

Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation

S. Zhou et al.

# Formation of gas-phase carbonyls from heterogeneous oxidation of polyunsaturated fatty acids at the air–water interface and of the sea surface microlayer

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

Motivated by the potential for reactive heterogeneous chemistry occurring at the ocean surface, gas-phase products were observed when a reactive sea surface microlayer (SML) component, i.e. the polyunsaturated fatty acid (PUFA) linoleic acid (LA), was exposed to gas-phase ozone at the air–seawater interface. Similar oxidation experiments were conducted with SML samples collected from two different oceanic locations, in the eastern equatorial Pacific Ocean and from the west coast of Canada. Online proton-transfer-reaction mass spectrometry (PTR-MS) and light-emitting diode cavity enhanced differential optical absorption spectroscopy (LED-CE-DOAS) were used to detect oxygenated gas-phase products from the ozonolysis reactions. The LA studies indicate that oxidation of a PUFA monolayer on seawater gives rise to prompt and efficient formation of gas phase aldehydes. The products are formed via the decomposition of primary ozonides which form upon the initial reaction of ozone with the carbon-carbon double bonds in the PUFA molecules. In addition, two highly reactive di-carbonyls, malondialdehyde (MDA) and glyoxal, were also generated, likely as secondary products. Specific yields relative to reactant loss were 78 %, 29 %, 4 % and < 1 % for *n*-hexanal, 3-nonenal, MDA and glyoxal, respectively, where the yields for MDA and glyoxal are likely lower limits. Heterogeneous oxidation of SML samples confirm for the first time that similar carbonyl products are formed via ozonolysis of environmental samples. The potential impact of such chemistry on the atmosphere of the marine boundary layer is discussed.

## 1 Introduction

The ocean covers more than 70 % of the Earth's surface and the sea surface microlayer (SML) is an important boundary which plays a crucial role in chemical exchange between the atmosphere and ocean (Donaldson and George, 2012). Recent field observations indicate missing sources for oxygenated hydrocarbons from the oceans in

### Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



atmospheric models (Myriokefalitakis et al., 2008; Sinreich et al., 2010). It is known that the SML is a complex organic and inorganic mixture (Pogorzelski and Kogut, 2003; Kozarac et al., 2005). The organic substances in the SML, including proteins, polysaccharides, humic-type materials and lipids, are likely produced from marine biota (Wilson and Collier, 1972; Zlatica et al., 1998). As a main component of lipids, fatty acids (FA) including polyunsaturated FA (PUFA), have been detected in considerable amounts in sea-surface water with concentrations of 3–200  $\mu\text{g L}^{-1}$  (Marty et al., 1979; Derieux et al., 1998; André et al., 2004; Parrish et al., 2005; Blaženka et al., 2007). PUFA contribute as much as  $\sim 43\%$  of the total FA measured, for example, in sub-Arctic Norwegian fjords (Blaženka et al., 2007). In addition, PUFA have also been detected in marine aerosols (Kawamura and Gagosian, 1987; Mochida et al., 2002; Fang et al., 2002).

As surfactants with carbon-carbon double bonds, PUFA reside at the air/water interface and provide information on the degradation state of the organic matter in SML and aerosols (Blanchard, 1964; Barger and Garrett, 1970, 1976; Donaldson and Vaida, 2006). Despite their environmental prevalence the atmospheric importance of PUFA remain poorly characterized. In particular, as a significant component of the SML, are these species reactive with atmospheric oxidants when present on the water surface? As a result of oxidation, what species are formed and are the products readily released to the atmosphere?

To date, the focus of laboratory studies in this area has been on the kinetics of heterogeneous oxidation of pure unsaturated FA compounds, especially on oleic acid (OA) (Zahardis and Petrucci, 2007). Besides studies on pure FA liquids and aerosols which indicate reactive uptake coefficients on the order of  $10^{-3}$ , notable studies include those of McNeil et al. (2007) who reported an uptake coefficient of roughly  $10^{-5}$  for ozone on oleate-aqueous salt aerosols and González-Lebrada et al. (2007) who measured  $10^{-6}$  for monolayer OA on aqueous droplets. These values are comparable with the initial uptake coefficients for ozone on terminal alkenes on self-assembled monolayer (Dubowski et al., 2004). Based on additional measurements involving the OH and  $\text{NO}_3$

**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

oxidants on oleate-aqueous salt particles by McNeil et al. (2007), the lifetime of unsaturated organics at the air–water interface can be estimated to be  $\sim 10$  min with respect to reaction with atmospheric levels of ozone (50 ppb) whereas the lifetimes with respect to OH reaction would be significantly longer (McNeil et al., 2007; González-Lebrada et al., 2007). Kinetics studies with PUFA such as linoleic acid (LA) and linolenic acid yield comparable results to those with OA (Moise and Rudich, 2002; Thornberry and Abbatt, 2004; Zhao et al., 2011).

Moreover, gas-phase aldehyde formation has been widely reported from studies with pure substrates (Zahardis and Petrucci, 2007, references therein). Among them, Moise and Rudich (2002) first quantified a yield of gas-phase nonanal as 28 % from  $O_3 + OA$  at room temperature, and  $\sim 50$  % yields were reported by Thornberry and Abbatt (2004) and Vesna et al. (2009). Thornberry and Abbatt (2004) also reported *n*-hexanal and nonenal yields of  $\sim 25$  % for the ozone reaction with LA thin film, suggesting that the two LA carbon-carbon double bonds have the same probability to be attacked by ozone.

In addition to gas-phase aldehydes, several lower volatility products, namely azelaic acid, nonanoic acid and 9-oxononanoic acid have been quantified from ozonolysis of pure OA, with 9-oxononanoic acid the most prevalent with yields of 14–35 % (Katrib et al., 2004; Hung et al., 2005; Ziemann, 2005), while azelaic and nonanoic acid yields are less than 10 % (Katrib et al., 2004; Ziemann, 2005). It is notable that these yields are different from King et al. (2009) who reported 87 % for nonanoic acid from heterogeneous ozonolysis of a monolayer of deuterated OA on water. This latter result implies that the heterogeneous ozonolysis mechanism may be different for an FA monolayer at the air–water interface than for a pure substance.

The goals of this work are three-fold. First, given the dominance of product studies performed with pure substances, there is the need to determine the gas-phase products that form from heterogeneous oxidation of PUFA when present as a monolayer on an aqueous substrate, to better match conditions at the air–sea water interface in the marine boundary layer (MBL). Of particular interest is whether soluble species are



**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

resolution PTR-MS (Ionicon Analytik GmbH) and an LED-CE-DOAS instrument were placed downstream of the flow tube to detect the gas-phase products, with 100 sccm going to the PTR-MS and 500 sccm to the LED-CE-DOAS. The residence time for ozone as well as gas-phase products in the flow tube is  $\sim 10$  s.

The proton transfer reaction mass spectrometry (PTR-MS) has been described in detail by de Gouw and Warneke (2007). Briefly, the instrument utilizes a soft chemical ionization technique, transferring  $H^+$  from the reagent ion,  $H_3O^+$ , to gas-phase species with a higher proton affinity than water. Here, the PTR-MS was run under either scan mode, in which the PTR-MS recorded multiplier signal in the  $m/z$  range of 21 to 150, or selected ion mode (SIM), in which only the signals from the masses of interest were recorded.

For the SML and some LA studies, a PTR-TOF-MS with a time-of-flight mass spectrometer was used along with a switchable reagent ion source (SRI, including  $H_3O^+$  and  $NO^+$ ) (Jordan et al., 2009). The SRI enables identification of VOC isomers indistinguishable with  $H_3O^+$  ionization, e.g. aldehyde and ketone isomers (Dunne et al., 2012). In this work,  $NO^+$  was used to differentiate aldehyde and ketone isomers, because  $NO^+$  reacts with aldehydes to produce mainly dehydrogenated cations  $(M-H)^+$  whereas its reaction with ketones yields  $NO^+$  cluster ions  $(M+NO)^+$  (Jordan et al., 2009).

The University of Colorado LED-CE-DOAS instrument (Thalman and Volkamer, 2010) employs a blue LED light source (420–490 nm) coupled to a high finesse optical cavity consisting of two highly reflective mirrors ( $R = 0.99997$ ) placed about 92 cm apart, leading to a wavelength dependent sampling path length of  $\sim 18$  km. The mirrors are purged with dry nitrogen gas, and the mirror reflectivity was determined by flowing helium and nitrogen gas; the mirror alignment is further monitored on-line by observing the slant column density of oxygen dimers ( $O_4$ ). The light exiting the cavity is projected onto a quartz optical fiber coupled to an Ocean Optics QE65000 spectrometer equipped with a CCD detector. The spectra recorded are stored on a computer and analyzed by means of DOAS least square fitting. The measured concentrations

are calibrated from knowledge of reference spectra of glyoxal (Volkamer et al., 2005a), nitrogen dioxide (Vandaele et al., 2002), ozone (Bogumil, 2003) and oxygen dimers (Hermans, 1999). The concentration for ozone was retrieved using an absolute intensity fitting procedure (Washenfelder et al., 2008) as the dominant absorption of ozone at these wavelengths is mostly broad-band. Detection limits for glyoxal, NO<sub>2</sub>, O<sub>4</sub>, and ozone were 20 pptv, 25 pptv, 0.01 % mixing ratio, and 30 ppbv respectively (Thalman and Volkamer, 2010).

To quantify the gas-phase products, the PTR-MS was calibrated with four aldehydes, namely propanal, 3-hexenal, *n*-hexanal and 2-nonenal, which was used as a surrogate for 3-nonenal that was commercially unavailable. The calibration was performed by introducing a known amount of either pure liquid sample or *n*-heptane solutions into a 1 m<sup>3</sup> Teflon chamber. *N*-heptane was used as solvent to dissolve the aldehydes because it had minimum interference with the selected *m/z* signals for the above mentioned aldehydes. In addition, the *n*-hexanal PTR-MS calibration from the chamber was verified by introducing a known pressure of *n*-hexanal into an evacuated 3 L glass reservoir, which was then diluted with nitrogen. The *n*-hexanal PTR-MS signal was calibrated using flow tube mixing ratios calculated from the pressure drop with time of the glass reservoir, as the flow was metered out through a needle valve. The PTR-TOF-MS was calibrated by diluting ppm level gas standards from a gas cylinder containing acetaldehyde, acrolein, acetone and 2-butanone (Ionimed Analytik GMBH).

Using the apparatus in Fig. 1 and the PTR-TOF-MS with H<sub>3</sub>O<sup>+</sup> as reagent ion, gas-phase products from the heterogeneous reaction of ozone, generated by passing 500 sccm of synthetic air through the ozone generator, with SML samples were investigated. The SML samples were collected in two locations, one from Patricia Bay, Canada (SML-CA) and the other from the eastern equatorial Pacific Ocean (SML-EqPOS). Detailed information about the SML sample collection is given in the Supplement. After the SML samples were collected they were transported in dry ice and kept frozen in the laboratory at -18 °C. The SML samples thawed at room temperature and 10 mL were added into the glass boat inside the flow tube. Control experiments

## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



were conducted in a manner analogous to the oxidation experiment without the SML sample present.

## 2.2 Chamber experiments

As will be shown later, malondialdehyde (MDA) and glyoxal were observed as products from ozonolysis of LA. The formation of MDA and glyoxal is mostly attributed to a second generation product from reaction of 3-nonenal with ozone. To prove this hypothesis, the gas-phase reaction of ozone with 3-hexenal, used as a surrogate for commercially unavailable 3-nonenal, was conducted in the 1 m<sup>3</sup> Teflon chamber. The chamber was made of PFA (perfluoroalkoxy) Teflon film with a Teflon-tape-wrapped metal frame inside to support the bag. The chamber was flushed overnight by purified air before starting the experiment. ~ 200 ppb cis-3-hexenal (50 % in triacetin, Sigma-Aldrich) and ~ 200 ppm cyclohexane (HPLC grade, ≥ 99.9 %) were added into the chamber before ~ 300 ppb ozone was introduced. Cyclohexane was present in excess to scavenge more than 95 % of OH radicals produced in the reaction. The reactants and products were detected by the PTR-MS and LED-CE-DOAS.

## 3 Results and discussion

### 3.1 LA monolayers on seawater

In the Type 1 experiments, it is expected that the drop of LA will spread to produce a monolayer over the seawater surface. To test this, a control experiment was conducted by adding 2 μL pure LA into a clean glass boat without seawater and passing ozone through the flow tube at the same levels as used in the oxidation experiments. The product signals recorded by the PTR-MS for the control were more than an order of magnitude lower than those for the Type 1 experiments, confirming that the LA does spread across the seawater surface but does not spread over a dry glass boat. Indeed, Rouviere and Ammann (2010) investigated the monolayer properties of fatty

## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



acids coated on deliquesced KI particles and reported that if more than a monolayer is deposited, the fatty acid formed a monolayer and the residual remained as an excess droplet in contact with the aqueous solution. It is expected that this is the case for the Type 1 experiments in this work.

## 3.2 Identification of gas-phase aldehydes from ozonolysis of monolayer LA

Figure 2 shows a typical mass spectrum for the gas-phase products from Type 1 experiments recorded by the PTR-MS under scan mode (a) and the evolution of selected ions recorded by PTR-TOF-MS (b). Based on previous studies (Moise and Rudich, 2002; Thornberry and Abbatt, 2004)  $m/z$  141 and 123 in Fig. 2a and 141.13 ( $C_9H_{17}O^+$ ) and 123.12 ( $C_9H_{15}^+$ ) in Fig. 2b were identified as protonated 3-nonenal ( $M + 1$ ) and its dehydrated ions ( $M - 18 + 1$ ), respectively.  $M/z$  101 and 83 in Fig. 2a and  $m/z$  101.10 ( $C_6H_{13}O^+$ ) and 83.08 ( $C_6H_{11}^+$ ) in Fig. 2b, are attributed to protonated *n*-hexanal ( $M + 1$ ) and its dehydrated ions ( $M - 18 + 1$ ), respectively. The signals at  $m/z$  123 and 83 from PTR-MS were used to quantify 3-nonenal and *n*-hexanal, respectively. Other  $m/z$  in Fig. 2 were from further decomposition of protonated or dehydrated 3-nonenal and *n*-hexanal, with exception of the signal at  $m/z$  73 in Fig. 2a.

Several aldehyde and ketone isomers, i.e. butanal, butanone, methyl glyoxal or malondialdehyde (MDA), have the same nominal unit mass molecular weight and may produce protonated molecular ions at  $m/z$  73 in the PTR-MS. Therefore, absolute identification of this product with PTR-MS alone is impossible. However, Fig. 3a gives the PTR-TOF-MS mass spectrum of this product with  $H_3O^+$  as reagent ion, showing the exact mass to be 73.02 ( $M + 1$ ) suggesting its molecular formula is  $C_3H_4O_2$  (Note the different scales in Fig. 3a with ozone off and on). Therefore, the monocarbonyls, butanal and butanone ( $C_4H_8O$ ), can be excluded from the candidate products. In Fig. 3b the reagent ion is switched from  $H_3O^+$  to  $NO^+$  just after run 30. The  $m/z$  73.02 ( $C_3H_5O_2^+$ ) signal was highest with  $H_3O^+$  as the reagent ion, with the signal dropping to background level with  $NO^+$ . Concurrently, the signal at  $m/z$  71.01 ( $C_3H_3O_2^+$ ) rises, indicating H-atom abstraction from the molecular ion  $C_3H_4O_2$ , while signal at

### Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



$m/z$  102.02 ( $C_3H_4O_2NO^+$ ) remains unchanged. This is consistent with the accepted mechanism by which  $NO^+$  reagent ions react with aldehydes. Note that methyl glyoxal can be ruled out as a candidate because a sample of this gas behaves differently with the  $NO^+$  reagent ion (Fig. S1) than the behavior displayed in the experiment, i.e. the  $m/z$  102.02 ( $C_3H_4O_2NO^+$ ) signal rises substantially when the reagent ion is switched from  $H_3O^+$  to  $NO^+$ . Hence, in combination with the mechanistic study to be described later, this product is attributed to MDA.

Finally, coincident with the products that are detected by PTR-MS, we note that glyoxal was observed to be formed simultaneously using the LED-CE-DOAS (Fig. 4).

As mentioned in the Introduction, the 3-nonenal and  $n$ -hexanal products have been identified in previous studies (Moise and Rudich, 2002; Thornberry and Abbatt, 2004) on the heterogeneous oxidation of pure LA thin film/particles by ozone. The present work demonstrates that the same products are formed when monolayer LA is oxidized on seawater. However, the formation of two gas-phase di-aldehydes, namely MDA and glyoxal, was observed for the first time.

### 3.3 Gas-phase aldehyde quantification

Figures 4 and 5 illustrate the temporal profiles of ozone and gas-phase aldehyde formation from Type 1 and 2 experiments, respectively. Upon ozone exposure,  $n$ -hexanal ( $m/z$  83) and 3-nonenal ( $m/z$  123) formed immediately and quickly reached steady-state levels in Type 1 experiments followed by slightly slower formation of the di-carbonyls, i.e. MDA ( $m/z$  73) and glyoxal (Fig. 4).

We interpret the steady-state, sustained production of volatile products in Type 1 experiments (Fig. 4) to indicate that the LA monolayer is being replenished by the excess LA droplet. In contrast, the Type 2 experiments, where only  $3.8 \times 10^{16}$  molecules (or  $1 \times 10^{14}$  molecules  $cm^{-2}$ ) of LA were added to the boat, demonstrate the consumption of the surface coverage. In both cases, we believe that the less volatile reaction products, potentially acids or hydroxyhydroperoxides (Katrib et al., 2004; Hung et al., 2005; Ziemann, 2005), dissolve in the water or remain at the surface. On the one hand, Voss

**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

et al. (2007), who investigated the reaction of ozone with OA monolayer on water, suggested that non-volatile products dissolved into the aqueous phase and did not remain at the interface. In contrast, King et al. (2009) investigated the similar reaction with deuterated OA at the air/water interface and reported that the nonanoic acid product remained at the surface. This latter scenario seems unlikely in the present work, otherwise the LA monolayer would have been diluted by the condensed phase products at the interface and the product signals in the Type 1 experiments would have decreased in intensity as the LA oxidation processed.

Tables 1 and 2 summarize the quantification of the gas phase aldehyde yields from Type 1 and 2 experiments, respectively. The product yields in Type 1 experiments were quantified relative to the amount of ozone consumed. In Type 2 experiments, the products were quantified by integrating the individual product peaks in Fig. 5 and the yields are reported relative to the amount of LA consumed on the seawater. The uncertainties in Table 1 reflect variability in the experiments. The largest systematic errors in the yields arise from the PTR-MS calibrations which, in combination with other uncertainties, are estimated to be on the order of  $\pm 20\%$ . The uncertainty in the glyoxal measurements is estimated to be  $\pm 10\%$ . Because the individual yields from the different experiment types are in excellent agreement, we report average yields for *n*-hexanal, 3-nonenal, and glyoxal of 78 %, 29 %, and 0.04 %, respectively.

We note, however, that glyoxal is a highly soluble substance (effective Henry's law constant,  $H_{\text{eff}} = 4.19 \times 10^5 \text{ M atm}^{-1}$ ; Ip et al., 2009) and may be experiencing dissolution into the condensed phase at the same time as some fraction is evaporating to the gas phase. As a result, we can only infer semi-quantitative information about the formation of glyoxal, and the yields reported in Tables 1 and 2 are likely to be lower limits. Given that other gas phase products account for close to 100 % of the reactants consumed, the glyoxal is not expected to be a major product. Nevertheless, we note that corrected yields for glyoxal in the flow tube experiments could be more than an order of magnitude larger than the yields listed in Tables 1 and 2, if the chemistry at the sea-water surface is different from that in the Teflon chamber. In addition, we note that the mechanism

## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

by which glyoxal may enter the condensed phase may be affected by the presence of the organic surface layer. In particular, molecular dynamics calculations show that organic monolayers can affect the interactions of molecules like  $O_3$  with an aqueous sub-phase. These calculations support that the net-collision rate in the presence of a thin organic layer (butanol, on  $NaI(aq)$ ) is virtually identical to that in the absence of the organic layer (D. Tobias, personal communication, 2013). It is likely that similar trapping applies to other molecules, including OVOCs. Given glyoxal's high solubility in water, and assuming that each collision of gas-phase glyoxal with the surface leads to glyoxal dissolution, the correction factors for glyoxal have the potential to be large. We conclude that the glyoxal yields from flow reactor experiments are limited by knowledge about correction factors.

Preparation of known gas phase levels of MDA is not easily achieved, and so this signal remains uncalibrated directly. Instead, we estimate the yields of MDA to be  $4 \pm 3\%$  based on the average of the calibration factors for other aldehydes, or using an indirect approach described below. The values plotted in the figures represent those from the indirect approach. However, we note that the same caveat described above for glyoxal also applies for MDA, given that it is expected to be highly soluble, i.e. the yields are expected to be lower limits.

While the 3-nonenal yield is similar to that from the study of the oxidation of pure LA by Thornberry and Abbatt (2004), the *n*-hexanal yield is higher by roughly a factor of 3. As mentioned above, the *n*-hexanal PTR-MS signal was calibrated with two different methods, i.e. using known mixing ratios prepared in a chamber and in the glass bulb/flow tube, and both calibration procedures resulted in similar results. As well, the similarity between the results from the Type 1 and Type 2 experiments suggest there is no error in the amount of reactant consumed. Thus, we conclude that the *n*-hexanal yield from oxidation of LA molecules is different when present as a monolayer on water as compared to the pure form, as studied by Thornberry and Abbatt (2004). The monolayer LA at the air–water interface is likely arranged with the hydrophilic headgroups ( $-COOH$ ) in direct contact with the aqueous phase and the carbon-carbon double bonds

containing hydrophobic tails oriented towards the air (Gill et al., 1983; Ellison et al., 1999; Donaldson and Vaida, 2006). As a result, the C12-C13 carbon-carbon double bond will be farther from the interface and may exhibit less steric hindrance than the C9-C10 bond in reactions with O<sub>3</sub> diffusing from the gas phase (Fig. 6). In contrast, when a pure LA liquid is oxidized, the two double bonds in LA may be randomly oriented and exhibit the same collision frequencies with O<sub>3</sub>.

### 3.4 Reaction mechanism for ozonolysis of LA monolayers

As shown in Fig. 6, the heterogeneous reaction between unsaturated FA and ozone is believed to proceed via addition of ozone to the carbon-carbon double bond forming primary ozonides (PO). The decomposition of the PO leads to aldehydes and the Criegee biradical, which further reacts with water to form acids, hydroxyhydroperoxides, or with carbonyls to form secondary ozonides (Wadia et al., 2000; Moise and Rudich, 2002; Hung and Ariya, 2007; Vesna et al., 2009). The gas-phase product yields indicate that roughly 100 % of the reactants (i.e. either ozone or LA) are converted to the two major products, *n*-hexanal and 3-nonenal. This is in contrast to the results from oxidation of liquid LA by Thornberry and Abbatt (2004) who reported 50 % aldehyde yield. As well, they saw roughly equal yields of *n*-hexanal and 3-nonenal. In the work of Thornberry and Abbatt (2004), the residence time of products and O<sub>3</sub> in the flow tube was on the order of 0.1 s, whereas in this work the timescale is ~ 10 s. Hence, further oxidation of 3-nonenal by ozone may produce *n*-hexanal leading to the higher ratio of *n*-hexanal to 3-nonenal, i.e. it is possible that both are formed initially at roughly 50 % yield and secondary reactions give rise to the observed enhancement of *n*-hexanal to 3-nonenal. While it is unlikely that the gas phase kinetics is fast enough to drive this oxidation pathway, it is possible that 3-nonenal is heterogeneously oxidized to *n*-hexanal. While speculative, it is for this reason that we indicate the branching ratios in Fig. 6 to the two primary ozonides to be 50 to 70 % and 30 to 50 %.

The roughly 100 % total yield of 3-nonenal and *n*-hexanal suggests that the PO decompose preferentially to form volatile aldehydes and that a Criegee bi-radical is likely

## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



formed on the side of the LA molecule containing a carboxylic acid function group. We anticipate that this Criegee intermediate then goes on to form soluble, low volatility species. The fact that the ozonide does not decompose with equal probability into two different sets of aldehydes and Criegee biradicals is somewhat surprising and it is the reason that we investigated the yields in two different experiments, i.e. the Type 1 and Type 2 experiments, and why we calibrated the PTR-MS to *n*-hexanal via two independent methods. The consistency of the results is excellent. We conclude that the conformation of the LA molecule, when existing as a monolayer at the air–water interface preferentially favors decomposition of the ozonide in the manner indicated.

This is the first study to probe the reaction mechanism for the heterogeneous reaction of O<sub>3</sub> with a PUFA at the air/water interface. As mentioned previously, King et al. (2009) reported a much higher yield of nonanoic acid (87%) from heterogeneous reaction of ozone with monolayer deuterated OA at air/water interface compared to previous studies with pure OA thin films or particles (~10%, Katrib et al., 2004; Ziemann, 2005), i.e. few volatile aldehydes are expected to have formed in the King et al. (2009) work. By contrast, the work of Wadia et al. (2000) reported a 50% yield of nonanal from the oxidation of 1-oleoyl-2-palmitoyl-sn-glycero-3-phosphocholine sitting at the air–water interface in a compressed state. Interestingly, in one set of experiments from Wadia et al. (2000) using an expanded film of 1-oleoyl-2-palmitoyl-sn-glycero-3-phosphocholine, the yield was two to three times higher than in the compressed state (see Table 2 of Wadia et al., 2000), i.e. matching the *n*-hexanal results from this work where it is likely that the LA films will also be in the expanded state. The present work and these past studies imply that the mechanisms and product yields may be highly dependent on the molecular arrangement for the substrates, and for soluble species also on the effective collision rate with the aqueous sub phase.

The formation of two di-aldehydes, i.e. MDA and glyoxal, may arise from secondary oxidation of 3-nonenal (Fig. 6). To test this reaction mechanism, the gas-phase reaction of ozone with 3-hexenal was investigated in the 1 m<sup>3</sup> Teflon chamber, where 3-hexenal was used as a surrogate for 3-nonenal that is commercially unavailable. The

**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

experiment was conducted in the presence of  $\sim 200$  ppm cyclohexane, which was used to scavenge more than 95 % of the OH radicals generated in the reaction. Figure 7a shows the time series of the reactant and product mixing ratios, where the signals at  $m/z$  81, 59 and 73 were used to quantify 3-hexenal, propanal and MDA, respectively.

After the signal at  $m/z$  81 stabilized, the oxidation of 3-hexenal was initiated by addition of ozone, leading to the production of propanal, MDA and glyoxal. The propanal and glyoxal formation yields can be determined from Fig. 7b to be  $74 \pm 14$  % and  $0.9 \pm 0.1$  %, respectively. From the mechanism for the reaction of ozone with 3-hexenal in Fig. 8 it is reasonable to assume the yield of MDA is  $25 \pm 5$  %, which in turn allowed us to indirectly calibrate the  $m/z$  73 signal to MDA.

MDA and glyoxal are formed as first generation oxidation products from ozonolysis of 3-hexenal (Fig. 7). Possible formation mechanisms for MDA and glyoxal are shown in Fig. 8 that rationalize the rapid observed formation of MDA and glyoxal in this system. A 1,4-H shift of the Criegee biradical can explain the rapid formation of small amounts of glyoxal. 1,4-H shifts have recently been proposed (Dibble et al., 2004a,b) to explain observations of minor products in the oxidation of isoprene (Volkamer et al., 2005b; Paulot et al., 2009; Galloway et al., 2011). The yields of products from 1,4-H shifts are generally small (few percent), consistent with those in this work.

The relative yield of glyoxal/MDA is  $\sim 1/20$  in the Teflon chamber, while this ratio in the flow tube is 3–5 times smaller. This might be due to the soluble loss of glyoxal in the aqueous sub-phase. If the same relative yields of glyoxal/MDA are assumed from ozonolysis of 3-hexenal and 3-nonenal, the glyoxal formation yields in the flow tube experiments could be higher (Table 1 and 2). The factor of 3–5 higher yields after correction are a lower limit for the overall losses that might be occurring in the flowreactor, since MDA concentrations have not been corrected for solubility in the aqueous sub phase. As such, efficient uptake for glyoxal would indicate that the presence of an organic SML is not an efficient barrier to prevent glyoxal losses to the aqueous sub phase (see also discussion in the previous section).





from the Teflon tubing used in the experiments. Meanwhile, additional strong signals were steady in the presence and absence of O<sub>3</sub>, such as *m/z* 81.02 and 85.03.

The PTR-TOF-MS responses to several aldehydes and ketones, namely acetaldehyde, acrolein, acetone and butanone, were found to have similar calibration factors.

Using an average calibration factor, the mixing ratios that arise upon ozone exposure of the gas-phase carbonyls from ozonolysis of SML are estimated. For the first set of products, they were ~ 200 ppt for C<sub>2</sub> and C<sub>3</sub> mono-carbonyls and ~ 30 ppt for the C<sub>4</sub> and C<sub>5</sub> mono-carbonyls and C<sub>3</sub> and C<sub>4</sub> di-carbonyls. For the second set of products, the maximum mono-carbonyl mixing ratios were estimated to be 30–90 ppt.

It should be noted that no di-carbonyls were calibrated with the PTR-TOF-MS, so the application of the calibration factor obtained from mono-carbonyls may induce high uncertainties in the di-carbonyl quantification. Moreover, even for the structurally similar carbonyls the calibration factors for different isomers can be significantly different (Warneke et al., 2003). Thus, the mixing ratios for the carbonyl products given above should be viewed as only initial estimates.

## 4 Conclusions and atmospheric implications

There are three main conclusions from this work. First, it has been demonstrated that volatile carbonyls, such as *n*-hexanal and 3-nonenal, are formed when LA exists as a monolayer on artificial seawater and is exposed to O<sub>3</sub>. These species are formed promptly and in high yields. With similar PUFA being common components of the SML, it is likely that exposure of the SML to ozone in the environment will lead to the release of similar volatile aldehydes. To our knowledge this is the first study of the oxidation of a PUFA existing as a monolayer on seawater. This adds to an extensive body of literature which demonstrates that such species are formed when pure unsaturated fatty acids are oxidized (Moise and Rudich, 2002; Thornberry and Abbatt, 2004; Vesna et al., 2009). As well, formation of small volatile organic compounds (VOCs) from heterogeneous oxidation of other types of unsaturated organics, such as ozone reaction

### Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

with vinyl terminated self-assembled monolayers (Dubowski et al., 2004), squalene film (Petrick and Dubowski, 2009) and fumaric acid aerosols (Najera et al., 2010) has also been reported. The only comparable system that has been studied at the air–water interface is the unsaturated phospholipid oxidation, studied by Wadia et al. (2000), where nonanal formation was observed in high yield.

Second, we have demonstrated that highly reactive gas-phase di-carbonyls, i.e. malondialdehyde and glyoxal, are formed in the PUFA reaction system, probably through secondary reactions of primary products. These mechanisms were confirmed by a chamber study on the gas-phase reaction of 3-hexenal with ozone (Fig. 7) and by further oxidation of primary products from ozonolysis of LA with OH radicals (Fig. 9). While glyoxal has been measured in the atmosphere (Sinreich et al., 2010), detection of MDA has not been reported. We note that in the biochemical literature, MDA is an important cross-linking agent that reacts with amino groups of enzymes, proteins and DNA (Tappel 1980; Wang et al., 2009; Passagne et al., 2012). Based on the thiobarbituric acid (TBA) reactive assay (Wang et al., 2009; Passagne et al., 2012), a number of studies suggest that MDA is formed from oxidation of lipid as well as PUFA (Pryor et al., 1976; Frankel, 1984; Scislawski et al., 2005; Santos-Zago et al., 2007). At this point, we are unable to accurately quantify the yields of glyoxal and MDA given that they may be dissolving to some degree in the aqueous sub phase. The yields reported in the paper are likely lower limits.

Our third conclusion is that ozone exposure to natural SML samples leads to the formation of a wide variety of oxygenated VOCs similar to those formed from PUFA oxidation, i.e. small mono- and di-carbonyls. While it is clear that SML materials are highly complex so that we cannot attribute these products to specific reactants, it is nevertheless important to demonstrate that the SML represents a reactive medium that may lead to VOC production via heterogeneous oxidation. This initial study warrants further investigations of SML – ozone interactions.

Supplementary material related to this article is available online at:  
[http://www.atmos-chem-phys-discuss.net/13/17545/2013/  
acpd-13-17545-2013-supplement.pdf](http://www.atmos-chem-phys-discuss.net/13/17545/2013/acpd-13-17545-2013-supplement.pdf).

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## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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**Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation**

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

**Table 1.** Gas-phase aldehyde formation yields relative to the amount of ozone consumed from Type 1 experiments with LA. The uncertainties reflect the variation in results in 3 experiments, except in the case of glyoxal where the experiment was conducted once.

O <sub>3</sub> consumed (ppb)	Gas-phase aldehyde yields (%)			
	<i>n</i> -hexanal	3-nonenal	MDA	glyoxal
85–96	78.5 ± 0.8	30.6 ± 2.0	1–4	0.03 <sup>a</sup> (0.1) <sup>b</sup>
144–150	76.3 ± 1.6	32.2 ± 1.5	2–5	0.04 <sup>a</sup> (0.2) <sup>b</sup>
Average	77.4 ± 1.9	31.4 ± 2.3	1–5	0.03 <sup>a</sup> (0.15) <sup>b</sup>

<sup>a</sup> Yield uncorrected for product dissolution in the aqueous sub-phase; significant product loss is expected, but correction factors are uncertain (see text in Sect. 3.3).

<sup>b</sup> Values in brackets are calculated assuming the ratio of glyoxal/MDA ~ 1/20 found in the Teflon chamber experiments.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 2.** Gas-phase aldehyde formation yields relative to the amount of LA consumed from Type 2 experiments with LA.

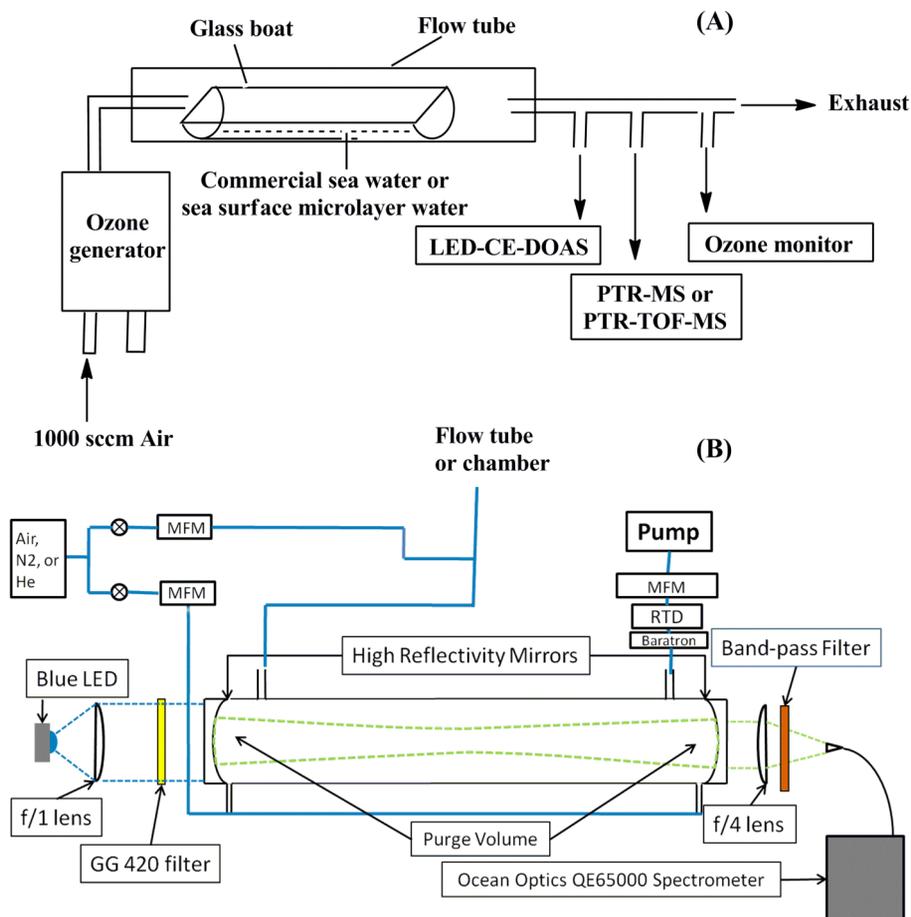
LA consumed (nmoles)	Gas-phase aldehyde yields (%)			
	<i>n</i> -hexanal	3-nonenal	MDA	glyoxal
32.1	78.5	24.3	2–6	0.06 <sup>a</sup> (0.20) <sup>b</sup>
64.2	76.7	27.1	2–7	0.05 <sup>a</sup> (0.23) <sup>b</sup>
Average	77.6 ± 0.9	25.7 ± 1.4	2–7	0.06 <sup>a</sup> (0.22) <sup>b</sup>

<sup>a</sup> Yield uncorrected for product dissolution in the aqueous sub-phase; significant product loss is expected, but correction factors are uncertain (see text in Sect. 3.3).

<sup>b</sup> Values in brackets are calculated assuming the ratio of glyoxal/MDA ~ 1/20 found in the Teflon chamber experiments.

## Formation of gas-phase carbonyls from heterogeneous oxidation

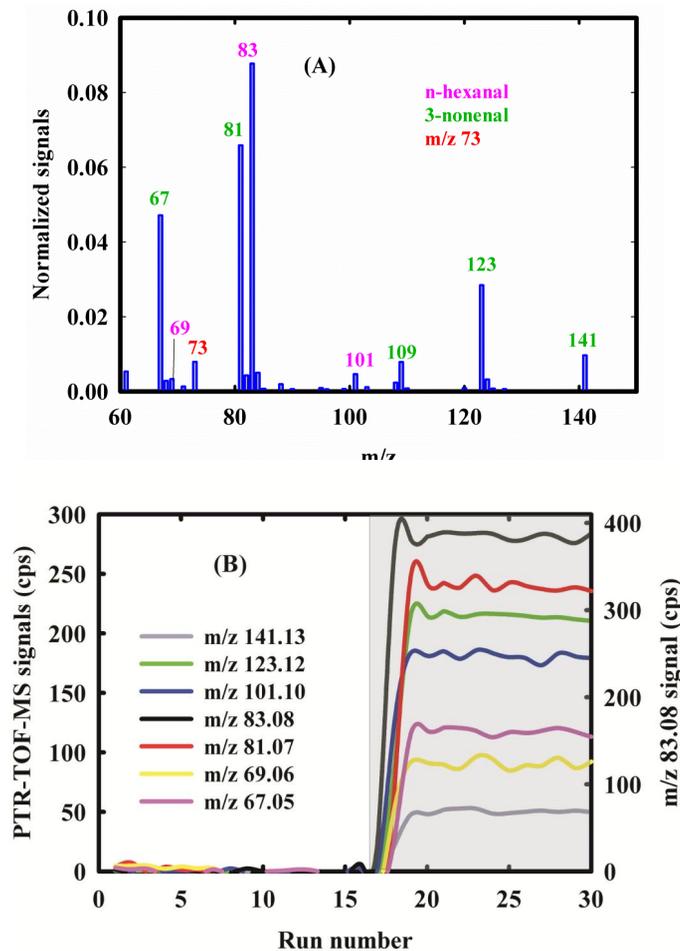
S. Zhou et al.



**Fig. 1.** Schematic of the flow tube apparatus **(A)** and LED-CE-DOAS instrument **(B)**.

## Formation of gas-phase carbonyls from heterogeneous oxidation

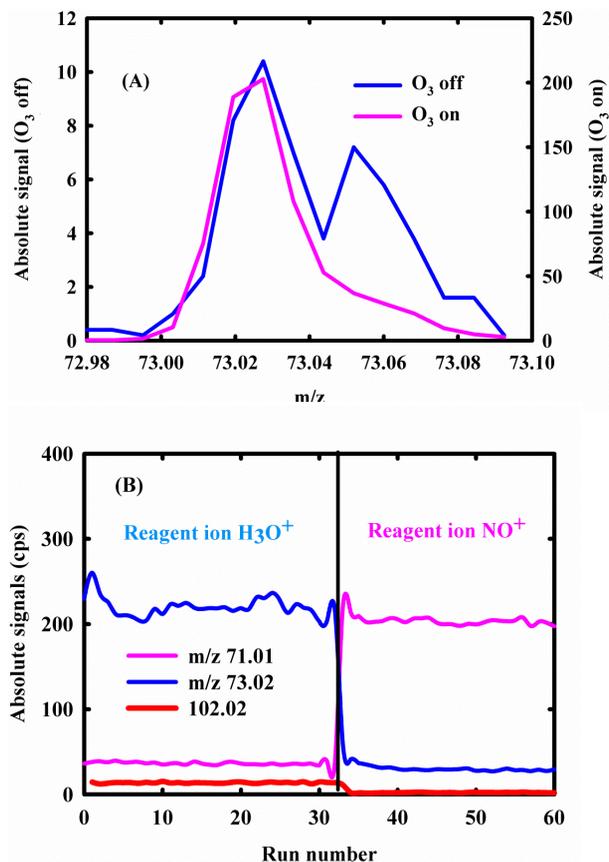
S. Zhou et al.



**Fig. 2.** Mass spectra for the gas-phase products from Type 1 experiments recorded by PTR-MS **(A)** and PTR-TOF-MS **(B)**. In **(B)**, the shaded area represents exposure to 500 ppb O<sub>3</sub>.

Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation

S. Zhou et al.



**Fig. 3.** PTR-TOF-MS mass spectrum of the signal at  $m/z$  73.02 recorded with  $\text{H}_3\text{O}^+$  as the reagent ion (A) and three signals recorded with PTR-TOF-MS as the reagent ion is switched from  $\text{H}_3\text{O}^+$  to  $\text{NO}^+$  (B) from Type 1 experiment with 500 ppb  $\text{O}_3$  exposure.

Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation

S. Zhou et al.

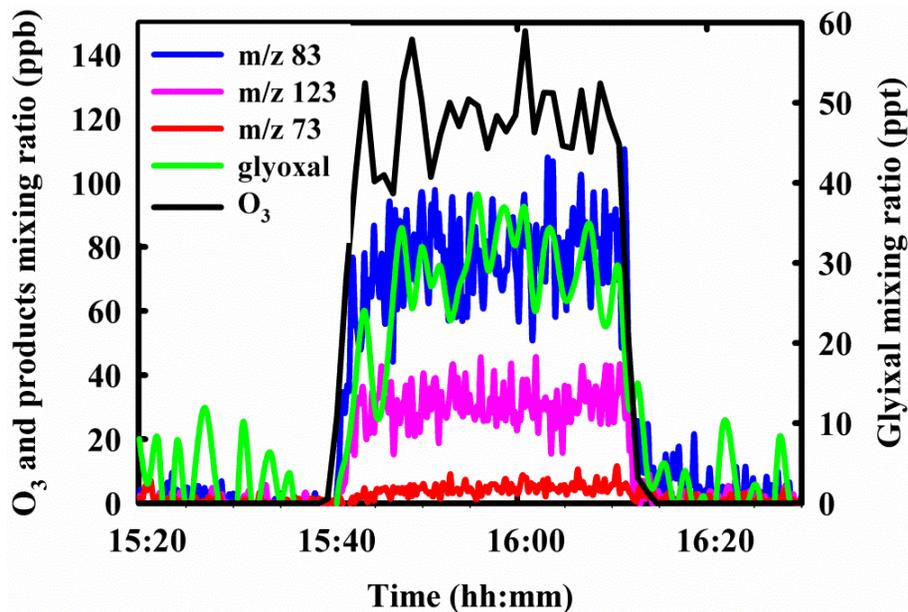


Fig. 4. Example of ozone and product profiles for a Type 1 LA experiment.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation

S. Zhou et al.

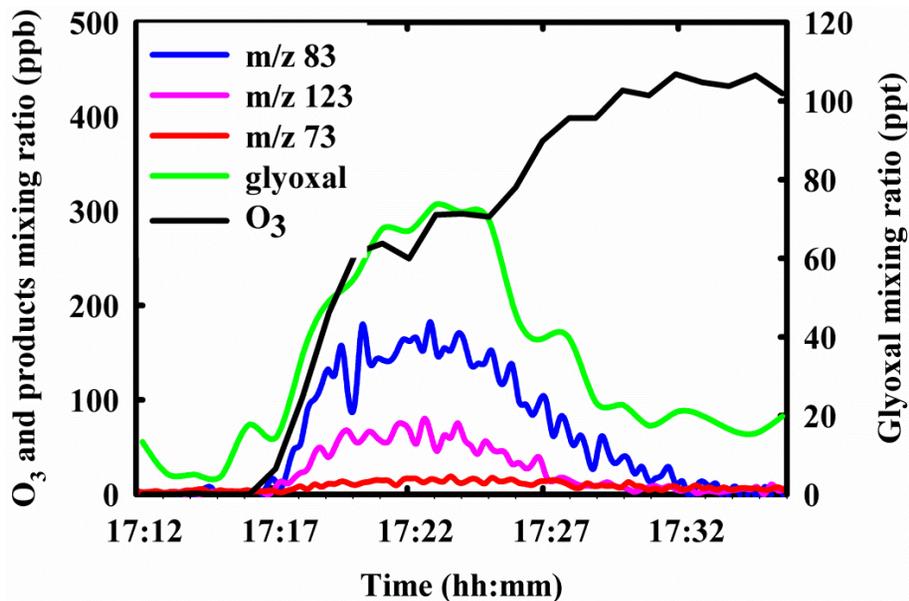
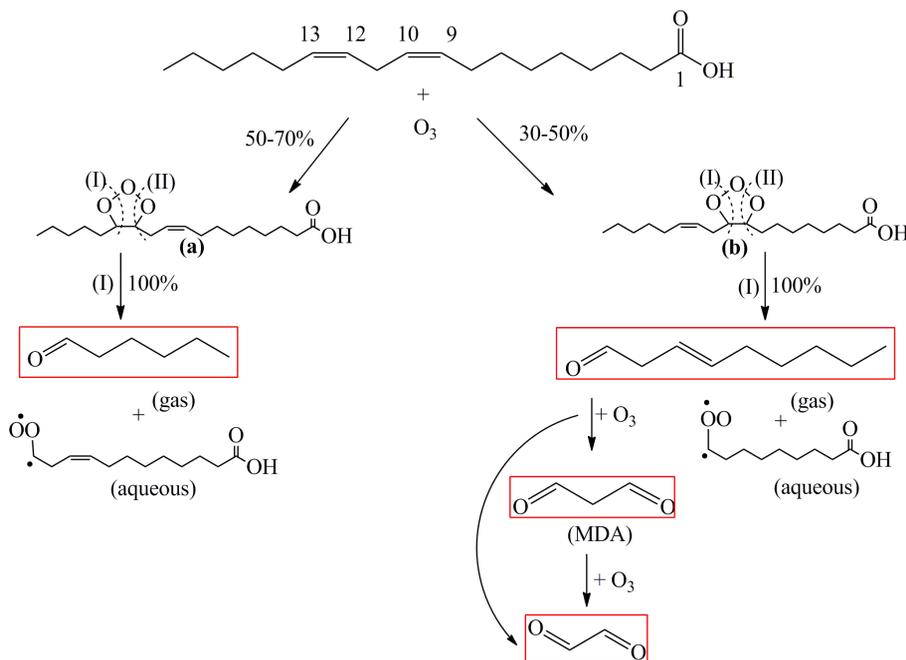


Fig. 5. Ozone and product profiles for Type 2 LA experiment.

## Formation of gas-phase carbonyls from heterogeneous oxidation

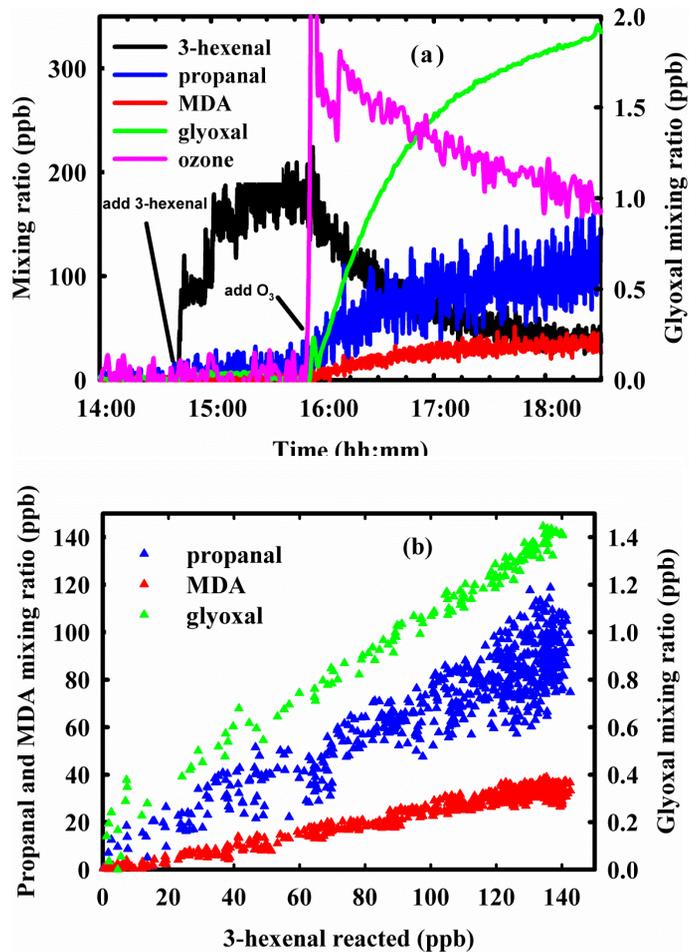
S. Zhou et al.



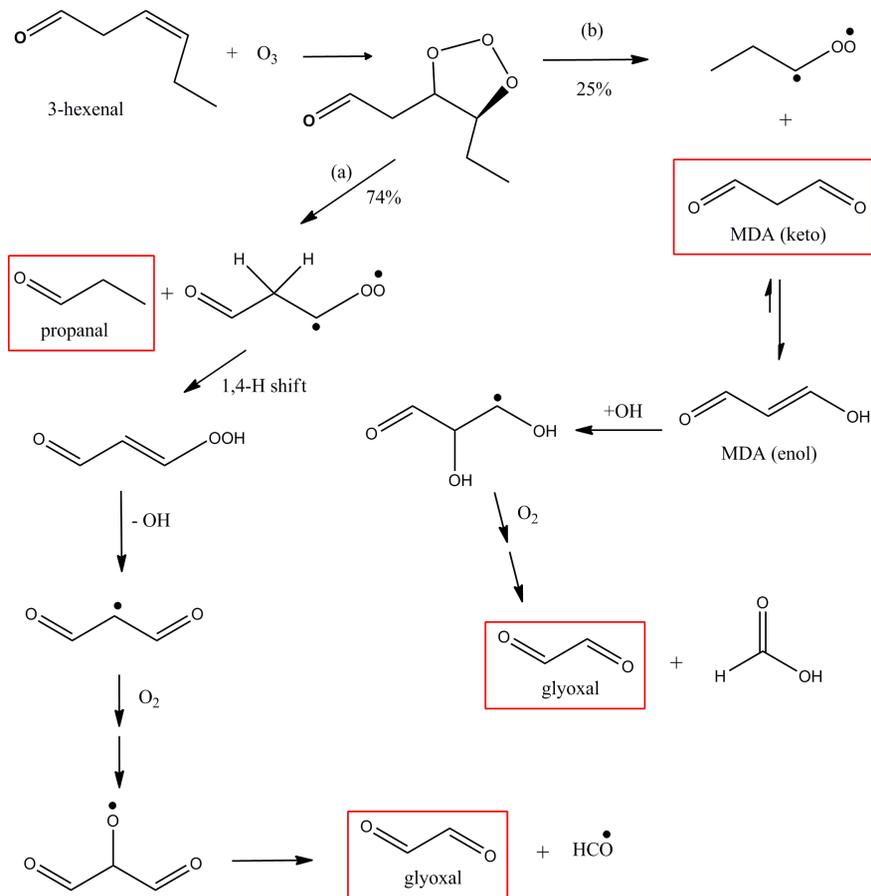
**Fig. 6.** Reaction mechanism for the heterogeneous reaction of ozone with LA at air–water interface.

Formation of  
gas-phase carbonyls  
from heterogeneous  
oxidation

S. Zhou et al.



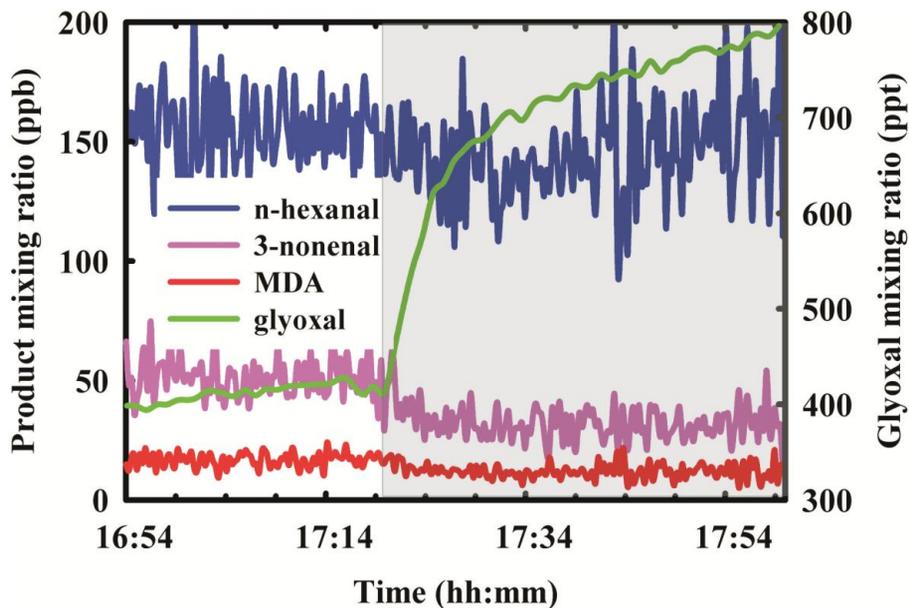
**Fig. 7.** (a) Time series of the reactants and products and (b) for the reaction of gas-phase 3-hexenal with ozone in the Teflon chamber.



**Fig. 8.** Reaction mechanism for ozonolysis of cis-3-hexenal and glyoxal formation from MDA oxidation.

## Formation of gas-phase carbonyls from heterogeneous oxidation

S. Zhou et al.



**Fig. 9.** Flow tube results when a UV lamp is turned on (in the shaded region) to form OH in a second flow tube in series downstream of the LA oxidation flow tube.

