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# Comparison of secondary organic aerosol formed with an aerosol flow reactor and environmental reaction chambers: effect of oxidant concentration, exposure time and seed particles on chemical composition and yield

A. T. Lambe<sup>1,2</sup>, P. S. Chhabra<sup>2,\*</sup>, T. B. Onasch<sup>1,2</sup>, W. H. Brune<sup>3</sup>, J. F. Hunter<sup>4</sup>,  
J. H. Kroll<sup>4</sup>, M. J. Cummings<sup>1</sup>, J. F. Brogan<sup>1</sup>, Y. Parmar<sup>1</sup>, D. R. Worsnop<sup>2</sup>,  
C. E. Kolb<sup>2</sup>, and P. Davidovits<sup>1</sup>

<sup>1</sup>Chemistry Department, Boston College, Chestnut Hill, MA, USA

<sup>2</sup>Aerodyne Research Inc., Billerica, MA, USA

<sup>3</sup>Department of Meteorology and Atmospheric Sciences, The Pennsylvania State University, State College, PA, USA

<sup>4</sup>Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

\*now at: Department of Chemical Engineering, University of Texas, Austin, Texas, USA

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Correspondence to: A. T. Lambe (lambe@aerodyne.com)

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## Abstract

We performed a systematic intercomparison study of the chemistry and yields of SOA generated from OH oxidation of a common set of gas-phase precursors in a Potential Aerosol Mass (PAM) continuous flow reactor and several environmental chambers. In the flow reactor, SOA precursors were oxidized using OH concentrations ranging from  $2.0 \times 10^8$  to  $2.2 \times 10^{10}$  molec cm<sup>-3</sup> over exposure times of 100 s. In the environmental chambers, precursors were oxidized using OH concentrations ranging from  $2 \times 10^6$  to  $2 \times 10^7$  molec cm<sup>-3</sup> over exposure times of several hours. The OH concentration in the chamber experiments is close to that found in the atmosphere, but the integrated OH exposure in the flow reactor can simulate atmospheric exposure times of multiple days compared to chamber exposure times of only a day or so. A linear correlation analysis of the mass spectra ( $m = 0.91$ – $0.92$ ,  $r^2 = 0.93$ – $0.94$ ) and carbon oxidation state ( $m = 1.1$ ,  $r^2 = 0.58$ ) of SOA produced in the flow reactor and environmental chambers for OH exposures of approximately  $10^{11}$  molec cm<sup>-3</sup> s suggests that the composition of SOA produced in the flow reactor and chambers is the same within experimental accuracy as measured with an aerosol mass spectrometer. This similarity in turn suggests that both in the flow reactor and in chambers, SOA chemical composition at low OH exposure is governed primarily by gas-phase OH oxidation of the precursors, rather than heterogeneous oxidation of the condensed particles. In general, SOA yields measured in the flow reactor are lower than measured in chambers for the range of equivalent OH exposures that can be measured in both the flow reactor and chambers. The influence of sulfate seed particles on isoprene SOA yield measurements was examined in the flow reactor. The studies show that seed particles increase the yield of SOA produced in flow reactors by a factor of 3 to 5 and may also account in part for higher SOA yields obtained in the chambers, where seed particles are routinely used.

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## 1 Introduction

Laboratory and field studies over the last decade have shown that organic components of atmospheric particles constitute 20 to 50 % of the fine particle mass (PM) in the continental mid-latitudes, though the organic content can be higher (up to 90 %) in tropical forested regions (Kanakidou et al., 2005). On a global scale, 50–90 % of submicron organic PM is composed of oxygenated organic aerosol (Zhang et al., 2005) that is typically associated with secondary organic aerosol (SOA) formed by condensation of oxidized gas-phase species (Jimenez et al., 2009). Field studies indicate that SOA particles may influence cloud formation (Levin et al., 2014; Mei et al., 2013; Moore et al., 2012; Sihto et al., 2011) and may be optically active in the UV/Visible region of the electromagnetic spectrum (Zhang et al., 2011). These studies have also revealed the complexity of organic aerosol compositions and their chemical evolution via oxidative aging. The atmospheric lifetime of ambient SOA ranges from hours to weeks, providing a wide range of atmospheric exposures to a variety of oxidant species. Measured ambient SOA chemical compositions range from hydrocarbon-like organic aerosol, such as observed directly downwind of the Deepwater Horizon oil site during the 2010 Gulf Oil Spill (Bahreini et al., 2012; De Gouw et al., 2011), to highly oxygenated OA, such as background SOA observed worldwide (Zhang et al., 2007). Much of this complexity is due to the thousands of organic compounds found in atmospheric particulate matter, specifically low volatility, highly functionalized species (Hallquist et al., 2009).

Laboratory experiments conducted in environmental chambers have been essential in providing SOA physical and chemical properties as well as yield data for predicting the rate of atmospheric SOA formation due to oxidation of biogenic and anthropogenic volatile organic compounds (VOCs) (Spracklen et al., 2011). Substantial progress has been made in understanding reaction mechanisms and the factors that influence SOA yields and composition. For example, SOA yields appear to have a complex dependence on VOC:NO<sub>x</sub> ratio (Loza et al., 2014; Ng et al., 2007), precursor concentration/volatility (Presto and Donahue, 2006), and oxidant exposure (Lambe et al., 2012).

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Modeling observed atmospheric SOA levels therefore remains a challenge (Shrivastava et al., 2011; Bergström et al., 2012; Jo et al., 2013; Li et al., 2013) because of the large number of modeling parameters and associated sensitivities that are required to capture mechanistic details of SOA formation (Chen et al., 2013; Fountoukis et al., 2014).

Oxidant exposure is the integral of the oxidant species concentration and the sample residence time. Relatively low oxidant exposures are a major limitation of current environmental chamber techniques, which operate at OH concentrations ranging from approximately  $10^6$  to  $10^7$  molec $\text{cm}^{-3}$  that are equal to or slightly more than daytime atmospheric OH concentrations. Chamber experiments are generally limited to residence times of several hours due to chamber deflation and the loss of oxidized vapors (Zhang et al., 2014) and/or particles to the chamber walls. This combination of low OH concentrations and residence time limits environmental chambers to simulating atmospheric aerosol particle lifetimes only up to 1 or 2 days, including the characterization of SOA yields. This limitation prevents the formation and the study of highly oxygenated SOA that is characteristic of aged atmospheric organic aerosol PM (Ng et al., 2010).

Recently, aerosol flow reactors have been developed to study SOA formation and evolution equivalent to multiple days of atmospheric OH exposure. In these reactors OH concentrations are typically  $\sim 10^9$  molec $\text{cm}^{-3}$  or greater, with reactor residence times of seconds to minutes (Kang et al., 2007; Hall IV et al., 2013; Keller and Burtscher, 2012; Lambe et al., 2011a; Slowik et al., 2012). With this range of OH concentrations and exposure times, flow reactors can simulate the full range of ambient levels of oxidation, measuring changes in SOA composition and yields over a wide range of equivalent atmospheric oxidation. Further, because of the short flow reactor residence times, experimental runs can be conducted on the scale of minutes rather than hours.

While flow reactors appropriately simulate the full range of integrated atmospheric oxidant exposures, in view of their short residence times and high oxidant concentrations it must be established how well the atmospheric aerosol chemistry is simulated (Renbaum and Smith, 2011). A growing set of studies indicates that flow reactor-

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generated SOA particles have compositions similar to ambient SOA, suggesting that the dominant oxidation reaction pathways in flow reactors are similar to those in ambient conditions (Bahreini et al., 2012; Lambe et al., 2012, 2011b; Kang et al., 2011; Massoli et al., 2010; Ortega et al., 2013; Slowik et al., 2012; Wang et al., 2012; Wong et al., 2011). However, these comparisons need to be extended over a wider range of reactants and experimental conditions than are currently available.

Here we describe systematic intercomparison studies of SOA chemistry and yields generated from a common set of precursors in a Potential Aerosol Mass (PAM) flow reactor (Lambe et al., 2011a) and four environmental chambers. SOA precursors studied are gas-phase alkane, biogenic, and aromatic compounds. SOA chemical composition and yield were characterized as a function of OH exposure. Additionally, the effect of sulfate seed particles on isoprene SOA yields was studied. Due to the limited oxidative exposure provided by the environmental chambers, direct comparison between the two techniques is possible only over a narrow range. However, reasonable extrapolations extend the range of interest.

## 2 Experimental

This manuscript compares properties of SOA produced in the PAM reactor to SOA produced in environmental chambers operated at the four institutions: California Institute of Technology (Caltech), Massachusetts Institute of Technology (MIT), Paul Scherrer Institut (PSI), and Carnegie Mellon University (CMU). The PAM reactor is a horizontal 13.3 L glass cylindrical chamber, 46 cm long × 22 cm ID and is operated in continuous flow mode with an average residence time of 100 s. The RH in the reactor was controlled in the range of 30–40%. The Caltech, MIT, PSI and CMU Teflon chambers range from 7.5 to 28 m<sup>3</sup> in volume and are operated in batch or semi-batch mode with experimental residence times ranging from 4 to 10 h. The relative humidity (RH) in the Caltech, MIT and CMU chamber experiments was less than 10%, and the RH in the PSI chamber experiments was controlled in the range of 40–50%. A summary of

the methods used for OH radical generation, particle generation, and data analysis is provided below.

## 2.1 OH radical generation

In the flow reactor, OH radicals were produced in the absence of  $\text{NO}_x$  via the reaction  $\text{O}(^1\text{D}) + \text{H}_2\text{O} \rightarrow 2\text{OH}$ , with  $\text{O}(^1\text{D})$  radicals produced from the reaction  $\text{O}_3 + h\nu \rightarrow \text{O}_2 + \text{O}(^1\text{D})$ .  $\text{O}_3$  was generated by  $\text{O}_2$  irradiation with a mercury lamp ( $\lambda = 185 \text{ nm}$ ) outside the flow reactor. The  $\text{O}(^1\text{D})$  atoms were produced by UV photolysis of  $\text{O}_3$  inside the flow reactor using four mercury lamps ( $\lambda = 254 \text{ nm}$ ). OH concentrations were varied by changing the UV light intensity, and were quantified by measuring the decay of  $\text{SO}_2$  and applying the known  $\text{OH} + \text{SO}_2$  rate constant (Davis et al., 1979). The concentrations ranged from approximately  $2.0 \times 10^8$  to  $2.2 \times 10^{10} \text{ molec cm}^{-3}$ . The corresponding OH exposures ranged from  $2.0 \times 10^{10}$  to  $2.2 \times 10^{12} \text{ molec cm}^{-3} \text{ s}$  or approximately 0.2 to 17 days of equivalent atmospheric exposure.

In the environmental chambers, OH radicals were generated by UV photolysis ( $\lambda = 350 \text{ nm}$ ) of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) with no added  $\text{NO}_x$ , or by UV photolysis of nitrous acid (HONO) or methyl nitrite ( $\text{CH}_3\text{ONO}$ ) with  $\text{NO}_x$ . In the present studies, OH radicals generated in the Caltech chamber were formed from photolysis of  $\text{H}_2\text{O}_2$ , HONO, or  $\text{CH}_3\text{ONO}$ , depending on the experiment, whereas OH radicals generated in the MIT, PSI and CMU chambers were formed exclusively from HONO photolysis. Typical chamber OH concentrations were approximately  $2 \times 10^6 \text{ molec cm}^{-3}$  ( $\text{H}_2\text{O}_2$ ) and  $2 \times 10^7 \text{ molec cm}^{-3}$  (HONO) during the initial stage of chamber experiments. Corresponding OH exposures ranged from  $5.4 \times 10^{10}$  to  $4.0 \times 10^{11} \text{ molec cm}^{-3} \text{ s}$  (Tab. 1), equivalent to approximately 0.4 to 3 days of atmospheric exposure at a typical 24 h average OH concentration of  $1.5 \times 10^6 \text{ molec cm}^{-3}$  (Mao et al., 2009).

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## 2.2 Particle generation

Figure 1 shows the gas-phase SOA precursors used in these studies: two biogenic gases (isoprene,  $\alpha$ -pinene), three aromatic compounds (toluene, *m*-xylene, naphthalene), and three alkanes (n-C<sub>10</sub>, cyclodecane, tricyclo[5.2.1.0<sup>2,6</sup>]decane, also known as JP10). In the flow reactor, SOA was generated via gas-phase OH oxidation of precursors followed by homogeneous nucleation, or by condensation onto sulfuric acid or ammonium sulfate seed particles. The sulfuric acid seed particles were generated by OH oxidation of SO<sub>2</sub> together with the SOA precursor, and ammonium sulfate seed particles were generated by atomizing an ammonium sulfate solution. The particles were dried and introduced continuously into the flow reactor along with the gas-phase SOA precursor. In environmental chambers, SOA was generated via gas-phase OH oxidation of precursors usually followed by condensation onto ammonium sulfate seed particles. For long residence time chamber experiments, wall condensation of precursor gas-phase species can be significant. Seed particles are used in chamber studies to reduce wall effects. In some of the flow reactor experiments seed particles were also used to study their effect on SOA yields.

## 2.3 Particle monitoring and analysis

Particle number concentrations and size distributions were measured with a TSI scanning mobility particle sizer (SMPS). Aerosol mass spectra were measured with an Aerodyne time-of-flight aerosol mass spectrometers (ToF-AMS) (DeCarlo et al., 2006; Drewnick et al., 2005). Elemental analysis (Aiken et al., 2008) was performed on the AMS data to determine the bulk aerosol hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios along with the average aerosol carbon oxidation state ( $\overline{\text{O}}\text{Sc}$ ) (Kroll et al., 2011). While AMS measurements provide basic information about SOA composition, additional supporting measurements are required to investigate SOA chemistry at the molecular level.

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SOA yields were calculated from the ratio of aerosol mass formed to precursor gas reacted. The aerosol mass was calculated from the integrated particle volume and the effective particle density ( $\rho = D_{va}/D_m$ ), where  $D_{va}$  is the mean vacuum aerodynamic diameter obtained from the ToF-AMS and  $D_m$  is the electric mobility diameter obtained from the SMPS. Flow reactor SOA yields were corrected using size-dependent bis(2-ethylhexyl) sebacate wall-loss measurements (Lambe et al., 2011a); the average magnitude of these corrections was 32 % ( $\pm 15$  %) and represents an upper limit as it combines losses into and through the reactor. Caltech chamber yields were corrected for particle wall losses using size-dependent first-order loss coefficients determined from ammonium sulfate wall-loss measurements (Keywood et al., 2004). The magnitude of these particle wall loss corrections typically ranged from 10–30 %.

MIT chamber experiments were corrected for particle wall losses using the AMS organic-to-sulfate ratio to generate an upper limit and SMPS measurements of particle loss to generate a lower limit for aerosol yield (Hildebrandt et al., 2009). In the MIT chamber, these corrections were between a factor of 1.5 to 3.0 at the highest yields and OH exposures. Although the residence time in the flow reactor is much shorter than in the chambers, the surface-to-volume ratio in the PAM reactor is much greater. As a result particle losses are comparable in the two systems. Flow reactor SOA yields were also corrected for UV lamp-induced temperature increases by applying yield corrections of  $-0.02$  per degree K of temperature rise (Qi et al., 2010; Stanier et al., 2007) relative to room temperature ( $\sim 293$  K). These temperature corrections ranged from 0–28 % (mean correction  $\pm 1\sigma = 7 \pm 7$  %). In the flow reactor, a known amount of precursor gas was introduced and the mass of reacted precursor gas was estimated from the OH exposure and known bimolecular rate constants (Atkinson, 1986). In environmental chamber studies, the mass of the remaining precursor gas was measured directly as a function of exposure time.



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anisms for organic aerosols (Heald et al., 2010). Typically, with oxidative aging the O/C ratio increases and H/C ratio of SOA decreases as oxygen-containing functional groups are added to a carbon backbone. Here, we use Van Krevelen diagrams to compare the composition of SOA formed in the flow reactor and environmental chambers for the organic precursors studied. Direct comparisons are possible in the overlapping OH exposure region. Typically the lowest OH exposures attained in the flow reactor overlap (or nearly overlap) with the highest OH exposures reached in environmental chambers (Table 1).

Figure 3 shows Van Krevelen diagrams obtained from laboratory SOA produced from the oxidation of gas-phase biogenic, aromatic, and alkane precursors. To simplify presentation, the data are displayed in three panels. Figure 3a shows biogenic SOA generated from isoprene and  $\alpha$ -pinene, Fig. 3b shows SOA generated from aromatic compounds, and Fig. 3c shows SOA produced from alkanes. In most cases, for a specific SOA type the most-oxidized chamber SOA and the least-oxidized flow reactor SOA have similar Van Krevelen plots at integrated OH exposures between approximately  $1 \times 10^{11}$  and  $2 \times 10^{11}$  molec $\text{cm}^{-3}$ s, or about 1–2 days of equivalent atmospheric oxidation. This observation suggests that in the range of available OH exposure overlap for the flow reactor and chambers, SOA elemental composition is similar whether the precursor is exposed to low OH concentrations over long exposure times or high OH concentrations over short exposures times. The flow reactor studies were done without added  $\text{NO}_x$ , whereas some of the environmental chamber studies were conducted in the presence of  $\text{NO}_x$ . The similarity in compositional parameters shown in Fig. 3 (e.g. H/C, O/C) were independent of the  $\text{NO}_x$  levels used in the environmental chambers in the region studied, as has been observed in previous studies (Chhabra et al., 2011). The nitrogen-to-carbon (N/C) ratio ranged from 0.031 to 0.054 for SOA produced in the MIT chamber with added  $\text{NO}_x$  (Hunter et al., 2014) but was not characterized for other measurements shown in Fig. 3.

### 3.3 Carbon oxidation state for flow reactor- and chamber-generated SOA

Recently, the average carbon oxidation state ( $\overline{\text{OSc}}$ ), defined as  $\overline{\text{OSc}} = 2 \times \text{O/C} - \text{H/C}$ , was proposed as a more accurate indicator of atmospheric oxidative aging processes than the O/C ratio alone because this measure takes into account the level of saturation of the carbon atoms in the SOA (Canagaratna et al., 2014; Kroll et al., 2011). As will be demonstrated,  $\overline{\text{OSc}}$  of lightly oxidized SOA is strongly precursor-dependent. Figure 4 shows a scatter plot of  $\overline{\text{OSc}}$  for flow reactor and chamber SOA for the eight gas-phase precursors studied. Different colored symbols are used to represent each of the environmental chambers used in the intercomparison. For each data point obtained from environmental chamber measurements, we used data from the flow reactor obtained at the OH exposure that was closest in magnitude. A total linear least squares fit to the data presented in Fig. 4 ( $\text{PAM}_{\overline{\text{OSc}}} = 1.1 \cdot \text{Chamber}_{\overline{\text{OSc}}} - 0.16$ ;  $r^2 = 0.54$ ) indicates that there is no systematic  $\overline{\text{OSc}}$  difference observed across multiple SOA types produced in chambers and in flow reactors. Figure 4 shows that the chambers and flow reactor provide similar  $\overline{\text{OSc}}$  for a specific SOA type over the range of measured SOA composition for comparable OH exposures. The observed deviations between PAM and chamber  $\overline{\text{OSc}}$  are no larger than deviations between two chambers (e.g.  $\alpha$ -pinene SOA produced in Caltech and PSI chambers, and cyclodecane SOA produced in MIT and CMU chambers).

### 3.4 SOA yields obtained in the flow reactor and environmental chambers

Several factors can affect SOA yields, including precursor concentration (Kang et al., 2011; Pfaffenberger et al., 2013; Presto and Donahue, 2006),  $\text{NO}_x$  (Presto et al., 2005; Ng et al., 2007), UV intensity/wavelength (Henry and Donahue, 2012), seed particle composition/loading (Hamilton et al., 2011; Volkamer et al., 2009) and treatment of interactions between SOA and chamber walls (Hildebrandt et al., 2009; Matsunaga and Ziemann, 2010; Pierce et al., 2008; Zhang et al., 2014). For reference, the range



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3. In the flow reactor, in all cases the SOA yield first increases as a function of OH exposure and then decreases. In some cases there is also evidence of a slight decrease in SOA yields at higher OH exposure in chambers (e.g. Fig. 5c).

One reason for the lower SOA yield in flow reactors may be the relative timescales for oxidation in the gas-phase vs. condensation onto pre-existing aerosols. For example, over a representative range of particle surface area concentrations used in the flow reactor ( $10$  to  $100 \mu\text{m}^2 \text{cm}^{-3}$ ), condensation timescales range from approximately  $2000$  to  $20\,000$  s assuming a mass accommodation coefficient of  $0.1$  (Saleh et al., 2013) and an average SOA molecular weight of  $150 \text{g mol}^{-1}$ . While our measurements do not constrain the mass accommodation coefficient, these timescales suggest that the residence time in the flow reactor ( $100$  s) may not be adequate to allow complete condensation of semivolatile organic gas-phase species into SOA. Another factor in causing the SOA yield difference may be due to the condensation conditions. All the chamber experiments displayed in this work were done in the presence of ammonium sulfate seed particles, whereas seed particles were not normally used in our flow reactor studies. The effect of seed particles on SOA yields in the flow reactor is examined further in Sect. 3.5.

The observation that the yields track each other is a further indication that the reactive chemistry in the two systems is similar. The decrease in SOA yield subsequent to increase as a function of OH exposure is possibly due to gas-phase species carbon-carbon bond breaking from continued oxidation or heterogeneous OH oxidation reactions at high OH exposure (Hunter et al., 2014; Lambe et al., 2012; Loza et al., 2012); this trend is most clearly evident in the flow reactor studies. These observations suggest that the first step in SOA formation is oxidation of gas-phase species leading to subsequent condensation. At low OH exposures equivalent to 1–2 days, heterogeneous reactions do not appear to play a significant role in SOA chemistry (Cappa and Wilson, 2012; Chen et al., 2013).









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**Table 2.** Experimental conditions for PAM reactor, Caltech chamber, and MIT chamber yield measurements shown in Figs. 5–7.

	seed concentration ( $\mu\text{g m}^{-3}$ )	maximum $[\text{NO}_x]$ added (ppb)	[isoprene] (ppb)	$[\alpha\text{-pinene}]$ (ppb)	[JP-10] (ppb)	Refs
Caltech chamber	0–29 <sup>a</sup>	0	49–91	13.8–52.4	–	1–3
MIT chamber	50–100 <sup>a</sup>	475	–	–	42.9	4
PAM flow reactor	0–59 <sup>a</sup> ; 0–114 <sup>b</sup>	0	462	41–100	55	5–7

<sup>a</sup> ammonium sulfate seed;

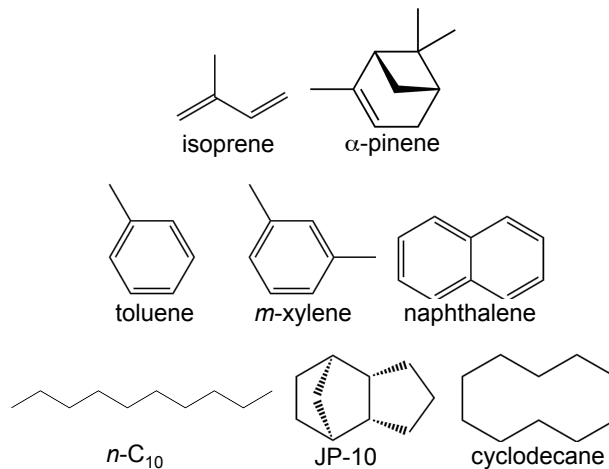
<sup>b</sup> sulfuric acid seed;

[1] Chhabra et al. (2010); [2] Ng et al. (2007); [3] Eddingsaas et al. (2012); [4] Hunter et al. (2014); [5] this work; [6] Lambe et al. (2012);

[7] Chen et al. (2013).

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**Figure 1.** Biogenic, aromatic, and alkane SOA precursors used in this study.

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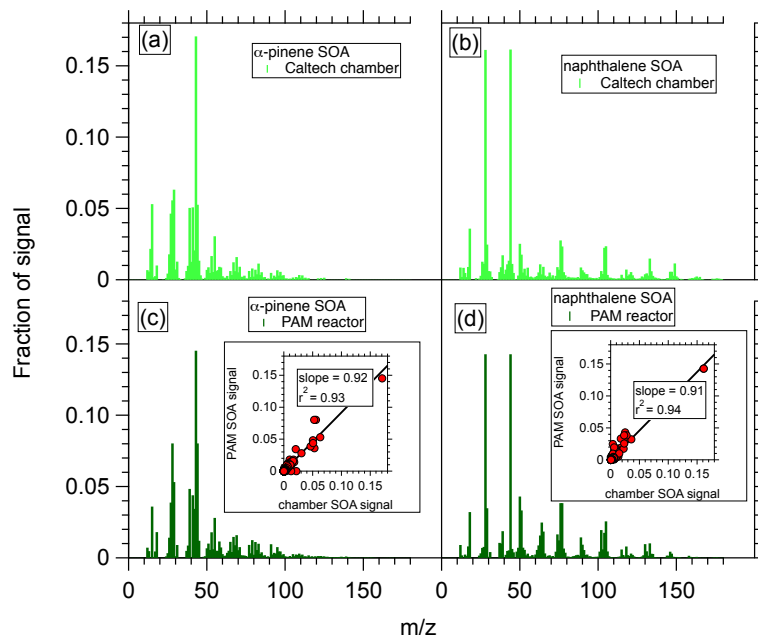
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**Figure 2.** Aerodyne ToF-AMS spectra of SOA generated in the (a and b) Caltech environmental chamber and (c and d) PAM flow reactor from the OH oxidation of  $\alpha$ -pinene and naphthalene. Caltech chamber data obtained from Chhabra et al. (2011).

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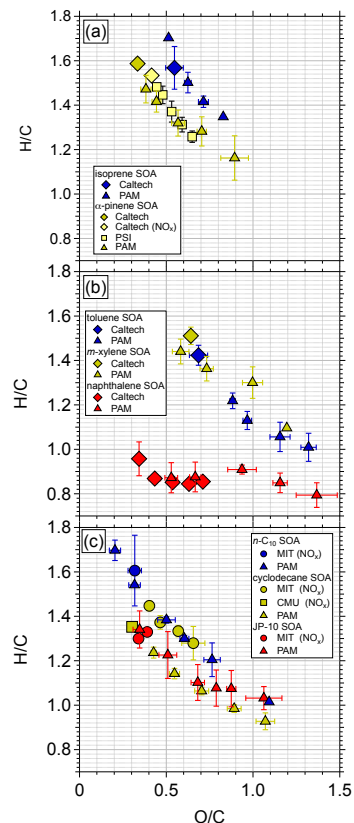
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## Properties of SOA formed in flow reactors and chambers

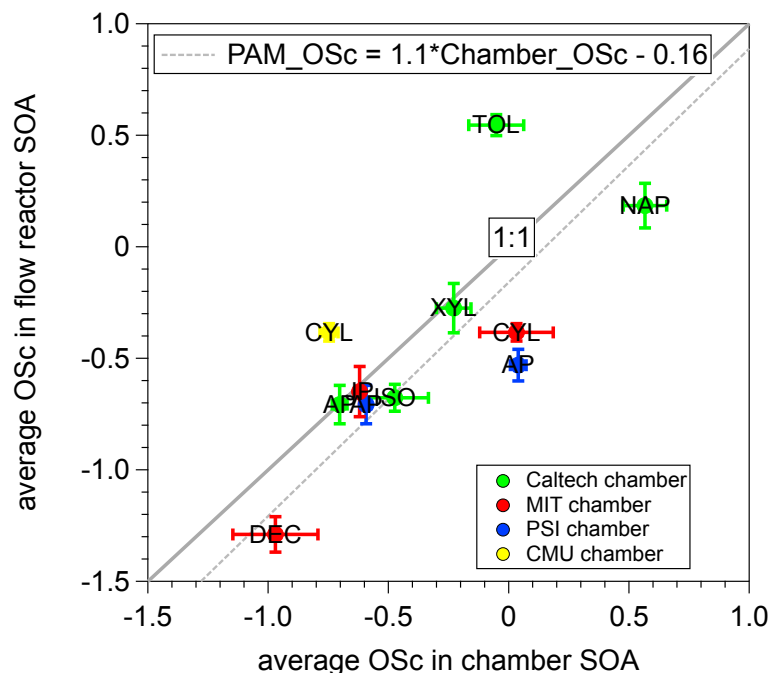
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**Figure 3.** Van Krevelen diagrams showing H/C ratio as a function of O/C ratio for SOA generated in the PAM flow reactor and environmental chambers by OH oxidation of **(a)** biogenic, **(b)** aromatic and **(c)** alkane precursors. Error bars indicate  $\pm 1\sigma$  uncertainty in binned O/C and H/C ratio measurements. Caltech, PSI, CMU, and MIT chamber data obtained from Chhabra et al. (2011); Pfaffenberger et al. (2013) (binned averages of O/C and H/C data from experiments # 1–9), Tkacik et al. (2012), and Hunter et al. (2014) respectively.

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**Figure 4.** Average carbon oxidation state ( $\overline{OSc}$ ;  $\overline{OSc} = 2 \times O/C - H/C$ ) of flow reactor- and environmental chamber-generated SOA. Error bars indicate  $\pm 1\sigma$  uncertainty in binned  $\overline{OSc}$  measurements. Markers indicate SOA precursor: TOL = toluene; NAP = naphthalene; XYL = *m*-xylene; CYL = cyclodecane; JP = JP-10; ISO = isoprene; AP =  $\alpha$ -pinene; DEC = *n*-C<sub>10</sub>. Caltech, PSI, CMU, and MIT chamber data obtained from Chhabra et al. (2011); Pfaffenberger et al. (2013); Tkacik et al. (2012), and Hunter et al. (2014) respectively.

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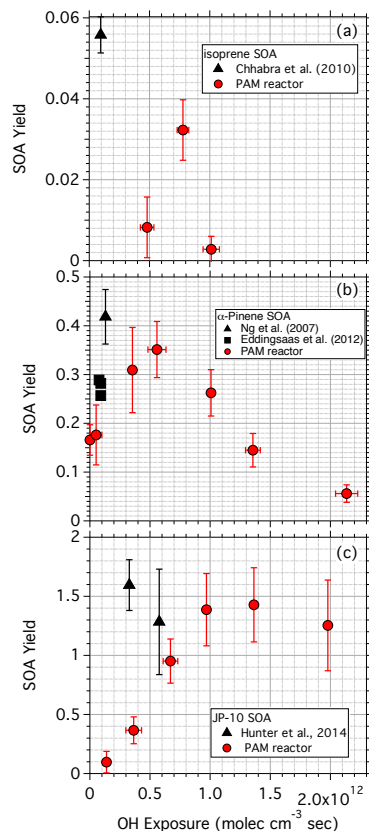
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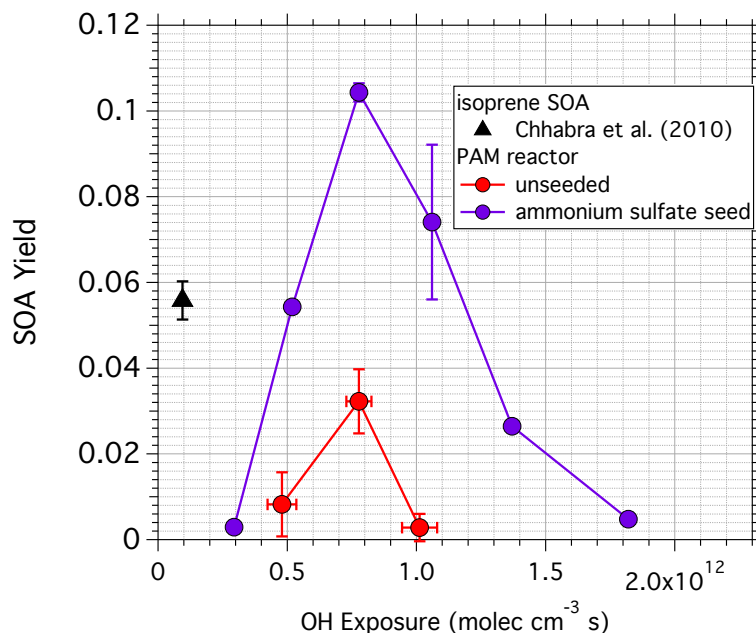
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**Figure 5.** Yields of SOA produced from photooxidation of **(a)** isoprene, **(b)**  $\alpha$ -pinene, and **(c)** tetracyclo[5.2.1.0<sup>2,6</sup>]decane (JP-10) in environmental chambers and PAM reactor as a function of OH exposure. Error bars indicate  $\pm 1\sigma$  uncertainty in binned measurements. Black markers indicate data from Chhabra et al. (2010); Eddingsaas et al. (2012), and Ng et al. (2007) obtained in the Caltech chamber and data from Hunter et al. (2014) was obtained in the MIT chamber.

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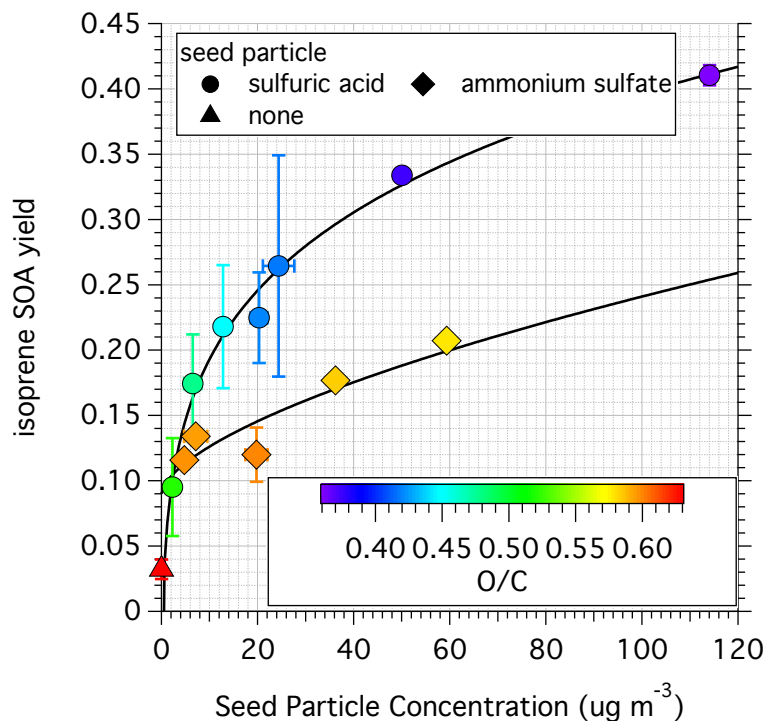


**Figure 6.** Yields of SOA produced from photooxidation of isoprene in the PAM reactor as a function of OH exposure in the presence of  $20 \mu\text{g m}^{-3}$  ammonium sulfate seed. Error bars indicate  $\pm 1\sigma$  uncertainty in binned measurements.

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**Figure 7.** Yields of isoprene SOA produced in the PAM reactor at an OH exposure of  $7.8 \times 10^{11} \text{ molec cm}^{-3} \text{ s}$  as a function of seed particle concentration using ammonium sulfate and sulfuric acid seeds. Error bars indicate  $\pm 1\sigma$  uncertainty in binned measurements. Lines are power law fits to guide the eye.