

**Halogenation  
processes of  
secondary organic  
aerosol**

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# Halogenation processes of secondary organic aerosol and implications on halogen release mechanisms

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Received: 1 December 2011 – Accepted: 17 January 2012 – Published: 27 January 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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## Abstract

Reactive halogen species (RHS), such as  $X\cdot$ ,  $X_2$  and HOX containing  $X$  = chlorine and/or bromine, are released by various sources like photo-activated sea-salt aerosol or from salt pans, and salt lakes. Despite many studies of RHS reactions, the potential of RHS reacting with secondary organic aerosol (SOA) and organic aerosol derived from biomass-burning (BBOA) has been neglected. Such reactions can constitute sources of gaseous organohalogen compounds or halogenated organic matter in the tropospheric boundary layer and can influence physicochemical properties of atmospheric aerosols.

Model SOA from  $\alpha$ -pinene, catechol, and guaiacol was used to study heterogeneous interactions with RHS. Particles were exposed to molecular chlorine and bromine in an aerosol smog-chamber in the presence of UV/VIS irradiation and to RHS released from simulated natural halogen sources like salt pans. Subsequently the aerosol was characterized in detail using a variety of physicochemical and spectroscopic methods. Fundamental features were correlated with heterogeneous halogenation, which result in new functional groups, changed UV/VIS absorption, or aerosol size distribution. However, the halogen release mechanisms were also found to be affected by the presence of organic aerosol. Those interaction processes, changing chemical and physical properties of the aerosol are likely to influence e.g. the ability of the aerosol to act as cloud condensation nuclei, its potential to adsorb other gases with low-volatility, or its contribution to radiative forcing and ultimately the Earth's radiation balance.

## 1 Introduction

Besides their importance for stratospheric ozone depletion, reactive halogen species (RHS) also play an important role during tropospheric ozone destruction (e.g. Barrie and Platt, 1997; Foster et al., 2001). These effects were indicated by smog-chamber experiments of halogen release from NaCl (e.g. Zetzsch et al., 1988; Behnke and Zetzsch, 1990). Various atmospheric halogen species were monitored within the

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5 tropospheric boundary layer (e.g. Platt, 2000), using Differential Optical Absorption Spectroscopy (DOAS: Platt and Stutz, 2008). Apart from anthropogenic halogen-organic sources, several natural sources for halogens and halogen-organics in the troposphere and the boundary-layer were investigated. Wagner et al. (2007) measured enhanced tropospheric BrO over the coast of Antarctica using multi-axis DOAS. Enami et al. (2007) report an iodine catalysed oxidation of bromide and chloride to molecular halogen species in the troposphere. Important sources for halogens in the troposphere are the halogen-release from sea-salt aerosol (e.g. Finlayson-Pitts, 2003) and the heterogeneous reactions on those aerosol surfaces (Rossi, 2003). Frinak and Abbatt (2006) report Br<sub>2</sub> production from heterogeneous reaction of gas-phase OH with aqueous salt solutions. The formation of Cl<sub>2</sub> by oxidation of Cl<sup>-</sup> in the presence of inorganic aerosols and a strong contribution to the overall chlorine tropospheric budget is suggested by Zetzsch and Behnke (1993). The tropospheric reaction mechanisms of halogens significantly differ from the stratospheric ones (Platt and Hönninger, 2003). The heterogeneous release of RHS from sea-salt aerosol or salt pans is based on the so called “bromine explosion” effect (Platt and Janssen, 1996). Von Glasow and Crutzen (2004) summarized the complex reaction mechanisms of halogen release from various sources, supported by model calculations. Modelling of measurements of tropospheric halogen chemistry above the Dead Sea (Tas et al., 2006) allowed a detailed view on complex reaction mechanisms. Interestingly, these halogen-release mechanisms seem to play a major role also in polar boundary-layer ozone depletion events (Simpson et al., 2007). Recent smog chamber studies exhibit halogen release from simulated salt pans with a wet NaCl/NaBr surface (Buxmann et al., 2012). Those release mechanisms seem to be very similar to the well-investigated ones of sea-salt aerosol.

25 While sources of reactive halogen species in the troposphere are relatively well studied, sinks are hardly known. A possible sink is the reaction with organic matter, which is well known from water disinfection (e.g. Gallard and von Gunten, 2002; Uyguner et al., 2004). Voudrias et al. (1985) report the reaction of phenolic compounds like phenol,

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catechol and guaiacol with free chlorine by drinking water treatment processes and the formation of chlorinated aromatic compounds.

Norwood et al. (1980) studied the chlorination of selected aromatic model substances of aquatic humic material and found the formation of chloroacetic acid. The formation of organochlorine compounds in the condensed phase from soil's humic acids, atmospheric humic-like substances (HULIS), and phenolic moieties were studied by Fahimi et al. (2003) and by Wentworth et al. (2011), suggesting a Fenton-type reaction mechanism. The natural abiotic formation of trihalomethanes (THM) in soil was characterized in detail by Huber et al. (2009). More than 40 reaction products, such as chlorinated ketones, carboxylic acids, ketoacids, lactones, and furanones, were identified from the chlorination of orcinol (3,5-dihydroxy-toluene) by Tretyakova et al. (1994). Ishikawa et al. (1986) studied the reaction of chlorine and bromine with humic substances and found a post-bromination of chlorinated compounds. Caregnato et al. (2007) used flash-photolysis experiments to study the reactions of chlorine radicals with humic acids and reported rate constants up to  $(3 \pm 2) \times 10^{10} \text{ mol}^{-1} \text{ s}^{-1}$ . They suggested that these high values could result from the interaction of  $\text{Cl}_2^-$  with carboxylic acids of humic acids.

THM formation from the reaction of molecular chlorine with humic substances was measured by Uyguner et al. (2004) in water-treatment processes. Schöler and Thiemann (2005) report the natural formation of THM in the marine and terrestrial environment. Halogenated methanes formed by haloform-type reactions were observed by Carpenter et al. (2005). Boyce and Hornig (1983) report the reaction pathways of THM formation by halogenation of dihydroxy-aromatic compounds, acting as models for humic acids. The authors proposed an abiotic formation pathway via reaction of HOX with organic material on the quasi-liquid layer above the sea ice/snow pack. Kopetzky and Palm (2006) reported the formation of halogenated methanes and acetones by halogenation of humic acids in highly saline solutions. Bromoform, bromoacetones, and THM are reported after ozonization of saline solutions containing significant amounts of humic acids (Sörgel, 2007).

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The formation of even simpler molecules in the atmosphere like phosgene, chloroacetone and 1,1-dichloroacetone after interaction of hydrocarbons with halogens released from NaCl aerosol was found by Zetzsch and Behnke (1992). A detailed review on these formation pathways is given by Behnke and Zetzsch (2005). The importance of hydrophobic organics with phenolic acidity in producing high amounts of brominated organics was reported by Huang et al. (2004).

Smodydzin and von Glasow (2007) discussed the influence of organic surface films on halogen release from sea salt aerosols. Rudich (2003) expects a simultaneous occurrence of high concentrations of bromine and chlorine, released from marine aerosols, with organic aerosols in marine environments. Moise and Rudich (2001) used a low-pressure flow reactor to study the reactive uptake of Cl and Br by organic monolayers of alkanes and alkenes. By using FTIR spectroscopy, they monitored an almost complete disappearance of aliphatic C–H bonds. Hydrogen abstraction and an enhancement of the hydrophilic character of the surfaces were reported (Rudich, 2003).

While the atmospheric chemistry community takes increasing interest in heterogeneous processing reactions of atmospheric aerosols, (e.g. George and Abbatt, 2010), only a few studies are focused on halogenated particulate matter or organic aerosols like secondary organic aerosol (SOA) or biomass burning organic aerosol (BBOA). Rahn et al. (1979) measured halogen-containing particles as anthropogenic pollutants in New York finding Br as the most important halogen. Halogenated aerosols were reported by Mosher et al. (1993) at Greenland and related to the photochemical aerosol production from biogenic organo-halogens. Cl-dominated particulate matter from anthropogenic sources, like pesticides, was measured by Xu et al. (2005) at a downtown site in Beijing. Holzinger et al. (2010) found halogenated compounds in organic aerosols at the Sonnblick observatory (Austria), but did not identify them. Basic work on SOA formation induced by chlorine atoms was done by Cai et al. (2006, 2008), when they studied the processing and SOA formation yields of  $\alpha$ -pinene,  $\beta$ -pinene, limonene and toluene. Karlsson et al. (2001) used a flash photolysis system and a continuous

flow reactor to study the homogeneous nucleation of toluene by chlorine atoms in detail.

The present study investigates physicochemical changes of SOA and related precursors caused by RHS. Figure 1 indicates these interactions of RHS released from sea-salt aerosol or salt lakes with SOA, BBOA or atmospheric HULIS and the formation of halogenated SOA/BBOA (halo-SOA/halo-BBOA), halogen-induced SOA formation (XOA) or volatile organic or inorganic halogen species. All studies were based on aerosol smog-chamber experiments. The biogenic  $\alpha$ -pinene and catechol and guaiacol were chosen for producing secondary organic aerosol in the smog chamber. The terpenoid  $\alpha$ -pinene is a well-known precursor for aliphatic SOA, investigated in several studies (e.g. Jonsson et al., 2007; Saathoff et al., 2009). Aerosol chamber studies have been applied to investigate particle formation and processing from  $\alpha$ -pinene (e.g. Iinuma et al., 2004). The transformation pathways of this model substance are summarized by Yu et al., 2008. The formation of secondary organic aerosol from catechol and guaiacol by ozone was investigated by Coeur-Tourneur et al. (2009), Ofner et al. (2010) and Ofner et al. (2011). The use of these aerosols as a model for the aromatic fraction of atmospheric HULIS was discussed by Ofner et al. (2011). The halogen interaction of these model aerosols was studied by photolysis of molecular chlorine and bromine and with halogens released from sea-salt aerosol or a simulated salt pan. The term aerosol must in this case be used according to its exact definition: particles and their surrounding gas phase, which contains, in addition to the common atmospheric gas-phase species, also volatile oxidation products of the aerosol formation process. This is especially important for aerosol smog-chamber studies, where particles and gas phase can be separated from meteorological effects.

## 2 Experimental setup and methods

Three different types of experimental setups were used to study the processing of SOA by RHS:

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also described in this publication. After one hour of aerosol formation, a stoichiometric amount (1 molecule of  $X_2$  to 1 molecule precursor) of molecular bromine or chlorine was added into the aerosol smog-chamber. A condensation-nucleus-counter and differential-mobility-particle-sizer (CNC/DMPs) were used for analysing the evolution of the aerosol size distribution. The experiments were performed with 300 ppb aerosol precursor, 1 ppm ozone and 300 ppb of molecular halogens. Various methods were used to investigate spectroscopic features of the particles, the chemical transformation of functional groups and gaseous species as well as to determine halogenated substances within the particles: Long-path FTIR spectroscopy (LP-FTIR), attenuated-total-reflection FTIR (ATR-FTIR), UV/VIS spectroscopy using an integrating Ulbricht sphere, Ultrahigh resolution mass spectroscopy (ICR-FT/MS). All methods are described in detail by Ofner et al. (2011). To achieve an adequate amount of particulate matter for the methods mentioned above, 5 ppm of the aerosol precursor, 20 ppm of ozone and, after one hour of aerosol formation, 5 ppm of molecular halogens were added.

## 2.2 Photochemical activation salt-pan experiments

The interaction of organic aerosols with halogens released from a simulated salt pan was studied using a 3500 l Teflon<sup>®</sup> smog-chamber with a salt pan mounted in the centre of the chamber (Buxmann et al., 2012). The chamber was flushed with purified air (Ofner et al., 2011). Seven 1200 W HMI lamps, with a water-cooled glass plate as described above, are used to simulate the solar spectrum. A multi-reflection cell (White-cell) coupled with DOAS was used to observe BrO levels directly. The concentrations of OH and Cl radicals were quantified indirectly by monitoring the decay of several hydrocarbons using the radical clock method (Zetzsch and Behnke, 1992). For details on the experimental setup, the analytical methods used and results about RHS release from the salt pan in the absence of SOA, see Buxmann et al. (2012).

Particle formation was studied using the same CNC-DMPs system as described above. ATR-FTIR spectroscopy, diffuse-reflectance UV/VIS spectroscopy and

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ICR-FT/MS were used to characterize physicochemical changes of the processed SOA.

The salt-pan experiments were carried out at 60 % relative humidity. SOA from catechol was formed in the dark for 30 min without activating the halogen-release mechanism. SOA from guaiacol could only be formed in the presence of simulated sunlight. 300 ppb of the SOA precursors were used to generate the SOA. One ppm of ozone was added to the smog chamber to start the SOA formation process (about 600 ppb were consumed by the SOA formation process) and to initiate the release of RHS from the salt pan.

### 3 Results of molecular reaction experiments

Based on former smog chamber experiments regarding SOA formation, we have carried out a molecular reaction experiment to determine the influence of well-defined halogen species on the different types of organic aerosol. The complex reaction schemes of halogen activation and release from heterogeneous surfaces have not been reinvestigated in the present study. We focus on the heterogeneous reaction of well-defined model aerosols with molecular halogens photolysed by the UV/VIS irradiation of the solar simulator, which gives access to the understanding of specific pathways of transformation with respect to the physicochemical properties.

#### 3.1 Change of aerosol size-distribution

The aerosol size distributions of the organic model aerosols are strongly influenced by the interaction with halogens (Fig. 2). The addition of halogens causes an increase of the medium particle diameter, observed with nearly all studied aerosols. The observed increase is stronger during the photochemical transformation in the presence of chlorine than of bromine. While this behaviour holds for SOA from catechol, SOA from guaiacol and  $\alpha$ -pinene exhibits some special features.

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The reaction of chlorine radicals with SOA from guaiacol forms a second mode of the aerosol size distribution. Due to the fact that the methyl-ether-group is the only difference between the catechol and the guaiacol precursor, the formation of this second particle mode might be related to this structural difference. The formation of this mode appears to be caused by a strong supersaturation of the remaining gas-phase species of the oxidized organic precursor. This second mode is not observed during the reaction with bromine radicals.

Although the mean particle diameter increases by the reaction of the organic aerosol from catechol and guaiacol with halogens, another effect appears during the reaction of  $\alpha$ -pinene SOA with the halogen species. The mean diameter increases immediately after adding the halogens, but it remains constant (at 0% relative humidity) or decreases slightly (at 25% relative humidity) afterwards. The decrease of the mean particle diameter is stronger during the reaction with bromine than during the reaction with chlorine.

Hence, the evolution of the aerosol size distribution of different organic aerosol reacting with halogens is not only depending on the reacting halogen (chlorine or bromine) and the relative humidity, but also on the chemical composition of the organic aerosol. The chemical structure of the organic precursor and therefore the structural and functional features of the resulting secondary organic aerosols strongly influence the evolution of the mean particle diameter.

### 3.2 Optical properties in the UV/VIS range

The optical properties of SOA in the UV/VIS spectral range are strongly altered by the reaction with halogens (Fig. 3). The diffuse-reflectance UV/VIS spectrum of organic aerosols from the aromatic precursors catechol and guaiacol, reported by Ofner et al. (2011), exhibits strong changes of the absorption peaks and band shapes. After the reaction with chlorine species, the reported main absorption regions at 222 and 275 nm shift down to 210 and 250 nm and the broad absorption up to 600 nm is reduced and limited up to 400–450 nm. The effect of bromine on the diffuse-reflectance UV/VIS

spectrum is totally different. While the main absorption of unprocessed SOA and SOA reacted with chlorine species is at 220 or 210 nm, SOA reacted with bromine species exhibits the maximum absorption between 300 and 350 nm, and the absorption of the visible spectrum is significantly enhanced up to the red end.

5 SOA from  $\alpha$ -pinene does not exhibit these strong effects. Only small changes of the diffuse-reflectance UV/VIS spectrum are caused by the reaction with halogens. The absorption up to higher wavelengths is slightly enhanced after reaction with bromine. For all halogen reactions, the maximum of absorption is located at 275 nm, while the maximum of the unprocessed SOA from  $\alpha$ -pinene is at 225 nm.

10 A full quantification of the diffuse-reflectance UV/VIS spectra was not possible, according to limitations (Kortüm and Oelkrug, 1966): The required thickness of the aerosol sample on the filters could not be achieved, limited by the particle density and weight, as well as by the aerosol smog-chamber volume. Therefore, calculation of a differential absorbance (dA) was employed in the UV/VIS range to demonstrate  
15 the optical changes caused by the different halogen species. The single absorption spectra were normalized at 200 nm to an absorbance of 1, and dA was calculated according to Eq. (1), where  $F(R)^*$  is the normalized absorption spectrum of the aerosol after the reaction with RHS and  $F(R)$  is the normalized absorption spectrum of the aerosol before the reaction.

$$20 \quad dA = F(R)^* - F(R) = -\lg \frac{I^*}{I_0} + \lg \frac{I}{I_0} = \lg \frac{I}{I^*} \quad (1)$$

The differential absorbance spectra clearly indicate changes of the optical properties of the organic aerosols according to the electronic spectrum caused by the heterogeneous reaction of SOA with RHS (Fig. 3). The aerosols from the aromatic precursors exhibit a negative dA at about 300 nm for the reaction with chlorine, which can be related to a bleaching of the aerosol. The highest maximum of absorption is shifted to  
25 the blue end of the diffuse-reflectance UV/VIS spectrum. The more aliphatic SOA from  $\alpha$ -pinene does not exhibit this behavior. Some absorbing compounds are formed by the reaction with chlorine up to 350 nm. The reaction with bromine shifts the absorption

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of all three aerosols to the red end of the spectrum. This behavior is strongest for the aromatic SOA from catechol and weakest for the aliphatic SOA from  $\alpha$ -pinene. The shift to the red end of the spectrum is also visible on the filter samples. SOA processed with bromine exhibit a red-brown golden color.

UV/VIS absorption of aerosols from aromatic precursors is more strongly influenced by halogens than the absorption of aliphatic aerosol from  $\alpha$ -pinene. However, the interaction of SOA with RHS significantly changes the absorption properties and the interaction with solar radiation.

### 3.3 Changes of vibrational features of gaseous species and particulate matter

During the reaction of RHS with the SOA several changes of gaseous species occur, which were identified by long-path absorption FTIR spectroscopy (Fig. 4). After injecting the halogens a strong increase of  $\text{CO}_2$  is monitored ( $2349$  and  $668\text{ cm}^{-1}$ ). At the same time, ozone, which was not totally consumed by the aerosol formation process, decreases ( $1044\text{ cm}^{-1}$ ). Furthermore, the H-X species are formed. Gaseous HCl, represented by the  $\nu(\text{H-Cl})$  at  $2887\text{ cm}^{-1}$ , is formed at higher yields than HBr ( $2559\text{ cm}^{-1}$ ). While  $\text{CO}_2$ , and HX are formed, the aromatic or aliphatic  $\nu(\text{C-H})$  functionalities degrade. This is observed with all three model aerosols: SOA from catechol only exhibits the aromatic  $\nu(\text{C-H})$  at  $3050\text{ cm}^{-1}$ , SOA from guaiacol, the aromatic  $\nu(\text{C-H})$  at  $3050\text{ cm}^{-1}$  and the aliphatic methyl-ether  $\nu(\text{C-H})$  between  $2800$  and  $3000\text{ cm}^{-1}$ . The aliphatic  $\nu(\text{C-H})$  of the  $-\text{CH}_3$  groups of SOA from  $\alpha$ -pinene also degrades by the influence of halogens. The prominent  $\delta(\text{C-H})_{\text{out-of-plane}}$  absorption at  $740\text{ cm}^{-1}$  at SOA from guaiacol (Ofner et al., 2011) also decreases. Furthermore, CO at  $2143\text{ cm}^{-1}$  is formed during the reaction of all organic aerosols with RHS under various conditions. In case of the interaction of SOA, derived from catechol, with RHS, CO is consumed by further reaction with chlorine at 0 % and 25 % relative humidity. Furthermore, an additional absorption at  $850\text{ cm}^{-1}$  occurs. This absorption is structured as typical of gaseous species showing *P*- and *R*-branches and can be allocated as phosgene

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( $\text{OCCl}_2$ ) (Siebert, 1966). The associated  $\nu(\text{C}=\text{O})$  at  $1827\text{ cm}^{-1}$  could not be identified because of the weakly structured carbonyl-stretching region. At  $1106\text{ cm}^{-1}$ , absorption of a gas-phase species with PQR-structured branches is visible in all long-path absorption spectra. The allocation of this vibration to a specific molecule is not clear. Formic acid could be a possible candidate with a very strong  $\nu(\text{C}-\text{O})$  at  $1105\text{ cm}^{-1}$ . The strong  $\tau$  vibration at  $638\text{ cm}^{-1}$  could be covered by  $\text{CO}_2$  and all other vibrations are weak or within the carbonyl-stretching region (Shimanouchi, 1972). All other gases were assigned by their reported group frequencies (Siebert, 1966). A detailed assignment of measured bands to functional groups is given in Table 1.

To investigate the transformation of functional groups, ATR-FTIR spectroscopy (Ofner et al., 2009) of the particulate phase of the aerosol was performed on KRS5 crystals (Fig. 5). The infrared spectra of the condensed phase of the model aerosols were reported for  $\alpha$ -pinene (Sax et al., 2005) and for catechol and guaiacol (Ofner et al., 2011). After reacting with halogens, significant changes occur in the infrared spectra of the aerosols. While the  $\nu(\text{C}=\text{O})$  absorption is the most prominent of the untreated aerosols, the vibration due to this functional group becomes less important. Especially the SOA from catechol processed with halogens exhibits two bands at  $1372$  and  $1303\text{ cm}^{-1}$  as the strongest ones. These two bands can also be found in the treated SOAs from guaiacol and  $\alpha$ -pinene. According to the literature (Shevchenko, 1963; Baes and Bloom, 1989; Ofner et al., 2011) these absorptions can be allocated to carboxylic acids, the carboxylate anion and other  $\nu(\text{C}-\text{O})$  vibrations of aromatic or aliphatic  $\text{C}-\text{OH}$ ,  $\text{R}-\text{COO}-\text{R}$  or  $\text{R}-\text{O}-\text{R}$ . The missing dominance of the carbonyl stretch vibration, as observed in the present study, was reported by Rontu and Vaida (2008), studying perfluorocarboxylic acids. In their study the most prominent absorption between  $1000$  and  $1400\text{ cm}^{-1}$  was  $\nu(\text{C}-\text{F})$  but also  $\nu(\text{C}-\text{O})$  bands are more intense than the  $\nu(\text{C}=\text{O})$  band. Hence, halogens seem to significantly influence carboxylic acids of SOA by degradation or changing their vibrational properties as  $\alpha$ - or  $\beta$ -substituent.

Absorptions between  $700$  and  $800\text{ cm}^{-1}$  were reported for SOA from catechol and guaiacol (Ofner et al., 2011), when the SOA is formed under simulated sunlight at 25 %

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relative humidity. For  $\alpha$ -pinene, the lowest observed absorption is located at  $854\text{ cm}^{-1}$  (Sax et al., 2008). The ATR spectra of treated SOA from catechol exhibit a strong absorption between  $800$  and  $700\text{ cm}^{-1}$  also for the SOA formation and reaction at  $0\%$  relative humidity. This absorption can be allocated to alcohols or carboxylic acids, but in case of the treatment with chlorine also to the  $\nu(\text{C}-\text{Cl})$  vibration (Socrates, 1980). Similar absorptions are observed for SOA from guaiacol and  $\alpha$ -pinene, but weaker. From the reaction with bromine, an additional absorption is observed at  $609\text{--}602\text{ cm}^{-1}$  for all three kinds of SOA which can be allocated to the  $\nu(\text{C}-\text{Br})$  vibration. Hence, most significant changes of the vibrational spectra of organic aerosols by treatment with halogens are observed for the reaction with bromine, influencing carboxylic acids and forming absorptions in the  $\nu(\text{C}-\text{Br})$  region.

### 3.4 Determination of the degree of halogenation of the particulate phase

Ultra-high resolution mass-spectroscopy was used in negative electrospray ionization mode to ionize most of these polar acidic compounds. The degree of halogenation as well as the main O/C and H/C ratios (Schmitt-Kopplin et al., 2010) and the averaged carbon oxidation state ( $\text{OS}_c$ ) values (Kroll et al., 2011) were calculated. For the molecular halogen photochemical experiments, the amount of halogenated compounds related to the unprocessed aerosol mass was deduced (Table 2). These calculations exhibit an increase of halogenated compounds with a decrease of aromaticity. While SOA from catechol only exhibits  $30\%$  of all brominated compounds, SOA from  $\alpha$ -pinene exhibits  $66\%$ . Further O/C and H/C values are reported in this table, based on  $0.1\text{ ppm}$  mass accuracy calculated CHOS elementary compositions (see Fig. 6 for the nominal mass 319 from unprocessed and halogenated SOA from catechol), as described for aerosol samples elsewhere (Schmitt-Kopplin et al., 2010). These ratios do not significantly differ from reported values of the unprocessed organic aerosols with very similar van Krevelen-diagram characteristics as previously described (Ofner et al., 2011), and the Br-compounds always covered these same large CHO area in the van

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Krevelen diagrams while the Cl-compounds showed lower compound amounts in specific positions (Fig. 7 – van Krevelen diagrams of processed SOA from  $\alpha$ -pinene). This confirms a high reactivity of Br towards most of CHO compounds without high specific reactivity of particular chemical substructures in the mixture such as observed with Cl.

5 The  $OS_c$  values of halogenated aerosols exhibit an increase of the oxidation state up to an  $OS_c$  of 2, while the entire organic aerosols do not reach oxidation states higher than 1 (Fig. 8). For the halogenation reaction with chlorine, halogenated compounds exhibit rather low numbers of carbon atoms. Brominated compounds are found over  
10 the whole range of carbon atoms, based on the unhalogenated aerosol. Ultra-high resolution mass-spectroscopy confirms the formation of a large number of halogenated compounds towards high molecular weights in the particle phase of processed SOA.

## 4 Results from combined SOA – salt-pan experiments

Results from the molecular halogen photochemical experiments were used to determine changes of the physicochemical properties of SOA, caused by RHS released  
15 from the simulated salt pan.

### 4.1 Change of aerosol size-distribution

RHS released from the simulated salt-pan experiments influence the aerosol size-distribution of SOA similar to those in the molecular halogen photochemical experiments (Fig. 9). An increase of the mean particle diameters was observed for all three  
20 types of model SOA, reacting with RHS from the salt pan. Although the relative humidity in the smog-chamber in combined experiments is about 60 % (maximum for molecular halogen photochemical experiments was 25 %), this effect can be related to the influence of RHS on SOA.

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## 4.2 Optical properties in the UV/VIS range

SOA processed by RHS released from the simulated salt pan exhibits similar diffuse-reflectance UV/VIS spectra compared with the spectra derived from SOA processed by molecular halogen species. To achieve detailed changes in the diffuse-reflectance UV/VIS absorption spectra, the differential absorbance was calculated. All three SOA samples exhibit both features observed for the molecular halogen photochemical experiments with chlorine and bromine (Fig. 10). An increase of the differential absorbance is observed for all three different model aerosols in the spectral range around 250 nm. A decrease in dA is observed above 380 nm for all three samples, which is strongest for the processed SOA from catechol. Hence, a bleaching is observed for all samples, which is strongest for the aromatic SOA from catechol. This bleaching is a strong hint at the dominance of chlorinated organic matter in the processed SOA.

## 4.3 Changes of vibrational features of particulate matter

Caused by the low precursor concentrations, which had to be used to avoid disturbance of the DOAS system installed in the smog chamber, only few particles could be sampled onto the ATR crystal using the method of electrostatic precipitation (Ofner et al., 2009). The resulting ATR-FTIR spectra are shown in Fig. 11.

For the molecular halogen photochemical experiments, a strong dominance of two absorptions at about 1380 and 1305  $\text{cm}^{-1}$  is visible in the vibrational spectra. The absorption of the carbonyl  $\nu(\text{C}=\text{O})$  vibration decreases for SOA from catechol and guaiacol. Only SOA from  $\alpha$ -pinene exhibits a strong  $\nu(\text{C}=\text{O})$  at about 1705  $\text{cm}^{-1}$ . This persistence of the carbonyl stretch region in processed SOA from  $\alpha$ -pinene was also observed in the molecular halogen photochemical experiments.

All three SOA samples exhibit rather medium to strong, broad bands at about 720  $\text{cm}^{-1}$  and above. This absorption can be assigned to the  $\nu(\text{C}-\text{Cl})$  vibration and indicates a possible halogenation of the organic aerosol. The shape of this band and the fact that it has exactly the same position for all three organic aerosols can be

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explained by a halogenation process involving only one specific halogen species reacting with the same structural or functional feature present in all three different SOAs (e.g. carboxylic acids). Absorptions in the same region reported for the unprocessed SOA (Ofner et al., 2011) are of different shape and line positions.

5 Concluding from the observations concerning the molecular processing experiments, a reaction of carboxylic groups with subsequent formation of carbon-chlorine bonds is likely. The formation of carbon-bromine bonds, which would result in absorptions between 600 and 650  $\text{cm}^{-1}$ , was not observed.

#### 4.4 Determination of the degree of halogenation of the particulate phase

10 The acquisition of ultra-high-resolution mass spectra of SOA processed with halogens released from the salt pan was impeded by matrix effects and the low organic aerosol content of the samples. Thus, only the calculated percentage of CHOCl- and CHOBr-containing species relative to the CHO-containing species is presented in Table 3. Due to the fact that not the total mass range was evaluated, the presented amounts of halo-

15 generated compounds in Table 3 give only hints at the halogenation processes which have taken place. Nevertheless, organic aerosols interacting with gaseous halogen species released from the salt pan contain high amounts of halogenated organic compounds. In contrast to the molecular halogen experiments and, as expected by the evolution of the aerosol size distribution, the differential UV/VIS-absorption and ATR-

20 FTIR-spectra, chlorination seems to be more important than bromination. Up to 52 % of chlorinated compounds in relation to 100 % of unhalogenated compounds could be measured in organic aerosol from guaiacol.

#### 4.5 Influence of the presence of SOA on the halogen release from the simulated salt-pan

25 While the mechanism of halogen release from the salt pan causes a rapid ozone depletion within 20 min and corresponding BrO formation of up to 6 ppb BrO (Buxmann

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et al., 2012), the organic aerosol appears to inhibit this process (Fig. 12). Ozone depletion is slowed down, and only less than 10% of BrO of the expected values are observed during experiments with SOA formation from catechol and guaiacol. During experiments without SOA precursors the BrO formation started immediately after the solar simulator was switched on, with an initial rate of up to  $d[\text{BrO}]/dt_{\text{initial}}=40 \text{ ppt s}^{-1}$  (Buxmann et al., 2012). The BrO formation in the presence of SOA was delayed: BrO exceeds the mean detection limit of 56 ppt after 18 and 87 min with catechol and guaiacol as precursors, respectively. The mean particle diameter reached 80 nm for both precursor substances at that time (catechol SOA formation is faster, as particle formation already occurs during the dark phase). This is a hint that interaction of BrO precursors (e.g. Br) with the organic substances already occurs with small particles or in the gas phase, but the involved reactions were not identified so far. Due to Mie-scattering (caused by SOA formation from  $\alpha$ -pinene, where the mean particle diameter was about 250 nm), the detection limit of the DOAS instrument was poor. No BrO was observed during experiments with  $\alpha$ -pinene above a detection limit of 200 ppt. During all salt pan experiments presented in this study, no free chlorine radicals could be found in the presence as well as in the absence of organic aerosols above a mean detection limit of  $5 \times 10^4 \text{ molecules cm}^{-3}$  or 0.002 ppt of the radical clock measurements. In general, primary  $\text{Br}_2$  release is favored as compared to  $\text{BrCl}$  and  $\text{Cl}_2$  release from sodium halide substrates (e.g. Behnke et al., 1999; Sjostedt and Abbatt, 2008), but formation of chlorinated compounds is possible (e.g. Behnke and Zetzsch, 1990). However, chlorination was dominating in the particulate phase over bromination during our studies, as mentioned above. It is well known that Br radicals mainly react with unsaturated hydrocarbons or partly oxidized species (e.g. aldehydes), whereas Cl radicals react with saturated hydrocarbons as well (e.g. Atkinson et al., 2006).

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## 5 Discussion

In general, halogens influence several properties of organic aerosols, but different types of SOA exhibit different transformations. The reactions depend on the SOA precursor and thus on the chemical composition of the organic aerosol, but also on the halogen species and the experimental conditions, which can even change the predominant halogenated species.

### 5.1 Molecular halogen photochemical experiments

Chlorine species cause a strong increase of the mean particle diameters, and in the case of ether groups, the formation of a second mode was observed. Therefore, the increase in particle diameter can be explained by the formation of low-volatile species in the surrounding gas phase, condensing onto the already present particles. Due to this effect, atmospheric halogen species might also exhibit an aerosol-formation potential as soon as the oxidation capacity, based on ozone and OH radicals, of the atmosphere is insufficient to produce further low-volatile compounds. The effect of bromine species on the aerosol size distributions is weaker than observed for chlorine. In fact, bromine is able to reduce the mean particle diameter, as observed for SOA from  $\alpha$ -pinene. This effect can be explained by halogen species not only forming new low-volatile compounds, thus contributing to existing particles or forming new particles, but also changing the chemical structure of the particulate matter itself. In general, due to the fact that the mean particle diameter increases during the reaction of SOA with halogens, a decrease of the saturation vapor pressure, caused by the reaction of RHS with SOA, is assumed.

The latter statement is underlined by the observation of the formation of various gaseous species due to the interaction of halogens with organic aerosols. Long-path absorption spectra indicate the formation of additional amounts of CO<sub>2</sub>, CO, and HCl or HBr. At the same time, a decrease in  $\nu(\text{C-H})_{\text{aromatic}}$  and  $\nu(\text{C-H})_{\text{aliphatic}}$  of the particle phase was observed. Thus, C–H bonds are destroyed. This is known to be the case

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for the reaction of chlorine with aliphatic compounds, but also bromine species show this behavior. Therefore, the observations might be explained by the reaction of BrO or HOBr with C–H bonds.

The spectra of the particulate matter of the organic aerosol itself also exhibit strong changes. While the carbonyl  $\nu(\text{C}=\text{O})$  band is the most dominant vibration of the unprocessed aerosols, this vibration is less important after the reaction with halogens. This decrease can also be observed for the  $\nu(\text{C}=\text{C})$  of the aromatic aerosols. The  $\nu(\text{C}-\text{Cl})$  and the  $\nu(\text{C}-\text{Br})$  stretching vibrations indicate the presence of halogenated compounds, even though the assignment of the vibrations to specific compounds was not possible. Also  $\nu(\text{O}-\text{Cl})$  (Evans et al., 1965) and spectral features of structural elements (Socrates, 1980) can be found in this spectral region. Most dominant are bands observed at about 1370 and 1300  $\text{cm}^{-1}$ . The assignment of those absorptions is difficult. Based on the observation that these bands are observed for halogenation processes with chlorine as well as with bromine at the same position, the influence of a functional group or a structural element is more likely than the formation of a halogenated compound. Therefore, a link of these absorptions with carboxylic acids, carboxylic acid halides, or derivatives is likely but not confirmed.

The transformations of the particulate matter also affect the optical properties of the aerosols in the UV/VIS spectral range. While the reaction with chlorine causes a bleaching of the particles, the reaction with bromine causes a higher absorbance towards higher wavelengths – the particulate phase appears “golden”.

High amounts of brominated and chlorinated compounds could be identified in the particulate matter of the organic aerosols using ultra-high-resolution mass spectroscopy. Halogenated SOA exhibits higher average carbon oxidation states than the unprocessed aerosols. Thus, the reaction of RHS with SOA causes a further oxidation of the organic matter of the aerosols, even when the surrounding atmosphere containing ozone and hydroxyl radicals is unable to do so.

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## 5.2 Interaction with RHS from the simulated salt-pan

To obtain details on possible natural halogenation processes involving organic aerosols, the model aerosols were exposed to natural systems which are known to release gaseous halogen species. The complex data obtained from these systems exhibit strong matrix effects, which hamper the detailed interpretation of the data sets. Thus, the results of the molecular halogen photochemical processing studies were used to identify physicochemical changes related to the organic aerosols.

Results from the interaction of organic aerosols with halogens released from the simulated salt pan are similar to those from experiments with  $X_2$  photolysis. A similar increase of the particle diameters is observed. ATR infrared spectra exhibit the same spectral features. The optical properties in the diffuse-reflectance UV/VIS spectral range are comparable to the observed spectra from the molecular experiments and red-shifts as well as blue-shifts are both observed. Although the mass spectra exhibit a poor signal-to-noise ratio, the formation of halogenated compounds (especially chlorinated) seems to be confirmed for the particulate matter.

## 5.3 General effects of RHS on SOA and SOA on RHS release-mechanisms

In general, the investigation of the transformation of physicochemical features of the organic aerosols led to the first steps of an understanding of the complex processes involved. A detailed understanding was not achieved at the present time, as it would require more molecular-based techniques to analyze the processes.

A strong influence of atmospheric halogen species on organic aerosols is indicated by the performed aerosol smog-chamber experiments. Several parameters used to characterize the model aerosols are changed by the halogenation process. These changes depend on the particular aerosol as well as on the halogen source. The chemical composition of the organic aerosols determines the details of the changes. Hence, no general “road map” for atmospheric halogenation processes could be identified.

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Depending on the kind of SOA and the halogen source, quite different changes in the aerosol size distribution can be observed. The chemical transformation and the related change in optical properties are indicated by the change in the color of the halogenated organic aerosols (haloSOA). The formation of secondary particles from the reacted SOA (XOA) is indicated. Further, the main identified gaseous species released from the aerosol are specified.

The reaction of organic aerosols with halogens from natural sources is confirmed by the influence of organic particles on the halogen release-mechanisms themselves. SOA strongly influences the RHS release-mechanism, hampering the bromine explosion and causing a decrease of the ozone depletion.

## 6 Conclusions

Concluding, halogens take part in the aging process of organic aerosols. Based on the results of our study, interactions occur in the gas phase as well as in the particle phase. The gas-phase halogenation generates additional low-volatile compounds, which condense onto the existing particles. Furthermore, the halogenation process releases simple gaseous molecules. The expected decrease in vapor pressure can also lead to new particle formation, caused by the halogenation of the SOA precursor or the oxidized SOA precursor. Therefore, halogens can interact in ways with organic molecules (possible SOA precursors) similar to those suggested in the current literature on nucleation and aging (Kroll et al., 2011).

Those widespread changes of physicochemical properties of SOA, processed with RHS from natural sources, might change the behavior of SOA in the atmosphere. Other important properties like the ability to act as CCN or ICN (ice condensation nuclei), the potential to absorb atmospheric organic vapors and water, or the contribution to radiative forcing could be strongly influenced. Therefore, the aerosol-halogen interaction might strongly contribute to the influence of organic aerosols on the climate system.

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*Acknowledgements.* The authors thank the German Science Foundation (DFG) for support within the research unit HALOPROC and the European Union for support within the infrastructure EUROCHAMP 2. Also they wish to thank Heinz-Ulrich Krüger for continuous technical support and Jenny Westphal for the measurement and pre-processing of the ICR-FT/MS analysis.

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**Table 1.** Assignment of measured absorptions to functional groups from SOA reacting with RHS using long-path absorption FTIR spectroscopy (L: simulated sunlight at 0% relative humidity; LW: simulated sunlight at 25% relative humidity; w: weak; s: strong; D: destruction; F: formation).

Mode	(cm <sup>-1</sup> )	Assignment	SOA catechol		SOA guaiacol		SOA $\alpha$ -pinene	
			L	LW	L	LW	L	LW
Reaction with RHS from chlorine								
$\nu(\text{C-H})$	3050	aromatic	wD	wD				
$\nu(\text{C-H})$	3000–2880	aliphatic			sD	sD	sD	sD
$\nu(\text{H-Cl})$	2887	gaseous HCl	sF	wF	wF	wF	wF	wF
$\nu(\text{C=O})$	2349	CO <sub>2</sub>	sF	sF	sF	sF	sF	sF
$\nu(\text{C=O})$	2143	CO	wD	wD	wF	wF	wF	wF
$\nu(\text{C-O})$	1106	formic acid?	sD	sD	sD	sD	wF	wF
$\nu_{\text{as}}(\text{C-Cl})$	851	phosgene?	wF	wF				
$\delta(\text{O=C=O})$	668	CO <sub>2</sub>	sF	sF	sF	sF	sF	sF
Reaction with RHS from bromine								
$\nu(\text{C-H})$	3050	aromatic	sD	sD				
$\nu(\text{C-H})$	3000–2880	aliphatic			wD	wD	sD	wD
$\nu(\text{H-Br})$	2559	gaseous HBr	wF	wF	sF	wF	wF	wF
$\nu(\text{C=O})$	2349	CO <sub>2</sub>	sF	sF	sF	sF	sF	sF
$\nu(\text{C=O})$	2143	CO	sF	wF	sF	sF	sF	sF
$\nu(\text{C-O})$	1106	formic acid?	wF		wD	wF	sF	wF
$\delta(\text{O=C=O})$	668	CO <sub>2</sub>	sF	sF	sF	sF	sF	sF

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**Table 2.** Relative amount of halogenated compounds (compared to the not halogenated bulk) and basic aerosol parameters like O/C and H/C ratios as well as the averaged carbon oxidation state  $OS_c$  observed in samples from the molecular reaction experiments.

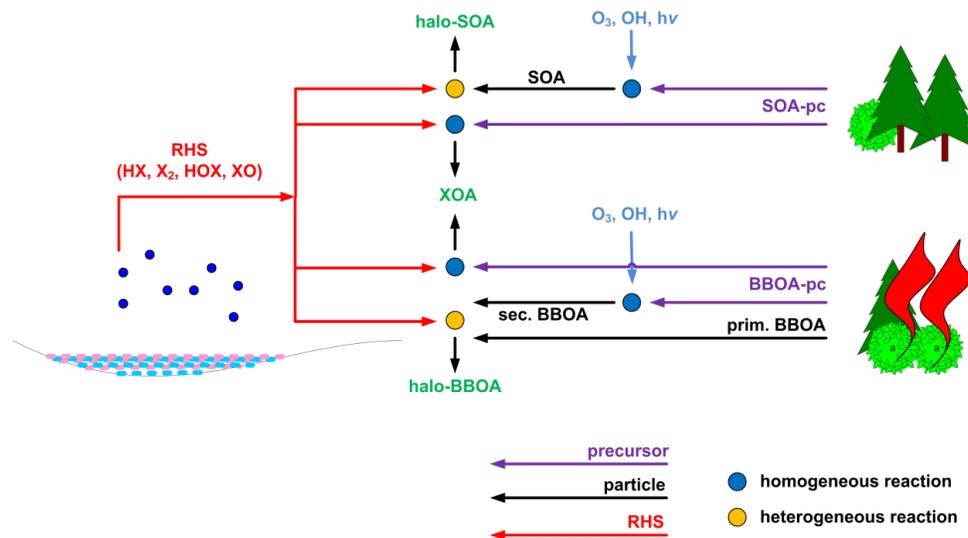
Sample and reaction	CHOCl	CHOBr	O/C	H/C	$OS_c$	$n_c$
SOA from catechol						
Chlorinated	3 %		0.31–0.67	0.81–1.08	0.3–2	10–27
Brominated		30 %	0.55–1.2	0.9–1.67	0.3–2	5–35
SOA from guaiacol						
Chlorinated	15 %		0.31–0.67	0.6–1.08	0.3–2	8–22
Brominated		53 %	0.6–1.2	0.9–1.67	0.1–1.8	5–35
SOA from $\alpha$ -pinene						
Chlorinated	33 %		0.33–0.54	1.31–1.67	0.5–1.5	7–30
Brominated		66 %	0.42–0.83	1.18–2	0.5–1.3	6–35

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**Fig. 1.** Possible interactions of RHS released from sea-salt aerosol or salt lakes with SOA, BBOA and related gaseous precursors (SOA-pc, BBOA-pc), forming halogenated SOA/BBOA (halo-SOA/halo-BBOA) via heterogeneous reaction or halogen-induced organic aerosol (XOA) via homogeneous reaction.

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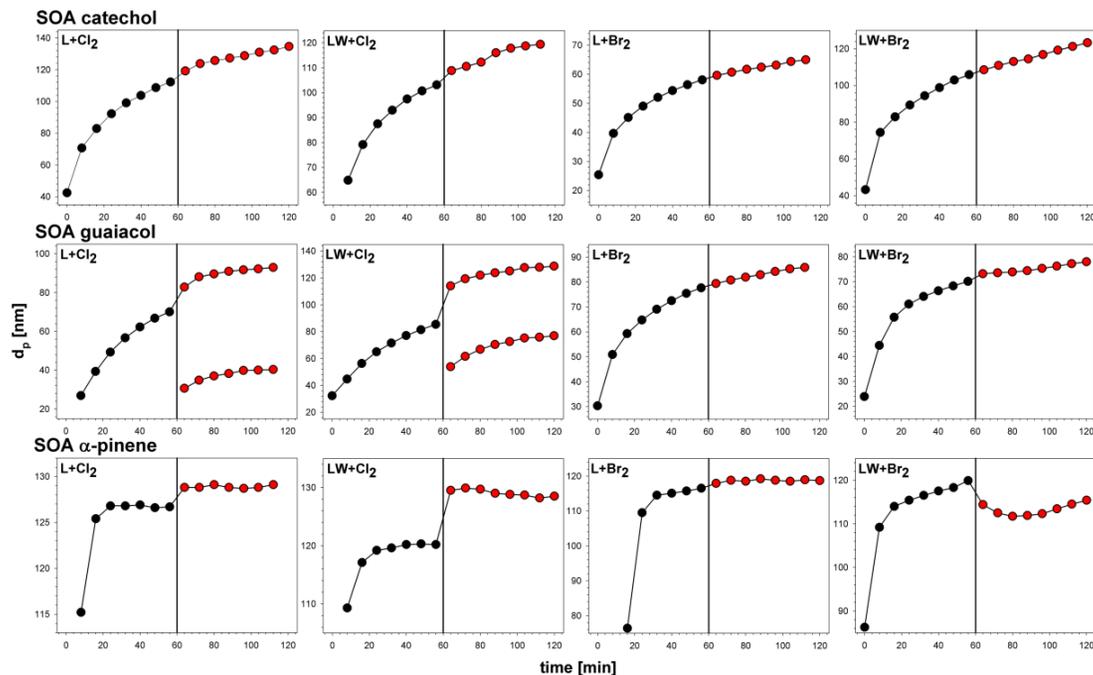
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**Fig. 2.** Change of the mean particle diameter of organic aerosols by the reaction with gaseous halogen species for aerosol smog chamber experiments with photolysed Cl<sub>2</sub> and Br<sub>2</sub>, respectively (L: SOA formed with simulated sunlight at 0% relative humidity; LW: SOA formed with simulated sunlight at 25% relative humidity). The injection of the molecular halogen species is marked by the vertical lines at about 60 min after starting the irradiation and SOA formation.

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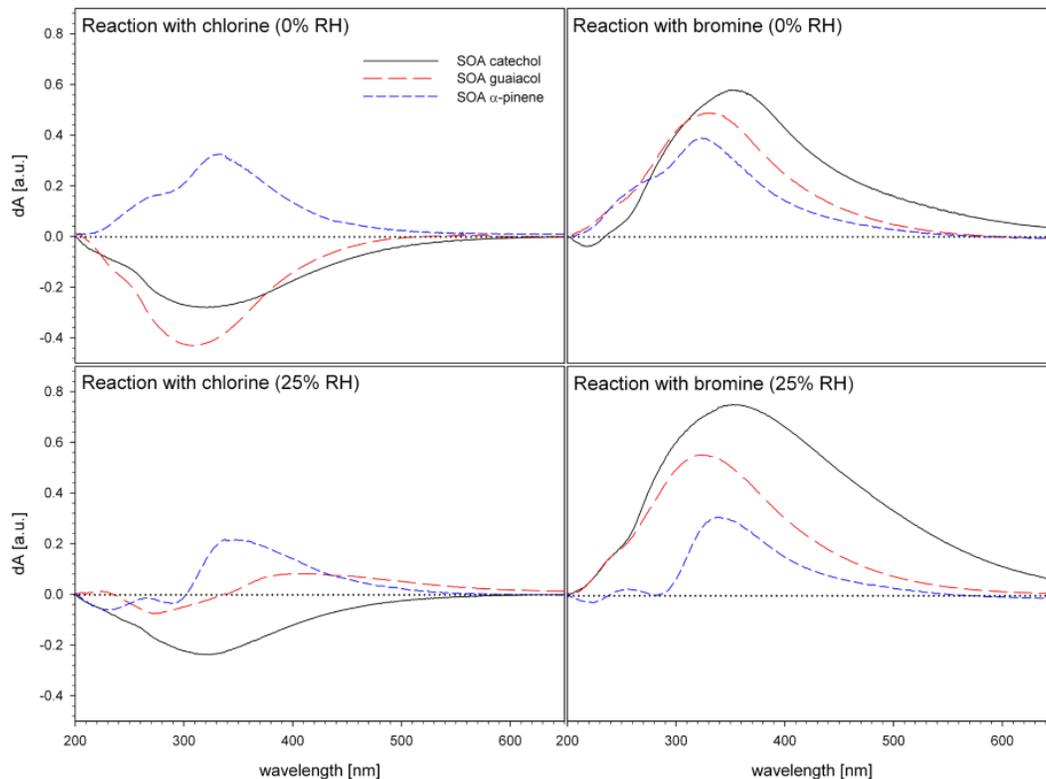
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**Fig. 3.** Change of the differential absorbance (dA) in the UV/VIS spectra region due to the reaction of SOA with RHS formed from photolysis of molecular chlorine or bromine.

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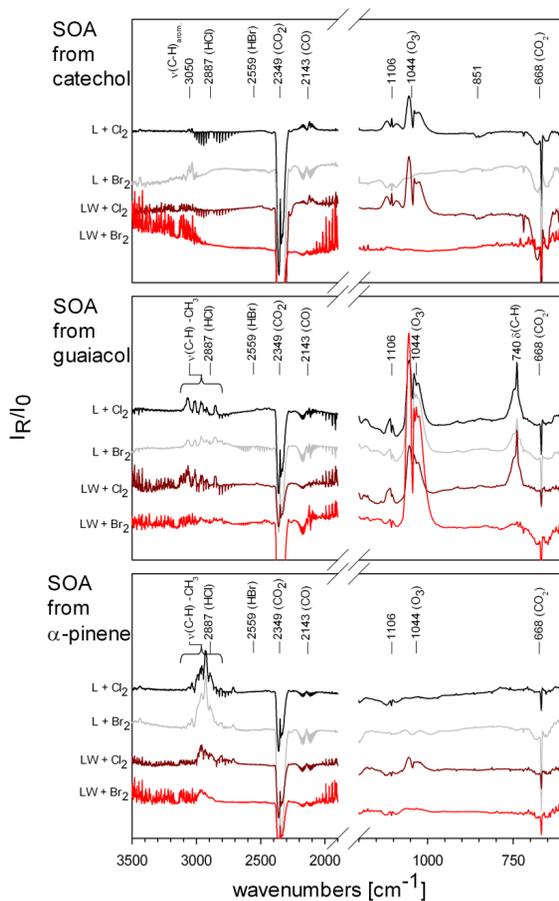
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**Fig. 4.** Long-path absorption FTIR spectra of the heterogeneous reaction of SOA with RHS: L: SOA formed with simulated sunlight at 0% relative humidity; LW: SOA formed with simulated sunlight at 25% relative humidity.

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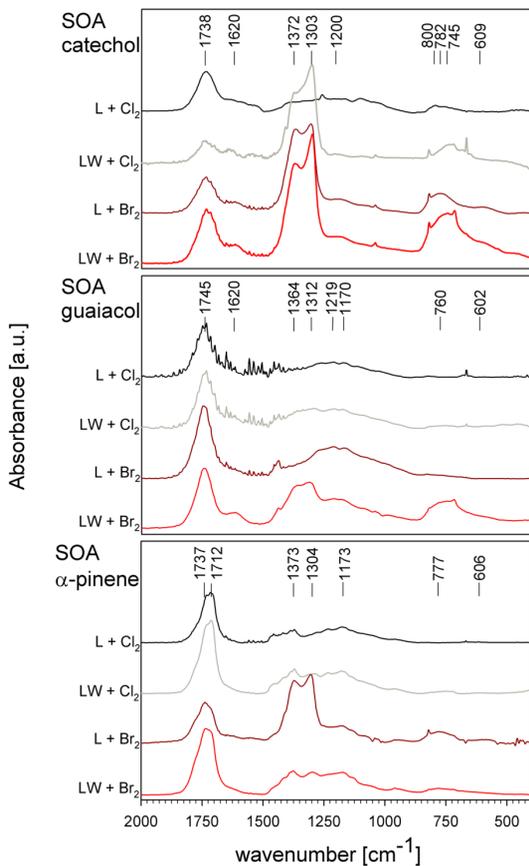
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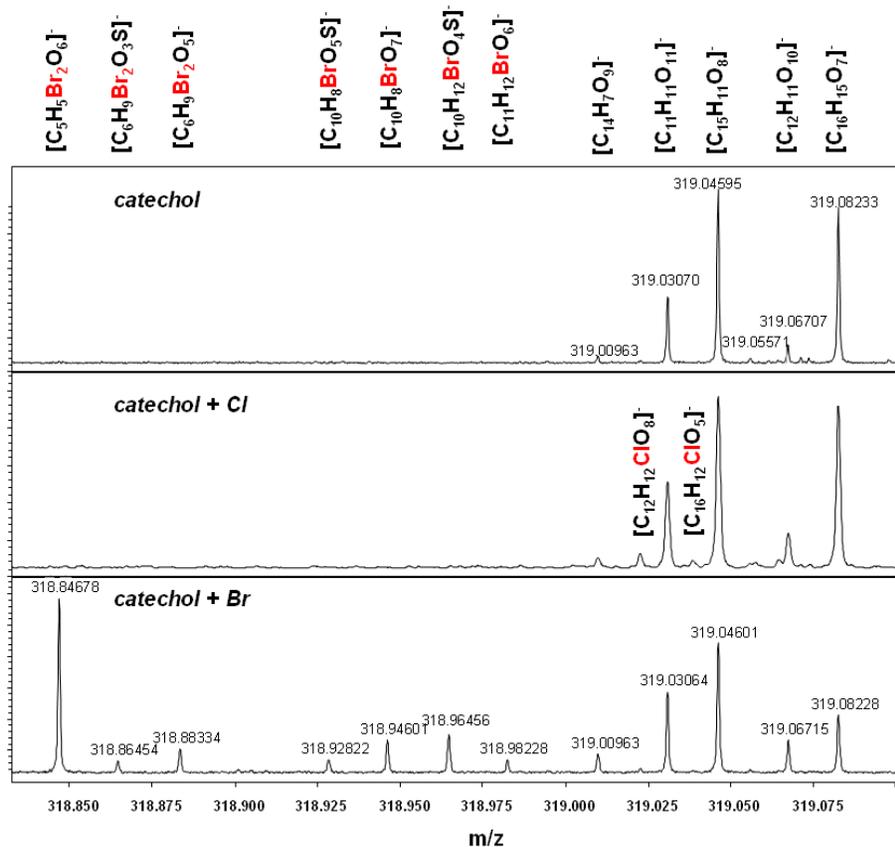
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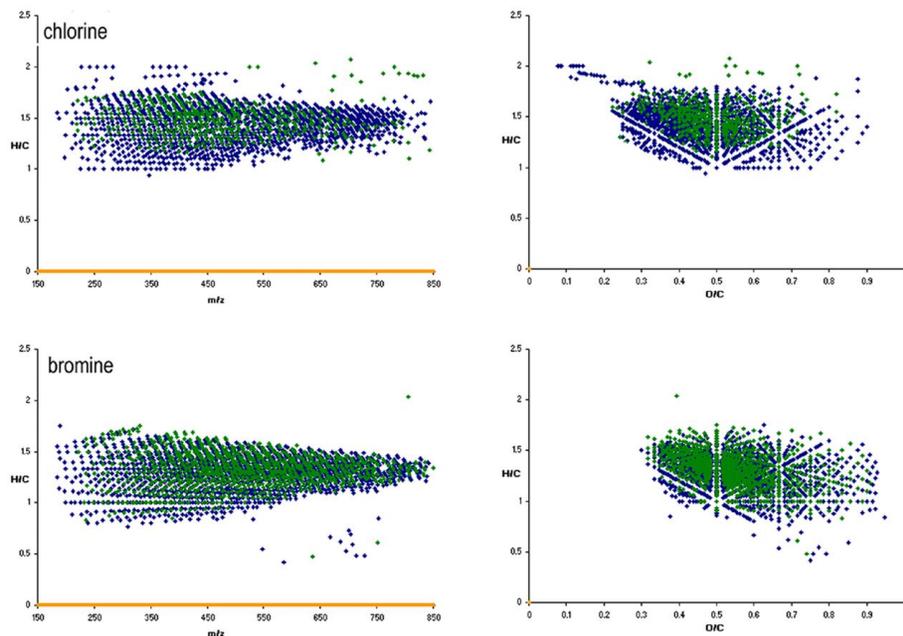
**Fig. 5.** ATR-FTIR spectra of SOA processed with RHS – carbonyl containing functional groups ( $1800\text{--}1650\text{ cm}^{-1}$ ) are strongly influenced by the heterogeneous interaction (L: SOA formed with simulated sunlight at 0% relative humidity; LW: SOA formed with simulated sunlight at 25% relative humidity).



**Fig. 6.** ICR-FT/MS nominal mass 319 with detailed halogenations with Cl and Br exemplified with catechol.

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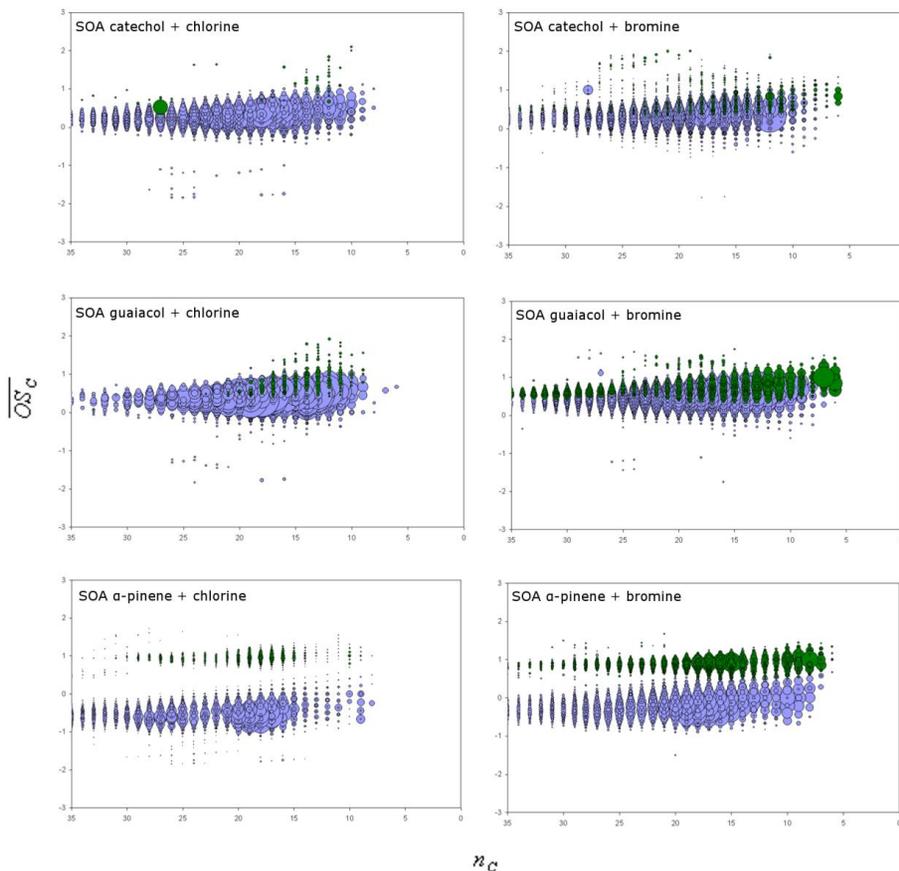


**Fig. 7.** van-Krevelen diagrams of SOA from  $\alpha$ -pinene processed with chlorine and bromine (green – halogenated species; blue – unprocessed SOA).

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**Fig. 8.** Carbon oxidation state as a function of the number of carbon atoms  $n_C$ : unprocessed SOA (blue), halogenated species in the particle phase (green). The SOA was formed and processed in the presence of simulated sunlight at 0% relative humidity. The bubble size expresses the signal intensity from the experimental data.

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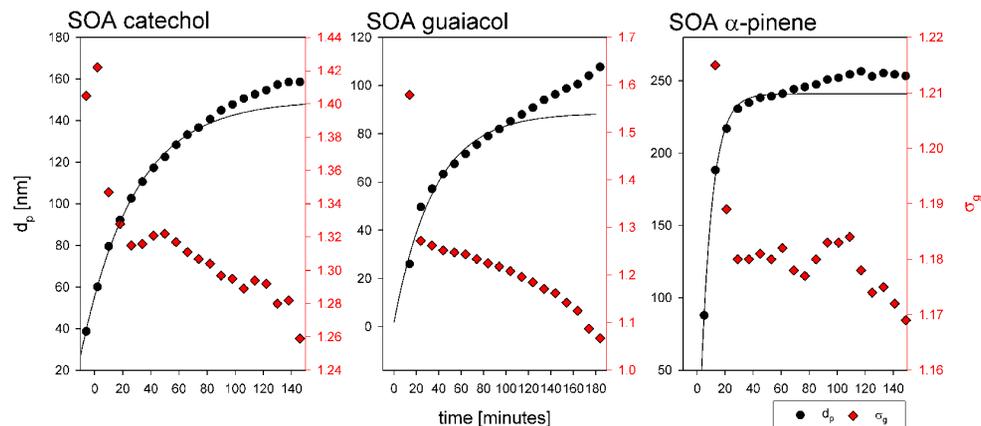
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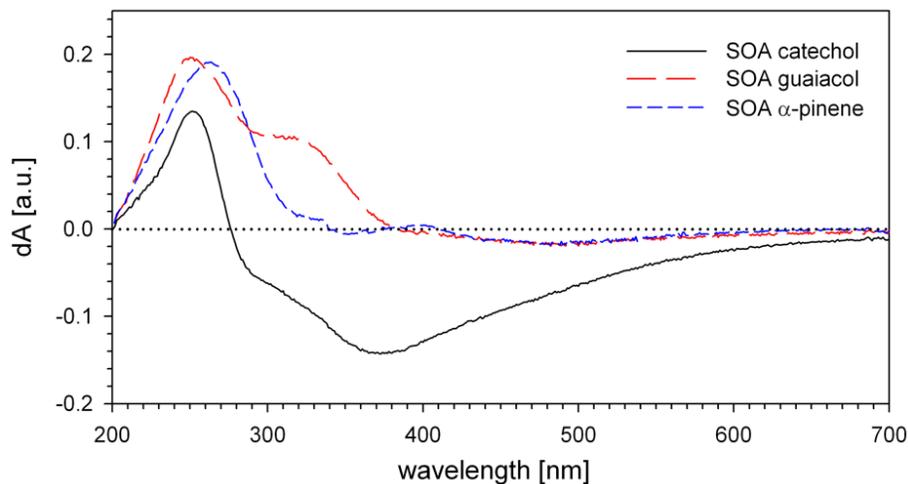


**Fig. 9.** Evolution of the mean particle diameter ( $d_p$ ) and the related geometric standard deviation ( $\sigma_g$ ) of SOA from the different model aerosols while interacting with RHS released from the simulated salt pan.

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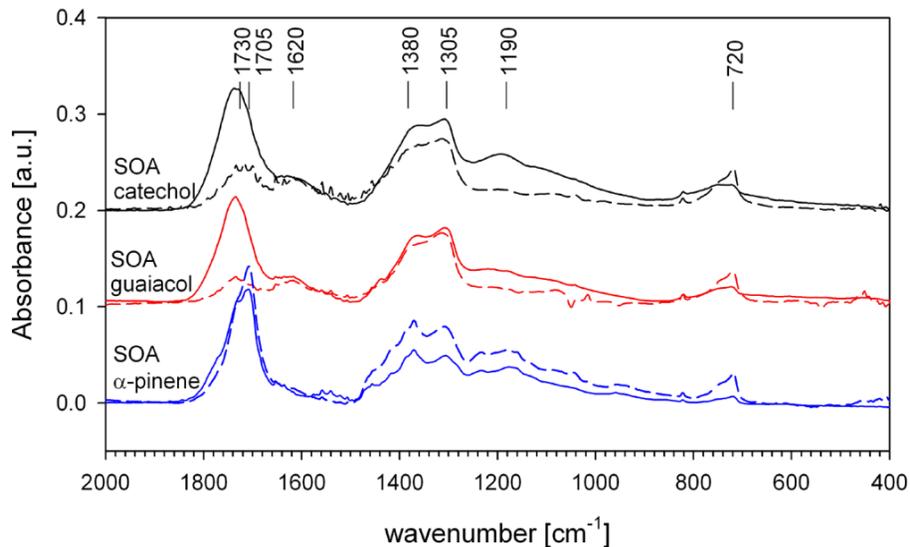


**Fig. 10.** Changes in the differential absorbance  $dA$  in the UV/VIS region due to the reaction of the organic aerosols with RHS released from the simulated salt pan, indicating a chlorination of the SOA.

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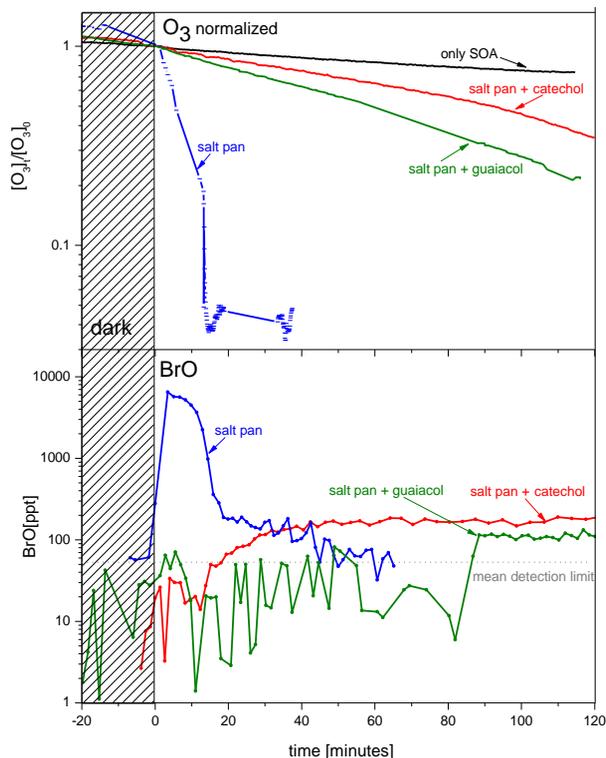


**Fig. 11.** ATR-FTIR spectra of the different SOA models (solid line) and processed with RHS (dashed line) released from the simulated salt pan, respectively.

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**Fig. 12.** Time series of Ozone (top) and BrO (bottom) show the influence of SOA from catechol and guaiacol on the release of RHS from the simulated salt pan. Ozone values are normalized to the  $O_3$  mixing ratios at  $t = 0$ . The experiments were carried out at 60% RH. During an experiment, where only the salt pan without SOA precursor was exposed to simulated sunlight (blue lines, from Buxmann et al., 2012), ozone was destroyed within less than 20 min and more than 6000 ppt BrO were formed. Measurements of  $O_3$  were performed only for limited periods of time (indicated by horizontal bars), to reduce dilution. During experiments with SOA precursors (indicated in red, green and black) ozone decay was much slower. BrO exceeds the mean detection limit of 57 ppt with a time delay (after the solar simulator was switched on at  $t = 0$ ) of 18 min for catechol and 87 min for guaiacol. Maximum BrO mixing ratios of less than 200 ppt were observed, one order of magnitude lower than without SOA.