1 **Ammonium-adduct chemical ionization to investigate**
2 **anthropogenic oxygenated gas-phase organic compounds in**
3 **urban air**
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27

28 **Abstract**

29 Volatile chemical products (VCPs) and other non-combustion-related sources have
30 become important for urban air quality, and bottom-up calculations report emissions of a
31 variety of functionalized compounds that remain understudied and uncertain in emissions
32 estimates. Using a new instrumental configuration, we present online measurements of
33 oxygenated ~~VCP~~organic compounds in a U.S. megacity over a 10-day wintertime
34 sampling period, when biogenic sources and photochemistry were less active.
35 Measurements were conducted at a rooftop observatory in upper Manhattan, New York
36 City, USA using a Vocus chemical ionization time-of-flight mass spectrometer with
37 ammonium (NH_4^+) as the reagent ion operating at 1 Hz. The range of observations
38 spanned volatile, intermediate-volatility, and semi-volatile organic compounds with
39 targeted analyses of ~150 ions whose likely assignments included a range of
40 functionalized compound classes such as glycols, glycol ethers, acetates, acids, alcohols,
41 acrylates, esters, ethanolamines, and ketones that are found in various consumer,
42 commercial, and industrial products. Their concentrations varied as a function of wind
43 direction with enhancements over the highly-populated areas of the Bronx, Manhattan,

44 and parts of New Jersey, and included abundant concentrations of acetates, acrylates,
45 ethylene glycol, and other commonly-used oxygenated compounds. The results provide
46 top-down constraints on wintertime emissions of these oxygenated/functionalized
47 compounds with ratios to common anthropogenic marker compounds, and
48 ~~compares~~comparisons of their relative abundances to two regionally-resolved emissions
49 inventories used in urban air quality models.

50

51 **Keywords:** Volatile chemical products, non-combustion-related emissions, personal care
52 products, solvents, glycol ethers, VOCs, IVOCs, SVOCs, urban air quality, New York
53 City, LISTOS~~, AEROMMA~~

54

55 **1. Introduction**

56 Non-combustion-related sources are increasingly important contributors of anthropogenic
57 emissions in developed regions and megacities with implications for tropospheric ozone
58 and secondary organic aerosols (SOA) (Coggon et al., 2021; Khare and Gentner, 2018;
59 Mcdonald et al., 2018; Pennington et al., 2021; Shah et al., 2020). These sources include
60 volatile chemical products (VCPs), asphalt, and other products/materials that emit
61 volatile-, intermediate- and semi-volatile organic compounds (VOCs, IVOCs, SVOCs),
62 which contribute to the atmospheric burden of reactive organic carbon (ROC) (Heald and
63 Kroll, 2020). Emissions occur over timescales ranging from minutes to several days and
64 up to years in some cases (Khare and Gentner, 2018). Compounds from VCPs are diverse
65 in terms of chemical composition and depend on application methods and uses of
66 different products and materials. Examples of compound classes found in consumer and
67 commercial products include hydrocarbons, acetates, alcohols, glycols, glycol ethers,
68 fatty acid methyl esters, aldehydes, siloxanes, ethanolamines, phthalates and acids (Bi et
69 al., 2015; Even et al., 2019, 2020; Khare and Gentner, 2018; Mcdonald et al., 2018).

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71 A subset of compounds from these classes have been investigated in indoor environments
72 for sources like building components (e.g. paints), household products (e.g. cleaners,
73 insecticides, fragrances), and for some from polymer-based items such as textiles and
74 toys (Bi et al., 2015; Even et al., 2020; Harb et al., 2020; Liang et al., 2015; Noguchi and
75 Yamasaki, 2020; Shi et al., 2018; Singer et al., 2006). Emissions are often dependent on
76 volatilization and thus can exhibit dependence on temperature (Khare et al., 2020).
77 However, other environmental factors such as relative humidity can sustain or enhance
78 indoor air concentrations of a wide range of compounds including alcohols, glycols and
79 glycol ethers for months after application of paints (Choi et al., 2010b; Markowicz and
80 Larsson, 2015). Similarly, mono-ethanolamines from degreasers and oxygenated third-

81 hand cigarette smoke compounds have also been shown to off-gas and persist in indoor
82 air for days or more after application or use (Schwarz et al., 2017; Sheu et al., 2020).

83

84 Non-combustion-related emissions of ROC can present health risks through direct
85 exposure in both indoor and outdoor environments and via SOA and ozone production
86 (Bornehag et al., 2005; Choi et al., 2010a; Destaillats et al., 2006; Masuck et al., 2011;
87 Pye et al., 2021; Qin et al., 2020; Wensing et al., 2005). These health impacts will be
88 modulated by the rate at which indoor emissions of ROC are transferred outdoors (Sheu
89 et al., 2021), but indoor sinks are uncertain and have often been neglected in emissions
90 inventory development for VCPs until recently (McDonald et al., 2018; Seltzer et al.,
91 2021b). Information on indoor and outdoor concentrations of many ROC compounds is
92 limited due to the historical focus on more volatile hydrocarbons and small oxygenated
93 compounds (e.g. methanol, isopropanol, acetone) and shorter timescales of solvent
94 evaporation (e.g. <1 day). In comparison, emissions of intermediate- and semi-volatile
95 compounds (I/SVOCs; including higher molecular weight oxygenates) and some
96 chemical functionalities (e.g. glycol ethers) are poorly constrained, owing to
97 instrumentation challenges and/or long emission timescales (Khare and Gentner, 2018).

98

99 Single-ring aromatic VOCs (e.g. benzene, toluene, ethylbenzene, xylenes) have
100 historically been well-known contributors to urban ozone and SOA production (Henze et
101 al., 2008; Venecek et al., 2018). On this basis, regulatory policies drove a shift towards
102 oxygenates to replace these aromatics and other unsaturated hydrocarbons as solvents
103 (Council of the European Union, 1999), which has influenced the ambient composition
104 of oxygenated volatile organic compounds (OVOCs) (Venecek et al., 2018). Recent top-
105 down measurements have revealed large upward fluxes of OVOCs in urban environments
106 that double the previous urban anthropogenic emission estimates (Karl et al., 2018).
107 Other studies have found substantial VCP-related emissions (e.g.
108 Decamethylcyclopentasiloxane or D5) to outdoor environments in several large cities
109 such as Boulder, CO; New York, NY; Los Angeles, CA and Toronto, Canada (Coggon et
110 al., 2018, 2021; Gkatzelis et al., 2021b, 2021a; Khare and Gentner, 2018; Mcdonald et
111 al., 2018; McLachlan et al., 2010). Offline laboratory experiments with select VCP-
112 related precursors have also shown significant SOA yields from oxygenated aromatic
113 precursors (Charan et al., 2020; Humes et al., 2022). Furthermore, bottom-up estimates
114 suggest that 75-90% of the non-combustion emissions are constituted by functionalized
115 species while only the remaining 10-25% are hydrocarbons (Khare and Gentner, 2018;
116 Mcdonald et al., 2018).

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118　Non-combustion-related emissions of ROC can present health risks through direct
119　exposure in both indoor and outdoor environments and via SOA and ozone production
120　(Bornehag et al., 2005; Choi et al., 2010a; Destaillats et al., 2006; Masuck et al., 2011;
121　Pye et al., 2021; Qin et al., 2020; Wensing et al., 2005). These health impacts will be
122　modulated by the air exchange rates at which indoor emissions of ROC are transferred
123　outdoors (Sheu et al., 2021), but indoor sinks are uncertain and have often been neglected
124　in emissions inventory development for VCP-related sources until recently (McDonald et
125　al., 2018; Seltzer et al., 2021b). Information on indoor and outdoor concentrations of
126　many ROC compounds is limited due to the historical focus on more volatile
127　hydrocarbons and small oxygenated compounds (e.g. methanol, isopropanol, acetone)
128　and shorter timescales of solvent evaporation (e.g. <1 day). In comparison, emissions of
129　intermediate- and semi-volatile compounds (I/SVOCs; including higher molecular weight
130　oxygenates) and some chemical functionalities (e.g. glycol ethers) are poorly constrained,
131　owing to instrumentation challenges and/or long emission timescales (Khare and
132　Gentner, 2018).

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134　To improve observational constraints on the abundances of widely-used oxygenated
135　VCPs that are expected to influence urban air quality, but are uncertain in emissions
136　inventories, we employed a Vocus chemical ionization time-of-flight mass spectrometer
137　(Vocus CI-ToF) using ammonium (NH_4^+) as a chemical reagent ion to increase
138　sensitivity to compound types that have traditionally provided measurement challenges.
139　Specifically, we: (a) evaluated the performance of the CI-ToF for a diverse array of
140　oxygenated VCPs and compare ambient observations between NH_4^+ and H_3O^+ reagent
141　ions; (b) examined ambient abundances of a subset of oxygenated gas-phase organics
142　related to VCP emissions and their dynamic atmospheric concentrations in New York
143　City (NYC) over a 10-day winter period with reduced biogenic emissions and secondary
144　OVOC production; (c) determined their ambient concentration ratios and covariances
145　with major tracer compounds; and (d) compared ambient observations against two
146　regionally-resolved emissions inventories to provide top-down constraints on the relative
147　emissions of major oxygenated VCPs that influence urban air quality. The findings of this
148　work highlight the diversity of functionalized organic species emitted from VCPs with
149　comparisons against inventories that inform our understanding of VCP composition and
150　emission pathways, and thus improve urban air quality models and policy.

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152　**2. Materials and methods**

153　The sampling site was located at the Rooftop Observatory at the Advanced Science
154　Research Center of the City University of New York (CUNY ASRC, 85 St.

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To improve observational constraints on the abundances of widely-used oxygenated VCPs that are expected to influence urban air quality, but are uncertain in emissions inventories, we employed a Vocus chemical ionization time-of-flight mass spectrometer (Vocus CI-ToF MS) using ammonium (NH_4^+) as a chemical reagent ion to increase sensitivity to compound types that have traditionally provided measurement challenges with other well-known techniques such as iodide (I^-)-CIMS and proton-transfer-reaction (PTR)-MS. These techniques have been frequently used in atmospheric studies with both advantages and limitations. While I^--CIMS has better sensitivity toward highly functionalized extremely low volatility organic compounds (ELVOCs) and also halogens (Robinson et al., 2022; Slusher et al., 2004; Thornton et al., 2010), PTR-MS can detect relatively lighter functionalized species and olefinic/aromatic hydrocarbons, however with highly reduced sensitivity toward certain compound classes e.g. alcohols, esters, glycols etc. due to large fragmentation losses (Gkatzelis et al., 2021a). The ability of NH_4^+ adduct to ionize functionalized organic compounds as well as less oxygenated organic precursors with negligible fragmentation across volatile to semi-volatile species is a key advantage (Canaval et al., 2019; Zaytsev et al., 2019b). Furthermore, it operates at relatively lower pressure (1-5 mbar) than (I^-)-CIMS, which could facilitate faster switching with PTR for quantitation of less oxygenated precursor species.

Specifically, using this technique, we: (a) evaluated the performance of the CI-ToF for a diverse array of oxygenated VCPs and compare ambient observations between NH_4^+ and H_3O^+ reagent ions; (b) examined ambient abundances of a subset of oxygenated gas-phase organics related to VCP-related emissions and their dynamic atmospheric concentrations in New York City (NYC) over a 10-day winter period with reduced biogenic emissions and secondary OVOC production; (c) determined their ambient concentration ratios and covariances with major tracer compounds; and (d) compared ambient observations against two regionally-resolved emissions inventories (including all anthropogenic sources) to provide top-down constraints on the relative emissions of a range of oxygenated compounds that may influence urban air quality. The findings of this work highlight the diversity of functionalized organic species emitted from VCPs with comparisons against inventories that inform our understanding of VCP composition and emission pathways, and thus improve urban air quality models and policy.
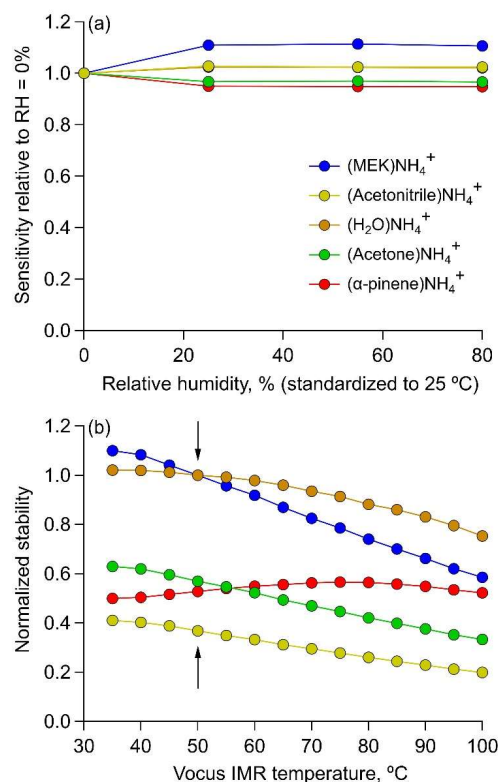
2. Materials and methods

The sampling site was located at the Rooftop Observatory at the Advanced Science Research Center of the City University of New York (CUNY ASRC, 85 St. Nicholas Terrace) in Upper Manhattan (Figures S1-2), which is the location of the Manhattan ground site for the upcoming AEROMMA research campaign (Warneke et al., n.d.).).

193 The ASRC is built on top of a hill 30 m above the mean sea level whose surface is
194 naturally elevated above the surrounding landscape. The observatory is 86 m above the
195 mean sea level and the inlet was at 89 m with minimally obstructed views to the
196 northwest and east towards the Bronx and Harlem, as well as to the south along the island
197 of Manhattan.
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200 Gas-phase VOCs and I/SVOCs were measured using a Vocus CI-ToF with a NH_4^+
201 reagent ion source (Krechmer et al., 2018), which had a higher sensitivity than most
202 previous state-of-the-art chemical ionization-ToF instruments (without focusing) by a
203 factor of 20 due to the quadrupole-based ion focusing, a mass resolving power of ~10,000
204 m/Δm, and was quantitatively independent of ambient humidity changes (Figure
205 1a).(Figure 1a) (Holzinger et al., 2019). The Vocus CI-TOF sampled at a frequency of 1
206 Hz continuously throughout the 10-day period from 21st to 31st January 2020. NH_4^+
207 ionization coupled with high frequency online mass spectrometry enables measurements
208 of functionalized compounds emitted from diverse, distributed sources in around New
209 York City. AmmoniumNH$_4^+$ has a long history of use as a positive-ion reagent gas in
210 chemical ionization mass spectrometry, but has only recently been applied to the study of
211 atmospheric chemistry with time-of-flight mass spectrometers (Canaval et al., 2019;
212 Westmore and Alauddin, 1986; Zaytsev et al., 2019b, 2019a). The NH_4^+ reagent ion
213 forms clusters effectively with polarizable molecules, providing mostly softly ionized
214 NH_4^+-molecule adducts, though some protonation, charge transfer, and fragmentation can
215 occur as alternate ionization pathways (Canaval et al., 2019). It has previously been
216 applied in laboratory studies in different configurations than the instrument described
217 here (Canaval et al., 2019; Zaytsev et al., 2019b), and to our knowledge this is the first
218 published atmospheric field measurement with NH_4^+ionization.

Figure 1: Vocus CI-ToF performance with low-pressure NH_4^+ ionization as a function of atmospheric conditions and instrument parameters. (a) Minimal effects of relative humidity (RH) on Vocus CI-ToF quantification for several major compounds using the NH_4^+ Vocus CI-ToF (b) Ion-adduct stability as a function of temperature in the focusing Ion Molecule Reaction (fIMR) region, with ambient measurements made at 50 °C in this study.

NH_4^+ selectively ionizes functionalized species including ones that have generally been difficult to measure using proton-transfer reaction ionization due to excess fragmentation (e.g. glycols) or low proton affinities (Karl et al., 2018). However, it excludes non-polar hydrocarbons and is not intended to examine emissions from hydrocarbon-dominated non-combustion sources (e.g. mineral spirits, petroleum distillates).

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236 To produce NH_4^+ reagent ions in the Vocus focusing ion molecule reactor (fIMR), 20
237 sccm of water (H_2O) vapor and 1 sccm of vapor from a 1% ammonium hydroxide in H_2O
238 solution were injected into the discharge ion source. In addition to forming (NH_4^+) H_2O
239 as the primary reagent ion, the relatively large amount of water buffers the source against
240 any changes in relative humidity, removing any quantitative humidity dependence and
241 the need for humidity-dependent calibrations. This lack of RH-dependence is shown in
242 Figure 1. The slight change in the sensitivity of methyl ethyl ketone (MEK) when
243 increasing from 0% RH likely resulted from the three-body stabilizing effect of water,
244 which enhances ion-adduct stability, thereby increasing this compound's sensitivity.
245 Further details on RH-dependence of a wider set of organic species could be found in Xu
246 et al (Xu et al., 2022). The Vocus axial voltage was maintained at a potential difference
247 of 425 V and the reactor was maintained at a pressure of 3.0 mbar and temperature of 50
248 °C (to maximize thermal stability as shown in Figure 1b), which corresponds to an E/N
249 value of 70 Td. Additional characterization tests, including scans of the voltage
250 differentials, are shown in Figure S3 and were used to inform our choice of instrument
251 settings for the ambient measurements.

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254 The instrument inlet was set up at the southeast corner of the observatory. 100 sccm of air
255 was subsampled into the Vocus CI-ToF from a Fluorinated Ethylene Propylene (FEP)
256 Teflon inlet 5 m long and with a 12.7 mm outer diameter that had a flowrate of 20 liters
257 min^{-1} resulting in a residence time of ~ 1 s. Importantly for measurements of semi-volatile
258 VCPs, no particulate filter was used on the inlet to enhance transmission of semi- and
259 low-volatility gases (Krechmer et al., 2016; Pagonis et al., 2017).

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262 The instrument background was measured every 15 minutes for 1 minute by injecting
263 purified air generated by a Pt/Pd catalyst heated to 400 °C. Every 4 hours, diluted
264 contents from a 14-component calibration cylinder (Apel-Riemer Environmental) were
265 injected for 1 minute to measure and track instrument response over time (Table S1). To
266 quantify CI-ToF signals for additional VCPs of interest, after the campaign we injected
267 prepared quantitative standards of specific water-soluble VCPs that were observed in
268 field measurements into the instrument from a Liquid Calibration System (LCS;
269 TOFWERK AG) and measured the instrument response to create multi-point calibration
270 curves. The LCS standards were then normalized using the cylinder calibrations during
271 and after the campaign with the same tank. Although the CI-ToF used the same settings
272 for calibrations as in the campaigns, this normalization accounted for differences in the
273 instrument performance during and after the campaign. A table of the standard
274 compounds along with their instrument responses can be found in Table S2.

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277 Data were processed using Tofware version 3.2.3 (Aerodyne Research, Inc.) in the Igor
278 Pro programming environment (Wavemetrics, Inc.). Compounds of interest were detected
279 as NH_4^+ adducts within 2 ppm mass accuracy, but for clarity we refer to detected signals
280 after subtracting the ammonium adduct (e.g. C_3H_6O instead of $(NH_4) C_3H_6O^+$) in the
281 Results and Discussion section below. For this focused analysis of urban emissions, data
282 filtering was also performed on a subset of compounds to remove the influence of
283 biomass burning events which resulted in elevated benzene to toluene ratios during
284 inflow of air from the less densely populated western direction. These additional
285 contributions from biomass burning-related emissions would not be included in the
286 inventoried emissions and would bias calculations of urban emission ratios in this study.
287 ~~Hourly periods with large contributions from biomass burning were filtered for affected~~
288 ~~compounds using a benzene-to-toluene ratio >2.~~Hourly periods with large contributions
289 from biomass burning were filtered for affected compounds using a benzene-to-toluene
290 ratio >1.8 (Figure S4), as acetonitrile was not well-correlated with benzene-to-toluene
291 ratios, which was a better indicator of the influence of biomass burning at the site
292 (Huangfu et al., 2021; Koss et al., 2018; Sheu et al., 2020). Thus, elevated concentrations
293 of oxygenated compounds coincided with inflow from the more densely populated areas
294 of the city.
295
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297 In addition to online measurements, a subset of adsorbent tube samples were also
298 collected during the Winter 2020 campaign for offline analysis using gas chromatography
299 electron ionization mass spectrometry (GC EI-MS) (Sheu et al., 2018) and were used
300 here ~~to confirm~~where possible within the ~~identifications~~instrument capabilites and range
301 of ~~oxygenated VCPs~~measured species to confirm the identifications of oxygenated
302 compounds (and their isomers) measured as molecular formulas by the online CI-TOF.
303 These supplemental tube samples were collected periodically during the measurement
304 period and their use here was intended to provide confirmational identifications of
305 isomers contributing to CI-TOF ion measurements, though may not be inclusive of all
306 possible OVOCs where compound or instrument configuration limitations exist (e.g., GC
307 transmission, reactivity, thermal instability, adsorbent/column configuration). Additional
308 measurements of meteorological parameters (e.g. wind speed/direction) (ATMOS 41
309 weather station) and carbon monoxide (Picarro G2401m) were also collected at the
310 sampling site. A co-located high-resolution proton-transfer-reaction time-of-flight mass
311 spectrometer (Ionicon Analytik PTR-ToF 8000) from Stony Brook University also made
312 coincident long-term measurements of a smaller subset of key species, some of which
313 were used to validate the performance of the CI-TOF with NH_4^+ ionization.
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315

316 ~~Annual~~To accompany other anthropogenic sources in the EPA emissions inventory,
317 annual emissions from VCPs in NYC counties were estimated using VCPy.v2.0 with a
318 sector-wide uncertainty of 15% on average (Seltzer et al., 2021, 2022). These are
319 discussed in subsequent sections together with contributions from other anthropogenic
320 sources (derived from National Emissions Inventory (NEI)) as NEI+VCPy (hereafter
321 VCPy+). Additional NYC-resolved comparisons are made with the FIVE-VCP
322 emissions inventory developed at the U.S. National Oceanic and Atmospheric
323 Administration using methods described by McDonald et al. (Mcdonald et al., 2018) and
324 updated for New York City in Coggon et al. ~~(Coggon et al., 2021)~~.(Coggon et al., 2021).
325 A major update in the latter study was updating the VCP speciation profiles to the most
326 recent surveys of consumer products, fragrances and architectural coatings. In VCPy, the
327 magnitude and speciation of organic emissions are directly related to the mass of
328 chemical products used, the composition of these products, the physiochemical properties
329 of the chemical product constituents that govern volatilization, and the timescale
330 available for these constituents to evaporate. The most notable updates to VCPy include
331 the incorporation of additional product aggregations (e.g., 17 types of industrial
332 coatings), variation in the VOC-content of products to reflect state-level area source rules
333 relevant to the solvent sector, and the adoption of an indoor emissions pathway.
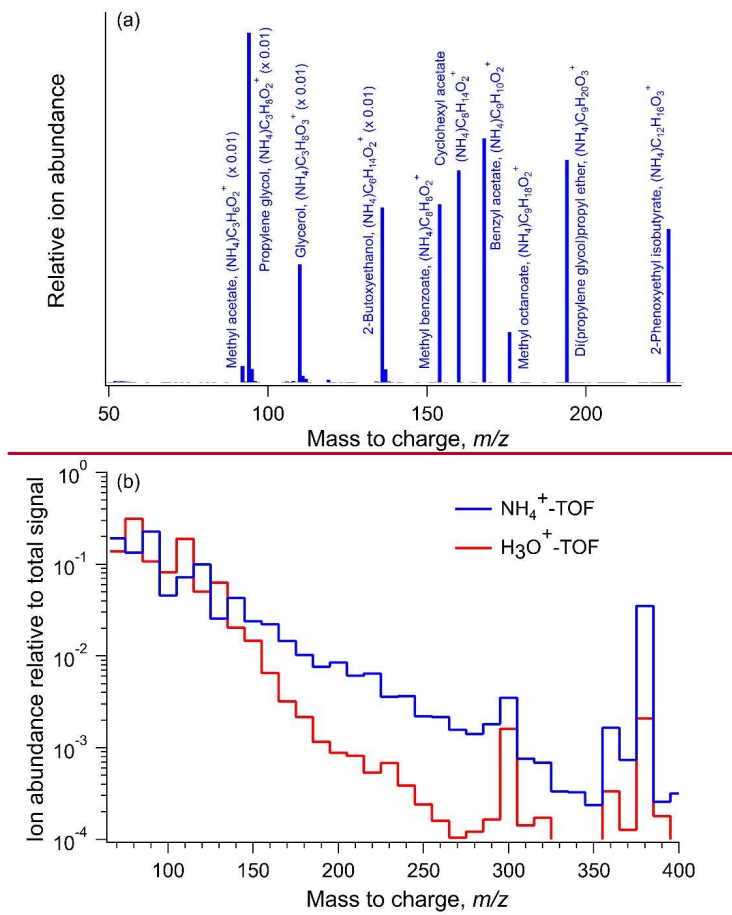334
335
336 To facilitate calculation of VCP indoor emissions in VCPy, each product category is
337 assigned an indoor usage fraction. All coating and industrial products are assigned a 50%
338 indoor emission fraction, all pesticides and automotive aftermarket products are assigned
339 a 0% indoor emission fraction, and all consumer and cleaning products are assigned a
340 100% indoor emission fraction. The lone exception are daily use personal care products,
341 which are assumed to have a 50% indoor emission fraction. This indoor emission
342 assignment enables the mass transfer coefficient to vary between indoor and outdoor
343 conditions. Typically, the mass transfer coefficient indoors is smaller than the mass
344 transfer coefficient outdoors due to more stagnant atmospheric conditions, and the newest
345 version of the modeling framework reflects these dynamics. Indoor product usage utilizes
346 a mass transfer coefficient of 5 m hr^{-1}, and the remaining outdoor portion is assigned a
347 mass transfer coefficient of 30 m hr^{-1} (Khare and Gentner, 2018; Weschler and Nazaroff,
348 2008). More details about the framework could be found elsewhere (Seltzer et al., 2021).
349 Annual production volumes for different chemical species used in discussion were taken
350 from U.S. EPA's Chemical Data Reporting database (U.S. Environmental Protection
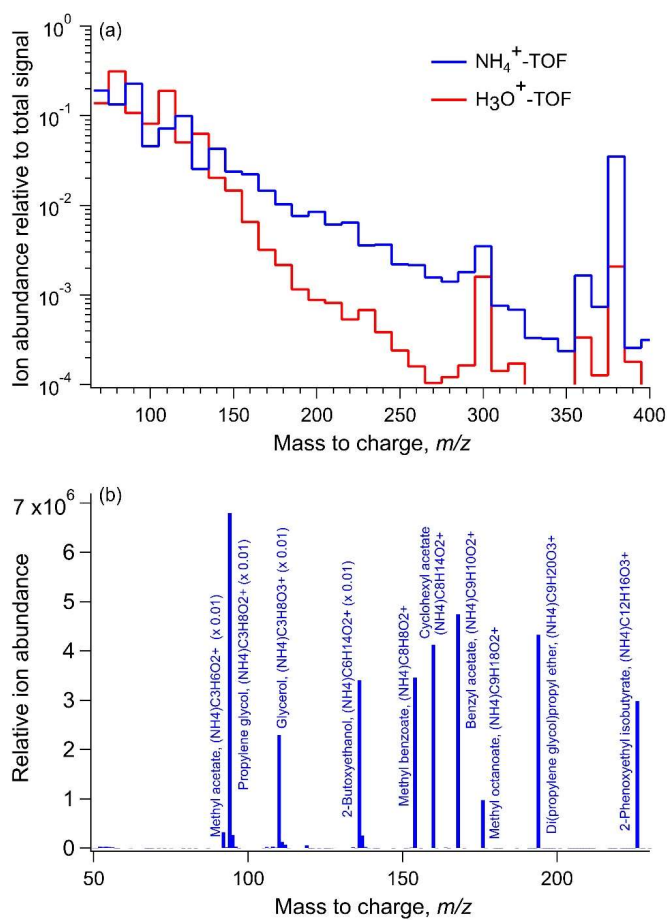351 Agency, Chemical Data Reporting, 2016).
352

353 **3. Results and discussion**

354 **3.1. Instrument response to diverse chemical functionalities**

Of the 1000's of ions observed in the urban ambient mass spectra (Figures 2a, ~~S4~~S5) during online sampling with ammonium-adduct ionization, 148 prominent ion signals were targeted for detailed analysis and assigned compound formulas representing a diverse range of chemical functionalities (Table S3). These ions were selected based on high signal-to-noise ratios (> 3.0) and likely isomer contributions from ~~VCPs~~VCP-related emissions. To confirm sensitivity toward these functional groups, the instrument was calibrated using 58 analytical standards that are also constituents of various consumer/commercial products. The mass spectrum of individual standards showed high parent ion-to-background signal and negligible fragmentation products (Figure 2a~~), thus simplifying~~). Further analysis also showed ammonium-adduct formation to be the dominant ionization pathway for these analytical standards for applied instrument settings (Table S4). This simplified the interpretation of the soft adduct parent ions in ambient air mass spectra in contrast to higher-fragmentation-prone proton transfer reaction spectra.

11

(a)

Relative ion abundance

Methyl acetate, $(NH_4)C_3H_6O_2^+$ (x 0.01)

Propylene glycol, $(NH_4)C_3H_8O_2^+$ (x 0.01)

Glycerol, $(NH_4)C_3H_8O_3^+$ (x 0.01)

2-Butoxyethanol, $(NH_4)C_6H_{14}O_2^+$ (x 0.01)

Methyl benzoate, $(NH_4)C_8H_8O_2^+$

Cyclohexyl acetate $(NH_4)C_8H_{14}O_2^+$

Benzyl acetate, $(NH_4)C_9H_{10}O_2^+$

Methyl octanoate, $(NH_4)C_9H_{18}O_2^+$

Di(propylene glycol)propyl ether, $(NH_4)C_9H_{20}O_3^+$

2-Phenoxyethyl isobutyrate, $(NH_4)C_{12}H_{16}O_3^+$

Mass to charge, m/z

(b)

Ion abundance relative to total signal

NH_4^+-TOF
H_3O^+-TOF

Mass to charge, m/z

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Figure 2. (a) Negligible parent ion fragmentation (with high signal-to-noise ratios) across diverse chemical functionalities in CI-ToF allows for measurements of understudied chemical species (examples from authentic standards shown). (b) Average ToF mass spectra obtained from NH_4^+ and H_3O^+ (i.e. PTR) ionization schemes binned over 10 m/z intervals using data from the same Vocus CI-ToF at the site. The CI-ToF spectra observed greater ion signal in the approximate intermediate-volatility into the semi-volatile region (e.g., ≥160 m/z). Note: In (b), the NH_4^+ and PTR signals are offset by 18 and 1 m/z respectively to account for the difference in the mass of the reagent ion and the averages are from different days when the reagent ion was switched.

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In laboratory tests with the authentic standards, the instrument showed the highest
response factors (i.e. ions ppb^{-1}) toward glycol ethers and ketones (Figure 3, Table S2)
with detection limits below 5 parts per trillion (ppt) for several chemical species (Table
S5). The response factors for most aliphatic and aromatic esters were one order of
magnitude smaller than glycol ethers and ketones. Standards for isomers were also run in
some cases of possible different compounds contributing to the same ion signal based on
multiple prominent compounds estimated in inventories or well-known VCP components.
While some isomers elicited similar responses from the instrument, others produced
considerably different sensitivities (Figure S5S6) (Bi et al., 2021). For 7 test cases here,
the difference in response factors tended to be most pronounced in the case of isomers
with small carbon numbers, e.g. ethyl acetate being 8 times higher than butyric acid,
while isomers with larger carbon numbers, e.g. ethylene glycol hexyl ether (EGHE) and
1,2 octanediol produced similar ion intensities. Overall, this sensitivity analysis showed
that the calculated concentrations could have significant differences (by a factor of 0.5 to
8 with a worst-case relative isomer contribution bias spanning 1:4 to 4:1), especially for
the smaller oxygenated compounds tested here, and is dependent on the relative
abundance of contributing isomers due to their effect on the overall mass response factor
(Figure S6). Hence, in each case where isomer sets were tested, the mass response factor
for the ion was estimated by averaging the instrument response to individual isomers.
This can still potentially cause some over- or under-estimation of ion concentrations in
ambient air depending on the relative contribution of isomers to the ion, which is affected
by the magnitude of emissions of individual isomers as well as their sources and sinks
(and indoor vs. outdoor emissions). We have further constrained this uncertainty by
confirming isomer identities wherever possible via offline GC-EIMS measurements using
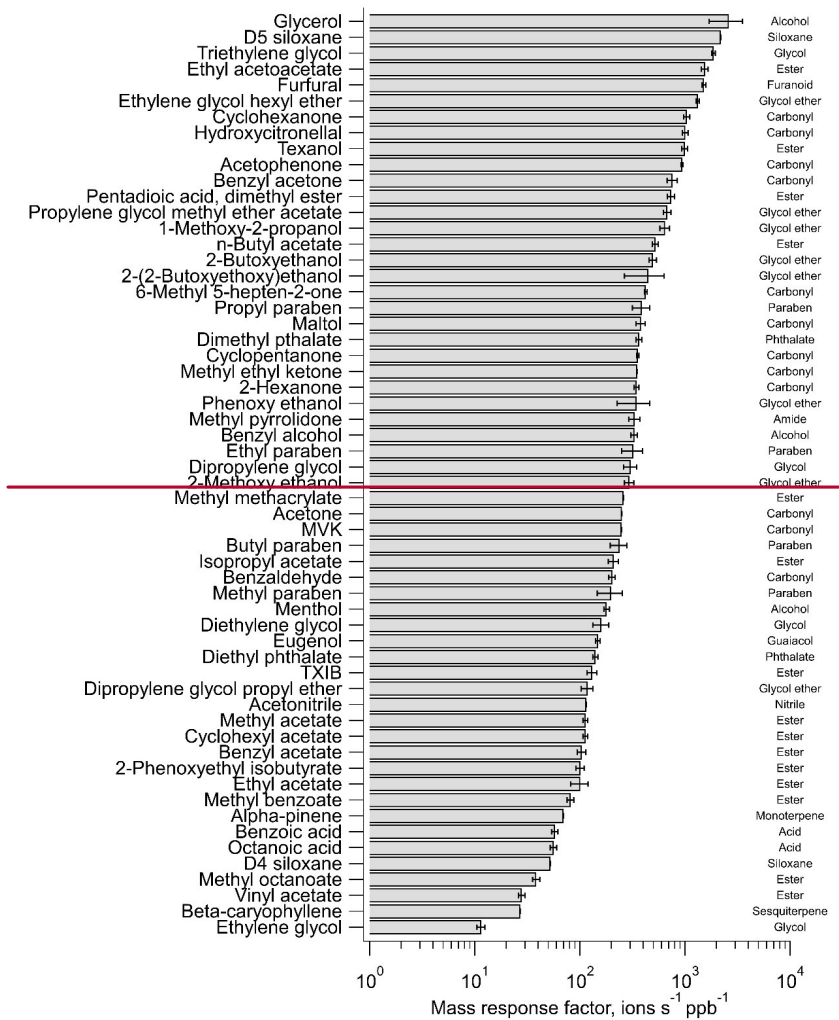adsorbent tubes (Table 1).

406

This variability in instrument response could also depend on other physiochemical
properties of the analytes because some acids, e.g. hexadecanoic, fumaric, adipic and
salicyclic acids, also responded poorly to calibration. This may be due to poor water
solubility in some cases (e.g. adipic and hexadecanoic acid) affecting the calibration
mixes, and, also the tendency of lower volatility compounds to partition to surfaces that
may reduce their transmission efficiency through the LCS delivery lines and the
instrument inlet thus contributing to this marked difference in instrument response
between some isomers. Sensitivity analysis showed that the calculated concentrations
could have large differences (by a factor of 0.5 to 8) depending on the relative abundance
of contributing isomers due to their effect on the overall mass response factor (Figure
S5). Hence, in each case where isomers were tested, the mass response factor for the ion
was estimated by averaging the instrument response to individual isomers. This can still

14

419 ~~potentially cause slight over- or under-estimation of ion concentrations in ambient air~~
420 ~~depending on the relative contribution of isomers to the ion, which is affected by the~~
421 ~~magnitude of emissions of individual isomers as well as their sources and sinks (e.g.~~
422 ~~indoor surfaces or reactions).~~

423

424 The signal intensities could also be influenced by changes in environmental factors such
425 as relative humidity that can modify the relative importance of different ionization
426 pathways in the reaction chamber. However, systematic tests conducted with acetone,
427 ~~methyl ethyl ketone (~~MEK~~),~~, acetonitrile and α-pinene found their NH_4^+-adduct signal
428 intensities to be independent of any changes in relative humidity in the CI-ToF ionization
429 region (Figure 1). Thus, day-to-day response factors for individual ions were comparable
430 across the entire sampling period and did not require RH-dependent corrections.
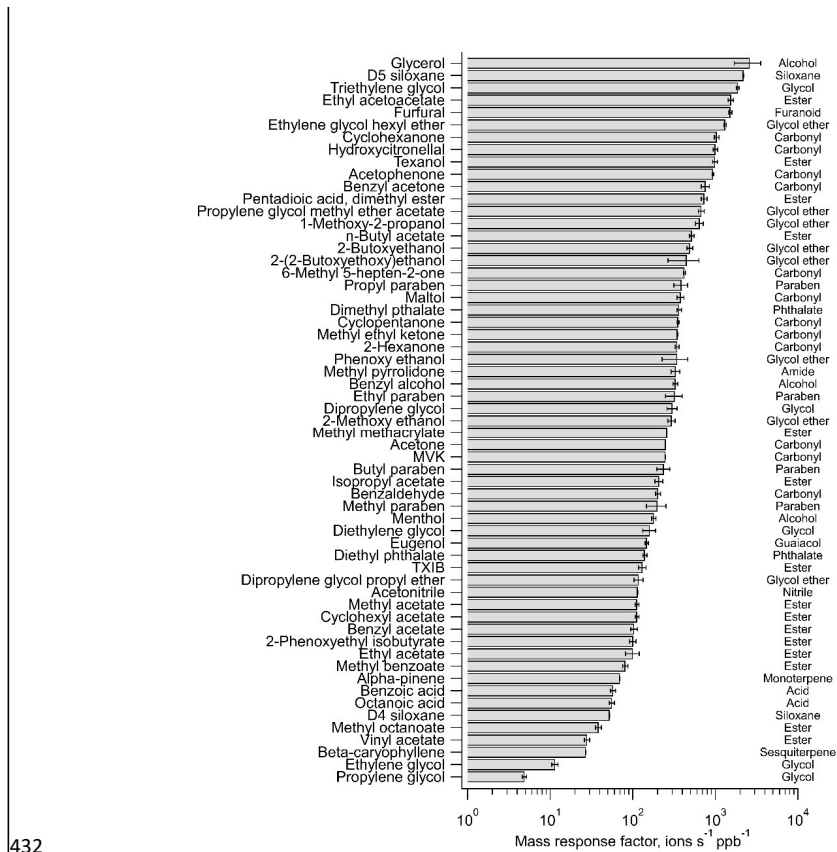
431

432

Figure 3. The response of the CI-ToF with NH₄⁺ ionization toward select calibration standards containing a diverse range of chemical functional groups and molecular structures, which are listed (right) for reference, but we note the multi-functionality of some of the compounds.

Additionally, the CI-ToF measurements were also validated by comparing the concentration timeseries of some of the OVOCs (i.e. acetone, methyl vinyl ketone (MVK), MEK) and monoterpenes across the entire sampling period with parallel measurements from a co-located PTR-ToF instrument. ~~The~~While the measurements largely agreed within 90~~%,~~% validating the performance of the CI-ToF instrument (Figure ~~S6).~~S7), the slight differences observed could be caused by variations in relative responses to isomers in different ionization schemes of the two instruments.

17

445
446 In case of ion signals that were not quantified, we have carefully considered factors such
447 as annual usage of likely compounds, their atmospheric reactivity and ionization
448 efficiency with the NH_4^+ adduct to inform our discussion of their formula assignments.
449 For example, minimal ethanol ions were observed during instrument calibration
450 suggesting limitations in its detection with NH_4^+ reagent ion. (Figure S8). Yet, C_2H_5OH
451 ion signal was measured during ambient sampling. Given the densely urban sampling
452 location, it is likelywe hypothesize that this measured C_2H_5OH signal was dimethyl ether
453 that is used in personal care products (propellant) and some potential use as fuel or
454 refrigerant. It was not calibrated for and we could not confirm its abundances using
455 another measurement in this study. However, ethanol emissions are still expected to
456 exceed those of dimethyl ether based on the inventories., and, instrument settings may
457 affect its relative sensitivity between these two isomers. Similar assessments are made
458 wherever possible in the discussion of temporal trends of uncalibrated ions.

459
460 Vocus CI-ToF captured relatively more ion signal in the 150-350 m/z range (i.e.
461 normalized to the total signal of the mass spectra) when compared with PTR ionization
462 using the same instrument at the same site (Figure 2b). This was due to formation of
463 strongly-bonded NH_4^+-analyte adduct molecules at low collision energies that preserved
464 large functionalized analytes. In comparison, PTR-ToF can strongly fragment certain
465 functionalized analytes (e.g. alcohols) during proton addition rendering interpretation
466 difficult. Hence, we are able to examine a greater diversity of volatile- to semi-volatile
467 functionalized compounds with CI-ToF measurements that are known to be emitted from
468 a wide range of volatile chemical products.

469
470 **3.2 Influence of atmospheric conditions and transport on observed concentrations**
471
472 The concentrations of measured ions varied significantly over the 10-day sampling period
473 influenced by changes in meteorology and dilution, as well as temporal changes in
474 emissions. The concentrations showed clear dependence on wind velocity (4.5 m/s avg.)
475 and direction, indicating variations in both emission rates and dispersion across different
476 areas upwind of the site. The highest concentration signals were observed between 22/1
477 and 25/1 when slower winds (<5 m/s) arrived from the southwest, south, and east across
478 various parts of Manhattan leading up to the site (Figures S2, S7S9). These areas are
479 characterized by a high population density and include a wide range of commercial
480 activities that could contribute to the concentration enhancements. Multiple types of
481 diverse sources of OVOCs can exist here, and in other urban areas, though current
482 emissions inventories suggest that the inventoried target species in Table 1 are primarily
483 emitted from VCPs in New York City with minimal or negligible contributions from
484 other sources such as on- and non-road sources and current inventory estimates of

18

cooking and biomass burning (Table S6). Similarly, recent source apportionment using mobile lab measurements in NYC also attributes the majority of the signal for several of the highly emitted species observed here (e.g. acetone, $C_2H_4O_2$, C_4H_8O) to a general VCP-related source factor (that may include minor contributions from other sources) (Gkatzelis et al., 2021b).

Additional concentration spikes and smaller enhancements were observed on 27/1 with similar southwesterly winds at higher speeds. Prolonged concentration enhancements were also observed 30/1-31/1 with slower (<5 m/s) winds predominantly from the east, passing over Harlem (Manhattan) after crossing the also densely-populated Bronx with varied commercial/industrial activities. Observed concentrations at the site were lowest with west-northwesterly and northwesterly winds originating from relatively less-densely populated areas, as well as periods of highest wind speeds.

Concentration trends generally overlapped across all compound classes with a few exceptions (e.g. $C_5H_8O_2$), with variations in their covariances (see Sec. 3.3). This demonstrates a major role for meteorology in determining local VOC concentrations at the site, and elsewhere in NYC. Still in some cases (e.g. nitropropane, 2,5 dimethyl furan), influence of certain short-term sources such as possible local/regional wintertime biomass burning contributions were observed as temporary sharp spikes in compound abundances.

By influencing the rate of advective transport of pollutants, wind speed also directly impacts the time available for chemical species to undergo oxidation in the atmosphere. Atmospheric oxidation can be an important sink for different chemical species and also a secondary source for some OVOCs (e.g. alcohols, carbonyls) (Franco et al., 2021; Mellouki et al., 2015). Therefore, accounting for their reaction timescales is necessary in the interpretation of their relative abundances. During this sampling campaign, with a local average wind speed of 4.5 m s^{-1} (Figure S7S9), this translated to 0.5-2 hours of daytime photochemical aging for emissions within 10-30 km of the site (encompassing all of Manhattan, Brooklyn, Queens, the Bronx, and much of urban metro NYC in New Jersey) (Figure S2).

For species under consideration in this study, the rate constants for reaction with hydroxyl radicals (OH$^.$) ranged from 10^{-11} to 10^{-13} molecule^{-1} cm^3 s^{-1} as obtained from the OPERA model and other studies (Aschmann et al., 2001; Mansouri et al., 2018; Picquet-

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Varrault et al., 2002; Ren et al., 2021). Given wintertime OH concentrations of approximately 10^6 molecules cm^3 in NYC (Ren et al., 2006; Schroder et al., 2018), this puts their daytime atmospheric lifetimes (i.e. e-folding times) between 1-2 days to several months with some variation ~~with~~across OH concentrations. For average wind speeds observed during sampling, this translated to daytime concentration losses of 10% or less for the vast majority of measured species if emitted within a distance of 10-15 kilometers of the site (Figure ~~S8~~S10), which includes all of Manhattan and other densely populated areas of ~~New York City~~NYC and adjacent New Jersey (Figure S2).

Secondary production represents a major potential source of OVOCs—one that will be at a relative minimum in the wintertime conditions, but long-distance transport of OVOCs in the background air entering NYC will include significant secondary contributions, as well as some transport of primary emissions from further upwind. In the subsequent calculations of urban enhancements (Table 1) used in the emission inventory comparison (Section 3.5), these incoming background contributions are minimized by subtracting the 5th percentile for each measured species to reduce the influence of non-local primary and secondary sources outside the scope of the NYC-focused inventories used here. These urban enhancement calculations (discussed further in Section 3.5) are aided by the very densely populated nature of NYC and the density of VCP-related and other anthropogenic sources. For example, recent mobile measurements that show over 95% reduction in D5 concentrations outside NYC relative to Manhattan and surrounding areas indicating minimal contributions from urban sources outside of NYC (Coggon et al., 2021). For the select VCP-related species examined in those studies and at our site, the mobile measurements (Coggon et al., 2021; Stockwell et al., 2021) in the relatively less densely-populated regions to the north and northwest of NYC show background concentrations comparable to our 5th percentile concentrations, which typically came with winds from that direction and/or periods with high wind speeds of 7-8 ms^{-1} or greater (enhancing dilution) (figures 4-5, S9).

Despite wintertime conditions, local secondary production of OVOCs via atmospheric oxidation will occur (over the distances described above) with the potential for locally-produced OVOCs that could be included in the urban enhancement calculations. However, the field site's location amongst a high density of VCP-related (and other) sources and the observed OVOC enhancements occurring with winds from more densely-populated areas (Figures 4, 5, S9) supports the dominance of primary emissions in wintertime and drives the well-correlated enhancements with OVOC tracers that aids the inventory comparison. For context, Gkatzelis et al.'s (ES&T 2021b) reported that only ~20% of wintertime acetone in NYC is related to secondary production, which would

559 include both contributions from oxidation locally and over longer distances, and the
560 approach here subtracts the latter background contributions.

561

562 For future work at the site, we note that daytime OH concentrations in NYC during
563 summer will be higher (e.g. five times the winter values in NYC, (Ren et al., 2006)),
564 which can affect the interpretation of source contributions to more reactive chemical
565 species with shorter lifetimes. and secondary production. The other important daytime
566 oxidant ozone is not likely to react significantly in the absence of non-aromatic
567 unsaturated C=C bonds in most targeted ions in this study (de Gouw et al., 2017),
568 especially during the winter. The reaction rate (k) values for nighttime oxidation with the
569 nitrate radicals are 1 to 4 orders of magnitude smaller ($\sim 10^{-12}$-10^{-15} molecule^{-1} cm^3 s^{-1})
570 with average NO$_3$ concentrations on the order of 10^8 molecules cm^{-3} (Asaf et al., 2010;
571 Cao et al., 2018). Thus, nighttime oxidation is not likely to lead to shorter VOC lifetimes
572 than those calculated for daytime OH oxidation. In all, it is unlikely that the emissions of
573 the target compounds in this study were substantially influenced by oxidative losses in
574 the ambient atmosphere, and were predominantly driven by the magnitude of emissions
575 in NYC and their atmospheric dilution. Yet, the observed ambient concentrations of
576 different species could be potentially affected by the extent of their indoor vs. outdoor
577 usage, seasonal patterns in applications (e.g., wintertime outdoor use of ethylene glycol
578 as antifreeze), or physical processes related to their sources or sinks (e.g. partitioning).

579
580
581 **3.3. Ambient measurements across diverse chemical classes**

582 Within the broader distribution of ion signals across the entire ambient mass spectra, we
583 identified a diversity of chemical species. A selection of the most prominent ions in
584 various compound categories are discussed in this section. Table S4S7 summarizes
585 different use sectors, but the vast majority have uses in personal care products,
586 fragrances, a wide range of solvents, and/or other volatile consumer products. As such,
587 some of the most abundant ions observed here were related to compounds found in the
588 formulations of these types of products and/or had large annual production volumes (U.S.
589 Environmental Protection Agency, Chemical Data Reporting, 2016). For some volatile
590 compounds that exhibited low atmospheric abundances despite large annual production,
591 it is possible that a substantial fraction of the production volume goes as feedstock to
592 manufacture derivatives or are otherwise not prone to gas-phase emissions. Yet, seasonal
593 differences in use, partitioning to the gas phase, and/or indoor-to-outdoor transport could
594 also contribute to potential inter-annual variations.

595

596 The ions above 100 ~~parts per trillion~~ (ppt~~)~~ on average included those with contributions
597 from acetates, C_2H_6O (e.g. ethylene glycol), C_3H_6O (e.g. acetone), C_2H_3N (e.g.
598 acetonitrile), $C_{10}H_{16}$ (e.g. monoterpenes), C_4H_8O (e.g. methyl ethyl ketone) and $C_5H_8O_2$
599 (e.g. methyl methacrylate) (Table 1). A detailed discussion of the trends in concentrations
600 and ion abundances of these and other ions is presented below and separated into distinct
601 categories based on chemical class or use-type.

602 **Table 1. List of ions calibrated with authentic standards (Table S2), probable**
603 **contributing isomers, geometric mean concentrations (with standard deviations),**
604 **annual emissions in each inventory, and mean concentration enhancement ratios**
605 **(with standard deviations of the mean and linear correlation coefficients) with**
606 **acetone and other prominent combustion-related tracers. Isomer identifications**
607 **marked with asterisks (*) were confirmed in offline GC-EI-MS measurements, with**
608 **additional possible isomers included in Table ~~S4~~S7.**

Compound formula, i	Probable compounds, i	Geo. mean concentration, ppt, i	Emissions, kg yr⁻¹ VCPy,+, FIVE-VCP	Ratios to tracer compounds (Δmol/Δmol) †			
				$\Delta i/\Delta$Benzene (r)	$\Delta i*1000/\Delta$CO (r)	$\Delta i/\Delta$Acetone (r)	$\Delta i/\Delta$Benzyl alcohol (r)
$C_2H_6O_2$	Ethylene glycol	2437±3622	361511, ~~260540~~236310	1.1E+01±1.7E+00 (0.79)	9.1E+00±1.3E+00 (0.83)	2.8E+00±4.3E-01 (0.95)	3.0E+02±4.2E+01 (0.88)
C_3H_6O	Acetone*	977±783	~~1333642,~~ ~~1647548~~1360720, 1587220	3.8E+00±4.8E-01 (0.83)	3.3E+00±3.7E-01 (0.87)	--	1.1E+02±1.1E+01 (0.92)
$C_4H_6O_2$	Methyl acrylate*, Diacetyl*	810±396	1905, 4638	2.1E+00±2.5E-01 (0.82)	1.8E+00±1.9E-01 (0.89)	5.6E-01±6.1E-02 (0.95)	5.9E+01±5.6E+00 (0.94)
$C_4H_8O_2$	Ethyl acetate*, Butyric acid	679±664	~~27958, 32~~330225, 293	2.8E+00±3.6E-01 (0.72)	2.3E+00±2.8E-01 (0.73)	7.2E-01±8.9E-02 (0.73)	7.6E+01±8.5E+00 (0.67)
$C_3H_6O_2$	Methyl acetate*, Propionic acid, Hydroxyacetone, Ethyl formate	435±377	50747, ~~114453~~103808	1.7E+00±2.2E-01 (0.64)	1.5E+00±1.6E-01 (0.65)	4.5E-01±5.3E-02 (0.76)	4.8E+01±5.0E+00 (0.7)
C_2H_3N	Acetonitrile	246±102		8.5E-01±9.0E-02 (0.32)	7.2E-01±6.4E-02 (0.24)	2.2E-01±2.2E-02 (0.35)	2.3E+01±1.9E+00 (0.33)
$C_{10}H_{16}$	Monoterpenes (e.g., limonene*, α-Pinene*)	156±105	~~60206, 171076~~0327, 15516	5.1E-01±6.5E-02 (0.79)	4.3E-01±4.9E-02 (0.87)	1.3E-01±1.6E-02 (0.85)	1.4E+01±1.5E+00 (0.94)
C_4H_8O	MEK, THF, Cyclopropyl carbinol*	126±82	~~41369, 293752~~57457, 277556	4.3E-01±5.1E-02 (0.79)	3.7E-01±3.8E-02 (0.84)	1.1E-01±1.2E-02 (0.93)	1.2E+01±1.1E+00 (0.85)
$C_5H_{10}O_2$	Isopropyl acetate*, n-propyl acetate*	114±106	~~2845, 58313~~457, 5289	4.4E-01±5.7E-02 (0.61)	3.7E-01±4.4E-02 (0.69)	1.1E-01±1.4E-02 (0.69)	1.2E+01±1.3E+00 (0.58)
$C_5H_8O_2$	Methyl methacrylate*	108±121	1102, -	4.1E-01±6.0E-02 (0.45)	3.5E-01±4.7E-02 (0.37)	1.1E-01±1.5E-02 (0.5)	1.1E+01±1.5E+00 (0.41)
$C_6H_{12}O_2$	Butyl acetate*	103±138	~~74432, 6269~~280120, 56862	4.9E-01±6.9E-02 (0.76)	4.1E-01±5.4E-02 (0.77)	1.3E-01±1.7E-02 (0.87)	1.3E+01±1.7E+00 (0.83)
$C_8H_8O_2$	Methyl benzoate*	92±15		1.1E-01±1.2E-02 (0.72)	9.1E-02±8.4E-03 (0.75)	2.8E-02±2.8E-03 (0.78)	3.0E+00±2.5E-01 (0.79)
$C_8H_{16}O_2$	Caprylic acid* (i.e., Octanoic acid), hexyl acetate	87±47	5281, -	2.5E-01±2.9E-02 (0.81)	2.1E-01±2.2E-02 (0.92)	6.5E-02±7.2E-03 (0.92)	6.9E+00±6.6E-01 (0.95)
$C_3H_8O_2$	2-Methoxy ethanol, propylene glycol*	82±51	240692, -	2.9E-01±3.3E-02 (0.71)	2.4E-01±2.4E-02 (0.71)	7.5E-02±8.0E-03 (0.85)	7.9E+00±7.3E-01 (0.77)
$C_9H_{18}O_2$	Methyl octanoate, Nonanoic acid*	77±24		1.4E-01±1.6E-02 (0.79)	1.2E-01±1.2E-02 (0.9)	3.7E-02±3.9E-03 (0.9)	3.9E+00±3.5E-01 (0.94)
C_7H_6O	Benzaldehyde*	76±37	~~142, 23~~156, 14833	2.1E-01±2.5E-02 (0.83)	1.8E-01±1.8E-02 (0.88)	5.4E-02±6.1E-03 (0.88)	5.7E+00±5.6E-01 (0.93)
$C_{15}H_{24}$	Sesquiterpenes (e.g., β-Caryophyllene)	70±11		7.3E-02±8.3E-03 (0.73)	6.2E-02±6.1E-03 (0.83)	1.9E-02±2.0E-03 (0.78)	2.0E+00±1.8E-01 (0.9)
$C_6H_{12}O$	2-Hexanone*, 4-Methyl-2-pentanone	59±42	6162, ~~16527~~14990	2.0E-01±2.5E-02 (0.83)	1.7E-01±1.9E-02 (0.84)	5.3E-02±6.1E-03 (0.92)	5.6E+00±5.7E-01 (0.91)
$C_7H_6O_2$	Benzoic acid*	59±9		5.8E-02±6.3E-03 (0.48)	4.9E-02±4.6E-03 (0.39)	1.5E-02±1.5E-03 (0.4)	1.6E+00±1.4E-01 (0.45)
C_4H_6O	MVK, MACR	58±39		1.9E-01±2.4E-02 (0.83)	1.6E-01±1.8E-02 (0.87)	4.9E-02±5.9E-03 (0.94)	5.1E+00±5.5E-01 (0.94)
$C_8H_{14}O_2$	Cyclohexyl acetate	43±20		1.2E-01±1.4E-02 (0.81)	1.0E-01±1.0E-02 (0.89)	3.2E-02±3.4E-03 (0.95)	3.4E+00±3.0E-01 (0.95)
$C_9H_{10}O_2$	Benzyl acetate	39±19	7, -	1.0E-01±1.2E-02 (0.82)	8.8E-02±9.0E-03 (0.89)	2.7E-02±3.0E-03 (0.87)	2.9E+00±2.7E-01 (0.95)

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Formula	Compound	Mean±SD	Inventory				
$C_6H_{14}O_3$	Dipropylene glycol	36±28	41085, 116574105732	1.4E-01±1.7E-02 (0.65)	1.2E-01±1.3E-02 (0.71)	3.6E-02±4.1E-03 (0.7)	3.8E+00±3.8E-01 (0.8)
$C_4H_{10}O_3$	Diethylene glycol	32±17	7026, 122315110939	8.9E-02±1.1E-02 (0.84)	7.5E-02±7.9E-03 (0.87)	2.3E-02±2.6E-03 (0.91)	2.4E+00±2.4E-01 (0.92)
$C_{10}H_{20}O$	Menthol, Decanal*	31±18	971, 0.0605	9.4E-02±1.1E-02 (0.77)	7.9E-02±8.2E-03 (0.89)	2.4E-02±2.7E-03 (0.9)	2.6E+00±2.5E-01 (0.96)
C_5H_8O	Cyclopentanone	30±16		8.4E-02±9.8E-03 (0.84)	7.1E-02±7.2E-03 (0.9)	2.2E-02±2.4E-03 (0.95)	2.3E+00±2.2E-01 (0.95)
$C_6H_{14}O_2$	2-Butoxyethanol*, 1-propoxy-2-propanol*	23±19	107758, 79520109288, 72125	8.9E-02±1.1E-02 (0.87)	7.5E-02±8.2E-03 (0.87)	2.3E-02±2.7E-03 (0.91)	2.4E+00±2.5E-01 (0.91)
$C_8H_{24}O_4Si_4$	D4 siloxane*	23±3	12872, 10221392707	2.3E-02±2.5E-03 (0.38)	2.0E-02±1.8E-03 (0.48)	6.0E-03±6.1E-04 (0.59)	6.4E-01±5.5E-02 (0.59)
$C_{16}H_{30}O_4$	TXIB*	18±4	-, 24962264	2.6E-02±3.0E-03 (0.73)	2.2E-02±2.2E-03 (0.83)	6.8E-03±7.2E-04 (0.75)	7.2E-01±6.5E-02 (0.86)
$C_{10}H_{12}O_2$	Eugenol	16±5	45, -	3.1E-02±3.5E-03 (0.82)	2.6E-02±2.5E-03 (0.85)	7.9E-03±8.4E-04 (0.91)	8.4E-01±7.6E-02 (0.92)
$C_9H_{20}O_3$	Dipropylene glycol propyl ether	16±4	4150, 65785966	2.3E-02±2.7E-03 (0.65)	2.0E-02±2.0E-03 (0.71)	6.1E-03±6.5E-04 (0.62)	6.4E-01±5.9E-02 (0.73)
$C_{12}H_{16}O_3$	2-Phenoxyethyl isobutyrate	16±2		1.6E-02±1.7E-03 (0.73)	1.3E-02±1.2E-03 (0.76)	4.1E-03±4.1E-04 (0.79)	4.4E-01±3.6E-02 (0.83)
$C_{10}H_{30}O_5Si_5$	D5 siloxane*	16±15	272778, 357202323982	6.7E-02±8.5E-03 (0.7)	5.7E-02±6.4E-03 (0.82)	1.7E-02±2.1E-03 (0.82)	1.8E+00±2.0E-01 (0.9)
$C_{12}H_{14}O_4$	Diethyl phthalate*	15±3	17138, -	2.3E-02±2.4E-03 (0.64)	1.9E-02±1.7E-03 (0.7)	5.9E-03±5.8E-04 (0.65)	6.2E-01±5.1E-02 (0.71)
C_7H_8O	Benzyl alcohol	14±6	22898, 2292320791	3.6E-02±4.1E-03 (0.85)	3.1E-02±3.0E-03 (0.92)	9.5E-03±1.0E-03 (0.92)	--
$C_8H_{14}O$	6-Methyl 5-hepten-2-one	14±7		4.1E-02±4.6E-03 (0.81)	3.4E-02±3.4E-03 (0.89)	1.1E-02±1.1E-03 (0.96)	1.1E+00±1.0E-01 (0.96)
$C_8H_8O_3$	Methyl paraben	14±4		2.4E-02±2.7E-03 (0.83)	2.1E-02±2.0E-03 (0.86)	6.3E-03±6.6E-04 (0.83)	6.7E-01±6.0E-02 (0.87)
$C_4H_{10}O_2$	1-Methoxy-2-propanol*	13±8	3405, 24053558, 2182	4.1E-02±4.9E-03 (0.78)	3.5E-02±3.6E-03 (0.85)	1.1E-02±1.2E-03 (0.89)	1.1E+00±1.1E-01 (0.89)
$C_5H_4O_2$	Furfural*	13±6	-, 0.01	3.4E-02±4.0E-03 (0.71)	2.9E-02±2.9E-03 (0.62)	8.8E-03±9.7E-04 (0.56)	9.3E-01±8.9E-02 (0.66)
$C_6H_{10}O$	Cyclohexanone	12±6	384, 10665396838	3.6E-02±4.1E-03 (0.84)	3.0E-02±3.0E-03 (0.91)	9.4E-03±1.0E-03 (0.96)	9.9E-01±9.1E-02 (0.92)
$C_6H_{12}O_3$	PGMEA*, 2-Ethoxyethyl acetate	12±11	10017, 821410327, 7450	4.7E-02±6.0E-03 (0.78)	4.0E-02±4.6E-03 (0.76)	1.2E-02±1.5E-03 (0.9)	1.3E+00±1.4E-01 (0.86)
$C_6H_6O_3$	Maltol	11±3		1.3E-02±1.6E-03 (0.59)	1.1E-02±1.2E-03 (0.44)	3.4E-03±3.8E-04 (0.42)	3.6E-01±3.5E-02 (0.49)
C_8H_8O	Acetophenone*	10±6	4, -	3.2E-02±3.8E-03 (0.81)	2.7E-02±2.9E-03 (0.85)	8.4E-03±9.4E-04 (0.89)	8.8E-01±8.7E-02 (0.9)
C_5H_9NO	Methyl pyrrolidone	9±3	12749, 1545214015	1.9E-02±2.2E-03 (0.72)	1.6E-02±1.6E-03 (0.78)	5.0E-03±5.3E-04 (0.77)	5.3E-01±4.8E-02 (0.78)
$C_8H_{10}O_2$	Phenoxyethanol*	9±3	9851, 0.2523	1.7E-02±2.0E-03 (0.78)	1.5E-02±1.5E-03 (0.84)	4.5E-03±4.9E-04 (0.86)	4.8E-01±4.4E-02 (0.91)
$C_8H_{18}O_3$	2-(2-Butoxyethoxy)ethanol, DGBE	8±4	48389, 6837048681, 62011	2.1E-02±2.4E-03 (0.85)	1.8E-02±1.8E-03 (0.91)	5.4E-03±5.9E-04 (0.89)	5.7E-01±5.4E-02 (0.94)
$C_{10}H_{10}O_4$	Dimethyl phthalate	7±1	70, -	9.1E-03±1.0E-03 (0.62)	7.7E-03±7.4E-04 (0.62)	2.4E-03±2.5E-04 (0.55)	2.5E-01±2.2E-02 (0.65)
$C_{12}H_{24}O_3$	Texanol*	7±4	267615, 197658179276	2.0E-02±2.4E-03 (0.57)	1.7E-02±1.8E-03 (0.74)	5.3E-03±5.9E-04 (0.67)	5.6E-01±5.5E-02 (0.74)
$C_9H_{10}O_3$	Ethyl paraben	6±1		7.0E-03±7.7E-04 (0.84)	5.9E-03±5.6E-04 (0.84)	1.8E-03±1.9E-04 (0.85)	1.9E-01±1.7E-02 (0.9)
$C_{11}H_{14}O_3$	Butyl paraben	6±1		8.5E-03±9.0E-04 (0.71)	7.2E-03±6.5E-04 (0.74)	2.2E-03±2.2E-04 (0.8)	2.3E-01±1.9E-02 (0.76)
$C_6H_{10}O_3$	Ethyl acetoacetate	4±2		1.3E-02±1.5E-03 (0.85)	1.1E-02±1.1E-03 (0.87)	3.4E-03±3.7E-04 (0.93)	3.6E-01±3.4E-02 (0.91)
$C_{10}H_{12}O$	Benzyl acetone	4±2		1.0E-02±1.2E-03 (0.85)	8.5E-03±8.8E-04 (0.91)	2.6E-03±2.9E-04 (0.94)	2.8E-01±2.6E-02 (0.97)
$C_7H_{12}O_4$	Pentadioic acid, dimethyl ester	4±1	4942, 2823225606	7.2E-03±8.0E-04 (0.8)	6.1E-03±5.8E-04 (0.84)	1.9E-03±1.9E-04 (0.87)	2.0E-01±1.7E-02 (0.89)
$C_{10}H_{12}O_3$	Propyl paraben	4±1		6.3E-03±7.1E-04 (0.54)	5.3E-03±5.3E-04 (0.46)	1.6E-03±1.7E-04 (0.42)	1.7E-01±1.6E-02 (0.51)
$C_{10}H_{20}O_2$	Hydroxycitronellal	3±1		5.3E-03±5.9E-04 (0.78)	4.5E-03±4.3E-04 (0.88)	1.4E-03±1.4E-04 (0.92)	1.5E-01±1.3E-02 (0.95)
$C_8H_{18}O_3$	Ethylene glycol hexyl ether*, 1,2-Octanediol	2±1	15836, 85447749	5.8E-03±6.7E-04 (0.8)	4.9E-03±4.9E-04 (0.88)	1.5E-03±1.6E-04 (0.87)	1.6E-01±1.5E-02 (0.94)
$C_3H_8O_3$	Glycerol	1±0.5	148441, 1046753949405	3.0E-03±3.5E3E-04±1.8E-04 (0.6664)	21.6E-03±2.5E8E-04 (0.6965)	7.9E5.3E-04±86.4E-05 (0.7574)	86.3E-02±7.6E8E-03 (0.7473)
$C_6H_{14}O_4$	Triethylene glycol	1±0.3	1718, 1053955	2.1E-02±2.4E-04 (0.47)	1.8E-02±1.7E-04 (0.45)	5.5E-04±5.8E-05 (0.4)	5.8E-02±5.2E-03 (0.51)

609 † NoteNotes: For comparison to the emissions inventories, the standard deviation of the mean was used for the compound ratios to
610 constrain the uncertainty of the average compound ratios over the 10-day period, yet we note that higher time resolution variations in
611 the observed ratios are expected given the spatiotemporal variations in emissions from contributing sources distributed around the site.
612 The listed mean concentrations are calculated from hourly averages of data sampled at 1 Hz throughout the measurement period.
613 Given the varied correlation coefficients against tracers (Figure 6), to reduce bias, background-subtracted geometric means are used to

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614 determine the compound ratios, though the geometric mean ratios and slopes are similar, especially for well-correlated compound
615 pairs (Figure S14S13). In the case of glycerol, given its low ambient concentration, the observed background level (i.e. 5th percentile)
616 was 0.1 ppt below its calculated limit of detection. Based on this, the glycerol ratio to acetone for the purposes of Figure 7's
617 comparison was determined based on their regression (5.3 E-04 mol/mol; r=0.74) when removing <LOD values. This has minimal
618 influence on the glycerol-related conclusions related to its substantially low relative abundance as the geometric mean enhancement
619 ratio calculation yielded a similar result (7.9E-04 mol/mol) when including all observations (Figure S13).

620

3.3.1 Esters

622 Prominent esters observed in this study and discussed here include acetates and acrylates.
623 $C_3H_6O_2$, $C_4H_6O_2$, $C_4H_8O_2$, $C_5H_{10}O_2$ and $C_6H_{12}O_2$ were ions with some of the highest
624 ambient concentrations in our data whose geometric mean concentrations varied between
625 0.1-0.8 ppb (Figure 4a-f). Small acetates (e.g. methyl-, ethyl-, propyl- and butyl- acetates)
626 are likely major contributors to these ion signals since they are being extensively used as
627 oxygenated solvents and contribute to natural and designed fragrances/flavorings. The
628 VCPy$\pm$ model estimates the annual emissions of these acetates to be on the order of 10^4-
629 10^5 kg yr^{-1} in NYC, but other compounds can also contribute to these ions. For example,
630 hydroxyacetone and propionic acid may add to $C_3H_6O_2$, diacetyl and γ-butyrolactone to
631 $C_4H_6O_2$, methyl propionate and butyric acid to $C_4H_8O_2$, isobutyl formate to $C_5H_{10}O_2$, and,
632 diacetone alcohol and methyl pentanoate to $C_6H_{10}O_2$. However, their estimated emissions
633 are 1-2 orders of magnitude smaller than each of the acetates, likely making them minor
634 contributors to observed ion intensities. $C_8H_{14}O_2$ (e.g. cyclohexyl acetate) and $C_9H_{10}O_2$
635 (e.g. benzyl acetate) were also important ions within this category with average
636 concentrations at 40 ± 20 ppt and peaks reaching up to 150 ppt during the measurement
637 period.

638

639 We observed hourly $C_5H_8O_2$ concentrations exceeding 1 ppb (Figure 5), which includes
640 methyl methacrylate (MMA) and potential contributions from 2,3-pentanedione and ethyl
641 acrylate given their use as solvents in various coatings and inks. MMA sees some use in
642 adhesives, paints and safety glazing (estimated emissions ~10^3 kg yr^{-1}; VCPy),;+), but
643 could also potentially be emitted from the common polymer poly-(methyl methacrylate)
644 (PMMA) which is used in plastic materials. With a geometric mean concentration of 100
645 $\pm$ 120 ppt, possible contributions of PMMA offgassing/degradation as a source of
646 ambient MMA warrants further investigation, but has been observed in polymer studies
647 (Bennet et al., 2010). In addition to isomer-specific observations of MMA, we note that
648 most of the acetates were also confirmed via offline measurements using adsorbent tubes
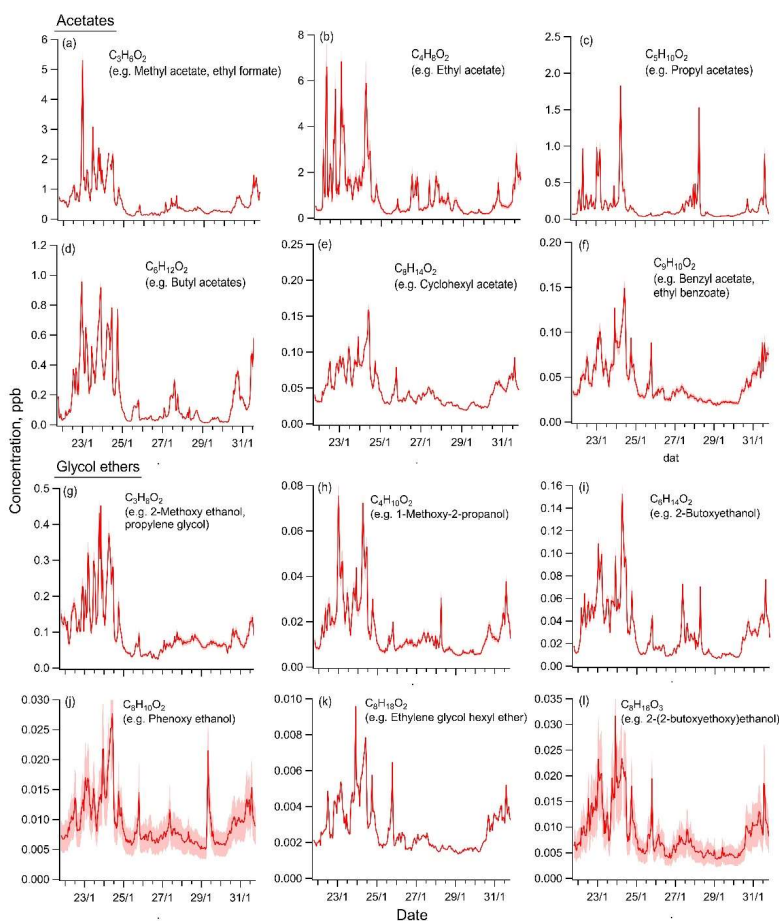649 that were analyzed using GC EI-MS for compound-specific identification (Table 1).

650
651
3.3.2 Carbonyls
653

24

654 Carbonyls are also extensively used as replacements for non-polar solvents in various
655 consumer/commercial applications along with use in cosmetics and personal care
656 products. Hence, C_3H_6O (e.g. acetone), C_4H_8O (e.g. methyl ethyl ketone) and $C_6H_{12}O$
657 (e.g. methyl butyl ketone) were expectedly present at relatively high concentrations.
658 Given the absence of considerable known emissions of other isomers, the ion intensities
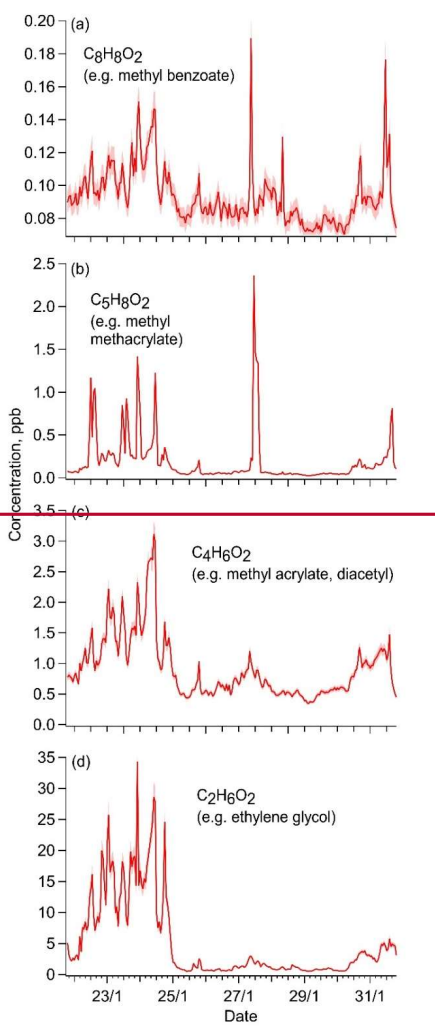659 were mainly attributed to these carbonyl compounds.

660

661 **Figure 4. The concentration timeseries of select, widely-used acetates and glycol**
662 **ethers. Timeseries are shown with major isomers as examples with a more**

663 **comprehensive list available in Tables 1 and S4S7. Displayed uncertainty bands are**
664 **a function of calibration uncertainties (including for isomer pairs) (Table S2).**

665

666 ~~Given the absence of considerable known emissions of isomers, the ion intensities were~~
667 ~~mainly attributed to these carbonyl compounds. Acetone showed the highest average~~
668 ~~concentrations in urban air among all carbonyl solvents detected (Table 1). Since~~
669 ~~biogenic and secondary sources of acetone (i.e. from atmospheric oxidation) are~~
670 ~~relatively limited in NYC wintertime conditions, the measurements are consistent with~~
671 ~~very high anthropogenic emissions in NYC (~10^6 kg yr^{-1}) and extensive use in products~~
672 ~~and by industries (~10^9 kg yr^{-1} nationwide).~~

673

We acknowledge that other primary and secondary sources may also exist for some
carbonyl species, including unknown contributions from combustion-related sources,
cooking or other anthropogenically-influenced sources. Yet, VCPs are the dominant
source of acetone in NYC as per the latest emissions inventories (VCPy+ and FIVE-
VCP) and recent source apportionment of wintertime mobile measurements in NYC that
attribute most of the observed acetone signal to the VCP-related source factor (Gkatzelis
et al., 2021b).

27

681   Acetone showed the highest average concentrations in urban air among all carbonyl
682   solvents detected (Table 1). Since biogenic and local secondary sources of acetone (i.e.
683   from atmospheric oxidation) are relatively reduced in NYC wintertime conditions, the
684   measurements are consistent with very high anthropogenic emissions in NYC ($\sim 10^6$ kg
685   yr^{-1}) and extensive use in products and by industries ($\sim 10^9$ kg yr^{-1} nationwide), and
686   recent work on acetone in NYC (Gkatzelis et al., 2021b).

687

688 **Figure 5. Concentration timeseries of select prominent ions that include**
689 **contributions from major VCP-related compounds (examples listed; see Tables 1**
690 **and ~~S4~~S7 for expanded list).**
691

692 MEK was the second highest carbonyl observed with C_4H_8O ion concentration spanning
693 from 50 to over 500 ppt. Its estimated emissions are 0.4-3 $x10^5$ kg yr^{-1} or greater in NYC
694 and it finds significant use in coatings with large annual nationwide consumption ($\sim10^8$
695 kg yr^{-1}). Methyl butyl ketone (MBK) and cyclohexanone were the next most abundant in
696 this category. The average concentration of MBK at 58 ± 42 ppt was nearly 50% of MEK
697 but reached up to 300 ppt during the initial 4 days of the sampling period. Cyclohexanone
698 however was much smaller at 12 ± 7 ppt with highest concentrations reaching up to only
699 35 ppt across the measurement period, which was consistent with its emissions in VCPy+
700 (~400 kg yr^{-1}) being at least two orders of magnitude smaller than other species in this
701 category, though its estimated emissions in FIVE-VCP were much higher (Table 1).

702
703
704 **3.3.3 Glycols and glycol ethers**

705 Glycols and glycol ethers are compound classes that have been traditionally challenging
706 to measure in real-time with PTR-ToF instruments, being prone to ionization-induced
707 fragmentation during online sampling. With Vocus CI-ToF, we were able to measure
708 signals of several glycol and glycol ether compounds. The most prominent ones included
709 ~~C_2H_6O~~$C_2H_6O_2$, $C_3H_8O_2$, $C_6H_{14}O_2$ and $C_4H_{10}O_2$ ions whose concentrations ranged
710 between 10-500 ppt across the sampling period (Figure 4g-l) with ~~C_2H_6O~~$C_2H_6O_2$
711 reaching ppb-levels.

712

713 $C_2H_6O_2$ (e.g. ethylene glycol) was the most abundant observed compound in this study
714 (Table 1). The emissions of ethylene glycol in NYC are estimated to be on the order of 3-
715 $4x10^5$ kg yr^{-1} which is a factor of 3 smaller than acetone ($\sim10^6$ kg yr^{-1}; VCPy+ and FIVE-
716 VCP). Still the mean concentration of $C_2H_6O_2$ (2.4 ± 3.6 ppb) was found to be
717 considerably larger than that of C_3H_6O (0.95 ± 0.73 ppb). This difference in their relative
718 ratio could not be explained by their atmospheric lifetimes since ethylene glycol is
719 estimated to be considerably shorter lived than acetone (1.5 vs 33 days).

720

721 The $C_3H_8O_2$ ion (20-450 ppt) likely represented propylene glycol, which was the highest
722 emitted isomer in NYC ($\sim10^5$ kg yr^{-1}; VCPy+ and FIVE-VCP) estimates with
723 comparatively minor contributions from 2-methoxy ethanol and dimethoxymethane, all
724 of which are used as solvents in varnishes and various cosmetics. $C_6H_{14}O_2$, including 2-

butoxyethanol, a coupling agent in water-based coatings as well as solvent in varnishes, inks, cleaning products and resins, was observed at 10-150 ppt. The estimated emissions of isomer hexylene glycol are 100 times smaller and would likely not have contributed much to the $C_6H_{14}O_2$ ion signal.

$C_4H_{10}O_2$, which ranged 10-80 ppt, includes 1-methoxy-2-propanol and 2-ethyoxyethanol as both are used as organic solvents in industrial and commercial applications. Based on emissions estimates, 1-methoxy-2-propanol is expected to be the dominant contributor to this signal with NYC emissions of $\sim$2-3x10^3 kg yr^{-1}, which are 30-50 times higher than 2-ethoxyethanol in estimates. $C_6H_{12}O_3$ varied over a similar concentration range (5-80 ppt) resulting from propylene glycol methyl ether acetate (a.k.a. PGMEA) emissions ($\sim$0.7-1x10^4 kg yr^{-1}). The estimated emissions of the other likely isomer, 2-ethoxyethyl acetate, were lower by a factor of 100. Relatively smaller concentrations of $C_8H_{10}O_2$, $C_8H_{18}O_2$ and $C_8H_{18}O_3$ ranging between 2-30 ppt were also observed (Figure 4j-l) which include glycol ethers based on their higher emissions relative to other isomers.

3.3.4 Select compounds related to personal care products
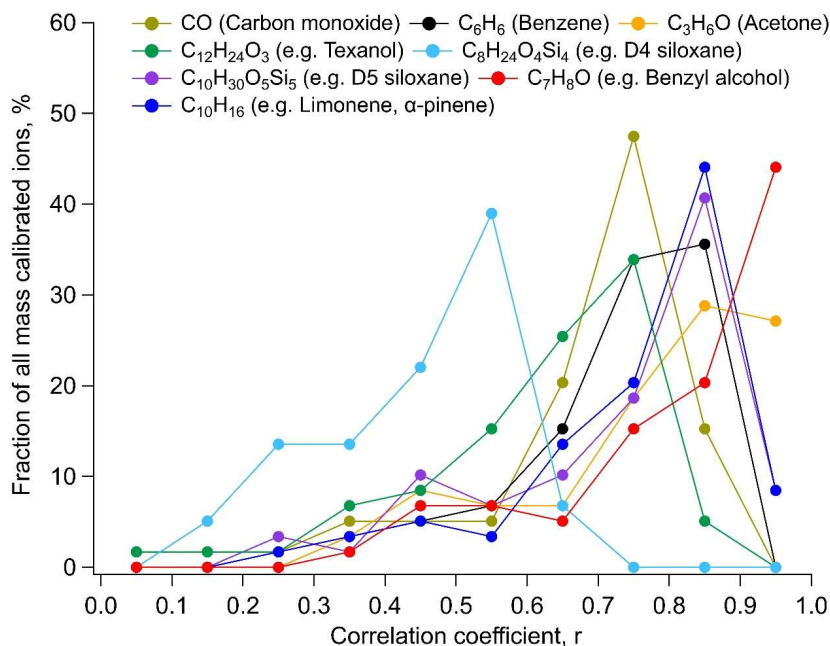
Many personal care products routinely include D5 which is often used as a tracer for emissions from this source category (Gkatzelis et al., 2021a). Hence, we attributed all of the measured $C_{10}H_{30}O_5Si_5$ ion abundance to D5 in this study. Both the VCPy+ and FIVE-VCP inventories estimate the annual emissions of D5 to be slightly higher ($\sim$10^5 kg yr^{-1}) than common oxygenated solvents, e.g. esters. However, its ambient concentration was found to be much lower in comparison to them and other oxygenated solvents, varying from 10 ppt to 140 ppt during the 10-day period with a geometric mean of 16 ppt. Other studies report similar concentrations in U.S. cities (Coggon et al., 2018; Stockwell et al., 2021). ~~Compared to the emissions inventories, ambient concentrations were lower by a factor of 2, potentially due to wintertime conditions (e.g. partitioning), the relative amount emitted indoors vs outdoors, and/or limitations in indoor-to-outdoor transport.~~Compared to the emissions inventories, the expected ambient concentrations relative to acetone were lower by a factor of 2 (see Section 3.5, Table 1). Hypotheses for this difference include potential variations with wintertime conditions (e.g. partitioning), the relative amount emitted indoors vs outdoors, limitations in indoor-to-outdoor transport with reduced wintertime ventilation and/or D5's behavior as a semi-volatile species in the presence of indoor condensational reservoirs (Abbatt and Wang, 2020; Wang et al., 2020). The distinct enhancement in ambient concentrations of D5 in the morning and evening hours in incoming winds over Manhattan indicated that people were a dominant emissions pathway of D5 emissions in NYC. ~~Since most people spend~~

764 ~~majority of their day indoors, D5 emissions are subjected to large~~ with relatively less
765 indoor ~~sinks thereby dampening their contribution to outdoors and will likely~~ to-outdoor
766 transport during the day, though that could be ~~sensitive to reduced~~influenced wintertime
767 ventilation conditions (Sheu et al., 2021; Wang et al., 2020). By comparison, while
768 estimated emissions of benzyl alcohol in NYC were only ~20% of D5, it had similar
769 average concentrations as D5 (Table 1) ranging from 8 to 40 ppt. With strong correlations
770 with many VCP-related compounds (Figure 6), wide use in various consumer product
771 formulations and a similar kOH to m-xylene (i.e., ~10^{-11} molecule^{-1} cm3 s^{-1}), ~~this~~
772 ~~suggests~~benzyl alcohol showed its potential as an additional VCP-related compound for
773 routine monitoring/analysis.

774

775 The glycerol-related $C_3H_8O_3$ ion was especially interesting. Only 1-7 ppt was detected
776 across the measurement period even though it is widely used in the personal care industry
777 with estimated annual emissions in NYC on the order of 10^5 kg yr^{-1}. However, Li et al
778 show in a laboratory evaporation study that glycerol evaporation is much slower than
779 expected (Li et al., 2018). Still, glycerol is expected to influence air quality based on its
780 projected emissions (Gkatzelis et al., 2021b) and no other isomers exist with significant
781 known emissions. Yet, the ratio of background-subtracted concentrations of $C_3H_8O_3$ to
782 D5 ($\Delta C_3H_8O_3/\Delta D5$) was 0.~~042~~035 despite a much higher ratio of estimated emissions (2,
783 12 mol/mol: VCPy~~,~~+, FIVE-VCP). This suggests that $C_3H_8O_3$ is significantly lower than
784 would be expected based on D5-related activities, and, potentially points to limitations in
785 evaporation, indoor-to-outdoor transport, or atmospheric partitioning—all of which could
786 be influenced by wintertime conditions.

Figure 6. A comparison of correlations to major tracer compounds. Distributions of correlation coefficients (using hourly-average data) for Table 1 compounds against select prominent compounds used as markers of VCP-related sources or general anthropogenic emissions (e.g. CO, benzene). Results binned into 0.1 intervals; for example, ~45% of compounds were highly-correlated at $0.9 < r < 1$ with C_7H_8O (i.e. benzyl alcohol). See SI for similar analysis including all uncalibrated target ions and correlation comparisons for all target compounds (Figures ~~S12-15, S17~~S14-17, S19).

$C_8H_8O_3$, $C_9H_{10}O_3$, $C_{10}H_{12}O_3$ and $C_{11}H_{14}O_3$ are paraben-related ions, but additional isomers (e.g. p-ethoxybenzoic acid for $C_{11}H_{14}O_3$) might also contribute to these ion signals. Several others are less likely to be found in the atmosphere since they are not directly used in formulations of volatile chemical products but rather as feedstocks for derivatives used in different industries. Some isomers such as vanillin and vanillylacetone are also used in food flavoring. Methyl paraben-related $C_8H_8O_3$ showed the highest concentration among these four ions ranging from 8 to 35 ppt across the sampling period. The remaining three had concentrations under 10 ppt throughout the sampling duration.

3.3.5 Select IVOCs related to coatings

The $C_{12}H_{24}O_3$ and $C_{16}H_{30}O_4$ ions were primarily attributed to texanol and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB) emissions that are widely used in coatings (Gkatzelis et al., 2021a). Even though estimated emissions of texanol (1.9-2.5 x 10^5 kg yr^{-1}) are much higher than TXIB (2500 kg yr^{-1}; FIVE-VCP), and, texanol production on a national scale (45-110 Gg) considerably exceeds TXIB (22-44 Gg) (U.S. Environmental Protection Agency, Chemical Data Reporting, 2016), the concentrations of both these species had a similar range (5-30 ppt) with enhancements in TXIB concentrations above the 5th percentile background being comparable to texanol on average (Table 1). Given reduced photochemistry, this may suggest differences in outdoor vs indoor application, some geographical variability in their use and/or larger diversity in TXIB sources than texanol in this particular urban area.

3.3.6 Phthalates and Fatty-acid methyl esters (FAMEs)

Phthalates have received considerable attention in indoor environments but their concentrations in ambient air are relatively less constrained. In this study, the ion intensities of $C_{10}H_{10}O_4$ and $C_{12}H_{14}O_4$ include dimethyl phthalate (DMP) and diethyl phthalate (DEP), respectively, two commonly used phthalates in various consumer products. $C_{10}H_{10}O_4$ and $C_{12}H_{14}O_4$ had similar ion abundances across the 10-day sampling period. After accounting for differences in instrument response, $C_{10}H_{10}O_4$ concentrations were found to be smaller than $C_{12}H_{14}O_4$ throughout the campaign which aligns with DEP emission estimates being greater than DMP in NYC. The ambient concentrations of the two ions ranged between 5-30 ppt and often synchronously peaked between midnight and early morning hours (12-6 AM) while the lowest daily concentrations were observed during afternoons. These concentration trends indicated that unlike compounds associated with personal care products, phthalate concentrations were less influenced by outdoor human activities.

FAMEs are also an important class of compounds used in various consumer products. We identified $C_9H_{18}O_2$ (e.g. methyl octanoate) and $C_{11}H_{22}O_2$ (e.g. methyl decanoate) ions via CI-ToF that varied similarly in their abundances across the campaign period. $C_9H_{18}O_2$ concentrations ranged from 50 ppt to 200 ppt and showed slightly higher ion abundances than $C_{11}H_{22}O_2$ even though the annual production of methyl octanoate for use in consumer/commercial products (0.5-9 Gg) is considerably lower than methyl decanoate (4.5-22 Gg) (U.S. Environmental Protection Agency, Chemical Data Reporting, 2016). This suggested that isomers such as heptyl acetate and propyl hexanoate, which are used in perfumes and food flavoring, may have also contributed to $C_9H_{18}O_2$ signal. Emissions

33

843 of pentyl butyrate, which has uses such as an additive in cigarettes are also possible. The
844 highest abundances in both $C_9H_{18}O_2$ and $C_{11}H_{22}O_2$ corresponded to wind currents from
845 Manhattan as well as the Bronx, which infers comparable emission rates within New
846 York City.

847

848 **3.4 Other observed ions of interest**

849 Of the total ions measured, a subset of isomers covering diverse chemical functionalities
850 were included for calibration while others were not calibrated or presented challenges
851 associated with their physiochemical properties that caused transmission issues during
852 LCS calibration. Hence, we will discuss trends in such ions in this subsection in terms of
853 their measured ion abundances (Table S3, figure ~~S9~~S11). These include ions with likely
854 contributions from ethanolamines, organic acids, large alkyl methyl esters and some
855 oxygenated terpenoid compounds that are used in a wide range of volatile chemical
856 products.

857

858 Anthropogenic sources are major contributors of oxygenated terpenoid compounds (i.e.
859 oxy-terpenoids) in many urban areas, especially during wintertime. Among relevant ions
860 observed, $C_{10}H_{16}O$ (e.g. camphor), $C_{10}H_{18}O$ (e.g. linalool), $C_{10}H_{20}O$ (calibrated with
861 menthol) and $C_7H_{10}O$ (e.g. norcamphor) were the most prevalent in terms of measured
862 abundances. A number of isomers that are similarly used in various consumer products
863 likely contributed to their signal intensities. It is interesting to note that $C_{10}H_{16}O$
864 exhibited higher ion abundance than $C_{10}H_{18}O$ despite comparable estimated emissions of
865 camphor and linalool ($\sim10^3$ kg yr^{-1}; VCP~~y~~+) in NYC. This could be due to differences in
866 CI-ToF response factors, the magnitude of relative isomer contributions, seasonal trends
867 in the use of chemical species, or uncertainties in fragrance speciation within emissions
868 inventories. The peaks in abundances of all oxy-terpenoids were observed synchronously
869 in the morning hours between 8-10 AM and in the evening between 6-8 PM, consistent
870 with major commuting periods, especially when wind currents blew in from over
871 Manhattan from the south and south-east where the outdoor activity peaks during
872 morning and evening commute hours.

873

874 We detected C_2H_7NO, $C_4H_{11}NO_2$ and $C_6H_{15}NO_3$ ions at the site, representing
875 ethanolamine, diethanolamine, and triethanolamine, respectively. Of these, $C_4H_{11}NO_2$
876 and $C_6H_{15}NO_3$ followed trends of other ~~VCPs~~VCP-related compounds. $C_4H_{11}NO_2$ showed
877 the highest ion abundance throughout the campaign with the exception of a 24-hour
878 period between 26/1 and 27/1 when C_2H_7NO abundances increased dramatically. This
879 peak in C_2H_7NO was potentially caused by biomass burning since ions pertinent to 2-

880 methylfuran, methyl isocyanate, nitromethane and 2,5 dimethylfuran also peaked
881 simultaneously during this period. The influence of biomass burning in all cases was
882 subsequently filtered from the ion abundance timeseries prior to investigating their linear
883 regressions with other species (figure S15). $C_4H_{11}NO_2$ showed much greater variations
884 with wind patterns, more similar to other VCPs, and peaks were noted in early morning
885 hours between 6-9 AM and during early evening hours around 6 PM. $C_6H_{15}NO_3$ showed
886 lower signal relative to C_2H_7NO and $C_4H_{11}NO_2$ which could be attributed to its smaller
887 annual production for use in consumer/commercial products (45-113 Gg), variations in
888 CI-ToF response factors and/or lower volatility that could decrease emission timescales
889 and cause it to partition to available surfaces indoors.

890

891 Several other major ions included $C_7H_{14}O_2$, $C_8H_{16}O_2$, $C_{12}H_{24}O_2$, $C_{16}H_{32}O_2$ and $C_{18}H_{34}O_2$
892 that were difficult to attribute to individual chemical species because of prevalence of
893 several possible isomers. These isomers were most probably esters and carboxylic acids
894 that are used in many consumer, commercial, and industrial applications. The esters
895 could have contributed more in some cases given their higher volatility, and also because
896 some carboxylic acids are used as feedstocks to produce esters. We briefly discuss these
897 ions here to guide future measurements.

898

899 $C_7H_{14}O_2$ was the most abundant ion in this group likely due to contributions from amyl
900 acetate, isoamyl acetate, and butyl propionate that are used as solvents,
901 fragrances/flavorings, and in other commercial/industrial applications, with possible
902 contributions from heptanoic acid. $C_8H_{16}O_2$ was the next most prominent and likely
903 related to octanoic acid, hexyl acetate, pentyl propanoate and butyl butyrate. $C_8H_{16}O_2$
904 emissions ($\sim 5 \times 10^3$ kg yr^{-1}) were predominantly (90%) estimated to be hexyl acetate by
905 the VCPy$\pm$ model. In comparison, amyl acetate (i.e. $C_7H_{14}O_2$) is estimated in much
906 smaller amounts across the two inventories ($\sim$5-500 kg yr^{-1}). Yet, the higher abundance
907 of $C_7H_{14}O_2$ suggested major contributions from other isomers and/or variations in CI-ToF
908 sensitivity. By comparison, we calibrated $C_8H_{16}O_2$ using octanoic acid given its
909 widespread use in various personal care and cosmetic products. This gave $C_8H_{16}O_2$
910 concentrations ranging from 50 to 300 ppt across the measurement period, but
911 considerable variation is possible with ester contributions to the ions' mass response
912 factors. Among other ions, the abundance of $C_{12}H_{24}O_2$ was comparable to $C_8H_{16}O_2$. The
913 larger ions, $C_{16}H_{32}O_2$ and $C_{18}H_{34}O_2$ showed very small (<10 ions s^{-1}) abundances
914 throughout the campaign. Interestingly, the low ion abundances occurred despite the
915 VCPy$\pm$ model's sizable emission estimates of alkyl methyl esters (C_{16}-C_{18}) on the order
916 of 10^5 kg yr^{-1} in NYC, which is similar to more volatile esters such as methyl or ethyl
917 acetates. This highlights the importance of further research on these semi-volatile organic

918 compounds across seasons to examine if they have lower emissions or could have
919 partitioned to the particle phase in the atmosphere during the winter.

920

921 **3.5 Assessment of ambient concentrations relative to current emissions inventories**

922 In our analysis, high emission estimates did not always translate to high average ambient
923 concentrations and vice versa (Figures 7, ~~S10~~S12), which warrants further examination of
924 ions (and contributing isomers) that were either highly abundant, differed significantly
925 from expected based on emissions inventories, or had limited prior measurements.
926 Though ambient concentrations of a chemical species may not always directly reflect the
927 magnitude of its primary emissions due to atmospheric processes, relative concentrations
928 are frequently used in studies to evaluate the relative magnitude of emissions of various
929 compounds (Gkatzelis et al., 2021a; Mcdonald et al., 2018).

930

931 Figures 7a-b shows the prevalence of such ions during the sampling period relative to
932 their estimated annual emissions against two different regionally-resolved inventories
933 specifically for NYC. The annual emissions were calculated as the sum of the annual
934 emissions of all isomers reported in inventories that contributed to each ion formula. ~~Both~~
935 ~~axes in figures 7a-b are ratioed to C_3H_6O (predominantly acetone) since it was among the~~
936 ~~most abundant ions measured in this study and its primary isomer, acetone, has extensive,~~
937 ~~diverse uses in various products and materials with the majority of anthropogenic~~
938 ~~emissions coming from VCP-related sources.~~Both axes in figures 7a-b are ratioed to
939 C_3H_6O (predominantly acetone) since it was among the most abundant ions measured in
940 this study and its primary isomer, acetone, has extensive, diverse uses in various products
941 and materials with the majority of anthropogenic emissions in NYC coming from VCP-
942 related sources (Gkatzelis et al., 2021b). Still, we acknowledge that acetone, like many
943 oxygenated compounds, could see contributions from oxidation processes. However,
944 such secondary production would be at its minimum during this January study period,
945 and, the short timescales of emitted compounds' transport within the urban footprint
946 reduces (Figure S2) its potential influence in this analysis. Furthermore, to account for
947 any regional background influence in the calculation of emission ratios for inventory
948 comparisons, we have subtracted the estimated ambient background using ~~the~~a 5th
949 percentile concentration value to focus on enhancements in the urban area during the
950 study~~, similar to prior work~~.

951

952 We also note that choosing an ideal denominator species in the middle of a complex,
953 dense urban environment with a wide array of spatiotemporally-dynamic sources is
954 highly challenging. Given the varying correlation coefficients between compounds

955   (Figure 6), Table 1 and Figure 7 are presented using geometric mean ratios of
956   concentration enhancements above the observed ambient background (i.e. 5th percentile).
957   This enables comparisons across all measured compounds, though a comparison of
958   concentration ratios versus slopes from least-squares regressions generally yielded
959   comparable results for acetone for well-correlated species (Figure S11).S13), which also
960   indicates the subtraction of average regional background to determine mean urban
961   enhancement ratios (Table 1) was similarly effective for inventory comparisons. We note
962   that this comparison is done with data from January in a very densely populated area and
963   acetone concentrations will have seasonal variations from biogenic and secondary
964   sources that should be considered in future comparisons between seasons/sites. During
965   this 10-day period, the benzene-to-acetone ratio was close to that predicted by the VCPy+
966   inventory, albeit with slightly greater than expected (i.e. 21.8:1) inferring additional
967   benzene anthropogenic or biomass burning related emissions than in the inventory (see
968   Section 2), but supports that acetone is not overestimated in the inventory when
969   compared to a more commonly-used anthropogenic tracer (i.e. benzene).

970

971   As common markers of anthropogenic activities, the observed ions were also compared
972   against CO and benzene, but, acetone and benzyl alcohol had a greater number of strong
973   correlations (0.9 < r < 1) in this densely populated area (Figure 6, Tables 1, S5S8).
974   Wherever appropriate, the following discussion in this subsection also draws upon
975   correlations with other ions that may inform source subtypes or emission pathways
976   (Figures S12-S15S14-S17), with more detailed discussion available in the supplemental
977   information (SI). There was some variation in the number of speciated compounds
978   included in each inventory and, a subset of calibrated ions in this study were not available
979   in one of the emissions inventories. The compounds not speciated in VCPy are presented
980   in Figure 7c with mean concentrations relative to acetone.

981

982   Of the 58 calibrated ions, emissions of one or more isomers were reported for 38 ions in
983   VCPy+ and 32 ions in FIVE-VCP inventories. The ambient concentration ratios of
984   roughly half of these numbers agreed within 1 order of magnitude (i.e. 1:10, 10:1) with
985   emissions reported in both inventories (Figure 7a-b). Within this sub-fraction,
986   concentrations of 50% of ions nearly matched with estimates, though with some
987   variability between inventories. In the case of VCPy+ (Figure 7a), some of the most
988   accurately estimated ions represented glycol and glycol ether compound categories, such
989   as dipropylene- and triethylene- glycols, 2-butoxyethanol, 2-methoxyethanol (with
990   propylene glycol), and phenoxyethanol, as well as D5, pentanedioic acid dimethyl ester,
991   methyl pyrrolidone, benzyl alcohol, monoterpenes and diethyl phthalate. Several other

992   ions also representing glycols and glycol ethers fell within the 1:10 range (Figure

993   S16S18), but not ethylene glycol (see discussion below).

995

Figure 7. Comparison of ambient observations to emission inventories. (including all inventoried anthropogenic sources). Urban concentration enhancement ratios against acetone (calculated via background-subtracted geometric means) compared to estimated emission ratios using the (a) VCPy model (plus other anthropogenic sources in NEI) and (b) FIVE-VCP inventory (shown for compounds with explicit estimates in each inventory, see Table 1). (c) Concentration enhancement ratios against acetone (and correlation coefficients) for calibrated ions where emissions data was not available in VCPy (panel a).

40

Note: Examples of isomers contributing to ions in (a) and (b) are listed in Tables 1 and S4S7.

The ions in closest agreement with FIVE-VCP estimates shown in Figure 7b represented benzyl alcohol, methyl pyrrolidone, MEK, D5 and a smaller number of glycol ethers that included ethylene glycol hexyl ether, and, dipropylene- and diethylene- glycols. Other ions within the tolerance bound included methyl- and butyl-acetates, 2-hexanone, cyclohexanone and pentanedioic acid dimethyl ester. It is notable that ambient measurements of glycols and glycol ethers made up approximately half of the total ions that broadly agreed with emission estimates in both emissions inventories. Additionally, the accuracy of benzyl alcohol estimates is also useful since ~45% of all mass calibrated ions and ~35% of the total observed ions in this study correlated strongly (0.9 < r < 1.0) with C_7H_8O (i.e. benzyl alcohol; Figures 6, S17-18S19-20), which may help in constraining emissions in future studies.

The observed ambient ratios of the remaining ~50% ions deviated considerably from those in emissions inventory estimates. The majority of these ions had greater concentration ratios in Figure 7a-b, which suggests that their emissions were higher than that expected based on emissions inventories. These elevated ratios above the 1:1 line could be due to underestimates in VCP-related sources as well as uncertainties in other sources, such as cooking (and the underlying foods/beverages), combustion-related sources, industrial/commercial activities, humans (e.g. skin oil-related products; e.g. 6-MHO), or other understudied non-traditional sources (e.g., building materials). Additionally, while at its minima in peak wintertime conditions, secondary oxidation products as a result of local chemistry (i.e. not in the regional background that was subtracted) could make minor contributions to the calculated urban enhancements in Table 1. Among glycols in particular, ethylene glycol was abundant with mean ambient concentration ratios slightly over 10 times the inventory-based value. This result could be influenced by seasonal variations in use, such as wintertime use as a de-icer for surfaces (or aircraft) or the particularly elevated concentrations (25-35 ppb) during the first 4 days of the measurement period (Figure 5) compared to the timeseries of other VOCs (Figure 4).) with wind currents from the southwestern direction to the sampling site. However, this concentration enhancement in ethylene glycol may not translate to other seasons due to change in the magnitude of its sources (e.g. no de-icing required in non-winter periods). Ethylene glycol also correlated strongly (r > 0.9) with a few other ions (e.g. MEK, MVK, cyclopentanone, cyclohexanone, benzyl alcohol) that may suggest a mix of co-located and/or shared source types. Among glycol ethers, the $C_8H_{10}O_2$ ion representing phenoxyethanol differed considerably between the two inventories, ranging from near expected in VCPy+ to a much higher ambient abundance relative to FIVE-VCP (Figure S16S18). This was likely due to estimated phenoxyethanol emissions being

1042 10^5 times higher in VCPy+ than in FIVE-VCP. However, 1,4-dimethoxybenzene might
1043 have also contributed to $C_8H_{10}O_2$ ion signal given its widespread use in personal care
1044 products but needs inclusion in emissions inventories. Similarly, monoterpenes during
1045 this study slightly exceeded the 10:1 value based on FIVE-VCP estimates (Figure 7),
1046 which was influenced by significantly different limonene emissions between the two
1047 inventories (60206 kg yr^{-1}; VCPy vs 17107 kg yr^{-1}; FIVE-VCP) that constituted over
1048 90% of the reported monoterpene emissions. D4-siloxane deviated in the other direction
1049 going from near expected in FIVE-VCP to considerably above the 10:1 bound in VCPy
1050 comparisons, which was likely due to a factor of 8 difference in its reported emissions
1051 between the two inventories. The cyclohexanone-related $C_6H_{10}O$ concentration ratio was
1052 somewhat lower than expected based on FIVE-VCP estimates though within the lower
1053 tolerance bound, but substantially exceeded VCPy+ estimates (Figure S16S18) given the
1054 ~280-fold difference in cyclohexanone emissions between the two inventories.

1055

1056 Some ions deviated even more substantially in ambient concentration ratios relative to
1057 inventory-based expectations (Figure 7a). The prominent ions in this group represented
1058 esters, e.g. $C_9H_{10}O_2$ (e.g. benzyl acetate), $C_4H_6O_2$ (e.g. methyl acrylate), $C_5H_8O_2$ (e.g.
1059 MMA), $C_5H_{10}O_2$ (e.g. isopropyl acetate) and $C_4H_8O_2$ (e.g. ethyl acetate). All these
1060 compounds (except MMA) are found in solvents, fragrances, food flavorings, and
1061 naturally in some food (e.g. fruits). Some fraction of their discrepancies may be attributed
1062 to uncertain fragrances source categories in emissions inventories which contributes, in
1063 part, to their higher than expected concentrations in our analysis. Hence, further work is
1064 needed to more comprehensively speciate and constrain synthetic and natural fragrance-
1065 related emissions. Other possibilities for these differences include missing sources that
1066 need to be accounted for in estimating total emissions for each ion. For example, diacetyl
1067 is also a likely isomer of $C_4H_6O_2$ that is currently excluded from emissions inventories.
1068 MMA concentrations at 100's of parts per trillion (Figure 5) is an interesting case due to
1069 its minimal use in consumer products, and, besides contributions from other isomers to
1070 $C_5H_8O_2$ ion, may indicate ambient observations of PMMA offgassing/degradation under
1071 ambient conditions. Similarly, higher than expected $C_{10}H_{10}O_4$ (e.g. dimethyl phthalate)
1072 concentrations could be contributed to by materials-related off-gassing and emissions
1073 from personal care products.

1074

1075 Ions related to benzaldehyde and menthol also exhibited higher than expected
1076 concentrations in both inventory assessments. $C_{10}H_{20}O$ (e.g. menthol) showed strong
1077 correlations (r > 0.95) with 14 other ions that spanned several compound classes
1078 including glycol ethers, carbonyls, esters and alcohol. This may be also contributed to by
1079 fragrance-related sources, or other isomers in the case of menthol. $C_9H_{10}O_2$ (e.g. benzyl

42

1080 acetate), $C_{10}H_{12}O_2$ (e.g. eugenol) and $C_6H_{10}O$ (e.g. cyclohexanone) ions also showed high
1081 concentrations in VCPy+ inventory comparisons while $C_5H_4O_2$ (e.g. furfural) exceeded
1082 expected concentrations based on FIVE-VCP estimates. Furfural could also be
1083 contributed by indoor emissions from wood-based materials (Sheu et al., 2021) though
1084 such a source will be lower in NYC than observed elsewhere given major differences in
1085 Manhattan building construction materials. Some of these isomers, e.g. eugenol,
1086 raspberry ketone and furfural are also appear in foods and are used in foodas flavorings,
1087 which remains largely unexplored as a potential source of emissions.

1088

1089 The glycerol-related $C_3H_8O_3$ ion presents a very interesting case among the few ions that
1090 exhibited considerably lower concentrations than expected., with regional background
1091 concentrations even dropping below its detection limit (see Table S5). Its annual
1092 estimated emissions are comparable to prominent carbonyls and esters with slight
1093 differences between the VCPy+ and FIVE-VCP inventories ($\sim 10^5$ kg yr^{-1} vs. $\sim 10^6$ kg yr^{-1}
1094). However, it is uncertain whether its low mean concentration during the sampling
1095 period (Table 1) was influenced by seasonal variations in ambient gas-to-particle
1096 partitioning and/or in emissions pathways (e.g. reduced evaporation or indoor-to-outdoor
1097 transport). Thus, further research would be valuable to evaluate atmospheric levels of
1098 glycerol including during summertime conditions when evaporative emissions from
1099 personal care products and indoor-to-outdoor transport are enhanced relative to January.
1100 The same factors may have also driven the somewhat lower concentrations of texanol
1101 relative to inventory-based predictions (Figures 7a-b, S16S18), though its concentrations
1102 are similar to summertime observations in NYC (Stockwell et al., 2021).

1103

1104 Among ions without any emissions estimates, $C_8H_8O_2$ (e.g. methyl benzoate), $C_9H_{18}O_2$
1105 (e.g. heptyl acetate) and $C_7H_6O_2$ (e.g. benzoic acid) had some of the highest
1106 concentration ratios to acetone (Figure 7c), and may warrant inclusion in emission
1107 inventories, potentially as part of "fragrances" or other uncertain source types.
1108 Observations of sesquiterpenes were 7% of acetone concentrations on average (Table 1).
1109 The mean sesquiterpenes to monoterpenes ratio was ~ 0.5 during the measurement period
1110 though sensitive to instrument calibration, emphasizing sizable contributions from the
1111 highly-reactive sesquiterpenes to urban air. Ions including C_4H_6O (e.g. MVK), $C_8H_{14}O_2$
1112 (e.g. cyclohexyl acetate), C_5H_8O (e.g. cyclopentanone) and $C_8H_{14}O$ (e.g. 6-methyl-5-
1113 hepten-2-one, a skin oil oxidation product) were not estimated in the inventory, but
1114 showed very strong correlations ($0.9 < r < 1.0$) with the acetone-related C_3H_6O ion.

1115

1116 **4. Conclusions and future work**

A Vocus CI-ToF using low-pressure NH_4^+ as the reagent ion enabled measurements of a wide range of oxygenated species in New York City whose urban enhancements were primarily attributed to anthropogenic sources given the peak wintertime conditions, but could vary under different meteorological conditions. Our results highlight the diversity of oxygenated compounds in urban air, including VCP-related compounds that extend considerably beyond the highly volatile, functionalized species found in oxygenated solvents. The measured ions had contributions from VOCs to I/SVOCs including acetates, glycols, glycol ethers, alcohols, acrylates and other functional groups. The atmospheric concentrations of these species varied over a large range but reached up to hundreds of ppt and into ppb-levels in several cases, which were comparable to the prevalence of known prominent OVOCs such as acetone, MEK and MVK. While emissions inventories predicted the relative abundance of many species in the atmosphere with relative accuracy (e.g. glycols and glycol ethers), several others deviatedshowed significantly different ambient concentrations than predicted (e.g. select esters). This informs measured over 10 times their expected values (Figure 7)).

While the species target list in this manuscript (Table 1) included an array of compounds that are known to occur in VCPs, the observed underestimates when compared to emission inventories may be contributed to not only VCP-related sources but also other established or uncertain urban sources in the inventories. Broad source classes such as cooking (and associated foods/fuels) represent one example that could be significant sources of some of the OVOCs studied here (e.g., esters, carbonyls, fatty acids, terpenoids). Similarly, while large biomass burning influences were filtered from the comparison to the emission inventories, we note that biomass burning remains an important source of regional and/or long-distance OVOCs. Regional and long-distance transport of secondary OVOCs (and associated pollutants) also remain important contributors to urban air quality across all seasons, and non-wintertime conditions will include a greater role for photochemical processing within/near NYC. Yet, local secondary OVOCs can be produced within the city, and future work with longer NH_4^+-based summertime datasets can further deconvolve OVOC contributions, including the contributions of local photochemical production (occurring from outdoor or indoor chemistry).

These results inform new avenues for investigation ofinvestigating the emissions or atmospheric dynamics of these species indoors or outdoors, and possible additional compounds and source contributions for inclusion in emissions inventories. Given the high ambient prevalence of some species, further research is also warranted to further enhance chemical speciation in inventories (and measurements) that will constrain potential contributions to SOA and ozone formation under varying environmental conditions. Future summertime studies (e.g. AEROMMA, GOTHAAM) will also provide valuable opportunities to compare seasonal abundances of observed species and to study

1156 ~~different seasonally-dependent emission pathways.~~<ins>Atmospheric Emissions and Reactions
1157 Observed from Megacities to Marine Areas (AEROMMA) (Warneke et al., 2022),
1158 Greater New York Oxidant, Trace gas, Halogen and Aerosol Airborne Mission
1159 (GOTHAAM)) will also provide valuable opportunities to compare seasonal abundances
1160 of observed species and to study different seasonally-dependent emission pathways.</ins>

1161

Author Contributions

1163 D.R.G., J.E.M. (SBU), and J.E.K. conceived the study, and J.E.K. performed the ambient
1164 Vocus CI-ToF measurements with support from R.T.C. P.K. led data analysis and writing
1165 with support from J.E.K and D.R.G., and contributions/review from other co-authors.
1166 P.K., J.E.M. (Yale) and J.W. prepared calibration mixes. J.E.M. (Yale), J.W. and J.E.K
1167 performed in-lab calibrations. T.H.M. collected EI-MS samples and conducted related
1168 analysis, along with J.W. and J.E.M. (Yale). K.M.S and H.O.T.P. developed the VCPy
1169 model and K.M.S. performed VCPy calculations for this work. B.M. provided the FIVE-
1170 VCP emissions inventory data used in this study. F.M. and F.L.H. developed and tested
1171 the Vocus CI-ToF instrument for this study. C.C. and J.E.M. (SBU) performed PTR-ToF
1172 measurements used for instrument cross-validation in this study. R.C. provided carbon
1173 monoxide data and R.T.C. helped setting up the measurement site.

1174

Competing interests

1176 Jordan E. Krechmer is employed by Aerodyne Research, Inc., which commercializes the
1177 Vocus CI-ToF instrument for geoscience research and Felipe Lopez-Hilfiker is an
1178 employee of Tofwerk, AG, which manufactures and sells the Vocus CI-ToF instrument
1179 used in this study.

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