



Cite this: *Environ. Sci.: Atmos.*, 2023, 3, 1174

Different chlorine and hydroxyl radical environments impact *m*-xylene oxidation products†

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Airborne emissions of aromatic hydrocarbons including benzene, ethylbenzene, toluene, and xylenes are associated with anthropogenic activities (e.g. transportation) and form secondary organic aerosol (SOA) when oxidized. While hydroxyl radicals (OH) dominate oxidation, chlorine radicals (Cl) react with alkyl substituted aromatics more rapidly and favor a different oxidative pathway. High concentrations of reactive chlorine species have been observed in continental and coastal regions, where mixed Cl/OH chemistry is expected to influence regional SOA formation and composition. This study uses environmental chamber experiments to assess SOA formation and composition from the oxidation of *m*-xylene in mixed Cl/OH oxidation environments. Experiments were conducted with hydrogen peroxide (H₂O₂), chlorine (Cl₂), and nitryl chloride (ClNO₂) radical precursors under high and low NO_x conditions. Data was collected with an Aerosol Chemical Speciation Monitor (ACSM), Scanning Electrical Mobility System (SEMS) and time of flight chemical ionization mass spectrometer with filter desorption (FIGAERO-CIMS) utilizing H₃O⁺ and I⁻ reagent ions. Different oxidative pathways in H₂O₂ and Cl₂ experiments resulted in bicyclic peroxide and methylbenzoquinone species, respectively. When Cl₂ was the sole radical precursor, SOA was more highly oxidized and less fragmented. ClNO₂ experiments formed substantial amounts of bicyclic peroxide and minimal methylbenzoquinone in the gas phase and less oxidized SOA with a lower fraction of organochlorides. These differences are related to secondary OH formation and slower ClNO₂ photolysis driving lower Cl radical concentrations. This study provides evidence that gas and particle-phase products vary depending on the oxidative environment and underlines the importance of studying novel oxidants and oxidative pathways.

Received 17th February 2023
Accepted 27th May 2023

DOI: 10.1039/d3ea00024a

rsc.li/esatmospheres

Environmental significance

Aromatic hydrocarbon oxidation forms atmospheric aerosols which impact health and climate. Previous environmental chamber studies focus on OH radical oxidation, but Cl radicals react faster with alkyl substituted aromatics along an alternate reaction pathway. Experiments with H₂O₂, Cl₂, and ClNO₂ examine gas phase chemistry, particle formation, and product composition from oxidation of *m*-xylene. We demonstrate OH and Cl oxidation results in different products. More highly oxidized organic aerosol is formed in experiments when only Cl₂ is a radical precursor. Using ClNO₂ as a radical precursor results in different chemistry and product distributions than Cl₂ + NO_x, indicating ClNO₂-laden air reacts differently than Cl₂ emissions in high NO_x environments. Exploration of radical precursors is required to constrain Cl oxidation impacts.

1 Introduction

Aromatic hydrocarbons are a substantial fraction of volatile organic compound (VOC) emissions globally and regionally.^{1–3} In urban environments, small aromatics including benzene, toluene, ethylbenzene, and xylenes (BTEX) often dominate observed VOCs, and their main source is thought to be transportation.^{4,5}

Atmospheric oxidation of these species leads to substantial formation of ozone, oxidized volatile organic compounds (OVOCs),^{6,7} and secondary organic aerosol (SOA).^{8–10} SOA impacts climate forcing¹¹ and human health,¹² and a complete understanding of formation mechanisms is necessary to evaluate policy options to reduce SOA. Environmental chamber experiments on hydroxyl radical (OH) oxidation of BTEX compounds show SOA yields ranging from 5–40% dependent on seed aerosol, NO_x concentration, and relative humidity (RH).^{10,13–15} Estimated SOA production from these aromatics ranges from 2–12 Tg annually.⁹

While hydroxyl radicals (OH) are the most abundant radical in the atmosphere and are thought to dominate aromatic

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3ea00024a>



hydrocarbon oxidation,^{10,16} chlorine radicals (Cl) may also have a substantial impact due to their more rapid reaction rate with substituted aromatic hydrocarbons.¹⁷ However, atmospheric Cl radical concentrations have been historically underestimated and consequently understudied.¹⁸ Rapid oxidation by Cl may enhance SOA formation due to rapid formation of semivolatile organic compounds (SVOCs).^{10,19} In addition, while OH radicals add to the aromatic ring in over 90% of initial oxidations,^{7,20} Cl radicals perform hydrogen abstraction from alkyl substituents on the aromatic ring.^{17,21} Previous work on toluene + Cl oxidation has illustrated differences in gas phase products compared to OH radical oxidation including formation of aldehyde, peroxy acid, and quinone species.²² Particles were more highly oxidized from Cl-initiated chemistry than from OH-initiated reactions, and chlorinated species were observed.^{22,23}

Prior work on chlorine oxidation typically utilized molecular chlorine (Cl₂) as the chlorine radical precursor.^{22–27} While Cl₂ has been observed far inland of marine and coastal sources including in urban environments,^{28,29} nitryl chloride (ClNO₂) is often more abundant than Cl₂ in these environments, particularly in early morning air masses.³⁰ Near oil and gas production well sites, Cl₂ concentrations were observed to be higher than ClNO₂.³¹ Atmospheric sources of Cl₂ are largely associated with industrial emissions and biocides, though some heterogeneous reactions on chloride aerosols have been shown to produce Cl₂.^{32,33} ClNO₂ is primarily produced from heterogeneous reaction of dinitrogen pentoxide (N₂O₅) with particulate or aqueous chloride from sources including sea salt aerosol, biomass burning aerosol, saline snowpack, playa dusts, and aerosol in polluted megacities.^{34–37} Beyond being an atmospherically relevant Cl source, ClNO₂ photolysis generates NO₂, which photolyzes to NO. Under these high NO_x conditions, Cl radical oxidation leads to formation of secondary OH radicals as NO reacts with HO₂.³⁸ Secondary hydroxyl radical production under high NO_x conditions has been shown to obscure the impact of Cl radicals from traditional VOC decay techniques for assessing Cl radical concentrations.³⁹ Furthermore, the presence of NO_x suppresses SOA formation from aromatics due to a shift in peroxy radical fate and subsequent fragmentation.^{10,14,40} Nitryl chloride generates a complex mixture of radicals and oxidants with substantial impacts on gas phase chemistry, SOA formation, and SOA composition.

Here, we evaluate the impacts of different oxidative environments on the formation of gas and particle phase products from the oxidation of *m*-xylene in an environmental chamber. We utilize chlorine gas, nitryl chloride, and hydrogen peroxide as radical precursors under high and low NO_x conditions, generating environments in which only OH, only Cl or a mixture of both radicals are initiating oxidation of hydrocarbons. These different oxidative environments have substantial impacts on gas and particle phase products and composition. We observe and discuss the formation of several gas phase products, and evaluate chemically-speciated particle composition using a thermal desorption technique. We also assess SOA mass yield and bulk composition.

2 Methods

2.1 Chamber photo-oxidation experiments

Oxidation experiments were conducted in a 10 m³ Teflon environmental chamber at 298 K at 30% relative humidity (RH) using UV black lights with a peak emission at 354 nm to generate radicals. Clean dry air was supplied to the chamber using a clean-air generator (model 727R, AADCO). The chamber was flushed overnight with humidified clean air to reach the target 30% RH. Dried ammonium sulfate seed particles were generated from 0.05 M aqueous ammonium sulfate injected with an aerosol generation system (AGS 2002, Brechtel). Chlorine gas (100.3 ppm in N₂, Airgas) was directly injected into the chamber. Multipoint calibrations of the I[−] CIMS for Cl₂ were performed based on repeated injections into the chamber. Nitryl chloride was generated reactively by passing Cl₂ (100.3 ppm in N₂) at a low flow rate (0.25 L min^{−1}) over a solution of sodium nitrite as previously described.⁴¹ Based on data from the iodide mode chemical ionization mass spectrometer (I[−] CIMS), >99% of Cl₂ is consumed at this flow rate (<1% of initial Cl₂ signal remains) and for calibration purposes, it is assumed that 100% of Cl₂ injected is converted to ClNO₂ during ClNO₂ injection to the chamber. Formation of the common NO₂ byproduct during ClNO₂ synthesis is not observed in this study. Multipoint I[−] CIMS calibration for ClNO₂ was performed based on repeated injection into the chamber based on this 100% conversion. Hydrogen peroxide was injected as an OH radical

Table 1 List of experimental conditions, SOA formation, and selected organic yields

#	Radical precursors	[VOC] ₀ (μg m ^{−3})	[Cl ₂] ₀ (ppb)	[ClNO ₂] ₀ (ppb)	[H ₂ O ₂] ₀ (ppm)	[NO _x] ₀ (ppb)	Max SOA ^a (μg m ^{−3})	Yield ^b (%)
1	ClNO ₂	340	<0.1	50	<0.1	<2	— ^c	—
2	ClNO ₂	340	<0.1	50	<0.1	<2	12.7	4.8
3	Cl ₂ + NO _x	340	25	<0.1	<0.1	20	12.0	—
4	Cl ₂	340	25	<0.1	<0.1	<2	24.3	8.8
5	Cl ₂	340	25	<0.1	<0.1	<2	— ^c	—
6	H ₂ O ₂ + NO _x	340	<0.1	<0.1	1	20	10.1	4.4
7	H ₂ O ₂	340	<0.1	<0.1	1	<2	11.2	—
8	Cl ₂ + ClNO ₂	340	10	30	<0.1	<2	11.3	—
9	Cl ₂ + H ₂ O ₂	340	10	<0.1	1	<2	— ^c	—
10	Cl ₂ + ClNO ₂ + H ₂ O ₂	340	5	15	1	<2	10.1	—

^a Peak SOA is calculated based on wall loss corrected ACSM organic loading following the UV illumination period. ^b Yield (organic aerosol mass yield) is calculated for experiments where H₃O⁺ CIMS data are available to measure xylene consumption. ^c Aerosol data unavailable for this experiment.



precursor by bubbling clean dry air at 2 L min^{-1} through a 30% hydrogen peroxide solution (Sigma Aldrich) for 1 hour. Hydrogen peroxide concentration was estimated at 1 ppm based on interference in the 254 nm photometric ozone monitor and the relative ratios of the absorption cross sections of ozone and hydrogen peroxide at 254 nm. I^- CIMS measurements of hydrogen peroxide injection indicated that injections were repeatable, and response was linear with respect to injection volume. *m*-Xylene (>99% purity, Sigma Aldrich) was injected into a glass gas sampling tube which was flushed into the chamber with heated clean air at 2 L min^{-1} for 30 minutes. Complete vaporization and injection of *m*-xylene into the chamber is assumed in calculating initial concentrations. Nitric acid (NO) (50.3 ppm in N_2 , Airgas) was directly injected into the chamber for high NO_x experiments. Initial VOC and oxidant precursor concentrations are listed in Table 1.

An example experimental time series is shown in Fig. 1. Following injection, VOCs, oxidant precursors, and seeds were allowed to mix and then UV lights were turned on (time = 0 in Fig. 1) to initiate photo-oxidation. Cl_2 (or other radical precursors) are photolyzed to form radicals which oxidize *m*-xylene to form oxidation products including SOA and OVOCs. Photo-oxidation continued for 1 to 2 hours until organic aerosol concentrations stabilized. Organic aerosol concentrations stabilized earlier for Cl_2 experiments due to its rapid photolysis rate compared to ClNO_2 and H_2O_2 . *m*-Xylene was typically not completely consumed. "Blank" experiments were conducted the day before and after photo-oxidation experiments where only oxidant precursors and ammonium sulfate seed were present. Minimal SOA formation ($<1 \mu\text{g m}^{-3}$) was observed in "blank" experiments.

2.2 Instrumentation

NO and total NO_x concentrations were monitored with a chemiluminescent monitor (200E, Teledyne); limit of detection (LOD)

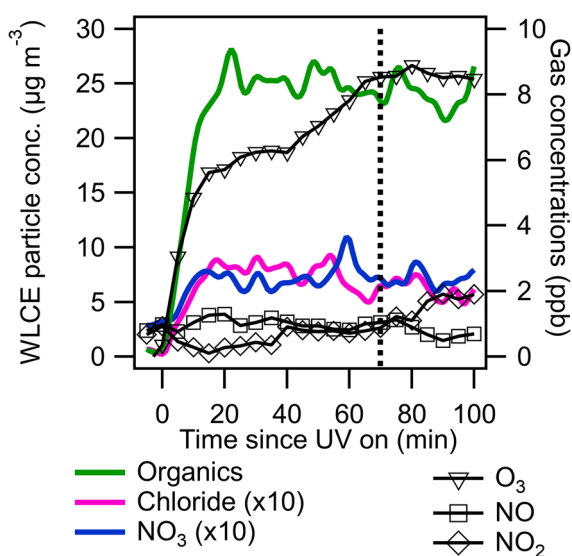


Fig. 1 Experiment 4 (Cl_2) wall loss and collection efficiency corrected (WLCE) ACSM data (left axis) and trace gas monitor data (right axis). Chloride and nitrate traces are multiplied by 10 for legibility. Vertical dashed line indicates end of UV light on period.

0.4 ppb and ± 0.2 ppb accuracy. NO_2 concentrations were measured directly using a monitor from Environnement (Model AS32M) using a cavity attenuated phase shift (CAPS) method; LOD 0.1 ppb and ± 0.05 ppb accuracy. Ozone concentrations were monitored with a photometric ozone analyzer (400E, Teledyne); LOD 0.6 ppb and ± 0.3 ppb accuracy. Particle size distributions in the 10–1000 nm size range were measured using a scanning electrical mobility system (SEMS, Brechtel model 2002). Bulk particle phase composition was assessed using an aerosol chemical speciation monitor (ACSM, Aerodyne),⁴² calibrated with 300 nm size-selected ammonium nitrate and ammonium sulfate particles. Particle phase concentrations from the ACSM were corrected for chamber wall losses and instrument collection efficiency by taking the ratio of organic to sulfate signal and multiplying by the initial ammonium sulfate seed concentration measured by the SEMS data as previously described.¹⁵ Wall loss and collection efficiency corrected (WLCE) ACSM data were used to calculate SOA yield for experiments 2, 4, and 6 where *m*-xylene consumption was measured by switching the CIMS reagent ion to the positive hydronium ion (H_3O^+ CIMS). A single CIMS system was utilized in this study and was switched between negative (I^-) and positive (H_3O^+) modes for some experiments. SOA yield was calculated as the change in wall loss corrected ACSM organic mass from before and after the UV photo-oxidation period divided by the mass of *m*-xylene consumed.

Gas and particle phase composition was assessed using a Filter Inlet for Gases and Aerosols coupled to an iodide mode chemical ionization mass spectrometer (FIGAERO-CIMS, Aerodyne). Iodide mode FIGAERO-CIMS has been described in detail elsewhere.^{43,44} In this application, real time gas phase chemistry was observed using I^- CIMS including the decay of oxidant precursors and the formation of oxidized VOCs. In addition, H_3O^+ CIMS was utilized to examine the decay of *m*-xylene during some oxidation experiments. Following UV photooxidation, lights were turned off and particles were collected on the FIGAERO-CIMS PTFE filter (1 μm pore Zefon filters) at 3 SLPM for 45 minutes. Filters were desorbed using heated N_2 (Airgas) which began at 25 $^\circ\text{C}$ and was heated to 300 $^\circ\text{C}$ over 30 minutes and held at 300 $^\circ\text{C}$ for 10 minutes. This particle desorption method allows for detailed speciation of a wide range of particle phase organic species.

For both gas and particle phase analysis of CIMS, high resolution peak fitting and identification was performed using the Tofware data analysis package. For I^- CIMS, all identified species are iodide adducts (elemental formula contains I^-) and it is assumed that I^- is from ionization in the instrument and was not present on the analyte. Similarly, H^+ or H_3O^+ adducts are formed in positive mode CIMS. CIMS can only provide elemental compositions without information about molecular structure. When species are discussed, their likely structures are inferred based on expected reaction mechanisms and products. I^- CIMS calibration was performed as described above for radical precursor species (H_2O_2 , Cl_2 , and ClNO_2). Such calibrations were performed within 6 weeks of the experiment to which they were applied. All other species detected in the I^- CIMS are presented normalized to I^- reagent ion signal where analyte signal is divided at each time point by I^- signal and multiplied by 100 000. This normalization procedure adjusts for variability in reagent



ion concentration. I^- reagent ion signal varied by 10–30% during experiments, particularly during Cl_2 experiments as Cl_2 depletes I^- reagent ion. I^- CIMS sensitivity is also highly dependent on sample humidity.⁴³ To stabilize instrument response, reagent ion flow is humidified to above 70% RH by bubbling the reagent ion source N_2 through purified water (MilliQ water purification system, ThermoScientific). Based on prior literature,⁴³ I^- CIMS limits of detection for compounds discussed here are in the 10 s of ppt or lower and accuracy is within ± 10 ppt.

Particle phase data from the FIGAERO is background subtracted and then integrated across the full thermal desorption period. In several cases, species are discussed and grouped based on their elemental composition. For example, organochlorine species with the composition $\text{C}_{2-10}\text{H}_y\text{O}_z\text{Cl}_{1-3}\text{I}^-$ are discussed and consist of the total summed signal of all species which contain 2 to 10 carbon atoms, 1 or more hydrogen, 1 or more oxygen, and 1 to 3 chlorine atoms.

2.3 Chamber box modeling

A chamber box model utilizing the Carbon Bond Mechanism (version 6, revision 4) from the Comprehensive Air Quality Model with Extensions (CAMx)⁴⁵ with previously described modifications for chlorine radical chemistry⁴⁶ was used to model these experiments. Radical precursor, *m*-xylene, NO_x , temperature, and humidity concentrations were initialized in the model. UV light intensity in the model is based on previously measured blacklight spectra (P-200 spectroradiometer, Apogee Instruments). Chamber characterization experiments⁴⁷ provided measured NO_2 photolysis rates, chamber leak rate (Cl_2 utilized as a leak tracer), and wall effects. Modeling was used to capture OH and Cl radical concentrations. Fig. 2a–c shows measured and modeled consumption of radical precursors alongside modeled *m*-xylene consumption for low NO_x Cl_2 , ClNO_2 , and H_2O_2 experiments. Model results indicate that Cl_2 is rapidly consumed, while ClNO_2 and H_2O_2 have much slower modeled rates of consumption due to a lower photolysis rate under chamber lighting conditions. While chlorine consumption shows good model agreement, nitryl chloride consumption deviates slightly and hydrogen peroxide consumption deviates substantially from model predictions. This difference in modeled and measured radical precursor decay may be due to uncertainties associated with the measured UV spectrum. The absorption cross sections of H_2O_2 and ClNO_2 overlap only slightly with the measured emission spectrum of the UV lights and small errors in spectrum or absorption cross section measurements may substantially alter modeled photolysis rates. Absorption cross sections for radical precursors and the measured light spectrum used in the chamber model are shown in Fig. S1.†

3 Results and discussion

3.1 Radical precursor identity alters gas phase products and degree of oxidation

Chlorine and hydroxyl radicals utilize different primary oxidation pathways as illustrated in Schemes 1 (Cl) and 2 (OH). Three selected products illustrate these reaction pathway differences: 2-methyl-1,4-benzoquinone is formed primarily through

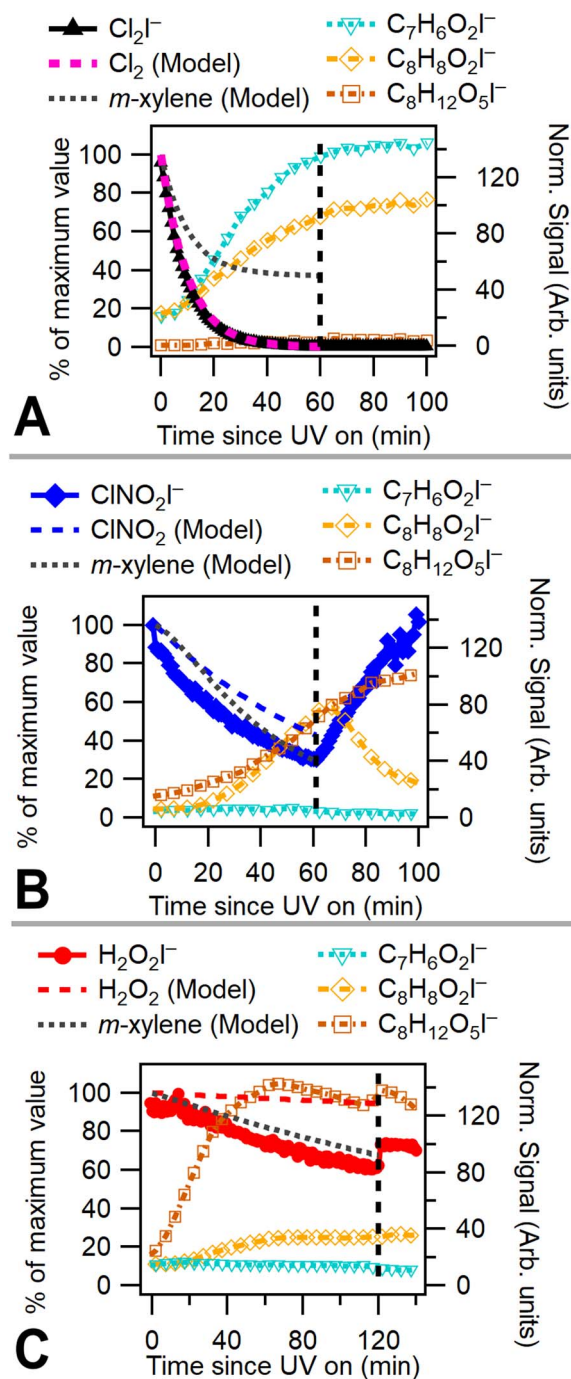
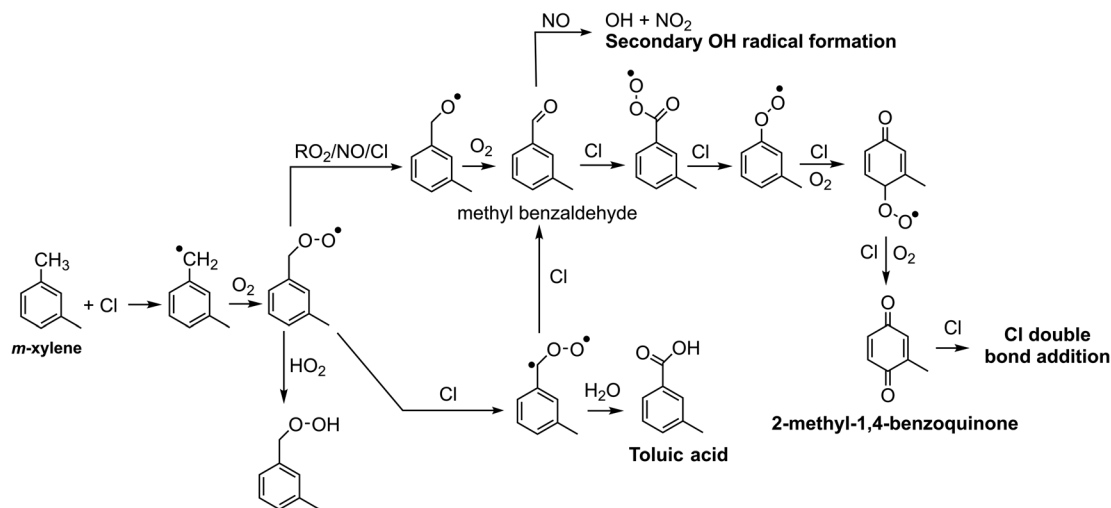


Fig. 2 (A)–(C) Normalized I^- CIMS data and chamber model results from (A) experiment 5 – Cl_2 (B) experiment 1 – ClNO_2 (C) experiment 7 – H_2O_2 . Model and radical precursor time series are normalized to maximum value. Vertical dashes show UV lights were turned off. $\text{C}_7\text{H}_6\text{O}_2\text{I}^-$ is consistent with 2-methyl-1,4-benzoquinone, $\text{C}_8\text{H}_8\text{O}_2\text{I}^-$ with *m*-toluic acid, and $\text{C}_8\text{H}_{12}\text{O}_5\text{I}^-$ with bicyclic peroxide.

hydrogen abstraction by the Cl radical, the bicyclic peroxide is formed from OH radical addition, and *m*-toluic acid can be formed by both radicals. Formation of these products is described briefly here.

Chlorine initiated oxidation of toluene forms 1,4-benzoquinone due to hydrogen abstraction of aldehydic hydrogen and



Scheme 1 Selected oxidation pathways for *m*-xylene + Cl.

additional Cl radical attack on peroxy radicals to form ClO.^{22,23,48} Applying this reaction pathway to *m*-xylene predicts the analogous species, 2-methyl-1,4-benzoquinone (C₇H₆O₂) measured here. Hydroxyl radicals can form quinone species through an OH ring addition pathway resulting in methyl phenol products, though this pathway is less common.^{49,50}

The OH ring addition pathway generates a bicyclic radical species with a wide variety of fates, including epoxidation, fragmentation, and the bicyclic peroxide product (C₈H₁₂O₅)^{20,51}

discussed here. Chlorine oxidation is not observed to cause ring addition and bicyclic radical species are not formed.¹⁷

Toluic acid is the result of hydrogen abstraction at the methyl group resulting in the carboxylic acid species. OH and Cl radicals form this product following attack on an aldehydic hydrogen. In addition, Cl oxidation generates toluic acid after forming a Criegee intermediate. Criegee intermediates form following the attack of chlorine on the peroxy radical⁵² and have been previously discussed for toluene + Cl systems.⁵³

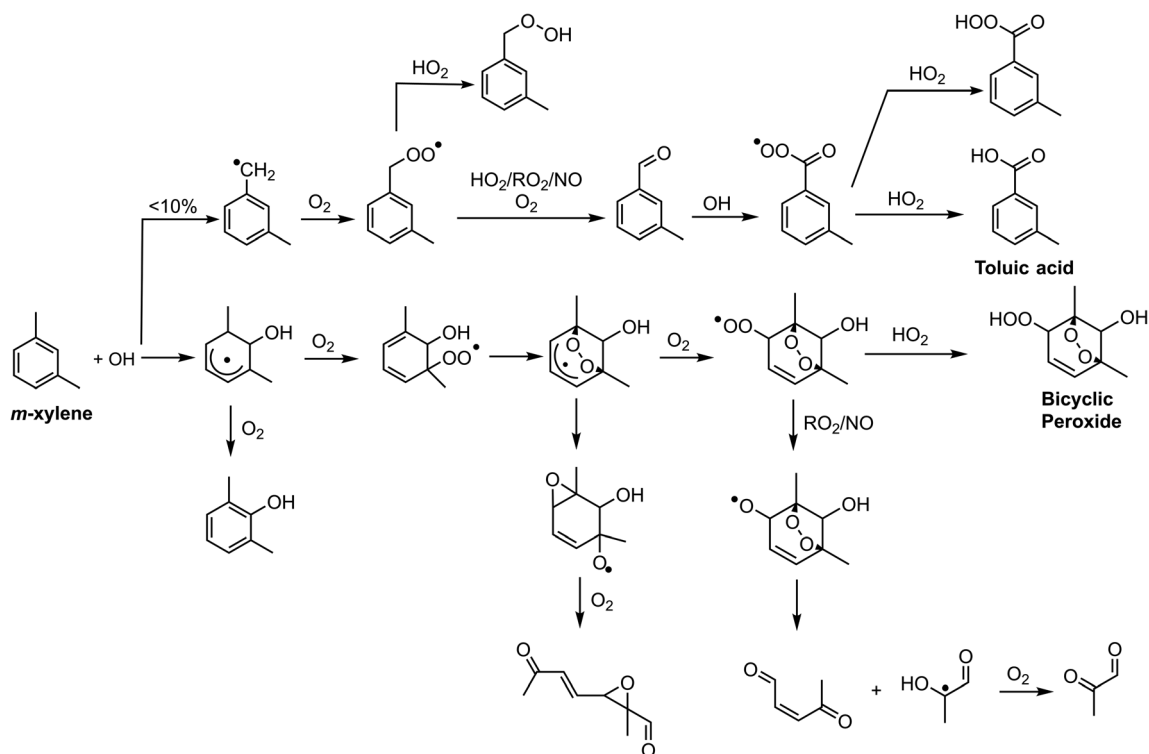
Scheme 2 Selected oxidation pathways for *m*-xylene + OH.

Fig. 2a–c plots 2-methyl-1,4-benzoquinone, the bicyclic peroxide and *m*-toluic acid for Cl₂, ClNO₂, and H₂O₂ experiments. Growth of 2-methyl-1,4-benzoquinone is only substantial when Cl₂ is present, including under high NO_x conditions (Fig. S2†), indicating that high Cl radical concentrations initiate this multigenerational chemistry. Greater relative formation of 2-methyl-1,4-benzoquinone over *m*-toluic acid and bicyclic peroxide occurred in both low NO_x Cl₂ experiments (Exp. 4 and 5). According to our chamber box model (Fig. S10†), integrated Cl radical exposures during the full UV exposure period are 8×10^9 molecules per cm³ per s and 14×10^9 molecules per cm³ per s under high and low NO_x conditions, respectively. In contrast, little growth of the quinone product is observed in a ClNO₂ experiment with modeled Cl radical exposure of 5×10^9 molecules per cm³ per s. In addition, model results (Fig. S10†) indicate Cl₂ generates peak Cl radical concentrations nearly 1 order of magnitude higher than ClNO₂ as a result of the high Cl₂ photolysis rate. Increased Cl radical concentrations may offer more opportunity for multiple radical oxidation events which drive formation of the quinone product. This mirrors previously observed differences in SOA formation from high NO_x *m*-xylene + OH systems.¹⁰ In this prior work, use of photolabile HONO produced a rapid plume of OH radicals which generated SOA not observed in classical high NO_x photooxidation experiments which rely on NO_x and HO_x cycling to generate OH radicals more slowly. Higher radical concentrations reduce the timescale of multigenerational chemistry and lower SVOCs wall losses in addition to potentially altering radical fate branching pathways.¹⁰

However, we observe continued formation of 2-methyl-1,4-benzoquinone in Cl₂ + NO experiments even after Cl radical concentrations fall below those observed in ClNO₂ experiments (Fig. S2 and S10†). This is likely related to differences in initial RO₂ radical fate which drive precursor availability. High initial Cl radical concentrations combined with the presence of NO bias Cl₂ + NO oxidation environments toward RO₂ + NO radical terminations or shift the fate of the Criegee intermediate toward reaction with Cl to form methyl benzaldehyde. Formation of these key precursors is suppressed in the ClNO₂ case due to slower formation of NO and higher OH to Cl ratio which drives HO₂ formation and efficient formation of the bicyclic peroxide radical. The presence of benzaldehyde and other precursors in Cl₂ + NO experiments enables formation of the benzoquinone products even as the OH to Cl ratio increases.

Bicyclic peroxide product formation is observed for all experiments except the low NO_x Cl₂ case. Unsurprisingly, hydrogen peroxide experiments rapidly generated this OH oxidation product. Chlorine gas in the absence of NO_x formed minimal secondary OH radicals with an OH radical exposure of 1.5×10^9 molecules per cm³ per s. In contrast, Cl₂ + NO and ClNO₂ experiments have OH radical exposures of 43 and 35×10^9 molecules per cm³ per s, respectively. This NO_x enhancement of hydroxyl radicals is driven both by the effect of OH regeneration through NO_x cycling and the presence of secondary OH formation pathways which are enhanced by NO_x reaction with peroxy radicals.³⁹ The formation of bicyclic peroxides in the ClNO₂ case was more rapid than in the Cl₂ + NO

case (Fig. S2†) and was observed in both ClNO₂ experiments (Exp. 1 and 2). Under both conditions, similar OH radical concentrations/exposures are achieved (Fig. S10†); however, slower formation of Cl radicals from ClNO₂ likely biases initial oxidation toward OH radical addition pathways compared to initial Cl oxidations in the Cl₂ + NO case. As discussed, peak Cl radical concentrations in the Cl₂ + NO case result in multigenerational Cl chemistry. The reduced Cl concentration in the nitryl chloride system generated an approximate 1 : 10 Cl : OH radical ratio, similar to ambient measurements of a 1 to 2 order of magnitude difference in Cl and OH radical concentrations in inland Texas.²⁸ In the case of Cl₂ + NO, we observe a shifting Cl : OH radical ratio of 1 : 2 initially to nearly 1 : 50 during hour-long photo-oxidation. In addition, dark chemistry is observed following photooxidation in the ClNO₂ experiment, as evidenced by growth in nitryl chloride and a decline in *m*-toluic acid. This may be related to heterogeneous chemistry which forms nitryl chloride from N₂O₅ interactions with chloride containing particles. We do see growth of N₂O₅ in the dark for ClNO₂ experiments (Fig. S6†), possibly from reaction of NO₂ and NO₃ in the gas phase which goes on to react with chloride and form nocturnal ClNO₂. This behavior is not observed when ClNO₂ is used in combination with Cl₂ and/or H₂O₂ (Exp. 8 and 10, Fig. S3 and S4†), likely due to lower availability of N₂O₅ precursors. Taken together, these results indicate that oxidative environments from fresh chlorine emissions in high NO_x areas differ from ClNO₂ rich air masses typically observed in the early morning.

m-Toluic acid is observed to form during photo-oxidation in all experiments. Formation of toluic acid is substantially lower in H₂O₂ experiments, consistent with the OH oxidation pathway which favors ring addition over hydrogen abstraction. Under high NO_x Cl₂ conditions (Fig. S2†), formation of toluic acid is more rapid than 2-methyl-1,4-benzoquinone. This may indicate termination of radical propagation is more rapid under high NO_x conditions or may be a result of additional competition for the Cl radical as it forms ClNO, ClONO, and ClNO₂ in the presence of NO_x.

In addition to these species, organochlorine species are formed in chlorine radical systems. Gas phase organochlorine fraction was calculated by dividing the total C_{2–10}H_yO_zCl_{1–3}I[–] signal by the total C_{1–10}I[–] signal (*i.e.* total organic species signal) averaged for 10 minutes following the end of UV photolysis. We assume a uniform sensitivity for all organic species. Under low NO_x conditions, we find a gas phase organochlorine fraction of 0.22 which falls to 0.18 under Cl₂ + NO and falls further to 0.07 when ClNO₂ is used. This is consistent with the growth in OH radical concentrations observed from Cl₂ to Cl₂ + NO to ClNO₂ experiments. These gas phase chlorinated species are a result of chlorine addition reactions, likely to available double bonds following aromatic ring breaking.

3.2 Chlorine oxidation yields more highly oxidized SOA

Differences in gas phase oxidation discussed above lead to differences in particle phase composition. Fig. 3 shows



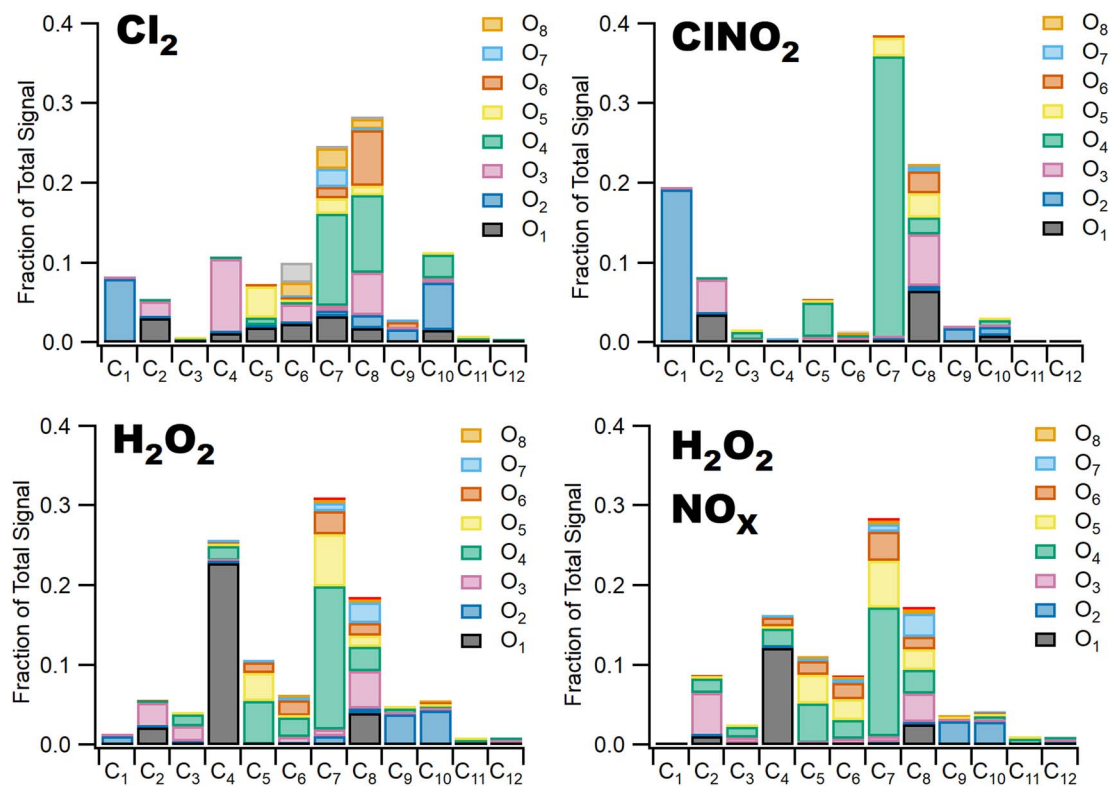


Fig. 3 | FIGAERO-CIMS desorption data from experiment 1 (ClNO_2), 4 (Cl_2), 6 ($\text{H}_2\text{O}_2 + \text{NO}_x$) and 7 (H_2O_2). Particle phase species are categorized by carbon and oxygen number, integrated over their desorption curves, summed and divided by total integrated desorption signal of represented species.

integrated particle composition data from the FIGAERO-CIMS from experiments 1, 4, 6, and 7. Particles were collected for 45 minutes following the end of UV exposure and desorbed on a 45 minutes heating cycle. Integration of the thermal desorption signal is performed over the full desorption temperature range (25–180 °C). Experiments using Cl_2 as radical precursor resulted in more highly oxidized organic aerosol; for example, the experiments formed a higher fraction of $\text{C}_{7-8}\text{O}_{4-8}$ species compared to experiments using ClNO_2 which formed a much smaller fraction of species with more than four oxygen atoms. This additional oxygen content may be related to the more rapid formation of Cl radicals under Cl_2 oxidation conditions, driving multigenerational oxidation chemistry. In addition, the fraction of ring retaining C_8 species is higher in SOA formed when Cl_2 was used as the radical precursor, consistent with functionalization of the methyl group after hydrogen abstraction. SOA formed in experiments where ClNO_2 or H_2O_2 serves as the radical precursor has a higher fraction of C_7 species. Even greater fragmentation to C_4 and C_5 species is observed in hydrogen peroxide experiments, consistent with the ring breaking fragmentation products resulting from the bicyclic radicals formed by OH ring addition chemistry.

These observations are consistent with bulk particle composition from the ACSM. Triangle plot analysis⁵⁴ (Fig. 4) shows that the fraction of the total organic signal due to organic mass at m/z 44 (f_{44}) was elevated and f_{43} was reduced in Cl_2 experiments. This indicated use of pure Cl_2 as a radical

precursor resulted in more highly oxidized SOA with increased formation of acid groups. Use of ClNO_2 resulted in similar f_{44} fractions to H_2O_2 experiments. In addition, f_{43} fractions were higher in H_2O_2 experiments, indicating that less oxidized SOA was the norm when primary OH radicals are present. This is consistent with observations of toluene + Cl and toluene + OH chemistry from Dhulipala *et al.* (2019)²² where toluene + Cl SOA had a lower f_{43} and higher f_{44} measured in the ACSM than toluene + OH SOA. This was attributed to formation of ring opened products from OH oxidation with unoxidized methyl groups related to higher f_{43} values. SOA from *m*-xylene + H_2O_2 experiments in Loza *et al.* (2011)⁵⁵ resulted in higher f_{43} values measured in the aerosol mass spectrometer (AMS) than reported here, though f_{44} values are similar.

Particle phase organochlorine content varied with radical precursor as shown by the ratio of HCl^+ (m/z 36) to organics in the ACSM. ACSM HCl^+ to organics ratio has been suggested as an improved semi-quantitative measure of particulate organochlorine compared to the detection utilizing Cl^+ (m/z 35).²⁴ Here, we found that the HCl^+ to organics ratio decreased from 0.037 in a Cl_2 experiment to 0.025 and 0.011 in $\text{Cl}_2 + \text{NO}$ and ClNO_2 experiments, respectively. FIGAERO-CIMS particle desorption signals show that in Cl_2 experiments organochlorine species make up 0.27 of total identified desorption signal. This falls to 0.07 for ClNO_2 experiments. This behavior is qualitatively consistent with gas phase decreases in organochlorine content



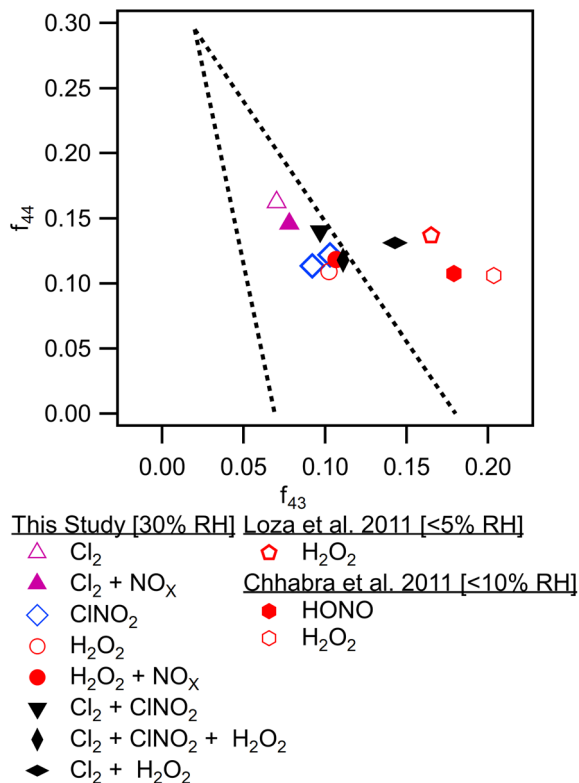


Fig. 4 f_{44} to f_{43} triangle plot for all chamber experiments from final average ACSM bulk particle composition. Data from literature sources is shown.^{46,47}

discussed earlier. The behavior is also qualitatively consistent with the ACSM HCl/Organics ratio.

While NO_x resulted in less oxidized SOA in Cl_2 experiments, it had little effect within peroxide experiments. This may be driven by H_2O_2 photolysis generating substantial HO_2 and favoring $\text{HO}_2 + \text{RO}_2$ and $\text{RO}_2 + \text{RO}_2$ chemistry over $\text{NO}_x + \text{RO}_2$ pathways. Use of HONO as a high NO_x source of OH radicals promoted a more substantial shift in SOA oxidation state compared to H_2O_2 for *m*-xylene oxidation in Chhabra *et al.* (2011).⁵⁶ This may be because the photolysis of HONO produces a lower HO_2 to RO_2 ratio as well as higher initial OH radical concentrations. The f_{43}/f_{44} differences in this study compared to literature may be related to instrument variability as noted in Ng *et al.* (2010).⁵⁴ Differences in f_{43}/f_{44} may also be driven by increased humidity as discussed in Zhang *et al.* (2019),¹³ where a shift in O:C ratio was observed for *m*-xylene + OH experiments. The higher RH in these experiments may reduce the degree of oxidation observed in the particle phase by reducing the formation of low-volatility oligomers. This effect has also been reported in toluene⁵⁷ and isoprene⁵⁸ studies.

3.3 Oxidant environment shifts SOA formation

In addition to SOA composition, SOA formation and yield is also dependent on radical precursor choice. Table 1 lists peak wall loss corrected SOA concentrations. Peak SOA formation is greatest for the low NO_x Cl_2 condition (experiment 4) compared

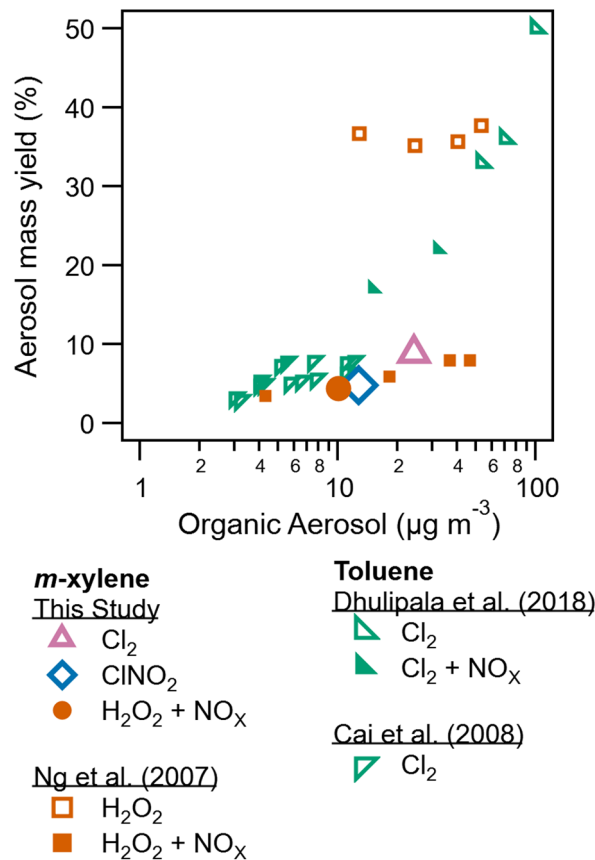


Fig. 5 Aerosol mass yield plotted against organic aerosol concentration from this study, Ng *et al.* (2007),¹⁰ Dhulipala *et al.* (2018),³³ and Cai *et al.* (2008).²³ This study and Ng *et al.* (2007)¹⁰ utilize *m*-xylene while the other studies utilize toluene. Data from this study are shown in larger symbols for emphasis.

to SOA formation for ClNO_2 (experiment 2) and high NO_x Cl_2 (experiment 3). This reduction in SOA formation due to NO_x has been previously reported for some aromatic and hydroxyl radical systems.¹⁰ Peroxy radical fate drives these differences, with $\text{NO} + \text{RO}_2$ pathways resulting in more volatile products compared to $\text{HO}_2 + \text{RO}_2$ reaction products.⁹

Secondary organic aerosol yields are determined as the mass concentration of SOA formed divided by the mass concentration of precursor consumed. Yields are reported for experiments 2, 4, and 6, the three experiments were measurements of *m*-xylene consumption were available based on H_3O^+ CIMS measurements. Measured and modeled *m*-xylene consumption is shown in Fig. S7–S9.† Fig. 5 compares yields from this study to literature. The highest yield (8.8%) is observed for the low NO_x Cl_2 condition. Yield for the *m*-xylene + ClNO_2 system was found to be 4.8% here. While yields for the *m*-xylene + Cl reaction has not been previously reported, toluene + Cl_2 experiments report yields as low as 5% (ref. 23) and as high as 82%.²² Toluene and *m*-xylene are similar molecules, though the additional methyl group on *m*-xylene may alter the volatility of expected product by providing an additional site for Cl hydrogen abstraction. In addition, previous studies differ substantially in use of seed aerosol, relative humidity, and Cl_2/VOC ratio from this one.



Prior studies have observed a substantial dependence of SOA formation from Cl radicals on Cl₂/VOC ratio.^{23,53}

For the high NO_x H₂O₂ system, yields agree with those presented in Ng *et al.* (2007).¹⁰ Substantially higher formation and yield is observed in Ng *et al.* (2007) for low NO_x conditions, though differences in humidity between these experiments and the one described there may play a role. Zhang *et al.* (2019)¹³ show a sharp drop in SOA yield with increasing RH, related to increased wall losses of semi volatile species and reduced oligomerization as previously discussed.

4 Conclusions

This environmental chamber study examined the impact of radical precursor identity on Cl and OH oxidation of *m*-xylene. Hydrogen peroxide experiments resulted in well studied hydroxyl radical chemistry which primarily leads to bicyclic radical formation and subsequent fragmentation due to OH ring addition. Chlorine gas used as a Cl precursor drove rapid oxidation by hydrogen abstraction from methyl substituents and addition of oxygenated functional groups. In addition, chlorine gas drove the formation of a multigenerational product (2-methyl-1,4-benzoquinone) under both high and low NO_x conditions. In contrast, nitril chloride generated a different high NO_x Cl radical environment which did not form 2-methyl-1,4-benzoquinone. Furthermore, the formation of secondary hydroxyl radicals is substantial and results in formation of bicyclic radical species in high NO_x Cl radical environments. In ambient air masses with high concentrations of chlorine gas, including marine regions or certain industrial plumes, functionalized aromatics and toxic compounds including quinones and organochlorine species will be rapidly formed. In those ambient early morning air masses with high nitril chloride concentrations, greater fragmentation of aromatic hydrocarbons is anticipated with reduced formation of organochlorine species as secondary OH radicals dominate oxidation. Broadly, differences in chlorine radical exposure, peak chlorine radical concentrations, and formation of secondary hydroxyl radicals all drive different chemical outcomes for environments dominated by fresh chlorine gas in the presence of NO_x compared to those dominated by nitril chloride.

In the particle phase, Cl₂ drove less fragmentation and greater functionalization of organic species than H₂O₂ consistent with previous observations of toluene + Cl/OH chemistry. Reduced fragmentation was also observed when ClNO₂ was used, though chlorine gas generated more highly oxidized aerosol. This is consistent with gas phase oxidation pathways described above as OH ring addition chemistry leads to the fragmentation of the bicyclic radical intermediate. Consistent with rates and degrees of precursor consumption, SOA mass formed under low NO_x Cl₂ conditions was greatest, while the presence of NO_x suppressed formation and yield as seen in other studies. Despite the high secondary hydroxyl radical formation observed in Cl radical experiments, the composition of organic aerosol from Cl₂ and ClNO₂ differs substantially from OH oxidation alone. Atmospherically, the reduced fragmentation and increased functionalization of particle phase

aromatics following Cl oxidation may substantially alter SOA properties. Functionalized aromatics may act as chromophores which alter aerosol light absorption, while organochlorine species may be toxic. Furthermore, organochlorine species in the aerosol phase may contribute to heterogeneous reactions that regenerate Cl₂ and ClNO₂. Accounting for the particle phase differences resulting from Cl oxidation compared to OH oxidation is necessary to fully capture climate and health impacts.

Oxidation of aromatic hydrocarbons and subsequent SOA formation may have substantial impacts on tropospheric pollution. As shown here, Cl₂ and ClNO₂ generate substantially different radical environments and subsequently form different product mixtures. Radical precursor identity and the resulting oxidative environment demands future study in both laboratory and field measurement settings. With growing evidence of high particulate chloride in polluted megacities and the evolution of chlorine radical precursors from industrial and mineral sources, there is a premium on better understanding and constraining the fate and transport of chlorine in the environment.

Data availability

Experimental data are available in the ICARUS database. Data published in the main manuscript's figures are available *via* the Texas Data Repository <https://doi.org/10.18738/T8/6XWHN9>. Underlying research data are also available by request to Lea Hildebrandt Ruiz (lhr@che.utexas.edu).

Author contributions

Nirvan Bhattacharyya: conceptualization, methodology, investigation, formal analysis, writing – original draft. Mrinali Modi: software, formal analysis, writing – review & editing. Leif G. Jahn: writing – review & editing. Lea Hildebrandt Ruiz: conceptualization, supervision, funding acquisition, writing – review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors would like to acknowledge the support of staff at the Center for Engineering and Environmental Resources including Denzil Smith, Susan McCoy and Nohemi Cazares in building management, ordering, and other logistics. The authors are also grateful for funding support from the National Science Foundation (Grant number 1653625) and the Welch Foundation (Grant numbers F-1925-20170325 and F-1925-20200401).

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