

# The Capability of CI-Orbitrap for Gas-Phase Analysis in Atmospheric Chemistry: A Comparison with the Cl-APi-TOF Technique

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1	The capability of CI-Orbitrap for gas-phase analysis in
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#### 11 Abstract

12 Chemical ionization Orbitrap mass spectrometry (CI-Orbitrap) represents a promising new technique 13 for gas-phase analysis in analytical and atmospheric chemistries mainly due to its very high mass 14 resolving power. In this work, we performed the first side-by-side comparison between a CI-Orbitrap 15 and the widely used atmospheric pressure interface time-of-flight mass spectrometry (CI-APi-TOF) 16 using two different chemical ionization methods, i.e., acetate-ion-based (CH<sub>3</sub>COO<sup>-</sup>) and aminium-ion-17 based (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) schemes. The capability of the CI-Orbitrap at accurately measuring low 18 concentrations of gaseous species formed from the oxidation of  $\alpha$ -pinene was explored. Although this 19 study reveals a lack of linearity of the CI-Orbitrap when measuring product ions at very low concentrations (< 1 x  $10^6$  molecules cm<sup>-3</sup>), very good agreement between both techniques can be 20 21 achieved by applying a newly developed linearity correction. It is experimentally shown that the 22 correction function is independent of the reagent ion used. Thus, accurate quantification of organic compounds at concentrations as low as  $1 \times 10^5$  molecules cm<sup>-3</sup> by the CI-Orbitrap can be achieved. 23 24 Finally, by means of tandem mass spectrometry, the unique capability of the Orbitrap allows the direct 25 determination of the binding energy of cluster ions between analyte and reagent ions, that is needed 26 for the assessment of a chosen ionization scheme.

#### 27 Introduction

28 Biogenic and anthropogenic activities constantly release a wide variety of volatile organic compounds (VOCs) into the atmosphere.<sup>1,2</sup> Once emitted, VOC are rapidly oxidized to form oxidized VOCs 29 (OVOCs) spanning a broad range of chemical formulas, and, thus, volatilities.<sup>1,3,4</sup> As a result, organic 30 31 compounds play a key role in the formation of atmospheric aerosol by either condensing onto preexisting aerosol particles or by forming new particles.<sup>1,2,5,6</sup> VOC emissions strongly impact 32 33 atmospheric chemistry, human health, and Earth's climate. More specifically, a critical starting point in 34 new particle formation (NPF) and growth is the generation of highly oxygenated multifunctional organic molecules (HOMs) through a process usually referred to as autoxidation.<sup>7-9</sup> In the course of 35 the autoxidation process, peroxy (RO<sub>2</sub>) radicals, formed via the oxidation of a VOC, undergo an 36 37 intramolecular hydrogen shift reaction, ROO  $\rightarrow$  QOOH, followed by the addition of molecular oxygen 38 resulting in the formation of a new R'O<sub>2</sub> radical: QOOH + O<sub>2</sub>  $\rightarrow$  OOQOOH (R'O<sub>2</sub>) ("Q" stands for 39 the organic group "R" after interamolecular H shift). This chain reaction can be repeated, yielding a broad diversity of products depending on the RO<sub>2</sub> radical termination steps.<sup>8,10–12</sup> As a result, HOMs 40 41 can be formed efficiently at high enough yields to consider them as a significant source of condensing, or, in certain cases, even nucleating, organic components.<sup>6-8,13-15</sup> Finally, RO<sub>2</sub> chemistry not only 42 43 controls the formation of HOMs and NPF but also impacts the production of secondary pollutants including O<sub>3</sub> and NO<sub>2</sub>.<sup>16</sup> While in the last decade major breakthroughs have been achieved within the 44 field of atmospheric oxidation processes and new particle formation,<sup>6–8,17</sup> a complete understanding of 45 46 how VOC oxidation products contribute to new particle and SOA formation remains poorly 47 constrained. Indeed, gas-phase oxidation processes of biogenic and anthropogenic VOCs yield a 48 number of oxidized products resulting in extremely complex mixture of oxygenated VOCs (OVOCs). 49 These span a wide range of chemical formulas, structures, and physicochemical properties and pose a 50 critical challenge in detecting, quantifying, and characterizing key atmospheric species including RO<sub>2</sub> 51 radicals and HOMs.

52 Mass spectrometric techniques have recently made enormous improvements in detecting and 53 quantifying gaseous oxygenated species.<sup>18–20</sup> In particular, chemical ionization mass spectrometry 54 (CIMS) has emerged as a prevailing tool due to its very low detection limits, good sensitivity, and

capability of measuring a wide variety of gaseous organic and inorganic species.<sup>8,10,10,21</sup> Chemical 55 56 ionization (CI) is a soft ionization technique where the analyte is ionized via a clustering process with the reagent ion with minimal fragmentation or via proton transfer processes.<sup>21–24</sup> As part of the rapid 57 development, multiple reagent ion schemes have been tested over the last few years. Due to the 58 59 improvements in sensitivity and/or selectivity, a wide variety of oxygenated species, including RO<sub>2</sub> radicals and stabilized Criegee intermediates, can now be directly analyzed.<sup>10,11,19,20,25,26</sup> However, 60 61 most of the CI mass spectrometers offer a rather limited mass resolving power (i.e., from 2 000 to 14 62 000), hindering yet a complete and unambiguous identification of the compounds of interest. 63 Consequently, the presence of multiple overlapping ions leads to significant uncertainties that can only 64 be partly resolved by computational techniques. To overcome these limitations, we have recently coupled a high-resolution mass spectrometer (Orbitrap) with a CI source.<sup>30</sup> The CI-Orbitrap combines 65 the benefits of soft atmospheric pressure ionization with a unique mass resolving power ( $R \ge 140\ 000$ 66 67 at m/z 200). In our first study we demonstrated the applicability of this new analytical method and evaluated its ability in detecting and characterizing OVOCs formed during the oxidation of two 68 monoterpenes using nitrate-based (NO<sub>3</sub><sup>-</sup>) CI.<sup>30</sup> Nonetheless, a direct comparison with the widely used 69 70 atmospheric pressure interface time-of-flight mass spectrometry (CI-APi-TOF) has not been 71 performed hitherto. Hence, the sensitivity as well as the linearity of the CI-Orbitrap with different 72 reagent ions operated in the positive or negative mode need to be determined and compared to those of 73 the CI-APi-TOF.

74 Within the present study, we performed the first side-by-side comparison between a CI-75 Orbitrap and a CI-APi-TOF applying two different chemical ionization schemes i.e., the acetate-ionbased  $(CH_3COO^{-})^{10,11}$  and the aminium-ion-based  $(n-C_3H_7NH_3^{+})^{11}$  product ionization. Unlike our 76 77 initial study, we performed our experiments in a free-jet system designed to probe the early stage of a 78 given reaction. A very short residence time was used as well as very low reactant conversion. As a 79 result, RO<sub>2</sub> radicals are the main products and experiments are performed within atmospheric reaction 80 conditions, where bimolecular steps are only important for relatively high  $RO_2/HO_2$  levels or in the 81 presence of high enough concentrations of additives (e.g., NO). Hence, very low concentrations of RO<sub>2</sub> radicals and OVOCs are produced from the ozone and OH radical initiated oxidation of α-pinene 82

83 in order to ascertain the benefit and the limitation of the CI-Orbitrap. We also explored the potential of 84 the CI-Orbitrap in evaluating the binding energies of RO<sub>2</sub> radicals and OVOCs clustered with acetate

and aminium  $(n-C_3H_7NH_3^+)$  by means of tandem mass spectral analyses  $(MS^2)$ .

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#### 86 EXPERIMENTAL SECTION

87 Ozonolysis and OH radical initiated oxidation of  $\alpha$ -pinene (C<sub>10</sub>H<sub>16</sub>) were performed under dry 88 conditions (RH < 0.1%) in air using a free-jet flow system at a temperature of 297  $\pm$  1 K and atmospheric pressure.<sup>10,11</sup> This flow system allows the investigation of VOC oxidation under 89 90 atmospheric conditions with negligible wall effects and a reaction time of 7.9 s. Ozone produced from 91 a low-pressure mercury lamp or isopropyl nitrite (IPN) was premixed with air (5 L/min (STP)) and 92 injected through the inner tube into the main gas stream (95 L/min (STP)) containing  $\alpha$ -pinene diluted 93 in air. Ozonolysis experiments (dark reaction) were performed in the absence of an OH scavenger, i.e., 94 the in-situ OH radical formation from ozonolysis led to a combined  $O_3/OH + \alpha$ -pinene reaction. In the 95 pure OH experiments based on IPN photolysis, 8 NARVA 36W Blacklight Blue lamps were used for 96 illuminating the flow system. All gas flows were set by means of calibrated gas flow controllers (MKS 1259/1179). The concentration of  $\alpha$ -pinene was maintained at 5.0 × 10<sup>11</sup> molecules cm<sup>-3</sup>, while ozone 97 and IPN were ramping up from  $2.5 \times 10^{10}$  to  $5.6 \times 10^{11}$  and from  $1.7 \times 10^{10}$  to  $6.7 \times 10^{11}$  molecules cm<sup>-</sup> 98 99 <sup>3</sup>, respectively.

100 The chemical composition of the oxygenated products was retrieved in real time by a Q-101 Exactive Orbitrap Plus mass spectrometer (Thermo Scientific) and a chemical ionization - atmospheric 102 pressure interface - time-of-flight mass spectrometer (CI-APi-TOF, Tofwerk AG). Both instruments have been described elsewhere and were equipped with a similar Eisele-type inlet.<sup>21,30–33</sup> While the CI 103 104 inlet mounted on the APi-TOF is manufactured by Airmodus (Finland), the CI inlet installed on the 105 Orbitrap is a home-built version with minor modifications regarding to the commercially available inlet (i.e., dimensions of the drift tube and specific flange, see for more details ref.<sup>30</sup>). The sample flow 106 107 rate for both instruments was set at ~ 10 L/min (STP). Protonated n-propylamine  $(n-C_3H_7NH_3^+)$  or 108 acetate (CH<sub>3</sub>COO<sup>-</sup>) ions were produced using an X-ray source or an Am-241 source for the Orbitrap 109 and the APi-TOF, respectively. In the ion-molecule-reaction (IMR) zone, the reagent ions from a clean 110 sheath nitrogen flow were guided into the concentric sample flow by an electrical field without 111 turbulent mixing of both streams. The residence time within the IMR zone was in the range of 200 –
112 300 ms in both instruments.

113 The reagent ions were  $(CH_3COOH)_n$ - $CH_3COO^-$  (n = 0,1) and  $(n-C_3H_7NH_2)_m$ -n- $C_3H_7NH_3^+$  (m 114 = 0,1) in the negative and positive mode, respectively. RO<sub>2</sub> radicals as well as closed-shell products, 115 called "prod" for all together, were detected as clusters with the respective reagent ions according to 116 the following reactions (1) and (2):

117

118 
$$(CH_3COOH)_n$$
- $CH_3COO^- + prod \rightarrow (prod)$ - $CH_3COO^- + (CH_3COOH)_n (n = 0, 1)$  (1)

119 
$$(n-C_3H_7NH_2)_m - n-C_3H_7NH_3^+ + \text{prod} \rightarrow (\text{prod}) - n-C_3H_7NH_3^+ + (n-C_3H_7NH_2)_m (m = 0, 1)$$
 (2)

120

It is important to mention that the absolute calibration of the detected oxygenated products is impossible due to a lack of authentic reference substances for RO<sub>2</sub> radicals and the majority of closedshell products. Thus, the product signals of both mass spectrometers were normalized to the sum of the reagent ions, i.e.,  $\Sigma[(CH_3COOH)_n-CH_3COO^- (n = 0,1)]$  or  $\Sigma[(n-C_3H_7NH_2)_m-n-C_3H_7NH_3^+ (m = 0,1)]$ . The resulting normalized signals were used for the comparison in order to evaluate the performance of both techniques.

127 However, the lower end value of the calibration factor f can be calculated considering the ionmolecule reaction within the CI-inlet,  $f = 1 / (k \times t \times f_{inlet})$ ,<sup>34</sup> where k is the rate coefficient of the ion-128 129 molecule reaction, t the reaction time and f<sub>inlet</sub> corresponds to the "prod" loss in the sampling tube. 130 Diffusion loss of the RO<sub>2</sub> radicals and OVOCs in the sampling lines to the CI-APi-TOF and the CI-131 Orbitrap were calculated to be 12% and 38%, respectively, assuming diffusion-controlled wall losses.<sup>10</sup> Taking into account this diffusion loss,  $f_{inlet} = 0.88$ , and a reaction time of the ion-molecule 132 reaction t = 0.2 - 0.3 s (which is similar for both instruments), a calibration of  $f_{calc} = (1.3 - 2.8) \times 10^9$ 133 134 molecules cm<sup>-3</sup> can be calculated. It should be mentioned that using the only reliable absolute calibration technique (i.e., sulfuric acid) a calibration factor of  $f_{H2SO4,exp} = 1.85 \times 10^9$  molecules cm<sup>-3</sup> 135 136 was determined in previous experiments. This value is in good agreement with the range of f<sub>calc</sub>. The 137 calibration factor f of reactions (1) and (2) was set equal to  $f_{H2SO4,exp}$  by practical reasons. The uncertainty of the lower end "prod" concentrations determined according to equation (1) or (2) is assumed to be not higher than a factor of two due to the expected uncertainty of the used calibration factor  $f_{H2SO4,exp} = 1.85 \times 10^9$  molecules cm<sup>-3</sup>, and possible inaccuracy connected with the duty cycle correction. Therefore, only lower limit product concentrations are available based on this calculated calibration factor.

Duty cycle correction was applied for the APi-TOF data in order to account for the m/zdiscrimination during the ion extraction.<sup>10,24,35</sup> In the case of the CI-Orbitrap, for each experiment, the ion transmission was evaluated by comparing the loss of the number of charges of the reagent ions with the increase of the number of charges of all the ions within the m/z 200 – 600 Th. This simple method provides a rough estimate of the ion transmission for the compounds of interest relative to the reagent ions. As a result, a factor of 2 was applied to correct for the lower ion transmission of the reagent ions in order to determine the normalized signals.

150 In addition, we further evaluated the ion transmission of the Q Exactive Orbitrap in the m/z 53 - 800 Th using the depletion method described by Heinritzi et al.<sup>36</sup> This method takes into 151 152 consideration losses within the inlet as well as the different ion optics and C-Trap (see Figure S1). In 153 short, 4 different perfluorinated acids were introduced into the mass analyzer in order to deplete the 154 reagent ions. As a result, the relative transmission efficiency can be obtained by comparing the 155 decrease of signal strength of the reagent ions with the rising signals from the perfluorinated acids at 156 larger masses (see supplementary information for more details). The relative ion transmission was 157 only determined for the Q-Exactive Orbitrap using nitrate-ion based chemistry. It should be pointed 158 out that the depletion method leads to significantly different results for the ion transmission of a mass spectrometer than absolute calibration methods.<sup>7,36–38</sup> Nevertheless, the results of the depletion method 159 160 provide a first insight into the ion transmission of a Q Exactive Orbitrap.

161 The Q Exactive Plus Orbitrap (Orbitrap-Tropos) was used in positive (i.e.,  $n-C_3H_7NH_3^+$ ) and 162 negative mode (i.e.,  $CH_3COO^-$ ) and connected to the free-jet flow system. The Q Exactive Orbitrap 163 (Orbitrap-IRCELYON) was solely used in negative mode ( $NO_3^-$ ) to determine the ion transmission 164 and to developed the linearity correction. Both instruments were operated using the same settings and 165 were run in full scan mode with a high mass resolving power of 140 000 (at m/z 200 Th), allowing an

166 identification of a wide variety of species. The instruments were operated in negative or positive 167 mode, scanning from m/z 50 to 750 Th with an automatic gain control (AGC) target of 1 x 10<sup>5</sup> 168 charges, a maximum injection time of 1 s, resulting in a scan rate of 0.2 scans/s. Spectra were 169 averaged of 5 microscans (1 microscan corresponding to 1 ion injection). The stacked-ring ion guide 170 (or S-Lens) is a radio frequency (RF) device efficiently capturing and focusing the ions into a tight 171 beam. As previously described it contains a series of electrodes where voltages are applied in order to 172 focus the ions. The S-lens level was maintained at 60%, to maximize ion transmission and the limit of 173 detection. The C-Trap consist of a RF-based ion collecting trap (Figure S1), which is automatically 174 controlled by the AGC (automatic gain control) in order to prevent space-charge effects. In order to 175 evaluate the impact of the number of charges collected in the C-trap, the AGC target of the Orbitrap-Tropos instrument was scanned from 5 x  $10^4$  to 1 x  $10^6$  charges. External mass calibrations were 176 177 performed prior to the experiments by injecting a 2 mM sodium acetate solution using an electrospray 178 ionization source. This procedure provided a suite of negative and positive adduct ions in the desired 179 mass range of m/z 59 – 700 Th. Tandem mass spectral (MS<sup>2</sup>) analyses were performed by ramping up 180 the normalized collision energy (NCE) from 1 - 7 eV (i.e., normalized to singly charged ions at m/z181 500). Thus, to retrieve the collision energy (CE) encountered by ions at any given m/z ratio within the 182 higher-energy collision dissociation (HCD) cell, the CE can be calculated as follows: CE = (m/z / 500)183 x NCE x f, where f stands for the number of charges of the ion. To ensure an optimal detection of the 184 product ions, the mass spectra obtained using the CI-APi-TOF and the CI-Orbitrap were averaged over 10 minutes each. A time resolution of 5 min was used for the  $MS^2$  analyses conducted by the Orbitrap. 185 186 The high-resolution Orbitrap data were analyzed by XCalibur 4.1 (Thermo Scientific) software 187 package to determine accurate composition and the abundance of the compounds of interest. Peak fitting of the CI-APi-TOF data was performed by means of the Matlab-based toftools software.<sup>37</sup> 188

189

#### 190 RESULTS AND DISCUSSION

191 **Characterization of the CI-Orbitrap.** Despite the wealth of studies using the Orbitrap technique, 192 little is known about the capability of the Orbitrap in measuring compounds on-line at low 193 concentrations. For example it has been reported that the Orbitrap can provide a non-linear response,

194 potentially impacting isotope ratios, determination and the quantification of compounds present at extremely low concentrations.<sup>39</sup> In view of these findings available from literature, we evaluated the 195 196 performance of the CI-Orbitrap by comparing the measured vs. the theoretical isotopic intensities 197 using product ions analyzed by the Orbitrap-Tropos using protonated n-propylamine  $(n-C_3H_7NH_3^+)$ 198 and acetate (CH<sub>3</sub>COO<sup>-</sup>). To further estimate the impact of different reagent ions, results from our 199 former study performed with the Orbitrap-IRCELYON using nitrate-ion based chemistry<sup>30</sup> are also 200 compared here. In both cases, OVOCs were continuously generated in the flow tube from either the 201 ozonolysis and/or OH radical initiated oxidation of α-pinene. Hence, the abundance of the main 202 OVOCs (e.g.,  $C_{10}H_{14} {}_{16}O_x$ ;  $C_{20}H_{30} {}_{32}O_x$ ) and RO<sub>2</sub> radicals (e.g.,  $C_{10}H_{15} {}_{17}O_x$ ) at nominal masses M, (M 203 + 1) and (M + 2), corresponding to their <sup>13</sup>C atom and <sup>18</sup>O atom fraction, were measured to cover a wide range of normalized product signals in the range of  $5 \times 10^{-7}$  to  $5 \times 10^{-2}$ . Signal intensities 204 reported in Figure 1A were obtained with an AGC target of  $1 \times 10^5$  charges. As depicted in Figure 1A, 205 when the ratio is equal to 1.0 for normalized signal > ~  $4 \times 10^{-4}$  to (~  $1 \times 10^{6}$  molecules cm<sup>-3</sup>), the 206 207 Orbitrap is providing a linear measure of the ion intensity. However, this ratio dropped significantly for normalized signals below ~  $4 \times 10^{-4}$ . Such a situation occurs when the ion intensity is close to the 208 209 instrumental threshold, i.e., by using standard settings the Orbitrap mass analyzer records only signals 210 if S/N > 1.3. The ion signals below this threshold are treated as undetected by the acquisition software. 211 Due to the statistics, peaks with an average S/N = 1.5 for example will appear above this threshold only in a limited amount of cases reducing the resulting peak intensity.<sup>40</sup> As a result, for a normalized 212 signal smaller than  $1 \times 10^{-5}$ , the CI-Orbitrap only detects 5 - 10 % of the "true ion number 213 214 distribution". That means, using the instrumental parameters and the calibration factor employed here  $(1.85 \times 10^9 \text{ molecules cm}^{-3})$  the limit of quantification (LoO, corresponding to lowest normalized 215 signal observed within the linear range) of the Orbitrap was evaluated to be ~  $1 \times 10^6$  molecules cm<sup>-3</sup> 216 217 at a 10-minute integration time. It is worth pointing out that the limit of detection (LoD, corresponding 218 to the lowest normalized signal observed) is likely one or two orders of magnitude lower than the LoO 219 but due to the lack of linearity accurate numbers cannot be directly provided. By adjusting the AGC 220 target the linear range can be shifted towards lower ion concentrations as shown in Figure 1B. This 221 can be explained by larger number of ions trapped within the C-trap prior to the Orbitrap scan resulting in more ions entering the Orbitrap mass analyzer. This leads to an enhanced S/N ratio and better statistics. Hence, we have evaluated the impact of the AGC target (scanned from 5 x  $10^4$  to 1 x  $10^6$  charges) on the linearity and found that by optimizing the AGC target, the LoQ of the CI-Orbitrap is anticipated to be greatly extended. However, as most of our previous experiments were performed using an AGC target of 1 x  $10^5$  charges, we kept this setting to perform the side-by-side comparison.

227 Comparison CI-Orbitrap vs CI-APi-TOF. To evaluate the performance of the CI-Orbitrap 228 compared to the widely used CI-APi-TOF technique we directly performed side-by-side experiments. Both instruments, equipped with a similar type of inlet originally designed by Eisele et al.<sup>31</sup> and 229 230 running with the same reagent ion, sampled concurrently RO<sub>2</sub> radicals as well as OVOCs produced 231 under well-controlled reaction conditions. We focused on the detection of RO<sub>2</sub> radicals produced from 232 the oxidation of  $\alpha$ -pinene. Using acetate and aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) as the reagent ions, the main RO<sub>2</sub> 233 radicals from  $\alpha$ -pinene oxidation, HO-C<sub>10</sub>H<sub>16</sub>(O<sub>2</sub>)<sub> $\alpha$ </sub>O<sub>2</sub> ( $\alpha = 0, 1, 2$ ), were detected by means of the CI-Orbitrap, in line with the findings of the CI-APi-TOF.<sup>24,30,35</sup> As depicted in Figures 2 and S2, the mass 234 235 resolving power of the Orbitrap can accurately distinguish the different species, which is often 236 impossible with typical TOF mass analyzers. To further illustrate the difference, we have directly 237 compared ion signals measured by the CI-Orbitrap and by the CI-APi-TOF equipped with a high 238 resolution mass analyzer (HR-TOF, resolution ~ 3000) (Figure 2).

239 Figure 3 shows the results of the OH radical-initiated oxidation of  $\alpha$ -pinene. The OH radicals 240 were generated by isopropyl nitrite (IPN) photolysis. The formation of the additional RO<sub>2</sub> radical HO- $C_{10}H_{15}(OH)(O_2)O_2$  can be explained by the reaction of HO- $C_{10}H_{16}(O_2)_2O_2$  with NO and subsequent 241 radical isomerization as discussed in a former study.<sup>35</sup> NO is formed from the IPN photolysis. In 242 243 addition to the RO<sub>2</sub> radicals, also closed-shell products were detected including carbonyls and organic nitrates produced from the  $RO_2$  + NO reactions.<sup>16</sup> Lastly, products arising from other bimolecular  $RO_2$ 244 245 reactions were not detected or were below the detection limit under the selected experimental conditions due to the relatively low RO<sub>2</sub> radical concentrations  $< 10^8$  molecules cm<sup>-3</sup> and the very 246 247 short reaction time of 7.9 s.

As shown in Figure 3, for uncorrected normalized intensities above  $(2 - 3) \times 10^{-4}$ (corresponding to ~  $(4-6) \times 10^5$  molecules cm<sup>-3</sup>) both techniques are in very good agreement. The lack 250 of linearity hampers the Orbitrap, unlike the APi-TOF, to accurately measure lower concentrations. 251 However, this lack of linearity appears to be independent of the instrument and the type of reagent 252 ions (Figure 1A). This behavior indicates that this instrumental limitation can be overcome in order to 253 retrieve the "correct" signal strength for peaks with lowest signal intensity. Indeed, using all 254 measurements from multiple experiments and reagent ions, a function named "sigmoidal correction 255 function" based on a fitting algorithm using a characteristic sigmoidal shape can be determined. 256 Therefore, raw normalized signals (corrected for sampling losses) measured with the CI-Orbitrap were 257 further corrected using the "sigmoidal correction function", see also Figure 1. By applying this 258 method, all the data were corrected (open markers), which greatly helps maintaining the good 259 agreement between both techniques (Figure 3). However, for uncorrected signal intensities below a threshold of  $5 \times 10^{-6} - 1 \times 10^{-5}$  this approach results in an overestimation of the ion concentrations as 260 261 the signal is likely very close to the noise level of the instrument. As a result, such data points were 262 not included in Figures 3, 4, S3 and S4. While the APi-TOF can further help correcting this lack of 263 linearity we preferred to propose a method based only on the signal acquired by the Orbitrap. Hence, 264 the reported LoD is likely an upper limit and might be even pushed further with appropriate and 265 collocated instrumentations.

266 Overall, product signals measured by CI-Orbitrap and the CI-APi-TOF are mostly within a factor of 2 (Figure 5) providing a good agreement between these two analytical techniques for 267 corrected normalized signal intensity ranging from ~  $5 \times 10^{-5}$  to  $1 \times 10^{-2}$  (corresponding to ~  $1 \times 10^{5}$  to 268 269  $2 \times 10^7$  molecules cm<sup>-3</sup>). Exception are the measurements of highly oxidized products using acetate 270 ionization. The reason for that is not clear at the moment. It is worth pointing out that the positive 271 mode measurements were less impacted by the lack of linearity compared to negative mode 272 measurements. This is explained by the fact that at a given product concentration, the resulting ion 273 intensity measured by aminium  $(n-C_3H_7NH_3^+)$  ionization is much greater than for acetate ionization. In 274 the case of the highest oxidized RO<sub>2</sub> radicals, i.e., HO-C<sub>10</sub>H<sub>16</sub>(O<sub>2</sub>)<sub>2</sub>O<sub>2</sub> and HO-C<sub>10</sub>H<sub>15</sub>(OH)(O<sub>2</sub>)O<sub>2</sub> 275 bearing -OH and -OOH moieties, the obtained corrected signal intensities are almost identical within a 276 factor of two applying either acetate or aminium  $(n-C_3H_7NH_3^+)$  for product ionization. This fact is 277 obviously due to strong binding of these RO<sub>2</sub> radicals to both reagent ions. Thus, a near-maximum detection sensitivity can be expected for these reagent ions.<sup>41,42</sup> On the other hand, for the less oxidized RO<sub>2</sub> radicals HO-C<sub>10</sub>H<sub>16</sub>O<sub>2</sub> and HO-C<sub>10</sub>H<sub>16</sub>(O<sub>2</sub>)O<sub>2</sub> the detection sensitivity based on aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) ionization is definitely higher compared to acetate ionization, i.e., by a factor of 500 – 1000 in the case of HO-C<sub>10</sub>H<sub>16</sub>O<sub>2</sub>.<sup>42</sup>

282 Ozonolysis experiments in the absence of an OH scavenger were conducted in order to 283 generate a larger variety of products, mainly RO<sub>2</sub> radicals, formed from the simultaneous ozone and 284 OH radical reactions of α-pinene. Accordingly, two types of RO<sub>2</sub> radicals have been formed, i.e., the 285 ozonolysis-derived RO<sub>2</sub> radicals O<sub>1</sub>O-C<sub>10</sub>H<sub>15</sub>(O<sub>2</sub>)<sub>x</sub>O<sub>2</sub> (x = 0, 1, 2, 3) and the OH-derived RO<sub>2</sub> radicals HO-C<sub>10</sub>H<sub>16</sub>(O<sub>2</sub>)<sub>a</sub>O<sub>2</sub> ( $\alpha = 0, 1, 2$ ).<sup>7,35</sup> Figure 4 presents the signal intensities of both types of RO<sub>2</sub> 286 287 radicals measured by means of aminium  $(n-C_3H_7NH_3^+)$  ionization. While the agreement for the most 288 oxidized RO<sub>2</sub> radicals is again very good, the signals of the less oxidized species  $O_2O-C_{10}H_{15}O_2$  and 289  $HO-C_{10}H_{16}O_2$  (Figures 3 and 4) are systematically higher using the CI-Orbitrap by a factor of two or 290 higher. In contrast, for the most oxidized  $RO_2$  the difference between the two instruments was only ~ 291 20%. Such a disparity might be explained by less efficient declustering of the relatively weakly bound 292 aminium clusters of  $O,O-C_{10}H_{15}O_2$  and  $HO-C_{10}H_{16}O_2$  in the CI-Orbitrap compared to the CI-APi-TOF. 293 This results in a more sensitive detection of the initially formed RO<sub>2</sub> radicals with relatively low 294 oxygen content. It is important to mention that by applying the transmission curve to the CI-Orbitrap 295 data, a larger discrepancy exist between the results of both instruments, see Figure S6. This 296 discrepancy is obviously due to the different ion transmission corrections. Indeed, using the 297 parameters selected in this study the ion transmission within the Orbitrap exhibit a steep increase 298 between from m/z 60 to 300 Th (SI). However, much more experimental effort is needed in the future 299 for a reliable determination of the ion transmission of both instruments and for different reagent ions. 300 Hence it would be possible to determine i) how good the duty cycle correction accounts for the overall 301 ion transmission of the CI-APi-TOF and ii) what is the accuracy of the depletion methods in 302 comparison to absolute calibration methods.

303 Overall, the side-by-side comparison displays a very good agreement of the results of the CI-304 Orbitrap and the CI-APi-TOF with the exception of the lowest oxidized reaction products. By using 305 the "sigmoidal correction function",  $1.85 \times 10^9$  molecules cm<sup>-3</sup>as the calibration factor for an AGC 306 target of  $1 \times 10^5$  charges, the LoQ of the CI-Orbitrap can be as low as  $1 \times 10^5$  molecules cm<sup>-3</sup> at a 10-307 minute integration time.

308 **Determination of cluster binding energy.** In common CI-APi-TOF approaches, the organic 309 molecules of interest are observed as molecular clusters with the reagent ion (e.g., with  $CH_3COO^-$  or 310  $n-C_3H_7NH_3^+$ ), see also eq. (1) and (2). In order to provide an accurate quantification of the compounds 311 of interest it is essential to constrain the sensitivity of the reagent ion to OVOCs. To reach this goal, 312 characterizing any limitations when detecting the compounds of interest, including the ion-molecule 313 collision limit and the ion-molecule reaction time is critical. The proficiency of any neutral molecule 314 to bind to the reagent ion is directly linked to the binding energy of the adduct.

315 Accordingly, a weakly bound adduct can undergo declustering, i.e., collision-induced 316 dissociation (CID), during the flight trough the mass analyzer. Ultimately, the binding energy of the 317 adduct and the energy of the collisions with gas molecules in the mass spectrometer will define the 318 survival probability of the adduct ions. To constrain this parameter, procedures based on CID 319 measurement coupled to quantum chemical methods have been proposed to investigate the behavior of adducts at different collision energies.<sup>43,44</sup> Nonetheless, carrying out such measurements is challenging 320 321 for the hundreds of different molecular ions, typically observed with a CI-APi-TOF, especially when 322 molecular structures remain unknown and/or are highly complex. Therefore, to quantitatively 323 constrain the effective binding energies of a wide range of OVOCs and RO<sub>2</sub> radicals, we employed the capability of the Orbitrap analyzer to perform untargeted MS<sup>2</sup> analyses. Hence, all ions were injected 324 325 into the HCD cell, where they collide at a defined collision energy with N<sub>2</sub> molecules. The NCE was 326 ramped up from 1 to 7 eV. During the declustering scans, all potentials upstream the HCD cell 327 remained identical and only the NCE within the HCD cell incremented, thereby avoiding any changes 328 in the ion transmission of the mass spectrometer.

An example of the declustering analysis is presented in Figure 6A for a set of typical oxidation products, for which the remaining fraction of individual ions is plotted as a function of the CE (retrieve for each ion based on their m/z). Following the approach previously proposed for iodidebased clusters,<sup>43–45</sup> a sigmoidal fit was applied to the acquired data (Figure S7), in order to obtain the following parameters: i) the collision energy at which half of the signal is removed (CE<sub>50</sub>), and ii) the 334 maximum amplitude of the sigmoidal function  $(S_0)$ , corresponding to the relative signal intensity that 335 would be measured in absence of declustering processes during the transmission through the mass 336 spectrometer. In Table S1, the CE<sub>50</sub> values of the OH-derived OVOCs and OH-derived RO<sub>2</sub> produced 337 from the OH radical-initiated oxidation of α-pinene are reported. While direct comparison with 338 quantum chemical calculations is not directly possible due to the absence of information on the studied 339 OVOCs, earlier studies indicate that the values reported in Table S1 are within a fairly good 340 agreement for binding energies determined for isoprene-derived oxidation products measured with CI-APiTOF using protonated n-propylamine or acetate.<sup>41,42</sup> For example, Berndt et al.<sup>42</sup> have estimated 341 342 binding energies of the HPALD-( $n-C_3H_7NH_3^+$ ) cluster ( $C_5H_8O_3$ ) cluster and HPALD-CH<sub>3</sub>COO<sup>-</sup> 343 cluster of 28.5 and 31.9 kcal mol<sup>-1</sup>, respectively, which is close to the values determined for OVOCs 344 and RO<sub>2</sub> radicals containing 3 oxygen atoms (Table S1) within this present study.

Following the method proposed in former studies,<sup>43,44</sup> we found that the maximum possible 345 346 transmission for each compound clustered with protonated n-propylamine  $(n-C_3H_7NH_3^+)$  is reached at 347 a binding energy of ~ 35 kcal mol<sup>-1</sup>. This indicates that for cluster ions having a greater binding 348 energy, the stability of the adduct will be sufficient to transit through the different ion optics without 349 significant declustering losses. These results are in line with the side-by-side comparison, where the 350 largest discrepancy is observed for the lowest oxygenated species (e.g.,  $O,O-C_{10}H_{15}O_2$ ; HO- $C_{10}H_{16}O_2$ ), 351 i.e., the compounds with the lowest binding energy (Table S1). By optimizing the different voltages, 352 the declustering processes occurring within the APi-TOF and/or within the Orbitrap can be reduced. 353 Finally, it is interesting to note that earlier work, performing CID experiments using iodide-based 354 chemistry, determined a similar threshold, i.e.,  $\sim 30$  kcal mol<sup>-1.44</sup>

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#### 356 CONCLUSIONS

357 In this work, we demonstrated the capability of the CI-Orbitrap in measuring  $RO_2$  radicals as well as 358 OVOCs at atmospherically relevant concentrations and compared them to simultaneous CI-APi-TOF 359 measurements. We explored the current limitations of this new analytical technique and demonstrated 360 that these can be partially overcome through a careful determination of a sigmoidal correction 361 function. In addition, to unambiguously identify OVOCs formed in the gas phase, the analysis by 362 means of the CI-Orbitrap is able to accurately quantify organic species at concentration down to  $1 \times$ 363  $10^5$  molecules cm<sup>-3</sup>. This LoQ is ~ one order of magnitude higher in comparison to the APi-TOF used 364 in this study. In addition to the much greater mass resolving power, another clear advantage over the APi-TOF technique is the capability of performing  $MS^2$  analyses needed to retrieve information on the 365 366 chemical structure of the compounds of interest and to determine the binding energy of the clusters. 367 Overall, the combination of high-mass resolving power of the Orbitrap and high sensitivity of the 368 aminium/ammonium CI represents a powerful analytical tool that can improve our current knowledge 369 regarding the complexity of the atmospheric gaseous composition. Thus, this new technique can help 370 to answer some of the questions that so far were unable to be answered due to the pre-existing 371 instrument limitations.



373 Figure 1. (A) Linearity of the Orbitrap as a function of normalized signal measured with protonated n-374 propylamine (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) and acetate (CH<sub>3</sub>COO<sup>-</sup>) reagent ions with the Orbitrap-Tropos and nitrate-375 ion based chemistry with the Orbitrap-IRCELYON, using identical parameter settings. All signal 376 intensities were corrected with respect to the sum of  $(CH_3COOH)_n$ - $CH_3COO^-$  (n = 0,1) at nominal 59 377 Th and 119 Th; to the sum of  $(n-C_3H_7NH_2)_m$ -n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup> (m = 0,1) at nominal 60 Th and 119 Th; and 378 to the sum of  $(HNO_3)_p$ -NO<sub>3</sub><sup>-</sup> (p = 0,1,2) at nominal 62, 125, 188 Th, for the respective reagent ions. 379 The black fit is the "sigmoidal correction function" based on a sigmoidal fitting algorithm. (B) Impact 380 of the AGC target on the linearity of the CI-Orbitrap-Tropos using aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) as the 381 reagent ion.





**Figure 2.** Mass spectra of ions at nominal m/z 245 from the combined ozonolysis and OH radical reaction of  $\alpha$ -pinene for different reaction conditions (A) measured with the CI-Orbitrap and (B) comparison of the ion signals recorded by the CI-Orbitrap and the CI-APi-TOF. C<sub>9</sub><sup>13</sup>CH<sub>16</sub>O<sub>3</sub> represents most likely the <sup>13</sup>C-isotope of pinonaldehyde and C<sub>10</sub>H<sub>17</sub>O<sub>3</sub> the initial RO<sub>2</sub> radical from the OH attack, HO-C<sub>10</sub>H<sub>16</sub>O<sub>2</sub>. Concentrations are given in molecules cm<sup>-3</sup>.



**Figure 3.** Normalized signals of  $RO_2$  radicals produced from the OH radical-initiated oxidation of  $\alpha$ pinene as a function of initial IPN concentration measured by the CI-APi-TOF (black) and the CI-Orbitrap (red). OH radicals have been formed via IPN photolysis. Full and open markers in red correspond to raw and corrected (using the sigmoidal correction function) signals measured with the Orbitrap, respectively. (**A**) Acetate and (**B**) aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) served as the reagent ion for otherwise identical reaction conditions in both cases.

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400 **Figure 4.** Normalized signals of **A**) OH-derived RO<sub>2</sub> radicals and **B**) O<sub>3</sub>-derived RO<sub>2</sub> radicals 401 produced from the O<sub>3</sub>/OH +  $\alpha$ -pinene reaction as a function of the ozone concentration. Results 402 obtained by the CI-APi-TOF are given in black and those from the CI-Orbitrap in red using aminium 403 (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>) ionization in both cases. The Orbitrap data were corrected using the sigmoidal 404 correction function.





407 **Figure 5**. (A) Comparison between lower limit  $RO_2$  radical concentrations measured with the CI-408 APiTOF and the CI-Orbitrap in the different experiments. (B) Correlation of the concentrations of 409 RO<sub>2</sub> radicals formed from the O<sub>3</sub>/OH +  $\alpha$ -pinene reaction measured by the CI-APi-TOF and the CI-

 $410 \qquad \text{Orbitrap using aminium } (n\text{-}C_3\text{H}_7\text{NH}_3^+) \text{ ionization.}$ 



431 **Figure 6.** Declustering scans of (**A**)  $C_{10}H_{16}O_{2.6}$  measured from the OH-initiated oxidation of α-pinene 432 with the CI-Orbitrap using aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>). (**B**) Relationship between fitting declustering 433 scans

434  $(1/S_0)$  as a function of collision energy. CE<sub>50</sub> is used as a measured of the relative binding energy and 435 corresponds to the collision energy where half of the signal is removed.  $S_0$  is the maximum amplitude 436 obtained from the sigmoidal fit of declustering scans (e.g., Figure S7) of RO<sub>2</sub> radicals (triangle 437 markers) and OVOCs (ON: square markers; non-ON: circle markers) formed from OH-initiated 438 oxidation of  $\alpha$ -pinene with the CI-Orbitrap using aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>).

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### 451 SUPPORTING INFORMATION

452 Figure S1 depicts the schematic of a Q Exactive mass spectrometer. Figure S2 shows the mass spectra 453 of ions at m/z 245 and 260 measured during the oxidation of  $\alpha$ -pinene. Figures S3 and S4 present the 454 normalized signals of the organic nitrates and carbonyls produced from the OH-initiated oxidation of 455  $\alpha$ -pinene, respectively. Figure S4 shows the correlation of the concentration measured species using 456 both instruments and formed from the OH radical initiated oxidation of  $\alpha$ -pinene using acetate-ion-457 based (CH<sub>3</sub>COO<sup>-</sup>) ionization. Figure S6 presents the normalized signals of RO<sub>2</sub> generated from the 458 oxidation of  $\alpha$ -pinene measured using aminium (n-C<sub>3</sub>H<sub>7</sub>NH<sub>3</sub><sup>+</sup>). Figure S7 presents the declustering 459 experiments performed on OVOCs formed from  $\alpha$ -pinene ozonolysis. Figure S8 shows the mass 460 Spectra of the different perfluorinated acids measured with CI-Orbitrap. Figure S9 presents the relative 461 ion transmission fit determined using the depletion method. The Supporting Information is available 462 free of charge on the ACS Publications website.

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