

1 **Contrasting impacts of humidity on the ozonolysis of** 2 **monoterpenes: insights into the multi-generation** 3 **chemical mechanism**

4
5 Shan Zhang, Lin Du*, Zhaomin Yang, Narcisse Tsona Tchinda, Jianlong Li, Kun Li*
6 Environment Research Institute, Shandong University, Qingdao 266237, China.

7 *Correspondence to:* Lin Du (lindu@sdu.edu.cn) and Kun Li (kun.li@sdu.edu.cn)
8

9 **Abstract.** Secondary organic aerosol (SOA) formed from the ozonolysis of biogenic monoterpenes is a
10 major source of atmospheric organic aerosol. It has been previously found that relative humidity (RH)
11 can influence the SOA formation from some monoterpenes, yet most studies only observed the increase
12 or decrease in SOA yield without further explanations of molecular-level mechanisms. In this study, we
13 chose two structurally different monoterpenes (limonene with an endocyclic double bond and an
14 exocyclic double bond, Δ^3 -carene with only an endocyclic double bond) to investigate the effect of RH
15 in a set of oxidation flow reactor experiments. We find contrasting impacts of RH on the SOA formation:
16 limonene SOA yield increases by ~100% as RH increases, while there is a slight decrease in Δ^3 -carene
17 SOA yield. Although the complex processes in the particle phase may play a role, we primarily attribute
18 it to the water-influenced reactions after ozone attack on the exocyclic double bond of limonene, which
19 leads to the increment of lower volatile organic compounds under high RH condition. However, as Δ^3 -
20 carene only has an endocyclic double bond, it cannot undergo such reactions. This hypothesis is further
21 supported by the SOA yield enhancement of β -caryophyllene, a sesquiterpene that also has an exocyclic
22 double bond. These results greatly improve our understanding of how water vapor influences the
23 ozonolysis of biogenic organic compounds and subsequent SOA formation processes.

24 **1 Introduction**

25 Secondary organic aerosol (SOA), as an important type of ambient fine particulate matter (PM_{2.5}:
26 aerosols with aerodynamic diameter $\leq 2.5 \mu\text{m}$) (Guo et al., 2014; Huang et al., 2014), has caused a series
27 of negative impacts on human health (Pye et al., 2021), air quality (Zhang et al., 2016) and global climate
28 (Levy et al., 2013). SOA produced from the oxidation of biogenic volatile organic compounds (BVOCs)
29 is a major component of SOA in heavy forest regions during summer (Sindelarova et al., 2014; Ahmadov
30 et al., 2012), and contributes by a large fraction (~40%-80%) to global OA budget (Cholakian et al.,

31 2019).

32 Monoterpenes, mostly emitted from coniferous trees, account for ~11% in total BVOCs
33 (Sindelarova et al., 2014; Kanakidou et al., 2005). Limonene is one of the most abundant monoterpenes,
34 with the annual emission budget of 11.4 Tg yr⁻¹ (Guenther et al., 2012). Apart from the biogenic source,
35 limonene can also be released from the indoor emission, mainly from essential oils (Ravichandran et al.,
36 2018; De Matos et al., 2019; Mot et al., 2022). Limonene has an endocyclic double bond and an exocyclic
37 double bond, and is thus more reactive than other monoterpenes towards oxidants such as ozone (O₃),
38 hydroxyl radical (OH), and nitrate radical (NO₃) (Chen and Hopke, 2010; Atkinson and Arey, 2003). Δ³-
39 carene is another kind of monoterpene that dominates the monoterpene emission from Scots pine (Bäck
40 et al., 2012). Different from limonene, Δ³-carene contains only one endocyclic double bond, which is
41 similar to most other monoterpenes.

42 Ozonolysis is an important reaction pathway for limonene and Δ³-carene. Although reactions with
43 OH and NO₃ are faster than that with O₃ for both two monoterpenes (Atkinson, 1991; Khamaganov and
44 Hites, 2001; Chen et al., 2015; Shaw et al., 2018), the atmospheric concentration of the latter
45 monoterpene is much higher than that of the former (Sbai and Farida, 2019). The contributions of O₃-
46 reactions with limonene and Δ³-carene to tropospheric degradation are 47% and 24%, respectively, in
47 the daytime (Ziemann and Atkinson, 2012). In pristine areas where NO₃ concentration is very low,
48 ozonolysis is also the dominant fate for limonene and Δ³-carene in the nighttime. In addition, it has been
49 previously found that the ozonolysis of monoterpenes can produce more extremely low volatility
50 products than OH-initiated oxidation, which contributes by a large fraction to the SOA production
51 (Jokinen et al., 2015). For either limonene or Δ³-carene, the first step for ozonolysis is attacking on the
52 endocyclic double bond to form two types of stabilized Criegee intermediates (sCI) with low energy (Fig.
53 S1) (Drozd and Donahue, 2011; Chen et al., 2019). The sCI will then trigger a series of chemical reactions,
54 like isomerization, decomposition and addition reactions. Correspondingly, the major components in Δ³-
55 carene SOA are caric acid, OH-caronic acid, and caronic acid (Ma et al., 2009; Thomsen et al., 2021),
56 while the major components from limonene SOA are limonaldehyde, keto-limonon aldehyde, limononic
57 acid and keto-limononic acid (Pathak et al., 2012; Wang and Wang, 2021).

58 Water is ubiquitous in the atmosphere and can affect the formation mechanism of SOA and its
59 relevant physical and chemical properties (Sun et al., 2013). A number of field measurements have shown

60 that the average molecular weight of the water/organic phase and activity coefficient of condensed
61 organics would be changed due to the change of relative humidity (RH) (Seinfeld et al., 2001; Li et al.,
62 2020). In addition, several laboratory studies have demonstrated that RH can influence the ozonolysis of
63 monoterpenes in different ways. Most of those studies have reported either an inhibitory effect or a
64 negligible effect of high RH on the particle formation (Bonn and Moortgat, 2002; Fick et al., 2002; Zhao
65 et al., 2021; Ye et al., 2018). Nevertheless, few other studies found that high RH can promote SOA
66 formation from the ozonolysis of limonene (Yu et al., 2011; Gong et al., 2018; Xu et al., 2021), but the
67 reason of this promotion effect remains unclear.

68 To fully examine the effects of water on SOA formation from the ozonolysis of monoterpenes,
69 especially the related chemical processes, we used an oxidation flow reactor (OFR) to investigate the
70 ozonolysis of limonene and Δ^3 -carene under different RH conditions in this study. An ultra-high
71 performance liquid chromatography with a quadrupole time-of-flight mass spectrometer (UPLC-Q-TOF-
72 MS) was deployed to analyze the molecular chemical composition of the SOA, which provided insights
73 into the physical and chemical processes influenced by the water content. With these state-of-the-art
74 techniques, we proposed mechanisms that may explain the inhibitory or enhancing RH effects on SOA
75 formation for different monoterpenes.

76 **2 Experimental methods**

77 **2.1 Oxidation flow reactor experiments**

78 A series of dark ozonolysis experiments of limonene and Δ^3 -carene were conducted in a custom-
79 made oxidation flow reactor (OFR). The OFR is a 602 mm long stainless cylinder with a volume of 2.5
80 L (Fig. S2) (Liu et al., 2019; Liu et al., 2014). A zero-air generator (XHZ2000B, Xianhe, China) was
81 used to generate dry clean air as the carrier gas for the OFR. As shown in Fig. S2, there are four gas paths
82 upstream of the OFR: the first path is the precursor gas channel through which monoterpenes are injected
83 via a syringe pump (ISPLab 01, Shenchen, China); the second path is for the flow of 300 sccm dry zero
84 air passing through a mercury lamp ($\lambda = 185$ nm) to generate O_3 ; the third path is connected to a water
85 bubbler to generate wet air; the fourth path is the extra dry zero air entering the OFR. The RH in the OFR
86 was controlled by adjusting the ratio of the wet and dry zero air flows. A water recycle system was
87 equipped to keep the temperature (T) around at 298 K. The total flow was 0.9 L min^{-1} , resulting in an

88 average residence time of 167 s. The RH and T in the OFR were monitored by a T/RH Sensor (HM40,
 89 VAISALA, Finland). The concentration of ozone and the consumption of the precursor gas were
 90 measured with an ozone monitor (Model 106L, 2B Technologies, USA) and a gas chromatography with
 91 flame ionization detector (GC-FID 7890B, Agilent Technologies, USA), respectively. The GC was
 92 equipped with a DB-624 column (30 m × 0.32 mm, 1.8 μm film thickness) whose temperature was set
 93 to ramp from 100 °C to 180 °C at a rate of 20 °C min⁻¹, and then held at 180 °C for 2 min. Before each
 94 experiment, O₃ was introduced into the OFR to clean it until the background aerosol mass concentration
 95 reached < 1 μg m⁻³.

96 The experimental conditions are shown in Table 1. In these OFR experiments, the precursor
 97 (limonene or Δ³-carene) concentration was set to ~320-340 ppb. A high O₃ concentration of ~6 ppm was
 98 used to realize an equivalent aging time of 0.41 day in the real atmosphere, assuming an average ambient
 99 O₃ concentration of 28 ppb (Sbai and Farida, 2019) (see Section S1 for the calculation). Under such
 100 conditions, most of the precursors were consumed, since the residence time was almost five and three
 101 times of the half-life for limonene and Δ³-carene, respectively. Correspondingly, the O₃ consumption for
 102 limonene and Δ³-carene were ~250 ppb and ~100 ppb, respectively. A series of RH conditions ranging
 103 from dry (1-2%) to 60% with a step of ~10% were used to investigate the effects of water content on
 104 SOA production and composition (see Table 1). All materials used in the experiments have been
 105 described in Section S2.

106 **Table 1.** Experimental conditions and results.

Exp.	[Precursor] (ppb)	[O] ₃ (ppm)	T (K)	RH (%)	N _(13.8-723.4 nm) ^a (cm ⁻³)	M _(13.8-723.4 nm) ^b (μg m ⁻³)	D _(mean) ^c (nm)	SOA yield (%)
limonene								
1	321±39	5.7	298	1–2	6.9×10 ⁵	980.9	138.2	62.9
2	321±39	6.0	298	10±2	1.3×10 ⁶	1377.5	126.8	88.4
3	321±39	5.9	298	20±2	9.0×10 ⁵	1573.3	150.9	90.2
4	321±39	5.9	298	30±2	1.4×10 ⁶	1573.3	128.9	100.9
5	321±39	6.0	298	40±2	1.7×10 ⁶	2051.4	130.7	131.6
6	321±39	5.5	298	50±2	1.5×10 ⁶	1962.7	137.8	125.9

7	321±39	5.5	298	60±2	1.5×10 ⁶	2211.1	139.0	141.8
Δ^3 -carene								
8	341±28	6.1	298	1–2	9.5×10 ⁴	346.0	195.8	19.4
9	341±28	6.4	298	10±2	1.4×10 ⁵	300.3	163.4	16.8
10	341±28	6.4	298	20±2	9.4×10 ⁴	244.9	176.9	13.7
11	341±28	6.0	298	30±2	5.9×10 ⁴	241.2	205.1	13.5
12	341±28	6.3	298	40±2	4.6×10 ⁴	205.8	203.2	11.5
13	341±28	6.3	298	50±2	6.8×10 ⁴	196.7	180.7	11.0
14	341±28	6.3	298	60±2	5.6×10 ⁴	198.5	190.2	11.1

107 ^a N_(14.1-735 nm) means the total particle number concentration from size 13.8 nm to 723.4 nm. ^b M_{(13.8-723.4}
108 nm) means the total particle mass concentration from size 13.8 nm to 723.4 nm. ^c D_(mean) means the particle
109 mean diameter.

110 2.2 SOA particle analysis

111 2.2.1 SOA yield

112 The SOA particle size distribution was measured with a scanning mobility particle sizer (SMPS),
113 which consists of a differential mobility analyzer (DMA) (model 3082, TSI Inc., USA) and a
114 condensation particle counter (CPC) (model 3776, TSI Inc., USA). The samples were measured by SMPS
115 every 5 minutes with a sampling flow and a sheath flow of 0.3 L min⁻¹ and 3 L min⁻¹, respectively. The
116 SOA mass concentration was calculated from the volume concentration measured with SMPS and the
117 aerosol density, which was estimated to be 1.25 cm⁻³ for limonene- and 1.09 g cm⁻³ for Δ^3 -carene-SOA
118 (Thomsen et al., 2021; Watne et al., 2017).

119 The SOA yield (Y) for individual organic gas can be calculated as:

$$120 Y = \frac{\Delta M}{\Delta HC}$$

121 Where ΔM is the total mass concentration of SOA, ΔHC is the mass concentration of reacted precursor
122 (Ng et al., 2007; Odum et al., 1996).

123 2.2.2 Ultra-high performance liquid chromatography quadrupole time-of-flight mass spectrometry 124 analysis

125 An ultra-high performance liquid chromatography (UPLC, UltiMate 3000, Thermo Scientific)
126 coupled with a quadrupole time-of-flight mass spectrometry (Q-TOFMS, Bruker Impact HD) was used

127 to analyze the molecular-level chemical composition of SOA. First, the SOA particles were collected on
128 the PTFE filters (47 mm diameter, 0.22 μm pore size, Jinteng, China). Next, these filters were dissolved
129 and extracted by 5 mL methanol for two times. Extracts were then filtered through PTFE syringe filters
130 (0.22 μm pore size), and were concentrated to near dryness by nitrogen-blowing. At last, the samples
131 were redissolved in a 200 μL solution with 0.1% (v/v) formic acid in 50:50 methanol/ultrapure water
132 mixture.

133 The parameters of LC-MS were set as follows: capillary voltage 4000 V, nebulizer pressure 0.4 bar,
134 dry heater temperature 200°C, end plate voltage -500 V, and flow of dry gas 4 L min^{-1} . A C_{18} column
135 (100 \AA , 3 mm particle size, 2.1 mm \times 50 mm, Waters, USA) was used with a column temperature of 35°C.
136 The mobile phase was 0.1 % formic acid in methanol (A) and 0.1 % formic acid in ultra-high purity
137 water (B) with a flow of 200 $\mu\text{L min}^{-1}$. The injection volume was 5 μL . The MS was operated in negative
138 ion mode, and the detection molecular weight range was from m/z 50 to 1500. The temperature ramp
139 program was: 0–3min with 0%–3% phase B, 3–25min with 3%–50% phase B, 25–43min with 50%–90%
140 phase B, 43–48 min with 90%–3% phase B, 48–60min with 3% phase B.

141 **3 Results and discussion**

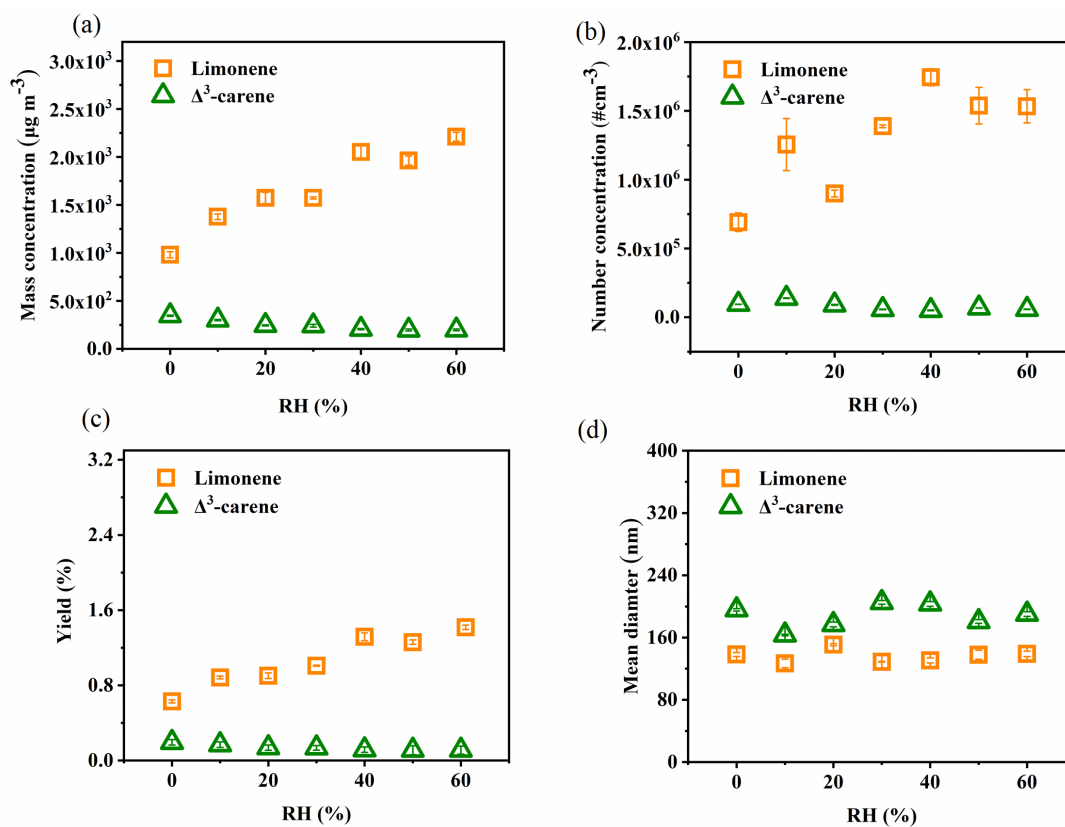
142 **3.1 SOA production under different RH conditions**

143 SOA formation of a representative experiment is shown in Fig. S3. It is found that the formed SOA
144 are mainly in the size range of 60-200 nm, and the number concentration and mass concentration are
145 relatively stable during the course of the OFR experiment. SOA formation from limonene and Δ^3 -carene
146 in terms of particle number concentration, particle mass concentration, and SOA yield as a function of
147 RH are illustrated in Fig. 1a-c. We find that all the above-mentioned 3 parameters of limonene-SOA
148 increase with the increasing RH. The increment of particle mass concentration and SOA yield from the
149 ozonolysis of limonene is $\sim 100\%$ higher at wet (60% RH) than at dry conditions. In contrast, SOA
150 formation from Δ^3 -carene is suppressed by $\sim 40\%$ under high RH. The distinct effects of RH on SOA
151 formation from the ozonolysis of limonene and Δ^3 -carene found in this study agree with most previous
152 studies (Yu et al., 2011; Jonsson et al., 2006b; Bonn et al., 2002; Gong and Chen, 2021; Li et al., 2019b).
153 As shown in Table 2, Yu et al. (2011) reported a positive correlation between SOA production and RH
154 for the ozonolysis of limonene in the chamber experiments without OH scavenger. Their experimental

155 condition is similar to that in our study regarding the absence of OH scavenger and, thus, similar results
156 were observed. However, in the presence of OH scavenger, results are quite different. Jonsson et al. (2006)
157 observed a similar enhancement effect of high RH on SOA production with 2-butanol as the OH
158 scavenger, while Bonn et al. (2002) found a negligible or suppressive effect with cyclohexane as the OH
159 scavenger. It should be noted that the OH scavenger not only has the ability to scavenge OH but also
160 produces additional products which may influence the reactions of target precursors. For example, there
161 is no difference between 2-butanol and cyclohexane in the scavenging ability of OH radical, though 2-
162 butanol will produce more HO₂· than cyclohexane and, consequently, R· will react with HO₂· to produce
163 more hydroxyl acids and hydroxyl per-acid products, most of which have low volatility and, thus high
164 partitioning into the particle phase. According to previous studies, the influence of different OH
165 scavengers can vary (Jonsson et al., 2008). This may explain the different findings with and without OH
166 scavenger for limonene-SOA. With regard to Δ³-carene, similar results are found in the absence of OH
167 scavenger, namely, high RH has negligible or slightly suppressive effect on SOA production (Bonn et al.,
168 2002; Fick et al., 2002). Same as limonene, the presence of OH scavenger and its different chemical
169 nature can explain the different results found previously (Jonsson et al., 2006a; Bonn et al., 2002).

170 The enhancement in limonene-SOA production under high RH can be due to several reasons from
171 either physical or chemical processes. First, the hygroscopic growth of the particles (i.e., absorption of
172 water content) can lead to higher mass concentration under higher RH, but the enhancement should be
173 at most ~30% as the growth factor (GF, the ratio of wet and dry diameter: $D_{\text{wet}}/D_{\text{dry}}$) of limonene-SOA is
174 ≤ 1.1 (Varutbangkul et al., 2006). However, we do not observe an obvious change in the mean diameter
175 when comparing dry and wet conditions (Fig. 1d). In addition, hygroscopic growth should also occur for
176 Δ³-carene SOA, but no obvious enhancement in particle mass is observed (Fig. 1a). Therefore, it is
177 suggested that physical processes regarding hygroscopic growth play a minor role in the enhancement in
178 limonene-SOA under high RH. As a consequence, we believe that chemical processes are likely the
179 reason of the enhancement in limonene-SOA under high RH. Water can influence chemical processes in
180 the gas phase or in the particle phase. Particle-phase reactions can promote the growth of small particles
181 and, thus, mainly lead to larger particle sizes. As the observed SOA enhancement is mainly from high
182 number concentration particles rather than the large size particles (Fig. 1b and 1d), it is likely that the
183 water-participated gas-phase reactions are the most possible reasons for the limonene-SOA enhancement.

184 The reaction mechanism is analyzed below based on the mass spectra information on the SOA.



185

186 **Figure 1.** The effect of RH on the SOA formation: (a) number concentration, (b) mass concentration, (c)

187 SOA yield, (d) mean diameter.

188

Table 2. Comparison with previous studies on the effect of RH.

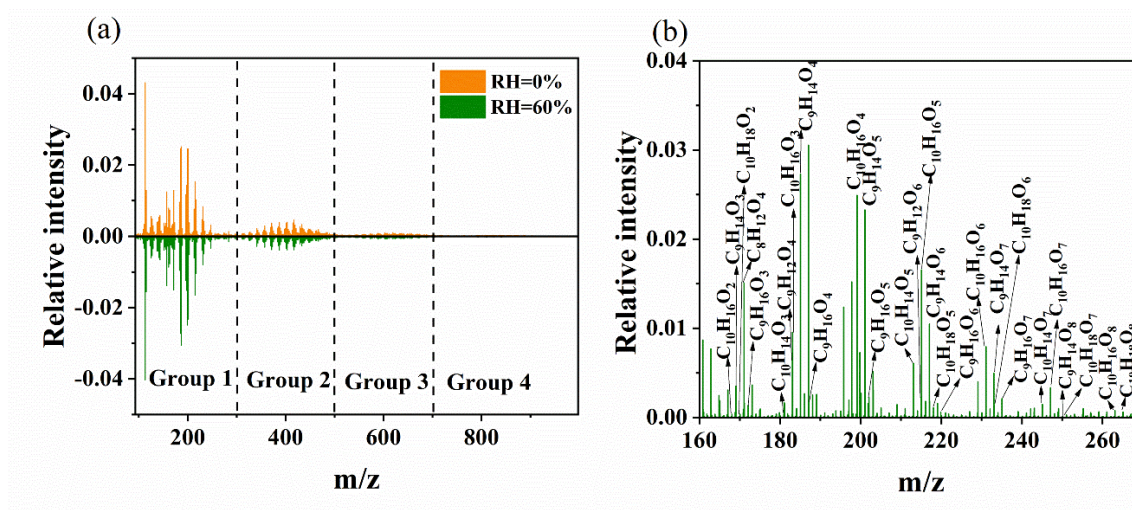
Precursor	Precursor	O ₃ concentration	Reactor	OH scavenger	T (K)	RH (%)	SOA Mass		M ^a	N ^b	Reference
	concentration	(ppb)					Concentration	SOA Yield (%)			
	(ppb)						(μg/m ³)				
limonene	1000	1000	flow reactor	cyclohexane	295±2	0.02 and 32.5	N.M ^c	N.M ^c	no effect	- ^c	Bonn et al. (2002)
	320	100±5	chamber	N.M. ^c	296±2	18±2, 50±3 and 82±2	24; 58; 120	17.4±1.3; 53.4±1.9	+ ^d (7 times)	+ ^d (8 times)	Yu et al. (2011)
	15 and 30	430.9	flow reactor	2-butanol	298±0.4	< 2-85	2.7-10.5 and 62-229	6.8-26.4 and 77.4-285.7	+ ^d	+ ^d	Jonsson et al. (2006)
	endocyclic (24.6) and exocyclic (15.2)	endocyclic (270) and exocyclic (12200)	flow reactor	2-butanol	298	10-50	(~11) and exocyclic (22-51)	(~7.4) and exocyclic (23.8-55.3)	(+ ^d) and endocyclic (- ^c)	N.M ^c	Gong and Chen (2021)
	1085	900±10	flow reactor	none	298	3-62	150; 200; 210	N.M	+ ^d	- ^c	Li et al. (2019)

	321±39	5786±203	flow reactor	none	298	0-60	980.9-2211.1	62.9-141.8	+ ^d (2 times)	+ ^d (3 times)	this study
	1000	1000	flow reactor	cyclohexane	295±2	0.02 and 32.5	N.M ^c	N.M ^c	no effect	- ^c	Bonn et al. (2002)
	14.2 and 29.4	2300	flow reactor	2-butanol	298±0.4	< 2-85	0.78-3.8 and 15.3-94;	2.1-10.1and 19.8- 116.7	+ ^d	+ ^d	Jonsson et al. (2006)
Δ ³ -carene	1111	900±10	flow reactor	none	298	3-62	75; 80; 90	N.M	- ^c	- ^c	Li et al. (2019)
	341±28	6257±140	flow reactor	none	298	0-60	346.0-198.5	19.4-11.1	- ^c	no effect	this study

190 ^a M means the change trend total particle mass concentration. ^b N means total particle number concentration. ^c N.M. means not mentioned. ^d Positive sign (+) means the
191 mass or number concentration increases with RH. ^e Negative sign (-) means the mass or number concentration decreases with RH.

192 **3.2 Molecular analysis of SOA particles**

193 The UPLC/ESI-Q-TOF-MS was used to examine the SOA molecular composition under high and
 194 low RH conditions. As shown in Fig. 2a, the mass spectra of limonene-SOA are divided into four groups:
 195 monomeric group (<m/z 300), dimeric group (m/z 300-500), trimeric group (m/z 500-700), and
 196 tetrameric group (m/z 700-1000), corresponding to products containing one, two, three, and four
 197 oxygenated limonene units, respectively (Bateman et al., 2009). Most of the SOA molecules are
 198 monomers (>60%) (Fig. 2b) and dimers (~25%), while trimers and tetramers contribute to very small
 199 fractions (<10% and ~3%) (Table S1). Correspondingly, the distribution of Δ^3 -carene-SOA can be
 200 divided into four groups (Fig. S4), comparable to that of limonene-SOA. Most of the SOA molecules are
 201 monomers (~70%) and dimers (~25%), while trimers and tetramers contribute to smaller proportions (~2%
 202 and <1%, respectively) (Table S2). Although the SOA mass concentration increases by ~100% under
 203 high RH condition, the relative intensities of MS peaks do not significantly change with varying RH
 204 conditions. In other words, we did not observe an obvious change in the overall MS patterns, and the
 205 fractions of the four groups only slightly differed under different RH conditions, e.g., the fraction of
 206 monomers was 62% under dry condition and 66% under wet conditions. However, if we take a closer
 207 look, the intensities and contributions of specific peaks are quite different with varying RH. For example,
 208 the relative intensity of $C_{10}H_{16}O_2$, a possible first-generation product (Gong et al., 2018), decreases by
 209 ~20% with increasing RH from dry to 60% (Table S3). This is likely due to the multi-generation reactions
 210 influenced by water vapor concentration, as discussed below with the proposed reaction mechanism of
 211 limonene ozonolysis.



212

213 **Figure 2.** UPLC/ (-) ESI-Q-TOF-MS mass spectra of SOA from limonene ozonolysis. (a) MS under
214 high and low RH conditions; (b) the identification of monomers under high RH condition.

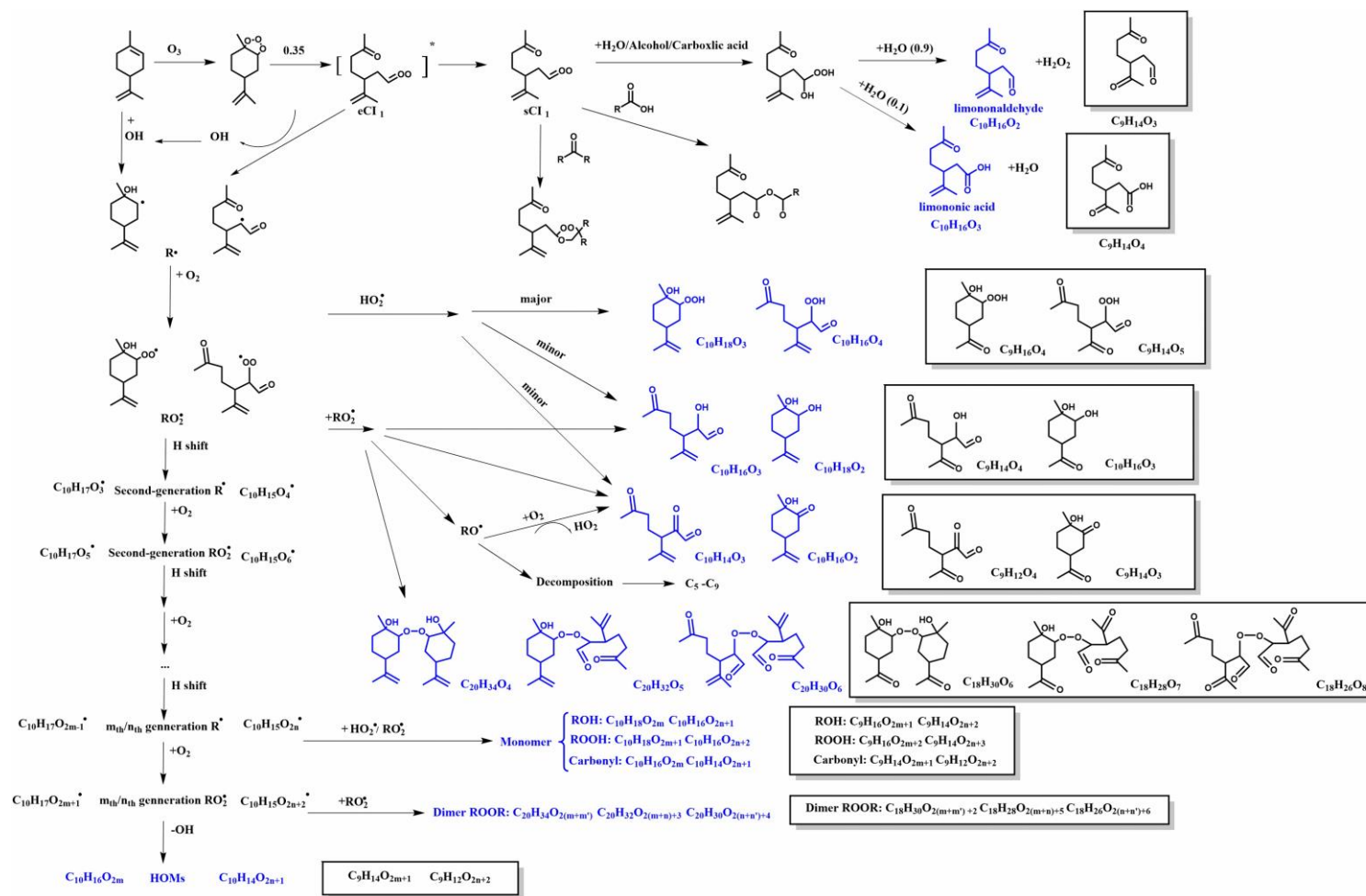
215 The proposed reaction mechanism of limonene ozonolysis is shown in Fig. 3 and Fig. 4. The initial
216 step in the reaction of O₃ with limonene is the attack of the endocyclic double bond to form eCI₁ and
217 eCI₂ (with branching ratios of 0.35 and 0.65, respectively). In the context of eCI₁, several complex
218 reactions occur, with the most dominant reaction being the generation of hydroxyl radicals (OH) and a
219 reaction pathway known as sCI₁. The sCI₁ pathway can proceed through three distinct reactions, as
220 depicted in Fig. 3. The first pathway is the reaction with H₂O, alcohol or carboxylic acid to form a
221 carboxylic acid species with hydroxyl, which would subsequently lose a molecule of water to form
222 limononaldehyde or lose a molecule of hydrogen peroxide to form limononic acid (Grosjean et al., 1992;
223 Li et al., 2019b). The second and third pathways involve reactions of sCI₁ with carboxylic acids and
224 carbonyls, respectively, leading to the formation of anhydrides and secondary ozonides. Additionally, the
225 generated OH radicals can react with limonene, giving rise to another alkyl radical, C₁₀H₁₇O·. These
226 alkyl radicals react with O₂ and form peroxy radicals (RO₂·). The atmospheric fate of produced RO₂· in
227 the absence of NO_x includes the reaction with RO₂· or HO₂· (Atkinson and Arey, 2003) and the
228 unimolecular H shift. The RO₂·+HO₂· route mainly form hydroperoxide (ROOH), and the minor fraction
229 is to form alcohols and carbonyls (Atkinson and Arey, 2003). The products of bimolecular reactions
230 between RO₂· and RO₂· are alcohols, carbonyls, alkoxy radicals, peroxides and ROOR dimers (Hammes
231 et al., 2019; Peng et al., 2019). The H shift of RO₂· can form second-generation R· and trigger a main
232 generation channel of highly oxidized molecules (HOMs), i.e., R· would go through a process of repeated
233 oxygen addition and hydrogen-atom shift to form HOMs with high O/C ratios of > 0.7–0.8 (Molteni et
234 al., 2018; Bianchi et al., 2019).

235 In addition to the eCI₁ route, the eCI₂ pathway is also responsible for the generation of various
236 products (Fig. 4). Since the reaction of the hydroxyl radical (OH) attacking limonene is already depicted
237 in Fig. 3, our main emphasis in Fig. 4 is on the pathways involved in the generation of SCI. First, sCI₂
238 reacts with H₂O and decomposes to limononaldehyde and H₂O₂. Additionally, sCI₂ could experience an
239 O₂ addition, ·OH loss and isomerization to produce two types of RO₂·, which can undergo the similar
240 reactions as the RO₂· formed from the sCI₁ route, and the major products are also shown in Fig. 4.

241 Since limonene and Δ³-carene both have an endocyclic double bond, the similar reactions as

242 mentioned above can occur for the ozonolysis of Δ^3 -carene (Fig. S5), and most corresponding formula
243 in Fig. S5 could be identified in Table S4. However, the reactivity of limonene towards O_3 is expected to
244 be higher owing to its exocyclic double bond. As shown in Fig. 4, the attack of O_3 to the exocyclic double
245 bond mainly leads to sCl_3 (highlighted in red) with the unpaired electrons outside the ring (Leungsakul
246 et al., 2005). sCl_3 can react with H_2O to form a carbonyl called keto-limonene. It should be noted that
247 this reaction can occur not only for limonene, but also for all the products that retain the exocyclic double
248 bond. As a result, the compounds that are colored in blue in Fig. 3 and Fig. 4 can undergo further reactions
249 to generate products with an additional carbonyl (see the boxes in Fig. 3 and Fig. 4). Furthermore, their
250 molecular formula shown in Table S5 have been identified using the Q-TOF-MS. This mechanism can
251 well explain the decrease in the relative intensity of $C_{10}H_{16}O_2$ from high RH to low RH and the increase
252 in the relative intensity of $C_9H_{14}O_3$ from low RH to high RH (Table S3).

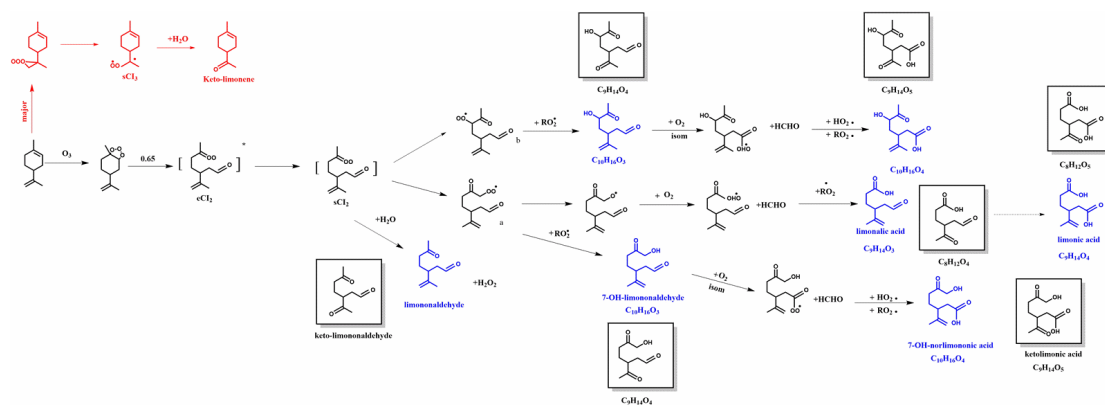
253 In such progress, we cannot rule out the possibility that relative humidity (RH) may influence the
254 generation of other free radicals (Ma et al., 2009), thereby impacting the formation of secondary organic
255 aerosols (SOA), such as, OH-radical reactions (Bonn et al., 2002; Fick et al., 2002). However, Molar OH
256 radical yields were reported as 0.65 ± 0.10 (Hantschke et al., 2021), 0.86 ± 0.11 (Aschmann et al., 2002)
257 and 0.56 to 0.59 (Wang et al., 2019) for Δ^3 -carene, while for limonene, the reported yields were 0.67 ± 0.10
258 (Aschmann et al., 2002) and 0.76 ± 0.06 (Herrmann et al., 2010). It seems that the OH radicals produced
259 from limonene and Δ^3 -carene are quite similar within the range of uncertainties. Therefore, the increased
260 ozone consumption by limonene seems primarily attributed to the presence of its exocyclic double bond.



261

262 **Figure 3.** Proposed formation mechanism for SOA formation from eCI₁ oxidation under high RH. The compounds in blue and in boxes are identified using UPLC/(-) ESI-Q-

263 TOF-MS.



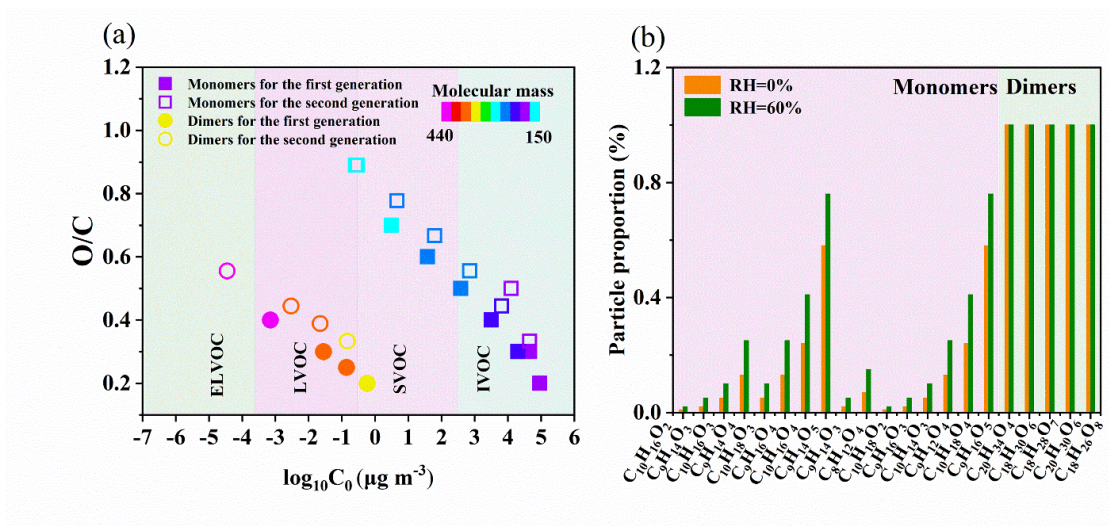
264

265 **Figure 4.** Proposed formation mechanisms for SOA formation from eCl₂ and exocyclic double bond
 266 oxidation under high RH. The compounds in blue and in boxes are identified using UPLC/ (-) ESI-Q-
 267 TOF-MS.

268

269 **3.3 Processes leading to the increase or decrease in SOA formation**

270 Based on the results and mechanisms shown above, we present evidence that high humidity
 271 enhances limonene-SOA formation. First, the presence of water vapor enhances the formation of
 272 carbonyls from the reaction of exocyclic double bond, and the oligomerization of these carbonyls
 273 generates more dimers including hemiacetal (or acetal) formation and aldol condensation (Zhang et al.,
 274 2022; Kroll et al., 2005; Jang et al., 2003). As shown in Table S6, the intensity of dimers generating from
 275 multi-carbonyls under high RH is higher than that under low RH, and 54 out of the total 187 dimers were
 276 exclusively observed for limonene under high humidity conditions, contributing to a corresponding
 277 intensity of ~19% (Table S7). These dimers can be classified as low-volatile organic compounds (LVOC;
 278 $3 \times 10^{-4} < C_0 < 0.3 \mu\text{g m}^{-3}$) and extremely low-volatile organic compounds (ELVOCs; $C_0 < 3 \times 10^{-4} \mu\text{g}$
 279 m^{-3}) (Fig. 5a), and thus promote the nucleation and new particle formation in different ways. This finding
 280 is similar to that from a previous study showing that high RH can promote dimer formation from the
 281 ozonolysis of α -pinene (Kristensen et al., 2014). Second, we find that high RH can also promote the
 282 formation of HOMs, although the mechanism remains unclear. As shown in Table S3, many HOMs
 283 proposed from the mechanism are detected under high RH condition but not detected under low RH
 284 condition, including both monomers and dimers. Many HOMs have low volatilities and, thus, can also
 285 promote new particle formation. Overall, the promoted dimer and HOM formation may greatly enhance
 286 the new particle number concentration under high RH condition (Fig. 6).

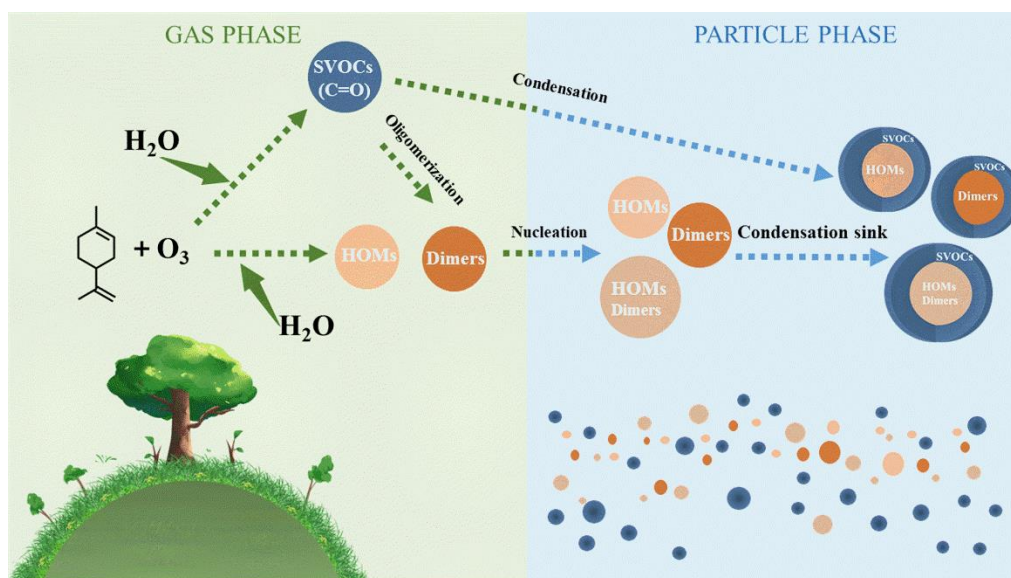


287

288 **Figure 5.** (a) Distribution of the limonene-SOA in the two-dimensional volatility basis set (2D-VBS)

289 space. (b) Partitioning coefficients of limonene monomers and dimers under low and high RH conditions.

290



291

292 **Figure 6.** Schematic diagram of the possible mechanisms for the enhancement of limonene-SOA.

293

294 High particle number concentration generally provides more surface areas for semi-volatile organic
 295 compounds (SVOCs; $0.3 < C_0 < 300 \mu\text{g m}^{-3}$) to condense on, which results in higher condensation sink
 296 (CS). In the OFR, the fates of SVOCs include condensing on aerosol, getting lost on the wall, and reacting
 297 with OH radicals to form functionalization and/or fragmentation products (Palm et al., 2016; Li et al.,
 298 2019a). The promoted condensation by higher CS leads to a higher fraction of SVOCs getting into the
 299 particle phase rather than getting lost on the wall or becoming smaller fragments staying in the gas phase,

300 and thus promoting SOA formation (Li et al., 2019a). Furthermore, the transformation from C-C double
301 bond to carbonyl shown in Fig. 3 and Fig. 4 decreases the volatility of molecules, which can largely
302 influence the gas-particle partitioning of the monomeric compounds (Fig. 5b). For example, the C_0 values
303 of $C_{10}H_{16}O_2$ and $C_{10}H_{16}O_3$ are 90701 and 19968 $\mu\text{g m}^{-3}$, corresponding to partitioning coefficients of
304 0.01 and 0.05, respectively (Fig. 5b and Table S3), with an SOA mass concentration of $\sim 1000 \mu\text{g m}^{-3}$
305 under dry condition. When they are converted to carbonyls $C_9H_{14}O_3$ and $C_9H_{14}O_4$, the values of C_0
306 become 45556 and 6479 $\mu\text{g m}^{-3}$, corresponding to partitioning coefficients of 0.02 and 0.13, respectively
307 (Fig. 5b and Table S3), with the same SOA loading. This enhancement in partitioning coefficient can
308 largely promote the condensation of SVOCs and, thus, enhance the SOA mass concentration. In addition,
309 the enhanced SOA formation can further influence the equilibrium, e.g., the partitioning coefficient of
310 $C_{10}H_{16}O_3$ increases from 0.05 to 0.10 when SOA mass concentration increases from $\sim 1000 \mu\text{g m}^{-3}$ under
311 dry condition to $\sim 2000 \mu\text{g m}^{-3}$ under wet condition (Fig. 5b and Table S3). The distribution of saturation
312 vapor pressure for monomers and dimers identified by MS has also been shown in Fig. 5a. As can be
313 seen from this figure, around 50% monomers are categorized as SVOCs, thus having the large fraction
314 in the particle phase when converting from dry to wet conditions. Overall, it is likely that the different
315 fate and partitioning of SVOCs largely enhance the amount of SVOCs in the particle phase (Fig. 6).

316 Concluding the analysis above, high humidity promotes the SOA formation from the ozonolysis of
317 limonene in two steps: nucleation of new particles and condensation of SVOCs on them (Fig. 6). While
318 our study highlights significant changes in gas-phase chemistry, we cannot exclude the possibility of
319 concurrent reactions occurring in the condensed phase. These two steps are closely related to the multi-
320 generation reactions of the exocyclic C=C bond, which are unlikely to happen for the ozonolysis of Δ^3 -
321 carene. Interestingly, Gong and Chen (2021) have found that high RH can inhibit the SOA formation
322 from the first-generation oxidation of limonene ozonolysis, but enhance the SOA formation from the
323 second-generation oxidation (Gong and Chen, 2021), their results agree well with the results and analysis
324 shown here. In contrast, Li et al. (2019b) found negligible change in dimers and HOMs in limonene- O_3
325 system when changing RH from 0 to 60%. The discrepancy is mainly attributed to the different
326 experimental conditions. The ozone exposure in this study is ~ 18 times higher than in Li et al. (2019b),
327 while the limonene concentration in this study is only $\sim 30\%$ of that in their study. These two conditions
328 both favor the multi-generation reactions occurred at the exocyclic double bond of limonene and its

329 products. Thus, we believe this leads to the different results regarding the formation of HOMs and dimers.

330 Regarding Δ^3 -carene, the mechanisms and processes are almost opposite to those of limonene. First,
331 water vapor reacts with $s\text{Cl}_1$ or $s\text{Cl}_2$ to promote the formation of α -hydroxyalkyl-hydroperoxides (Fig.
332 S5). Their subsequent products without second ozonolysis of exocyclic double bond have higher
333 volatility, and may most likely prevail in the gas phase. In addition, it has been found that α -hydroxyalkyl
334 hydroperoxides preferentially decompose into aldehydes and H_2O_2 (Kumar et al., 2014; Chen et al., 2016),
335 i.e., 3-caronaldehyde for Δ^3 -carene, which has higher volatility than the products from other reaction
336 pathways. Correspondingly, the number and relative intensity of HOMs and dimers detected under high
337 RH conditions are both lower than those under low RH conditions (Table S8). Furthermore, out of a total
338 of 178 dimers, 63 dimers were exclusively identified under low RH conditions (Table S7). As a result,
339 high RH shows an inhibitory effect on the SOA formation from Δ^3 -carene ozonolysis.

340 To investigate the multi-generation reactions of limonene under low-concentration conditions, we
341 conducted low-concentration limonene ozonolysis experiments, and the results are shown in Fig. S6. In
342 these experiments, the limonene and O_3 concentrations were 20.5 ppb and 5.7 ppm, respectively.
343 According to the experimental results, the number concentration of SOA formed from limonene
344 ozonolysis increased by approximately 1.4 times under high RH, which is similar to the increase observed
345 under high-loading conditions. The mass concentration increased by approximately 1.3 times at a
346 precursor concentration of 20.5 ppb. The relatively small increase in mass concentration compared to the
347 high-concentration conditions may be attributed to the less pronounced distribution of SVOCs at low
348 mass concentrations. This result suggests that the enhancement effect on limonene SOA by high RH is
349 still valid for low precursor concentrations.

350 To further confirm the assumption that water-influenced multi-generation reactions of the exocyclic
351 double bond enhance the SOA formation, we conducted two comparative analyses: firstly, we examined
352 the ozonolysis of the endocyclic double bond in limonene, leaving the exocyclic double bond unreacted.
353 This was done by applying a low O_3 concentration (~ 67 ppb), since the reaction of O_3 with endocyclic
354 double bond is ~ 30 times faster than the reaction of O_3 with exocyclic double bond (Shu and Atkinson,
355 1994). Interestingly, when limonene was oxidized at only the endocyclic double bond, we observed a
356 slight decrease in both the number and mass concentrations as the RH increased (Fig. S7). This is similar
357 to the results obtained for Δ^3 -carene, which contains only one endocyclic double bond. Secondly, we

358 compared the ozonolysis of structurally similar β -caryophyllene, which has an exocyclic C-C double
359 bond that can undergo further reactions (Fig. S8). As expected, we observe a large enhancement in SOA
360 formation under high RH condition (Table S9 and Fig. S9). This implies that monoterpenes,
361 sesquiterpenes, and other BVOCs with two unsaturation double bonds may follow similar reaction
362 mechanisms during ozonolysis, and thus have a RH dependency in SOA production.

363 **4 Conclusions**

364 In this study, the effect of humidity on SOA production from the ozonolysis of two monoterpenes
365 (limonene and Δ^3 -carene) was investigated with an OFR. Contrasting impacts of RH on the SOA
366 formation were observed: limonene-SOA yield increases by $\sim 100\%$ when RH changes from $\sim 1\%$ to
367 $\sim 60\%$, while Δ^3 -carene-SOA yield slightly decreases. By analyzing the chemical composition of SOA
368 with ESI-Q-TOF-MS, we find that the multi-generation reactions of the exocyclic C-C double bond are
369 likely the driving force of the enhancement in limonene-SOA. The presence of water promotes the
370 formation of carbonyls from the reaction of exocyclic double bond, and further favors the formation of
371 dimers and HOMs. This leads to promoted new particle formation and subsequent condensation of
372 SVOCs. These reactions also lower the volatilities of the SVOCs, and further promote the gas-particle
373 partitioning. Moreover, this hypothesis is supported by a similar behavior of the ozonolysis of β -
374 caryophyllene (sesquiterpene with an exocyclic double bond) in SOA enhancement under high RH
375 condition. However, since aerosol dynamics of small clusters and particles are very complex, we do not
376 rule out a series of reactions that may occur in the particle phase. The results in this study suggest that
377 multi-generation reactions play an important role in SOA formation from the ozonolysis of BVOCs,
378 which are significantly influenced by humidity. This impact is largely dependent on the molecular
379 structure of the SOA precursors (e.g., with or without the exocyclic double bond), thus highlighting the
380 importance to consider the molecular structure of monoterpenes in modeling and field studies of biogenic
381 SOA.

382

383 **Data availability.** Experimental data are available upon request to the corresponding authors.

384 **Supplement.** The supplement related to this article is available online.

385 **Author contributions.** LD and SZ designed the experiments and SZ carried them out. SZ performed

386 data analysis with assistance from KL, LD, ZY, and JL. SZ and KL wrote the paper with contributions
387 from all co-authors.

388 **Declaration.** The authors declare that they have no conflict of interest.

389 **Acknowledgements.** We thank Guannan Lin, Jingyao Qu and Zhifeng Li from the State Key Laboratory
390 of Microbial Technology of Shandong University for help and guidance with MS measurements.

391 **Financial support.** This research has been supported by the National Natural Science Foundation of
392 China (grant no. 22076099), and the Fundamental Research Fund of Shandong University (grant no.
393 2020QNQT012).

394 **Reference**

395 Ahmadov, R., McKeen, S. A., Robinson, A. L., Bahreini, R., Middlebrook, A. M., de Gouw, J. A.,
396 Meagher, J., Hsie, E. Y., Edgerton, E., Shaw, S., and Trainer, M.: A volatility basis set model for
397 summertime secondary organic aerosols over the eastern United States in 2006, *J. Geophys. Res.-Atmos.*,
398 117, D6301, <https://doi.org/10.1029/2011JD016831>, 2012.

399 Aschmann, S. M., Arey, J., and Atkinson, R.: OH radical formation from the gas-phase reactions of O₃
400 with a series of terpenes, *Atmos. Environ.*, 36, 4347-4355, [https://doi.org/10.1016/S1352-2310\(02\)00355-2](https://doi.org/10.1016/S1352-2310(02)00355-2), 2002.

402 Atkinson, R.: Kinetics and mechanisms of the gas-phase reactions of the NO₃ radical with organic
403 compounds, *J. Phys. Chem. Ref. Data*, 20, 459-507, <https://doi.org/10.1063/1.555887>, 1991.

404 Atkinson, R. and Arey, J.: Gas-phase tropospheric chemistry of biogenic volatile organic compounds: a
405 review, *Atmos. Environ.*, 37, 197-219, [https://doi.org/10.1016/S1352-2310\(03\)00391-1](https://doi.org/10.1016/S1352-2310(03)00391-1), 2003.

406 Bäck, J., Aalto, J., Henriksson, M., Hakola, H., He, Q., and Boy, M.: Chemodiversity of a Scots pine
407 stand and implications for terpene air concentrations, *Biogeosciences*, 9, 689-702,
408 <https://doi.org/10.5194/bg-9-689-2012>, 2012.

409 Bateman, A. P., Nizkorodov, S. A., Laskin, J., and Laskin, A.: Time-resolved molecular characterization
410 of limonene/ozone aerosol using high-resolution electrospray ionization mass spectrometry, *Phys. Chem.*
411 *Chem. Phys.*, 11, 7931-7942, <https://doi.org/10.1039/b905288g>, 2009.

412 Bianchi, F., Kurtén, T., Riva, M., Mohr, C., Rissanen, M. P., Roldin, P., Berndt, T., Crounse, J. D.,
413 Wennberg, P. O., Mentel, T. F., Wildt, J., Junninen, H., Jokinen, T., Kulmala, M., Worsnop, D. R.,

414 Thornton, J. A., Donahue, N., Kjaergaard, H. G., and Ehn, M.: Highly oxygenated organic molecules
415 (HOM) from gas-phase autoxidation involving peroxy radicals: a key contributor to atmospheric aerosol,
416 Chem. Rev., 119, 3472-3509, <https://doi.org/10.1021/acs.chemrev.8b00395>, 2019.

417 Bonn, B. and Moortgat, G. K.: New particle formation during α - and β -pinene oxidation by O₃, OH and
418 NO₃, and the influence of water vapour: particle size distribution studies, Atmos. Chem. Phys., 2, 183-
419 196, <https://doi.org/10.5194/acp-2-183-2002>, 2002.

420 Bonn, B., Schuster, G., and Moortgat, G. K.: Influence of water vapor on the process of new particle
421 formation during monoterpene ozonolysis, J. Phys. Chem. A, 106, 2869-2881,
422 <https://doi.org/10.1021/jp012713p>, 2002.

423 Chen, H., Ren, Y., Cazaunau, M., Dalele, V., Hu, Y., Chen, J., and Mellouki, A.: Rate coefficients for the
424 reaction of ozone with 2- and 3-carene, Chem. Phys. Lett., 621, 71-77,
425 <https://doi.org/10.1016/j.cplett.2014.12.056>, 2015.

426 Chen, L., Huang, Y., Xue, Y., Shen, Z., Cao, J., and Wang, W.: Mechanistic and kinetics investigations
427 of oligomer formation from Criegee intermediate reactions with hydroxyalkyl hydroperoxides, Atmos.
428 Chem. Phys., 19, 4075-4091, <https://doi.org/10.5194/acp-19-4075-2019>, 2019.

429 Chen, L., Wang, W., Wang, W., Liu, Y., Liu, F., Liu, N., and Wang, B.: Water-catalyzed decomposition
430 of the simplest Criegee intermediate CH₂OO, Theor. Chem. Acc., 135, 131,
431 <https://doi.org/10.1007/s00214-016-1894-9>, 2016.

432 Chen, X. and Hopke, P. K.: A chamber study of secondary organic aerosol formation by limonene
433 ozonolysis, Indoor Air, 20, 320-328, <https://doi.org/10.1111/j.1600-0668.2010.00656.x>, 2010.

434 Cholakian, A., Beekmann, M., Coll, I., Ciarelli, G., and Colette, A.: Biogenic secondary organic aerosol
435 sensitivity to organic aerosol simulation schemes in climate projections, Atmos. Chem. Phys., 19, 13209-
436 13226, <https://doi.org/10.5194/acp-19-13209-2019>, 2019.

437 de Matos, S. P., Teixeira, H. F., de Lima, Á. A. N., Veiga-Junior, V. F., and Koester, L. S.: Essential oils
438 and isolated terpenes in nanosystems designed for topical administration: a review, Biomolecules, 9, 138,
439 <https://doi.org/doi:10.3390/biom9040138>, 2019.

440 Drozd, G. T. and Donahue, N. M.: Pressure dependence of stabilized Criegee intermediate formation
441 from a sequence of alkenes, J. Phys. Chem. A, 115, 4381-4387, <https://doi.org/10.1021/jp2001089>, 2011.

442 Fick, J., Pommer, L., Andersson, B., and Nilsson, C.: A study of the gas-phase ozonolysis of terpenes:

443 the impact of radicals formed during the reaction, *Atmos. Environ.*, 36, 3299-3308,
444 [https://doi.org/10.1016/s1352-2310\(02\)00291-1](https://doi.org/10.1016/s1352-2310(02)00291-1), 2002.

445 Gong, Y. and Chen, Z.: Quantification of the role of stabilized Criegee intermediates in the formation of
446 aerosols in limonene ozonolysis, *Atmos. Chem. Phys.*, 21, 813-829, [https://doi.org/10.5194/acp-21-813-](https://doi.org/10.5194/acp-21-813-2021)
447 2021, 2021.

448 Gong, Y., Chen, Z., and Li, H.: The oxidation regime and SOA composition in limonene ozonolysis: roles
449 of different double bonds, radicals, and water, *Atmos. Chem. Phys.*, 18, 15105-15123,
450 <https://doi.org/10.5194/acp-18-15105-2018>, 2018.

451 Grosjean, D., Williams, E. L., and Seinfeld, J. H.: Atmospheric oxidation of selected terpenes and related
452 carbonyls: gas-phase carbonyl products, *Environ. Sci. Technol.*, 26, 1526-1533,
453 <https://doi.org/10.1021/es00032a005>, 1992.

454 Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.:
455 The model of emissions of gases and aerosols from nature version 2.1 (MEGAN2.1): an extended and
456 updated framework for modeling biogenic emissions, *Geosci. Model Dev.*, 5, 1471-1492,
457 <https://doi.org/10.5194/gmd-5-1471-2012>, 2012.

458 Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., Du, Z., Wu, Z., Shao, M., Zeng, L.,
459 Molina, M. J., and Zhang, R.: Elucidating severe urban haze formation in China, *Proc. Natl. Acad. Sci.*
460 *U. S. A.*, 111, 17373-17378, <https://doi.org/10.1073/pnas.1419604111>, 2014.

461 Hammes, J., Lutz, A., Mentel, T., Faxon, C., and Hallquist, M.: Carboxylic acids from limonene oxidation
462 by ozone and hydroxyl radicals: insights into mechanisms derived using a FIGAERO-CIMS, *Atmos.*
463 *Chem. Phys.*, 19, 13037-13052, <https://doi.org/10.5194/acp-19-13037-2019>, 2019.

464 Hantschke, L., Novelli, A., Bohn, B., Cho, C., Reimer, D., Rohrer, F., Tillmann, R., Glowania, M.,
465 Hofzumahaus, A., Kiendler-Scharr, A., Wahner, A., and Fuchs, H.: Atmospheric photooxidation and
466 ozonolysis of Δ^3 -carene and 3-caronaldehyde: rate constants and product yields, *Atmos. Chem. Phys.*,
467 21, 12665-12685, [10.5194/acp-21-12665-2021](https://doi.org/10.5194/acp-21-12665-2021), 2021.

468 Herrmann, F., Winterhalter, R., Moortgat, G. K., and Williams, J.: Hydroxyl radical (OH) yields from the
469 ozonolysis of both double bonds for five monoterpenes, *Atmos. Environ.*, 44, 3458-3464,
470 <https://doi.org/10.1016/j.atmosenv.2010.05.011>, 2010.

471 Huang, X., Yun, H., Gong, Z., Li, X., He, L., Zhang, Y., and Hu, M.: Source apportionment and secondary

472 organic aerosol estimation of PM_{2.5} in an urban atmosphere in China, *Sci. China-Earth Sci.*, *57*, 1352-
473 1362, <https://doi.org/10.1007/s11430-013-4686-2>, 2014.

474 Jang, M. S., Carroll, B., Chandramouli, B., and Kamens, R. M.: Particle growth by acid-catalyzed
475 heterogeneous reactions of organic carbonyls on preexisting aerosols, *Environ. Sci. Technol.*, *37*, 3828-
476 3837, [10.1021/es021005u](https://doi.org/10.1021/es021005u), 2003.

477 Jokinen, T., Berndt, T., Makkonen, R., Kerminen, V.-M., Junninen, H., Paasonen, P., Stratmann, F.,
478 Herrmann, H., Guenther, A. B., Worsnop, D. R., Kulmala, M., Ehn, M., and Sipilä, M.: Production of
479 extremely low volatile organic compounds from biogenic emissions: Measured yields and atmospheric
480 implications, *Proc. Natl. Acad. Sci. U. S. A.*, *112*, 7123-7128,
481 <https://doi.org/doi:10.1073/pnas.1423977112>, 2015.

482 Jonsson, A. M., Hallquist, M., and Ljungstrom, E.: Impact of humidity on the ozone initiated oxidation
483 of limonene, Δ^3 -carene, and α -pinene, *Environ. Sci. Technol.*, *40*, 188-194,
484 <https://doi.org/10.1021/es051163w>, 2006a.

485 Jonsson, A. M., Hallquist, M., and Ljungstrom, E.: Impact of humidity on the ozone initiated oxidation
486 of limonene, Delta(3)-carene, and alpha-pinene, *Environ. Sci. Technol.*, *40*, 188-194,
487 <https://doi.org/10.1021/es051163w>, 2006b.

488 Jonsson, A. M., Hallquist, M., and Ljungstrom, E.: Influence of OH scavenger on the water effect on
489 secondary organic aerosol formation from ozonolysis of limonene, Δ^3 -carene, and α -pinene, *Environ. Sci.*
490 *Technol.*, *42*, 5938-5944, <https://doi.org/10.1021/es702508y>, 2008.

491 Kanakidou, M., Seinfeld, J. H., Pandis, S. N., Barnes, I., Dentener, F. J., Facchini, M. C., Van Dingenen,
492 R., Ervens, B., Nenes, A., Nielsen, C. J., Swietlicki, E., Putaud, J. P., Balkanski, Y., Fuzzi, S., Horth, J.,
493 Moortgat, G. K., Winterhalter, R., Myhre, C. E. L., Tsigaridis, K., Vignati, E., Stephanou, E. G., and
494 Wilson, J.: Organic aerosol and global climate modelling: a review, *Atmos. Chem. Phys.*, *5*, 1053-1123,
495 <https://doi.org/10.5194/acp-5-1053-2005>, 2005.

496 Khamaganov, V. G. and Hites, R. A.: Rate constants for the gas-phase reactions of ozone with isoprene,
497 α - and β -pinene, and limonene as a function of temperature, *J. Phys. Chem. A*, *105*, 815-822,
498 <https://doi.org/10.1021/jp002730z>, 2001.

499 Kristensen, K., Cui, T., Zhang, H., Gold, A., Glasius, M., and Surratt, J. D.: Dimers in α -pinene secondary
500 organic aerosol: effect of hydroxyl radical, ozone, relative humidity and aerosol acidity, *Atmos. Chem.*

501 Phys., 14, 4201-4218, <https://doi.org/10.5194/acp-14-4201-2014>, 2014.

502 Kroll, J. H., Ng, N. L., Murphy, S. M., Varutbangkul, V., Flagan, R. C., and Seinfeld, J. H.: Chamber
503 studies of secondary organic aerosol growth by reactive uptake of simple carbonyl compounds, J.
504 Geophys. Res.-Atmos., 110, 10.1029/2005JD006004, 2005.

505 Kumar, M., Busch, D. H., Subramaniam, B., and Thompson, W. H.: Role of tunable acid catalysis in
506 decomposition of α -Hydroxyalkyl hydroperoxides and mechanistic implications for tropospheric
507 chemistry, J. Phys. Chem. A, 118, 9701-9711, <https://doi.org/10.1021/jp505100x>, 2014.

508 Leungsakul, S., Jaoui, M., and Kamens, R. M.: Kinetic Mechanism for Predicting Secondary Organic
509 Aerosol Formation from the Reaction of d-Limonene with Ozone, Environ. Sci. Technol., 39, 9583-9594,
510 <https://doi.org/10.1021/es0492687>, 2005.

511 Levy, H., II, Horowitz, L. W., Schwarzkopf, M. D., Ming, Y., Golaz, J.-C., Naik, V., and Ramaswamy,
512 V.: The roles of aerosol direct and indirect effects in past and future climate change, J. Geophys. Res.-
513 Atmos., 118, 4521-4532, <https://doi.org/10.1002/jgrd.50192>, 2013.

514 Li, J. Y., Zhang, H. W., Ying, Q., Wu, Z. J., Zhang, Y. L., Wang, X. M., Li, X. H., Sun, Y. L., Hu, M.,
515 Zhang, Y. H., and Hu, J. L.: Impacts of water partitioning and polarity of organic compounds on
516 secondary organic aerosol over eastern China, Atmos. Chem. Phys., 20, 7291-7306,
517 <https://doi.org/10.5194/acp-20-7291-2020>, 2020.

518 Li, K., Liggió, J., Lee, P., Han, C., Liu, Q., and Li, S.-M.: Secondary organic aerosol formation from α -
519 pinene, alkanes, and oil-sands-related precursors in a new oxidation flow reactor, Atmos. Chem. Phys.,
520 19, 9715-9731, <https://doi.org/10.5194/acp-19-9715-2019>, 2019a.

521 Li, X., Chee, S., Hao, J., Abbatt, J. P. D., Jiang, J., and Smith, J. N.: Relative humidity effect on the
522 formation of highly oxidized molecules and new particles during monoterpene oxidation, Atmos. Chem.
523 Phys., 19, 1555-1570, <https://doi.org/10.5194/acp-19-1555-2019>, 2019b.

524 Liu, Q., Liggió, J., Breznan, D., Thomson, E. M., Kumarathasan, P., Vincent, R., Li, K., and Li, S.-M.:
525 Oxidative and Toxicological Evolution of Engineered Nanoparticles with Atmospherically Relevant
526 Coatings, Environ. Sci. Technol., 53, 3058-3066, 10.1021/acs.est.8b06879, 2019.

527 Liu, Y., Liggió, J., Harner, T., Jantunen, L., Shoeib, M., and Li, S.-M.: Heterogeneous OH Initiated
528 Oxidation: A Possible Explanation for the Persistence of Organophosphate Flame Retardants in Air,
529 Environ. Sci. Technol., 48, 1041-1048, 10.1021/es404515k, 2014.

530 Ma, Y., Porter, R. A., Chappell, D., Russell, A. T., and Marston, G.: Mechanisms for the formation of
531 organic acids in the gas-phase ozonolysis of 3-carene, *Phys. Chem. Chem. Phys.*, 11, 4184-4197,
532 <https://doi.org/10.1039/b818750a>, 2009.

533 Molteni, U., Bianchi, F., Klein, F., El Haddad, I., Frege, C., Rossi, M. J., Dommen, J., and Baltensperger,
534 U.: Formation of highly oxygenated organic molecules from aromatic compounds, *Atmos. Chem. Phys.*,
535 18, 1909-1921, <https://doi.org/10.5194/acp-18-1909-2018>, 2018.

536 Mot, M.-D., Gavrițaș, S., Lupitu, A. I., Moisa, C., Chambre, D., Tit, D. M., Bogdan, M. A., Bodescu, A.-
537 M., Copolovici, L., Copolovici, D. M., and Bungau, S. G.: *Salvia officinalis* L. essential oil:
538 characterization, antioxidant properties, and the effects of aromatherapy in adult patients, *Antioxidants*,
539 11, 808, <https://doi.org/10.3390/antiox11050808>, 2022.

540 Ng, N. L., Kroll, J. H., Chan, A. W. H., Chhabra, P. S., Flagan, R. C., and Seinfeld, J. H.: Secondary
541 organic aerosol formation from m-xylene, toluene, and benzene, *Atmos. Chem. Phys.*, 7, 3909-3922,
542 <https://doi.org/10.5194/acp-7-3909-2007>, 2007.

543 Odum, J. R., Hoffmann, T., Bowman, F., Collins, D., Flagan, R. C., and Seinfeld, J. H.: Gas/particle
544 partitioning and secondary organic aerosol yields, *Environ. Sci. Technol.*, 30, 2580-2585,
545 <https://doi.org/10.1021/es950943+>, 1996.

546 Palm, B. B., Campuzano-Jost, P., Ortega, A. M., Day, D. A., Kaser, L., Jud, W., Karl, T., Hansel, A.,
547 Hunter, J. F., Cross, E. S., Kroll, J. H., Peng, Z., Brune, W. H., and Jimenez, J. L.: In situ secondary
548 organic aerosol formation from ambient pine forest air using an oxidation flow reactor, *Atmos. Chem.*
549 *Phys.*, 16, 2943-2970, <https://doi.org/10.5194/acp-16-2943-2016>, 2016.

550 Pathak, R. K., Salo, K., Emanuelsson, E. U., Cai, C., Lutz, A., Hallquist, A. M., and Hallquist, M.:
551 Influence of ozone and radical chemistry on limonene organic aerosol production and thermal
552 characteristics, *Environ. Sci. Technol.*, 46, 11660-11669, <https://doi.org/10.1021/es301750r>, 2012.

553 Peng, Z., Lee-Taylor, J., Orlando, J. J., Tyndall, G. S., and Jimenez, J. L.: Organic peroxy radical
554 chemistry in oxidation flow reactors and environmental chambers and their atmospheric relevance,
555 *Atmos. Chem. Phys.*, 19, 813-834, <https://doi.org/10.5194/acp-19-813-2019>, 2019.

556 Pye, H. O. T., Ward-Caviness, C. K., Murphy, B. N., Appel, K. W., and Seltzer, K. M.: Secondary organic
557 aerosol association with cardiorespiratory disease mortality in the United States, *Nat. Commun.*, 12,
558 <https://doi.org/10.1038/s41467-021-27484-1>, 2021.

559 Ravichandran, C., Badgujar, P. C., Gundev, P., and Upadhyay, A.: Review of toxicological assessment of
560 d-limonene, a food and cosmetics additive, *Food Chem. Toxicol.*, 120, 668-680,
561 <https://doi.org/10.1016/j.fct.2018.07.052>, 2018.

562 Sbai, S. E. and Farida, B.: Photochemical aging and secondary organic aerosols generated from limonene
563 in an oxidation flow reactor, *Environ. Sci. Pollut. Res.*, 26, 18411-18420, [https://doi.org/10.1007/s11356-](https://doi.org/10.1007/s11356-019-05012-5)
564 019-05012-5, 2019.

565 Seinfeld, J. H., Erdakos, G. B., Asher, W. E., and Pankow, J. F.: Modeling the formation of secondary
566 organic aerosol (SOA). 2. The predicted effects of relative humidity on aerosol formation in the α -Pinene-,
567 β -Pinene-, sabinene-, Δ^3 -Carene-, and cyclohexene-ozone systems, *Environ. Sci. Technol.*, 35, 1806-
568 1817, <https://doi.org/10.1021/es001765+>, 2001.

569 Shaw, J. T., Lidster, R. T., Cryer, D. R., Ramirez, N., Whiting, F. C., Boustead, G. A., Whalley, L. K.,
570 Ingham, T., Rickard, A. R., Dunmore, R. E., Heard, D. E., Lewis, A. C., Carpenter, L. J., Hamilton, J. F.,
571 and Dillon, T. J.: A self-consistent, multivariate method for the determination of gas-phase rate
572 coefficients, applied to reactions of atmospheric VOCs and the hydroxyl radical, *Atmos. Chem. Phys.*,
573 18, 4039-4054, <https://doi.org/10.5194/acp-18-4039-2018>, 2018.

574 Shu, Y. G. and Atkinson, R.: Rate Constants for the gas-phase reactions of O₃ with a series of terpenes
575 and OH radical formation from the O₃ reactions with sesquiterpenes at 296 ± 2K, *Int. J. Chem. Kinet.*, 26,
576 1193-1205, 10.1002/kin.550261207, 1994.

577 Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrou, T., Müller, J. F., Kuhn, U.,
578 Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model
579 over the last 30 years, *Atmos. Chem. Phys.*, 14, 9317-9341, <https://doi.org/10.5194/acp-14-9317-2014>,
580 2014.

581 Sun, Y., Wang, Z., Fu, P., Jiang, Q., Yang, T., Li, J., and Ge, X.: The impact of relative humidity on
582 aerosol composition and evolution processes during wintertime in Beijing, China, *Atmos. Environ.*, 77,
583 927-934, <https://doi.org/10.1016/j.atmosenv.2013.06.019>, 2013.

584 Thomsen, D., Elm, J., Rosati, B., Skonager, J. T., Bilde, M., and Glasius, M.: Large discrepancy in the
585 formation of secondary organic aerosols from structurally similar monoterpenes, *ACS Earth Space*
586 *Chem.*, 5, 632-644, <https://doi.org/10.1021/acsearthspacechem.0c00332>, 2021.

587 Varutbangkul, V., Brechtel, F. J., Bahreini, R., Ng, N. L., Keywood, M. D., Kroll, J. H., Flagan, R. C.,

588 Seinfeld, J. H., Lee, A., and Goldstein, A. H.: Hygroscopicity of secondary organic aerosols formed by
589 oxidation of cycloalkenes, monoterpenes, sesquiterpenes, and related compounds, *Atmos. Chem. Phys.*,
590 6, 2367-2388, <https://doi.org/10.5194/acp-6-2367-2006>, 2006.

591 Wang, L., Liu, Y., and Wang, L.: Ozonolysis of 3-carene in the atmosphere. Formation mechanism of
592 hydroxyl radical and secondary ozonides, *Phys. Chem. Chem. Phys.*, 21, 8081-8091,
593 10.1039/c8cp07195k, 2019.

594 Wang, L. Y. and Wang, L. M.: The oxidation mechanism of gas-phase ozonolysis of limonene in the
595 atmosphere, *Phys. Chem. Chem. Phys.*, 23, 9294-9303, <https://doi.org/10.1039/d0cp05803c>, 2021.

596 Watne, A. K., Westerlund, J., Hallquist, A. M., Brune, W. H., and Hallquist, M.: Ozone and OH-induced
597 oxidation of monoterpenes: Changes in the thermal properties of secondary organic aerosol (SOA), *J.*
598 *Aerosol Sci*, 114, 31-41, <https://doi.org/10.1016/j.jaerosci.2017.08.011>, 2017.

599 Xu, L., Tsona, N. T., and Du, L.: Relative humidity changes the role of SO₂ in biogenic secondary organic
600 aerosol formation, *J. Phys. Chem. Lett.*, 12, 7365-7372, <https://doi.org/10.1021/acs.jpcclett.1c01550>,
601 2021.

602 Ye, J., Abbatt, J. P. D., and Chan, A. W. H.: Novel pathway of SO₂ oxidation in the atmosphere: reactions
603 with monoterpene ozonolysis intermediates and secondary organic aerosol, *Atmos. Chem. Phys.*, 18,
604 5549-5565, <https://doi.org/10.5194/acp-18-5549-2018>, 2018.

605 Yu, K. P., Lin, C. C., Yang, S. C., and Zhao, P.: Enhancement effect of relative humidity on the formation
606 and regional respiratory deposition of secondary organic aerosol, *J. Hazard. Mater.*, 191, 94-102,
607 <https://doi.org/10.1016/j.jhazmat.2011.04.042>, 2011.

608 Zhang, H., Wang, S., Hao, J., Wang, X., Wang, S., Chai, F., and Li, M.: Air pollution and control action
609 in Beijing, *J. Clean Prod.*, 112, 1519-1527, <https://doi.org/10.1016/j.jclepro.2015.04.092>, 2016.

610 Zhang, Y., He, L., Sun, X., Ventura, O. N., and Herrmann, H.: Theoretical Investigation on the
611 Oligomerization of Methylglyoxal and Glyoxal in Aqueous Atmospheric Aerosol Particles, *ACS Earth*
612 *Space Chem.*, 6, 1031-1043, 10.1021/acsearthspacechem.1c00422, 2022.

613 Zhao, R. R., Zhang, Q. X., Xu, X. Z., Zhao, W. X., Yu, H., Wang, W. J., Zhang, Y. M., and Zhang, W. J.:
614 Effect of experimental conditions on secondary organic aerosol formation in an oxidation flow reactor,
615 *Atmos. Pollut. Res.*, 12, 392-400, <https://doi.org/10.1016/j.apr.2021.01.011>, 2021.

616 Ziemann, P. J. and Atkinson, R.: Kinetics, products, and mechanisms of secondary organic aerosol

617 formation, Chem. Soc. Rev., 41, 6582-6605, <https://doi.org/10.1039/c2cs35122f>, 2012.

618