzene		1,3,5-trimethylbenzene	
	Low-NO <sub>x</sub>	Medium-NO <sub>x</sub>	Low-NO <sub>x</sub>	Medium-NO <sub>x</sub>	Low-NO <sub>x</sub>	Medium-NO <sub>x</sub>	Low-NO <sub>x</sub>	Medium-NO <sub>x</sub>	Low-NO <sub>x</sub>	Medium-NO <sub>x</sub>
VOC mixing ratio (ppb)	245	510	57	58	221	230	237	245	470	485

**Table 1 - VOC concentrations during single experiments for each precursor**

## 2.2 Measurements

### 2.2.1 FIGAERO-I-CIMS

170 A time of flight chemical ionisation mass spectrometer (Lee et al., 2014) using an iodide ionisation system was coupled with a filter inlet for gases and aerosols (FIGAERO) (Lopez-Hilfiker et al., 2014) for detection of particle phase composition (I-CIMS herein). Particle mass concentrations were monitored using a TSI Scanning Mobility Particle Sizer and collection time on the FIGAERO filter was varied to ensure comparable mass of aerosol in each

sample for the different precursors. The FIGAERO thermal desorption cycle consisted of a 15 minute temperature ramp to 200 °C, held at that temperature for 10 minutes and then cooled down over 15 minutes.

175 The gas phase inlet consisted of a piece of 0.5 m length ¼" I.D. **Perfluoroalkoxy alkene (PFA)** tubing from which the I-CIMS sub-sampled 2 slpm. The aerosol phase inlet consisted of 0.5 m stainless steel through which 2 slpm was pulled over a Teflon filter. I<sup>-</sup> reagent ion was made by flowing N<sub>2</sub> over a permeation tube containing methyl iodide(CH<sub>3</sub>I), followed by ionisation through a Po-210 ionisation source. This flow enters an ion molecule reaction region (IMR) which was maintained at a pressure of 100 mbar using an SSH-112 pump fitted with a  
180 pressure controller. The IMR pressure was automatically maintained at a set value using an actuated valve connected to the pump line.

### 2.2.2 Vocus-PTR

A Vocus proton-transfer-reaction time of flight mass spectrometer (PTR-TOFMS; Vocus hereafter) was used in this experiment to measure gas-phase organic compounds (Krechmer et al., 2018). Equipped with a newly-  
185 designed focusing ion-molecule reactor (FIMR), the Vocus was able to measure organics with a wide range of volatilities (Riva et al., 2019). An SSQ (short-segmented quadrupole) pressure of 2.0 mbar and an axial voltage of 420V were used, corresponding to an E/N ratio of ~ 100 Td, which was lower than typical to reduce fragmentation of labile SVOCs (Krechmer et al., 2018). A total sample flow of 2.2 LPM was maintained by a pump to minimise delay times due to the inlet (Pagonis et al., 2017), of which approximately 125 sccm was  
190 sampled into the FIMR through the PEEK tube. To reduce inlet blockages by the high mass loadings of aerosols from the OFR, a filter was connected just before the entrance of the Vocus, which may have reduced transmission of some SVOCs and LVOCs. Background checks by injection of clean air and calibrations by injection from a multi-component standard cylinder (Apel-Riemer environmental) were performed every 2 hours in this experiment. With a resolving power of 12000 Th/Th at 200 Th, molecular formula could be  
195 assigned to most of detected ions with a mass accuracy better than 3ppm.

### 2.2.3 Orbitrap LC-MS

Ultra-performance liquid chromatography ultra-high resolution mass spectrometry (Dionex 3000, Orbitrap QExactive, ThermoFisher Scientific) was used for sample analysis. Compound separation was achieved using a reverse-phase C18 column (Accucore, ThermoFisher Scientific) with the following dimensions: 100 mm (length)  
200 × 2.1 mm (width) and 2.6 µm particle size. The column was heated to 40 °C during analysis. The solvent composition consisted of water with 0.1 % (v/v) of formic acid (A) and methanol (B) (optima LC-MS grade, ThermoFisher Scientific). Gradient elution was used, starting at 90 % (A) with a 1 minute post-injection hold, decreasing to 10 % (A) at 26 minutes, returning to the starting mobile phase conditions at 28 minutes, with a 2  
205 minute hold to re-equilibrate the column (total run time = 30 minutes). The flow rate was set to 0.3 ml/min with a sample injection volume of 2 µl. Samples were stored in a temperature controlled autosampler tray during analysis which was set to 4 °C. The mass spectrometer was operated in negative and positive ionisation mode with a scan range of m/z 85 to 750. Heated electrospray ionisation was used, with the following parameters: capillary and auxiliary gas temperature of 320 °C, sheath gas flow rate of 70 (arb.) and auxiliary gas flow rate of  
210 3 (arb.). Tandem mass spectrometry was performed using higher energy collision dissociation with a normalised collision energy of 65, 115. Data was analysed using Compound Discoverer version 2.1 (ThermoFisher Scientific). Full details regarding the data processing methodology can be found in Pereira et. al (2020) (under-review in ES&T). Briefly, molecular formulae assignments were allowed unlimited C, H, O atoms, up to 2 S atoms and 5 N atoms, plus > 2 Na atoms and 1 K atom in positive ionisation mode. Only compounds with a mass error < 3 ppm and signal-to-noise ratio > 3, hydrogen-to-carbon ratio of 0.5 to 3 and oxygen-to-carbon ratio of 0.05 to 2 were  
215 included in the data set. Instrument artefacts were removed from the sample data if the sample/artefact peak area ratio > 3.

## 2.3 Data Analysis

Data analysis of I-CIMS and Vocus was performed using the "Tofware" package (version 3.1.0) running in the Igor Pro (WaveMetrics, OR, USA) environment(Stark et al., 2015). Time of flight values were converted to mass-to-charge ratios in the I-CIMS using I<sup>-</sup>, I.H<sub>2</sub>O<sup>-</sup> and I<sub>3</sub><sup>-</sup>. The instrument was operated at a ~ 8000 Th/Th resolving  
220

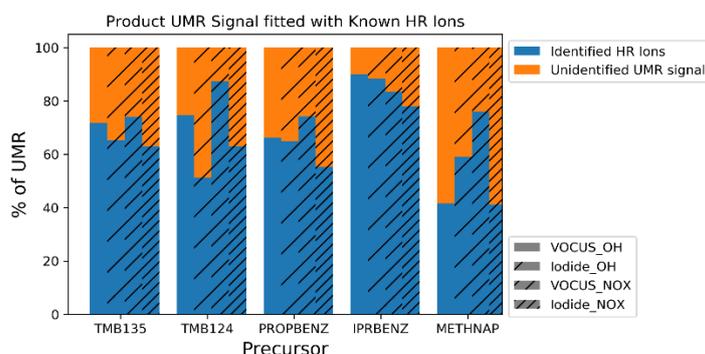
power. Several impurity ions, ions from ubiquitous VOCs, and ions from oxidation of products were used for the mass calibration of Vocus, which are all clear and unique peaks in the mass spectrum, including  $C_2H_5O^+$  (acetaldehyde, 45.033491 Th),  $C_2H_7O_3^+$  (hydrate ion of acetic acid, 79.038971 Th),  $C_6H_9O_3^+$  (common oxidation product of all precursors in our experiments, 129.054621 Th),  $C_8H_{11}O_2^+$  (common oxidation product of all precursors in our experiments, 139.075356 Th), and  $C_{10}H_{31}O_5Si_5^+$  (decamethylcyclopentasiloxane (D5, contaminations from personal care products (Coggon et al., 2018)), 371.101233 Th). It should be noted that glyoxal, a major product from aromatic oxidation is detected by the Vocus as  $C_3H_3O_2^+$  which is dominated in these experiments by protonated acetone. The sensitivity of glyoxal in PTR is almost one tenth of that of acetone, and furthermore  $C_3H_3O_2^+$  can also be influenced by fragmentation, and thus is not included in the analysis herein (Stöninger et al., 2017). Further analysis was carried out in custom Python 3 procedures using the packages Pandas, Matplotlib and Numpy.

In this work, the chemical composition of the gas phase species generated in all the experiments is characterised by the Vocus. While the FIGAERO is capable of providing information about both gas and particle phases, the gas phase I-CIMS spectra obtained during the medium  $NO_x$  experiments was complicated by the presence of high nitric acid formed in the OFR from the  $N_2O$  precursor (Lambe et al., 2017; Peng et al., 2018). High nitric acid depletes the I<sup>-</sup> reagent ion to form  $NO_3^-$ , which subsequently acts as an additional reagent ion and complicates interpretation of the observed CIMS spectrum. Thus, the gas phase FIGAERO measurements were deemed unsuitable for the comparison of medium and low  $NO_x$  conditions and the HR analysis of the I-CIMS spectra has been carried out only for the particle phase I-CIMS FIGAERO data obtained in all the experiments, for which nitric acid levels were lower, resulting in pure iodide reagent ion chemistry. While this setup provides thermal desorption profiles which have been previously used to draw conclusions about the volatility distribution of ions (Lopez-Hilfiker et al., 2016b; Schobesberger et al., 2018; Stark et al., 2017), in this study we instead integrate the desorption profiles in order to compare the overall composition of the different precursors.

The observed mass spectra were first mass calibrated (10 ppm mass accuracy) and then the observed high resolution peaks were fit using a multi-peak fitting algorithm. The exact mass of the multiple peaks are then matched with the most likely elemental formula. A consistent approach was taken for the high resolution (HR) peak identification in all experiments. To eliminate bias, separate peak lists were generated for each precursor and experimental condition. Mass ranges were selected in order to focus on the more oxidised products: m/z 200-500 for I-CIMS and m/z 75-300 for Vocus (except m/z 79-81, 117-123 for all precursors, and 143-144 only for methylnaphthalene, the range dominated by the signals of precursor, solvent, the hydrated ion of acetic acid, and their isotopes). It should be noted that this mass range omits methyl glyoxal, a dominant product of aromatic oxidation, which was observed by Vocus in all experiments. The mass spectra in this range were fitted with peaks in order of descending signal contribution until the signal-to-noise made peak identification not possible. Predicted oxidation products for each aromatic precursor were obtained from the MCM v3.3.1 using the "extract" function on the web portal (mcm.york.ac.uk). Fitted unknown peaks were firstly compared with this list of MCM products and assigned through use of the iterative peak assignment method which assigns unknown peaks to elemental formulae in a reference list if they are in the correct position (Stark et al., 2015).

Quantification of highly oxidised species measured by I-CIMS is challenging due to the lack of availability of standards for many of the observed products. Previous attempts at quantification have used functional group dependencies, collision limit sensitivities or those derived from ion-adduct declustering scans (Lopez-Hilfiker et al., 2016a). Experimental limitations exist in the use of these techniques, meaning that quantification remains a challenge. For PTR, it has previously been reported that the  $H_3O^+$  capture rate and therefore the sensitivity of PTR to all ions lies within a very narrow distribution, unlike iodide sensitivity which can vary by several orders of magnitude. Due to the unusually low E/N value in the Vocus FIMR used in these experiments, absolute contributions of certain ions is challenging to ascertain due to the formation of both protonated molecules and hydrate cluster ions of the same molecule alongside fragmentation. Unpicking these is not trivial, though the impact of hydrate formation upon the overall product distribution is not significant on the analysis carried out herein.

270 Considering these factors, we did not correct for sensitivity and use raw ion signal for both I-CIMS and Vocus  
measurements. Gas phase I-CIMS observations were used for cross calibration between I-CIMS and Vocus under  
low-NO<sub>x</sub> conditions(S2), showing a generally consistent calibration factor for ions containing 1-6 oxygen atoms,  
indicating that these results are not influenced by vastly different I-CIMS sensitivities. This is further confirmed  
275 by similar ion signal distributions observed between both the I-CIMS and Vocus. Comparison of I-CIMS and  
Vocus data (Figure S1) shows that 30-60 % of the I-CIMS signal is from ions with chemical formulas which are  
also observed in the Vocus. **It should be noted that we have not attempted to relate ion signals to yields, and  
thus the comparison of ion signals in this study should not be assumed to be related to product yields derived  
from models such as those implementing mechanisms including the MCM.**



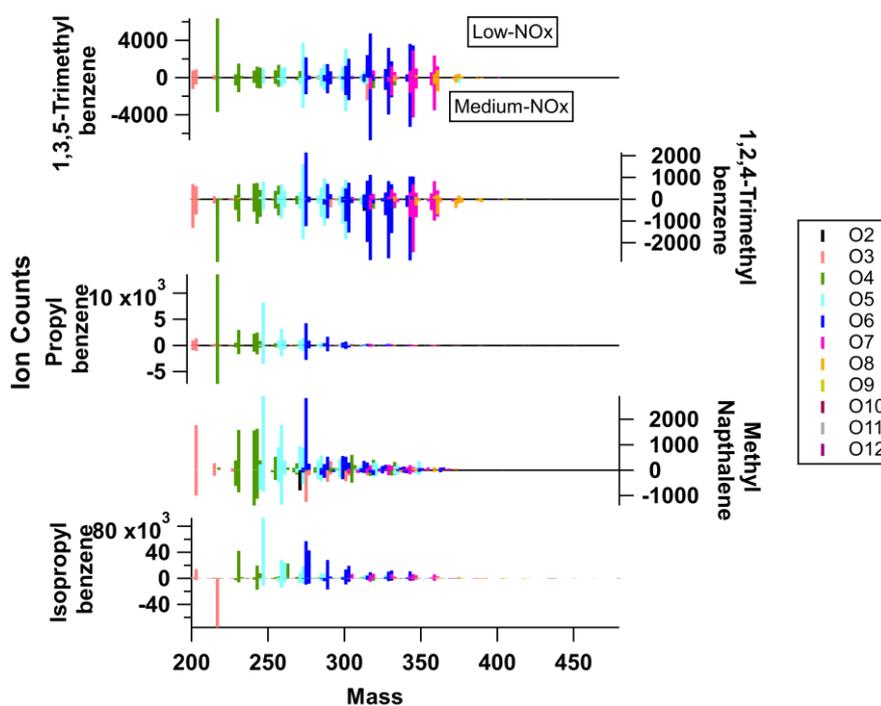
280 **Figure 1 Proportion of UMR signal fitted by identified HR ions for all precursors and experimental conditions from I-CIMS and Vocus**

The signal fitted by identified HR ions was compared with the total unit mass resolution (UMR) signal, excluding ions known to be unrelated to the experiment using OFR and instrument backgrounds. This comparison shows that between 40 and 90 % of the observed signal has been assigned elemental formulae, with the residual signal (orange) of unidentified signal being either the result of poor signal to noise or complex overlapping peaks, making peak identification infeasible. This signal may also have some contribution from ion fragments in the Vocus and from thermal decomposition of desorbed products for the I-CIMS data. Analysis herein has been carried out for the blue proportion of signal, for which elemental formulae have been selected.

285

### 3 Results

#### 290 3.1 Overview of gas and particle phase oxidation products

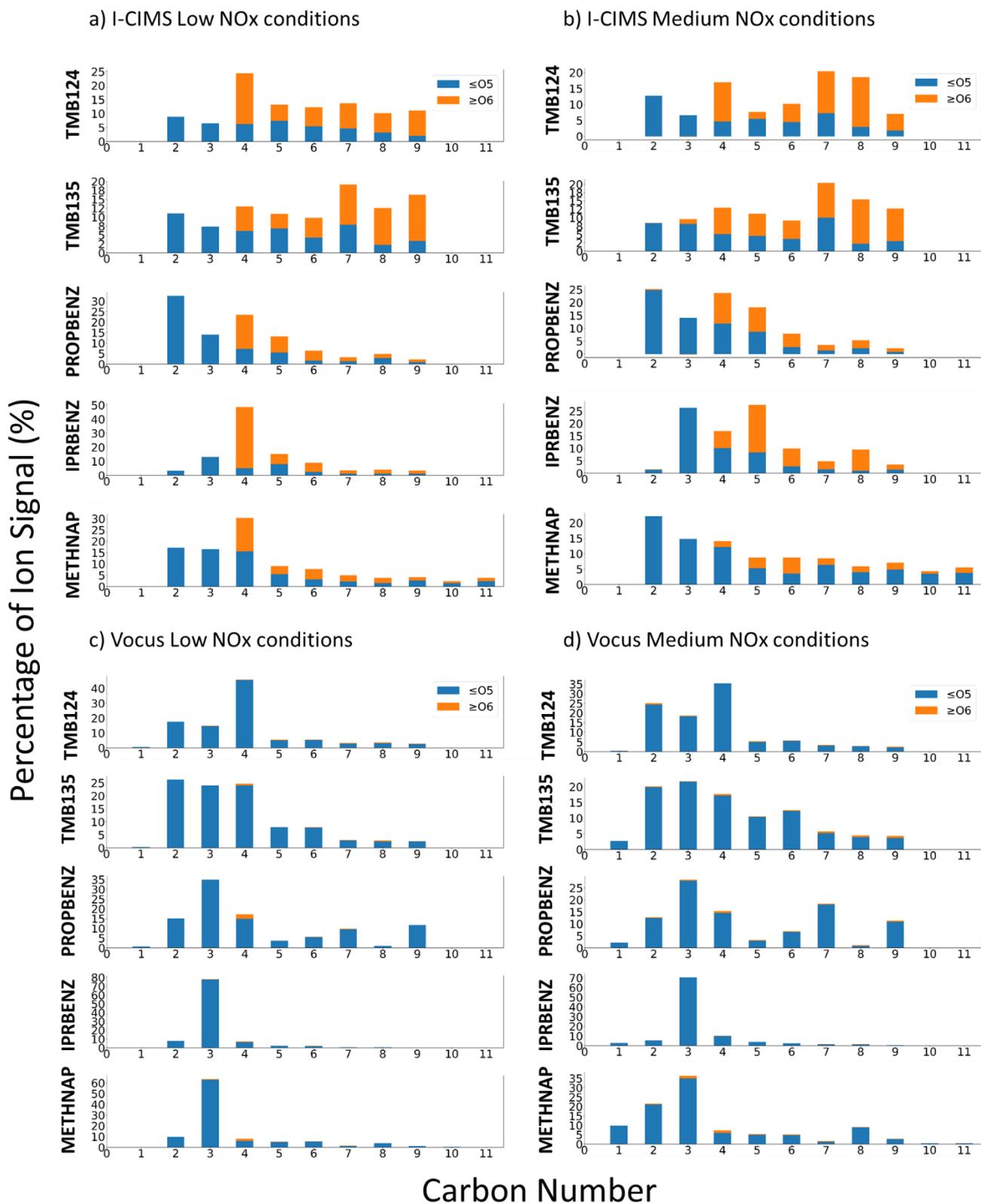


**Figure 2** Average mass spectra of particle phase measurements from I-CIMS for all precursors under low-NO<sub>x</sub> conditions (upwards) and medium-NO<sub>x</sub> conditions (downwards – negative values correspond to magnitude of positive signal)

The gas phase (low-NO<sub>x</sub>) mass spectra are dominated by small non-HOM oxidation products, with most of the signal in the C<sub>2</sub>-C<sub>4</sub> range. A similar distribution is seen for the gas phase (medium-NO<sub>x</sub>) mass spectra, although 1,3,5-TMB and *n*-propylbenzene show an increase in the contribution of the signal at higher C numbers that will be discussed below. As expected, the particle phase mass spectra show a higher fraction of signal at higher C number and an increase in the relative proportion of HOM signal. There are marked differences between the distributions of particle phase products, although there are many common ion formulas observed, which will be discussed in section 4.1.2. The particle phase mass spectra obtained for each precursor are also included in Figure 2, with the particle phase (low-NO<sub>x</sub>) spectra shown pointing upwards and the particle phase (medium-NO<sub>x</sub>) spectra pointing downwards. The ion peaks have been coloured according to the number of O atoms found in the molecular formula. The two TMB isomers have very similar mass spectra. These two highly substituted ring species have a larger proportion of very oxidised ions (O<sub>6</sub>-O<sub>8</sub>) than the other precursors whose spectra are dominated by compounds with O<sub>3</sub>-O<sub>5</sub>. N-containing ions do not contribute significantly to product signal under medium-NO<sub>x</sub> conditions (< 10 % except for 1-methyl naphthalene).

To compare the carbon skeleton of the oxidation products, the ion intensity of all ions with the same carbon number in the average mass spectra have been summed and are presented for each precursor in figure 3 for the gas phase and particle phases. This data has been further split into non-HOMS (O<sub>5</sub>) and HOMS (O<sub>6</sub>) based on the definition in Bianchi et al., 2019. Comparison shows clear differences in distribution of products from different precursors, and in particular, between isomers of the C<sub>9</sub>-aromatics.

Through comparison of these precursors under similar oxidation conditions, we can see that lumping of VOC isomers may not be valid in the context of SOA formation. It is possible that lumping VOCs based on single and multi- substituent could prove useful for model parameterisations. Furthermore, the evident HOM formation under elevated NO<sub>x</sub> conditions is important to consider for effective policy implementation. Detailed trends in gas and particle composition for each precursor will be discussed in the following sections.



320 **Figure 3** Signal distribution across carbon number coloured by proportion of HOM signal for a) I-CIMS particle phase under low-NOx conditions b) I-CIMS particle phase under medium-NOx conditions c) Vocus gas phase under low-NOx conditions and d) Vocus gas phase under medium-NOx conditions [only signal contributions up to precursor carbon number are included (C9 for TMB124,TMB135,PROP BENZ & IPR BENZ, C11 for METH NAP) capturing both the ring-retaining and ring scission products for mechanistic discussions below. There is very little signal above C9 for the C9-aromatic precursors.]

## 325 3.2 Individual VOC SOA Product Composition

### 3.2.1 1,2,4-trimethyl benzene

330 In the gas phase (low-NO<sub>x</sub>) mass spectrum (Fig 3a), over 40 % of signal comes from C<sub>4</sub> ions, with the two largest ions being C<sub>4</sub>H<sub>6</sub>O<sub>2</sub> and C<sub>4</sub>H<sub>8</sub>O<sub>3</sub>. In the particle phase (low-NO<sub>x</sub>) MS, the signal is distributed more broadly across ions of different carbon numbers. The largest contribution is also from the C<sub>4</sub> ions (25 %) with the C<sub>5</sub>-C<sub>9</sub> all contributing ~ 15 % each. The majority of the C<sub>4</sub> product signal comes from C<sub>4</sub>H<sub>4</sub>O<sub>6</sub>, with the other largest single ions being C<sub>5</sub>H<sub>6</sub>O<sub>5</sub>, C<sub>7</sub>H<sub>10</sub>O<sub>6</sub> and C<sub>9</sub>H<sub>12</sub>O<sub>6</sub>.

335 Under medium-NO<sub>x</sub> conditions, the dominant gas phase ions are consistent with those produced under low-NO<sub>x</sub> conditions and the product signal shows a broadly similar distribution to the medium-NO<sub>x</sub> conditions, with a small reduction in the fraction of C<sub>4</sub> product ions and an increase in C<sub>2</sub> product signal **which can be attributed to an increase in C<sub>2</sub>H<sub>4</sub>O<sub>3</sub>**. A small contribution to signal comes from N-containing ions (3.8 %). In the particle phase, the mass spectrum and C number distribution is fairly similar to the low-NO<sub>x</sub> conditions, although there is a doubling in the fraction of HOMs with C<sub>7</sub>-C<sub>8</sub>. In addition, 9.3 % of the particle product signal is from N-containing ions; specific ions have not been included in further analysis due to potential contributions from thermal decomposition.

### 340 3.2.2 1,3,5-trimethyl benzene

The most abundant contribution to the gas phase (low-NO<sub>x</sub>) MS comes from an almost equal split between C<sub>2</sub>-C<sub>4</sub> ions (together ~ 75 % of product signal), with the most dominant ions being C<sub>4</sub>H<sub>6</sub>O<sub>2</sub> and C<sub>3</sub>H<sub>6</sub>O<sub>2</sub>. The spread of signal in particle phase (low-NO<sub>x</sub>) MS is across ions with a broader range of carbon numbers, with C<sub>7</sub>-C<sub>9</sub> HOM ions contributing ~ 40 % of product signal. The most dominant of these ions are C<sub>7</sub>H<sub>10</sub>O<sub>6</sub> and C<sub>9</sub>H<sub>12</sub>O<sub>6</sub>.

345 In the gas phase medium-NO<sub>x</sub> mass spectrum, there is a shift with an increased contribution from ions with larger carbon numbers than under the low-NO<sub>x</sub> conditions. The most dominant gas phase ions were C<sub>4</sub>H<sub>6</sub>O<sub>2</sub>, C<sub>3</sub>H<sub>6</sub>O<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>O<sub>3</sub> and C<sub>5</sub>H<sub>6</sub>O<sub>3</sub>. Nitrogen containing ions contribute only 2.8 % of observed signal. In the particle phase (medium-NO<sub>x</sub>) mass spectrum the most abundant ions are consistent with those under low-NO<sub>x</sub> conditions. There is a 7.8 % contribution to the product signal from nitrogen containing ions.

### 350 3.2.3 Propyl benzene

355 Similar to the TMB isomers, the majority of gas phase (low-NO<sub>x</sub>) mass spectrum signal comes from C<sub>2</sub>-C<sub>4</sub> ions, but in this case the C<sub>3</sub> ions have the highest intensity (C<sub>3</sub>H<sub>8</sub>O<sub>2</sub> and C<sub>3</sub>H<sub>6</sub>O<sub>2</sub>). 10 % of signal contribution is from C<sub>9</sub> ions, with the most dominant ion being C<sub>9</sub>H<sub>10</sub>O, most likely propiophenone, the first generation ketone from OH attack on the *n*-propyl chain (Bloss et al., 2005). In contrast, the bulk of signal in the particle phase (low-NO<sub>x</sub>) mass spectrum exists at <C<sub>5</sub>, with a smaller contribution from HOM ions than the TMB isomers. The majority of ions observed correspond to predicted oxidation products in the MCM. Abundant oxidised ions not included in the MCM include C<sub>5</sub>H<sub>6</sub>O<sub>6</sub> and C<sub>5</sub>H<sub>6</sub>O<sub>5</sub>.

360 The gas phase (medium-NO<sub>x</sub>) mass spectrum product distribution is largely similar to low-NO<sub>x</sub> conditions, however there is an enhanced contribution from C<sub>7</sub>H<sub>6</sub>O, most likely benzaldehyde. N-containing ions contribute 3.5 % to gas phase product signal. In the particle phase (medium-NO<sub>x</sub>) mass spectrum, the dominant ions are largely consistent with those observed under low-NO<sub>x</sub> conditions. N-containing ions contribute 5.8 % of the signal.

### 3.2.4 Isopropyl benzene

365 In the gas phase (low-NO<sub>x</sub>) mass spectrum ~ 80 % of the product signal can be attributed to C<sub>3</sub> ions potentially formed from scission of the iso-propyl group from the ring, with the two largest ions being C<sub>3</sub>H<sub>8</sub>O<sub>2</sub> and C<sub>3</sub>H<sub>6</sub>O<sub>2</sub>. In the particle phase (low-NO<sub>x</sub>) mass spectrum, however, by far the largest contribution (~ 50 %) was from highly oxygenated C<sub>4</sub> ions, C<sub>4</sub>H<sub>4</sub>O<sub>6</sub> and C<sub>4</sub>H<sub>6</sub>O<sub>6</sub>.

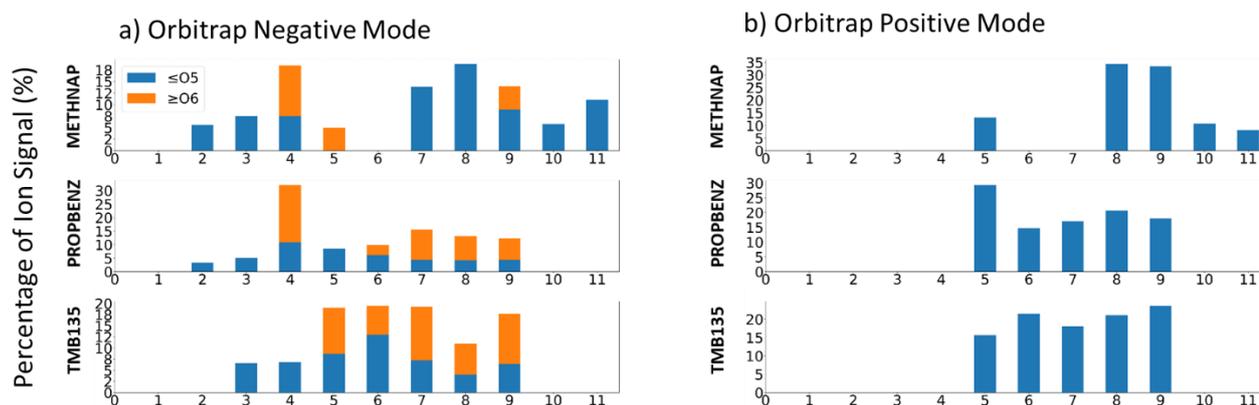
The gas phase (medium-NO<sub>x</sub>) mass spectral product distribution was largely similar as under low-NO<sub>x</sub> conditions, with a slightly increased contribution from higher carbon number ions. There is a 3.6 % contribution to signal from N-containing ions. The particle phase (medium-NO<sub>x</sub>) mass spectral product distribution was strikingly different compared to low-NO<sub>x</sub> conditions, with a larger contribution from C<sub>3</sub>, C<sub>5</sub> and higher carbon number ions and the largest single ions were C<sub>3</sub>H<sub>6</sub>O<sub>3</sub>, C<sub>4</sub>H<sub>4</sub>O<sub>4</sub> and C<sub>5</sub>H<sub>6</sub>O<sub>6</sub>. In particular, there is a significant contribution from C<sub>5</sub>-C<sub>8</sub> HOMs ions. Overall, there was a 2.5 % contribution to signal from N-containing ions.

### 3.2.5 Methyl Naphthalene

In the gas phase (low-NO<sub>x</sub>) mass spectrum, ~ 60 % of gas phase product signal is attributable to just a few C<sub>3</sub> ions (C<sub>3</sub>H<sub>8</sub>O<sub>2</sub>, C<sub>3</sub>H<sub>6</sub>O<sub>2</sub> and C<sub>3</sub>H<sub>4</sub>O<sub>3</sub>). The particle phase shows a broader spread of product signal across the carbon number range, with a significant contribution of oxidised (>O<sub>6</sub>) ions ranging from C<sub>4</sub>-C<sub>10</sub>, with the largest contribution being from C<sub>4</sub>H<sub>4</sub>O<sub>6</sub> and C<sub>4</sub>H<sub>4</sub>O<sub>5</sub>.

The gas phase (medium-NO<sub>x</sub>) mass spectrum showed an increased contribution from C<sub>2</sub> and C<sub>8</sub> ions compared with low-NO<sub>x</sub> conditions. The most dominant ions observed were largely consistent with low-NO<sub>x</sub> conditions. Overall, N-containing ions contributed a much larger fraction of the signal in both gas (16.2 %) and particle phases (22.3 %) than for the other precursors. In the particle phase (medium-NO<sub>x</sub>) mass spectrum, the product distribution was again similar to low-NO<sub>x</sub> conditions, with a slight shift in signal distribution to higher carbon numbers. The most dominant ions in the particle phase were consistent with those observed under low-NO<sub>x</sub> conditions.

### 3.3 Comparison with Orbitrap Analysis



**Figure 4 Signal distribution across carbon number coloured by proportion of HOM signal for a) Orbitrap Negative mode and b) Orbitrap Positive Mode [only signal contributions up to precursor carbon number are included (C<sub>9</sub> for TMB135 and PROP BENZ, C<sub>11</sub> for METHNAP) capturing relevant products for mechanistic discussions below. Ions which contributed less than 0.5 % of observed signal were assumed to be background and removed.]**

Offline filters of SOA generated from the low-NO<sub>x</sub> oxidation of 1-methyl naphthalene, propyl benzene and 1,3,5-trimethyl benzene were analysed by Orbitrap LC-MS. The data presented shows all ions above 0.5 % of total ion signal; this was selected as a threshold to remove contributions from ions which may be contaminants. Though some ions are observed at higher carbon and oxygen numbers in Orbitrap measurements, these are not included in this analysis and we focus on products up to precursor carbon number as we can apply current mechanistic understanding in interpretation of these.

Results from both negative and positive modes are shown in Figure 4; negative mode shows most similarity to the composition observed by I-CIMS while positive mode looks very different. Positive mode is generally more sensitive to peroxide and carbonyl species, and similar ion distributions are observed for the C<sub>9</sub>-aromatics, with a relatively larger contribution from C<sub>5</sub> ions in the case of propyl benzene. 1-methyl naphthalene shows a major contribution from C<sub>8</sub>-C<sub>9</sub> products which are minor components in I-CIMS.

The distribution of ions for 1,3,5-trimethyl benzene is similar between I-CIMS and negative mode, with a larger relative contribution of C<sub>5</sub>-C<sub>6</sub> ions and a smaller relative contribution of C<sub>2</sub>-C<sub>3</sub> ions in negative mode compared with I-CIMS. Propyl benzene also shows very similar ion distributions to I-CIMS data, with a smaller contribution from C<sub>2</sub>-C<sub>3</sub> ions and a larger relative C<sub>7</sub>-C<sub>9</sub> contribution in both HOM and non-HOM ions. 1-methyl naphthalene shows significant differences between the I-CIMS and negative mode data in for higher carbon numbers (C<sub>7</sub> – C<sub>9</sub> ion contributions are small in I-CIMS but contribute significantly to negative mode) but are largely similar for low carbon number with C<sub>4</sub> ions contributing the dominant proportion of signal.

## 4 Discussion

### 4.1 Composition

#### 4.1.1 Comparison with the MCM

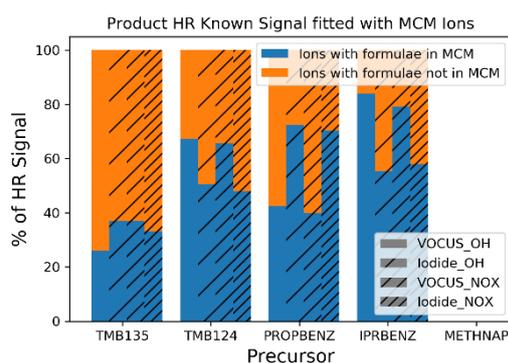


Figure 5 Comparison of signal contribution of ions predicted to form by the MCM and those observed

The Master Chemical Mechanism (MCM, [mcm.york.ac.uk](http://mcm.york.ac.uk)) is a near-explicit chemical mechanism which describes the detailed gas-phase chemical processes involved in the atmospheric degradation of a series of primary emitted VOCs. These include a large number of major emitted anthropogenic and biogenic species, and all of the C<sub>9</sub>-aromatic isomers studied in these experiments.

The construction protocol developed to allow the building of comprehensive, consistent gas phase degradation schemes for aromatic VOCs in the MCM is given in Jenkin et al., 2003, which was subsequently updated, and evaluated/optimised using an extensive range of chamber experiments in 2005 by Bloss et al., (2005a); Bloss et al., (2005b). The general philosophy behind the MCM is to directly use the most up to date available literature information on the kinetics and products of elementary reactions relevant to VOC oxidation in order to build near-explicit representations of atmospheric degradation mechanisms. A fundamental assumption in the mechanism construction process is that the kinetics and products of a large number of unstudied reactions can be defined on the basis of the studied reactions of a smaller subset of similar chemical species, by analogy and with the use of structure-reactivity correlations (structure activity relationships (SARs))(Vereecken et al., 2018) to estimate the otherwise unknown parameters needed to construct the mechanisms.

Comparisons of the observed ions against the gas-phase oxidation products of aromatic hydrocarbons produced in the aromatic chemical schemes in the MCM can act as benchmarks to determine the relative importance of new pathways for different aromatic precursors. **Note that the MCM was not run for any particular conditions for these comparisons, and instead the potential products included in the MCM simply compared with the ions observed in this study.** It also provides a basis for understanding where gas phase mechanisms could be improved in order to describe SOA formation. For the four average spectra of each precursor (1-methyl naphthalene is not within the MCM), the percentage of the mass spectral signal associated ion formulas also predicted by the MCM was calculated and is shown in Figure 5.

The proportion of mass spectral signal associated with ions consistent with MCM products was variable between precursors and techniques, ranging from 25 % (gas phase (low-NO<sub>x</sub>) for 1,3,5-TMB) to 80 % (gas phase (low-NO<sub>x</sub>) for isopropylbenzene). The mechanisms contained within the MCM do not capture the same product profile for the trimethyl benzene isomers, though it should be noted that this agreement would not be expected in the particle phase as the MCM is a gas phase mechanism. Previous chamber experiments have shown good agreement between gas-phase measurements and MCM results, suggesting that its gas phase oxidation is well represented (Metzger et al., 2008; Rickard et al., 2010; Wyche et al., 2009). It may be that conditions in the OFR are dissimilar to these previous chamber experiments or that the measurements herein are more sensitive to previously undetected species. These are signal comparisons, and though in I-CIMS these may be effected by differences in sensitivity, the fact that the Vocus and I-CIMS see similar trends suggests that this does not affect our conclusions that the common ions contribute the majority of product signal as discussed in section 2.3.

#### 4.1.2 Comparison between precursors

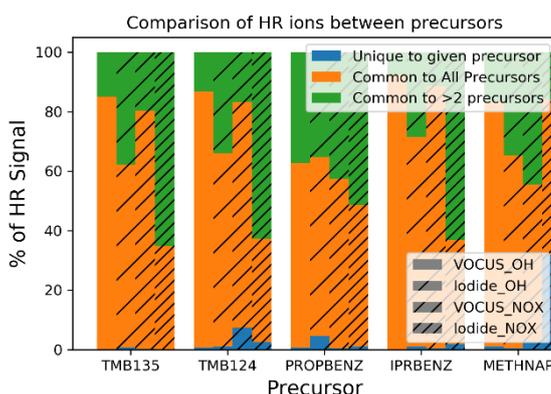
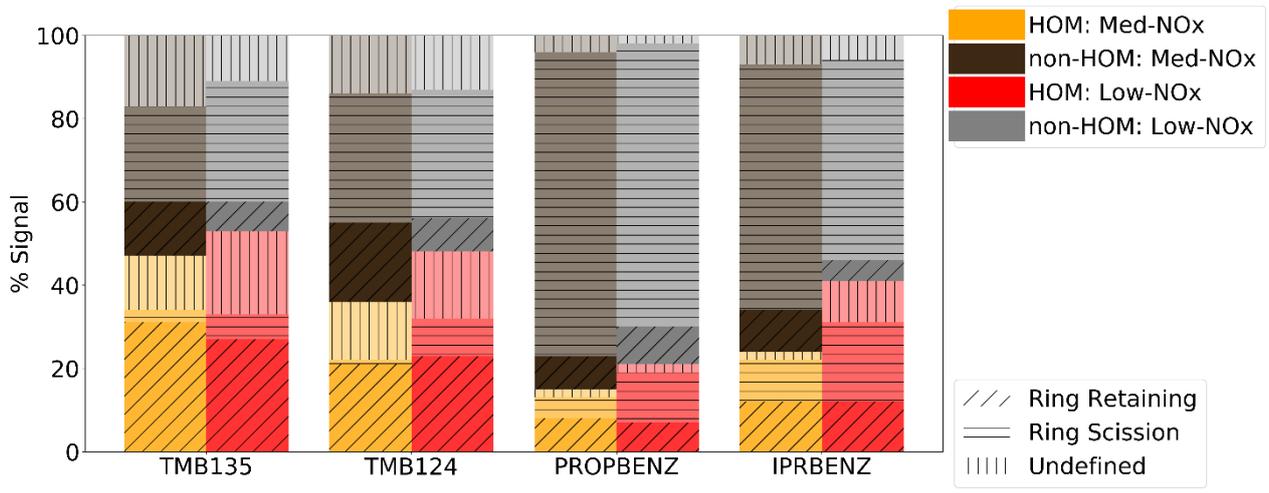


Figure 6 Comparison of signal contributions of ions which were commonly observed from all precursors (orange), ions common to two or more precursors (green) and ions unique to the given precursor (blue) for all precursors and experiments

Here we investigate the similarities and differences in the observed ions across precursors. Products within the MCM are expected to be common between the different aromatic precursors as the decomposition pathways built into the mechanism for the aromatics follow a specific mechanism building protocol (Bloss et al., 2005). The majority of product signal (average of 94 % for I-CIMS, average of 98 % for Vocus) comes from ions with molecular formula that are common between either multiple (green) or all (orange) of the precursors investigated, leaving an incredibly small contribution from ions which are unique (blue) to any given precursor. As discussed previously, most commonalities are between the C<sub>9</sub> precursors (Fig S4) and within this subset, between the trimethyl benzenes. In all cases, unique oxidation products from these different precursors contribute only a tiny amount to overall product signal even in cases where they may contribute significantly to the number of ions (S3). These patterns between observed products are consistent under both low and medium-NO<sub>x</sub> conditions, for the gas and the particle phase. The majority of the common products are ring scission products while a large proportion are also HOMs.

HOMs have varying contribution to the SOA of different aromatic precursors; the proportions of the particle phase (low-NO<sub>x</sub>) and (medium-NO<sub>x</sub>) mass spectra that can be attributed to HOM are shown in Figure 7. The fraction of the particle mass spectra assigned as HOMs is within a few percentage difference under the low and medium-NO<sub>x</sub> conditions for all precursors, except 1-methyl-naphthalene where the proportion drops by half when NO<sub>x</sub> is added (27 % versus 14%). The precursor with the highest fraction of HOMs is 1,3,5-TMB (44-47 %) and the lowest fraction is for propyl benzene (12-15%).

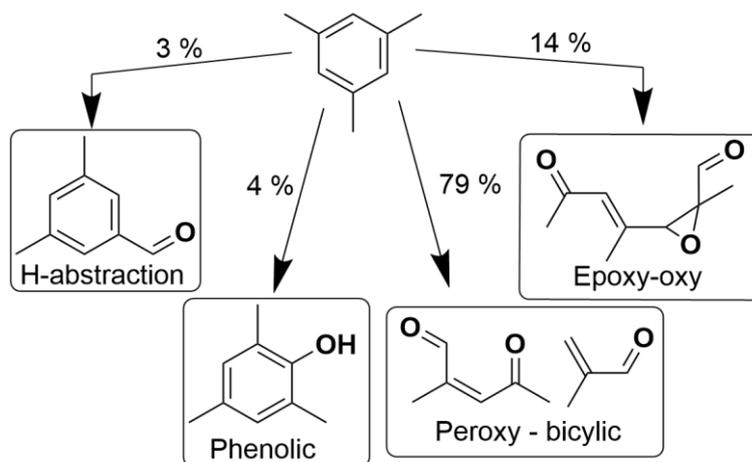


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**Figure 7 Contribution to I-CIMS product signal from HOM and Non-HOM ions under low and medium NOx conditions. The hatched and shaded areas are grouped by ring retaining, scission and for those which we have no definition, derivation of these classifications will be discussed in Section 4.2.**

## 4.2 Mechanisms

480 Aromatic oxidation can proceed via hydrogen abstraction or OH-addition to the ring, with OH addition giving the highest branching ratio (Bloss et al., 2005). Upon OH addition, further oxidation proceeds via the phenolic, epoxy-oxy or bicyclic peroxy radical (BPR) pathways, which have varying relative yields for the different aromatics. These different pathways can result in a variety of ring-retained or ring-scission products, both of which are expected to contribute to SOA (Calvert, 2002; Schwantes et al., 2017).



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**Figure 8 Schematic of OH-initiated oxidation pathways of 1,3,5-trimethyl benzene as included in MCM v3.1 adapted from Metzger et al., 2008**

490 Benzaldehyde and phenolic channels are predicted in the MCM to be less important for more substituted aromatics. Recent work has identified a potential source of ring-retained products from pathways of ipso-addition followed by dealkylation (Loison et al., 2012; Noda et al., 2009), however this has been reported as negligible and thus is not included in the new MCM SARs (Jenkin et al., 2018). Yields from the epoxy-oxy pathway have been measured as significantly smaller than predicted by the MCM (Zaytsev et al., 2019) which are consistent with theoretical work (Li and Wang, 2014; Wu et al., 2014). The relative yields of different pathways are not known for the propyl benzene isomers and are estimated based on toluene (Bloss et al., 2005). The epoxy-oxy radical route is included in the MCM to represent the balance of chemistry not accounted for by other routes (Jenkin et al., 2003). This highlights the importance of more detailed mechanistic work to evaluate the relative importance of different pathways for different isomers.

500 Decomposition via the BPR intermediate or its stabilised isomer is the dominant pathway for all precursors (Jenkin et al., 2018), and recent work has shown that this pathway, which has previously been expected to yield only ring-scission products, can also contribute to the formation of ring-retaining HOMs via oxygen addition (Jenkin et al., 2018) and subsequent autoxidation (Molteni et al., 2018; Wang et al., 2017). It has been suggested that H-migration in BPRs of substituted aromatics may be faster and compete with HO<sub>2</sub>/NO reactions, thereby resulting in increased HOM formation (Wang et al., 2017). Due to the formation of both ring-retaining and ring scission products from the BPR intermediate, it is challenging to predict which precursors would be expected to form more ring-scission or ring retained products.

510 Ring scission products, mainly formed from the decomposition of BPR have been commonly observed from different aromatic precursors (Arey et al., 2009; Wang et al., 2007; Yu et al., 1997). Theoretical studies expect the decomposition of these intermediates into 1,2-dicarbonyls and co-products (Li and Wang, 2014; Wu et al., 2014). The larger co-products have been found at systematically lower yields than the corresponding 1,2-dicarbonyl products (Arey et al., 2009), suggesting further photochemical processing is taking place. Though most studies of these dicarbonyls have been in the gas phase, they have recently been observed in the particle phase from oxidation of aromatics (Zaytsev et al., 2019).

In this study, we provide a comparison of composition for the aromatic precursors and compare the relative importance of different oxidation pathways for different C<sub>9</sub> aromatics. This comparison is important for understanding differences in SOA formation and composition from these often grouped precursors. A companion paper provides detailed discussion of the mechanisms responsible for formation of the dominant oxidised products from these precursors (Wang et al., 2020).

In order to evaluate the ions in a mechanistic context, they have been classified as ring scission or ring-retaining. Ring scission products can be unambiguously defined as ions  $\leq C_5$ . This leaves a subset of larger carbon number ions which could be ring-retaining or ring scission products. To obtain a more accurate representation of ring-retaining products, the double bond equivalency (DBE) was calculated, with ring-retaining ions having a DBE of at least 4. Further classification was attempted through use of an Aromaticity Index (AI), however this proved unsuitable for HOMs which have high oxygen content. The discussion herein is based on ring scission products having  $\leq C_5$  and ring-retaining products being  $\geq C_6$  with a DBE of 4. However, there may be some species, for instance, from the epoxy-oxy route that will be mislabelled using this approach, but their contribution is expected to be minor.

#### 4.2.1 Ring Scission Products

Ring-scission from different aromatics is known to yield a range of alpha-dicarbonyl products and alpha, beta-unsaturated-gamma dicarbonyl, furanone and small acid co-products (Arey et al., 2009; Calvert, 2002; Smith et al., 1998, 1999), many of which are included within the MCM (Bloss et al., 2005). We compare our data to scission products common to a range of aromatics identified by Arey et al. 2009 and all of these were observed in our experiments by I-CIMS (I), Vocus (V) or both (V+I) (Table 4). Ring-scission products are largely dominant in the gas phase, though they play a role in the particle phase composition, particularly so for the less substituted aromatics. In some cases, such as 1,3,5-TMB, known ring scission ions given in Arey et al. are abundant products, for example C<sub>5</sub>H<sub>6</sub>O<sub>3</sub> is the 10<sup>th</sup> largest signal in the particle phase under low-NO<sub>x</sub> conditions. In the MCM, BPR is near exclusively decomposed into ring-scission products which proves suitable for describing the major observed particle phase products for propyl and isopropyl benzene (C<sub>5</sub>H<sub>6</sub>O<sub>6</sub>, C<sub>5</sub>H<sub>6</sub>O<sub>5</sub> and C<sub>4</sub>H<sub>4</sub>O<sub>6</sub>) and explains the larger proportion of product signal observed (Figure 5).

A large proportion of the ring scission products observed in the particle phase are more oxidised than those previously reported (Arey et al., 2009) and many fit the definition of HOM by Bianchi et al., 2019. These products appear to have undergone oxygen addition to the same carbon backbone as many of the small gas phase dicarbonyls, suggesting that further gas phase oxidation and partitioning of dicarbonyl co-products may be an important contributor to SOA. Further processing of these ring-opened products may explain the discrepancy between 1,2-dicarbonyls and their co-products observed in many gas phase studies of aromatic oxidation (Arey et al., 2009). This has been shown previously for SOA formed from 1,3,5-trimethyl benzene where 3-methyl maleic anhydride (C<sub>5</sub>H<sub>4</sub>O<sub>3</sub>), 2-methyl-4-oxo-2-pentenal (C<sub>6</sub>H<sub>8</sub>O<sub>2</sub>) and 3,5-dimethyl-5(2H)-2-furanone (C<sub>6</sub>H<sub>8</sub>O<sub>2</sub>) contribute to SOA formation and growth through further oxidative processing (Johnson et al., 2005; Rickard et al., 2010). Further examples of this are exhibited in our results, including C<sub>7</sub>H<sub>10</sub>O<sub>2</sub>, which is observed from both trimethyl benzene isomers in Vocus gas phase mass spectra, and C<sub>7</sub>H<sub>10</sub>O<sub>(4-7)</sub> formulas that are some of the most dominant product ions observed in SOA from both trimethyl benzene isomers. In the case of 1,2,4-TMB, C<sub>5</sub>H<sub>6</sub>O<sub>2</sub> is observed in the gas phase while C<sub>5</sub>H<sub>6</sub>O<sub>(3-7)</sub> are dominant ions in the particle phase. This is also the case for propyl benzene, where C<sub>5</sub>H<sub>6</sub>O<sub>5</sub> and C<sub>5</sub>H<sub>6</sub>O<sub>6</sub> are the two largest contributors to the particle phase. Other observed products can be explained by further oxidation of scission products within the MCM, such as C<sub>4</sub>H<sub>6</sub>O<sub>6</sub> which is a major ion from isopropyl benzene oxidation.

Dicarbonyl Products	TMB124	TMB135	PRBZ	MN	IPRBZ
C <sub>5</sub> H <sub>6</sub> O <sub>2</sub>	V	V	V	V	V
C <sub>6</sub> H <sub>8</sub> O <sub>2</sub>	V	V+I	V	V	V

C <sub>7</sub> H <sub>10</sub> O <sub>2</sub>	V+I	V	V+I	V	V+I
C <sub>5</sub> H <sub>6</sub> O <sub>3</sub>	V +I	V+I	V+I	V	V
C <sub>6</sub> H <sub>8</sub> O <sub>3</sub>	V+I	V+I	V+I	V+I	V+I

555 **Table 2 Dicarboxyl products observed in gas and particle phase from Arey (2009) under low-NO<sub>x</sub> conditions (V and I stand for Vocus and I-CIMS respectively)**

The most dominant of the scission products we observe in gas and particle phases are lower carbon number than those within the MCM, with C<sub>3</sub> products being most dominant in the gas phase for PROPBENZ, IPRBENZ and METHNAP, and C<sub>4</sub> products being more important in the TMBs. In the particle phase, C<sub>4</sub> scission products have the largest contribution for TMB124 and METHNAP. Scission products we observe have previously been detected from oxidation of 1,2,4-trimethyl benzene including C<sub>5</sub>H<sub>8</sub>O<sub>3</sub>, C<sub>4</sub>H<sub>6</sub>O<sub>3</sub> and C<sub>3</sub>H<sub>4</sub>O<sub>2</sub> (Zaytsev et al., 2019). Ring scission remains a dominant pathway under the NO<sub>x</sub> conditions, though the spread across carbon numbers increases in the gas and particle phases as shown in the carbon number distributions. Ring-scission HOMs are most commonly observed in the particle phase for the C<sub>4</sub> and C<sub>5</sub> products and are particularly important in the case of the C<sub>9</sub> aromatics. Newly proposed epoxy-dicarboxyl products (Li and Wang, 2014) have also been observed in this study (C<sub>4</sub>H<sub>4</sub>O<sub>3</sub> – epoxybutanedial, C<sub>5</sub>H<sub>6</sub>O<sub>3</sub> – methyl epoxybutanedial and C<sub>6</sub>H<sub>8</sub>O<sub>3</sub> – dimethyl epoxybutanedial) from all aromatic precursors in the particle phase.

#### 4.2.2 Ring-retaining Products

Ring-retaining products can form from two different pathways: hydrogen abstraction (from the attached alkyl groups) which can result in fragmented ring-retaining products or via the BPR pathway which results in non-fragmented ring-retaining products.

Ring-retaining HOMs from 1,3,5-trimethyl benzene oxidation have been identified from experiments carried out in a range of different chambers and conditions (Molteni et al., 2018; Sato et al., 2012; Tsiligiannis et al., 2019). Our observations show good agreement with ion formulas observed in these experiments, with divergence at significantly higher NO<sub>x</sub> conditions (Tsiligiannis et al., 2019). This includes observations of ions such as C<sub>9</sub>H<sub>12</sub>O<sub>(2-8)</sub> which are observed by Molteni et al., 2018 and consistent with closed shell products expected by the mechanisms outlined in Wang et al., 2017, alongside ions observed by LC-ToF-MS(Sato et al., 2012, 2019) which were all important in our experiments (Table S1). Ring retention was previously found to contribute ~ 25 % of SOA mass from a study 1,2,4-trimethyl benzene under elevated NO<sub>x</sub> conditions which were attributed to BPR, phenolic and benzaldehyde channels despite low ring-retaining concentrations in the gas phase, consistent with our observations. These results identified ions such as C<sub>9</sub>H<sub>12</sub>O<sub>(4-6)</sub> which are also dominant in our observations for both 1,2,4- and 1,3,5-trimethyl benzenes, though we also observed a significant contribution from more oxidised ions such as C<sub>9</sub>H<sub>12</sub>O<sub>6</sub> and C<sub>9</sub>H<sub>14</sub>O<sub>6</sub> (Zaytsev et al., 2019).

Molteni et al. (2018) suggested that ring-retaining products with ion formulas containing 4-6 more hydrogen atoms more than their parent hydrocarbon could be attributed to multiple-OH attacks. More recently, Tsiligiannis et al. (2019) has shown that C<sub>9</sub>H<sub>14</sub>O<sub>2</sub> products from oxidation of 1,3,5-trimethyl benzene have characteristics of second generation products due to their enhanced contributions in experiments with higher OH exposures. Thus, in order to obtain a lower bound estimate of the contribution multi-generational OH attack, ions with greater than 14 hydrogen atoms were classed as multi-generational products. Overall their contribution to signal is < 10 % in all experiments (Figure S5 – S6).

Previous results have suggested that C<sub>8</sub> and C<sub>7</sub> compounds such as C<sub>8</sub>H<sub>10</sub>O<sub>(4-5)</sub> and C<sub>7</sub>H<sub>8</sub>O<sub>(4-5)</sub> from 1,2,4-trimethyl benzene oxidation can be formed from the dealkylation pathway, though they may also be formed from multiple pathways (Noda et al., 2009; Zaytsev et al., 2019)). However, other studies have shown that dealkylation is not a significant pathway (Aschmann et al., 2010; Loison et al., 2012). In our results, C<sub>8</sub> ions are only important for the trimethyl benzenes indicating that this pathway may be important for these precursors

but not for others. Though we observe the less oxidised C<sub>8</sub> products, the major C<sub>7-8</sub> products we observe are C<sub>8</sub>H<sub>10</sub>O<sub>6</sub> for TMB124 and C<sub>8</sub>H<sub>10</sub>O<sub>7</sub> for TMB135.

To gain a broader overview of the importance of ring-retaining products across the various precursors, we have estimated the contribution of ring-retaining ions to total product signal. Our results show that ring retained  
600 HOM formation is most important for TMB135 where these ions contribute 27 % of total observed product signal in the particle phase measured by I-CIMS, with a smaller contribution of 23 % to TMB124, and a minor contribution to IPRBENZ (12 %) and PROPBENZ (7 %) under low-NO<sub>x</sub> conditions (Figure 7).

This indicates that ring-retaining product formation is important for the aromatics hydrocarbons with more  
605 substituent groups on the ring rather than a single alkyl side chain, suggesting that the substitution plays a role in favouring retention of the ring during both H-abstraction and OH addition. This may be due to stabilisation of substituent ring or due to the steric hindrance of the methyl groups which make OH attack less favourable and result in a larger than estimated branching ratio of H-abstraction from the methyl group. It is apparent in our results that ring-retained HOMs persist upon perturbation by NO, suggesting that favourable transition state geometry of the more substituted aromatics may play a role in ensuring autoxidation of BPR remains  
610 competitive at higher NO conditions. This is not observed for the less substituted aromatics, which generally produce less HOM in the presence of NO<sub>x</sub>.

Under low-NO<sub>x</sub> conditions, the relative importance of autoxidation for formation of ring-retaining HOMs from BPR intermediates varies for the different precursors and such impacts upon the relative yields of ring-retaining vs. ring-scission products. In the cases of propyl and isopropyl benzene, ring-retained HOM formation has a  
615 minor contribution to products highlighting the role that substituent groups on the aromatic ring play in favouring autoxidation leading to ring-retained HOM formation. Isopropyl benzene SOA has a larger contribution from ring-opened HOMs in the particle phase despite a larger contribution from ring-retaining products in the gas phase, suggesting though their formation occurs, they undergo further oxidation and scission before partitioning.

620 Though we lack knowledge of specific pathways for methyl naphthalene, our observations of products which are assumed to contain a single ring ( $\leq$  C<sub>10</sub>) are consistent with that of the C<sub>9</sub>-aromatics, suggesting that beyond the opening of the first aromatic ring, the oxidation proceeds via similar pathways to that of the C<sub>9</sub>-aromatics. Overlap in observations between C<sub>9</sub>-aromatics and the PAH could prove useful as a basic description of the major products formed in the photo oxidation of methyl naphthalene.

### 625 4.3 Implications for Ambient Observations

Aromatic oxidation leads to formation of oxidised products, which are largely common to all aromatic precursors. This makes identifying their contribution to ambient SOA challenging using online techniques. Furthermore, unique product ions contribute a tiny proportion of signal and thus it is challenging to differentiate between different aromatics. However, markers are widely used for the interpretation of ambient  
630 measurements, and many of the ions we observe correspond to formulas which have been reported as markers of other precursors or oxidation pathways. This is shown in Table 5 where we compare the major ions observed from all aromatics with previous literature and suggests that some of these source attributions may not be valid when aromatics are present.

A rapid increase in the development and application of novel mass spectrometric techniques has given a wealth  
635 of near-molecular level detail which is unprecedented in atmospheric chemistry (Isaacman-VanWertz et al., 2017; Laskin et al., 2018). Such high resolution observational datasets are extremely useful for the development and evaluation of detailed chemical mechanisms used to understand and simulate gas and aerosol phase composition in a wide variety of science and policy applications related to air quality and climate. Comparing our results with other laboratory and field experimental observations shows that some major ions from  
640 aromatic oxidation are concurrent with other sources or VOC systems which has implications for marker identification in ambient datasets. For example, C<sub>9</sub>H<sub>12</sub>O<sub>6</sub>, observed in all aromatic oxidation experiments which

has previously been identified in cases of biomass burning (Kourtchev et al., 2016) and also as a product of limonene oxidation (Hamilton et al., 2011).  $C_7H_8O_6$  and  $C_9H_{12}O_7$  have been observed from aromatic autoxidation (Molteni et al., 2018), however  $C_7H_8O_6$  is also as a product of alpha phellandrene ozonolysis (Mackenzie-Rae et al., 2018). Another product observed from all aromatic precursors is  $C_8H_{12}O_6$  which is widely reported as MBTCA, a marker of monoterpene SOA (Hu et al., 2013; Kourtchev et al., 2016). The majority of these observations are from CIMS approaches which lack the separation of LC or GC.

Though we observe some unique ion signal, this signal is distributed amongst many ions so no single ion has a large enough signal intensity to be used as a marker, and these low signal intensity ions are thus likely to be absent in complex ambient spectra. Even in single component experiments they are not ideal unambiguous markers of SOA, thus, in more complex and ambient SOA samples, it is hard to see how they could be used effectively. Furthermore, due to these ions being minor components, they are difficult to assign formulas due to a relatively poor SNR and as many of them are small carbon numbers, they could be the result of low signal intensity. Thus, comparison of precursors suggests that identifying tracers from aromatic precursors using online techniques with no pre-separation is not possible. Most striking is the fact that methyl naphthalene, which is a  $C_{11}$  molecule has > 68 % of signal common with the other precursors in all cases, despite the fact that its oxidation will proceed differently. Tracer based detection of SOA is thus not likely to be useful in ambient measurements, and though potentially isomeric information may provide unique markers, ion formulas themselves are unlikely to uniquely identify sources between different aromatic precursors.

Ion Formula common to all aromatic experiments	Sources Previously Reported	References
$C_9H_{12}O_6$	Limonene	(Hamilton et al., 2011)
$C_8H_{10}O_6$	Isoprene	(Nguyen et al., 2011)
$C_8H_{10}O_7$	Biomass burning, Guaiacol	(Qi et al., 2019; Romonosky et al., 2014)
$C_7H_8O_6$	Guaiacol	(Romonosky et al., 2014)
$C_9H_{12}O_7$	$\alpha$ -pinene	(Romonosky et al., 2014)
$C_4H_4O_6$	Tartaric acid	(Cheng et al., 2016)
$C_8H_{12}O_6$	$\alpha$ -pinene	(Szmigielski et al., 2007)
$C_3H_4O_4$	Pinene, burning, seasalt	(Isaacman-Vanwertz et al., 2018; Legrand et al., 2007)
$C_6H_6O_6$	Biomass burning	(Qi et al., 2019)
$C_7H_8O_7$	Biomass burning	(Qi et al., 2019)
$C_7H_8O_5$	o-cresol	(Schwantes et al., 2017)
$C_4H_4O_4$	$\alpha$ -Pinene	(Zhang et al., 2015)
$C_4H_4O_5$	$\alpha$ -pinene	(Takeuchi and Ng, 2019)
$C_3H_4O_5$	Maleic acid	(Gallimore et al., 2011)
$C_5H_4O_4$	Biomass burning	(Priestley et al., 2018)
$C_8H_{12}O_5$	$\alpha$ -pinene	(Shilling et al., 2009)

C <sub>8</sub> H <sub>10</sub> O <sub>5</sub>	a/b-pinene	(Takeuchi and Ng, 2019)
C <sub>8</sub> H <sub>8</sub> O <sub>7</sub>	Biomass burning	(Qi et al., 2019)
C <sub>7</sub> H <sub>8</sub> O <sub>8</sub>	a-pinene	(Krechmer et al., 2016)
C <sub>4</sub> H <sub>6</sub> O <sub>6</sub>	Isoprene	(Krechmer et al., 2016)
C <sub>7</sub> H <sub>10</sub> O <sub>4</sub>	Limonene	(Faxon et al., 2018)

660 **Table 3 Comparison of ions observed commonly from all aromatic precursors with these ions reported in literature**

## 5 Conclusions

Oxidation of different C<sub>9</sub>-aromatic isomers results in formation of similar products, however the signal distribution of these products in the gas phase and particle phases are distinct. Gas and particle phase compositions are distinct from one another, with many HOMs being observed almost exclusively in the particle phase I-CIMS measurements and many small scission products exclusively in the Vocus measurements.

665 Comparison of observations with the gas phase MCM mechanism highlights that the MCM does not capture the full extent of observed ions, particularly the more oxidised HOM products formed from autoxidation pathways which have not been included in this mechanism. Comparing the online I-CIMS and Offline Orbitrap UPLC-MS observations shows good agreement in negative mode, with a large overlap in ring-retaining HOM ions observed by both techniques.

670 Evaluating products in terms of their formation mechanisms shows that oxidation of the more substituted aromatic precursors leads to a larger contribution of ring-retained products, while the single substituent aromatics yield large proportions of scission products. Overall, ring-retaining HOM products are the minor contributor to SOA product signal (< 40 %) while known scission products appear to undergo further oxidation and are major contributors to SOA from all aromatic precursors.

680 Perturbation of the oxidation system with NO<sub>x</sub> shows that HOM formation from aromatics proceeds at higher NO and this effect is most important for the more substituted trimethyl benzene isomers which continue to form ring-retained HOMs at higher NO<sub>x</sub>. The variation in composition between the C<sub>9</sub>-aromatic isomers suggests that grouping VOCs by carbon number for SOA formation may not be valid and the number of substituent groups may be a more valid grouping to capture their different SOA product distributions. Comparison with 1-methyl naphthalene shows that the products from a different starting precursor are largely similar, with the distributions being the key to differentiation of SOA from different precursors.

685 Comparison of ions observed from aromatic oxidation with literature shows overlap with those from other sources, suggesting that some source attributions may not be valid when aromatics are present. Correspondences between laboratory and ambient spectra have been observed for oxidation products of biogenic VOCs (Yan et al., 2016), however this approach has not been taken for anthropogenic VOCs. Through co-measurement of many ions, these results are expected to support studies evaluating the importance of aromatics for urban SOA formation. This study has focused on single components; however, future work is required to identify the impact that mixing aromatics with biogenics has upon SOA composition (McFiggans et al., 2019).

## 6 Author Contribution

695 AM and HC designed the experiments. Instrument deployment and operation were carried out by AM, YW, JEK, AL, FM, PC, MAM, and MRC. I-CIMS data analysis was carried out by AM and Vocus data analysis by YW. DJB prepared the aerosol samples for LC-MS analysis. KLP designed the non-targeted LC-MS analytical and data processing methodology, analysed the samples and provided the processed data. AM, YW and JFH wrote the

paper. All co-authors discussed the results and comments on the manuscript. The authors declare that they have no conflicts of interest.

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## 8 Competing Interests

The authors declare that they have no conflict of interest.

## 705 9 Data Availability

Data is available upon request from the corresponding author.

## 10 Supplement

Supplement is attached.

## 11 References

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