



Secondary Organic Aerosol Formation in Coastal Air Modulated by Continental Outflow and High Humidity

Ya-Nan Zhan^{1,2,3}, Dan Dan Huang^{2*}, Yaqin Gao², Sheng'ao Jing², Jun Pan⁴, Yingjie Li², Juntao Huo⁴, Yi Sun⁴, Haobin Zhong⁵, Wei Xu⁶, Jing Duan¹, Ting Wang^{1,6}, Qianying Liu⁷, Lulu Zeng⁷, Yong Jie Li⁷, Cheng Huang⁴, Hongli Wang², Qingyan Fu², and Ru-Jin Huang^{1,3*}

¹State Key Laboratory of Loess Science, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China

²Key Laboratory of Formation and Prevention of Urban Air Pollution Complex, Ministry of Ecology and Environment, Shanghai Academy of Environmental Sciences, Shanghai, 200233, China

³Institute of Global Environmental Change, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China

⁴Shanghai Environmental Monitoring Center, Shanghai 200235, China

⁵School of Advanced Materials Engineering, Jiaxing Nanhu University, Jiaxing, 314001, China

⁶Center for Excellence in Regional Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China

⁷Department of Civil and Environmental Engineering, Department of Ocean Science and Technology, and Centre for Regional Oceans, Faculty of Engineering, University of Macau, Taipa, Macau SAR, 999078, China

* To whom correspondence should be addressed: Dan Dan Huang (huangdd@saes.sh.cn),
Ru-Jin Huang (rujin.huang@icecas.cn)



28 **Abstract:**

29 Secondary organic aerosol (SOA) formation in coastal regions, where a substantial world
30 population resides, remains poorly understood, hindering estimation of its effects on air quality
31 and human health. Here, SOA formation from coastal air oxidation was investigated using a
32 field-deployed oxidation flow reactor at Tanxu Island in the Yangtze River Delta, China. High-
33 humidity conditions with relative humidity (RH) >90% resulted in maximum SOA production
34 of $3.7 \mu\text{g m}^{-3}$, more than three times that under RH <90% ($1.2 \mu\text{g m}^{-3}$). This discrepancy could
35 be attributed to an enhanced contribution of aqueous-phase processing, together with the supply
36 of anthropogenic precursors from continental outflow. In turn, when humid coastal air was
37 transported to nearby cities such as Shanghai, SOA production could increase, as indicated by
38 the organic aerosol loading effect. Closure analysis indicated that the gas-phase OH oxidation
39 of measured gaseous organics explained 57% of the measured SOA production at equivalent
40 photochemical ages <3 days and RH <80%, with the overlooked contributions from oxygenated
41 aromatics (18%) and furans (6%) highlighted. By isolating air mass origins, we found that SOA
42 production with continental air masses was more than three times that in marine air masses at
43 RH <90%; the unexplained fraction for SOA production in continental air masses (49%) was
44 also higher than that in marine air masses (35%), suggesting unidentified anthropogenic
45 precursors such as volatile chemical products. These results provide quantitative constraints on
46 SOA formation in coastal air, with implications for understanding SOA pollution in downwind
47 coastal cities.



48 1. Introduction

49 Air pollution is a global environmental issue that adversely affects human health and the
50 climate (Huang et al., 2025a; Burnett et al., 2018; Li et al., 2022). Much of the world's
51 population and economic activity is concentrated in coastal regions (Lopez-Rivas and Cardenas,
52 2024), with approximately 38% of the global population living within 100 km of the shoreline
53 (Cosby et al., 2024). Air quality in coastal regions is influenced by both continental and marine
54 sources. As early as summer 2009, marine sources accounted for 15.7% of the total mass of
55 organic aerosol (OA) in Paris, a heavily urbanized megacity located about 200 km from the
56 ocean, despite the dominance of continental OA (Crippa et al., 2013). In recent years,
57 anthropogenic emissions, particularly primary particle emissions, have declined substantially
58 in many coastal cities because of effective regulatory efforts (Guo et al., 2024; Chow et al.,
59 2022; Font et al., 2019; Enayati Ahangar et al., 2021), and marine emissions and their
60 interactions with continental emissions may become increasingly important in shaping coastal
61 air quality.

62 Secondary organic aerosol (SOA) is a major component of OA and is mainly formed
63 through gas-phase photochemical oxidation of diverse organic precursors initiated by OH
64 radicals (Huang et al., 2025a; Kroll and Seinfeld, 2008). Most observations usually focus on
65 ambient SOA without considering the SOA formation of precursors remaining in ambient air.
66 Coastal air often experiences intense photochemical activity (Zhang et al., 2024a; Xu et al.,
67 2025), with reported daily OH concentrations reaching $(0.5\text{--}1.0) \times 10^7$ molecules cm^{-3} (Zhang
68 et al., 2024a; Zou et al., 2023). Sea-land breeze, a thermally driven local circulation in coastal
69 regions, can prolong the residence times of organic precursors in coastal regions (Zeren et al.,
70 2022; Xu et al., 2025), favoring their OH oxidation and SOA formation. Moreover, high relative
71 humidity (RH) in coastal regions might further enhance SOA formation via aqueous-phase
72 processes (Chao et al., 2025; Kommula et al., 2021). Together, SOA formation of coastal air
73 may be non-negligible, and the SOA may be transported back to nearby cities, where it may
74 contribute to SOA pollution and influence SOA physicochemical properties, such as
75 hygroscopicity, with implications for climate (Kommula et al., 2021; Chen et al., 2025). Yet,
76 our understanding of SOA formation in the coastal atmosphere remains poorly understood.



77 A key challenge in estimating SOA formation potential in coastal air arises from the
78 complexity of precursor mixtures and atmospheric chemical processes. Coastal air lies at the
79 interface between urban and marine environments, where gaseous organic precursors originate
80 from both anthropogenic and marine sources, including volatile organic compounds (VOCs)
81 and intermediate-/semi-volatile organic compounds (I/SVOCs). Although particulate pollutants
82 have declined markedly, emissions of anthropogenic gaseous organic precursors remain
83 substantial, and their source distribution is changing (Huang et al., 2025a; Zheng et al.,
84 2018). Volatile chemical products (VCPs), such as those emitted from paints and personal care
85 products, have emerged as an increasingly important precursor source and rival or even exceed
86 transportation-related emissions in some regions (Gkatzelis et al., 2021a; Chang et al., 2022).
87 However, the precursor composition of VCPs remains poorly constrained, and they may include
88 numerous emerging SOA precursors that have not yet been identified. For marine emissions,
89 gaseous organic precursors can be released from biogenic activities (e.g., phytoplankton blooms)
90 (Broadgate et al., 1997; Rocco et al., 2025) and from photochemical reactions at the air-water
91 interface (Brüggemann et al., 2018). In addition, shipping activities might introduce substantial
92 organic matter into the coastal atmosphere (Tong et al., 2024). These multiple sources make
93 precursor mixtures in coastal air highly complex, whereas current observations cover only a
94 limited range of compounds (Sun et al., 2024; Xu et al., 2025). Beyond the difficulty of
95 comprehensively characterizing precursors, SOA formation from mixed precursors under real
96 ambient conditions can be highly nonlinear and is influenced by inorganic species and
97 meteorological factors (Chen et al., 2024; Moore et al., 2024; Li et al., 2021). As a result, the
98 accurate assessment of SOA formation potential in coastal air cannot be adequately achieved
99 using traditional yield-based methods (Gao et al., 2025; Zhang et al., 2021a; Hui et al., 2019;
100 Li et al., 2020) or chemical models (Hu et al., 2017a), because these approaches strongly depend
101 on information about known precursors.

102 The field-deployable oxidation flow reactor (OFR), coupled with online mass
103 spectrometers, offers a useful approach to quantifying SOA production from ambient air
104 oxidation. Ambient air can be directly introduced into the OFR and exposed to sufficient OH
105 radicals to form SOA. This approach has been applied in several environments, including urban



106 areas (Liu et al., 2018; Duan et al., 2025; Ortega et al., 2016; Zhang et al., 2024b), coastal
 107 regions (Kang et al., 2018), forests (Palm et al., 2016; Palm et al., 2017), tunnels and roadsides
 108 (Tkacik et al., 2014; Liu et al., 2019a). A previous OFR study of ambient air oxidation on
 109 Baengnyeong Island, Korea, investigated the SOA formation at an OH exposure (OH_{exp})
 110 equivalent to 4.6 days and found that OA response to photochemical oxidation varied with
 111 ambient aerosol composition (Kang et al., 2018). Yet, how SOA formation potential in coastal
 112 air evolves across a broader OH_{exp} range remains unclear, limiting assessment of its potential
 113 implications for SOA pollution in nearby coastal cities. Identifying the major SOA precursors
 114 is likewise important for developing effective air pollution control strategies in coastal regions.
 115 In this study, in situ OFR photochemical oxidation of ambient air was performed at Tanxu Island,
 116 a coastal site adjacent to the Yangtze River Delta, one of the most economically developed
 117 regions in China. SOA formation and aging from OH oxidation of coastal air were investigated
 118 across different levels of OH_{exp} , RH, and OA loadings, and SOA production was quantified.
 119 Based on concurrent measurements of gaseous organics and OFR-derived SOA, the major
 120 precursors and their contributions to SOA production were estimated. In addition, SOA
 121 production was compared between continental and marine air masses, and the underlying
 122 influencing factors were analyzed.

123 **2. Materials and Methods**

124 **2.1 Field Measurements and In Situ OFR Oxidation Experiments**

125 Ambient measurements were conducted at Tanxu Island (30.61°N, 121.63°E) from 29
 126 April to 11 July 2024. Tanxu Island is located in Hangzhou Bay, China, covers an area of
 127 approximately 0.6 km², and is surrounded by the sea (**Figure S1**). The site is approximately 25
 128 km from the nearest coastline and 70 km from downtown Shanghai. During the observation
 129 period, the site was influenced by multiple air masses, including continental outflow from the
 130 Yangtze River Delta and marine air masses. This geographical setting makes Tanxu Island a
 131 suitable site for investigating the SOA formation of coastal air influenced by both continental
 132 and marine air masses.

133 Ambient air oxidation experiments were carried out using a commercial potential aerosol
 134 mass (PAM) reactor (Aerodyne Research, Billerica, MA, USA) from 3 June to 11 July 2024. A



schematic of the experimental setup is shown in **Figure S2**. Ambient air was introduced directly into the OFR chamber at a total flow rate of 12.5 L min^{-1} , resulting in a residence time of ~ 64 s. The OFR was operated in OFR185 mode, in which OH radicals were generated via photolysis of H_2O at $\lambda = 185 \text{ nm}$ and photolysis of O_3 at $\lambda = 254 \text{ nm}$. The voltage applied to the mercury lamps (GPH436T5VH/4P, Light Sources Inc.) was adjusted to vary OH_{exp} . OH_{exp} in the OFR was estimated using an empirical equation established through a series of calibration experiments, as described in our previous study (Liu et al., 2025). In this study, OH_{exp} ranged from 1.4×10^{11} to $1.9 \times 10^{12} \text{ molecules cm}^{-3} \text{ s}$, corresponding to an equivalent photochemical age of 1.1-14.9 days when ambient OH concentration is assumed to be $1.5 \times 10^6 \text{ molecules cm}^{-3}$ (Mao et al., 2009). The adopted ambient OH concentration falls within the reported range for 24 h mean OH concentration in coastal atmospheres ($1.5\text{-}2.3 \times 10^6 \text{ molecules cm}^{-3}$) (Zhang et al., 2024a; Zou et al., 2023) and has also been used in previous coastal OFR studies (Kang et al., 2018). In addition, particle losses through the OFR chamber were corrected by comparing aerosol component concentrations measured downstream of the OFR under dark conditions with the corresponding ambient concentrations measured in the bypass line (see **SI-1** for details).

2.2 Measurement of Gaseous and Particulate Components

Gaseous organics were measured primarily using a combination of online gas chromatography-mass spectrometry/flame ionization detection (GC-MS/FID, TH-300, Wuhan Tianhong Instrument, China) and a proton transfer reaction time-of-flight mass spectrometer (PTR-ToF-MS, ToFwerk, Switzerland) coupled with H_3O^+ chemistry. Formaldehyde was measured separately using a G2307 gas analyzer (Picarro, USA). GC-MS/FID and PTR-ToF-MS were calibrated daily using gas standards (Linde Gas, USA). When specific compounds were simultaneously measured by both GC-MS/FID and PTR-ToF-MS, data from GC-MS/FID were preferentially used because of its superior isomer-resolving capability (Gao et al., 2023). The identification and quantification of gaseous organics followed the data processing protocol described by (Gao et al., 2023). A total of 229 gaseous organics were quantified in this study. These compounds were classified into 12 categories, namely, alkanes, alkenes, alkynes, single-ring aromatics (SRAs), polycyclic aromatic hydrocarbons (PAHs), oxygenated aromatic compounds (O-aromatics), alcohols and ethers, aldehydes and ketones, acids and esters, furans,



164 terpenoids, and other compounds.

165 Non-refractory aerosol components, including OA, nitrate, sulfate, ammonium, and
166 chloride, were measured using a time-of-flight aerosol chemical speciation monitor (ToF-
167 ACSM-X, Aerodyne Research, USA) equipped with a capture vaporizer. A collection efficiency
168 of 1 was applied for the ACSM-X (Hu et al., 2017b), and the ionization efficiency was
169 calibrated using size-selected ammonium nitrate particles. Aerosol component mass
170 concentrations were derived from high-resolution peak fitting of the ACSM-X mass spectra.
171 Positive matrix factorization analysis was further performed on the organic mass spectra to
172 resolve the mass concentration of primary organic aerosol and SOA, following the procedures
173 outlined in Ulbrich et al. (2009) and Zeng et al. (2026). Concurrent measurements of inorganic
174 gases (SO₂, NO_x, O₃, and CO), and meteorological parameters (RH, temperature, wind speed,
175 and wind direction) were also available at Tanxu Island. Detailed information can be found in
176 **SI-2**.

177 **2.3 Estimation of SOA Production**

178 SOA production from the detected gaseous organic precursors was estimated based on
179 their consumption upon OH oxidation and their SOA yields at the corresponding OA loading
180 in the OFR, following Equations (1) and (2) (Gao et al., 2025; Huang et al., 2024). This method
181 has been described in detail in our previous study (Huang et al., 2024) and **SI-3**, and is only
182 briefly summarized here. A total of 117 potential SOA precursors were considered in this study,
183 and their OH reaction rate constants and SOA yield parameters are listed in **Tables S1-S3**. For
184 compounds lacking reported OH rate constants, the values were estimated using the empirical
185 Equation (3) proposed by Donahue et al. (2013). SOA yields were derived from OA-dependent
186 yield curves parameterized using the secondary organic aerosol potential (SOAP) method, the
187 two-product model, and the volatility basis set (VBS) model. The average NO_x concentration
188 during the campaign was 9.7 ppb, and therefore, laboratory SOA yield parameters determined
189 in the presence of NO_x were applied. For precursors without experimentally determined SOA
190 yields, yield parameters from surrogate compounds with similar chemical structures and
191 categories were adopted (Akherati et al., 2020; Sasidharan et al., 2023). Specifically, SRAs with
192 carbon numbers greater than eight were represented by m/p-xylene (Akherati et al., 2020);



193 PAHs by naphthalene (Akherati et al., 2020); O-aromatics by benzyl alcohol (Sasidharan et al.,
 194 2023); and furans by furan and methyl furan (Akherati et al., 2020).

$$195 \quad \text{SOA} = \Delta \text{Precursor}_i \times [Y_i] \dots\dots\dots (1)$$

$$196 \quad \Delta \text{Precursor}_i = [\text{Precursor}_i] \times (1 - e^{-k_{OH,i} \times OH_{exp}}) \dots\dots\dots (2)$$

197 where SOA ($\mu\text{g m}^{-3}$) is the mass concentration of SOA production, $[Y_i]$ is the SOA yield of
 198 precursor i at the corresponding OA loading in the OFR, $\Delta \text{Precursor}_i$ ($\mu\text{g m}^{-3}$) and $[\text{Precursor}_i]$
 199 ($\mu\text{g m}^{-3}$) is the reacted mass concentration and the initial concentration of the precursor i , $k_{OH,i}$
 200 ($\text{molecules cm}^{-3} \text{s}^{-1}$) is the OH reaction rate constant of precursor i , and OH_{exp} (molecules cm^{-3}
 201 s) is the OH exposure inside the OFR chamber.

$$202 \quad k_{OH,i} = -1.2 \times 10^{-12} \times (n_c + 9 \times n_o - 10 \times (\frac{n_o}{n_c})^2) \dots\dots\dots (3)$$

203 where n_c and n_o are the carbon and oxygen numbers of precursor i .

204 3 Results and Discussion

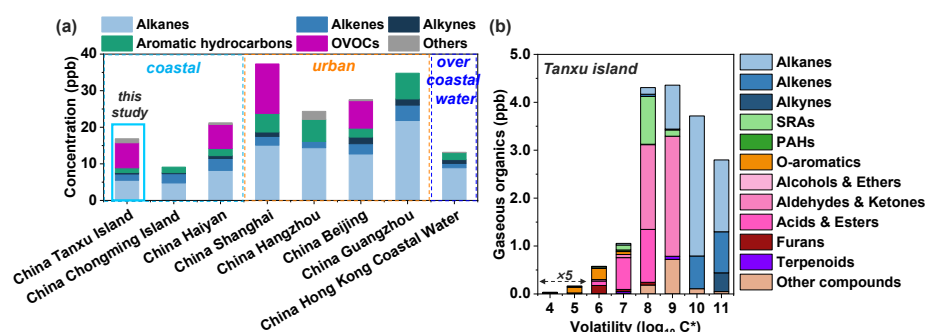
205 3.1 Characterization of Ambient Organic Components

206 The campaign-average concentration of non-refractory aerosol (i.e., the sum of organics,
 207 sulfate, nitrate, ammonium, and chloride) was $5.6 \pm 4.8 \mu\text{g m}^{-3}$ at Tanxu Island, which was
 208 higher than that at the typical marine site of Mace Head ($0.9 \mu\text{g m}^{-3}$) (Chevassus et al., 2025),
 209 but much lower than those at urban sites ($15.0\text{-}18.9 \mu\text{g m}^{-3}$) (**Figure S3**) (Shan et al., 2026;
 210 Zhang et al., 2025; Li et al., 2023; Yin et al., 2023). At Tanxu Island, OA was the dominant
 211 aerosol component, and SOA accounted for about 75% of OA. This high SOA fraction was
 212 broadly consistent with that observed at most sites in **Figure S3**, highlighting the important role
 213 of secondary formation in ambient OA. In contrast to marine and coastal sites in the United
 214 States and Europe, where sulfate dominates, and nitrate remains low (25-46% vs. 2-10%),
 215 Tanxu Island exhibited an elevated nitrate fraction (20%) comparable to those in nearby urban
 216 sites in China, such as Shanghai (20%) and Hangzhou (17%). The NO_x concentration at Tanxu
 217 Island (9.7 ± 5.6 ppb) was also relatively high, about an order of magnitude higher than that at
 218 Crete, Greece (0.5 ppb) (Florou et al., 2024). The high nitrate fraction suggests a significant
 219 influence of continental outflow on aerosol composition at Tanxu Island.

220 Consistent with the aerosol characteristics, gaseous organics at Tanxu Island also showed
 221 relatively low concentrations, with chemical composition being influenced by continental



222 outflow. A comparison of gaseous organics measured by GC-MS, supplemented by PTR-ToF-
 223 MS at some sites, is shown in **Figure 1**. The average concentration of measured gaseous
 224 organics was 16.8 ± 8.2 ppb at Tanxu Island, comparable to that at another coastal site, Haiyan
 225 in Hangzhou Bay (~ 21 ppb) (Xu et al., 2025), but markedly lower than that at urban Shanghai
 226 (~ 43 ppb) (Gao et al., 2025). Most measured compounds were highly volatile and were
 227 classified as VOCs, accounting for 97% of the total concentration (**Figure 1b**). Alkanes (C2-
 228 C8) and oxygenated volatile organics (OVOCs), mainly C1-C6 alcohols and ethers, aldehydes
 229 and ketones, and acids and esters (**Figure S7**), were the most abundant classes. They can
 230 substantially consume OH radicals (Yang et al., 2016; Qu et al., 2021; Qian et al., 2025) but are
 231 expected to make only a low contribution to SOA formation because of their low SOA yields
 232 (**Table S1**). Aromatic hydrocarbons, a well-known class of SOA precursors, had a total
 233 concentration of 1.3 ppb, lower than the concentrations reported at urban sites (2.1-6.0 ppb)
 234 (Liu et al., 2019b; Liu et al., 2020; Zhang et al., 2021b; Qian et al., 2025) but comparable to
 235 those at coastal sites (1.6-2.0 ppb) (Tian et al., 2025; Qian et al., 2025) and over the coastal
 236 waters of Hong Kong (1.9 ppb) (Sun et al., 2024). 32 oxygenated aromatics and 13 furans were
 237 also identified at Tanxu Island. Their photochemical oxidation may also contribute to ambient
 238 SOA due to their considerable OH reactivity and SOA yields (**Table S3**), which favor the
 239 formation of highly oxidized, low-volatility products (Humes et al., 2022; Liang et al., 2024).



240
 241 **Figure 1.** Concentrations of gaseous organic components among different sites during the warm
 242 season, measured by GC-MS and supplemented by PTR-ToF-MS coupled with H_3O^+ chemistry
 243 at some sites (Tian et al., 2025; Liu et al., 2019b; Liu et al., 2020; Zhang et al., 2021b; Sun et
 244 al., 2024; Qian et al., 2025). OVOCs were unavailable at some sites and are therefore not shown.



245 Detailed information can be found in **Table S5**. (b) Concentration distribution of identified
 246 gaseous organics at Tanxu Island as a function of volatility ($\log_{10} C^*$). The calculation method
 247 for effective saturation concentration (C^* , $\mu\text{g m}^{-3}$) is provided in **SI-3**.

248

249 **3.2 Photochemical SOA Production in Coastal Air**

250 SOA production in coastal air at Tanxu Island was investigated using in situ OFR OH
 251 oxidation experiments, with the difference between OA mass concentrations measured after and
 252 before OFR oxidation (hereafter referred to as “SOA enhancement”) used as the quantitative
 253 metric. We found that $\sim 90\%$ RH marked a distinct humidity regime for SOA enhancement
 254 (**Figure S8**). SOA enhancement increased significantly under $\text{RH} > 90\%$, reaching up to $22 \mu\text{g m}^{-3}$
 255 m^{-3} , whereas it remained below $5 \mu\text{g m}^{-3}$ and showed only weak RH dependence under $\text{RH} <$
 256 90% . Accordingly, the OFR experiments were separated into two groups: $\text{RH} < 90\%$ and
 257 $\text{RH} > 90\%$. Experiments with $\text{RH} < 90\%$ represent typical ambient conditions with relatively
 258 weak RH influence, whereas those with $\text{RH} > 90\%$ reflect high-humidity conditions frequently
 259 observed in coastal areas (**Figure S9**).

260 As shown in **Figure 2**, SOA enhancement in both RH conditions first increased and then
 261 decreased with increasing OH_{exp} , and the maximum SOA enhancement ($1.2 \mu\text{g m}^{-3}$ at $\text{RH} < 90\%$
 262 and $3.7 \mu\text{g m}^{-3}$ at $\text{RH} > 90\%$) was observed at an equivalent photochemical age of ~ 3.2 days.
 263 This pattern reflects SOA formation and aging, which has been well established in ambient air
 264 oxidation at multiple sites (Hu et al., 2022; Dou et al., 2025; Ortega et al., 2016; Zhang et al.,
 265 2024b). The initial increase in SOA enhancement was driven by efficient condensation of low-
 266 volatility oxygenated products from precursor oxidation (Jimenez et al., 2009). At higher OH_{exp} ,
 267 intensive oxidation may have increasingly promoted gas-phase fragmentation of oxidation
 268 products before condensation, together with heterogeneous oxidation-induced OA
 269 fragmentation, thereby reducing the SOA enhancement (Ortega et al., 2016; Kroll et al., 2015).
 270 The OH_{exp} at which maximum SOA enhancement occurred at Tanxu Island (~ 3.2 days) was
 271 higher than that at the forest sites (~ 0.7 days), but fell within the range reported for urban sites
 272 (~ 1.5 – 3.9 days). This similarity to urban air suggests that anthropogenic gaseous organic
 273 precursors likely played an important role in SOA formation at Tanxu Island, consistent with

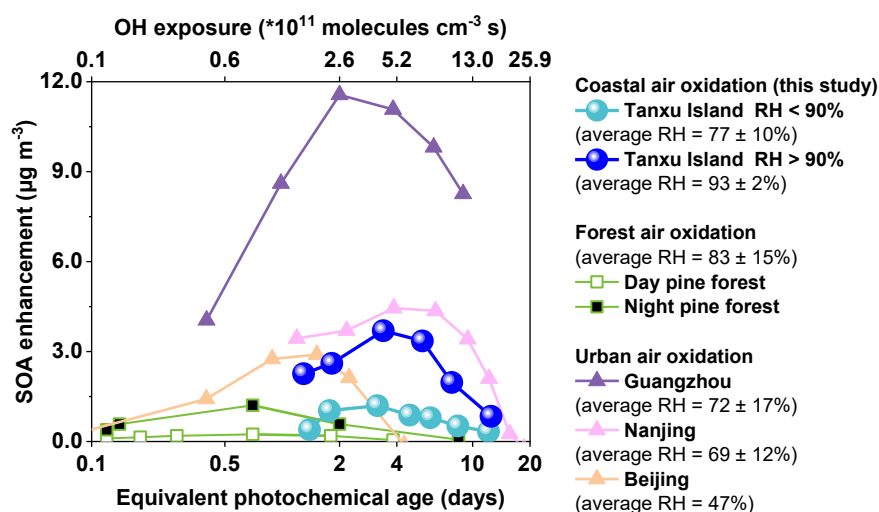


274 the strong influence of continental transport discussed in **Section 3.1**. In contrast, forest sites
275 are typically enriched in biogenic precursors (e.g., monoterpenes at concentrations of 0.1-0.5
276 ppb (Palm et al., 2016)), which react with OH radicals more rapidly than aromatic hydrocarbons
277 and can therefore drive faster SOA accumulation and reach maximum SOA enhancement at
278 relatively low OH_{exp} .

279 At $\text{RH} < 90\%$, SOA enhancement at Tanxu Island was lower than that at urban sites, as
280 expected from the cleaner atmosphere at this coastal site. For example, benzene and toluene at
281 Tanxu Island were 0.13 ppb and 0.35 ppb, whereas their concentrations were 0.7 ppb and 0.7
282 ppb in Beijing (Zhang et al., 2024b), respectively. However, when RH exceeded 90%, the
283 maximum SOA enhancement at Tanxu Island increased substantially and reached $3.7 \mu\text{g m}^{-3}$.
284 This value was approximately 3.1 times that at $\text{RH} < 90\%$ and comparable to the levels observed
285 in summer Beijing (Zhang et al., 2024b) and Nanjing (Dou et al., 2025) (**Figure 2**). During the
286 OFR experiments at Tanxu Island, $\text{RH} > 90\%$ occurred during periods influenced by continental
287 outflow. The higher SOA enhancement at $\text{RH} > 90\%$ was partly attributable to the elevated
288 concentrations of organic precursors. For example, the total concentration of SRAs, PAHs, O-
289 aromatics, furans, and terpenes (i.e., the major precursors identified in **Section 3.3**) was about
290 1.6 times that at $\text{RH} < 90\%$. Notably, after normalization to precursor consumption, maximum
291 SOA enhancement at $\text{RH} > 90\%$ remained 1.8 times that at $\text{RH} < 90\%$ (**Figure S10a**), indicating
292 that precursor abundance alone could not fully account for the observed enhancement and that
293 aqueous-phase processing also played an important role. Aerosol liquid water content at
294 $\text{RH} > 90\%$ exceeded $20 \mu\text{g m}^{-3}$ and was approximately one order of magnitude higher than that
295 at $\text{RH} < 90\%$ (**Figure S10b**), favoring the gas-to-particle partitioning of hydrophilic oxidation
296 products and their subsequent aqueous-phase reactions to form highly oxidized species
297 (Gkatzelis et al., 2021b; Faust et al., 2017; Li et al., 2018). Moreover, at comparable equivalent
298 photochemical ages, SOA at $\text{RH} > 90\%$ exhibited a higher carbon oxidation state (**Figure S10c**),
299 and the aqueous-SOA-related ions $\text{C}_2\text{H}_2\text{O}_2^+$ and CH_2O_2^+ (**Figure S11**) showed greater
300 enhancements than at $\text{RH} < 90\%$, further supporting the important role of aqueous-phase
301 processing (Wang et al., 2024). Overall, the greater SOA enhancement observed during coastal
302 air oxidation at $\text{RH} > 90\%$ highlights the combined effects of continental outflow and aqueous-



303 phase processing in driving SOA pollution in coastal areas.



304

305 **Figure 2.** SOA enhancement from OH oxidation of coastal air (i.e., ambient air at Tanxu Island),
 306 forest air and urban air during the warm season (Hu et al., 2022; Dou et al., 2025; Ortega et al.,
 307 2016; Zhang et al., 2024b). Error bars for the Tanxu Island measurements are provided in
 308 **Figure S12.**

309 3.3 Major Precursor Contributions to SOA Production

310 To assess the contribution of gas-phase OH oxidation of measured precursors to SOA
 311 production in coastal air, an SOA mass closure analysis was conducted by comparing the
 312 estimated SOA production from these precursors with the observed SOA enhancement
 313 downstream of the OFR. To minimize the influences of extensive oxidative aging and aqueous-
 314 phase processing on SOA production (**Section 3.2**), the analysis was restricted to equivalent
 315 photochemical ages <3 days and RH <80% (mean aerosol liquid water content = 2 µg m⁻³).
 316 Overall, the estimated SOA production accounted for approximately 57% of the observed SOA
 317 enhancement (**Figure 3a**). SRAs were the largest precursor class, contributing 23% of SOA
 318 enhancement, mainly through the OH oxidation of m-/p-xylene, toluene, ethylbenzene, benzene,
 319 and o-xylene (**Figure S13a**). This is consistent with previous urban air oxidation studies, which
 320 also identified SRAs as important SOA precursors (Hu et al., 2022; Dou et al., 2025; Zhang et
 321 al., 2024b). PAHs and terpenes accounted for 4% and 2%, respectively. Notably, O-aromatics



accounted for 18% of the SOA enhancement, approaching the contribution from SRAs. Major compounds in this group included phenol, benzenediols, benzoquinone, hydroxybenzoquinone, and benzofuran (**Figure S13b**). Furans also contributed 6%, highlighting their non-negligible role as SOA precursors. The importance of O-aromatics and furans is also supported by observations in urban Shanghai, where oxygenated VOCs, mainly including O-aromatics, furans, and carbonyls, were estimated to account for a larger fraction of the summed theoretical SOA formation potential of the measured precursors than SRAs (22% vs. 19%) (Gao et al., 2025). Note that the Shanghai study estimated only the theoretical SOA formation potential of the measured precursors (Gao et al., 2025). In contrast, oxidation of ambient air in this study experimentally quantified SOA enhancement, providing direct evidence for the importance of O-aromatics and furans in ambient SOA production. Highly volatile compounds, including alkanes, alkenes, and aldehydes/ketones, made little contribution to SOA enhancement (**Figure 3a**) despite their dominant atmospheric concentrations (**Figure 3b**).

Apparent SOA yields were derived as the ratio of SOA enhancement upon OFR oxidation to the consumed concentrations of major SOA precursors, including SRAs, PAHs, O-aromatics, furans, and terpenes. As shown in **Figure 3c**, apparent SOA yields of coastal air at Tanxu Island increased with OA mass concentration, consistent with the behavior of typical SOA precursors such as isoprene (Liu et al., 2016), benzene (Ng et al., 2007), and naphthalene (Ma et al., 2017). These results suggest that ambient OA may be an important factor influencing SOA production, consistent with absorptive gas-particle partitioning theory, whereby OA provides an absorptive phase that promotes the partitioning of oxidation products (Odum et al., 1996). This OA-loading effect may have implications for SOA production when coastal air recirculates toward nearby cities under sea-breeze conditions. Shanghai, a coastal city near Tanxu Island, serves as a relevant example. Previous studies have suggested that coastal-air recirculation can aggravate PM_{2.5} pollution in Shanghai (Zhou et al., 2019), and southeasterly coastal regions were also identified as potential source areas for summertime SOA in Shanghai (**Figure S14**). At the campaign-average wind speed of 2.0 m s⁻¹, air transported from Tanxu Island could reach Shanghai within approximately 10 h, suggesting that it may retain the capacity for further SOA formation. Based on the fitted apparent SOA yield curve for coastal air in **Figure 3c**, the



apparent SOA yield estimated at the average OA loading in Shanghai ($6.6 \mu\text{g m}^{-3}$) (Yin et al., 2023) was approximately twice the campaign-average value at Tanxu Island under $\text{RH} < 90\%$. This illustrative comparison suggests that higher OA loading in Shanghai may favor additional SOA production in recirculated coastal air, potentially aggravating urban SOA pollution. Given that sea-land breezes are prevalent during summer (Shen et al., 2019; Huang et al., 2025b), coastal SOA formation and recirculation should be considered in air-quality assessment and forecasting in coastal cities. Further studies combining atmospheric transport and chemical models are needed to quantify this contribution.

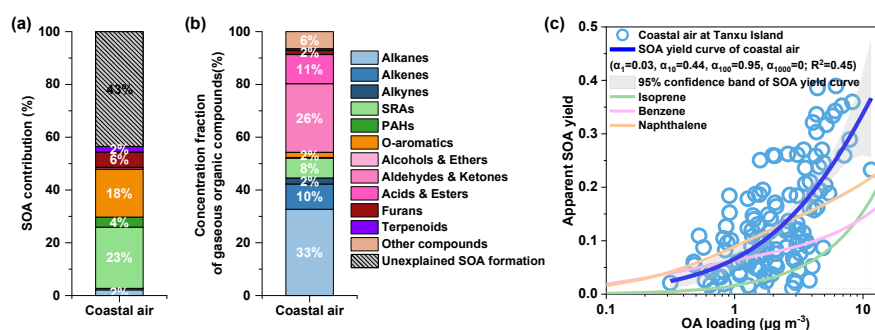


Figure 3. (a) Estimated contributions of gas-phase OH oxidation of identified gaseous organic compound categories to the measured SOA enhancement at equivalent photochemical ages < 3 days and $\text{RH} < 80\%$; (b) their fractions of the total concentration of identified gaseous organic compounds; and (c) the apparent SOA yield of coastal air at Tanxu Island under $\text{RH} < 90\%$, based on OFR experiments at equivalent photochemical ages < 3 days and fitted using the VBS model. Here, “coastal air” refers to ambient air at Tanxu Island, regardless of air-mass origin.

3.4 Contrasting SOA Production from Marine and Continental Air Masses

Tanxu Island, alternately influenced by continental and marine air masses, provides a natural setting for comparing SOA production under the two air-mass regimes. Based on hourly back-trajectory analysis, periods influenced by marine and continental air masses were selected. Details of the classification are provided in SI-2. Under $\text{RH} < 90\%$ conditions, upon OH oxidation, continental air masses exhibited a maximum SOA enhancement of $1.85 \mu\text{g m}^{-3}$, about 3.5 times that of marine air masses ($0.53 \mu\text{g m}^{-3}$), as shown in Figure S15b. This is expected, as the concentrations of gaseous organics associated with marine air masses (11.4 ppb) were



374 much lower than those associated with continental air masses (21.7 ppb), especially for
375 aromatic compounds (**Figures 4a and S17**). For example, toluene reached 0.65 ppb in
376 continental air masses, more than 20 times that in marine air masses (0.03 ppb). In contrast,
377 marine air masses were enriched in low-molecular-weight OVOCs that have extremely low
378 SOA yields. Acetone, formaldehyde, and acetaldehyde remained at comparable levels in marine
379 air masses (1.5, 1.3, and 1.2 ppb, respectively) and continental air masses (1.1, 1.6, and 1.1 ppb,
380 respectively). In addition to VOCs, ambient OA loading also influenced SOA production, as
381 shown in **Figure S17**. Only continental air masses reached higher OA levels ($\text{OA} > 2 \mu\text{g m}^{-3}$),
382 under which apparent SOA yields continued to increase, whereas marine air masses were
383 mostly limited to low OA conditions.

384 SOA production from the gas-phase OH oxidation of detected precursors was estimated
385 for marine and continental air masses using the same analytical approach as in **Section 3.3**, and
386 the results are shown in **Figure 4b**. The unexplained fraction of the measured SOA
387 enhancement was greater for continental air masses (49%) than for marine air masses (35%),
388 suggesting a greater compositional complexity of SOA precursors associated with continental
389 emissions. Because this analysis focused primarily on conventionally measured gas-phase
390 organic compounds (mainly VOCs), it inevitably overlooked some potentially SOA precursors,
391 including I/SVOCs and unidentified compounds. Long-chain alkanes (C₈-C₂₀) are important
392 anthropogenic SOA precursors (Gao et al., 2025; Huang et al., 2024) and have been reported to
393 contribute 8-20% of SOA production in urban air oxidation in downtown Guangzhou (Hu et al.,
394 2022). The lack of long-chain alkane measurements may partly explain the larger SOA closure
395 gap for continental air masses. VCPs may also represent an important missing source of SOA
396 precursors, as their total SOA production in urban areas has been reported to exceed that from
397 vehicular emissions (Shah et al., 2020). Another source of uncertainty arises from interactions
398 among oxidation products in mixed-precursor systems. These interactions may either suppress
399 or enhance SOA production (Takeuchi et al., 2022; Li et al., 2021), but were not accounted for
400 in this study when estimating precursor contributions to SOA production. Nevertheless, our
401 results indicate that the currently resolved gaseous species can explain a substantial fraction of
402 the SOA produced, especially for marine air masses.

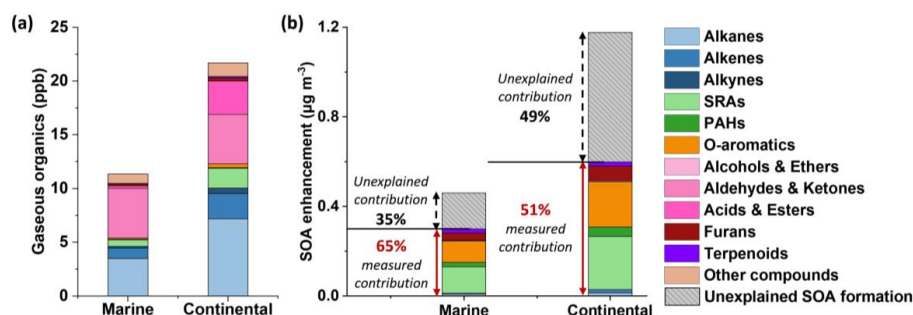


Figure 4. Comparison of marine and continental air masses, including (a) concentration of identified compound categories, and (b) measured SOA enhancement and the estimated contributions from the gas-phase OH oxidation of identified SOA precursors at equivalent photochemical ages <3 days and RH <80%

4. Conclusions and implications

This study quantitatively characterized the SOA production of coastal air under varying ambient conditions, including OH_{exp} , RH, precursors, OA loading, and air-mass type, through in situ OFR photochemical oxidation experiments at Tanxu Island. In addition to typical aromatic hydrocarbons, O-aromatics and furans were found to make nonnegligible contributions to ambient SOA production, indicating that attention should also be given to their sources and atmospheric oxidation. O-aromatics, in particular, may originate in part from the oxidation of aromatic hydrocarbons (Gao et al., 2025), highlighting the important role of multigenerational oxidation in contributing to SOA production. The larger SOA mass closure gap in continental than in marine air masses may reflect contributions from unmeasured anthropogenic precursors. VCP emissions represent one potential source of such precursors and should be further investigated, given their increasing contribution to VOC emissions as traffic and industrial emissions have declined in many regions (He et al., 2026; McDonald et al., 2018). Routine atmospheric measurements and future emission regulations should therefore include a broader range of gaseous organics. Particular attention should be paid to identifying emerging SOA precursors through ambient observations and laboratory experiments that constrain their atmospheric abundances, reaction kinetics, and SOA yields. Such efforts are important not only



426 for improving the mass closure between modeled and observed urban aerosol levels, but also
427 for advancing the understanding of SOA pollution in coastal regions influenced by continental
428 outflow.

429 Ambient OA loading can influence the SOA production of coastal air. The apparent SOA
430 yield curve derived as a function of OA concentration may provide a preliminary reference for
431 estimating SOA production in coastal regions where in situ OFR experiments are unavailable.
432 More in situ OFR experiments should be conducted across diverse coastal environments to
433 establish more comprehensive apparent SOA yield parameterizations and improve our
434 understanding of coastal SOA pollution. Moreover, extremely humid conditions ($RH > 90\%$)
435 significantly increased SOA production in coastal air to levels comparable to those reported for
436 urban areas. The effects of OA loading and high humidity revealed in this study have
437 implications for a better understanding of air pollution in coastal cities. Upon recirculation into
438 nearby urban areas, SOA production in coastal air may be further enhanced under higher urban
439 OA loadings. Given the frequent occurrence of daytime sea breezes in summer (Shen et al.,
440 2019; Huang et al., 2025b), the potential impact of coastal air and associated SOA formation
441 on the downwind urban air quality warrants greater attention and further investigation.



442 **Data availability**

443 The data used in this publication are available to the community and can be accessed by request
444 to the corresponding author.

445 **Supplement**

446 The supplement related to this article is available online at

447 **Author contributions**

448 RJH and DDH designed the study. YNZ performed the data analysis and interpretation, with
449 contribution from RJH, DDH, YQG, QYL and LLZ. YNZ, YQG, SJ, JP, YJL, JTH, YS
450 conducted the field sampling and experiments. YNZ, RJH and DDH wrote the manuscript, HBZ,
451 WX, JD, TW, YJL, CH, HLW and QYF provided guidance on the research design and
452 contributed to the interpretation of results. All authors contributed to scientific discussions and
453 revision of the manuscript.

454 **Competing interests**

455 The contact author has declared that none of the authors has any competing interests.

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