

# Volatile oxidation products and secondary organosiloxane aerosol from D<sub>5</sub> + OH at varying OH exposures

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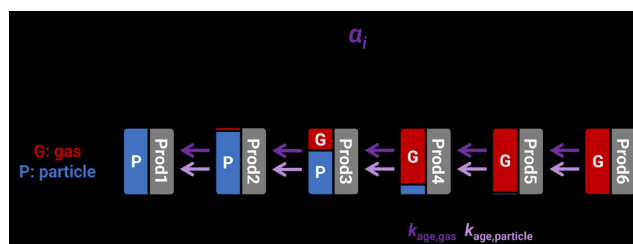
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**Abstract.** Siloxanes are composed of silicon, oxygen, and alkyl groups and are emitted from consumer chemicals. Despite being entirely anthropogenic, siloxanes are being detected in remote regions and are ubiquitous in indoor and urban environments. Decamethylcyclopentasiloxane (D<sub>5</sub>) is one of the most common cyclic congeners, and smog chamber and oxidation flow reactor (OFR) experiments have found D<sub>5</sub> + OH to form secondary organosiloxane aerosol (SOSiA). However, there is uncertainty about the reaction products and the reported SOSiA mass yields ( $Y_{\text{SOSiA}}$ ) appear inconsistent. To quantify small volatile oxidation products (VOPs) and to consolidate the  $Y_{\text{SOSiA}}$  in the literature, we performed experiments using a potential aerosol mass OFR while varying D<sub>5</sub> concentration, humidity, and OH exposure ( $\text{OH}_{\text{exp}}$ ). We use a proton transfer reaction time-of-flight mass spectrometer to quantify D<sub>5</sub>, HCHO, and HCOOH and to detect other VOPs, which we tentatively identify as siloxanols and siloxanyl formates. We determine molar yields of HCHO and HCOOH between 52 %–211 % and 45 %–127 %, respectively. With particle size distributions measured with a scanning mobility particle sizer, we find  $Y_{\text{SOSiA}}$  to be < 10 % at  $\text{OH}_{\text{exp}} < 1.3 \times 10^{11} \text{ s cm}^{-3}$  and  $\sim 20$  % at  $\text{OH}_{\text{exp}}$ , corresponding to that of the lifetime of D<sub>5</sub> at atmospheric OH concentrations. We also find that  $Y_{\text{SOSiA}}$  is dependent on both organic aerosol mass loading and  $\text{OH}_{\text{exp}}$ . We use a kinetic box model of SOSiA formation and oxidative aging to explain the  $Y_{\text{SOSiA}}$  values found in this study and the literature. The model uses a volatility basis set (VBS) of the primary oxidation products as well as an aging rate coefficient in the gas<sup>TS1</sup> and particle phases of  $k_{\text{age,gas}}$  of  $1.14 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$  and  $k_{\text{age,particle}}$  of  $2.18 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ . The combination of a primary VBS and OH-dependent oxidative aging predicts SOSiA formation much better than a standard-VBS parameterization that does not consider aging (root mean square error = 42.6 vs. 96.5). In the model, multi-generational aging of SOSiA products occurred predominantly in the particle phase. The need for an aging-dependent parameterization to accurately model SOSiA formation shows that concepts developed for secondary organic aerosol precursors, which can form low-volatile products at low  $\text{OH}_{\text{exp}}$ , do not necessarily apply to D<sub>5</sub> + OH. The resulting yields of HCHO and HCOOH and the parameterization of  $Y_{\text{SOSiA}}$  may be used in larger-scale models to assess the implications of siloxanes for air quality.

## Graphical abstract: schematic of the kinetic box model



## 1 Introduction

Organosiloxanes are molecules composed of silicon–oxygen bonds with alkyl groups on the silicons and encompass linear and cyclic species, some of which have vapor pressures on par with volatile organic compounds (VOCs). Siloxanes are entirely anthropogenic pollutants (Rücker and Kümmerer, 2015) commonly used in consumer and industrial chemical products (Seltzer et al., 2021a; Gkatzelis et al., 2021) and their emissions are projected to increase in the coming decades (Tansel and Surita, 2017). Decamethylcyclopentasiloxane (D<sub>5</sub>, C<sub>10</sub>H<sub>30</sub>O<sub>5</sub>Si<sub>5</sub>), where “D” refers to silicon center atoms bonded to two oxygens, is a ubiquitous cyclosiloxane in the ambient environment.

Siloxanes have been detected in the indoor environment (Tang et al., 2015; Tran and Kannan, 2015; Arata et al., 2021; Katz et al., 2021; Kaikiti et al., 2022; Wang et al., 2022), near landfills (Schweigkofler and Niessner, 1999), and near sewage treatment sites (Lee et al., 2014; Horii et al., 2019). Siloxanes are also found in outdoor urban air (Xiang et al., 2021), and organosilicon compounds have been found in varying amounts in ambient particulates in China (Lu et al., 2019; Cheng et al., 2021; Meng et al., 2021; Song et al., 2022; Xu et al., 2022) and the United States (Milani et al., 2021).

Siloxanes are suspected to be environmentally persistent or emitted continuously to appear as such (Howard and Muir, 2010; Xiang et al., 2021), while other studies have found that methyl siloxanes would be removed on timescales of days to weeks (Graiver et al., 2003; Whelan and Kim, 2021). Reaction rate coefficients of D<sub>5</sub> with atmospheric oxidants have been reported, and Atkinson (1991) found D<sub>5</sub> to be effectively unreactive with atmospheric concentrations of O<sub>3</sub> ( $k_{D_5+O_3} < 3 \times 10^{-20} \text{ cm}^3 \text{ s}^{-1}$ ) and NO<sub>3</sub> radicals ( $k_{D_5+NO_3} < 3 \times 10^{-16} \text{ cm}^3 \text{ s}^{-1}$ ) at  $\sim 298 \text{ K}$ . While D<sub>5</sub> is reactive with OH and Cl, Alton and Browne (2020) calculated that the removal of D<sub>5</sub> by Cl radicals would only be a few percent of that by OH radicals at typical ambient oxidant concentrations.

Atkinson (1991), Safron et al. (2015), Xiao et al. (2015), Kim and Xu (2017), and Alton and Browne (2020) have measured  $k_{D_5+OH}$  at  $\sim 298 \text{ K}$  to be  $1.55 \times 10^{-12}$ ,  $2.6 \times 10^{-12}$ ,  $2.46 \times 10^{-12}$ ,  $1.46 \times 10^{-12}$ , and  $2.1 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ , re-

spectively. These measurements are summarized in Table S1 in the Supplement. Xiao et al. (2015) derived  $k_{D_5+OH}$  computationally as  $2.90 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ . In this paper, we use  $k_{D_5+OH} = 2.0 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ , which is a rounded average of the empirically determined rate coefficients. This  $k_{D_5+OH}$  corresponds to a D<sub>5</sub> atmospheric lifetime of about 4 d via removal by OH, assuming a daily average OH concentration ( $[OH]_{avg}$ ) of  $1.5 \times 10^6 \text{ cm}^{-3}$ .

D<sub>5</sub> is expected to suppress O<sub>3</sub> formation in urban environments. Carter et al. (1993) performed a series of chamber experiments mimicking urban air conditions and found that D<sub>5</sub> siloxane would inhibit ozone formation by suppressing the OH radical. In contrast, formaldehyde (HCHO) is known to contribute to O<sub>3</sub> formation (Derwent et al., 1996). Fu et al. (2020) predicted the formation of HCHO as a product of D<sub>5</sub> + OH in low-NO/HO<sub>2</sub> conditions using quantum chemical calculations and kinetics modeling, but an experimental yield of HCHO from D<sub>5</sub> + OH has not been reported. Atkinson (1991) proposed HCHO as a product of the siloxane alkoxy radical (RO) pathway, assuming an analogous mechanism to that of VOCs. Sommerlade et al. (1993) suggested that HCHO may arise from siloxane RO decomposition and from ROOH rearrangement in the presence of acids and H<sub>2</sub>O. Alton and Browne (2022) predicted HCHO as a product of RO<sub>2</sub> rearrangement in the case of D<sub>3</sub> siloxane. Because HCHO is a secondary product, the O<sub>3</sub> formation potential of D<sub>5</sub> may differ between at a source and at downwind locations.

Formic acid (HCOOH) is a common acid catalyst in the atmosphere (Hazra et al., 2014) and a particle-nucleating species (Yu, 2000). Studies have identified some HCOOH sources in the atmosphere (Millet et al., 2015; Franco et al., 2021); however, HCOOH is suspected to have unidentified anthropogenic sources in the troposphere (Millet et al., 2015; Chen et al., 2021) as some urban sources remain unaccounted for (Le Breton et al., 2012; Yuan et al., 2015). Chandramouli and Kamens (2001) proposed that the RO<sub>2</sub> initially formed from D<sub>5</sub> + OH makes a siloxanyl formate (D<sub>4</sub>T(OCHO), where “T” refers to a silicon center bonded to three oxygens) that reacts with H<sub>2</sub>O to form a siloxanol (D<sub>4</sub>T(OH)) and HCOOH. However, we are unaware of experimental HCOOH yields reported for D<sub>5</sub> + OH.

Whelan et al. (2004) used known siloxane chemistry in a partitioning model to assess the atmospheric fate of siloxanes and found that silanols are the predominant oxidation products. These silanols are generally water soluble and either removed from the atmosphere via wet deposition or undergo a pH-dependent process of hydrolysis, forming smaller and smaller silanols (Whelan et al., 2004). Eventually, the small silanols are converted to SiO<sub>2</sub>, H<sub>2</sub>O, and CO<sub>2</sub> through photolytic reactions in water or biological processes in soil (Spivack et al., 1997; Stevens, 1998; Graiver et al., 2003).

The intermediate products between D<sub>5</sub> and those small silanols are less studied, and the OH-oxidation rate coefficients of these intermediates have not been reported. Som-

merlade et al. (1993) and Alton and Browne (2022) used mass spectrometry to study the gaseous products of D<sub>5</sub> oxidation in chambers, while Fu et al. (2020) used quantum chemistry modeling. These studies found that gaseous intermediates are composed of a variety of alcohols, aldehydes, esters, and hydroperoxides. Given that such volatile oxidation products (VOPs) in experiments with higher OH<sub>exp</sub> are likely to undergo multiple oxidation steps, there is a need to address their subsequent oxidation rate coefficients. Moreover, while the formation of HCHO and HCOOH has been predicted in mechanisms, it has not been quantified.

Secondary aerosol mass yield ( $Y$ , Eq. 1) is defined as the ratio of produced aerosol mass ( $\Delta m(\text{SOSiA})$ ) to reacted precursor mass ( $\Delta m(\text{D}_5)$ ), which we adopt here for secondary organosiloxane aerosol (SOSiA). Reports about secondary aerosol formation from D<sub>5</sub> siloxane seem conflicting, with some experiments reporting much higher  $Y_{\text{SOSiA}}$  than others. For instance, Wu and Johnston (2017) and Janecek et al. (2019) saw maximum  $Y_{\text{SOSiA}}$  of 23 % and 50 %, respectively, in their photo-oxidation chamber and oxidation flow reactor (OFR) experiments, albeit at different OH exposures (OH<sub>exp</sub>). Charan et al. (2022) found a  $Y_{\text{SOSiA}}$  of 158 % with their OFR at an OH<sub>exp</sub> of  $3.2 \times 10^{12} \text{ s cm}^{-3}$ . Avery et al. (2023) reported a wide range of  $Y_{\text{SOSiA}}$  values (2 %–146 %) from their OFR experiments.

$$Y_{\text{SOSiA}} = \frac{\Delta m(\text{SOSiA})}{\Delta m(\text{D}_5)} \quad (1)$$

In contrast, Charan et al. (2022) reported almost negligible  $Y_{\text{SOSiA}}$  (< 5 %) from their chamber studies where [OH] was on the order of  $\sim 10^6 \text{ cm}^{-3}$ , which is closer to [OH] found in ambient conditions (Peng and Jimenez, 2020). Han et al. (2022) conducted OFR experiments and found that  $Y_{\text{SOSiA}}$  would be 2 % at [OH] of  $4.6 \times 10^8 \text{ cm}^{-3}$  or OH<sub>exp</sub> of  $5.5 \times 10^{10} \text{ s cm}^{-3}$ . The variation of  $Y_{\text{SOSiA}}$  reported in the literature suggests that oxidation conditions need to be considered to accurately parameterize  $Y_{\text{SOSiA}}$ , especially given that D<sub>5</sub> is being considered in air-quality models as a part of volatile chemical product inventories (Pennington et al., 2021; Seltzer et al., 2021a, b).

In this study, we aim to assess the OH oxidation of D<sub>5</sub> by determining the rate coefficients of secondary reactions of VOPs with OH (i.e., chemical aging) and providing a first quantification of HCHO and HCOOH yields. We also measure  $Y_{\text{SOSiA}}$  under diverse OH<sub>exp</sub> and [D<sub>5</sub>]<sub>0</sub> conditions. Lastly, we develop parameterizations of SOSiA yield using a kinetic model with a chemical aging reaction scheme to reconcile the reported  $Y_{\text{SOSiA}}$  from D<sub>5</sub> + OH in the literature and for use in air-quality models.

## 2 Method and materials

### 2.1 Experiments

The Aerodyne Research (Billerica, MA, USA) potential aerosol mass OFR (PAM-OFR) (Kang et al., 2007) has a volume of 13.3 L and is made of chromated aluminum (Xu and Collins, 2021). We operated the PAM-OFR in OFR185 mode (Peng and Jimenez, 2020), where 185 nm lamps that also emit 254 nm light (GPH436T5VH, LightSources, Orange, CT, USA) generate OH and O<sub>3</sub> with injected H<sub>2</sub>O vapor from a Nafion humidifier (FC-100-80-6MKK, Perma Pure, Lakewood, NJ, USA). There were two of these 185 nm lamps placed across from each other in clear fused quartz sleeves. The 185 nm lamps were wrapped with covers at even intervals to reduce the UV intensity so that 90 % of the lamp surface was covered. We operated the PAM-OFR at residence times ( $\tau_{\text{res}}$ ) of 120 and 180 s with flow rates of 6.65 and 4.43 L min<sup>−1</sup>, respectively. Additional details about the experiment setup are summarized in Fig. S1 and Sect. S1.

We use the D<sub>5</sub> siloxane trace measured from the proton transfer reaction mass spectrometer (PTR-MS) to calculate OH<sub>exp</sub> with Eq. (2), where  $k_{\text{D}_5+\text{OH}} = 2.0 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ . [D<sub>5</sub>]<sub>0</sub> and [D<sub>5</sub>]<sub>final</sub> are the D<sub>5</sub> concentrations before and after the exposure to OH.

$$\text{OH}_{\text{exp}} = -\frac{1}{k_{\text{D}_5+\text{OH}}} \times \ln \left( \frac{[\text{D}_5]_{\text{final}}}{[\text{D}_5]_0} \right) \quad (2)$$

Prior to experiments, we checked the background particle and D<sub>5</sub> concentrations with the scanning mobility particle sizer (SMPS) and PTR-MS. In all experiments, the background particle number concentrations were < 10 cm<sup>−3</sup>, and the background [D<sub>5</sub>] values were below the limit of detection ( $3\sigma = 80 \text{ ppt}$ ). Then, we injected D<sub>5</sub> with a syringe pump while monitoring the PTR-MS, with major ions at  $m/z$  371 and  $m/z$  355. We performed the experiments with a target [D<sub>5</sub>]<sub>0</sub> of 50, 100, or 200 ppb. With these target [D<sub>5</sub>]<sub>0</sub> values, we get external OH reactivities (OHR<sub>ext</sub>) of 2.5–9.8 s<sup>−1</sup> at 298.15 K and 1 atm, where OHR<sub>ext</sub> is the reactivity caused by the injection of D<sub>5</sub> into the PAM-OFR (Peng and Jimenez, 2020). With these OHR<sub>ext</sub> values, we reduce the risk of OH suppression and VOCs photolysis (Peng and Jimenez, 2020).

When the D<sub>5</sub> trace stabilized near the target [D<sub>5</sub>]<sub>0</sub>, we began the experiment by turning the UV lamps in the PAM-OFR on at either 2.4 or 8.0 V. We waited 30 min for the UV lamps to stabilize and for the PAM-OFR walls to equilibrate with gaseous species. The  $Y_{\text{SOSiA}}$  values (Eq. 1) were calculated using the average SOSiA mass concentration from four SMPS cycles following that 30 min. We obtained  $\Delta m(\text{D}_5)$  as the difference between [D<sub>5</sub>]<sub>0</sub> and [D<sub>5</sub>]<sub>final</sub>. At the end of an experiment, we turned off the UV lamps to check the D<sub>5</sub> trace return.

To clean the PAM-OFR between experiments, we stopped the syringe pump and removed the syringe from the glass bulb while keeping the humid airflow in the PAM-OFR. We

turned on the PAM-OFR UV lamps and connected the outlet directly to the exhaust, until D<sub>5</sub> and particle number concentrations were below the limit of detection. We used Igor Pro 9 (WaveMetrics, Portland, OR, USA) for data post-processing and visualization.

## 2.2 Instrumentation

### 2.2.1 PTR-MS

To measure D<sub>5</sub> and VOPs, we used a PTR-MS (PTR-TOF 1000, IONICON Analytik, Innsbruck, Austria) equipped with the extended volatility range (EVR) option (Piel et al., 2021), where the wetted inlet components and the drift tube are passivated with a silicon coating. The PTR-MS also had an ion transfer lens between the drift tube and time-of-flight mass spectrometer (Jordan et al., 2009). An internal permeation source (PerMaSCal) emitted a steady stream of 1,3-diiodobenzene into the mass spectrometer for mass calibration scale adjustments. Additional PTR-MS details are in Sect. S1.

To reduce H<sub>2</sub>O clusters at high humidities, we operated the PTR-MS at 137 Td ( $U_{\text{drift}} = 600$  V; Td is the Townsend unit where  $1 \text{ Td} = 10^{-17} \text{ V cm}^2$ ) for quantification. The drift tube pressure and temperature were set to 2.30 mbar and 80 °C. For the reagent ion source, we set the  $U_s$ ,  $U_{so}$ , and H<sub>2</sub>O flow rate to 150 V, 80 V, and 6.00 sccm respectively. The ion source hollow-cathode discharge current was set to 5.0 mA. The PTR-MS drift tube was 9.6 cm long, and at 137 Td the [H<sub>2</sub>O]H<sup>+</sup> reaction time ( $\Delta t$ ) was 94  $\mu\text{s}$  (de Gouw et al., 2003). We calculate the primary reagent ion signal, [H<sub>2</sub>O]H<sup>+</sup>, by multiplying the signal of its isotope, [H<sub>2</sub><sup>18</sup>O]H<sup>+</sup>, by 500.

We use the PTR-MS data for the quantification of D<sub>5</sub> ( $m/z$  371), HCHO ( $m/z$  31), and HCOOH ( $m/z$  47), where the primary reagent ion counts were normalized to 10<sup>6</sup> counts per second (ncps). For D<sub>5</sub>, we used a calibration gas cylinder (Apel-Riemer Environmental, Miami, FL, USA) containing D<sub>5</sub> to calibrate the PTR-MS. We also calculate the normalized measurement sensitivity (ncps ppb<sup>-1</sup>) of D<sub>5</sub>, HCHO, and HCOOH using Eq. (3) adapted from de Gouw and Warneke (2007).  $I_{(\text{VOC})\text{H}^+}$  and  $I_{(\text{H}_2\text{O})\text{H}^+}$  are the ion counts of the protonated VOCs and the reagent ion, respectively. Additional details on the mass spectra interpretation and quantification are in Sects. S1.5 and S3.

$$\text{Sensitivity} = \frac{\frac{I_{(\text{VOC})\text{H}^+}}{I_{(\text{H}_2\text{O})\text{H}^+}} \times 10^6}{[\text{VOC}]} \quad (3)$$

We tested the instrument sensitivity response with humidity by keeping the species concentrations constant while changing the sample air humidity. The sensitivity of D<sub>5</sub> at  $m/z$  371 was not heavily affected by humidity at 137 Td, and we did not correct for humidity in the D<sub>5</sub> quantification (Fig. S5). On the other hand, HCHO and HCOOH sensitivities varied

with humidity, and we corrected their sensitivities as detailed in Sect. S3. Prior to experiments, we tuned the micro-channel plate (MCP) to prevent signal bias against higher-mass ions (Müller et al., 2014). We adjusted the MCP voltage in steps to increase the signal strength at  $m/z$  331, a diiodobenzene ion, until the relative signal increase was < 20 %.

### 2.2.2 Scanning mobility particle sizer

An SMPS 3938 (TSI, Shoreview, MN, USA) equipped with an impactor (0.0508 cm) measured the particle mobility diameter size distribution between diameters of 14.3 and 723.4 nm. The SMPS consisted of a model 3082 electrostatic classifier, a model 3081A differential mobility analyzer (DMA), a model 3088 soft X-ray neutralizer, and a model 3756 ultrafine condensation particle counter. We set the SMPS sheath flow at 3.0 L min<sup>-1</sup> and the aerosol flow rate at 0.3 L min<sup>-1</sup>, and the DMA voltage ranged from 10.6 to 9921.4 V. The SMPS scanned for 150 s, followed by a 5 s retrace and 10 s purge while recording on a 3 min cycle. We referred to the manufacturer's recommendations when deciding these SMPS settings (TSI Inc., 2012), and a sample particle size distribution from experiment 12 (Table 1) is shown in Fig. S4.

For the  $Y_{\text{SOSiA}}$  calculations, we convert the SMPS integrated particle volumes into mass using a SOSiA mass density ( $\rho_{\text{SOSiA}}$ ) of 1.07 g cm<sup>-3</sup> for all experiments. We obtained this  $\rho_{\text{SOSiA}}$  from PAM-OFR experiments separate from the ones described here, where we weighed the masses of SOSiA collected on filters and obtained particle volumes with the SMPS. Additional details on  $\rho_{\text{SOSiA}}$  are available in Sect. S2.

## 2.3 Volatility distribution parameterization

Janecek et al. (2019) and Charan et al. (2022) fitted their  $Y_{\text{SOSiA}}$  data to the Odum two-product model (Odum et al., 1996), and we follow the same methodology for comparison with the literature (Sect. S4). Similarly, we fit the standard volatility basis set (VBS) parameters  $\alpha$  (Donahue et al., 2006) in Eq. (4) to the measured  $\Delta m(\text{SOSiA})$  using the measured  $\Delta m(\text{D}_5)$ , where  $\alpha_i$  is the product mass yield for volatility bin  $i$ .

$$\Delta m(\text{SOSiA}) = \Delta m(\text{D}_5) \times \sum_{i=1}^n \frac{\alpha_i}{1 + \frac{C_i^*}{C_{\text{OA}}}} \quad (4)$$

In the experiments, the organosiloxane aerosol mass loading ( $C_{\text{OA}}$ ) was equivalent to the SOSiA mass concentrations. As the produced aerosol mass in the experiments ranged from 3.7 to 965.7  $\mu\text{g m}^{-3}$ , we use six logarithmically spaced effective saturation mass concentration ( $C^*$ ) bins ranging from 0.1 to 10 000  $\mu\text{g m}^{-3}$  at 298.15 K to cover the low- and high-volatility products. For reference, D<sub>5</sub> liquid has a vapor pressure of 20.4 Pa at 298.15 K or  $C^* = 3.05 \times 10^6 \mu\text{g m}^{-3}$  (Lei et al., 2010). Since the experiments had slight variations in

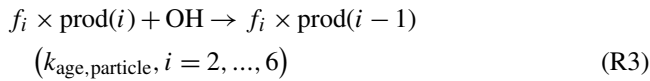
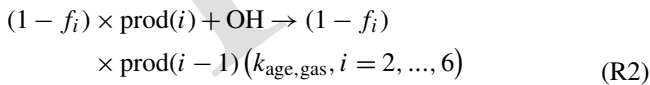
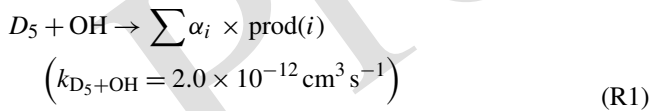


**Table 1.** Summary of SOSiA mass yields ( $Y_{\text{SOSiA}}$ ) with aerosol sampling line corrections assuming  $\rho_{\text{SOSiA}} = 1.07 \text{ g cm}^{-3}$  for all experiments.  $[\text{H}_2\text{O}]$  is the molar mixing ratio of  $\text{H}_2\text{O}$  in air. For  $\text{C}_{\text{OA}}$  and  $[\text{D}_5]$  the errors are the standard deviation of the data points averaged, while for  $Y_{\text{SOSiA}}$  they are calculated with error propagation. For reference, at  $25^\circ\text{C}$  and 1 atm, 1 ppb of  $\text{D}_5$  is  $\sim 15 \mu\text{g m}^{-3}$  and 1 d equivalent of  $\text{OH}_{\text{exp}}$  is  $\sim 1.3 \times 10^{11} \text{ s cm}^{-3}$  at a daily  $[\text{OH}]_{\text{avg}}$  of  $1.5 \times 10^6 \text{ cm}^{-3}$ . [TS2](#)

Experiment	$Y_{\text{SOSiA}}$ (%)	$[\text{H}_2\text{O}]$ (%)	$\text{C}_{\text{OA}}$ ( $\mu\text{g m}^{-3}$ )	$\text{OH}_{\text{exp}}$ ( $\text{s cm}^{-3}$ )	$[\text{OH}]$ ( $\text{cm}^{-3}$ )	$[\text{D}_5]_0$ (ppb)	$1 - [\text{D}_5]_{\text{final}}/[\text{D}_5]_0$
1	$5.9 \pm 0.9$	0.892	$10.5 \pm 0.7$	$1.73 \times 10^{11}$	$9.59 \times 10^8$	$43.4 \pm 1.3$	0.292
2	$4.9 \pm 0.6$	0.828	$19.0 \pm 0.6$	$1.90 \times 10^{11}$	$1.06 \times 10^9$	$85.7 \pm 2.5$	0.316
3	$3.3 \pm 0.6$	0.742	$17.7 \pm 0.5$	$1.26 \times 10^{11}$	$6.99 \times 10^8$	$165.8 \pm 4.5$	0.222
4	$19.5 \pm 1.5$	1.95	$75.2 \pm 1.9$	$4.66 \times 10^{11}$	$2.59 \times 10^9$	$44.0 \pm 1.7$	0.606
5	$29.3 \pm 2.7$	2.06	$179.2 \pm 3.1$	$3.80 \times 10^{11}$	$2.11 \times 10^9$	$78.3 \pm 3.2$	0.532
6	$26.5 \pm 1.8$	2.09	$286.2 \pm 7.1$	$3.12 \times 10^{11}$	$1.73 \times 10^9$	$157.8 \pm 3.6$	0.464
7	$8.6 \pm 0.5$	0.733	$36.8 \pm 1.3$	$5.76 \times 10^{11}$	$3.20 \times 10^9$	$43.8 \pm 1.3$	0.684
8	$18.6 \pm 1.7$	0.736	$118.6 \pm 5.6$	$4.00 \times 10^{11}$	$2.22 \times 10^9$	$78.9 \pm 3.2$	0.550
9	$21.8 \pm 1.1$	0.797	$304.5 \pm 2.8$	$4.19 \times 10^{11}$	$2.33 \times 10^9$	$166.8 \pm 4.1$	0.567
10	$39.8 \pm 2.2$	1.93	$212.9 \pm 8.1$	$9.01 \times 10^{11}$	$5.00 \times 10^9$	$43.8 \pm 1.4$	0.835
11	$47.4 \pm 1.9$	2.08	$420.2 \pm 3.0$	$7.78 \times 10^{11}$	$4.32 \times 10^9$	$76.5 \pm 2.2$	0.789
12	$54.0 \pm 2.4$	2.15	$965.7 \pm 25$	$7.39 \times 10^{11}$	$4.10 \times 10^9$	$156.9 \pm 3.9$	0.772
13	$4.7 \pm 1.7$	0.712	$3.9 \pm 0.3$	$8.70 \times 10^{10}$	$7.25 \times 10^8$	$37.9 \pm 1.6$	0.160
14	$1.9 \pm 0.4$	0.718	$4.1 \pm 0.3$	$1.09 \times 10^{11}$	$9.10 \times 10^8$	$80.8 \pm 2.3$	0.196
15	$1.1 \pm 0.3$	0.704	$3.7 \pm 0.7$	$8.29 \times 10^{10}$	$6.91 \times 10^8$	$162.8 \pm 4.9$	0.153

temperature, we correct for temperature impacts on  $C^*$  between experiments using the Clausius–Clapeyron equation and an enthalpy of vaporization of  $60 \text{ kJ mol}^{-1}$ , which is that of  $\text{D}_5$  siloxane (Lei et al., 2010).

As the experiments were performed for a range of  $\text{OH}_{\text{exp}}$ , the products between experiments may have varied due to multi-generational aging (Zhao et al., 2015). To account for aging and parameterize  $Y_{\text{SOSiA}}$  as a function of  $\text{OH}_{\text{exp}}$ , we also analyze the yield data using a kinetic box model with four chemical reactions (Reactions R1–R3) written in MATLAB (MathWorks, Natick, MA, USA).



Reaction (R1) describes the initial oxidation of  $\text{D}_5$  and immediate formation of products of varying volatility. Here,  $\text{prod}(i)$  refers to the sum of products (gas + particle) in volatility bin  $i$ , which are formed with a molar branching ratio  $\alpha_i$ . We assume that  $\text{prod}(i)$  values have the same molecular weights ( $\text{g mol}^{-1}$ ) as  $\text{D}_5$ , and so the  $\alpha_i$  values are equivalent to the product mass yields at  $\text{OH}_{\text{exp}} \rightarrow 0$ . In the model, a fraction  $f_i$  of each oxidation product partitions instantaneously from the gas phase to the particle phase according to absorptive partitioning theory (Donahue et al., 2006) (Eq. 5).

$$f_i = \left( \frac{1}{1 + \frac{C_i^*}{\text{C}_{\text{OA}}}} \right) \quad (5)$$

Reactions (R2) and (R3) describe how  $\text{OH}_{\text{exp}}$  causes volatility to decrease (Robinson et al., 2007). This decrease in volatility via “bin hopping” (Sommers et al., 2022) occurs at a rate proportional to the chemical aging rate coefficients for gas- and particle-phase species ( $k_{\text{age,gas}}$  and  $k_{\text{age,particle}} \text{ cm}^3 \text{ s}^{-1}$ ). [TS3](#) Here we assume that products in the lowest-volatility bin ( $i = 1$ ) cannot be removed from that bin and that the highest-volatility bin ( $i = 6$ ) does not receive product with aging. The  $[\text{OH}]$  values are set by dividing the experimental  $\text{OH}_{\text{exp}}$  from Eq. (2) by the PAM-OFR residence times.

We use  $k_{\text{age,gas}}$  and  $k_{\text{age,particle}}$  as aggregate chemical aging rate coefficients, not specific to any species or volatility bin. Studies on chamber experiments (Robinson et al., 2007) and ambient measurements (Sommers et al., 2022) have applied chemical aging only to the gas phase as heterogeneous aging is slower. However, studies have found that the high oxidant concentrations in OFRs would appreciably oxidize organic aerosol (OA) within experiment timescales (Kessler et al., 2012; Kroll et al., 2015). To accommodate OH uptake to the bulk phase, we include particle-phase aging that also decreases the volatility of particle-phase products. The timescales and atmospheric relevance of heterogeneous oxidation in OFRs are areas of ongoing research (Zhao et al., 2019; Peng and Jimenez, 2020), but for now we opt to fit chemical aging rate coefficients for each phase. [TS4](#)

We fit  $k_{\text{age,gas}}$ ,  $k_{\text{age,particle}}$ , and  $\alpha_i$  in the aging-VBS model to the experimental SOSiA mass using the Monte Carlo genetic algorithm (MCGA) (Berkemeier et al., 2017). We obtain a best model fit and a fit ensemble consisting of 548 TSS parameter sets for which the model's root mean square error (RMSE) is below the threshold of 50. We find this ensemble to estimate the parametric uncertainty associated with the model fit (Berkemeier et al., 2021).

We use the OFR chemistry template with KinSim (Peng and Jimenez, 2020) to estimate the RO<sub>2</sub> fates and expect the fates to have been uniform across the experiments (Sect. S5). Although there are uncertainties in the RO<sub>2</sub> reaction rate coefficients for siloxanes, we expect that the variation in  $Y_{\text{SOSiA}}$  is not driven by RO<sub>2</sub> fate in these experiments. We also report the condensational sink and condensation lifetimes (Palm et al., 2016) calculated using the particle size distributions in Sect. S1.3.

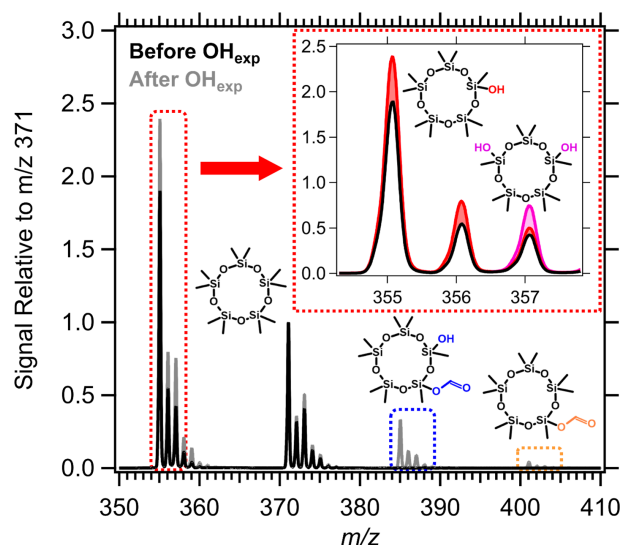
### 3 Results and discussion

#### 3.1 Volatile organic products (VOPs)

##### 3.1.1 Siloxanol and formate ester trends

In Fig. 1, the PTR-MS signals before and after D<sub>5</sub> is oxidized are displayed relative to the protonated D<sub>5</sub> ion at  $m/z$  371 on the y axis. We perform this scaling because the isotopologues of the product fragment ions overlap with the isotopologues of D<sub>5</sub>. Thus, changes in signal intensity are caused by both product formation and D<sub>5</sub> oxidation. We choose to normalize the spectra at  $m/z$  371 because we assume that no product ion peaks overlap with the [D<sub>5</sub>]H<sup>+</sup> signal at  $m/z$  371. While this scaling makes the product peaks appear larger, the changes in the mass spectrum are also qualitatively highlighted. For example, D<sub>5</sub> loses a methyl group during the PTR, which forms a large signal at  $m/z$  355. The isotopologues of the -CH<sub>4</sub> fragment of [D<sub>5</sub>]H<sup>+</sup> overlap with fragments of VOPs. By scaling the mass spectrum with the ratio of [D<sub>5</sub>]H<sup>+</sup> signal before and after oxidation, the signal of the VOPs is separated from that of remaining D<sub>5</sub>.

Using the mass spectra and species reported by Alton and Browne (2022), we attribute the indicated ions in Fig. 1 to siloxanol (D<sub>4</sub>T(OH)), siloxanediol (D<sub>3</sub>T<sub>2</sub>(OH)<sub>2</sub>), siloxanyl formate (D<sub>4</sub>T(OCHO)), and siloxanoly formate (D<sub>3</sub>T<sub>2</sub>(OH)(OCHO)). Here, D and T refer to silicon centers bonded to two and three oxygen atoms, respectively. The multifunctional VOPs are reported to arise from multiple steps of oxidation (Alton and Browne, 2022). The red and pink shaded areas in the inset of Fig. 1 refer to the enhancement in signal over that of the -CH<sub>4</sub> fragment of [D<sub>5</sub>]H<sup>+</sup>, which we attribute to the -H<sub>2</sub>O fragments of [D<sub>4</sub>T(OH)]H<sup>+</sup> and [D<sub>3</sub>T<sub>2</sub>(OH)<sub>2</sub>]H<sup>+</sup>, respectively. We use the masses of the -H<sub>2</sub>O fragments of the protonated siloxanols as large alcohols dissociate during the PTR (Brown et al., 2010). We also attribute the ions in the blue- and yellow-dotted

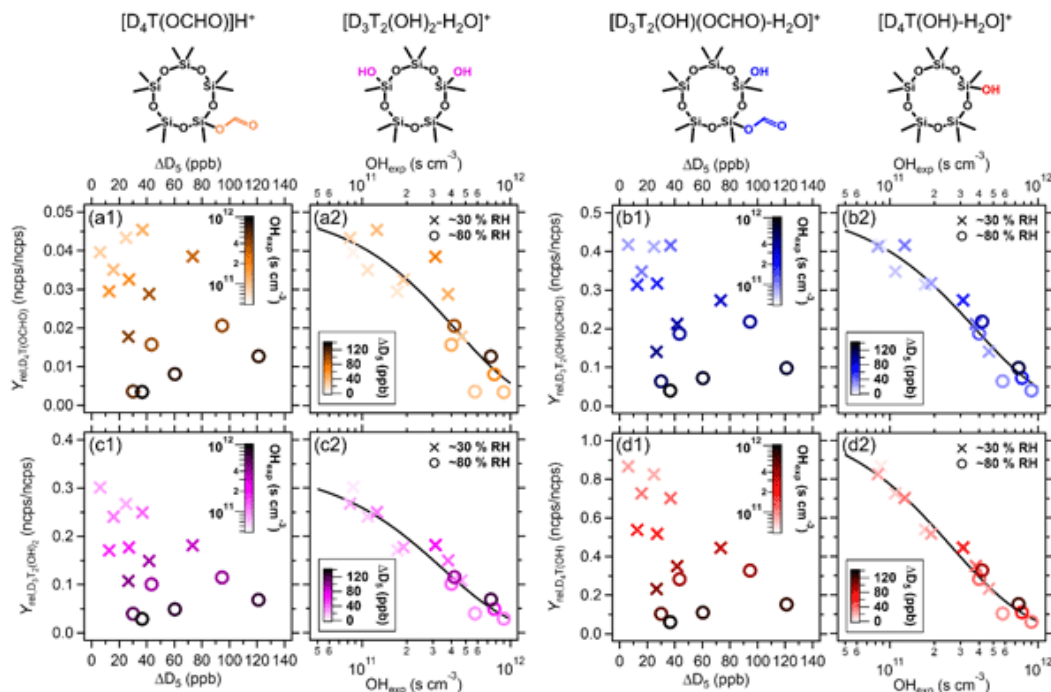


**Figure 1.** Example PTR-MS mass spectra from experiment 12 and proposed VOP ions. For visualization, the signal intensities before (black) and after (gray) oxidation are shown relative to the maximum signal intensity of the [D<sub>5</sub>]H<sup>+</sup> ion at  $m/z$  371, which is set to 1. The multifunctional species (blue, pink) are expected to be formed through multiple steps of OH oxidation. The red and pink areas in the inset each refer to the enhancement in signal attributed to D<sub>4</sub>T(OH) and D<sub>3</sub>T<sub>2</sub>(OH)<sub>2</sub> over that of the -CH<sub>4</sub> fragment of [D<sub>5</sub>]H<sup>+</sup> and isotope signals, respectively.

boxes to the -H<sub>2</sub>O fragments of [D<sub>3</sub>T<sub>2</sub>(OH)(OCHO)]H<sup>+</sup> and [D<sub>4</sub>T(OCHO)]H<sup>+</sup>.

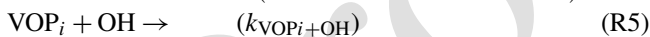
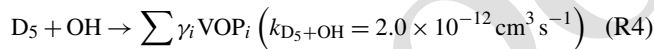
As we did not have calibration standards to quantify these VOPs, we calculate the molar yields of the VOPs relative to that of protonated D<sub>5</sub> siloxane at  $m/z$  371 to study the trends of siloxane VOPs (Fig. 2). For each VOP, we choose a characteristic peak in the mass spectrum and calculate the change in signal due to VOP formation (Sect. S1.5). Then, we calculate the ratios of the changes in the VOP and D<sub>5</sub> signals to get the relative molar yields ( $Y_{\text{rel,VOP}i}$ ). In the right-side panels for each VOP in Fig. 2, the  $Y_{\text{rel,VOP}i}$  decreases with increasing OH<sub>exp</sub> ( $x$  axes). This decrease in VOP signal is consistent with these gaseous products undergoing further oxidation or increased gas–particle partitioning due to higher C<sub>OA</sub> at higher OH<sub>exp</sub>. We use the colors to highlight the functional groups on the D<sub>5</sub> backbone.

In the left-side panels for each VOP in Fig. 2, the relative signals of the VOPs ( $y$  axes) decrease with increasing OH<sub>exp</sub> (color scale). Then, assuming that [OH] is constant throughout the PAM-OFR, that D<sub>5</sub> + OH is the rate-limiting step in VOP formation, and that removal via gas–particle partitioning is negligible (Alton and Browne, 2022), we can consider a simplified D<sub>5</sub> + OH chemical mechanism, Reactions (R4)



**Figure 2.** Relative molar yields of VOPs as a function of OH<sub>exp</sub> and D<sub>5</sub> consumed: (a1, a2) D<sub>4</sub>T(OCHO), (b1, b2) D<sub>3</sub>T<sub>2</sub>(OH)(OCHO), (c1, c2) D<sub>3</sub>T<sub>2</sub>(OH)<sub>2</sub>, and (d1, d2) D<sub>4</sub>T(OH). The colors correspond to the attributed mass ions and molecular structures shown at the top. We did not have a calibration for the suspected VOPs, so the y axes are relative molar yields (ncps / ncps) calculated with the change in signal attributed to each VOP and that of D<sub>5</sub> at *m/z* 371. The relative molar yields decrease with OH<sub>exp</sub>, which is used to fit their OH-oxidation rate coefficients and  $\gamma_i$  (black lines).

and (R5).



In Reaction (R4),  $\gamma_i$  is the relative molar yield of a given VOP<sub>*i*</sub> found by extrapolating  $Y_{\text{rel}, \text{VOP}_i}$  (y axes in Fig. 2) to OH<sub>exp</sub> → 0. With ordinary differential equations (Eqs. 6 and 7) from these reactions (Reactions R7 and R8) and experimental inputs, we fit  $\gamma_i$  and the VOP<sub>*i*</sub> + OH rate coefficient ( $k_{\text{VOP}_i+\text{OH}}$ , cm<sup>3</sup> s<sup>-1</sup>). The fits are shown as black lines in the right-side panels of each VOP in Fig. 2.

$$\frac{d[\text{D}_5]}{dt} = -k_{\text{D}_5+\text{OH}} [\text{D}_5][\text{OH}] \quad (6)$$

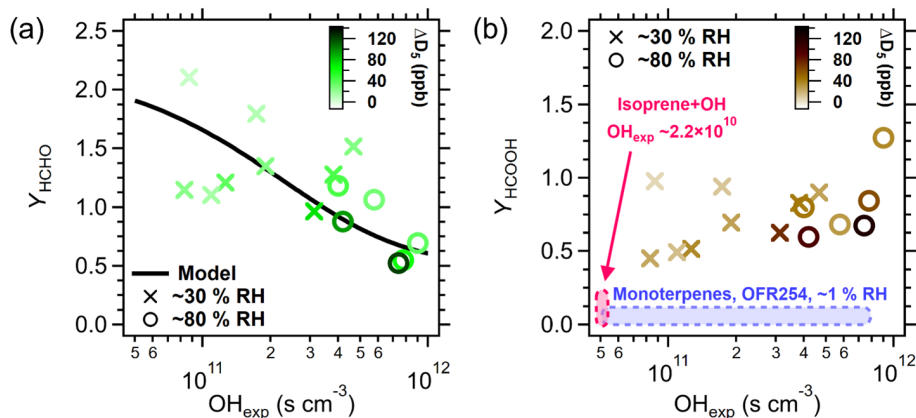
$$\frac{d[\text{VOP}_i]}{dt} = \gamma_i k_{\text{D}_5+\text{OH}} [\text{D}_5][\text{OH}] - k_{\text{VOP}_i+\text{OH}} [\text{VOP}_i][\text{OH}] \quad (7)$$

The fitted  $k_{\text{VOP}_i+\text{OH}}$  values for each VOP are on the order of  $\sim 10^{-12}$  cm<sup>3</sup> s<sup>-1</sup> (Table S7) but faster than  $k_{\text{D}_5+\text{OH}}$ , which suggests that these VOPs have atmospheric lifetimes shorter than that of D<sub>5</sub>. Alton and Browne (2022) have estimated these VOPs to be volatile with quantitative structure–activity relationship models. However, there are uncertainties in those models, and the VOPs may have lower-saturation

mass concentrations than expected. Moreover, the chemical mechanism might be more complex than the one outlined with simple Reactions (R4) and (R5). Consequently, we present these  $k_{\text{VOP}_i+\text{OH}}$  values as estimates for secondary chemistry in this simplified reaction scheme, and future work using quantitative measurements should improve the calculated lifetimes of these intermediate D<sub>5</sub> + OH products in the atmosphere.

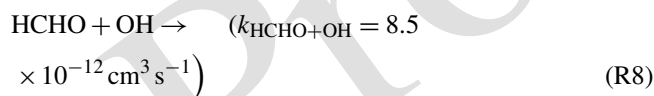
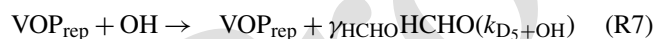
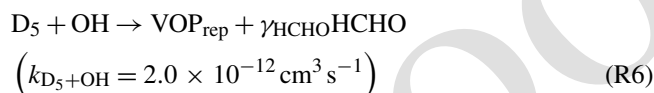
### 3.1.2 Formaldehyde (HCHO) yields

As shown in Table S8 and Fig. 3, the experimental molar yields of HCHO ( $Y_{\text{HCHO}}$ ,  $\Delta\text{HCHO}/\Delta\text{D}_5$  in ppb ppb<sup>-1</sup>) exceed 100 % at low OH<sub>exp</sub> and decrease with higher OH<sub>exp</sub>. We attribute the decreasing  $Y_{\text{HCHO}}$  with increasing OH<sub>exp</sub> to HCHO removal by OH in the PAM-OFRR. HCHO has a lifetime of 0.91 d at  $[\text{OH}]_{\text{avg}} = 1.5 \times 10^6 \text{ cm}^{-3}$  (Atkinson et al., 2006) or 78 s at  $[\text{OH}] = 1.5 \times 10^9 \text{ cm}^{-3}$ . In such high-[OH] conditions, some HCHO is oxidized while being produced, which is consistent with the decreasing  $Y_{\text{HCHO}}$  with increasing OH<sub>exp</sub> (Fig. 3a). However, HCHO formation likely occurs over multiple oxidation steps (Fu et al., 2020), and how VOP + OH branches to produce HCHO and the rate coefficients for those reactions are not experimentally constrained.



**Figure 3.** Experimental molar yields of selected VOPs: (a) HCHO and (b) HCOOH as functions of  $\text{OH}_{\text{exp}}$ . The blue shaded area in (b) is the range of  $Y_{\text{HCOOH}}$  ( $< 10\%$ ) measured by Friedman and Farmer (2018) with monoterpenes under low-RH and low- $\text{NO}_x$  conditions. The pink shaded area refers to  $Y_{\text{HCOOH}}$  from isoprene + OH chamber experiments (Link et al., 2020) at lower  $\text{OH}_{\text{exp}}$ .

Consequently, we implement a simplified mechanism (Reactions R6–R8) where  $\text{D}_5 + \text{OH}$  produces a representative VOP ( $\text{VOP}_{\text{rep}}$ ) and yields HCHO at each oxidation step. The subsequent  $\text{VOP}_{\text{rep}} + \text{OH}$  reactions share the same rate coefficient as  $\text{D}_5 + \text{OH}$  and produce HCHO with the same yield ( $\gamma_{\text{HCHO}}$ ). This  $\gamma_{\text{HCHO}}$  is the cumulative molar yield of HCHO or the molar yield of HCHO as  $\text{OH}_{\text{exp}} \rightarrow 0$ . This  $\gamma_{\text{HCHO}}$  is also used to correlate satellite column retrievals of HCHO with VOC emissions (Millet et al., 2006) where an empirical value can be used to constrain uncertainty.



We fit  $\gamma_{\text{HCHO}}$  to be 223 % (black line in Fig. 3a), assuming a constant  $[\text{OH}]$  in the PAM-OFRR and that HCHO removal via partitioning or reactive uptake is negligible. This  $\gamma_{\text{HCHO}}$  is consistent with the modeled yields of those for VOCs used by Millet et al. (2006), who used  $\gamma_{\text{HCHO}}$  from chemical models ranging from 60 %–230 % for a variety of VOCs. Thus,  $\text{D}_5$  has a comparable  $\gamma_{\text{HCHO}}$  to that of isoprene or aromatic VOCs. An improved mechanism and additional rate coefficients are needed to accurately model HCHO formation.

Fu et al. (2020) proposed a mechanism for  $\text{D}_3$  siloxane where high  $Y_{\text{HCHO}}$  is produced under low- $\text{NO}/\text{HO}_2$  conditions. In that mechanism,  $\text{RO}_2$  rearrangement and  $\text{ROH}$  shift is fast, and HCHO is produced at each rearrangement step. The  $\gamma_{\text{HCHO}}$  exceeding 100 % in these  $\text{D}_5$  experiments is consistent with HCHO production over multiple rapid oxidation steps. The results we report suggest that a similar HCHO production mechanism exists for  $\text{D}_5$ .

Mao et al. (2009) found that models under-predicted tropospheric HCHO during their aircraft campaign studying Asian pollution outflows into the Pacific Ocean. This discrepancy between the measurements and calculations was pronounced near the surface and up to 2 km. They proposed that there is some missing OH reactivity and that the unaccounted species would be reactive with OH and yield HCHO when oxidized. Based on the  $\text{D}_5$  experiments present here, the inclusion of siloxane species may reduce the HCHO formation gap; Coggon et al. (2021) already noted that including volatile chemical products in their model would increase HCHO production.

The large formation of HCHO may entail  $\text{D}_5$  siloxane contributing to  $\text{O}_3$  formation, albeit indirectly. We were unable to observe  $\text{O}_3$  enhancement due to the high concentrations of  $\text{O}_3$  produced from the PAM-OFRR internal chemistry itself and the lack of  $\text{NO}_x$ . Given that  $k_{\text{D}_5+\text{OH}}$  is relatively slow compared to that of other common anthropogenic VOCs, we suspect that the oxidation of  $\text{D}_5$  will occur downwind of urban sources in low- $\text{NO}_x$  conditions or in cases of air stagnation. Whether  $\text{D}_5$  has a net positive or negative effect on  $\text{O}_3$  formation in these VOC/ $\text{NO}_x$  scenarios needs to be assessed with models. To get a rough estimate of  $\text{O}_3$  production, we consider a case where 20 ppt of  $\text{D}_5$  reacts with OH to form 40 ppt of HCHO, which also fully reacts. This  $\text{D}_5$  concentration is within the range reported by Coggon et al. (2018) in ambient urban air. The molar maximum incremental reactivity of HCHO under high- $\text{NO}_x$  conditions is  $\sim 20\%$  (Carter et al., 1995), which makes HCHO a prominent precursor for tropospheric  $\text{O}_3$ . By multiplying the maximum incremental reactivity with the HCHO reacted with OH, we can estimate an  $\text{O}_3$  formation potential of 8 ppt from  $\text{D}_5$  in urban air.



### 3.1.3 Formic acid (HCOOH) yields

We find molar yields of HCOOH ( $Y_{\text{HCOOH}}$ ,  $\Delta\text{HCOOH}/\Delta\text{D}_5$  ppb ppb<sup>-1</sup>) between 45 %–127 %, as shown in Fig. 3b, although a trend with  $\text{OH}_{\text{exp}}$  is not obvious (Fig. 3b). We assume HCOOH loss via OH oxidation to be minor given the rate coefficient of  $k_{\text{HCOOH}+\text{OH}} = 4.5 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$  at 298.15 K (Atkinson et al., 2006), which corresponds to 17 d of  $\text{OH}_{\text{exp}}$  at  $[\text{OH}]_{\text{avg}} = 1.5 \times 10^6 \text{ cm}^{-3}$  or an OH-oxidation lifetime of 440 s in our highest- $\text{OH}_{\text{exp}}$  experiment. In addition to D<sub>4</sub>T(OCHO) hydrolysis, HCOOH may have been produced by heterogeneous reactions of HCHO at the surface of the SOSiA or the OFR walls in these humid experiments. In the atmosphere, HCOOH is presumed to form heterogeneously from HCHO and methanediol (HOCH<sub>2</sub>OH) in the presence of wet particles (Franco et al., 2021).

The  $Y_{\text{HCOOH}}$  values from D<sub>5</sub> + OH we report are higher than the values from isoprene + OH (Link et al., 2020) or monoterpene + OH reported by Friedman and Farmer (2018), who quantified the  $Y_{\text{HCOOH}}$  of seven monoterpenes at varying  $\text{OH}_{\text{exp}}$  without NO<sub>x</sub>. The range of  $Y_{\text{HCOOH}}$  values from these references is shown as shaded areas in Fig. 3b. The  $Y_{\text{HCOOH}}$  from D<sub>5</sub> is on par with the humid isoprene ozonolysis cases reported by Link et al. (2020). Friedman and Farmer (2018) also used a PAM-OFR, but with 254 nm UV lamps in dry conditions ( $\sim 1\%$  RH), and Link et al. (2020) used a reaction chamber, which limits a direct comparison with our results. Nevertheless, Friedman and Farmer (2018) found  $Y_{\text{HCOOH}}$  of 0.64 %–8.5 % at  $\text{OH}_{\text{exp}} = 2.0 \times 10^{11} \text{ s cm}^{-3}$ . Aside from the different precursor VOCs and mechanism, Friedman and Farmer (2018) may have encountered less heterogeneous production of HCOOH due to the dry OFR conditions. While D<sub>5</sub> + OH may produce more HCOOH than isoprene + OH, the global emissions of D<sub>5</sub> (McLachlan et al., 2010) are about 4 orders of magnitude smaller than those of isoprene (Guenther et al., 2012). Nevertheless, the product class of siloxanes may constitute a minor atmospheric HCOOH source in urban locations, especially if emissions were to increase.

## 3.2 SOSiA mass yields

### 3.2.1 Volatility basis set parameterization

The Odum two-product model does not accurately capture the  $Y_{\text{SOSiA}}$  in the literature in the high  $C_{\text{OA}}$  range (Sect. S4), so we apply a VBS model. Figure 4a shows the fitted aerosol mass yield curve (blue line) using a standard-VBS model (Eq. 4), but the experimental  $Y_{\text{SOSiA}}$  ( $y$  axis) appears to depend on both  $C_{\text{OA}}$  ( $x$  axis) and  $\text{OH}_{\text{exp}}$  (color scale). To address whether accounting for the varying  $\text{OH}_{\text{exp}}$  in these experiments would improve the VBS model outputs, we fit the produced SOSiA mass using a standard-VBS model (Eq. 4) and a kinetic model with VBS and chemical aging rate co-

efficients (“aging-VBS model”, Reactions R1–R3) based on  $\text{OH}_{\text{exp}}$  and  $[\text{D}_5]_0$  (Table 1).

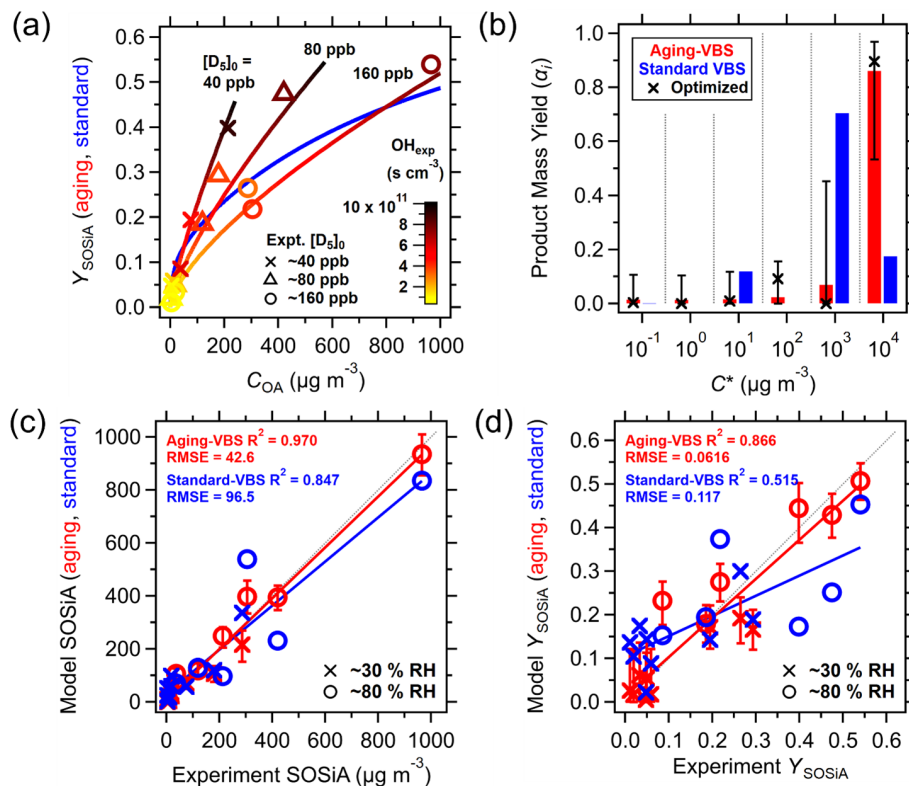
We fit  $k_{\text{age,gas}}$  and  $k_{\text{age,particle}}$  in the aging-VBS model to be  $1.14 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$  and  $2.18 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ , respectively. The fitted aging-VBS model parameters are summarized in Table S11. Figure 4a also shows the aerosol mass yield curves calculated with the aging-VBS model over varying  $\text{OH}_{\text{exp}}$ . Since the aging-VBS model is kinetic, the  $Y_{\text{SOSiA}}$  values are dependent on both  $[\text{D}_5]_0$  and  $\text{OH}_{\text{exp}}$ , and we calculate three yield curves using the approximate experimental  $[\text{D}_5]_0$ . The yield curves generated with the aging-VBS model are more consistent with the experiments and show how  $Y_{\text{SOSiA}}$ ,  $[\text{D}_5]_0$ , and  $\text{OH}_{\text{exp}}$  are intertwined in the proposed aging mechanism.

Secondary organic aerosol (SOA) mass yield often exhibits a maximum as a function of  $\text{OH}_{\text{exp}}$ , after which the yield decreases due to fragmentation becoming dominant at high  $\text{OH}_{\text{exp}}$  (Isaacman-VanWertz et al., 2018). We do not find such a maximum in the range of  $\text{OH}_{\text{exp}}$  studied, which suggests that an even higher  $Y_{\text{SOSiA}}$  could have been found at higher  $\text{OH}_{\text{exp}}$ . Moreover, SOSiA is reported to be non-hygroscopic compared to SOA (Janecek et al., 2019), and we do not see an obvious relationship between the experimental humidity conditions and aerosol formation.

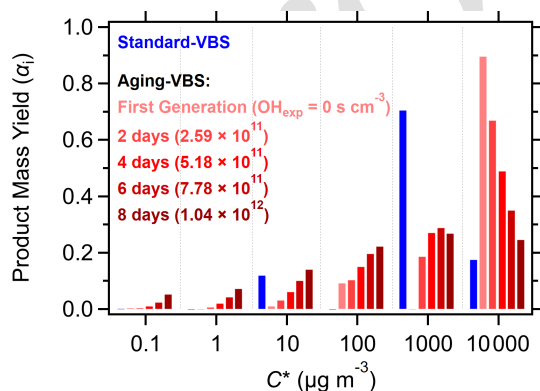
In both the standard and aging-VBS model fits (blue and red, respectively, in Fig. 4b),  $\sim 95\%$  of the D<sub>5</sub> + OH product mass is in the gas phase at a  $C_{\text{OA}}$  of  $10 \mu\text{g m}^{-3}$ . The high fraction of gaseous products is consistent with low  $Y_{\text{SOSiA}}$  in the lower- $\text{OH}_{\text{exp}}$  experiments, whereas additional oxidation in the higher- $\text{OH}_{\text{exp}}$  experiments leads to a shift towards products that partition into the particle phase, thus increasing  $Y_{\text{SOSiA}}$ . The optimized  $\alpha_i$  values for the aging-VBS model are shown as markers in Fig. 4b. The error bars indicate the minimum and maximum values of the fitted  $\alpha_i$  in the ensemble parameter sets, which are further expanded in Fig. S12a. The fit ensemble suggests that products from D<sub>5</sub> + OH must be largely volatile ( $C^* \geq 10^3 \mu\text{g m}^{-3}$ ) in order to reproduce the experimental SOSiA yields.

Figure 4c and d show comparisons of the standard and aging-VBS models with experimental SOSiA mass concentrations and  $Y_{\text{SOSiA}}$ . The error bars indicate the range of model outcomes within the fit ensemble. We see an improvement in the RMSE and  $R^2$  with the aging-VBS model over the standard-VBS model, suggesting that incorporating  $\text{OH}_{\text{exp}}$  into the yield parameterization improves model performance. Figure 5 compares the standard-VBS model with the aging-VBS model for a range of  $\text{OH}_{\text{exp}}$ , showing that product volatility gradually decreases with increasing  $\text{OH}_{\text{exp}}$  in the aging-VBS model. The high volatility of the initial products is consistent with the lack of the rapid formation of low-volatile species, such as highly oxygenated molecules known to form SOA (Isaacman-VanWertz et al., 2018).

We find that the model is very sensitive to  $k_{\text{age,particle}}$ , as a higher  $k_{\text{age,particle}}$  will result in higher model SOSiA formation (Fig. S11a), but not sensitive to  $k_{\text{age,gas}}$ . In ad-



**Figure 4.** Application of standard-VBS and aging-VBS models to experimental data. **(a)**  $Y_{SOSiA}$  as a function of  $C_{OA}$ , where the  $Y_{SOSiA}$  appears to be correlated with  $OH_{exp}$ . The standard-VBS model is shown in blue, and the aging-VBS model is shown with  $OH_{exp}$  (color scale) as it is a kinetic model. **(b)** VBS product mass yields for each volatility bin. For the aging-VBS model, the values are those of the first-generation products. **(c)** Comparison of SOSiA mass concentrations and **(d)** comparison of  $Y_{SOSiA}$  between the aging-VBS and standard-VBS models against measurements. The error bars indicate the minimum and maximum values from the parameter fit ensemble. The aging-VBS model shows a lower RMSE and higher  $R^2$ .



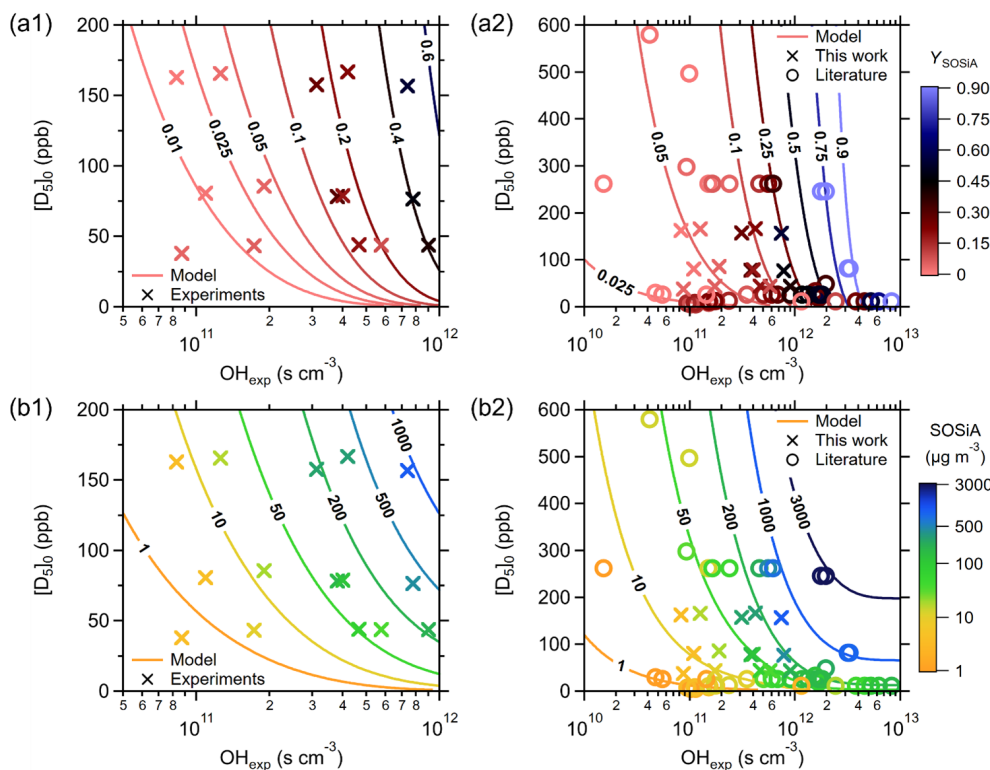
**Figure 5.** Evolution of the volatility distribution with  $OH_{exp}$ . The standard-VBS model parameterization (blue bars) is dominated by the  $C^* = 1000 \mu\text{g m}^{-3}$  volatility bin. In the aging-VBS model, the first-generation volatility distribution is dominated by the highest-volatility bin ( $C^* = 10000 \mu\text{g m}^{-3}$ ) but decreases with increasing  $OH_{exp}$  (red bars).

dition,  $k_{age,particle}$  is tightly constrained in the ensemble of

model fits around a value of  $2 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$  (Fig. S12b). When fitting the model with deactivated particle-phase aging ( $k_{age,particle} = 0$ ), model–experiment RMSE is significantly increased and the fitted  $k_{age,gas}$  becomes unphysically large. The numerical value of the fitted  $k_{age,particle}$ , on the other hand, is physically reasonable as it corresponds to an effective uptake coefficient of OH molecules colliding with the particle surface of less than one (Sect. S1.6). We hence postulate that multi-generational aging of SOSiA occurs predominantly in the particle phase. [TS7](#)

### 3.2.2 Consolidating literature $Y_{SOSiA}$

To address the variation in the literature  $Y_{SOSiA}$  and to generate parameters for air-quality models, we fit the parameters in the aging-VBS model with all available data in the literature and those from our experiments. Given that the literature used differing  $\rho_{SOSiA}$  values to calculate  $Y_{SOSiA}$  from SMPS data, we adjust the  $Y_{SOSiA}$  and  $C_{OA}$  reported in the literature to that of the  $\rho_{SOSiA}$  used here ( $\rho_{SOSiA} = 1.07 \text{ g cm}^{-3}$ ). Similarly, we re-calculate the  $OH_{exp}$  in the literature using Eq. (2) and the  $[D_5]_0$  and  $[D_5]_{final}$  values.



**Figure 6.** Comparison of experiments, model results, and literature values: (a)  $Y_{SOSiA}$  and (b) SOSiA mass concentrations as a function of  $[D_5]_0$  and  $OH_{exp}$ . The aging-VBS model is fit using experimental data from (1) this study and (2) those in the literature. SOSiA formation generally increases with  $[D_5]_0$  and  $OH_{exp}$ . The aging-VBS model can capture the broad range of  $Y_{SOSiA}$  reported in the literature.

Figure 6 shows experimental values (markers) and model outputs (contours) of  $Y_{SOSiA}$  (panels a1 and a2) and SOSiA mass concentrations (panels b1 and b2) as a function of  $[D_5]_0$  and  $OH_{exp}$ . Figure 6a1 and b1 are generated using the aging-VBS model fit using only data from experiments presented in this study, while Fig. 6a2 and b2 show a fit including data from the literature. The aging-VBS model captures the increasing  $Y_{SOSiA}$  with increasing  $[D_5]_0$  and  $OH_{exp}$ . At a given  $[D_5]_0$ ,  $Y_{SOSiA}$  and the SOSiA mass concentrations increase with higher  $OH_{exp}$ . Figure 6a2 shows that the relatively high  $Y_{SOSiA}$  ( $> 50\%$ ) is feasible at  $OH_{exp} > 10^{12}\ s\ cm^{-3}$ . Moreover, the aging-VBS model predicts that  $Y_{SOSiA}$  is almost negligible ( $< 5\%$ ) under atmospheric concentrations of  $D_5$  and  $OH_{exp}$ .

Figure S8 shows that the aging-VBS model used here leads to a much higher correlation between modeled and experimental values for SOSiA mass concentration compared to the same analysis with a standard-VBS model (RMSE = 105 vs. 259). The better correlation suggests that the volatility distribution evolves with  $OH_{exp}$  and that chemical aging should be considered when evaluating the volatility distribution of SOSiA from  $D_5 + OH$ .

We note that bulk-phase chemistry is more complex than logarithmic shifts in volatility with  $OH_{exp}$  and is not fully captured in the proposed aging-VBS parameterization. For

example, Wu and Johnston (2017), Avery et al. (2023), and Chen et al. (2023) characterized  $D_5 + OH$  SOSiA with mass spectrometry and found spectra indicative of oligomers. The formation of oligomers may reduce the bulk volatility by more than one bin and change the gas–particle equilibrium timescales (Berkemeier et al., 2020). Here, we incorporate  $k_{age,gas}$  and a simple bin hopping approach to illustrate that a change in the volatility distribution with  $OH_{exp}$  can adequately capture the  $Y_{SOSiA}$  variation in the literature. Future work with more sophisticated chemical models should close that gap further.

#### 4 Conclusions and atmospheric implications

With a PAM-OFR, PTR-MS, and SMPS, we studied the formation of VOPs and SOSiA under various  $OH_{exp}$  conditions. Using a simplified VOP oxidation scheme (Reactions R4 and R5), we find that the VOPs of tentatively identified siloxanols and formate esters have shorter  $OH$ -oxidation lifetimes than their precursor  $D_5$  (Table S7). In addition, we find the mass yield of HCHO of  $D_5$  comparable to that of isoprene or aromatics (Millet et al., 2006), suggesting that  $D_5$  siloxane is a potential  $O_3$ -contributing species in downwind scenarios. We find  $Y_{HCOOH}$  ranging from 45%–127%, which suggests that  $D_5 + OH$  is a source of atmospheric HCOOH, albeit smaller

than isoprene, which is emitted in higher amounts by orders of magnitude.

An aging-VBS model incorporating OH<sub>exp</sub> and chemical aging adequately describes gas–particle partitioning at atmospheric OH<sub>exp</sub> and CO<sub>A</sub>. Based on these experiments, low-NO<sub>x</sub> Y<sub>SOSiA</sub> should be < 5 % under commonly observed atmospheric OH<sub>exp</sub> < 5 × 10<sup>11</sup> s cm<sup>-3</sup> (Fig. 6a1). The first-generation products of D<sub>5</sub> + OH are likely volatile, but their volatility decreases with increasing OH<sub>exp</sub> (Fig. 5). This evolution in volatility suggests that further oxidation of secondary products would reduce the volatility enough to form SOSiA. Unlike α-pinene (Isaacman-VanWertz et al., 2018) or other precursors for SOA, D<sub>5</sub> + OH does not appear to produce low-volatile species within a single oxidation step. Instead, additional OH<sub>exp</sub> is needed to form aerosol, which suggests that multiple oxidation steps lead to a gradual decrease of product volatility. Hence, concepts that can be successfully applied to SOA formation may not accurately capture SOSiA formation, for which models must consider chemical aging. In the atmosphere, SOSiA from D<sub>5</sub> + OH may be easier to detect downwind of urban sources due to the higher OH<sub>exp</sub> and dilution and/or removal of competing OH-reactive species.

Based on KinSim calculations (Sect. S5), we expect that the RO<sub>2</sub> fate is dominated by RO<sub>2</sub> + HO<sub>2</sub> and RO<sub>2</sub> + OH, which is consistent with the calculations performed by Avery et al. (2023). However, we note that the reaction rate coefficients of RO<sub>2</sub> and its subsequent products are uncertain for D<sub>5</sub>, and we cannot directly address the atmospheric relevance of these calculated RO<sub>2</sub> fates at this time. To improve Y<sub>SOSiA</sub> parameterizations for the atmosphere, there is a need to study the impact NO<sub>x</sub> has on siloxane RO<sub>2</sub> chemistry, given that siloxanes are likely emitted from urban sources where [NO<sub>x</sub>] is high. In such scenarios, RO<sub>2</sub> + NO<sub>x</sub> is likely an important fate (Peng et al., 2019; Newland et al., 2021). Han et al. (2022) found that the addition of N<sub>2</sub>O into their OFR would reduce Y<sub>SOSiA</sub>, although the cause is unclear. However, Charan et al. (2022) did not find Y<sub>SOSiA</sub> to change with NO<sub>x</sub> in their chamber experiments, which is consistent with rapid RO formation across RO<sub>2</sub> fates. Quantifying secondary species across RO<sub>2</sub> fates and identifying their subsequent oxidation reactions may also be useful to adapt the D<sub>5</sub> oxidation mechanism into more sophisticated chemical kinetics models.

We also find that the aging-VBS model is sensitive to  $k_{\text{age,particle}}$  (Fig. S11) and not sensitive to  $k_{\text{age,gas}}$  (Fig. S12), suggesting that heterogeneous aging (TS10) should be considered in these models. The condensation timescale calculations suggest that the loss of low-volatile species to the wall is small (Sect. S1.3); however, these calculations assume a high mass accommodation coefficient for SOSiA and do not account for particle nucleation. Should particle nucleation be delayed or happen slowly, the gas wall loss may be higher than expected, leading to under-quantification of SOSiA. Furthermore, the aging-VBS model assumes that  $k_{\text{age,gas}}$  is

uniform across products or that chemical aging results in a 10-fold decrease in volatility.

While the proposed model assumes that the particles are internally well mixed, the high [OH] used in OFRs may induce faster radical reactions and dimerization near the particle surface (Zhao et al., 2019), which affects particle composition and equilibrium timescales. While dimers and oligomers have been found in SOSiA (Wu and Johnston, 2017; Avery et al., 2023; Chen et al., 2023), the model currently does not account for particle-phase oligomer formation. How oligomerization in the D<sub>5</sub> + OH SOSiA system evolves the volatility distribution and particle properties is currently not considered in the aging-VBS model. Moreover, high degrees of oxidation should lead to fragmentation and increasing volatility (Isaacman-VanWertz et al., 2018), which is also not considered in the aging-VBS model. Hence, multiphase modeling to evaluate SOSiA chemistry and translate experimental findings to atmospheric conditions remains a direction for future research.



## Appendix A: Abbreviations

C <sub>OA</sub> :	organic aerosol mass loading
C <sup>*</sup> :	effective saturation mass concentration
D <sub>5</sub> :	decamethylcyclopentasiloxane
EVR:	extended volatility range
I <sub>254</sub> , I <sub>185</sub> :	flux of 254 and 185 nm photons
ncps:	normalized counts per second
NO <sub>x</sub> :	nitric oxide and nitrogen dioxide
OA:	organic aerosol
OFR:	oxidation flow reactor
OH:	hydroxyl radical
[OH] <sub>avg</sub> :	24 h average daily hydroxyl radical concentration
OH <sub>exp</sub> :	hydroxyl radical exposure
OHR <sub>ext</sub> :	external hydroxyl radical reactivity
O <sub>3</sub> :	ozone
PAM:	potential aerosol mass
PTR:	proton transfer reaction
PTR-MS:	proton transfer reaction mass spectrometer
RH:	relative humidity
RMSE:	root mean square error
RO:	alkoxyl radical
RO <sub>2</sub> :	peroxyl radical
SMPS:	scanning mobility particle sizer
SOA:	secondary organic aerosol
SOSiA:	secondary organosiloxane aerosol
UV:	ultraviolet radiation
VBS:	volatility basis set
VOPs:	volatile oxidation products
Y <sub>HCHO</sub> :	formaldehyde molar yield from D <sub>5</sub>
Y <sub>HCOOH</sub> :	formic acid molar yield from D <sub>5</sub>
Y <sub>rel, VOP</sub> :	relative molar yield of VOP from D <sub>5</sub>
Y <sub>SOSiA</sub> :	SOSiA mass yield from D <sub>5</sub>
γ:	molar yields extrapolated to when OH <sub>exp</sub> → 0
ρ <sub>SOSiA</sub> :	SOSiA aerosol mass density
τ <sub>res</sub> :	residence time

**Data availability.** Summary data are available in the Supplement. Additional data will be provided upon reasonable request.

**Supplement.** The supplement related to this article is available online at: <https://doi.org/10.5194/acp-23-1-2023-supplement>.

**Author contributions.** HGK, YC, and YP conducted the experiments. YP performed the offline calibrations of OH exposure on the PAM-OFR. HGK analyzed the data. HGK and TB developed the kinetic models. HGK, TB, and HK wrote the manuscript with contributions from all co-authors. HK supervised the experiments, and TB supervised the model analyses.

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