Highly oxygenated organic molecules (HOM) formation in the isoprene oxidation by NO_3 radical

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Abstract

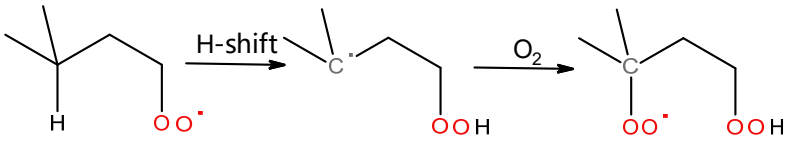
Highly oxygenated organic molecules (HOM) are found to play an important role in the formation and growth of secondary organic aerosol (SOA). SOA is an important type of aerosol with significant impact on air quality and climate. Compared with the oxidation of volatile organic compounds by O_3 and OH, HOM formation in the oxidation by NO_3 radical, an important oxidant at night-time and dawn, has received less attention. In this study, HOM formation in the reaction of isoprene with NO_3 was investigated in the SAPHIR chamber (Simulation of Atmospheric PHotochemistry In a large Reaction chamber). A large number of HOM including monomers (C_5), dimers (C_{10}), and trimers (C_{15}), both closed-shell compounds and open-shell peroxy radicals, were identified and were classified into various series according to their formula. Their formation pathways were proposed based on the peroxy radicals observed and known mechanisms in the literature, which were further constrained by the time profiles of HOM after sequential isoprene addition to differentiate first- and second-generation products. HOM monomers containing one to three N atoms (1-3N monomers) were formed, starting with NO_3 addition to carbon double bond, forming peroxy radicals (RO_2), followed by autoxidation. 1N monomers were formed by both the direct reaction of NO_3 with isoprene and of NO_3 with first-generation products. 2N-monomers (e.g. $C_5H_8N_2O_{n\ (n=7-13)}$, $C_5H_{10}N_2O_{n\ (n=8-14)}$) were likely the termination products of $C_5H_9N_2O_n$•, which was formed by the addition of NO_3 to C5-hydroxynitrate ($C_5H_9NO_4$), a first-generation product containing one carbon double bond. 2N-monomers, which were second-generation products, dominated in monomers and accounted for ~34% of all HOM, indicating the important role of second-generation oxidation in HOM formation in the isoprene+NO_3 reaction under our ~~reaction~~experimental conditions. H-shift of alkoxy radicals to form peroxy radicals and subsequent autoxidation ("alkoxy-peroxy" pathway) was found to be an important pathway of HOM formation. HOM dimers were mostly formed by the accretion reaction of various HOM monomer RO_2 and via the termination reactions of dimer RO_2 formed by further reaction of closed-shell dimers with NO_3 and possibly by the reaction of C5-RO_2 with isoprene. HOM trimers were likely formed by the accretion reaction of dimer RO_2 with monomer RO_2. The concentrations of different HOM showed distinct time profiles during the reaction, which was linked to their formation pathway. HOM concentrations either showed a typical time profile of first-generation products, or of second-generation products, or a combination of both, indicating multiple formation pathways and/or multiple isomers. Total HOM molar yield was estimated to be 1.2% $^{+1.3\%}_{-0.7\%}$, which corresponded to a SOA yield of ~3.6% assuming the molecular weight of $C_5H_9NO_6$ as the lower limit.

This yield suggests that HOM may contribute a significant fraction to SOA yield in the reaction of isoprene with NO_3.

1 Introduction

Highly oxygenated organic molecules (HOM) are an important class of compounds formed in the oxidation of volatile of organic compounds (VOC) including biogenic VOC (BVOC) and anthropogenic VOC (Crounse et al., 2013; Ehn et al., 2014; Jokinen et al., 2014; Rissanen et al., 2014; Jokinen et al., 2015; Krechmer et al., 2015; Mentel et al., 2015; Rissanen et al., 2015; Kenseth et al., 2018; Molteni et al., 2018; Garmash et al., 2019; McFiggans et al., 2019; Molteni et al., 2019; Quelever et al., 2019). A number of recent studies have demonstrated that HOM play a pivotal role in both nucleation and- also particle growth of pre-existing particles, thus contributing to~~growth of~~ secondary organic aerosol (SOA) (Ehn et al., 2014; Kirkby et al., 2016; Tröstl et al., 2016). Particularly, in the early stage of aerosol growth, HOM may contribute a significant fraction of SOA mass (Tröstl et al., 2016).

HOM are formed by the autoxidation of peroxy radicals (RO_2), which means they undergo intra~~er~~molecular H-shift forming alky radicals, followed by O_2 addition leading to formation of new RO_2 as shown ~~in R1~~below (Vereecken et al., 2007; Crounse et al., 2013; Ehn et al., 2017; Bianchi et al., 2019; Møller et al., 2019; Nozière and Vereecken, 2019; Vereecken and Nozière, 2020).



~~(R1)~~

Besides autoxidation, the RO_2 can also react with HO_2, RO_2 and NO_3, either forming a series of termination products (R1-3), including organic hydroxyperoxide, alcohol, and carbonyl, or forming alkoxy radicals (RO, R4-5) via the following reactions.

$$RO_2+R'O_2 \rightarrow ROH+R=O \quad (R1)$$

$$RO_2+R'O_2 \rightarrow R=O+R'OH \quad (R2)$$

$$RO_2+HO_2 \rightarrow ROOH \quad (R3)$$

$$RO_2+R'O_2 \rightarrow RO+R'O+O_2 \quad (R4)$$

$$RO_2+NO_3 \rightarrow RO+NO_2+O_2 \quad (R5)$$

$$RO_2+R'O_2 \rightarrow ROOR'+O_2 \quad (R6)$$

The termination products are detected in the mass spectra at masses M+1, M-15, M-17 respectively with M being the molecular mass of the parent RO_2 (Ehn et al., 2014; Mentel et al., 2015). In case that RO_2 is an acyl peroxy radical, percarboxylic acids and carboxylic acids are formed instead of hydroperoxides and alcohols in R3 and R1, respectively (Atkinson et al., 2006; Mentel et al., 2015). RO_2 can also form HOM dimers by the accretion reaction of two RO_2 (R6) (Berndt et al., 2018a; Berndt et al., 2018b; Valiev et al., 2019). Additionally, HOM can be formed via H-shift in RO followed by O_2 addition (referred to as "alkoxy-proxy" pathway) (Finlayson-Pitts and Pitts, 2000; Vereecken and Peeters, 2010; Vereecken and Francisco, 2012; Mentel et al., 2015). These pathways are summarized in a recent comprehensive review (Bianchi et al., 2019), which also further clarifies HOM definition.

Currently, most laboratory studies of HOM formation focus on the VOC oxidation by OH and O_3 (Crounse et al., 2013; Ehn et al., 2014; Jokinen et al., 2014; Rissanen et al., 2014; Jokinen et al., 2015; Krechmer et al., 2015; Mentel et al., 2015; Rissanen et al., 2015; Kirkby et al., 2016; Tröstl et al., 2016; Kenseth et al., 2018; Molteni et al., 2018; Garmash et al., 2019; McFiggans et al., 2019; Molteni et al., 2019; Quelever et al., 2019; Wang et al., 2020; Yan et al., 2020). HOM formation in the oxidation of VOC with NO_3 has received much less attention. NO_3 is another important oxidant of VOC mainly operating during nighttime. Particularly, NO_3 has high reactivity with unsaturated BVOC such as monoterpene and isoprene. It is often the dominant oxidant of these compounds at night, especially in regions where biogenic and anthropogenic emissions mix (Geyer et al., 2001; Brown et al., 2009; Brown et al., 2011). The reaction products contribute to SOA formation (Xu et al., 2015; Lee et al., 2016). Also, the organic nitrates produced in these reactions play an important role in nitrogen chemistry by altering NO_x concentration, which further influences photochemical recycling and ozone formation in the next day. Among these reaction products, HOM ~~may~~ can also be formed (Xu et al., 2015; Lee et al., 2016; Yan et al., 2016). Despite the potential importance, studies of HOM formation in the oxidation of BVOC by NO_3 are still limited compared with the HOM formation via oxidation by O_3 and OH. Although a number of laboratory studies have investigated the reaction of NO_3 with BVOC (Ng et al., 2008; Fry et al., 2009; Rollins et al., 2009; Fry et al., 2011; Kwan et al., 2012; Fry et al., 2014; Boyd et al., 2015; Schwantes et al., 2015; Nah et al., 2016; Boyd et al., 2017; Claflin and Ziemann, 2018; Faxon et al., 2018; Draper et al., 2019; Takeuchi and Ng, 2019; Novelli et al., 2021; Vereecken et al., 2021), these studies mostly focus on either SOA yield and composition, or on the gas-phase chemistry mechanism mainly for "traditional" oxidation products that stem from few oxidation steps.

Importantly, HOM formation in the reaction of NO_3 with isoprene, the most abundant BVOC accounting for more than half of the global BVOC emissions, has not been explicitly addressed yet, to the best of our knowledge. Although isoprene from plants are mainly emitted under light conditions, i.e., in the daytime, ~~and its chemical lifetime with respect to its reaction with OH is typically only a few hours, its concentration~~isoprene can remain high after sunset in significant concentrations (Starn et al., 1998; Stroud et al., 2002; Brown et al., 2009) because of the reduced consumption by OH and is found to decay rapidly. A substantial fraction of isoprene can then be oxidized by NO_3 (Brown et al., 2009). Regarding the budget of NO_3, the reaction of isoprene with NO_3 can contribute to a significant or even dominant fraction of NO_3 loss at night in regions where VOC is dominated by isoprene such as Northeast US (Brown et al., 2009). Under some circumstances, the reaction of isoprene with NO_3 can contribute to a significant fraction during the afternoon and afterwards (Ayres et al., 2015; Hamilton et al., 2021)~~the reaction of isoprene with NO_3 contributes to a significant fraction of NO_3 loss at night, and in some circumstances even during the day, especially in the afternoon and afterwards (Ayres et al., 2015)~~. The reaction of isoprene with NO_3 is the subject of a number of studies (Ng et al., 2008; Perring et al., 2009; Rollins et al., 2009; Kwan et al., 2012; Schwantes et al., 2015; Vereecken et al., 2021). These studies focus on the oxidation mechanism and "traditional" oxidation products, as well as SOA yields. The initial~~s~~ step is the NO_3 addition to one of the C=C double bounds, preferentially to the carbon C1 (Schwantes et al., 2015), followed by O_2 addition forming a nitrooxyalkyl peroxy radical (RO_2). This RO_2 can undergo the reactions described above, forming a

series of products such as C5-nitrooxyhydroperoxide, C5-nitrooxycarbonyl, and C5-hydroxynitrate (Ng et al., 2008; Kwan et al., 2012), as well as methyl vinyl ketone (MVK), potentially methacrolein (MACR), formaldehyde, OH radical, and NO_2 as minor products (Schwantes et al., 2015). A high nitrate yield (57-95%) was found (Perring et al., 2009; Rollins et al., 2009; Kwan et al., 2012; Schwantes et al., 2015). Products in the particle phase such as C_{10} dimers were also detected (Ng et al., 2008; Kwan et al., 2012; Schwantes et al., 2015). The SOA yield varies from 2% to 23.8% depending on the organic aerosol concentration (Ng et al., 2008; Rollins et al., 2009). These studies have provided valuable insights in oxidation mechanism, particle yield and composition. However, because HOM formation was not the focus of these studies, only a limited number of products, mainly moderately oxygenated ones (oxygen number $\leq$2 in addition to NO_3 functional groups), were detected in the gas phase. The detailed mechanism of HOM formation and their yields in the reaction of BVOC+NO_3 are still unclear.

In this study, we investigated the HOM formation in the oxidation of isoprene by NO_3. We report the identification of HOM, including HOM monomers, dimers, and trimers. According to the reaction products and literature, we discuss the formation mechanism of these HOM. The formation mechanism of various HOM is further constrained with time series of HOM upon repeated isoprene additions. We also provide an estimate of HOM yield in the isoprene+NO_3- reaction and assess their roles in SOA formation.

2 Experimental

2.1 Chamber setup and experiments

Experiments investigating the reaction of isoprene with NO_3 were conducted in the SAPHIR chamber (Simulation of Atmospheric PHotochemistry In a large Reaction chamber) at Forschungszentrum Jülich, Germany. The details of the chamber have been described before (Rohrer et al., 2005; Zhao et al., 2015a; Zhao et al., 2015b; Zhao et al., 2018). Briefly, SAPHIR is a Teflon chamber with a volume of 270 m^3. It can utilize natural sunlight for illumination and is equipped with a louvre system to switch between light and dark conditions. In this study, the experiments were conducted in the dark with the louvres closed.

Temperature and relative humidity were continuously measured. Gas and particle phase species were characterized using a comprehensive set of instruments with the details described before (Zhao et al., 2015b). VOC were characterized using a Proton Transfer Reaction Time-of-Flight Mass Spectrometer (PTR-ToF-MS, Ionicon Analytik, Austria). NO_x and O_3 concentrations were measured using a chemiluminescence NO_x analyzer (ECO PHYSICS TR480) and an UV photometer O_3 analyzer (ANSYCO, model O341M), respectively. OH, HO_2 and RO_2 concentrations were measured using a laser induced fluorescence system (LIF) (Fuchs et al., 2012). NO_3 and N_2O_5 were detected by a custom-built instrument based on cavity ring-down spectroscopy. The design of the instrument is similar to that described by Wagner et al. (2011). NO_3 was directly detected in one cavity by its absorption at 662 nm and the sum of NO_3 and N_2O_5 in a second, heated cavity, which had a heated inlet to thermally decompose N_2O_5 to NO_3. The sampling flow rate was 3 to 4 liters per minute. The detection by cavity ring-down spectroscopy was achieved by a diode laser that was periodically switched on and off with a

repetition rate of 200 Hz. Ring-down events were observed by a digital oscilloscope PC card during the time when the laser was switched off and were averaged over 1s. The zero-decay time that is needed to calculate the concentration of NO_3 was measured every 20 s by chemically removing NO_3 in the reaction with excess nitric oxide (NO) in the inlet system. The accuracy of measurements was limited by the uncertainty in the correction for inlet losses of NO_3 and N_2O_5. In the case of N_2O_5 a transmission of (85±10) % was achieved and in the case of NO_3 of (50±30) %.

Before an experiment, the chamber was flushed with high purity synthetic air (purity>99.9999% O_2 and N_2). Experiments were conducted under dry condition (RH<2 %) and temperature was at 302±3 K. NO_2 and O_3 were added to the chamber first to form N_2O_5 and NO_3, reaching concentrations of ~60 ppb for NO_2 and ~100 ppb for O_3. After around half an hour, isoprene was sequentially added into the chamber for three times at intervals of ~1 h. Around 40 min after the third isoprene injection, NO_2 was added to compensate the loss of NO_3 and N_2O_5. Afterwards, three isoprene additions were repeated in the same way as before. O_3 was added before the fifth and the sixth isoprene addition to compensate for its loss by reaction. The schematic for the experimental procedure is shown in Fig. S1. Experiments were designed such that the chemical system was dominated by the reaction of isoprene with NO_3 and the reaction of isoprene with O_3 did not play a major role (<3% of the isoprene consumption). Figure S2 shows the relative contributions of the reaction of O_3 and NO_3 with isoprene to the total chemical loss of isoprene using the NO_3 and O_3 concentrations measured. The reaction with NO_3 accounted for >95% of the isoprene consumption ~~at all time~~for the whole experiments. The contribution of the reaction of isoprene with trace amount of OH, mainly produced in the reaction of isoprene+O_3 via Criegee intermediates (Nguyen et al., 2016), is negligible as the OH yield is less than one (Malkin et al., 2010) and thus its contribution is less than that of isoprene+O_3. This is consistent with the contribution determined using measured OH concentration, despite some uncertainty in measured OH concentration due to the interference from NO_3. In these experiments, RO_2 fate is estimated to be dominated by its reaction with NO_3 according to the measured NO_3, RO_2, and HO_2 concentration and their rate constants for the reactions with RO_2 (MCM v3.2(Jenkin et al., 1997; Jenkin et al., 2003; Saunders et al., 2003; Jenkin et al., 2015), via website: http://mcm.leeds.ac.uk/MCM) despite uncertainties of the measured RO_2 and HO_2 concentration due to interference from NO_3. As a large portion of RO_2 is not measured by LIF (Vereecken et al., 2021) and thus RO_2 is underestimated, we expected the reaction of RO_2+RO_2 to be also important. Overall, we estimate that he RO_2 fate is dominated the reaction RO_2+NO_3 with significant contribution of RO_2+RO_2.

2.2 Characterization of HOM

In this study we refer to similar definition for HOM by Bianchi et al. (2019)~~,~~ i.e., HOM typically contain six or more oxygen atoms formed via autoxidation and related chemistry of peroxy radicals.~~-~~ HOM were detected using a Chemical Ionization time-of-flight Mass Spectrometer (Aerodyne Research Inc., USA) with nitrate as the reagent ion (CIMS) (Eisele and Tanner, 1993; Jokinen et al., 2012). ^{15}N nitric acid was used to produce $^{15}NO_3^-$ in order to distinguish the NO_3 group in target molecules formed in the reaction from the reagent ion. The details of the instrument are described in our previous publications (Ehn et al., 2014; Mentel et al., 2015; Pullinen et al., 2020). The CIMS has a mass resolution of ~4000 (m/dm). Examples of peak fitting are shown in Fig. S3. HOM

concentrations were estimated using the calibration coefficient of H_2SO_4 as described by Pullinen et al. (2020) because the charge efficiency of HOM and H_2SO_4 can be assumed to be equal and close to the collision limit (Ehn et al., 2014; Pullinen et al., 2020). The details of the calibration with H_2SO_4 are provided in the supplement S1. Since HOM contain more than six oxygen atoms and their clusters with nitrate ions are quite stable (Ehn et al., 2014), the charge efficiency of HOM is thus assumed to be equal to that of H_2SO_4, which is close to the collision limit (Viggiano et al., 1997). If HOM do not charge with nitrate ions at their collision limit or the clusters formed break during the short residence time in the charger, its concentration would be underestimated as pointed by Ehn et al. (2014). Thus, our assumption provides a lower limit of the HOM concentration. The HOM yield was derived using the concentration of the HOM produced, divided by the concentration of isoprene that was consumed by NO_3. The uncertainty of HOM yield was estimated to -55%/+103%. The loss of HOM to the chamber was corrected using a wall loss rate of 6×10^{-4} s^{-1} as quantified previously (Zhao et al., 2018). HOM concentrations were also corrected for dilution due to the replenishment flow needed to maintain a constant overpressure of the chamber (loss rate ~1×10^{-6} s^{-1}) (Zhao et al., 2015b). The influence of wall loss correction and dilution correction on HOM yield was ~12% and <1%, respectively. Although the wall loss rate of vapors in this study might not be exactly the same as in our previous photo-oxidation experiments (Zhao et al., 2018), HOM yield is not sensitive to the vapor wall loss rate. An increase of wall loss rate by 100% or a decrease by 50% only changes the HOM yield by 11% and -6%, respectively.

3 Results and discussion

3.1 Overview of HOM

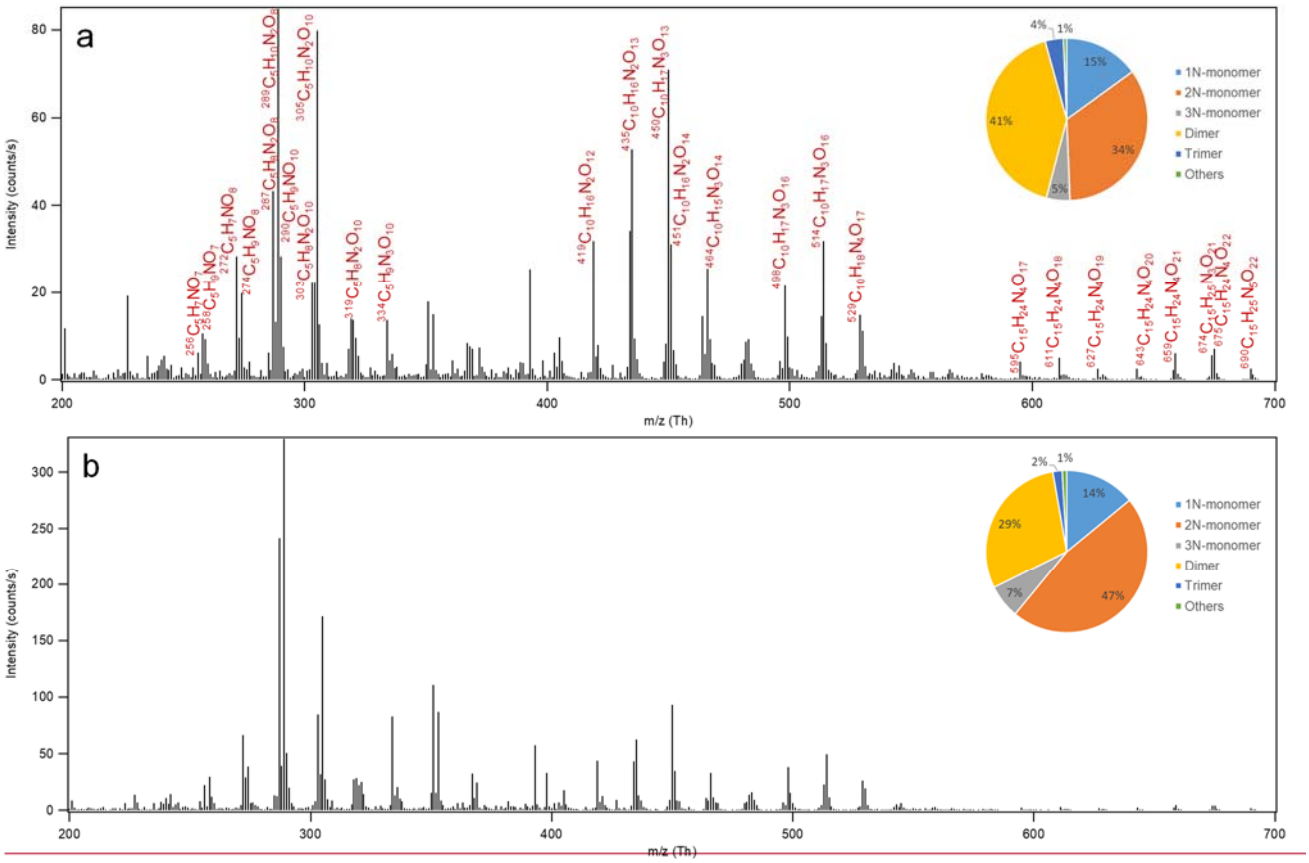
The mass spectra of HOM in the gas phase formed in the oxidation of isoprene by NO_3 are shown in Fig. 1. A large number of HOM were detected. Almost all peaks are assigned HOM containing nitrogen atoms with possibly few exceptions such as $C_5H_{10}O_8$ and $C_5H_8O_{11}$ with very minor peaks (<~1% of the maximum peak). The reaction products can be roughly divided into three classes: monomers (C5, ~200-400 Th), dimers (C10, ~400-600 Th), and trimers (C15, ~>600 Th), according to their mass to charge ratio (m/z). The detailed peak assignment of monomers, dimers, and trimers is discussed in the following sections.

3.2 HOM monomers and their formation

3.2.1 Overview of HOM monomers

HOM monomers showed a roughly repeating pattern in the mass spectrum at every 16 Th (corresponding to the mass of oxygen) (Fig. 1a). Here a number of series of HOM monomers with continuously increasing oxygenation were found, such as $C_5H_9NO_n$, $C_5H_7NO_n$, $C_5H_8N_2O_n$, $C_5H_{10}N_2O_n$ (Table 1, Table S1-2 and Fig. 2). These monomers included both stable closed-shell molecules and open-shell radicals, such as $C_5H_8NO_n$• and $C_5H_9N_2O_n$•. The open-shell molecules were likely RO_2 radicals because of their much longer life time and hence higher concentrations compared with alkoxy radicals (RO) and alkyl radicals (R). Since the observed stable products were mostly termination products of RO_2 reactions, we describe the stable products in

a RO_2-oriented approach. It is worth noting that some of the termination products may contain multiple isomers formed from different pathways.



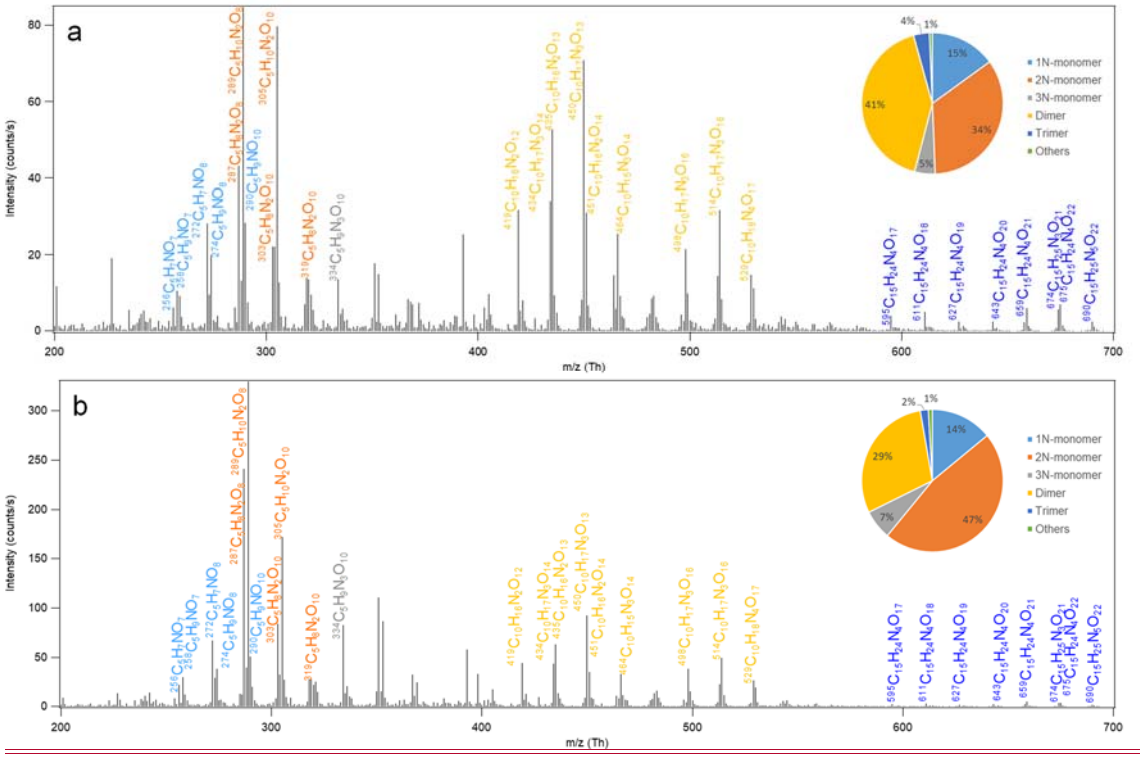
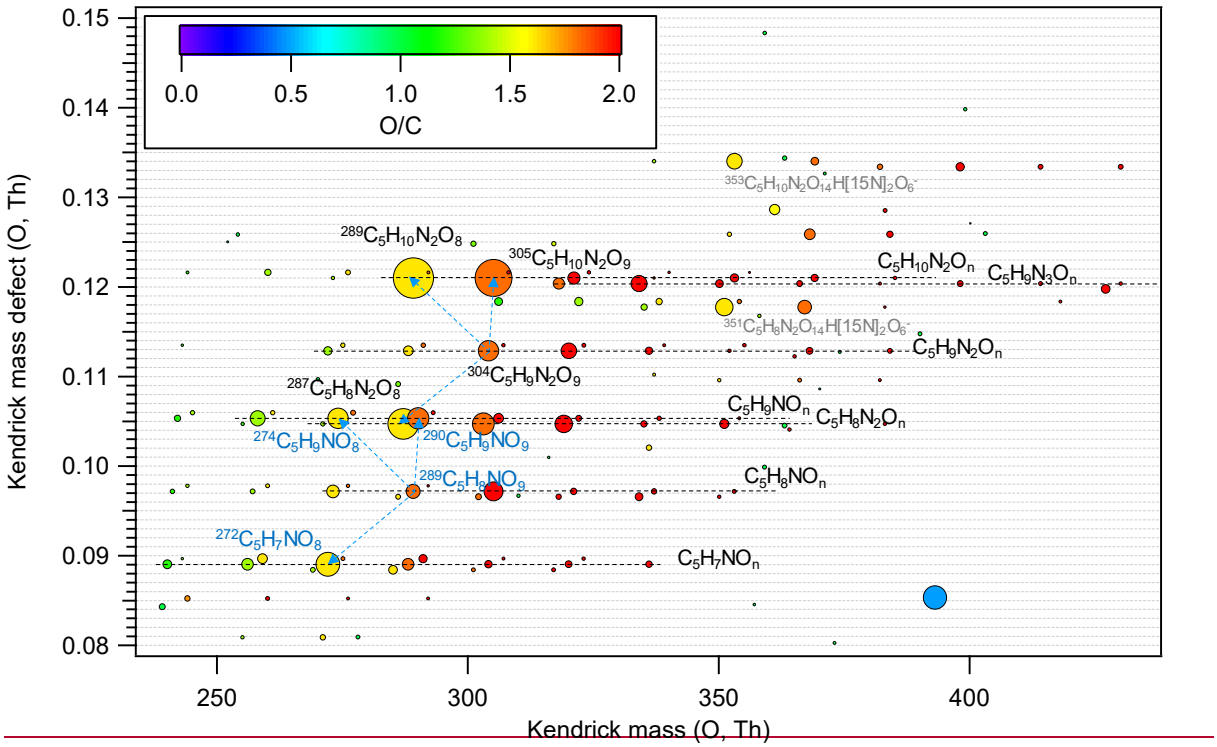


Figure 1. Mass spectrum of the HOM formed in the oxidation of isoprene by NO_3. HOM are detected as clusters with the reagent ion $^{15}NO_3^-$, which is not shown in the molecular formula in the figure for simplicity. Panel

a and b show the average spectrum during the first isoprene addition period (P1) and for the whole period of six isoprene additions (P1-6), respectively. The insets show the contributions of different classes of HOM. 1-3N-monomer refers to the monomers containing 1-3 nitrogen atoms in the molecular formula.

HOM monomers were classified into 1N-, 2N-, and 3N-monomers according to the number of nitrogen atoms that they contain. HOM without nitrogen atoms were barely observed except for very minor peaks (<~1% of the maximum peak) possibly assigned to $C_5H_{10}O_8$ and $C_5H_8O_{11}$. The contribution of 2N-monomers such as $C_5H_{10}N_2O_n$ and $C_5H_8N_2O_n$ was higher than that of the 1N-HOM monomers, and that of 3N-monomers was the least (Fig. 1, inset). The most abundant monomers were $C_5H_{10}N_2O_8$, $C_5H_{10}N_2O_9$, and $C_5H_8N_2O_8$. The termination products of $C_5H_9NO_8$, $C_5H_9NO_9$, and $C_5H_7NO_8$ also showed relatively high abundance. These limited number of compounds dominated the HOM monomers. Since 2N-monomers were second-generation products as discussed below, the higher abundance 2N- monomers indicate that the second-generation HOM play an important role in the reaction of NO_3 with isoprene in the reaction conditions of our study, as also seen by Wu et al. (2020) . This is more evident for the mass spectrum averaged over six isoprene addition periods (Fig. 1b), where the abundance of $C_5H_{10}N_2O_n$ and $C_5H_8N_2O_n$ were more dominant. This observation is in contrast with the finding for the reaction of O_3 with BVOC which contains only one double bond such as α-pinene (Ehn et al., 2014), where HOM are mainly first-generation products formed via autoxidation. The higher abundance of HOM 2N-monomers than 1N-monomers is likely because HOM production rate via the autoxidation of 1N-monomer RO_2 following the reaction of isoprene with NO_3 may be slower than that of the reaction of 1N-monomers (including both HOM and non-HOM monomers) with NO_3. We would like to note that some less oxygenated 1N-monomers such as $C_5H_9NO_{4/5}$ and $C_5H_7NO_4$ may have high abundance but are not detected by NO_3^--CIMS and are not HOM and thus not included in HOM 1N-monomers.



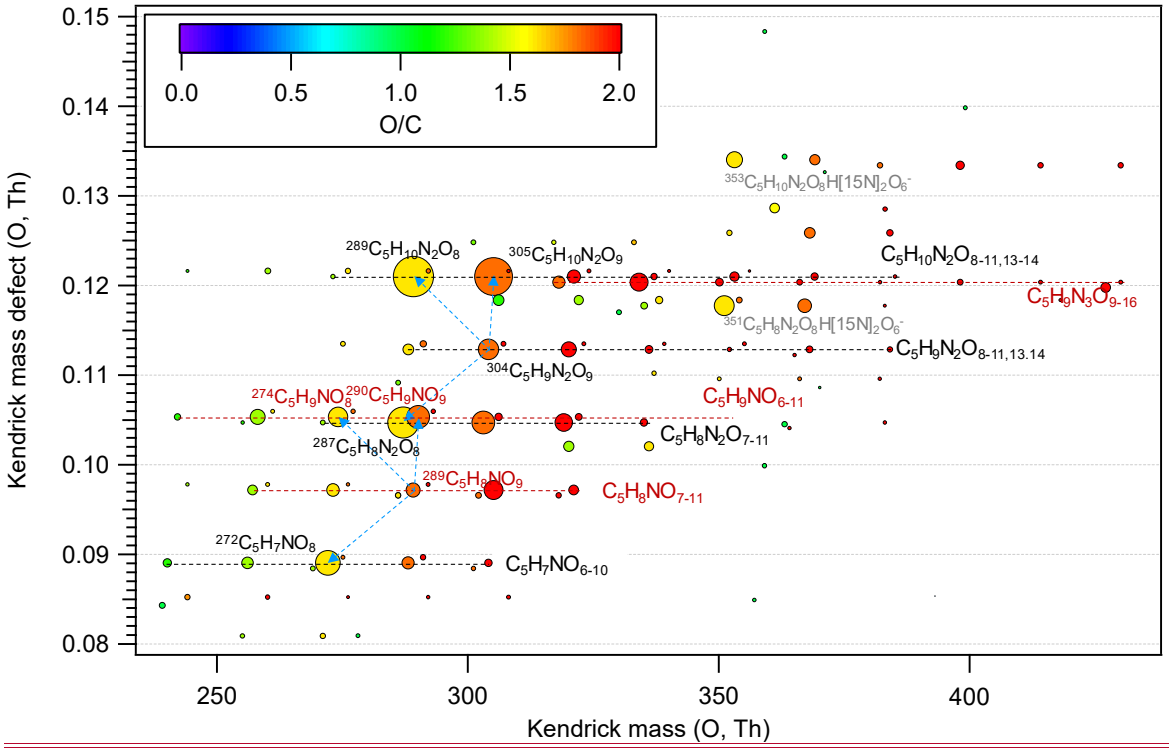


Figure 2. Kendrick mass defect plot for O of HOM monomers. The m/z in the molecular formula include the reagent ion $^{15}NO_3^-$, which is not shown for simplicity. The size (area) of circles is set to be proportional to the average peak intensity of each molecular formula during the first isoprene addition period (P1). The species at m/z 351 and 353 (labelled in grey) are the adducts of $C_5H_8N_2O_8$ and ~~$C_5H_8N_2O_8$~~ $C_5H_{10}N_2O_8$ with $H[15N]_2O_6^-$, respectively. The blue dashed lines with arrows indicate the termination product hydroperoxide (M+H), alcohol (M-O+H), and ketone (M-O-H) with M the molecular formula of a HOM RO_2.

3.2.2 1N-monomers

In our experiments we observed a $C_5H_8NO_n$• (n=7-12) series (series M1), as well as its corresponding termination products $C_5H_7NO_{n-1}$, $C_5H_9NO_{n-1}$, and $C_5H_9NO_n$ via the reactions with RO_2 and HO_2, which contain carbonyl, hydroxyl, and hydroperoxy group, respectively. Overall, the peak intensities of $C_5H_9NO_n$ and $C_5H_7NO_n$ series first increased and then decreased as oxygen number increased (Fig. 2), with the peak intensity of $C_5H_9NO_8$ and $C_5H_7NO_8$ being the highest within their respective series when averaged over the whole experiment period.

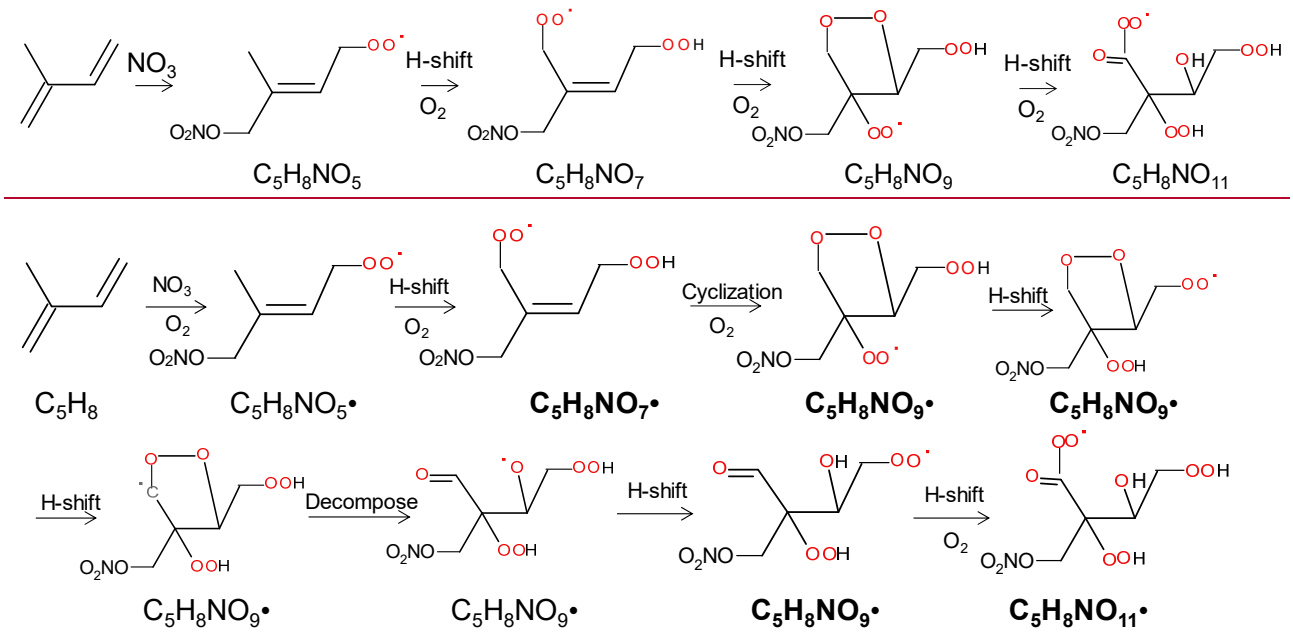
Table 1. HOM monomers formed in the oxidation of isoprene by NO_3.

Series Number	Product	Type[a]	Pathway of RO_2
M1a/b	$C_5H_8NO_n$ (n=7-~~12~~11)	RO_2	Isoprene+NO_3 Isoprene+NO_3+NO_3
	$C_5H_9NO_n$ (n=6-11)	ROOH/ROH	
	$C_5H_7NO_n$-~~1~~ (n=6-10)	R=O	
M2a/b	$C_5H_9N_2O_n$ (n=~~9~~8-11,13,14~~14~~)[b]	RO_2	Isoprene +NO_3+NO_3
	$C_5H_{10}N_2O_n$ (n=8-11,13,14)[b]	ROOH/ROH	
	$C_5H_8N_2O_n$-~~1~~ (n=7-11)	R=O	

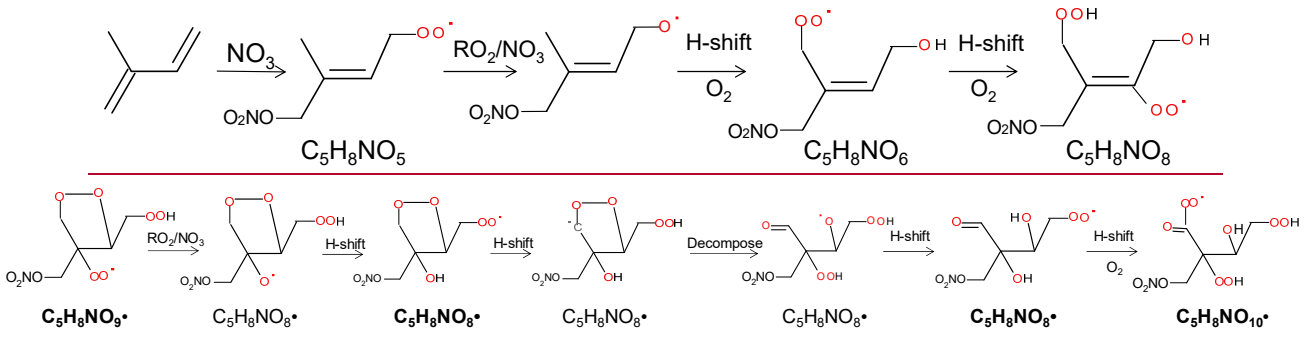
	$C_5H_9N_3O_{n+2\ (n=9\text{-}16)}$[b]	PNRO_2NO_2	
M3	$C_5H_7N_2O_{n\ (n=9)}$ $C_5H_8N_2O_{n\ (n=8,\ 9)}$ $C_5H_6N_2O_{n-1\ (n=8)}$	RO_2 ROOH R=O	Isoprene +NO_3+NO_3
M4	$C_5H_{10}NO_{n\ (n=8\text{-}9)}$ $C_5H_{11}NO_{n\ (n=7\text{-}9)}$ $C_5H_9NO_{n-1\ (n=7\text{-}8)}$	RO_2 ROOH/ROH R=O	Isoprene +NO_3+OH

[a]: RO_2 denotes peroxy radical and ROOH, ROH, and R=O, and RO_2NO_2 denote the termination products containing hydroperoxy, hydroxyl, and carbonyl group, and peroxynitrate, respectively.

[b]: Peak assignment of compounds with n=13,14 may be subject to uncertainties.



(a)



(b)

Scheme 1. The example pathways to form HOM RO_2 $C_5H_8NO_n$• (n=7, 9, 11) series (a) and $C_5H_8NO_n$• (n=8, 10~~, 12~~) series (b) in the reaction of isoprene with NO_3. The detected products are in bold.

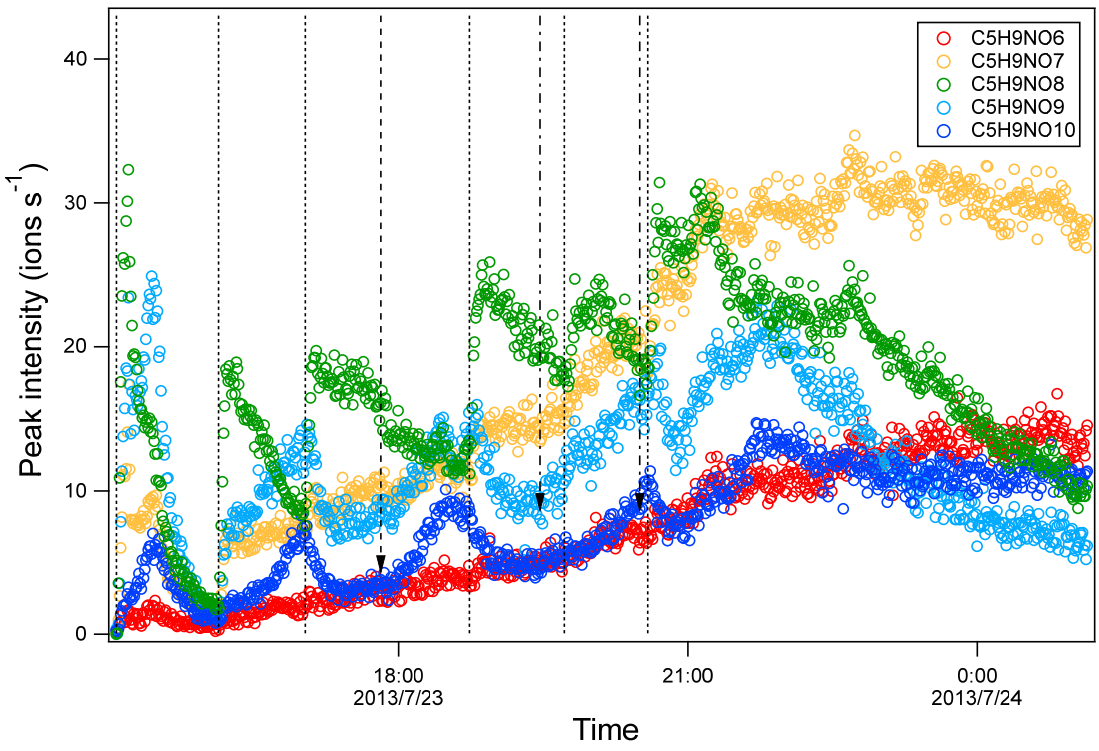
$C_5H_8NO_n$• with odd number oxygen atoms (n=7, 9, 11, series M1a) were possibly formed by the attack of NO_3 to one double bond (preferentially to C1 according to previous studies (Skov et al., 1992; Berndt and Böge, 1997; Schwantes et al., 2015) and followed by autoxidation (Scheme 1a). We would like to note that NO_3^--CIMS only observed HOM with oxygen numbers ≥ 6 in this study due to its selectivity of detection. $C_5H_8NO_n$• with even number oxygen atoms (n=8, 10,~~ 12)~~ (~~series M1b in Table 1) were possibly formed after H-shift of an alkoxy radical formed in reaction ~~R5~~ R4 or ~~R6~~ R5 and subsequent O_2 addition ("alkoxy-peroxy" channel) (Scheme 1b), where the alkoxy radicals can be formed both from the RO_2+NO_3 and RO_2+RO_2 reactions. The hydroxy-RO_2 formed can undergo further autoxidation adding two oxygen atoms after each H-shift. We would like to note that the scheme and other schemes in this study only show example isomers and pathways to form these molecules. It is likely that many of the reactions occurring are not the dominant channels as otherwise there would be much higher HOM yield as discussed below.

Some HOM monomers may contain multiple isomers and be formed via different pathways. For example, $C_5H_9NO_n$ can contain alcohols ~~($C_5H_9NO_n$) corresponding to~~derived from RO_2 $C_5H_8NO_{n+1}$•, hydroperoxides derived from~~($C_5H_9NO_n$) corresponding to~~ RO_2 $C_5H_8NO_n$• or the ketones from RO_2 $C_5H_{10}NO_{n+1}$•. Some RO_2 $C_5H_8NO_n$• may be formed via the reaction of first-generation products with NO_3 in addition to direct reaction of isoprene with NO_3. For example, $C_5H_8NO_7$• can be formed by the reaction of NO_3 with $C_5H_8O_2$, which is a first-generation product observed previously in~~ in~~ the reaction of isoprene with NO_3 or OH (Scheme S1b) (Kwan et al., 2012). Moreover, RO_2 $C_5H_8NO_n$• can be formed from C5-carbonylnitrate, a first-generation product, with OH (Scheme S1a). Trace amount of OH can be produced in the reaction of isoprene with NO_3 (Kwan et al., 2012; Wennberg et al., 2018). OH can also be formed via Criegee intermediates formed in the isoprene+O_3 reaction (Nguyen et al., 2016), but this OH source was likely minor because the contribution of the isoprene+O_3 reaction to total isoprene loss was negligible (<5%, Fig. S2). In addition, $C_5H_8NO_8$• may also be formed by the reaction of NO_3 with $C_5H_8O_3$, which is a first-generation product observed in the reaction of isoprene with OH (Kwan et al., 2012). The $C_5H_8NO_n$• formed via direct reaction of isoprene with NO_3 is a first-generation RO_2 while that formed via other indirect pathways is a second-generation RO_2. The time profile of the isomers from these two pathways, however, are expected to be different as will be discussed below.

Time series of HOM can shed light on their formation mechanisms. It is expected that first-generation products increase fast with isoprene addition and reach a maximum earlier in the presence of wall loss of organic vapour, while second-generation products reach a maximum in the later stage or increase continuously if the production rate is higher than the loss rate. As a reference to analyze the time profiles of HOM, the times profile of isoprene, NO_3, and N_2O_5 are also shown (Fig. ~~S3~~S4). After isoprene was added in each period, NO_3 and N_2O_5 dropped dramatically and then gradually increased. We found that termination products within the same M1 series showed different time profiles. For example, in $C_5H_9NO_n$ series, $C_5H_9NO_8$ clearly increased instantaneously with isoprene addition, and decreased fast afterwards (Fig. 3a), indicating that it was a first-

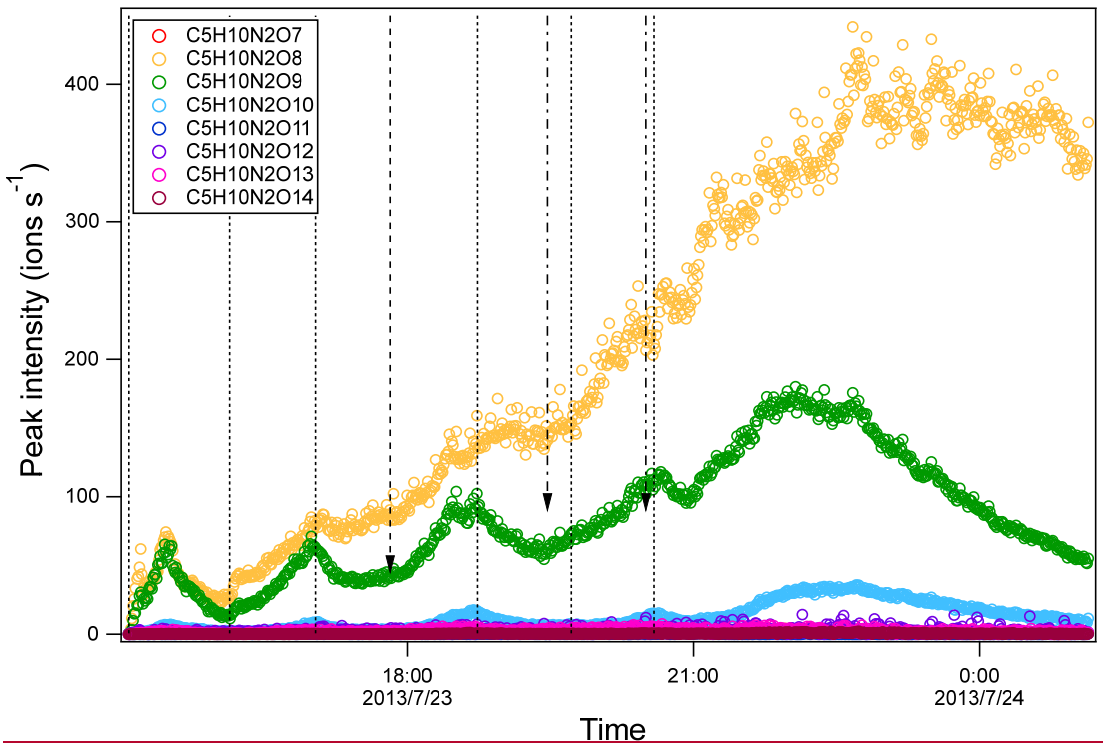
generation product, which was expected according to the mechanism Scheme 1. $C_5H_9NO_6$ and $C_5H_9NO_{10}$ had a general increasing trend with time. While $C_5H_9NO_6$ increased continuously with time, $C_5H_9NO_{10}$ reached maximum intensity in the late phase of each isoprene addition period and then decreased naturally or after isoprene addition. The faster loss of $C_5H_9NO_{10}$ than $C_5H_9NO_6$ may result from the faster wall loss due to its lower volatility. $C_5H_9NO_7$ and $C_5H_9NO_9$ showed a mixing time profile with features of the former two kinds of time profiles, increasing almost instantaneously with isoprene additions, especially in the first two periods, while increasing continuously or decreasing first with isoprene additions and then increasing later in each period~~s~~. This kind of time series indicates that there were significant contributions from both first- and second-generation products.

The second-generation products may be different isomers formed in pathways other than shown in Scheme 1. Second-generation $C_5H_9NO_6$ can be formed via $C_5H_8NO_7$•, which can also be formed by the reaction of NO_3 and O_2 with $C_5H_8O_2$ as mentioned above (Scheme S2b), or by the reaction of OH with $C_5H_7NO_4$ (Scheme S2a). The time profiles of $C_5H_8NO_{7/8}$• did show~~ed~~ more contribution of second-generation processes because it continuously increased with time in general. If the pathways via the reaction of NO_3 and O_2 with $C_5H_8O_2$ and the reaction of OH with $C_5H_7NO_4$ contribute most to $C_5H_9NO_6$, $C_5H_9NO_6$ would show mostly a time profile of second-generation products. Similarly, second-generation $C_5H_9NO_7$ can be formed via $C_5H_8NO_7$• or $C_5H_8NO_8$•. The time series of ~~$C_5H_8NO_7$~~$C_5H_8NO_8$• did show the contribution of both the first- and second-generation processes, which generally increased with time while also responding to isoprene addition (Fig. ~~S4~~S5). ~~The time profiles of $C_5H_8NO_8$• showed more contribution of second-generation processes because it continuously increased with time in general. If the pathways via the reaction of NO_3 and O_2 with $C_5H_8O_2$ and the reaction of OH with $C_5H_7NO_4$ contribute most to $C_5H_9NO_6$, $C_5H_9NO_6$ would show mostly a time profile of second-generation products.~~ Similar to $C_5H_9NO_6$, the second-generation pathway for $C_5H_9NO_7$, $C_5H_9NO_9$, and $C_5H_9NO_{10}$ are shown in Scheme S1, S3, S4. For the ~~-~~ RO_2 in $C_5H_8NO_n$• series other than $C_5H_8NO_{7/8}$•, the peak of $C_5H_8NO_n$• overlaps with $C_5H_{10}N_2O_n$ in the mass spectra, which is a much larger peak, and thus cannot be differentiated from $C_5H_{10}N_2O_n$. Therefore, it is not possible to obtain reliable separate time profiles in order to differentiate their major sources. It is worth noting that nitrate CIMS may not be able to ~~sensitively~~ detect all isomers of $C_5H_9NO_6$ due to the sensitivity limitation. Therefore, we cannot exclude the possibility that the absence of some first-generation isomers of $C_5H_9NO_6$ was due to the low sensitivity of these isomers. ~~Similar to $C_5H_9NO_6$, the second-generation pathway for $C_5H_9NO_7$, $C_5H_9NO_9$, and $C_5H_9NO_{10}$ are shown in Scheme S1, S3, S4.~~

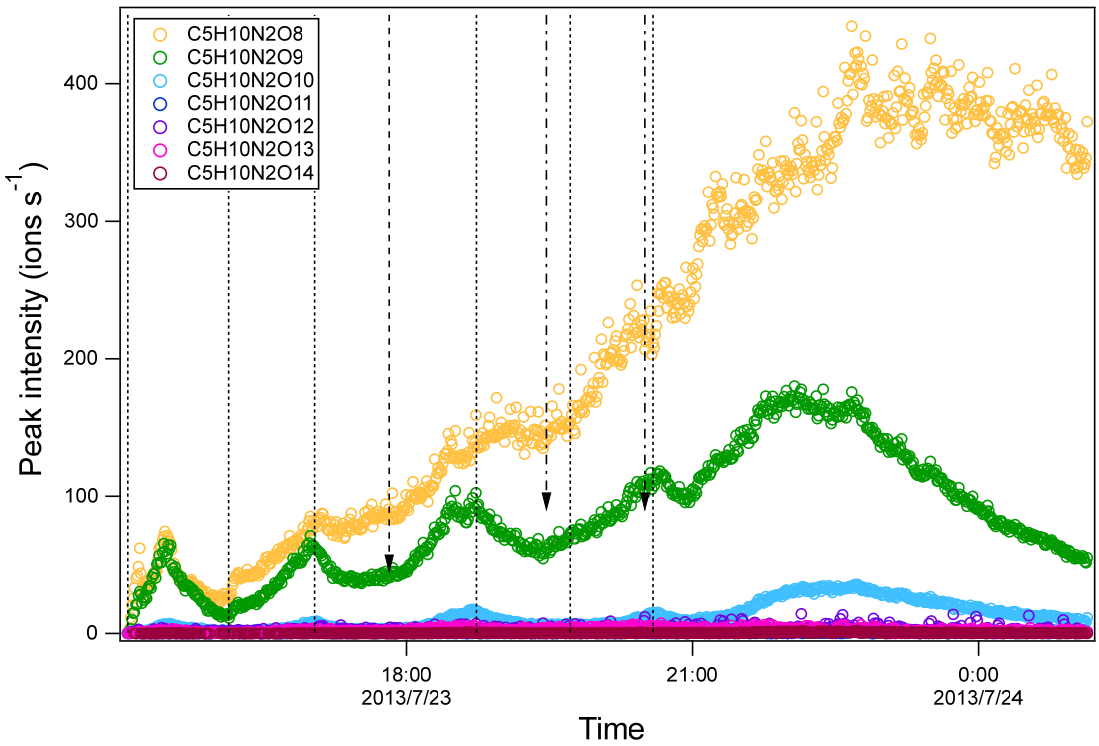

C5H9NO6
C5H9NO7
C5H9NO8
C5H9NO9
C5H9NO10
Peak intensity (ions s-1)
40
30
20
10
0
18:00
2013/7/23
21:00
0:00
2013/7/24
Time

337

338 (a)



339



340

341 (b)

342 Figure 3. Time series of peak intensity of several HOM monomers of $C_5H_9NO_n$ series (a) and of $C_5H_{10}N_2O_n$
343 series (b). They are likely the termination products of RO_2 $C_5H_8NO_n$• and $C_5H_9N_2O_n$•, respectively. The dashed lines
344 indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted
345 arrows indicate the time of O_3 additions.

Among the termination products of the 1N-monomer RO_2, carbonyl and hydroxyl/hydroperoxide species had comparable abundance in general (Table S1), suggesting that disproportionation reactions between RO_2 and RO_2 forming hydroxy and carbonyl species (R1-2) was likely an important RO_2 termination pathway. However, dependence of the exact ratio of carbonyl species to hydroxyl/hydroperoxide species on the number of oxygen atoms did not show a clear trend (Table S1), suggesting that the reactions of HOM RO_2 depended on their specific structure. There was no clear difference in the abundance between the termination products from $C_5H_8NO_n$• with odd and even number of oxygen atom in general, although the most abundant termination product of $C_5H_8NO_n$• , i.e. $C_5H_7NO_8$, was likely formed from $C_5H_8NO_9$• in series M1a. This fact indicates that both the peroxy pathway and alkoxy-peroxy pathway were important for the HOM formation in the isoprene+NO_3 reaction under our conditions, in agreement with the significant formation of alkoxy radicals from the reaction of RO_2 with NO_3 and RO_2.

In addition to the termination products of RO_2 M1, minor peaks of the RO_2 series $C_5H_{10}NO_n$• (n=8-9) (M4, Table 1) and their corresponding termination products including hydroperoxide, alcohol and carbonyl species were detected (Table S3). $C_5H_{10}NO_n$ were likely formed by sequential addition of NO_3 and OH to two double bonds of isoprene (Scheme S5). OH can react fast with isoprene or with the first-generation products of the reaction of isoprene with NO_3, thus forming $C_5H_{10}NO_n$•. In addition, a few very minor but noticeable peaks of $C_5H_9O_n$• and their corresponding termination products $C_5H_{10}O_n$ and $C_5H_8O_n$ were also observed. These HOM may be formed by the reactions of isoprene with trace amount of OH and with O_3, although their contributions to reacted isoprene were negligible. These HOM were also observed in the reaction of isoprene with O_3 with and without OH scavengers (Jokinen et al., 2015).

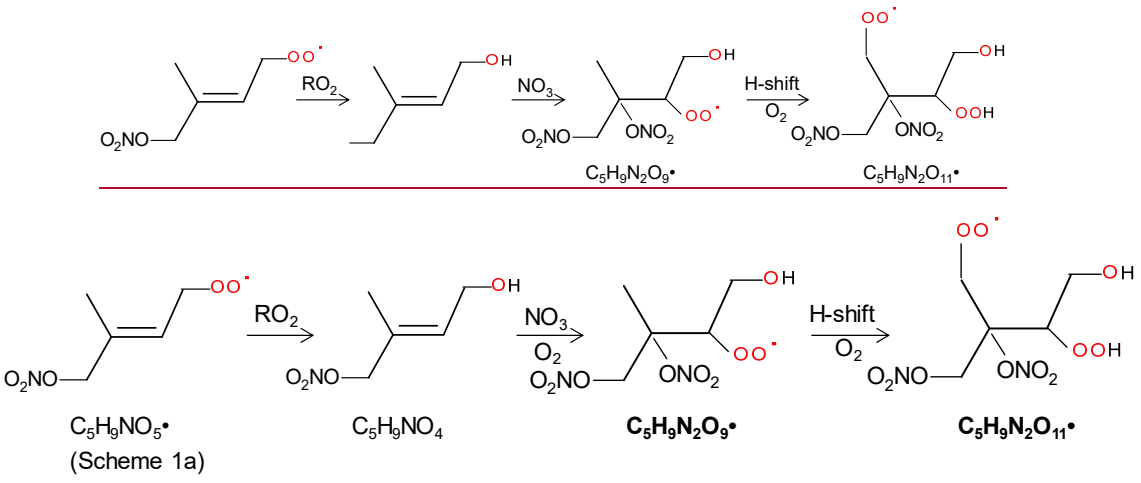
Among 1N-monomer HOM, $C_5H_9NO_7$ has been observed in the particle phase using ESI-TOFMS by Ng et al. (2008) while others have not been observed in previous laboratory studies of the reaction of isoprene with NO_3, to our knowledge. A number of C_5 organic nitrates have been observed in field studies. For example, $C_5H_{7\text{-}11}NO_{4\text{-}9}$ have been observed in aerosol particles during the Southern Oxidant and Aerosol Study in rural Alabama, US, where isoprene is abundant (Lee et al., 2016). Those compounds were also observed in chamber experiments of the reaction of isoprene with OH in the presence of NO_x (Lee et al., 2016). $C_5H_xNO_{4\text{-}9}$ and $C_5H_xNO_{4\text{-}10}$ have been observed in the gas phase and particle, respectively, in a rural area in southwest Germany (Huang et al., 2019).

3.2.3 2N-mononmers

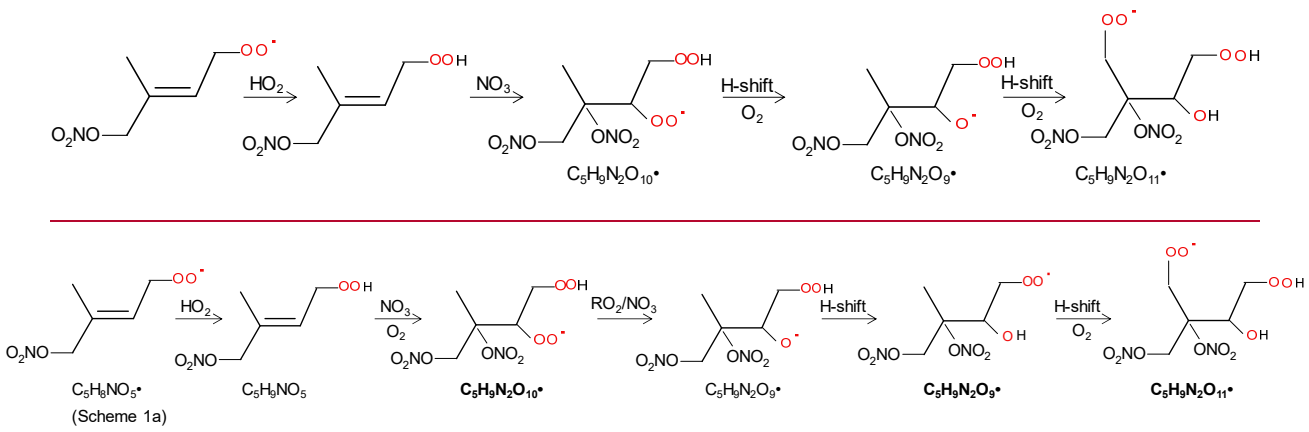
The 2N-monomer RO_2 series $C_5H_9N_2O_n$•(n=98-14) series, were observed, as well as its likely termination products, $C_5H_8N_2O_n$ and $C_5H_{10}N_2O_n$, which contain a carbonyl and hydroxyl or hydroperoxide functional group, respectively. The RO_2 series $C_5H_9N_2O_n$• with oddeven number of oxygen atoms (n=9, 11) (M2a in Table 1) were likely formed from the first-generation product $C_5H_9NO_4$ (C5-hydroxynitrate) by adding NO_3 to the remaining double bond, forming $C_5H_9N_2O_9$•, followed by autoxidation (Scheme 2a). This RO_2 series can also be formed by the addition of NO_3 to the double bond of first-generation products (e.g. $C_5H_9NO_5$, C5-nitrooxyhydroperoxide) and a subsequent alkoxy-peroxy step (Scheme 2b). $C_5H_9N_2O_n$• with even number of

oxygen atoms (n=8, 10, 12) (M2b in Table 1), can be formed by the addition of NO_3 to the double bond of $C_5H_9NO_5$ followed by autoxidation (Scheme. 3a), or of $C_5H_9NO_4$ followed by an alkoxy-peroxy step (Scheme. 3b). The formation pathways of $C_5H_9N_2O_{13/14}$• and $C_5H_9N_2O_8$• cannot be well explained, as they contain too many or too few oxygen atoms to be formed via the pathways in Scheme 2 or 3. In Scheme 2 and 3, we show the reactions starting from 1-NO_3-isoprene-4-OO as an example. In the supplement, we have also shown the pathways starting from 1-NO_3-isoprene-2-OO peroxy radicals, which is indicated in a recent study by Vereecken et al. (2021) to be the dominant RO_2 in the reaction of isoprene with NO_3. ~~The formation pathways of $C_5H_9N_2O_{13/14}$• cannot be well explained, as they contain too many oxygen atoms to be formed via the pathways in Scheme 2 or 3.~~

Formation through either Scheme 2 or 3 means that $C_5H_8N_2O_n$ and $C_5H_{10}N_2O_n$ were second-generation products. The time series of $C_5H_{10}N_2O_n$ species clearly indicates that they were indeed second-generation products. $C_5H_{10}N_2O_n$ species generally did not increase immediately with isoprene addition (Fig. 3b), but increased gradually with time and reached its maximum in the later stage of each period before decreasing with time (in the period 1 and 6), or decreasing after the next isoprene addition (periods 2-5). This time profile can be explained by the time series of the precursor of $C_5H_{10}N_2O_n$, $C_5H_9N_2O_n$• (RO_2) (Fig. ~~S5~~S6). The changing rate (production rate minus destruction rate) of $C_5H_{10}N_2O_n$ concentration was dictated by the concentration of $C_5H_9N_2O_n$• and the wall loss rate. During periods 2 to 5, $C_5H_9N_2O_n$• gradually increased but decreased sharply after the isoprene additions, resulted from chemical reactions of $C_5H_9N_2O_n$• and additionally from wall loss. When the rate of change of the $C_5H_{10}N_2O_n$ concentration was positive, the concentration of $C_5H_{10}N_2O_n$ increased with time. After isoprene additions, the rate of change of the $C_5H_{10}N_2O_n$ concentration decreased dramatically to even negative, leading to decreasing concentrations. Similar to $C_5H_{10}N_2O_n$, the $C_5H_8N_2O_n$ series did not respond immediately to isoprene additions (Fig. ~~S6~~S7), which is expected for second-generation products according to the mechanism discussed above (Scheme 2-3). Particularly, the continuing increase of $C_5H_8N_2O_n$ even after isoprene was completely depleted (~~–~~at ~21:40, Fig. S7~~6~~) clearly indicates that these compounds were second-generation products, although in the end they decreased due to wall loss.

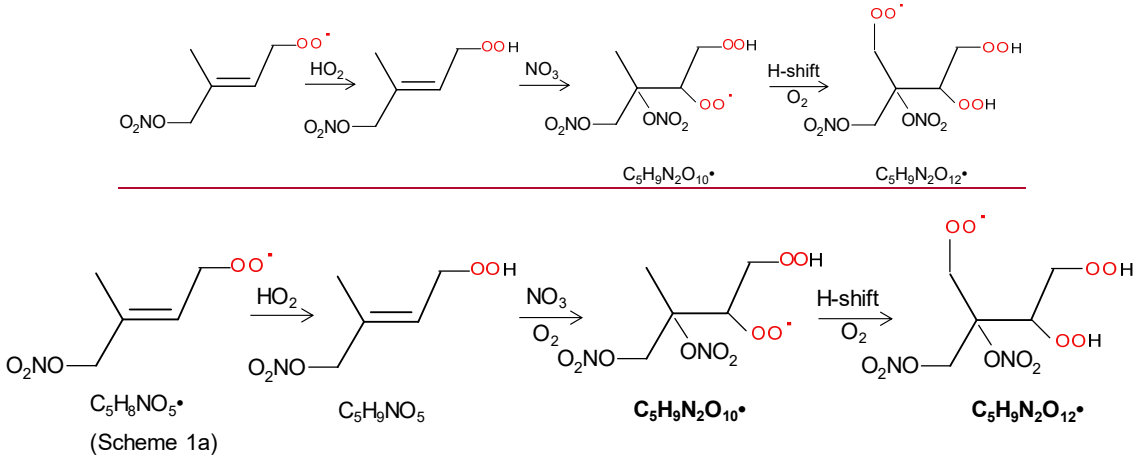


(a)

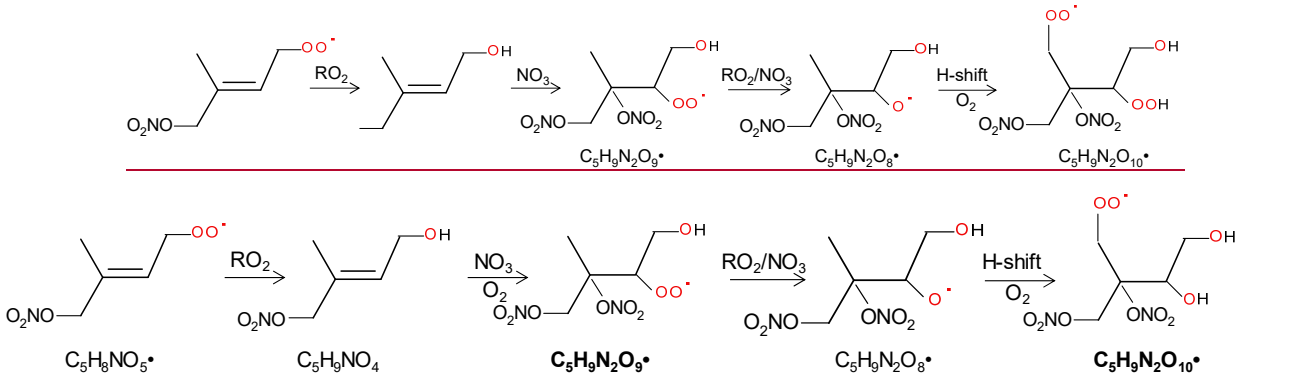


(b)

Scheme 2. The example pathways to form $C_5H_9N_2O_n$ (n=9, 11) HOM RO_2 series by RO_2 channel (a) and alkoxy-peroxy channel. The detected products are in bold.



(a)



(b)

Scheme 3. The example pathways to form $C_5H_9N_2O_n$ (n=~~8,~~10, 12) HOM RO_2 series by RO_2 channel (a) and alkoxy-peroxy channel (b). The detected products are in bold.

According to the finding of Ng et al. (2008), C5-hydroxynitrate decays much faster than C5-nitrooxyhydroperoxides. Additionally, C5-hydroxynitrate concentration is expected to be higher than that of nitrooxyhydroperoxides because RO_2+RO_2 forming alcohol is likely more important than RO_2+HO_2 forming

hydroperoxide in this study. Therefore, it is likely that $C_5H_9N_2O_n$• M2a series was mainly formed from $C_5H_9NO_4$ instead of $C_5H_9NO_5$, while $C_5H_9N_2O_n$• M2b were formed from $C_5H_9NO_4$ followed by an alkoxy-peroxy step. That is, Scheme 2a and 3b~~Scheme 2~~ ~~was~~ appear more likely.

Similar to $C_5H_8NO_n$•, the intensity of carbonyl species from $C_5H_9N_2O_n$• was also comparable with that of hydroxyl/hydroperoxide species, suggesting that RO_2+RO_2 reaction forming ketone and alcohol was likely an important pathway of HOM formation in the isoprene+NO_3 reaction. In general, the intensity of the termination products from $C_5H_9N_2O_n$• with both even and odd oxygen numbers were comparable. This again suggests that both peroxy and alkoxy-peroxy pathways were important for HOM formation in the isoprene+NO_3 reaction. The intensity of ~~$C_5H_{10}N_2O_n$ and~~ $C_5H_8N_2O_n$ first increased and then decreased with oxygen number while $C_5H_{10}N_2O_n$ decreased with oxygen number, with ~~the~~ $C_5H_{10}N_2O_8$ and $C_5H_8N_2O_8$ being the most abundant within their respective series.

Some 2N-monomers have been detected in previous studies of the reaction of isoprene with NO_3. $C_5H_{10}N_2O_8$ has been detected in the particle phase by Ng et al. (2008) and $C_5H_8N_2O_7$ was detected in the gas phase by Kwan et al. (2012). $C_5H_9N_2O_9$• has been proposed to be formed via the pathway as in Scheme 2a (Ng et al., 2008), and it was directly detected in our study. $C_5H_8N_2O_7$ species has been proposed to be a dinitrooxy epoxide formed by the oxidation of nitrooxyhydroperoxide (Kwan et al., 2012), instead of being a dinitrooxy ketone proposed in our study, a termination product of $C_5H_9N_2O_8$•. Admittedly, $C_5H_8N_2O_7$ may contain both isomers. In addition, Ng et al. (2008) detected $C_5H_8N_2O_6$ in the gas phase, which was not detected in this study likely due to the selectivity of NO_3^--CIMS. ~~(Xu et al., 2021)~~

One could suppose that $C_5H_7N_2O_n$• should also be formed since C5-nitrooxycarbonyl ($C_5H_7NO_4$) also contains one double bond that can be attacked by NO_3 in a second oxidation step. However, concentrations of $C_5H_7N_2O_n$ were too low to assign molecular formulas with confidence except for $C_5H_7N_2O_9$•, clearly showing that $C_5H_7N_2O_n$• was not important. This fact is consistent with the finding of Ng et al. (2008) that C5-nitrooxycarbonyls react slowly with NO_3. Additionally, the peroxy radical formed in the reaction of C5-nitrooxycarbonyls with NO_3 likely leads to more fragmentation in H-shift as found in the OH oxidation of methacrolein (Crounse et al., 2012), which may also contribute to the low abundance of $C_5H_7N_2O_n$. T~~In addition,~~ ~~t~~he presence of HOM containing two N atoms is in line with the finding by Faxon et al. (2018) who detected products containing two N atoms in the reaction of NO_3 with limonene, which also contain two carbon double bonds. It is anticipated that for VOC~~s~~ with more than one double bond, NO_3 can add to all the double bonds as for isoprene and limonene.

3.2.4 3N-monomers

HOM containing three nitrogen atoms, $C_5H_9N_3O_n$ (n=9-16), were observed. These compounds were possibly peroxynitrates formed by the reaction of RO_2 ($C_5H_9N_2O_n$•) with NO_2. The time series of $C_5H_9N_3O_n$ was examined to check whether they match such a mechanism. If $C_5H_9N_3O_n$ were formed by the reaction of $C_5H_9N_2O_{n-2}$• with NO_2, the concentration would be a function of the concentrations of $C_5H_9N_2O_{n-2}$• and NO_2 as follows:

$$\frac{d[C_5H_9N_3O_n]}{dt} = k[C_5H_9N_2O_{n-2}\bullet][NO_2] - k_{wall}[C_5H_9N_3O_n]$$

where $[C_5H_9N_3O_n]$, $[C_5H_9N_2O_{n-2}\bullet]$, and $[NO_2]$ are the concentration of these species, k is the rate constant and k_{wall} is the wall loss rate. Because the products of $C_5H_9N_2O_{n-2}\bullet$ and NO_2 were at their maximum at the end of each period and decreased rapidly after isoprene addition (Fig. ~~S7~~S8), the concentration should have ~~the~~ its maximum increasing rate at the end of each isoprene addition period. However, we found that only $C_5H_9N_3O_{12,\ 15,\ 16}$ showed such a time profile (Fig. ~~S8~~S9), while $C_5H_9N_3O_{9,\ 10,\ 11,\ 13,\ 14}$ generally increased with time, different from what one would expect based on the proposed pathway. Therefore, it is likely that $C_5H_9N_3O_{12,\ 15,\ 16}$ were mainly formed via the reaction of $C_5H_9N_2O_n\bullet$ with NO_2, whereas $C_5H_9N_3O_{9,10,11,13,14}$ were not. Moreover, $C_5H_9N_3O_9$ cannot be explained by the reaction $C_5H_9N_2O_n\bullet$ ($n\geq9$) with NO_2 or NO_3, because these reactions would add at least one more oxygen atom. One possible pathway to form $C_5H_9N_3O_9$ was the direct addition of N_2O_5 to the carbon double bond of C5-hydroxynitrate, forming a nitronitrate. Such a~~n~~ mechanism has been proposed previously in the heterogeneous reaction of N_2O_5 with 1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine (POPC) because $-NO_2$ and $-NO_3$ groups were detected (Lai and Finlayson-Pitts, 1991). This pathway generally matched the time series of $C_5H_9N_3O_{9,10,11,13,14}$ typical of second-generation products since C5-hydroxynitrate was a first-generation product. It is possible that the main pathway of $C_5H_9N_3O_{9,10,11,13,14}$ was the reaction of $C_5H_9NO_{4,5,6}$ with N_2O_5, although the reaction of N_2O_5 with C=C double bonds in common alkenes and unsaturated alcohols are believed to be not important (Japar and Niki, 1975; Pfrang et al., 2006).

3N-monomers, $C_5H_9N_3O_{10}$, has been observed in the particles formed in the isoprene+NO_3 reaction by Ng et al. (2008). Here a complete series of $C_5H_9N_3O_n$ were observed. $C_5H_9N_3O_{10}$ was previously proposed to be formed by another pathway, i.e. the reaction of RO_2 ($C_5H_9N_2O_9\bullet$) and NO_3 (Ng et al., 2008). We further examined the possibility of such a pathway in our study. Similar to NO_2, if $C_5H_9N_3O_n$ were formed by the reaction of $C_5H_9N_2O_{n-2}\bullet$ with NO_3, the concentration would have ~~the~~ its maximum increasing rate at the end of each isoprene addition period. Among $C_5H_9N_2O_n\bullet$, the precursors of $C_5H_9N_3O_n$, $C_5H_9N_2O_{9,\ 10,\ 13,\ 14}\bullet$ showed a maximum increasing rate and a subsequent decrease after isoprene addition. The difference in oxygen number between $C_5H_9N_3O_{12,\ 15,\ 16}$, the termination products, and $C_5H_9N_2O_{9,\ 10,\ 13,\ 14}\bullet$, the corresponding RO_2 with the consistent time profile is mostly two. Since the reaction of $C_5H_9N_2O_n$ with NO_2 and NO_3 result an increased oxygen number by two and by one, respectively, we infer that it is more likely that $C_5H_9N_3O_{12,\ 15,\ 16}$ were formed by the reaction of $C_5H_9N_2O_{10,\ 13,\ 14}\bullet$ with NO_2 rather than NO_3, and thus they were likely peroxynitrates rather than nitrates formed by the reaction of RO_2 with NO_3. Since alkyl peroxynitrates decompose rapidly (Finlayson-Pitts and Pitts, 2000; Ziemann and Atkinson, 2012), it is possible that these compounds contained peroxyacylnitrates.

Little attention has been paid to the RO_2+NO_2 pathway in nighttime chemistry of isoprene in the literature (Wennberg et al., 2018), which is likely due to the instability of the products. According to this pathway, $C_5H_8N_2O_n$, which was proposed to be a ketone formed via $C_5H_9N_2O_9\bullet$ in the M2 series (Table 1) as discussed above, can also comprise peroxynitrate formed by the reaction of $C_5H_8NO_n\bullet$ (M1a RO_2) with NO_2.

3N dimer such as $C_5H_9N_3O_{10}$ as well as 2N-monomers such as $C_5H_8N_2O_8$ and $C_5H_8N_2O_{10}$ have been observed in a recent field study in polluted cities in east China (Xu et al., 2021).

3.3 HOM dimers and their formation

Table 2. HOM dimers and trimers formed in the oxidation of isoprene by NO_3.

Series Number	Formula	Type	Pathway of RO_2
Dimer 1	$C_{10}H_{16}N_2O_n$ (n=10-17)	ROOR[a]	M1[b] +M1
Dimer 2	$C_{10}H_{17}N_3O_n$ (n=11-19)	ROOR	M1+M2/M3+M4
Dimer 3	$C_{10}H_{18}N_4O_n$ (n=15-18)	ROOR	M2+M2
Dimer 4	$C_{10}H_{18}N_2O_n$ (n=10-16)	ROOR	M1+M4
Dimer 5	$C_{10}H_{15}N_3O_n$ (n=13-17)	ROOR	M1+M3
Dimer 6	$C_{10}H_{19}N_3O_n$ (n=14-15)	ROOR	M2+M4
Dimer 7	$C_{10}H_{14}N_2O_n$ (n=~~11~~10-~~12~~16)	ROOR	Unknown
Dimer 8	$C_{10}H_{15}NO_n$ (n=9-12)	ROOR	$C_{10}H_{16}NO_n$
Dimer 9	$C_{10}H_{17}NO_n$ (n=~~11~~9-15~~9~~)	ROOR	$C_{10}H_{16}NO_n$
Dimer R1	$C_{10}H_{16}N_3O_n$ (n=12-15)	RO_2	Dimer 1+NO_3
Dimer R2	$C_{10}H_{17}N_2O_n$ (n=11-12)	RO_2	Dimer 1+OH
Dimer R3	$C_{10}H_{17}N_4O_n$ (n=16-18)	RO_2	Dimer 2+NO_3
Dimer R4	$C_{10}H_{16}NO_n$ (n=10-~~16~~14)	RO_2	M1+C_5H_8
Trimer 1	$C_{15}H_{24}N_4O_n$ (n=17-~~23~~22)	ROOR	Dimer R1+M1
Trimer 2	$C_{15}H_{25}N_5O_n$ (n=20-22)	ROOR	Dimer R3+M1; Dimer R1+M2
Trimer 3	$C_{15}H_{25}N_3O_n$ (n=~~12~~13-20)	ROOR	Dimer R2+M1; Dimer R4+M2
Trimer 4	$C_{15}H_{26}N_4O_n$ (n=17-21)	ROOR	Dimer R2+M2

[a]: ROOR denotes for organic peroxide.

[b]: The numbering is referred to Table 1.

A number of HOM dimer series were observed, including $C_{10}H_{16}N_2O_n$ (n=10-17), $C_{10}H_{17}N_3O_n$ (n=11-19), and $C_{10}H_{18}N_4O_n$ (n=15-18), $C_{10}H_{18}N_2O_n$ (n=10-16), $C_{10}H_{15}N_3O_n$ (n=~~14~~13-17), and $C_{10}H_{19}N_3O_n$ (n=14-15) series (Table 2, Table S3). $C_{10}H_{16}N_2O_n$ series (dimer 1, Table 2) was likely formed by the accretion reaction of two monomer RO_2 of M1a/b (Reaction R7).

$$C_5H_8NO_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{10}H_{16}N_2O_{n1+n2-2}+O_2 \quad \text{R7}$$

Similarly, $C_{10}H_{18}N_4O_n$ series (dimer 2, Table 2) were likely formed by the accretion reaction of two monomer RO_2 of M2 (Reaction R8). As n1 and n2 are ≥ 9, the number of oxygen in $C_{10}H_{18}N_4O_n$ is expected to be ≥16. This is consistent with our observation that only $C_{10}H_{18}N_4O_n$ with n≥16 had significant concentrations.

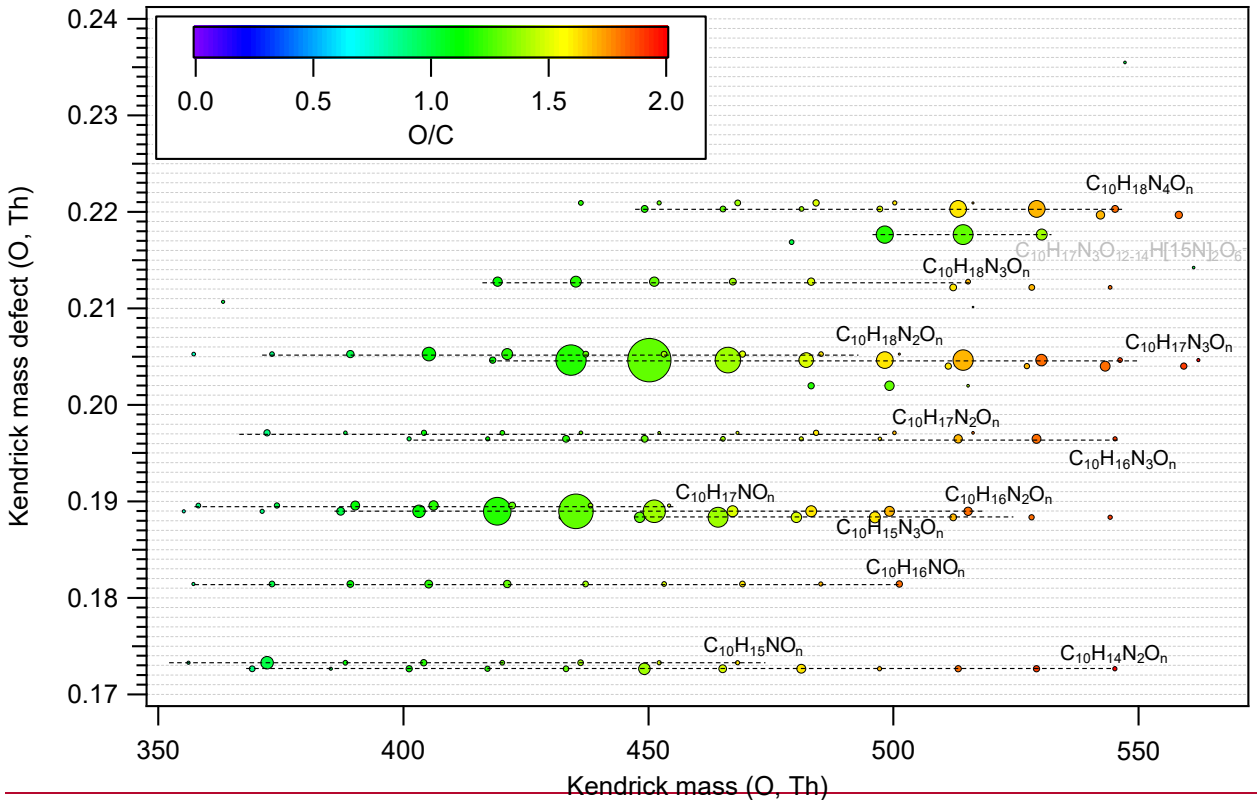
$$C_5H_9N_2O_{n1}\bullet + C_5H_9N_2O_{n2}\bullet \rightarrow C_{10}H_{18}N_4O_{n1+n2-2}+O_2 \quad \text{R8}$$

$C_{10}H_{17}N_3O_n$ series (dimer 3, Table 2) were likely formed by the cross accretion reaction of one M1 RO_2 and one M2 RO_2 (reaction R9). Since n1 is ≥5 and n2 is ≥9, the number of oxygen atoms in $C_{10}H_{17}N_3O_n$ is expected to be ≥12, which is also roughly consistent with our observation that only $C_{10}H_{17}N_3O_n$ with n≥11 were detected.

$$C_5H_8NO_{n1}\bullet + C_5H_9N_2O_{n2}\bullet \rightarrow C_{10}H_{17}N_3O_{n1+n2-2} + O_2 \quad \text{R9}$$

Similarly, $C_{10}H_{18}N_2O_{n\ (n=10\text{-}16)}$ and $C_{10}H_{15}N_3O_{n\ (n=14\underline{13}\text{-}17)}$ series (dimer 4, dimer 5, Table 2) were likely formed from the accretion reaction ~~of~~ between one M1 RO_2 and one M4 RO_2, and ~~of~~ between one M1 RO_2 and one M3 RO_2 ($C_5H_7N_2O_9\bullet$). Other dimer series than dimer 1-5 were also present. However, they had quite low intensity (Fig. 4), which was consistent with the low abundance of their parent monomer RO_2. They can be formed from various accretion reactions of monomer RO_2. For example, $C_{10}H_{19}N_3O_n$ can be formed by the accretion reaction of $C_5H_9N_2O_n\bullet$ and $C_5H_{10}NO_n\bullet$ (Table 2).

Similar to monomers, a few species dominated in HOM dimers spectrum. The dominant dimer series were $C_{10}H_{17}N_3O_x$ and $C_{10}H_{16}N_2O_x$ series, with $C_{10}H_{17}N_3O_{12\text{-}14}$ and $C_{10}H_{16}N_2O_{12\text{-}14}$ showing highest intensity among each series (Fig. 4). In addition, the O/C ratio or oxidation state of HOM dimers were generally lower than that of monomers (Fig. 2, Fig. 4), which resulted from the loss of two oxygen atoms in the accretion reaction of two monomer RO_2.



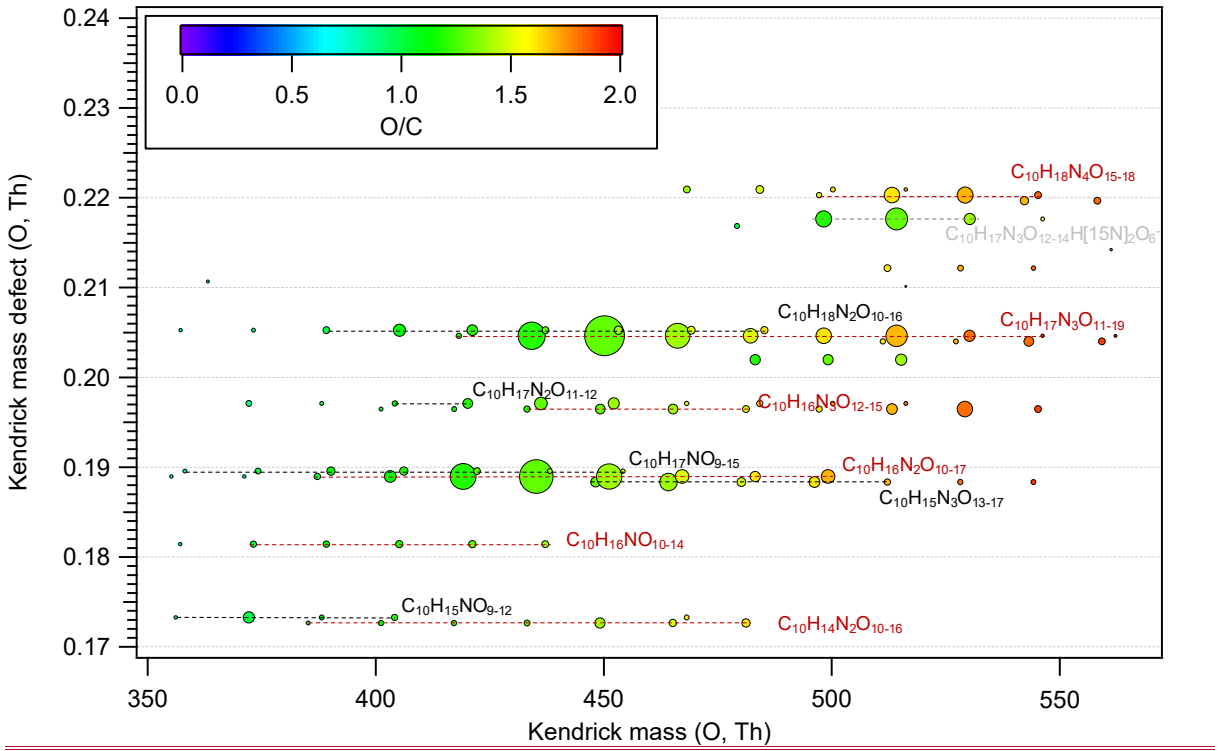


Figure 4. Kendrick mass defect plot for O of HOM dimers formed in ~~isoprene+NO$_3$~~the isoprene+NO_3 reaction. The size (area) of circles is set to be proportional to the average peak intensity of each molecular formula during the first isoprene addition period (P1). The molecular formula include the reagent ion $^{15}NO_3^-$, which is not shown for simplicity. The species labelled in grey ($C_{10}H_{17}N_3O_{12-14}$ $H[15N]_2O_6^-$) are the adducts of $C_{10}H_{17}N_3O_{12-14}$ with $H[15N]_2O_6^-$.

According to the mechanism above (R7-9), we attempt to explain the relative intensities of the dimers using the signal intensities of monomer RO_2. Assuming that the rate constant for each of HOM-RO_2+ HOM-RO_2 reaction forming dimers is the same considering that all HOM-RO_2 are highly oxygenated with a number of functional groups, it is expected that the dimer formed by the recombination between the most abundant RO_2 has the highest intensity. The most abundant monomer RO_2 were $C_5H_9N_2O_9$• and $C_5H_9N_2O_{10}$• and thus the most abundant dimers are expected to be $C_{10}H_{16}N_4O_{16}$, $C_{10}H_{16}N_4O_{17}$, and $C_{10}H_{16}N_4O_{18}$. This expected result is in contrast with our observation showing that the most abundant dimers were $C_{10}H_{17}N_3O_{12\text{-}14}$ and $C_{10}H_{16}N_2O_{12\text{-}14}$ (Fig. 4). The discrepancy is possibly attributed to the presence of less oxygenated RO_2 (with O≤5) that have a low detection sensitivity in the NO_3-CIMS (Riva et al., 2019) due to their lower oxygenation compared with other HOM RO_2 shown above. These RO_2 may react with $C_5H_9N_2O_9$• and $C_5H_9N_2O_{10}$•. For example, $C_5H_8NO_5$• (RO_2) is proposed to be an important first-generation RO_2 in the oxidation of isoprene by NO_3 (Ng et al., 2008; Rollins et al., 2009; Kwan et al., 2012; Schwantes et al., 2015). Although $C_5H_8NO_5$• showed very low signal in our mass spectra, it was likely to have high abundance since it was the first RO_2 formed in the reaction of isoprene with NO_3. Indeed, we found that the termination products of $C_5H_8NO_5$• such as $C_5H_9NO_5$, $C_5H_7NO_4$, and $C_5H_9NO_4$ had high abundance in another study Wu et al. (2020), indicating the high abundance of $C_5H_8NO_5$•. The accretion reaction of $C_5H_8NO_5$• with $C_5H_{98}N_2O_{9\text{-}10}$• and $C_5H_8NO_{9\text{-}10}$• can explain the high abundance of $C_{10}H_{17}N_3O_{12\text{-}14}$ and $C_{10}H_{16}N_2O_{12\text{-}14}$ among all dimers.

Provided that $C_5H_8NO_5$• is abundant, we still cannot explain the relative intensity of $C_{10}H_{17}N_3O_{12}$, $C_{10}H_{17}N_3O_{13}$, and $C_{10}H_{17}N_3O_{14}$ that were all formed by the accretion reaction with $C_5H_8NO_5$•. $C_{10}H_{17}N_3O_{12}$ should have the highest intensity among $C_{10}H_{17}N_3O_{12\text{-}14}$ as its precursor RO_2, $C_5H_9N_2O_9$•, is the most abundant. This suggests that accretion reactions other than those of $C_5H_8NO_5$• with $C_5H_{98}N_2O_{9\text{-}10}$• also contributed to $C_{10}H_{17}N_3O_{12\text{-}14}$. Admittedly, the assumption of different RO_2 having similar rate constants in accretion reactions may not be valid. For example, self-reaction of tertiary RO_2 is slower than secondary and primary RO_2 (Jenkin et al., 1998; Finlayson-Pitts and Pitts, 2000). Different rate constants may also lead to the observation that the most abundant dimers could not be explained the most abundant RO_2.

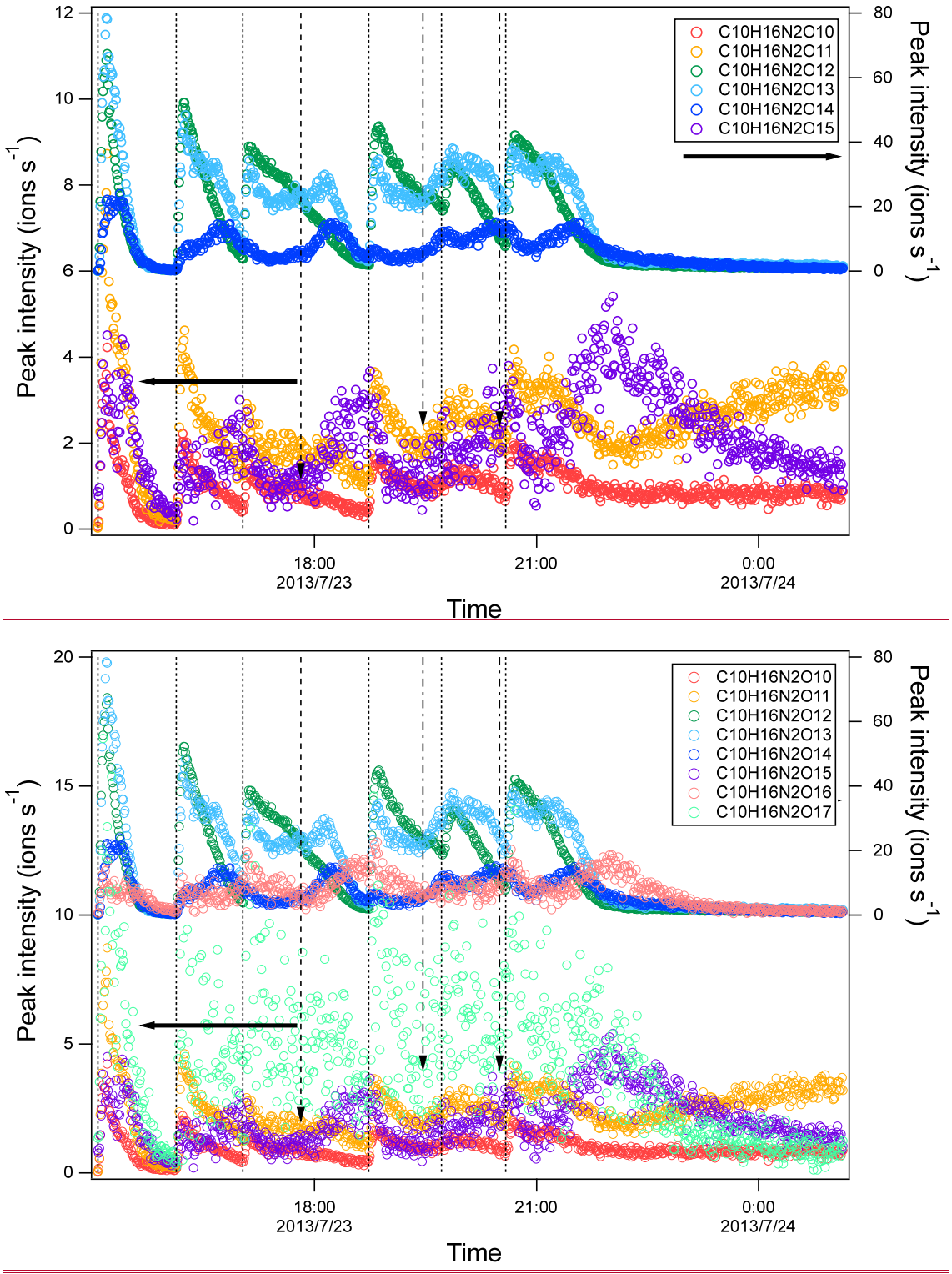


Figure 5. Time series of peak intensity of several HOM dimers of $C_{10}H_{16}N_2O_n$ series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions. The horizontal arrows indicate y-axis scales for different markers.

The time profiles of $C_{10}H_{16}N_2O_n$ indicate contributions of both the first- and second-generation products. The dominance of the first- or second-generation products depended on the specific compounds. Most $C_{10}H_{16}N_2O_n$ compounds increased instantaneously after isoprene additions, indicating significant contributions of first-generation

products. Since the formation of $C_{10}H_{16}N_2O_n$ likely involved $C_5H_8NO_5$• as discussed above, the instantaneous increase may result from the increase of $C_5H_8NO_5$• as well as other first-generation RO_2. After the initial increase, $C_{10}H_{16}N_2O_{10\text{-}12}$ then decayed with time (Fig. 5) while $C_{10}H_{16}N_2O_{13\text{-}15}$ increased again in the later phase of a period ~~besides~~ and when NO_2 and O_3 were added. The second increase indicated that $C_{10}H_{16}N_2O_{13\text{-}15}$ may contain more than one isomer~~s~~, which had different production pathways. As discussed above, $C_5H_8NO_n$• can be either a first-generation RO_2 formed directly via the reaction of isoprene with NO_3 and autoxidation, or a second-generation RO_2, e.g. formed via the reaction of with $C_5H_8O_2$ with NO_3. Therefore the second increase of $C_{10}H_{16}N_2O_{13\text{-}15}$ may result from the reaction of two first-generation RO_2 and of two second-generation RO_2 or between one first-generation and one second-generation RO_2. The increase of $C_{10}H_{16}N_2O_{14\text{-}15}$ after isoprene addition was not ~~obvious~~large, indicating the larger contributions from second-generation products compared with other $C_{10}H_{16}N_2O_n$. Overall, as the number of oxygen increased, the contribution of second-generation products to $C_{10}H_{16}N_2O_n$ increased.

In contrast to $C_{10}H_{16}N_2O_n$ series, $C_{10}H_{18}N_4O_n$ increased gradually after each isoprene addition and then decreased afterward (Fig. 6), either naturally or after isoprene additions, which is typical for second-generation products. Since $C_{10}H_{18}N_4O_n$ was likely formed by the accretion reaction of $C_5H_9N_2O_n$• (RO_2), the time profile of $C_{10}H_{18}N_4O_n$ was as expected since $C_5H_9N_2O_n$• was formed via the reaction of NO_3 with first-generation products $C_5H_9NO_n$. The $C_{10}H_{18}N_4O_n$ concentration depended on the product of the concentrations of two $C_5H_9N_2O_n$•. Taking $C_{10}H_{18}N_4O_{16}$ as an example, its concentration can be expressed as follows:

$$\frac{d[C_{10}H_{18}N_4O_{16}]}{dt} = k[C_5H_9N_2O_9][C_5H_9N_2O_9] - k_{wl}[C_{10}H_{18}N_4O_{16}]$$

When the concentration of $C_5H_9N_2O_9$• increased, the changing rate of $C_{10}H_{18}N_4O_{16}$ was positive and increased and thus the concentration of $C_{10}H_{18}N_4O_{16}$ increased. When the concentration $C_5H_9N_2O_9$• decreased sharply after isoprene additions, the changing rate of $C_{10}H_{18}N_4O_{16}$ decreased and even became negative values, and thus the concentration of $C_{10}H_{18}N_4O_{16}$ decreased after isoprene addition.

Similar to the $C_{10}H_{16}N_2O_n$ series, while $C_{10}H_{17}N_3O_n$ first increased instantaneously with isoprene addition, it increased again during the later stage of each period (Fig. ~~S9~~S10), showing a mixed behavior of the first-generation products and second-generation products. The time series of $C_{10}H_{17}N_3O_n$ was as expected in general because $C_{10}H_{17}N_3O_n$ was likely formed via the accretion reaction of $C_5H_8NO_n$• (M1 RO_2) and $C_5H_9N_2O_n$• (M2 RO_2), which were first- or second-generation, and second-generation RO_2, respectively,

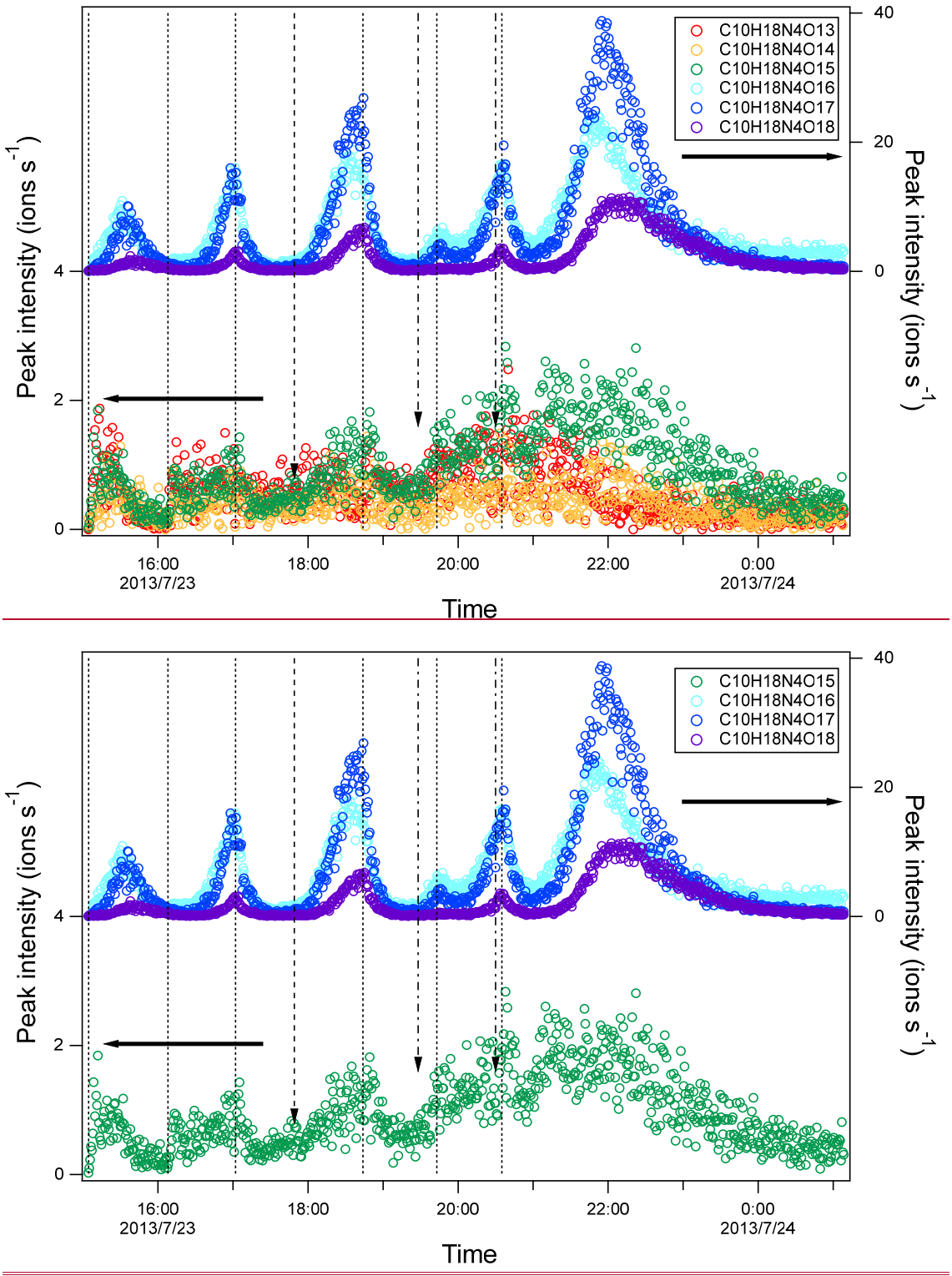


Figure 6. Time series of peak intensity of several HOM dimers of $C_{10}H_{18}N_4O_n$ series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions. The horizontal arrows indicate y-axis scales for different markers.

Some dimers that cannot be explained by accretion reactions such as $C_{10}H_{16}N_3O_n$ (n=12-15)•, $C_{10}H_{17}N_2O_n$ (n=11-12)•, $C_{10}H_{16}NO_n$ (n=10-~~16~~14)•, $C_{10}H_{15}NO_n$ (n=9-12), $C_{10}H_{17}NO_n$ (n=~~11~~9-15~~9~~) were also observed. These dimers had low abundance. We note that due to their low signals in the mass spectra, their assignment and thus range of n may be

subject to uncertainties. Since $C_{10}H_{16}NO_{n\ (n=10-16)}$•, $C_{10}H_{16}N_3O_{n\ (n=12-15)}$•, and $C_{10}H_{17}N_2O_n$• contain unpaired electrons, they cannot be formed via the direct accretion reaction of two RO_2. Instead, $C_{10}H_{16}N_3O_{n\ (n=12-15)}$ • (dimer R1) and $C_{10}H_{17}N_2O_n$• (dimer R2) were likely RO_2 formed by the reaction of HOM dimers containing a double bond (dimer 1) with NO_3 and with OH, respectively, followed by the reaction with O_2.

$$C_{10}H_{16}N_2O_n+NO_3+O_2 \rightarrow C_{10}H_{16}N_3O_n\bullet \quad \text{R10}$$

$$C_{10}H_{16}N_2O_n+OH+O_2 \rightarrow C_{10}H_{17}N_2O_n\bullet \quad \text{R11}$$

The corresponding termination products of $C_{10}H_{16}N_3O_n$• RO_2 series such as $C_{10}H_{15}N_3O_n$ (ketone), $C_{10}H_{17}N_3O_n$ (hydroperoxide/alcohol) were also observed, although these compounds can also be formed via reactions between two RO_2 radicals (R9 and R11). Among the termination products, $C_{10}H_{15}N_3O_n$ had low intensity. Reaction R13 and the termination reaction of $C_{10}H_{17}N_2O_n$• with HO_2 provided an additional pathway to $C_{10}H_{17}N_3O_n$ besides the R9 pathway discussed above. Similarly, other dimers may also be formed by the termination reactions of dimer RO_2 with RO_2 or HO_2. E.g., $C_{10}H_{18}N_4O_n$ can be formed via termination reaction of $C_{10}H_{17}N_4O_n$• with another RO_2 wherein $C_{10}H_{17}N_4O_n$• can be formed as follows:

$$C_{10}H_{17}N_3O_n+NO_3+O_2 \rightarrow C_{10}H_{17}N_4O_n\bullet \quad \text{R12}$$

$C_{10}H_{16}NO_{n\ (n=10-\sout{16}14)}$• could be explained by the reaction of monomer RO_2 with isoprene.

$$C_5H_8NO_n\bullet+C_5H_8+O_2 \rightarrow C_{10}H_{16}NO_n\bullet \quad \text{R13}$$

Only $C_{10}H_{16}NO_n$• with n≥10 were detected, while according to the mechanism of self-reaction between $C_5H_8NO_n$•, the n range of $C_{10}H_{16}NO_n$• is expected to be 7-14. The absence of $C_{10}H_{16}NO_{n(n<10)}$• is likely attributed to their low abundance, which might result from low precursor concentrations, low reaction rates with isoprene, and/or faster reactive losses with other radicals.~~It seems that only $C_5H_8NO_n$• with more than eight oxygen atoms reacted with isoprene, because only $C_{10}H_{16}NO_n$ with n>8 were detected.~~ Such a reaction of RO_2 with isoprene has been proposed by Ng et al. (2008) and Kwan et al. (2012). The corresponding termination products of $C_{10}H_{16}NO_n$• are $C_{10}H_{15}NO_n$ (ketone) and $C_{10}H_{17}NO_n$ species (hydroperoxide/alcohol). $C_{10}H_{17}NO_n$ species showed a time profile of typical first-generation products (Fig. ~~S10~~S11), i.e. increasing immediately with isoprene addition and then decaying with time. This behaviour further supports the possibility of reaction R13. Yet, the reaction rate of alkene with RO_2 is likely low due to the high activation energy (Stark, 1997, 2000). It is worth noting that to our knowledge no experimental kinetic data on the addition of RO_2 to alkenes in the gas phase in atmospheric relevant conditions are available, though fast, low-barrier ring closure reactions in unsaturated RO_2 radicals have been reported (Vereecken and Peeters, 2004, 2012; Kaminski et al., 2017; Richters et al., 2017; Chen et al., 2021). We would like to note that there is unlikely interference to C_{10}-HOM from monoterpenes, which has been reported previously (Bernhammer et al., 2018), as the concentration of monoterpenes in the chamber during this study was below the limit of detection, which was ~50 ppt (3σ).~~(Bernhammer et al., 2018)~~

Some of the dimers discussed above have been observed in previous studies. Ng et al. (2008) found $C_{10}H_{16}N_2O_8$ and $C_{10}H_{16}N_2O_9$ in the gas phase and $C_{10}H_{17}N_3O_{12}$, $C_{10}H_{17}N_3O_{13}$, $C_{10}H_{18}N_4O_{16}$, and $C_{10}H_{17}N_5O_{18}$ in the particle phase. $C_{10}H_{16}N_2O_8$ and $C_{10}H_{16}N_2O_9$ were also observed in our study, but their intensity in the MS was too low to assign molecular formulas with high confidence. The low intensity may be due to the low sensitivity of $C_{10}H_{16}N_2O_{8,\ 9}$ in NO_3^--CIMS. According to modelling results of the products formed in cyclohexene ozonolysis by Hyttinen et al. (2015), at least two hydrogen bond donor functional groups are needed for a compound to be detected

in a nitrate CIMS. As $C_{10}H_{16}N_2O_8$ and $C_{10}H_{16}N_2O_9$ have no and only one H-bond donor function groups, respectively, they are expected to have low sensitivity in NO_3^--CIMS. Moreover, the low intensity can be partly attributed to the much lower isoprene concentrations used in this study compared to previous studies, leading to the low concentration of $C_{10}H_{16}N_2O_8$ and $C_{10}H_{16}N_2O_9$ (Ng et al., 2008). $C_{10}H_{17}N_3O_{12}$, $C_{10}H_{17}N_3O_{13}$, $C_{10}H_{18}N_4O_{16}$, and $C_{10}H_{17}N_5O_{18}$ were all observed in the gas phase in this study, wherein the concentration of $C_{10}H_{17}N_5O_{18}$ was very low. The formation pathways of $C_{10}H_{17}N_3O_{12}$, $C_{10}H_{17}N_3O_{13}$, and $C_{10}H_{18}N_4O_{16}$ (R8) were generally similar to those proposed by Ng et al. (2008) except that the products from H-shift of RO_2 were involved in the formation of $C_{10}H_{17}N_3O_{13}$. Among the two pathways of $C_{10}H_{18}N_4O_{16}$ formation (R8 and via R12), our results indicate that R8 was the main pathway, based on the low concentrations of $C_{10}H_{17}N_4O_{16/17}$• and other termination product of them, $C_{10}H_{16}N_4O_{15/16}$. That the time profile of $C_{10}H_{18}N_4O_{16}$ was consistent with what is expected from R8 as discussed above offers additional evidence to that conclusion.

3.4 HOM trimers and their formation

A series of HOM trimers were observed, such as $C_{15}H_{24}N_4O_n$ (n=17-~~23~~22), $C_{15}H_{25}N_5O_n$ (n=20-22), $C_{15}H_{25}N_3O_n$ (n=~~12~~13-20), $C_{15}H_{26}N_4O_n$ (n=17-21), and $C_{15}H_{24}N_2O_n$ (n=12-16). Among the trimers, $C_{15}H_{24}N_4O_n$ ~~(n=17-23)~~ was the most abundant series (Fig. ~~S11~~S12). The $C_{15}H_{24}N_4O_n$ series can be explained by the accretion reaction of one monomer HOM RO_2 and one dimer HOM RO_2.

$$C_{10}H_{16}N_3O_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{15}H_{24}N_4O_{n1+n2-2} + O_2 \quad \text{R14}$$

The formation pathways of dimer RO_2 $C_{10}H_{16}N_3O_n$ (n=~~14~~12-~~20~~15) and $C_{10}H_{17}N_2O_n$ are shown above (reaction ~~R14~~R10 and R11).

The other trimers were likely formed via similar pathways (Table 2 and Supplement S2). Since NO_3^--CIMS cannot provide the structural information of these HOM trimers, we cannot elucidate the major pathways. However, in all these pathways, dimer-RO_2 is necessary to form a trimer, and most of the dimer-RO_2 formation pathways require at least one double bond in the dimer molecule except for the reaction of RO_2 with isoprene. Since one double bond has already reacted in the monomer-RO_2 formation, we anticipate that in the reaction with NO_3 it is more favourable for precursors (VOC) containing more than one double bonds to form trimer molecules than precursors containing only one double bond, as it is easier to generate new RO_2 radicals from these dimers by attack on the remaining double bond(s).

The time profile of $C_{15}H_{24}N_4O_n$ showed the mixed behavior of first- and second-generation products (Fig. S1~~3~~2), consistent with the mechanism discussed above since $C_5H_8NO_n$• and $C_{10}H_{16}N_3O_n$• were of first- or second-generation and second-generation, respectively. The contributions of the second-generation products became larger as the number of oxygen atoms increased. In contrast, $C_{15}H_{25}N_3O_n$ showed instantaneous increase with isoprene addition (Fig. S1~~4~~3), which was typical for time profiles of first-generation products. Both proposed~~the~~ formation pathways of $C_{15}H_{25}N_3O_n$ (RS6 and RS7) contained a second-generation RO_2, which was not in line with the time profile observed. The observation cannot be well explained, unless we assume molecular adducts of a dimer with one monomer. It is also possible that some $C_{10}H_{17}N_2O_n$• were formed very fast or that there were other formation pathways of $C_{15}H_{25}N_3O_n$ ~~that have~~ not ~~been~~ accounted for here.

3.5 Contributions of monomers, dimer, and trimers to HOM

The concentration (represented by peak intensity) of monomers was higher than that of dimers, but overall their concentrations remained of the same order of magnitude (Fig 1a, inset). The concentration of trimers was much lower than that of monomers and dimers. The relative contributions of monomers, dimers, and trimers evolved in time due to the changing concentration of each HOM species. Comparing the contributions of various classes of HOM in period 1 with those in periods 1-6 reveals that the relative contribution of monomers increased with time, especially that of 2N-monomers, while the contribution of dimers decreased. This trend is attributed to the larger wall loss of dimers compared to monomers because of their lower volatility and also to the continuous formation of second-generation monomers, mostly 2N-momomers. Overall, the relative contribution of total HOM monomers decreased immediately after isoprene addition while the contribution of HOM dimers increased rapidly (Fig. ~~S14~~S15), which was attributed to the faster increase of dimers intensity due to their rapid formation. Afterwards, the contribution of monomers to total HOM gradually increased and that of dimers decreased, which was partly due to the faster wall loss rate of dimers and to the continuous formation of second-generation monomers.

3.6 Yield of HOM

The HOM yield in the oxidation of isoprene by NO_3 was estimated using the sensitivity of H_2SO_4. It was derived for the first isoprene addition period to minimize the contribution of multi-generation products and to better compare with the data in literature, thus denoted as primary HOM yield (Pullinen et al., 2020) and was estimated to be $1.2\%^{+1.3\%}_{-0.7\%}$ ~~using the sensitivity of H_2SO_4 (Pullinen et al., 2020)~~. The uncertainty was estimated as shown in the Supplement S1. Despite the uncertainty, the primary HOM yield here was much higher than the HOM yield from the ozonolysis and photooxidation of isoprene (Jokinen et al., 2015). The difference may be attributed to the more efficient oxygenation in the addition of NO_3 to carbon double bonds. Compared with the reaction with O_3 or OH, the initial peroxy radicals contains 5 oxygen atoms when isoprene reacts with NO_3, while the initial peroxy radicals contains only 3 oxygen atoms when reacting with OH, and the ozonide contains 3 oxygen atoms in the case of O_3.

4 Conclusion and implications

HOM formation in the reaction of isoprene with NO_3 was investigated in the SAPHIR chamber. A number of HOM monomers, dimers, and trimers containing one to five nitrogen atoms were detected, and their time-dependent concentration profiles were tracked throughout the experiment. ~~The~~ Some formation mechanisms ~~of~~ for various HOM were proposed according to the molecular formula identified, and the available literature. HOM showed a variety of time profiles with multiple isoprene additions during the reaction. First-generation HOM increased instantaneously after isoprene addition and then decreased while second-generation HOM increased gradually and then decreased with time, reaching a maximum concentration at the later stage of each period. The time profiles provide additional constraints on their formation mechanism beside the molecular formula, suggesting whether they were first-generation products or second-generation products or a combination of both. 1N-monomers (mostly C_5) were likely formed by NO_3 addition to a double bond of isoprene, forming monomer RO_2, followed by autoxidation and termination via the reaction with HO_2, RO_2, and NO_3. Time series suggest that some 1N-monomer could also be

formed by the reaction of first-generation products with NO_3, and thus be of second-generation. 2N-monomers were likely formed via the reaction of first-generation products such as C5-hydroxynitrate with NO_3 and thus second-generation products. 3N-monomers likely comprised peroxy/peroxyacyl nitrates formed by the reaction of 2N-monomer RO_2 with NO_2, and possibly nitronitrates formed via the direct addition of N_2O_5 to the first-generation products. HOM dimers were mostly formed by the accretion reactions between various HOM monomer RO_2, either first-generation or second-generation or with the contributions of both, and thus showed time profiles typical of either first-generation products, or second-generation products, or a ~~mixture~~ combination of both. Additionally, some dimers peroxy radicals (dimer RO_2) were formed by the reaction of NO_3 ~~dimer~~ with ~~NO_3~~ dimers containing a C=C double bond~~forming dimer RO_2~~. HOM trimers were proposed to be formed by accretion reactions between the monomer RO_2 and dimer RO_2, ~~the latter formed by the reaction of NO_3 with dimers containing a C=C double bond.~~

Overall, both HOM monomers and dimers contribute significantly to total HOM while trimers only contributed a minor fraction. Within both the monomer and dimer compounds, a limited set of compounds dominated the abundance, such as $C_5H_8N_2O_n$, $C_5H_{10}N_2O_n$, $C_{10}H_{17}N_3O_n$, and $C_{10}H_{16}N_2O_n$ series. 2N-monomers, which were second-generation products, dominated in monomers and accounted for ~34% of all HOM, indicating the important role of second-generation oxidation in HOM formation in the isoprene+NO_3 reaction~~isoprene+NO_3~~. Both RO_2 autoxidation and "alkoxy-peroxy" pathways were found to be important for 1N- and 2N-HOM formation. In total, the yield of HOM monomers, dimers, and trimers accounted for $1.3\%^{+1.3\%}_{-0.7\%}$ of the isoprene reacted, which was much higher than the HOM yield in the oxidation of isoprene by OH and O_3 reported in the literature (Jokinen et al., 2015). This means that the reaction of isoprene with NO_3 is a competitive pathway of HOM formation from isoprene.

The HOM in the reaction of isoprene with NO_3 may account for a significant fraction of SOA. If all the HOM condense on particles, using the molecular weight of the HOM with the least molecular weight observed in this study ($C_5H_9NO_6$), the HOM yield corresponds to a SOA yield of 3.6%. Although SOA concentrations were not measured in this study, Ng et al. (2008) reported a SOA yield of the isoprene+NO_3 reaction~~isoprene+NO_3~~ of 4.3%-23.8%. Rollins et al. (2009) reported a SOA yield of 2% at low organic aerosol loading (~0.52 μg m^{-3}) and 14% if the further oxidation of the first-generation products are considered in the isoprene+NO_3 reaction~~isoprene+NO_3~~. Comparing the potential SOA yield produced by HOM with SOA yields in the literature suggests that HOM may play an important role in the SOA formation in the isoprene+NO_3 reaction~~isoprene+NO_3~~.

The RO_2 lifetime is approximately 20-50 s in our experiments, which is generally comparable or shorter than the lifetime of RO_2 in the ambient atmosphere at night, varying from several 10 s to several 100 s (Fry et al., 2018), depending on the NO_3, HO_2, and RO_2 concentrations. Assuming a HO_2, RO_2, and NO_3 concentration of 5 ppt, 5 ppt (Tan et al., 2019), and 300 ppt (Brown and Stutz, 2012) respectively, the RO_2 lifetime in our study is comparable to the nighttime RO_2 lifetime (50 s) found in urban locations and areas influenced by urban plume. In areas with longer RO_2 lifetime such as remote areas, the autoxidation is expected to be more important relative to bimolecular reactions. This may enhance HOM yield and thus enhance SOA yield. However, on the other hand, at lower RO_2 concentration and thus longer RO_2 lifetime, reduced rates of RO_2+RO_2 reactions producing low-volatility dimers can reduce the SOA yield via reducing dimer yield (McFiggans et al., 2019; Pullinen et al., 2020). The RO_2 fate in our experiments is dominated the reaction RO_2+NO_3 with significant contribution of RO_2+RO_2, which can also represent the RO_2 fate

in the urban areas and areas influenced by urban plume. Our experiment condition cannot represent the chemistry in HO_2-dominated regions such as clean forest environment (Schwantes et al., 2015).

We observed the second-generation products formed by the reaction of first-generation products. The lifetime of first-generation nitrates in the ambient atmosphere, according their rate constants with OH and NO_3 (Wennberg et al., 2018), are ~5 h and ~1.3-4 h, respectively, with respect to the reaction with OH and NO_3 assuming a typical OH concentration of 2×10^6 molecules cm^{-3} (Lu et al., 2014; Tan et al., 2019) and NO_3 concentration of 100-300 ppt in urban areas (Brown and Stutz, 2012). Therefore, they have the chance to react further with OH and NO_3 at dawn. In our experiments, the lifetimes of these first-generation nitrates with respect to OH and NO_3 are comparable to the aforementioned lifetime due to comparable OH and NO_3 concentrations with these ambient conditions. Therefore, our findings on the second-generation products are relevant to the ambient urban atmosphere and areas influenced by urban plumes. Some of these products such as $C_5H_{810}N_2O_8$ and multi-generation nitrooxyorganosulfates have been observed in recent field studies in polluted megacities in east China (Hamilton et al., 2021; Xu et al., 2021).

Data availability

All the data in the figures of this study are available upon request to the corresponding author (t.mentel@fz-juelich.de).

Competing interests

The authors declare that they have no conflict of interest.

Author contribution

TFM, HF, SS, DZ, IP, AW, and AKS designed the experiments. Instrument deployment and operation were carried out by IP, HF, SS, IA, RT, FR, DZ, and RW. Data analysis was done by DZ, HF, SS, RW, IA, RT, FR, YG, SK. DZ, TFM, RW, JW, SK, and LV interpreted the compiled data set. DZ and TFM wrote the paper. All co-authors discussed the results and commented on the paper.

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Supplement of

Highly oxygenated organic molecules (HOM) formation in the isoprene oxidation by NO_3 radical

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In the supplement we describe the derivation of calibration coefficient of NO_3^--CIMS for H_2SO_4. In addition, more tables and figures besides those in the main text are provided.

1 S1 Deriving calibration coefficient of H_2SO_4 in NO_3^--CIMS and HOM yield

In order to convert peak intensity in mass spectra to concentration, the calibration coefficient of H_2SO_4 is derived. H_2SO_4 was produced in-situ in SAPHIR chamber by the oxidation SO_2 by OH. SO_2 (~15 ppb) was added into the chamber and the roof was opened to initiate photo-oxidation. In SAPHIR chamber, OH radicals are mainly formed by the photolysis of HONO (nitrous acid) directly coming off the chamber walls through a photolytic process (Rohrer et al., 2005;Zhao et al., 2016). NO (~20 ppb) was added which can enhance OH production by photochemical recycling. OH concentration was characterized by using laser induced fluorescence (LIF) with the details described in (Fuchs et al., 2012). SO_2 concentrations was characterized using an SO_2 analyzer (Thermo Systems 43i).

The concentration of H_2SO_4 in the chamber can be described by the following equation.

$$\frac{d[H_2SO_4]}{dt} = k[SO_2][OH] - (k_{wl} + k_{dil})[H_2SO_4] \quad \text{(Eq. 1)}$$

where $[H_2SO_4]$, $[SO_2]$, [OH] are the concentration of these species, k is the rate constant for the reaction of SO_2 with OH, k_{wl} is the wall loss rate of H_2SO_4 (~6.0×10^{-4} s^{-1} as characterized for low volatility compounds in our previous publication (Zhao et al., 2018)) and k_{dil} is the dilution rate of H_2SO_4 (~1×10^{-5} s^{-1}).

$$[H_2SO_4]=C\times I \quad \text{(Eq. 2)}$$

where C is the calibration coefficient of H_2SO_4, I is the peak intensity of H_2SO_4 determined by normalized peak area of H_2SO_4 at time t, i.e., the peak area divided by total signal of mass spectrum (termed as normalized count (nc)).

Substituting Eq.2 to Eq. 1, one can get

$$C\frac{dI}{dt} = k[SO_2][OH] - C(k_{wl} + k_{dil})I \quad \text{(Eq. 3)}$$

Integrating Eq.3, one can get

$$C = \frac{k[SO_2][OH]}{\frac{I-I_0}{t}+(k_{wl}+k_{dil})I} \quad \text{(Eq. 4)}$$

where I_0 is the peak intensity at time zero. C was determined to be 2.5×10^{10} molecules cm^{-3} nc^{-1}. The second term of denominator in Eq. 4 is much lower the first term and can omitted. The uncertainty of C was estimated to -52%/+ 101% from the uncertainty of SO_2 concentration (~7 %), OH concentration (~ 10 %), I (~ 10%) and k ($\Delta logk=\pm0.3$) using error propagation, which corresponds to (1.2-5.0)$\times10^{10}$ molecules cm^{-3} nc^{-1}. The C value is generally consistent with the value of 3.7×10^{10} molecules cm^{-3} nc^{-1} in our previous calibration (Pullinen et al., 2020).

HOM yield was calculated as

$$Y = \frac{[HOM]}{[VOC]_r} = \frac{I(HOM)C}{[VOC]_r} \quad \text{(Eq. 5)}$$

where [HOM] is concentration of HOM and $[VOC]_r$ is the concentration of VOC reacted. The uncertainty of HOM yield was estimated to -55%/+ 103% from the uncertainty of HOM intensity (~10 %), VOC concentration (~ 15 %) and C using error propagation.

2 S2 Detailed mechanisms of trimer formation

The $C_{15}H_{25}N_5O_n$ series can be formed by the following reactions:

$$C_{10}H_{16}N_3O_{n1}\bullet + C_5H_9N_2O_{n2}\bullet \rightarrow C_{15}H_{25}N_5O_{n1+n2-2} + O_2 \quad \text{RS1}$$

$$C_{10}H_{17}N_4O_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{15}H_{25}N_5O_{n1+n2-2} + O_2 \quad \text{RS2}$$

$$C_{10}H_{18}N_3O_{n1}\bullet + C_5H_7N_2O_{n2}\bullet \rightarrow C_{15}H_{25}N_5O_{n1+n2-2} + O_2 \quad \text{RS3}$$

The $C_{10}H_{18}N_3O_n$ (n=14-20) and $C_{10}H_{17}N_4O_n$ can be formed by the dimers with NO_3.

$$C_{10}H_{18}N_2O_n + NO_3 + O_2 \rightarrow C_{10}H_{18}N_3O_n\bullet \quad \text{RS4}$$

$$C_{10}H_{17}N_3O_n + NO_3 + O_2 \rightarrow C_{10}H_{17}N_4O_n \quad \text{RS5}$$

R21 is likely to be unimportant because both the abundance of $C_{10}H_{18}N_3O_n$ and $C_5H_7N_2O_n$ were low. Since the peaks of $C_{10}H_{18}N_3O_n$ (n=14-20) series overlap with $C_{10}H_{16}N_2O_n$, we can only assign them with low confidence. Similarly, $C_{10}H_{17}N_4O_n$ series overlap with $C_{10}H_{15}N_3O_n$ series (dimer 5).

The $C_{15}H_{25}N_3O_n$ series can be formed by the following reactions:

$$C_{10}H_{17}N_2O_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{15}H_{25}N_3O_{n1+n2-2} + O_2 \quad \text{RS6}$$

$$C_{10}H_{16}NO_{n1}\bullet + C_5H_9N_2O_{n2}\bullet \rightarrow C_{15}H_{25}N_3O_{n1+n2-2} + O_2 \quad \text{RS7}$$

The $C_{15}H_{26}N_4O_n$ series can be formed by the following reactions:

$$C_{10}H_{17}N_2O_{n1}\bullet + C_5H_9N_2O_{n2}\bullet \rightarrow C_{15}H_{26}N_4O_{n1+n2-2} + O_2 \quad \text{RS8}$$

$$C_{10}H_{18}N_3O_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{15}H_{26}N_4O_{n1+n2-2} + O_2 \quad \text{RS9}$$

$$C_{10}H_{16}N_3O_{n1}\bullet + C_5H_{10}NO_{n2}\bullet \rightarrow C_{15}H_{26}N_4O_{n1+n2-2} + O_2 \quad \text{RS10}$$

R28 is likely to be unimportant because both the abundance of $C_{10}H_{16}N_3O_n$ and $C_5H_{10}NO_n$ were low.

The $C_{15}H_{24}N_2O_n$ series can be formed by the following reactions:

$$C_{10}H_{16}NO_{n1}\bullet + C_5H_8NO_{n2}\bullet \rightarrow C_{15}H_{24}N_2O_{n1+n2-2} + O_2 \quad \text{RS11}$$

$C_{10}H_{16}NO_{n1}\bullet$ is formed via R15 as mentioned above.

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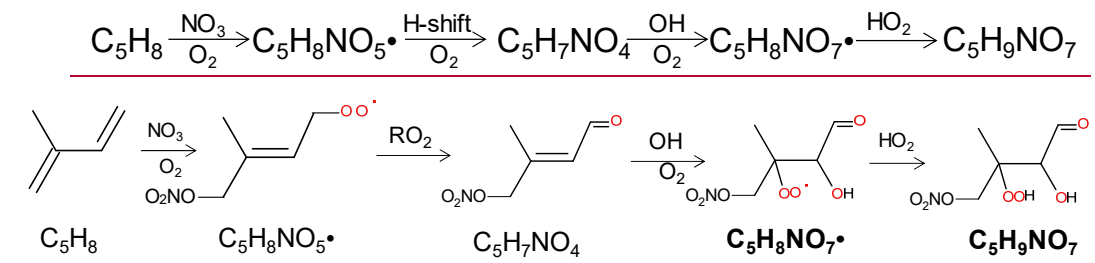
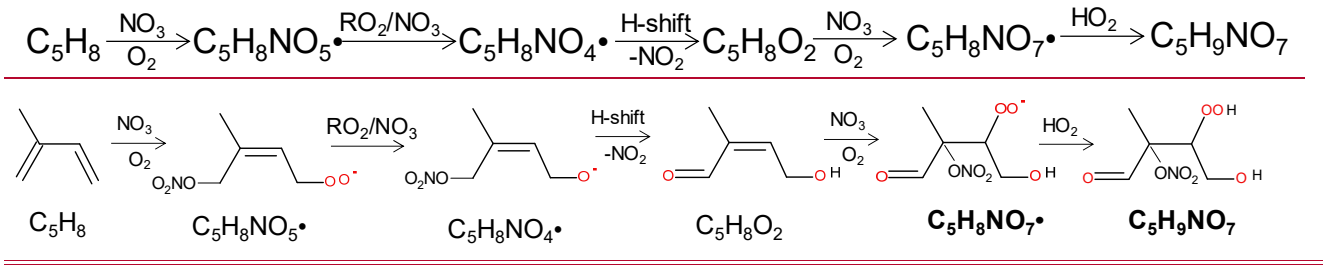
90 photooxidation of alpha-pinene and limonene, Atmos. Chem. Phys., 18, 1611-1628, 10.5194/acp-18-1611-2018, 2018.

91

Supplement figures and tables

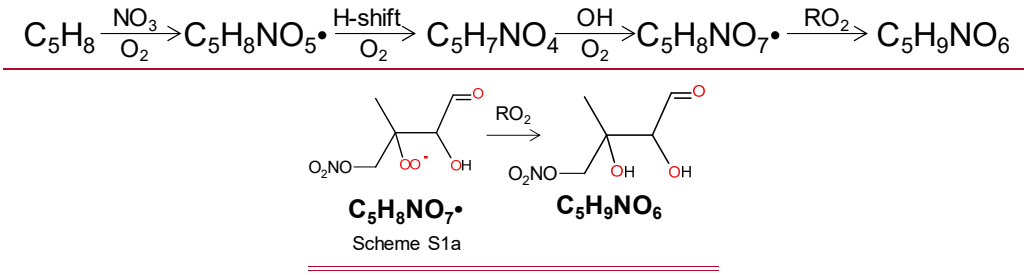


(a)



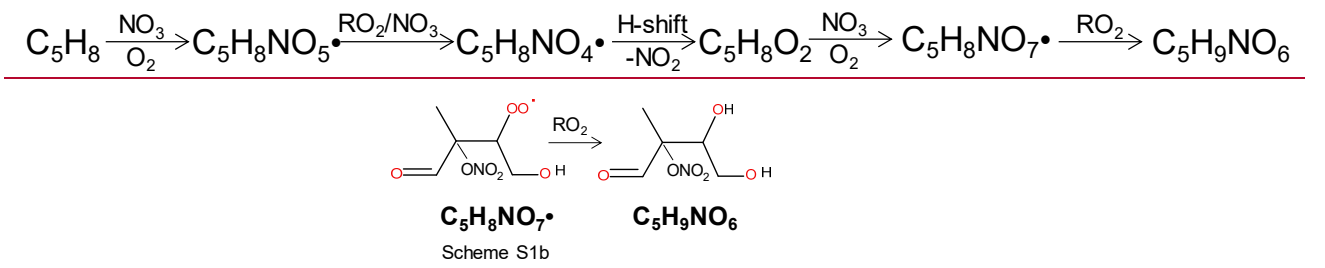
(b)

Scheme S1. The example pathway to form second-generation $C_5H_9NO_7$



Scheme S1a

(a)

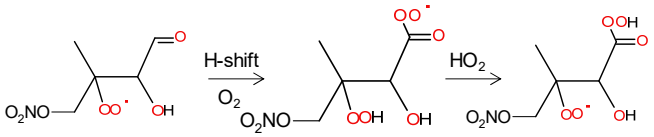


Scheme S1b

(b)

Scheme S2. The example pathway to form second-generation $C_5H_9NO_6$.

$C_5H_8 \xrightarrow{NO_3} C_5H_8NO_5\bullet \xrightarrow{\text{H-shift}} C_5H_7NO_4 \xrightarrow{OH} C_5H_8NO_7\bullet \xrightarrow{\text{H-shift}} C_5H_8NO_9\bullet \xrightarrow{HO_2} C_5H_9NO_9$

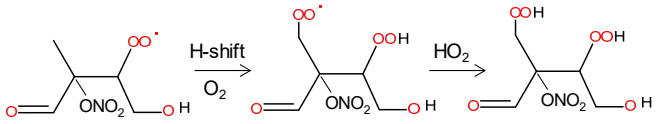


$C_5H_8NO_7\bullet$ **$C_5H_8NO_9\bullet$** **$C_5H_9NO_9$**

Scheme S1a

(a)

$C_5H_8 \xrightarrow[O_2]{NO_3} C_5H_8NO_5\bullet \xrightarrow{RO_2/NO_3} C_5H_8NO_4\bullet \xrightarrow[-NO_2]{\text{H-shift}} C_5H_8O_2 \xrightarrow[O_2]{NO_3} C_5H_8NO_7\bullet \xrightarrow[O_2]{\text{H-shift}} C_5H_8NO_9\bullet \xrightarrow{HO_2} C_5H_9NO_9$



$C_5H_8NO_7\bullet$ **$C_5H_8NO_9\bullet$** **$C_5H_8NO_9$**

Scheme S1b

(b)

$C_5H_8 \xrightarrow[O_2]{NO_3} C_5H_8NO_5\bullet \xrightarrow[O_2]{\text{H-shift}} C_5H_7NO_4 \xrightarrow[O_2]{OH} C_5H_8NO_7\bullet \xrightarrow[O_2]{\text{H-shift}} \xrightarrow[O_2]{\text{H-shift}} C_5H_8NO_{11}\bullet \xrightarrow{RO_2/NO_3} C_5H_8NO_{10}\bullet \xrightarrow{RO_2} C_5H_9NO_9$

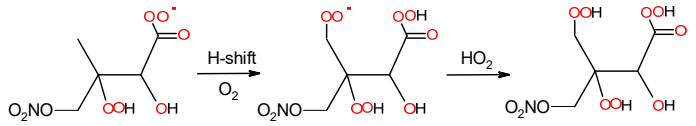
~~(c)~~

$C_5H_8 \xrightarrow[O_2]{NO_3} C_5H_8NO_5\bullet \xrightarrow{RO_2/NO_3} C_5H_8NO_4\bullet \xrightarrow[-NO_2]{\text{H-shift}} C_5H_8O_2 \xrightarrow[O_2]{NO_3} C_5H_8NO_7\bullet \xrightarrow[O_2]{\text{H-shift}} \xrightarrow[O_2]{\text{H-shift}} C_5H_8NO_{11}\bullet \xrightarrow{RO_2/NO_3} C_5H_8NO_{10}\bullet \xrightarrow{RO_2} C_5H_9NO_9$

~~(d)~~

Scheme S3. The example pathway to form second-generation $C_5H_9NO_9$.

$C_5H_8 \xrightarrow[O_2]{NO_3} C_5H_8NO_5\bullet \xrightarrow[O_2]{\text{H-shift}} C_5H_7NO_4 \xrightarrow[O_2]{OH} C_5H_8NO_7\bullet \xrightarrow[O_2]{\text{H-shift}} \xrightarrow[O_2]{\text{H-shift}} C_5H_8NO_{11}\bullet \xrightarrow{RO_2} C_5H_9NO_{10}$

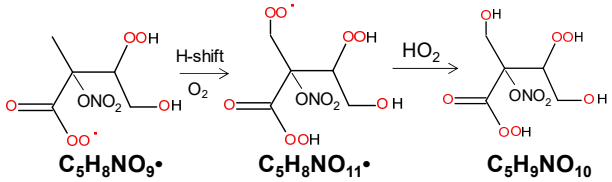


$C_5H_8NO_9\bullet$ **$C_5H_8NO_{11}\bullet$** **$C_5H_9NO_{10}$**

Scheme S3a

(a)

$C_5H_8 \xrightarrow[O_2]{NO_3} C_5H_8NO_5\bullet \xrightarrow{RO_2/NO_3} C_5H_8NO_4\bullet \xrightarrow[-NO_2]{\text{H-shift}} C_5H_8O_2 \xrightarrow[O_2]{NO_3} C_5H_8NO_7\bullet \xrightarrow[O_2]{\text{H-shift}} \xrightarrow[O_2]{\text{H-shift}} C_5H_8NO_{11}\bullet \xrightarrow{RO_2} C_5H_9NO_{10}$

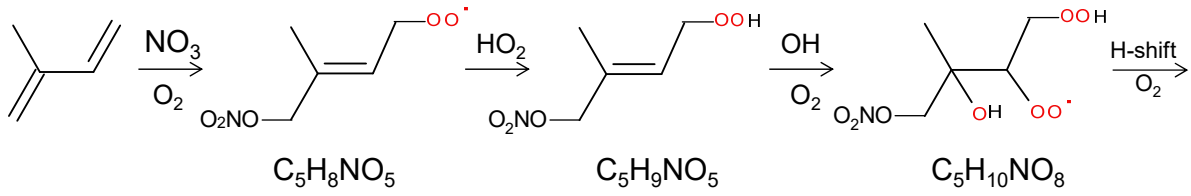


$C_5H_8NO_9\bullet$ **$C_5H_8NO_{11}\bullet$** **$C_5H_9NO_{10}$**

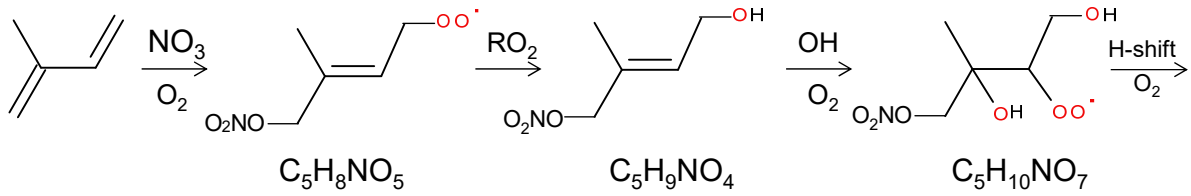
Scheme S3b

(b)

Scheme S4. The example pathway to form second-generation $C_5H_9NO_{10}$

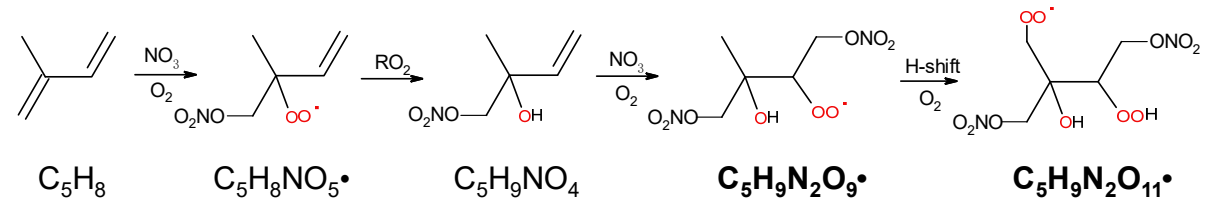


(a)

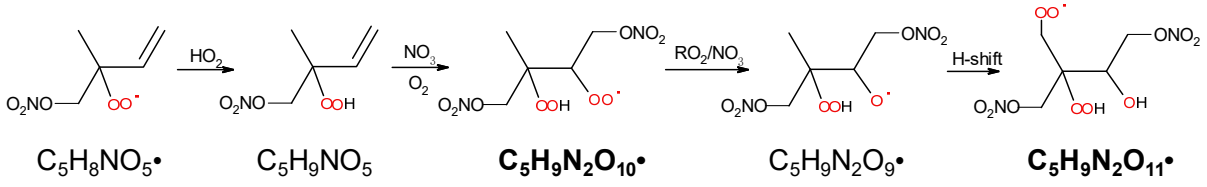


(b)

Scheme S5. The pathway to form $C_5H_{10}NO_{n(n\geq7)}$• RO_2 series with even (a) and odd (b) number of oxygen atoms.

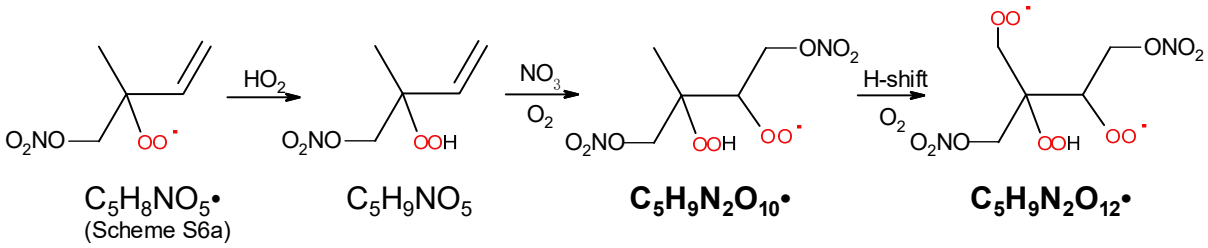


(a)



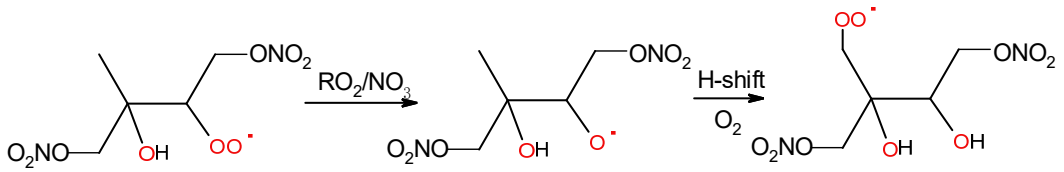
(b)

Scheme S6. The example pathway to form $C_5H_9N_2O_n$ (n=9, 11) HOM RO_2 series via 1-NO_3-isoprene-2-OO RO_2 by RO_2 channel (a) and alkoxy-peroxy channel. The detected products are in bold.



$C_5H_8NO_5$• (Scheme S6a) $C_5H_9NO_5$ **$C_5H_9N_2O_{10}$•** **$C_5H_9N_2O_{12}$•**

(a)



$C_5H_9N_2O_9$• (Scheme S6a) $C_5H_9N_2O_8$• **$C_5H_9N_2O_{10}$•**

(b)

Scheme S7. The example pathway to form $C_5H_9N_2O_n$ (n=8, 10, 12) HOM RO_2 series via 1-NO_3-isoprene-2-OO RO_2 by RO_2 channel (a) and alkoxy-peroxy channel. The detected products are in bold.

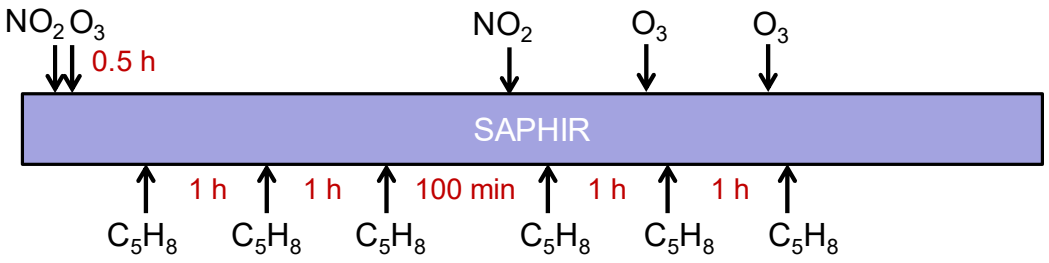
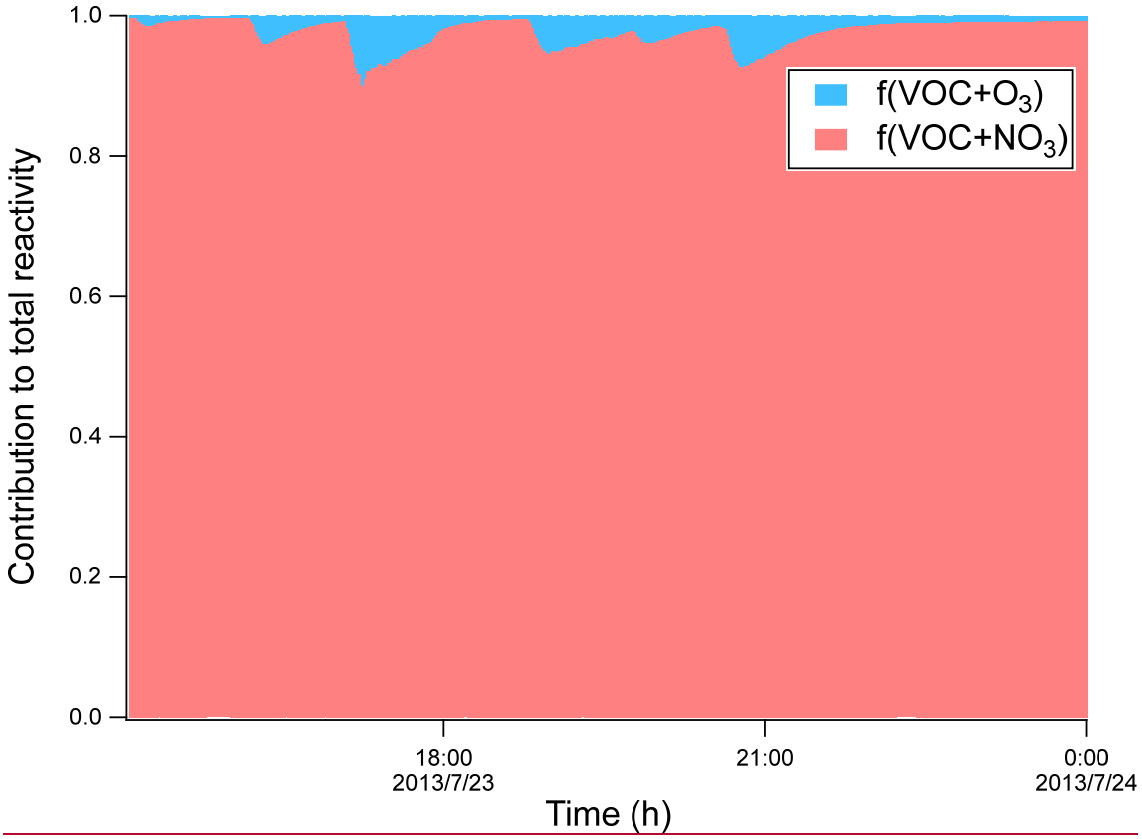


Figure S1. Schematic of the experimental procedure.


1.0
0.8
0.6
0.4
0.2
0.0
Contribution to total reactivity
f(VOC+O3)
f(VOC+NO3)
18:00
2013/7/23
21:00
0:00
2013/7/24
Time (h)

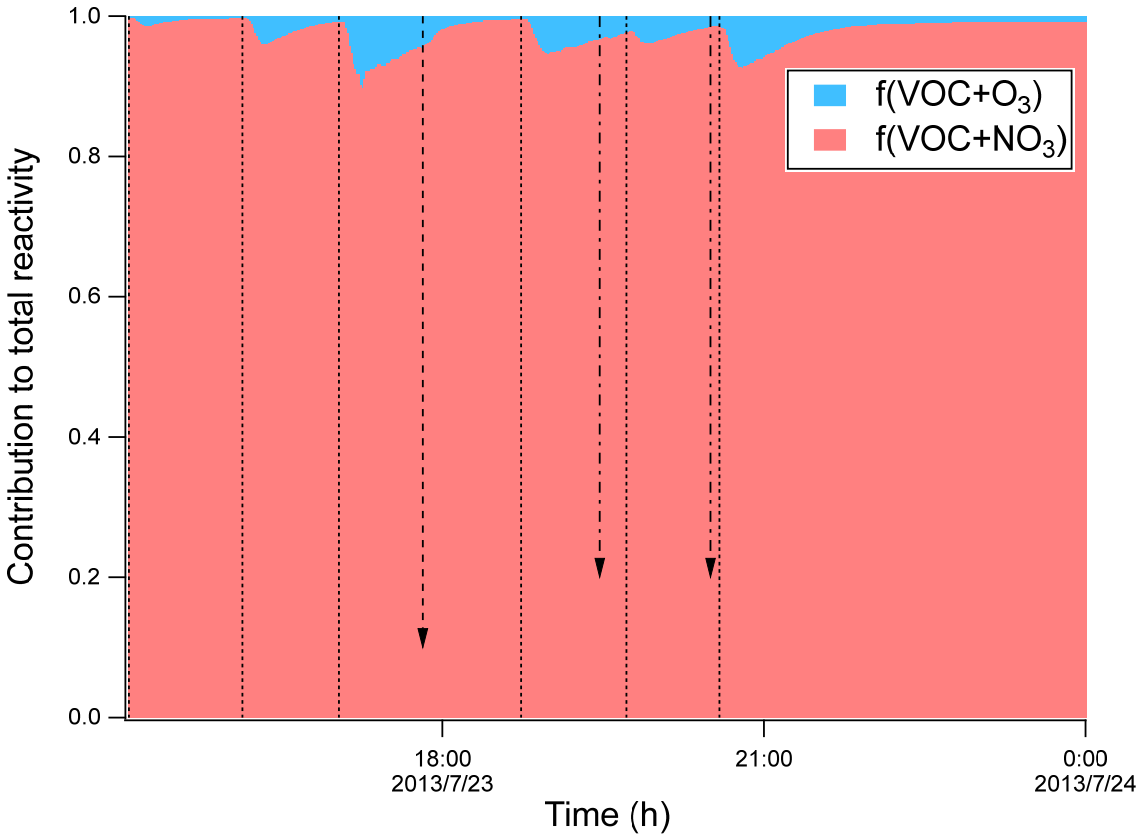
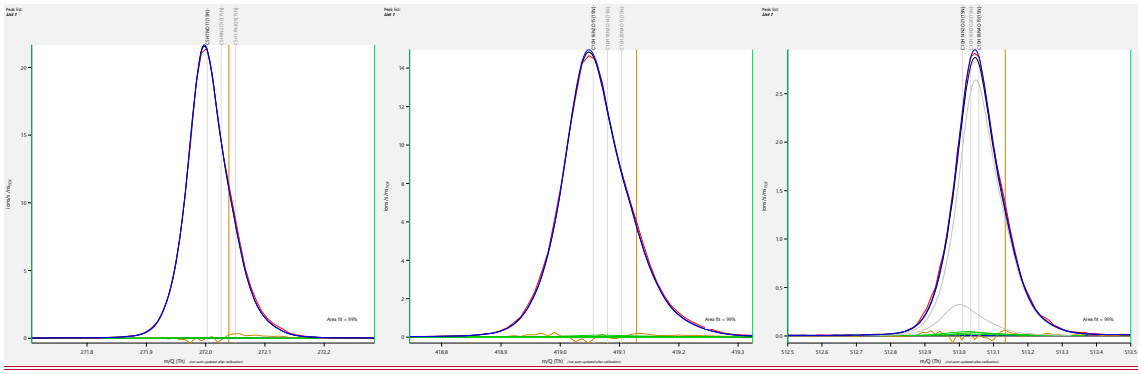

1.0
0.8
0.6
0.4
0.2
0.0
Contribution to total reactivity
f(VOC+O3)
f(VOC+NO3)
18:00
2013/7/23
21:00
0:00
2013/7/24
Time (h)

Figure S2. Relative contributions of the reaction rates of isoprene with NO_3 and with O_3 to the total isoprene loss. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.



(a) (b) (c)

Figure S3. Examples of peak fitting. Formula in grey indicate compounds that have no noticeable effect on fitting residues and thus not included in the peak list.

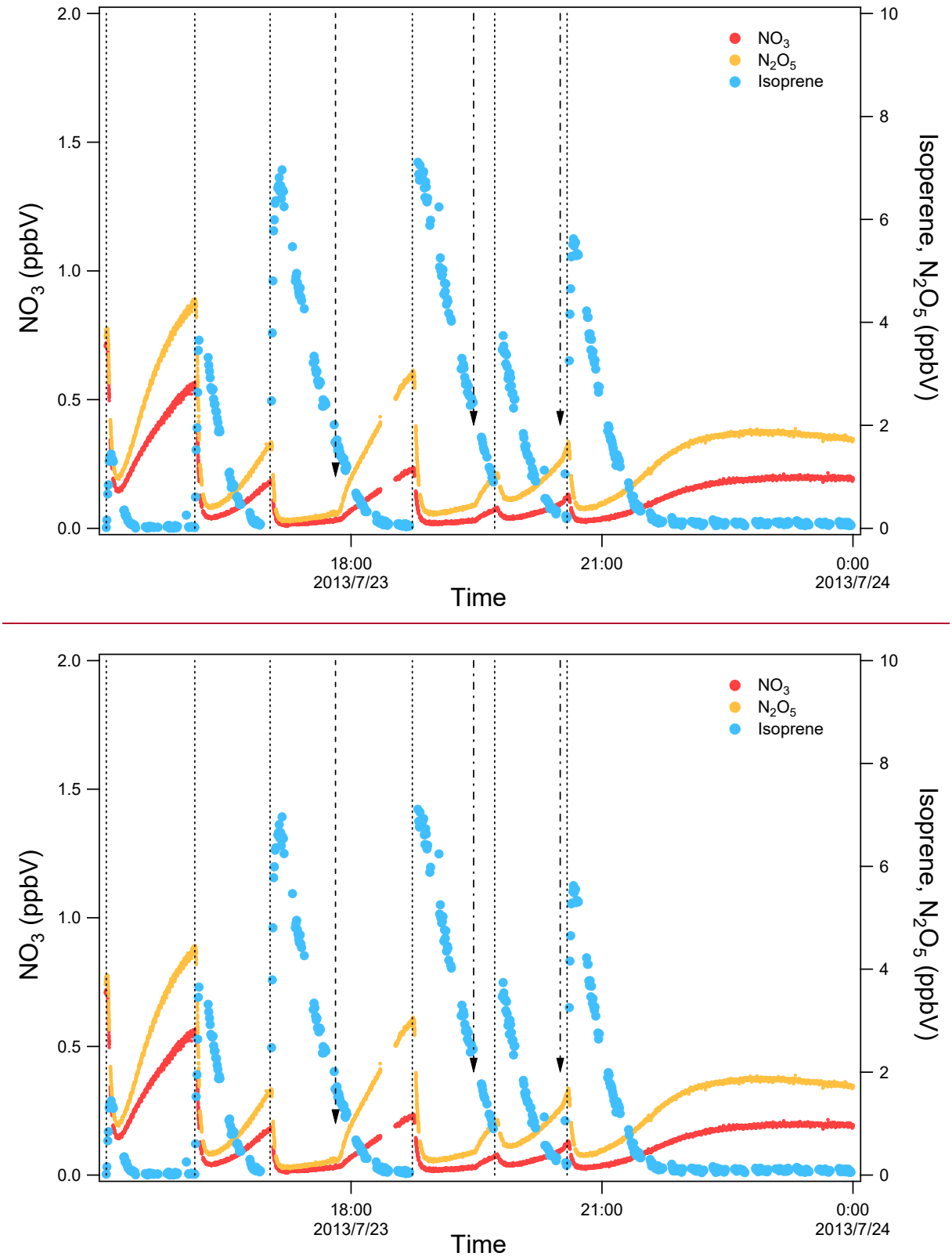


Figure ~~S3~~S4. Time series of the of isoprene, NO_3, and N_2O_5 concentration. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

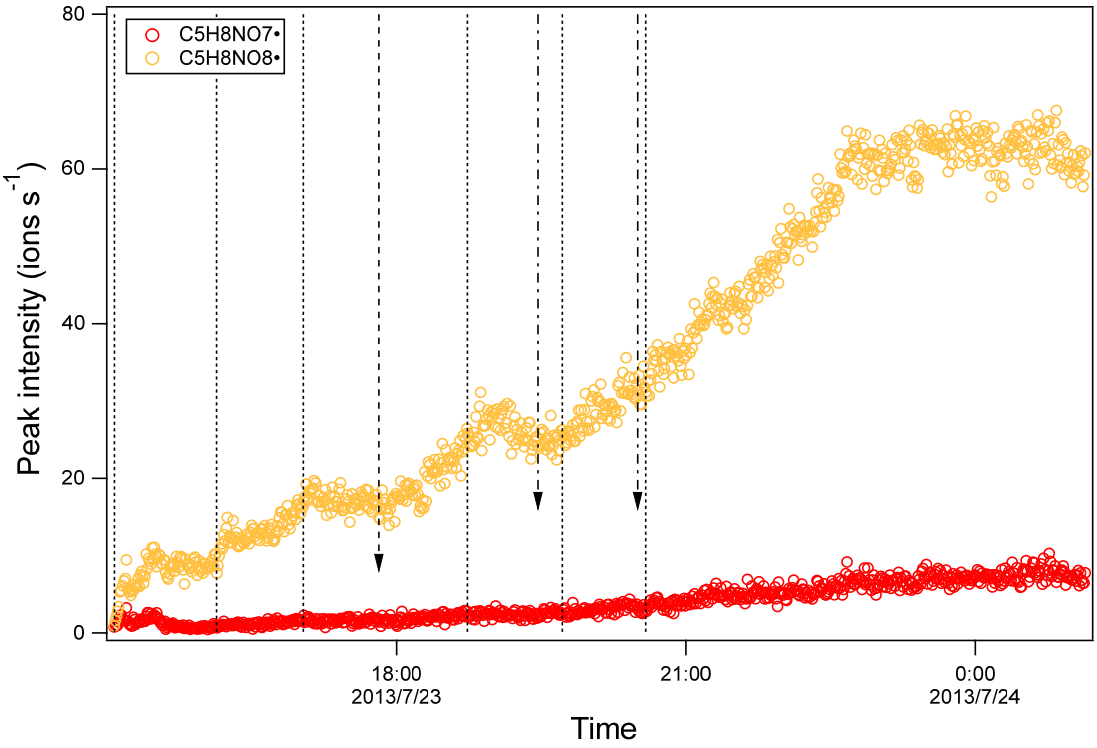


Figure ~~S4~~S5. Time series of peak intensity of several HOM monomers of the $C_5H_8NO_n$• series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

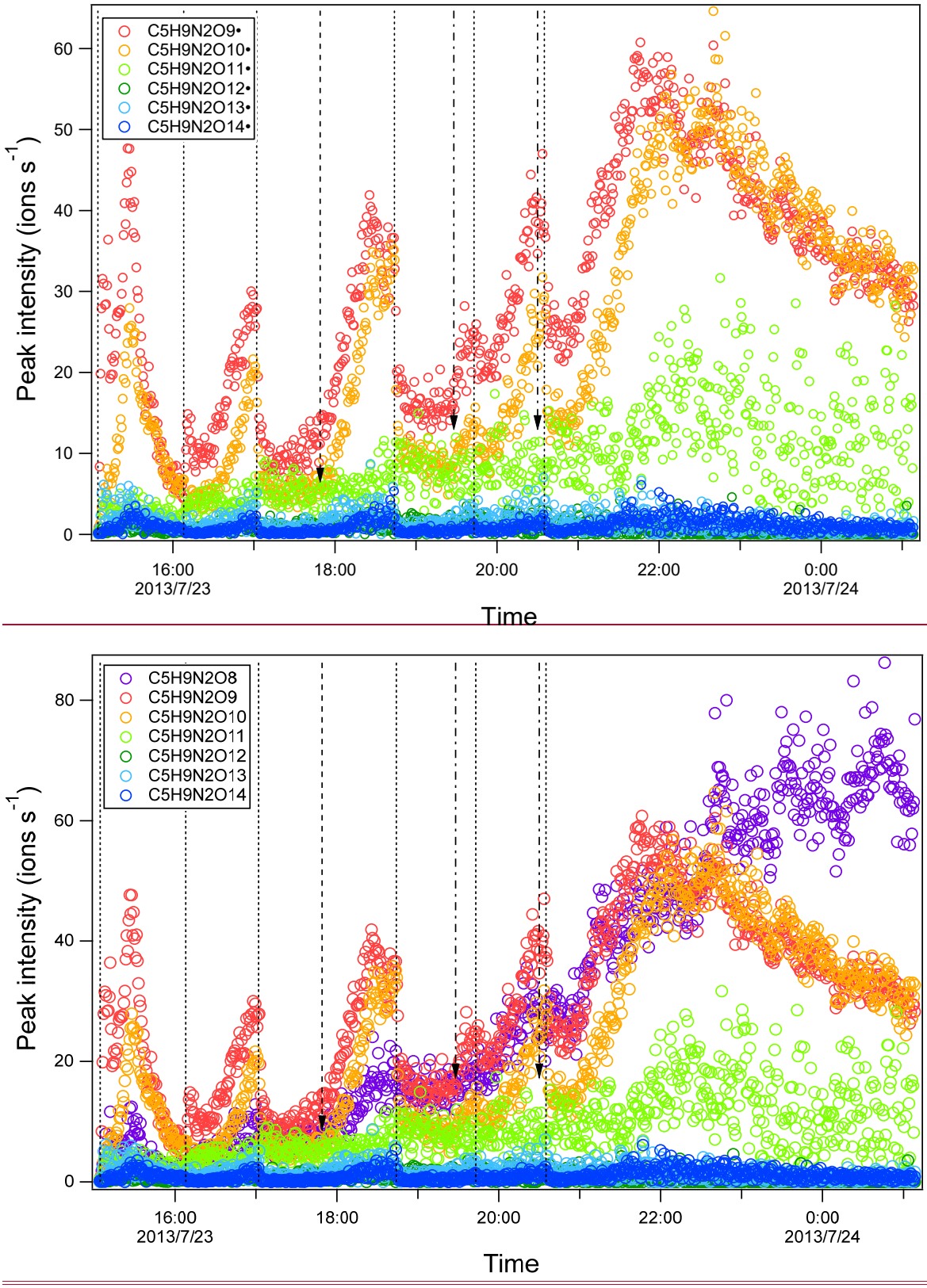


Figure ~~S5~~S6. Time series of peak intensity of HOM monomers of the $C_5H_9N_2O_n$• series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

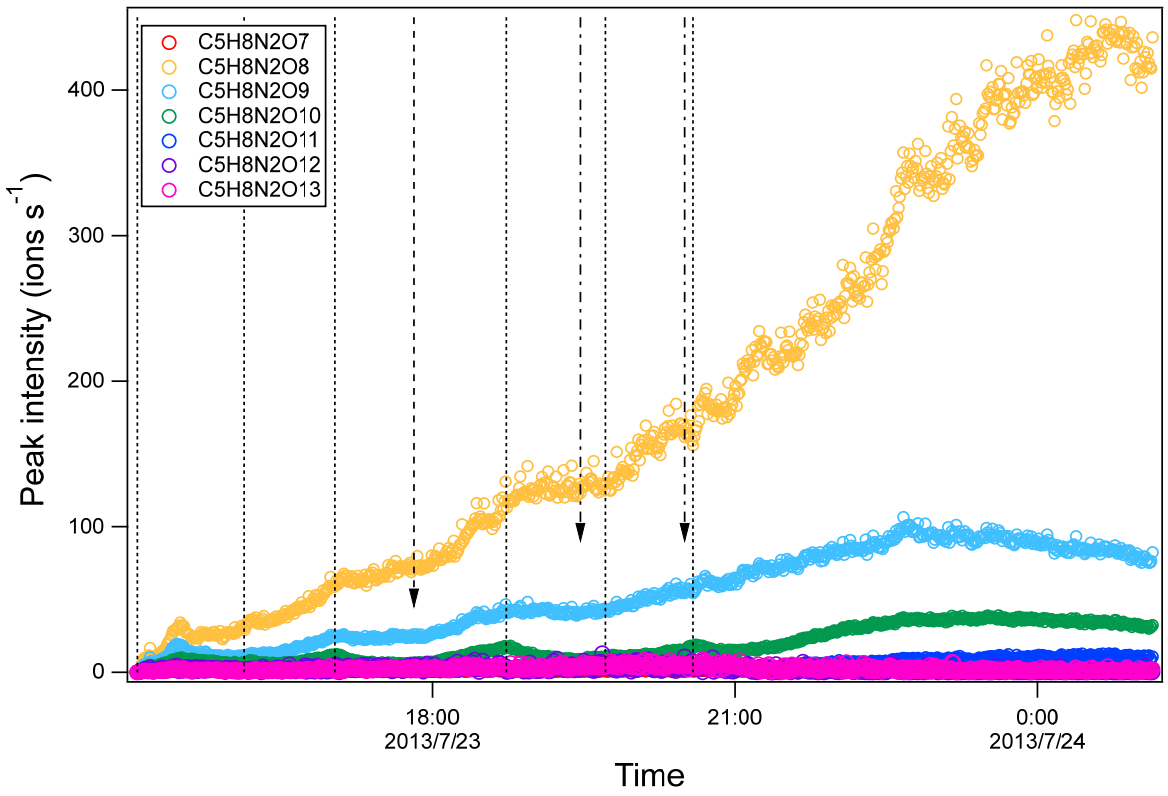


Figure S~~7~~6. Time series of peak intensity of several HOM monomers of the $C_5H_8N_2O_n$ series (termination products of RO_2 $C_5H_9N_2O_n$). The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

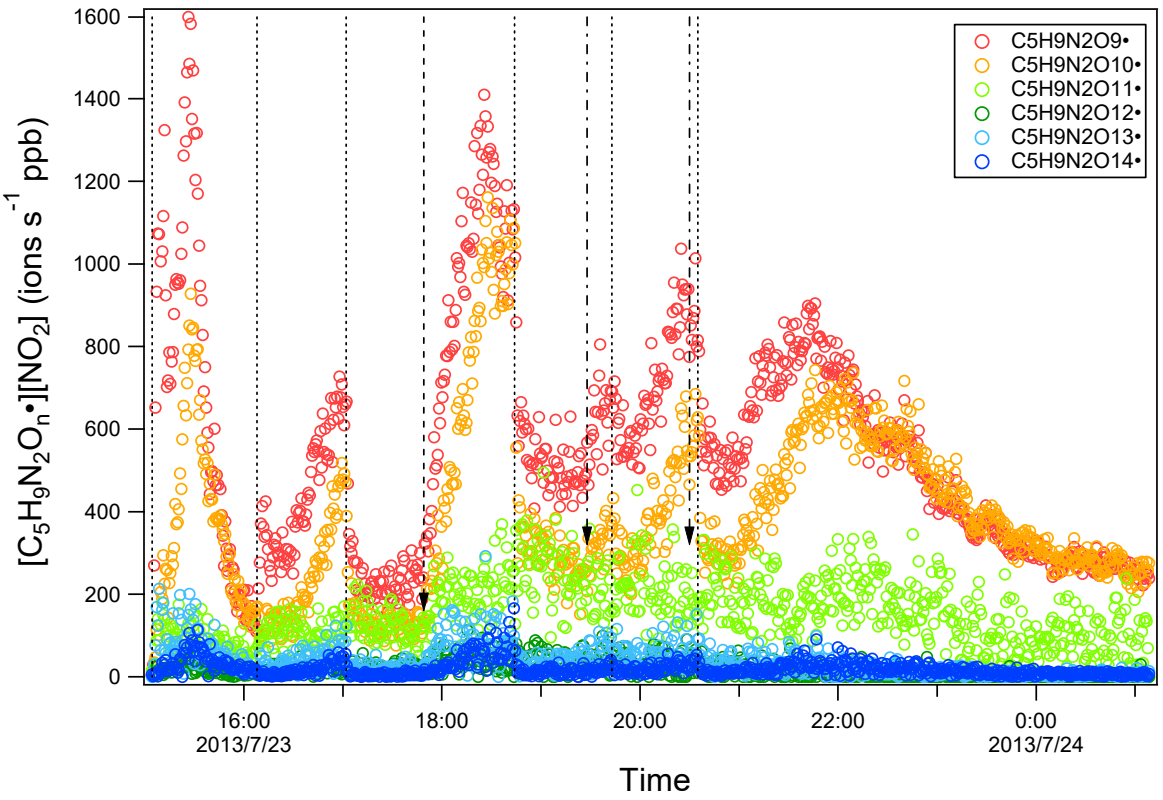
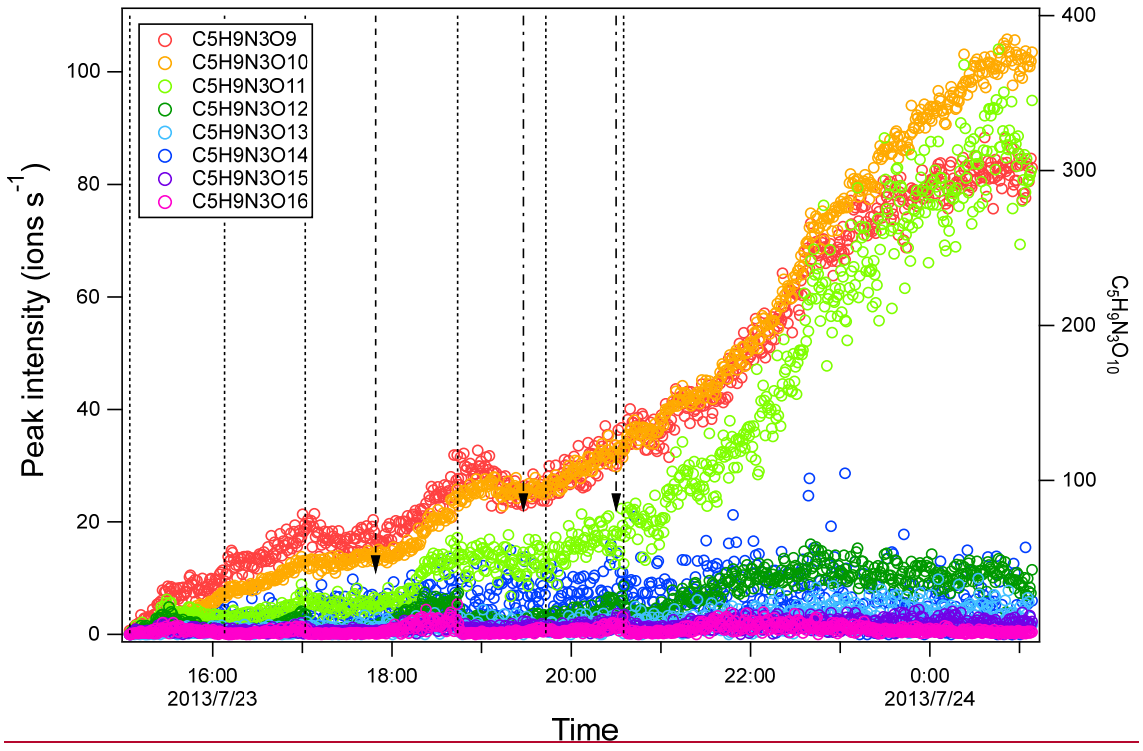


Figure S~~8~~7. Time series of the product of the peak intensity of $C_5H_9N_2O_n$• and NO_2 concentration. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.


C5H9N3O9
C5H9N3O10
C5H9N3O11
C5H9N3O12
C5H9N3O13
C5H9N3O14
C5H9N3O15
C5H9N3O16
Peak intensity (ions s-1)
0
20
40
60
80
100
400
300
200
100
C5H9N3O10
16:00
2013/7/23
18:00
20:00
22:00
0:00
2013/7/24
Time

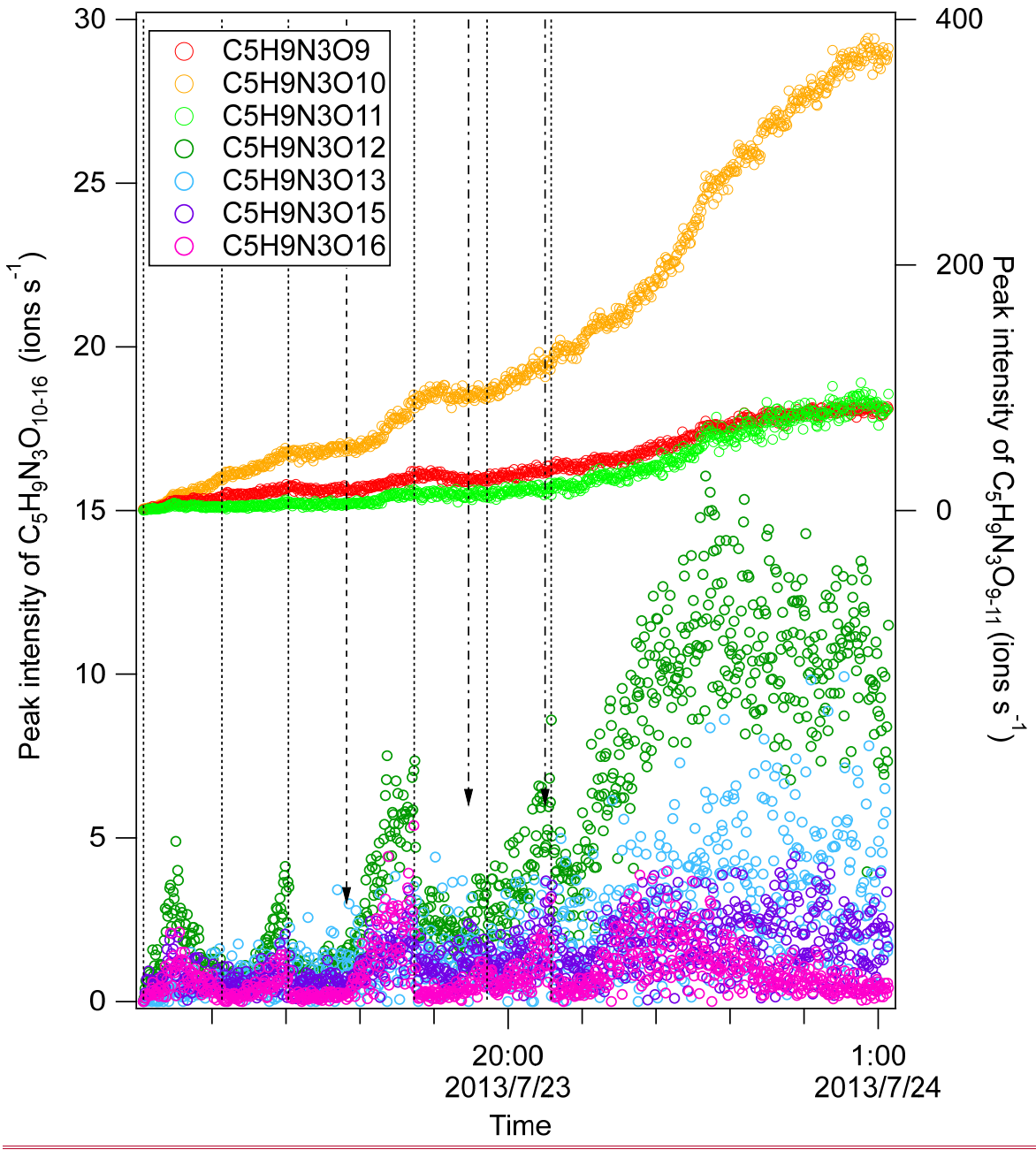
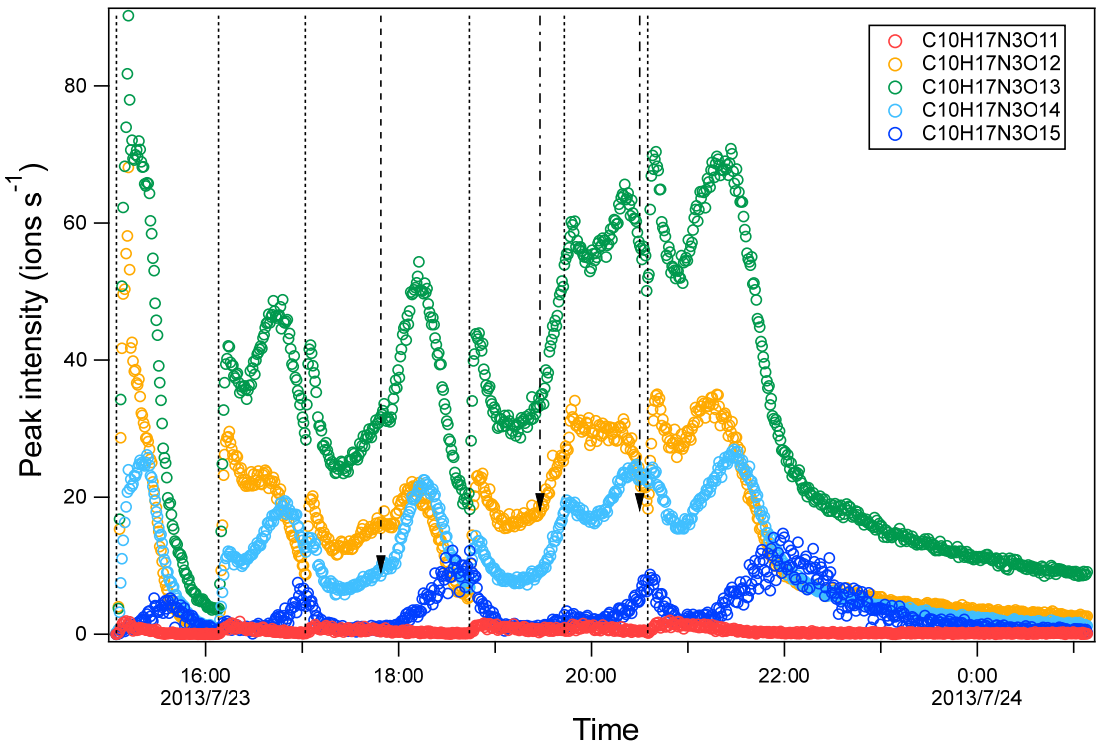
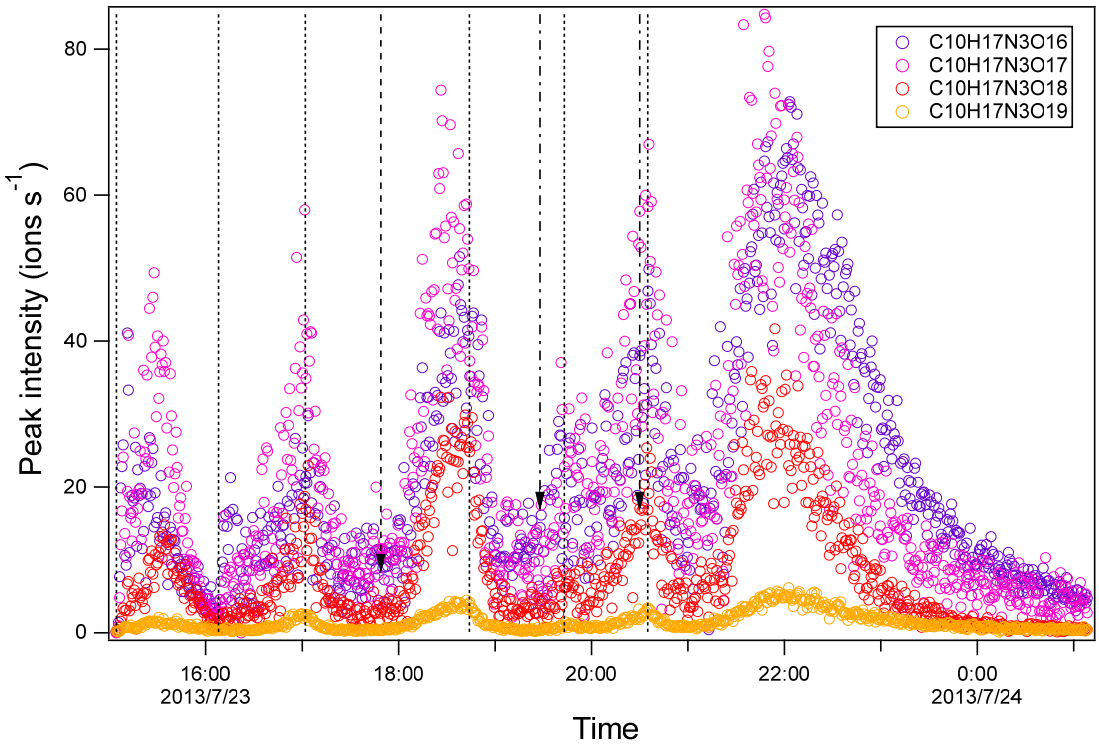


Figure S~~8~~9. Time series of peak intensity of HOM monomers of the $C_5H_9N_3O_n$ series. The peak intensity of is shown on the left axis except for $C_5H_9N_3O_{10}$. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.



(a)



(b)

Figure ~~S9~~S10. Time series of peak intensity of several HOM dimers of the $C_{10}H_{17}N_3O_n$ series for n=11-15(a) and 16-19 (b). The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

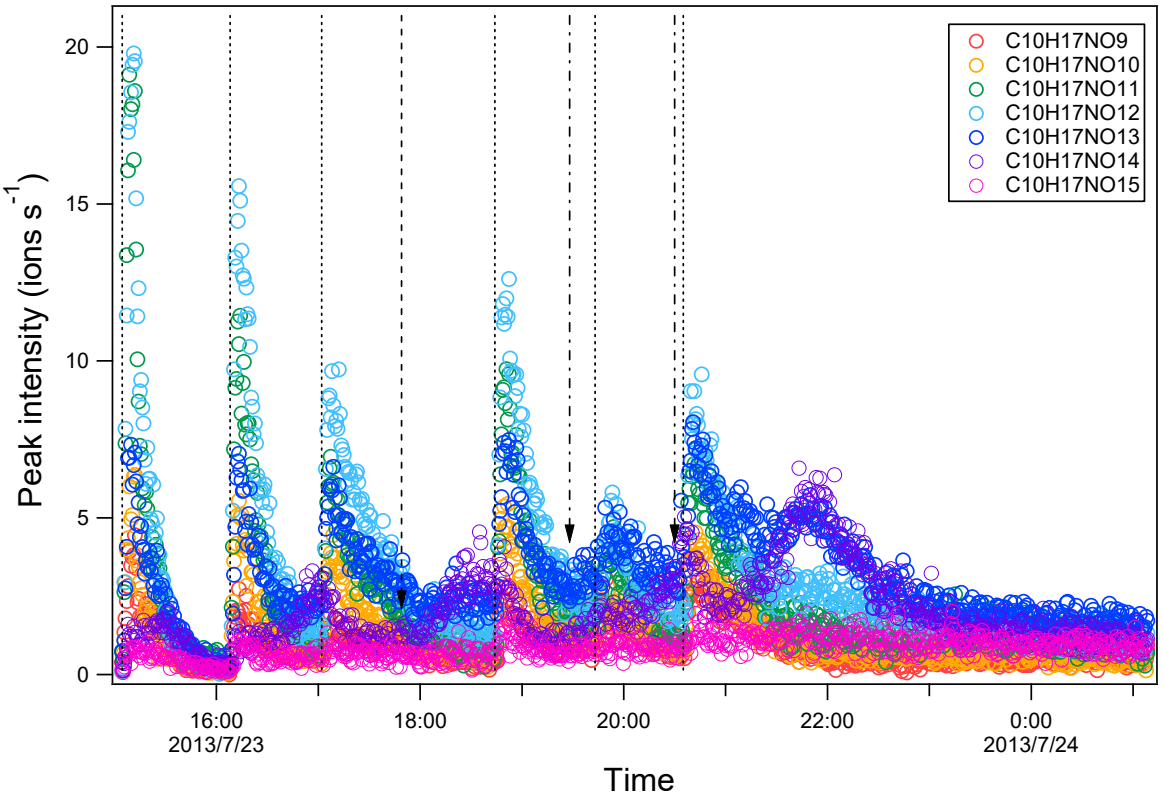


Figure ~~S10~~S11. Time series of peak intensity of HOM monomers $C_{10}H_{17}NO_n$ series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

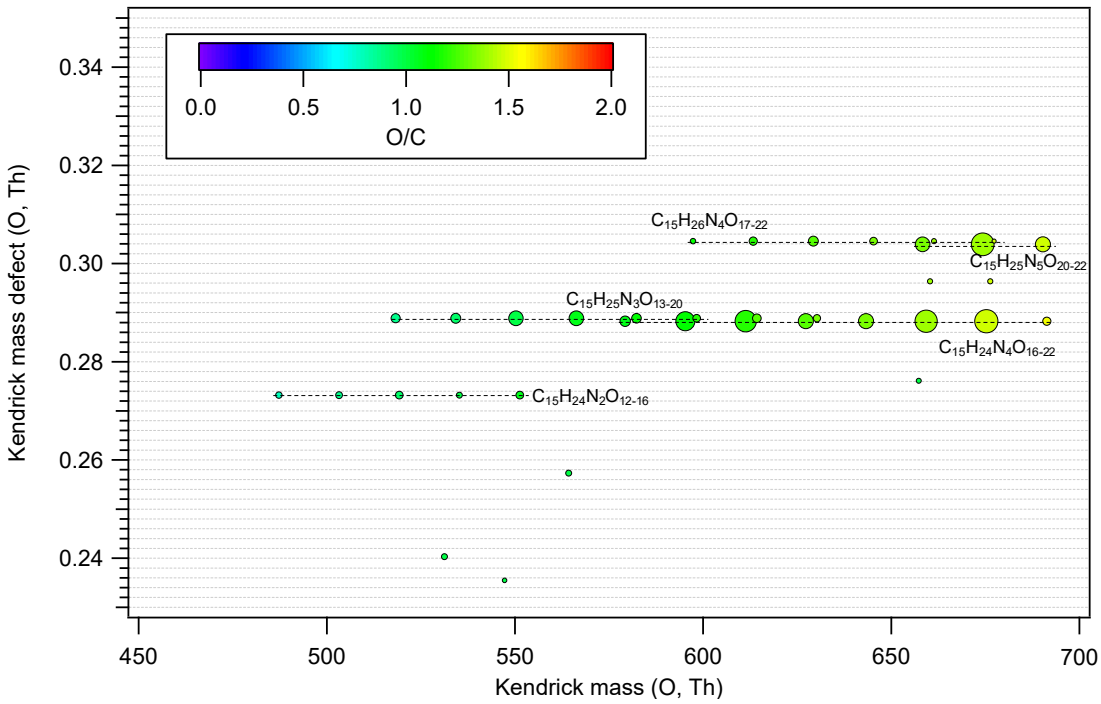


Figure ~~S11~~S12. Kendrick mass defect with Kendrick base O of HOM trimers formed in isoprene+NO_3. The area of the circles is set to be proportional to the average peak intensity of each molecular formula during the first isoprene addition period (P1).

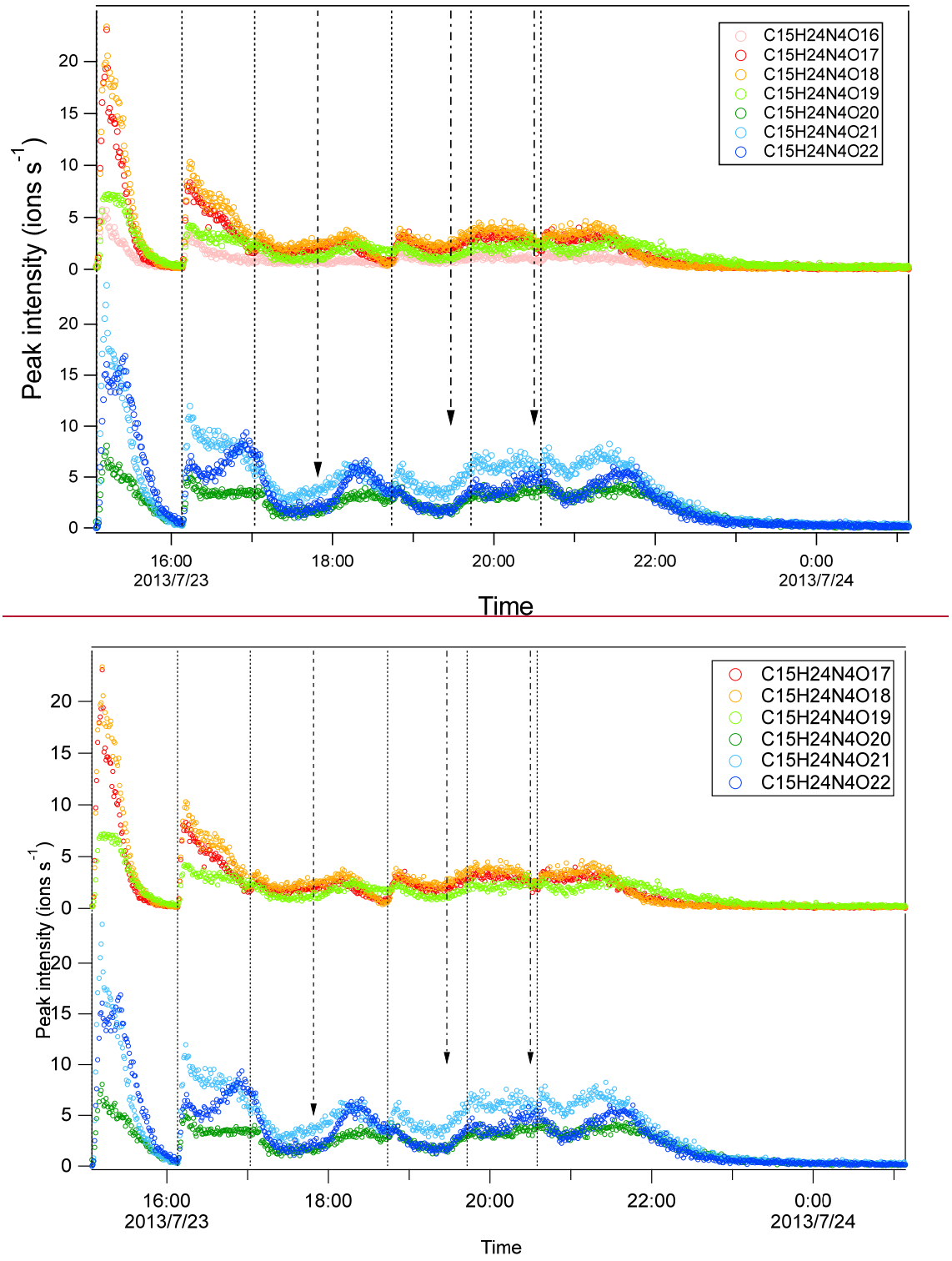


Figure ~~S12~~S13. Time series of peak intensity of several HOM dimers of the $C_{15}H_{24}N_4O_n$ series. It is noted that the compounds are plotted in two panels for clarity. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

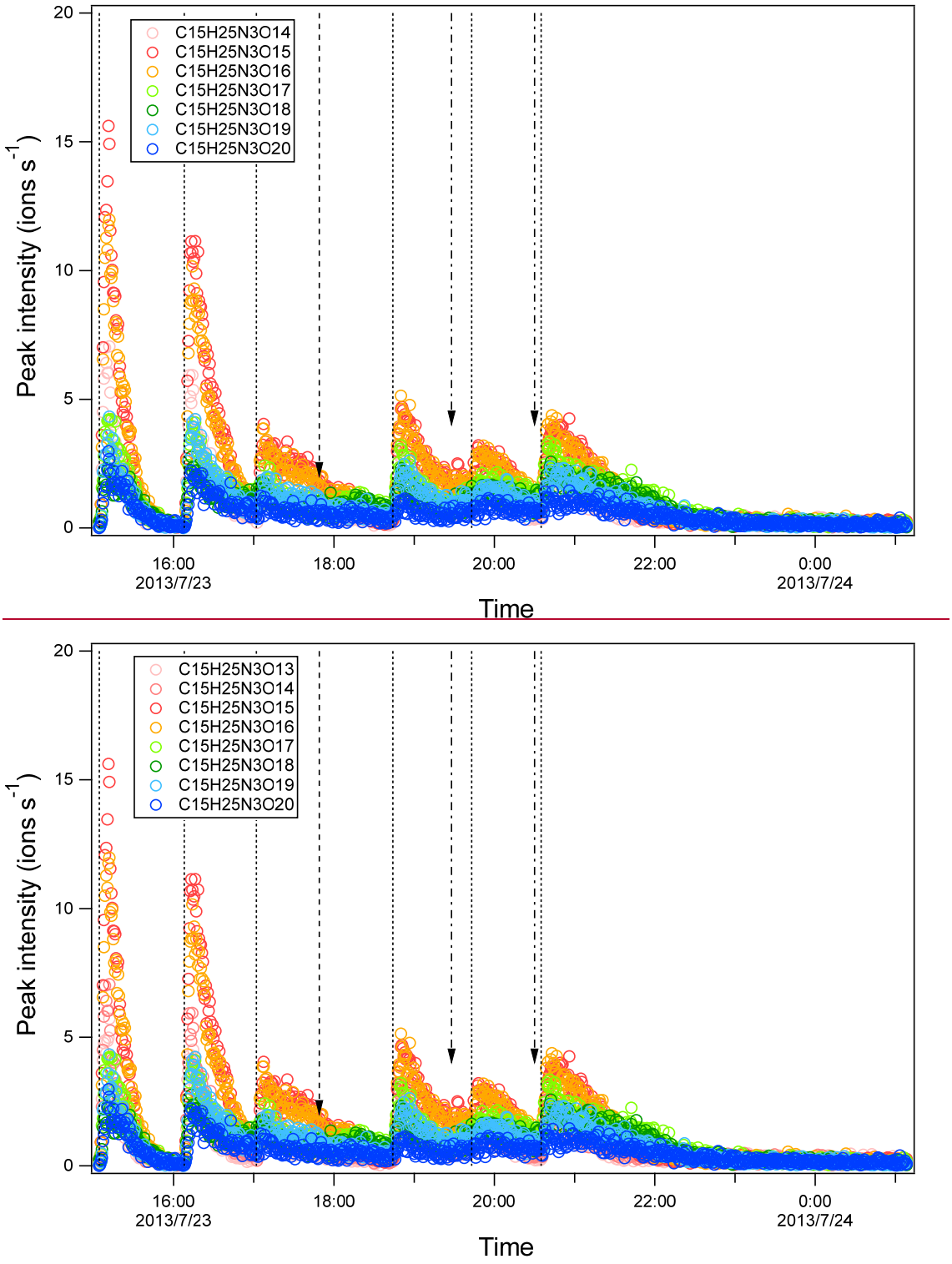


Figure ~~S13~~S14. Time series of peak intensity of several HOM dimers of the $C_{15}H_{25}N_3O_n$ series. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

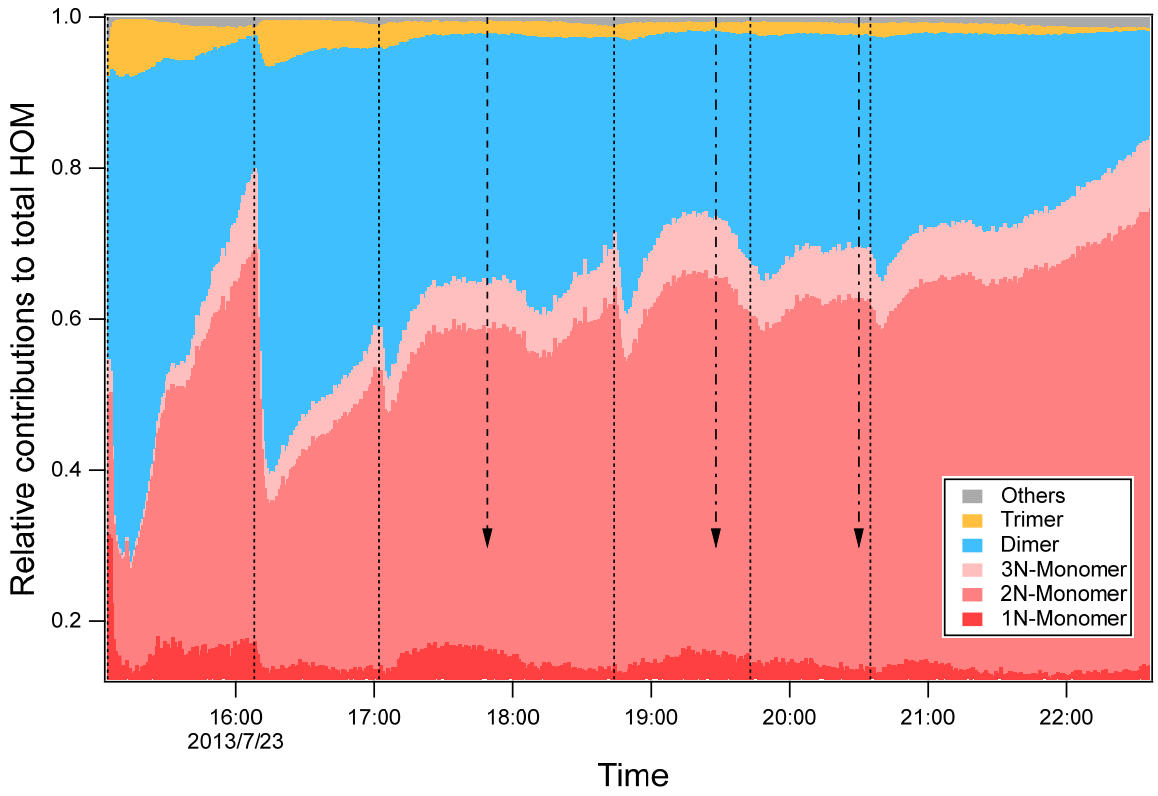


Figure ~~S14~~S15. Relative contributions of HOM monomers, dimers, and trimers. Monomer 1-3N refers to the monomers containing 1-3 nitrogen atoms. The dashed lines indicate the time of isoprene additions. The long-dashed arrow indicates the time of NO_2 addition. The dash-dotted arrows indicate the time of O_3 additions.

Table S1. Intensity of HOM monomers $C_5H_8NO_n$ and their corresponding termination products.

Series	Peroxy radical	Carbonyl	Hydroxyl[c]	Hydroperoxide[c]	Carbonyl /Hydroxyl
m/z	m	m-17	m-15	m+1	
M1a	$C_5H_8NO_7$ 257.016 1.5%[a]	$C_5H_7NO_6$ 240.013 4.5%	$C_5H_9NO_6$ 242.028 2.5%	$C_5H_9NO_7$ 258.023 13.9%	1.8
M1b	$C_5H_8NO_8$ 273.010 9.7%	$C_5H_7NO_7$ 256.008 8.1%	$C_5H_9NO_7$ 258.023 13.9%	$C_5H_9NO_8$ 274.018 24.9%[c]	0.6
M1a	$C_5H_8NO_9$ 289.0053 11.9%[b]	$C_5H_7NO_8$ 272.0026 34.0%	$C_5H_9NO_8$ 274.0182 24.9%	$C_5H_9NO_9$ 290.0131 28.5%	1.4
M1b	$C_5H_8NO_{10}$ 305.000 22.2%[b]	$C_5H_7NO_9$ 287.998 8.3%	$C_5H_9NO_9$ 290.013 28.5%	$C_5H_9NO_{10}$ 306.008 5.8%	0.3
M1a	$C_5H_8NO_{11}$ 320.995 2.3%	$C_5H_7NO_{10}$ 303.992 3.0%	$C_5H_9NO_{10}$ 306.008 5.8%	$C_5H_9NO_{11}$ 322.003 2.0%	0.5
M1b	~~$C_5H_8NO_{12}$~~ ~~336.990~~ ~~1.7%~~	~~$C_5H_7NO_{11}$~~ ~~319.987~~ ~~3.0%~~	$C_5H_9NO_{11}$ 322.003 2.0%	~~$C_5H_9NO_{12}$~~ ~~337.998~~ ~~2.0%~~	~~1.5~~

[a]: The intensities are average intensity of each peak in MS during the first cycle (C1) normalized to the peak with the maximum intensity ($C_{10}H_{17}N_3O_{13}$).

[b]: These intensities may be subject to higher uncertainties due to the overlap with $C_5H_{10}N_2O_8$ and $C_5H_{10}N_2O_9$.

[c]: The relative contribution of HOM with hydroxyl or hydroperoxide cannot be differentiated and thus the total intensity is listed here.

Table S2. Intensity of HOM monomers $C_5H_9N_2O_n$ and their corresponding termination products.

Series	Peroxy radical	Carbonyl	Hydroxyl	Hydroperoxide	Carbonyl /Hydroxyl
m/z	m	m-17	m-15	m+1	
M2b	$C_5H_9N_2O_8$	$C_5H_8N_2O_7$	~~$C_5H_{10}N_2O_7$~~	$C_5H_{10}N_2O_8$	
	288.021	271.019	~~273.034~~	289.029	
	5.6%[a]	1.3%	~~0.8%~~	99.1%	1.6
M2a	$C_5H_9N_2O_9$	$C_5H_8N_2O_8$	$C_5H_{10}N_2O_8$	$C_5H_{10}N_2O_9$	
	304.0162	287.0135	289.0291	305.024	
	24.9%	57.9%	**99.1%**	82.3%	0.6
M2b	$C_5H_9N_2O_{10}$	$C_5H_8N_2O_9$	$C_5H_{10}N_2O_9$	$C_5H_{10}N_2O_{10}$	
	320.011	303.008	305.024	321.019	
	14.4%	29.7%	82.3%	9.3%	0.4
M2a	$C_5H_9N_2O_{11}$	$C_5H_8N_2O_{10}$	$C_5H_{10}N_2O_{10}$	$C_5H_{10}N_2O_{11}$	
	336.006	319.003	321.019	337.014	
	3.3%	18.3%	9.3%	0.4%	2.0
M2b	$C_5H_9N_2O_{12}$	$C_5H_8N_2O_{11}$	$C_5H_{10}N_2O_{11}$	$C_5H_{10}N_2O_{12}$	
	352.001	334.998	337.014	353.009	
	0.7%	2.5%	0.4%	4.3%	7.1

[a]: The intensities are the average intensities of each peak in MS during the first cycle (C1) normalized to the peak with the maximum intensity ($C_{10}H_{17}N_3O_{13}$).

[b]: The relative contribution of HOM with hydroxyl or hydroperoxide cannot be differentiated and thus the total intensity is listed here.

Table S3. Summary of the 50 major HOM ~~product~~peaks in the reaction of isoprene with NO_3

~~Molecular Formula~~	~~m/Q~~	~~HOM series[a]~~
~~C5H7NO5~~	~~224.017~~	~~Monomer 1~~
~~C5H7NO6~~	~~240.012~~	~~Monomer 1~~
~~C5H8NO10~~	~~241.020~~	~~Monomer 1~~
~~C5H9NO6~~	~~242.028~~	~~Monomer 1~~
~~C5H7NO7~~	~~256.007~~	~~Monomer 1~~
~~C5H8NO6~~	~~257.015~~	~~Monomer 1~~
~~C5H9NO7~~	~~258.023~~	~~Monomer 1~~
~~C5H11NO7~~	~~260.038~~	~~Monomer 4~~
~~C5H7NO8~~	~~272.002~~	~~Monomer 1~~
~~C5H8NO11~~	~~273.010~~	~~Monomer 1~~
~~C5H9NO8~~	~~274.018~~	~~Monomer 1~~
~~C5H10NO8~~	~~275.025~~	~~Monomer 4~~
~~C5H11NO8~~	~~276.033~~	~~Monomer 4~~
~~C5H8N2O8~~	~~287.013~~	~~Monomer 2~~
~~C5H7NO9~~	~~287.997~~	~~Monomer 1~~
~~C5H8NO7~~	~~289.005~~	~~Monomer 1~~
~~C5H10N2O8~~	~~289.029~~	~~Monomer 2~~
~~C5H9NO9~~	~~290.013~~	~~Monomer 1~~
~~C5H10NO9~~	~~291.020~~	~~Monomer 4~~
~~C5H11NO9~~	~~292.028~~	~~Monomer 4~~
~~C5H9N3O10~~	~~302.024~~	~~Monomer 2~~
~~C5H8N2O9~~	~~303.008~~	~~Monomer 2~~
~~C5H7NO10~~	~~303.992~~	~~Monomer 1~~
~~C5H9N2O9~~	~~304.016~~	~~Monomer 2~~
~~C5H8NO12~~	~~305.000~~	~~Monomer 1~~
~~C5H10N2O9~~	~~305.023~~	~~Monomer 2~~
~~C5H9NO10~~	~~306.007~~	~~Monomer 1~~
~~C5H11NO10~~	~~308.023~~	~~Monomer 4~~
~~C5H9N3O11~~	~~318.019~~	~~Monomer 2~~
~~C5H9N3O9~~	~~318.019~~	~~Monomer 2~~
~~C5H8N2O10~~	~~319.003~~	~~Monomer 2~~
~~C5H7NO11~~	~~319.987~~	~~Monomer 1~~
~~C5H9N2O10~~	~~320.011~~	~~Monomer 2~~
~~C5H8NO8~~	~~320.995~~	~~Monomer 1~~
~~C5H10N2O10~~	~~321.018~~	~~Monomer 2~~
~~C5H9NO11~~	~~322.002~~	~~Monomer 1~~
~~C5H11NO11~~	~~324.018~~	~~Monomer 4~~
~~C5H9N3O12~~	~~334.014~~	~~Monomer 2~~
~~C5H8N2O11~~	~~334.998~~	~~Monomer 2~~
~~C5H7NO12~~	~~335.982~~	~~Monomer 1~~
~~C5H9N2O11~~	~~336.005~~	~~Monomer 2~~
~~C5H10N2O11~~	~~337.013~~	~~Monomer 2~~
~~C5H9NO12~~	~~337.997~~	~~Monomer 1~~
~~C5H9N3O13~~	~~350.009~~	~~Monomer 2~~
~~C5H9N2O12~~	~~352.000~~	~~Monomer 2~~

C5H8NO9	352.984	Monomer 1
C5H10N2O12	353.008	Monomer 2
C5H9N3O14	366.003	Monomer 2
C5H9N2O13	367.995	Monomer 2
C5H10N2O13	369.003	Monomer 2
C5H9N3O15	381.998	Monomer 2
C5H9N2O14	383.990	Monomer 2
C10H16N2O10	387.065	Dimer 1
C10H18N2O10	389.081	Dimer 4
C10H16N2O11	403.060	Dimer 1
C10H17N2O11	404.069	Dimer R2
C10H18N2O11	405.076	Dimer 4
C10H17N3O11	418.071	Dimer 2
C10H16N2O12	419.055	Dimer 1
C10H17N2O12	420.064	Dimer R2
C10H18N2O12	421.071	Dimer 4
C10H16N3O12	433.059	Dimer R1
C10H17N3O12	434.066	Dimer 2
C10H16N2O13	435.050	Dimer 1
C10H18N2O13	437.066	Dimer 4
C10H15N3O13	448.045	Dimer 5
C10H16N3O13	449.054	Dimer R1
C10H17N3O13	450.061	Dimer 2
C10H16N2O14	451.045	Dimer 1
C10H18N2O14	453.061	Dimer 4
C10H15N3O14	464.040	Dimer 5
C10H16N3O14	465.049	Dimer R1
C10H17N3O14	466.056	Dimer 2
C10H16N2O15	467.040	Dimer 1
C10H18N2O15	469.056	Dimer 4
C10H15N3O15	480.035	Dimer 5
C10H16N3O15	481.044	Dimer R1
C10H17N3O15	482.051	Dimer 2
C10H16N2O16	483.035	Dimer 1
C10H18N2O16	485.050	Dimer 4
C10H15N3O16	496.030	Dimer 5
C10H16N3O16	497.038	Dimer R1
C10H18N4O15	497.062	Dimer 3
C10H17N3O16	498.046	Dimer 2
C10H16N2O17	499.030	Dimer 1
C15H25N3O12	502.129	Trimer 3
C10H15N3O17	512.025	Dimer 5
C10H17N4O16	512.049	Dimer R3
C10H18N4O16	513.057	Dimer 3
C10H17N3O17	514.041	Dimer 2
C15H25N3O13	518.124	Trimer 3
C10H17N4O17	528.044	Dimer R3
C10H18N4O17	529.052	Dimer 3

~~C10H17N3O18~~	~~530.036~~	~~Dimer 2~~
~~C15H25N3O14~~	~~534.119~~	~~Trimer 3~~
~~C10H17N4O18~~	~~544.039~~	~~Dimer R3~~
~~C10H18N4O18~~	~~545.046~~	~~Dimer 3~~
~~C10H17N3O19~~	~~546.031~~	~~Dimer 2~~
~~C15H25N3O15~~	~~550.114~~	~~Trimer 3~~
~~C15H25N3O16~~	~~566.109~~	~~Trimer 3~~
~~C15H25N3O17~~	~~582.104~~	~~Trimer 3~~
~~C15H24N4O17~~	~~595.099~~	~~Trimer 1~~
~~C15H26N4O17~~	~~597.115~~	~~Trimer 4~~
~~C15H25N3O18~~	~~598.099~~	~~Trimer 3~~
~~C15H24N4O18~~	~~611.094~~	~~Trimer 1~~
~~C15H26N4O18~~	~~613.110~~	~~Trimer 4~~
~~C15H25N3O19~~	~~614.094~~	~~Trimer 3~~
~~C15H24N4O19~~	~~627.089~~	~~Trimer 1~~
~~C15H26N4O19~~	~~629.105~~	~~Trimer 4~~
~~C15H25N3O20~~	~~630.089~~	~~Trimer 3~~
~~C15H24N4O20~~	~~643.084~~	~~Trimer 1~~
~~C15H26N4O20~~	~~645.099~~	~~Trimer 4~~
~~C15H25N5O20~~	~~658.095~~	~~Trimer 2~~
~~C15H24N4O21~~	~~659.079~~	~~Trimer 1~~
~~C15H26N4O21~~	~~661.094~~	~~Trimer 4~~
~~C15H25N5O21~~	~~674.090~~	~~Trimer 2~~
~~C15H24N4O22~~	~~675.074~~	~~Trimer 1~~
~~C15H25N5O22~~	~~690.085~~	~~Trimer 2~~

Detected mass (m/Q)	HOM mass (Da)	HOM Formula
256.008	193.022	C5H7NO7
258.023	195.038	C5H9NO7
272.003	209.017	C5H7NO8
273.010	210.025	C5H8NO8
274.018	211.033	C5H9NO8
287.013	224.028	C5H8N2O8
287.997	225.012	C5H7NO9
289.005	226.020	C5H8NO9
289.029	226.044	C5H10N2O8
290.013	227.028	C5H9NO9
303.008	240.023	C5H8N2O9
304.016	241.031	C5H9N2O9
305.000	242.015	C5H8NO10
305.024	242.039	C5H10N2O9
306.008	243.023	C5H9NO10
318.019	255.034	C5H9N3O9
319.003	256.018	C5H8N2O10
320.011	257.026	C5H9N2O10
321.019	258.034	C5H10N2O10
334.014	271.029	C5H9N3O10
351.006	224.028	C5H8N2O8

353.022	226.044	C5H10N2O8
367.001	240.023	C5H8N2O9
368.009	241.031	C5H9N2O9
369.017	242.039	C5H10N2O9
372.055	309.070	C10H15NO10
403.061	340.075	C10H16N2O11
405.076	342.091	C10H18N2O11
419.056	356.070	C10H16N2O12
434.067	371.081	C10H17N3O12
434.067	371.081	C10H17N3O12
435.051	372.065	C10H16N2O13
450.062	387.076	C10H17N3O13
451.046	388.060	C10H16N2O14
464.041	401.055	C10H15N3O14
466.056	403.071	C10H17N3O14
467.040	404.055	C10H16N2O15
482.051	419.066	C10H17N3O15
498.046	435.061	C10H17N3O16
498.059	371.081	C10H17N3O12
499.030	436.045	C10H16N2O17
513.057	450.072	C10H18N4O16
514.041	451.056	C10H17N3O17
514.054	387.076	C10H13N3O13
529.052	466.067	C10H18N4O17
530.036	467.051	C10H17N3O18
611.094	548.109	C15H24N4O18
659.079	596.093	C15H24N4O21
674.090	611.104	C15H25N5O21
675.074	612.088	C15H24N4O22

[a]: The numbering of HOM series is referred to the main text.