



HAL
open science

Evaluating major anthropogenic VOC emission sources in densely populated Vietnamese cities.

Pamela A Dominutti, James R Hopkins, Marvin Shaw, Graham P Mills, Hoang Anh Le, Duong Huu Huy, Grant L Forster, Sekou Keita, To Thi Hien, David E Oram

► To cite this version:

Pamela A Dominutti, James R Hopkins, Marvin Shaw, Graham P Mills, Hoang Anh Le, et al.. Evaluating major anthropogenic VOC emission sources in densely populated Vietnamese cities.. *Environmental Pollution*, 2023, 318, pp.120927. <10.1016/j.envpol.2022.120927>. <hal-03912788>

HAL Id: hal-03912788

<https://hal.science/hal-03912788v1>

Submitted on 23 Jul 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

1 Evaluating major anthropogenic VOC emission sources in densely
2 populated Vietnamese cities.

3 Pamela A. Dominutti^{1a*}, James R. Hopkins^{1,2}, Marvin Shaw^{1,2}, Graham P. Mills³, Hoang Anh Le⁴,
4 Duong Huu Huy⁵, Grant L. Forster^{3,6}, Sekou Keita⁷, To Thi Hien^{8,9}, and David E. Oram^{3,6}

5
6 ¹ Wolfson Atmospheric Chemistry Laboratories, Department of Chemistry, University of York, York, YO10
7 5DD, United Kingdom.

8 ² National Centre for Atmospheric Science, University of York, York, YO10 5DD, UK

9 ³ Centre for Ocean and Atmospheric Science, School of Environmental Sciences, University of East Anglia,
10 Norwich, UK

11 ⁴ Faculty of Environmental Sciences, University of Science, Vietnam National University, Hanoi, Vietnam

12 ⁵ Faculty of Food Science and Technology, Ho Chi Minh City University of Food Industry, Ho Chi Minh City,
13 Vietnam

14 ⁶ National Centre for Atmospheric Science, School of Environmental Sciences, University of East Anglia,
15 Norwich, United Kingdom

16 ⁷ Département Mathématiques-Physique-Chimie, Université Peleforo Gon Coulibaly, BP 1328 Korhogo, Côte
17 d'Ivoire

18 ⁸ Faculty of Environment, University of Science, Ho Chi Minh City, Vietnam

19 ⁹ Vietnam National University, Ho Chi Minh City, Vietnam

20 ^a Now at: Université Grenoble Alpes, CNRS, IRD, INP-G, Institut des Géosciences de l'Environnement (UMR
21 5001), 38400 Grenoble, France

22

23 * **Corresponding author:** *Pamela Dominutti* (pamela.dominutti@univ-grenoble-alpes.fr)

24

25 **Abstract**

26 Volatile organic compounds (VOCs) play an important role in urban air pollution, both as primary pollutants
27 and through their contribution to the formation of secondary pollutants, such as tropospheric ozone and
28 secondary organic aerosols. In this study, more than 30 VOC species were continuously monitored in the two
29 most populous cities in Vietnam, namely Ho Chi Minh City (HCMC, September-October 2018 and March
30 2019) and Hanoi (March 2019). In parallel with ambient VOC sampling, grab sampling was used to target the
31 most prevalent regional-specific emission sources and estimate their emission factors (EFs).

32 Emission ratios (ERs) obtained from ambient sampling were compared between Vietnamese cities and other
33 cities across the globe. No significant differences were observed between HCMC and Hanoi, suggesting the
34 presence of similar sources. Moreover, a good global agreement was obtained in the spatial comparison within
35 a factor of 2, with greater ER for aromatics and pentanes obtained in the Vietnamese cities.

36 The detailed analysis of sources included the evaluation of EF from passenger cars, buses, trucks, motorcycles,
37 3-wheeled motorcycles, waste burning, and coal-burning emissions. Our comparisons between ambient and
38 near-source concentration profiles show that road transport sources are the main contributors to VOC
39 concentrations in Vietnamese cities.

40 VOC emissions were calculated from measured EF and consumption data available in Hanoi and compared
41 with those estimated by a global emission inventory (EDGAR v4.3.2). The total VOC emissions from the road
42 transport sector estimated by the inventory do not agree with those calculated from our observations which
43 showed higher total emissions by a factor of 3. Furthermore, the inventory misrepresented the VOCs
44 speciation, mainly for isoprene, monoterpenes, aromatics, and oxygenated compounds. Accounting for these
45 differences in regional air quality models would lead to improved predictions of their impacts and help to
46 prioritise pollution reduction strategies in the region.

47

48 **Keywords:** emission ratios, regional emission sources, global inventories, Southeast Asia

49

1. Introduction

The World Health Organization (WHO) defines poor air quality as the most significant single environmental health risk and attributed 4.2 million deaths to ambient air pollution exposure in 2021 (WHO, 2021). 75 % of those air pollution-related deaths occur in low-middle income countries, such as those in Asia (Lelieveld et al., 2018).

Among the various pollutants present in the troposphere, volatile organic compounds (VOCs) play a crucial role in urban air pollution and include a large number of species. Although VOCs can be emitted from both anthropogenic and biogenic sources, the former is the primary source in urban areas. Once released into the atmosphere, VOCs can undergo several chemical reactions (oxidation) due mainly to the hydroxyl radical ($\cdot\text{OH}$) and ozone during the day and with the nitrate radical at night. This leads to the formation of secondary oxygenated VOCs (OVOC) (Atkinson, 2000; Goldstein and Galbally, 2007), tropospheric ozone (Seinfeld and Pandis, 2006), and secondary organic aerosols (Fuzzi et al., 2006; Hester and Harrison, 1995; Kopppmann, 2007).

Many primary pollutants are known to be decreasing in urban areas in the northern mid-latitudes, including those related to vehicle emissions (Uherek et al., 2010). For example, some studies have shown a decrease in VOC and carbon monoxide (CO) concentrations by almost two orders of magnitude over the past five decades in Los Angeles (Warneke et al., 2012), USA. In the United Kingdom, long-term measurements also show significant decreases for VOC and CO (up to 26 % and 12 %, respectively (von Schneidemesser et al., 2010), a downward trend that is also reflected in emission inventories (EIs). Figure S1 shows the total annual anthropogenic VOC emissions estimated in the Emissions Database for Global Atmospheric Research (EDGARv4.3.2 global inventory https://edgar.jrc.ec.europa.eu/dataset_ap432_VOC_spec, Huang et al., 2017). According to the inventory, total VOC emissions have decreased significantly over the past 40 years in the United States and Europe, with totals of 7 and 10 Tg yr⁻¹, respectively, in 2012. In developing countries, however, VOC emissions have been steadily increasing over that time period, with the Southeast Asia (SEA) region reaching up to 8 Tg yr⁻¹ in 2012, surpassing those from Europe.

Accurately quantifying the spatial and temporal distribution of emissions is a challenge, even more so in the developing world (e.g., SEA region), where ambient measurements and local emissions data are scarce. EIs in these regions typically combine bottom-up and top-down approaches to estimate emissions, using emission factors (EFs) from northern mid-latitudes countries (such as the European Environment Agency - European Monitoring and Assessment Programme (EMEP/EEA)), together with any regional or national activity data. In consequence, uncertainties from many data sources are aggregated in the overall estimation of the magnitude and speciation of emission. Several studies have reported emission inventory (EI) assessment in developed countries using ground or aircraft-based measurements of ambient pollutants (Borbon et al., 2013; Kim et al., 2011; Wilde et al., 2021). For example, urban emission ratios (ERs) of various VOCs to a combustion tracer (CO, acetylene) are commonly used to constrain and assess regional EIs in urban areas (Borbon et al., 2013, 2022; Coll et al., 2010; Warneke et al., 2007). Recent studies reveal significant discrepancies when contrasting

86 observations and inventories of VOC emissions, by several orders of magnitudes mainly for the road
87 transportation sector (Borbon et al., 2013; Dominutti et al., 2019; Salameh et al., 2016a; Thera et al., 2019).
88 Furthermore, the misrepresentation of VOCs speciation in global inventories was also revealed when
89 compared with in-situ observations, as in the case of Sao Paulo, Brazil (Dominutti et al., 2020).

90 Vietnam is one of the fastest-growing economies in the SEA, and the country has undergone rapid population
91 growth, with more than 96 million inhabitants in 2019 (General Statistics Office, 2020; General Statistics
92 Office of Vietnam, 2020). Such rapid growth has led to the deterioration of air quality, with exposure to
93 ambient air pollution being one of Vietnam's most important unknown public health risks (Phung et al., 2016).
94 However, short-term studies conducted in Vietnam have shown that vehicular emissions, biomass burning, and
95 secondary formation processes are important sources of fine particulate matter (PM_{2.5}) and other pollutants
96 (Hai and Kim Oanh, 2013; Hang et al., 2014; Hien et al., 2019). Indeed, the transport sector is still increasing,
97 with motorcycles accounting for 86% of the total vehicle fleet in the country. Ho Chi Minh City (HCMC) and
98 Hanoi are the most densely populated cities in Vietnam, with an estimated 9 and 8 million inhabitants in 2019,
99 respectively (General Statistics Office, 2020). Hanoi, the capital of Vietnam, typically experiences several air
100 pollution episodes each year. Recent studies in HCMC have also shown poor air quality and PM
101 concentrations surpassing the WHO air quality recommendations (Hien et al., 2019).

102 Despite the potential impacts of air pollution in Vietnam, a limited number of studies have conducted long-
103 term air quality or emission source measurements to better tackle air pollution and its related health effects.
104 Although some inventories have been developed at local and regional scales in Vietnam, their uncertainties are
105 unknown, and the speciation of VOCs is generally not taken into account (Ho and Clappier, 2011; Trang et al.,
106 2015; Tung et al., 2011). The paucity of observations in the SEA region is an important limitation when it
107 comes to developing accurate EIs. Therefore, *in-situ* observations can be a powerful tool to help improve EIs
108 that consider the specificity of regional emission sources. Furthermore, a better understanding of emission
109 sources and air pollutants also provides direct indications of population exposure to air pollution and valuable
110 information for policymakers in developing abatement policies.

111 Herein we present our findings from the “A Two City study of Air Quality in Vietnam” project that took place
112 in the two most densely populated cities in Vietnam. We evaluate urban VOC emission sources using detailed
113 *in-situ* observations comprising comprehensive near-source and ambient VOC measurements at urban sites.

114 2. Materials and methods

115 Intensive field campaigns were conducted in 2018 and 2019 in Hanoi and HCMC. The main purpose of the
116 project was to better understand the key drivers for air pollution under different synoptic conditions and how
117 they are affected by different types of longer-range transportation of pollutants.

118 Hanoi, located in the north of Vietnam, is the country's second-largest city in terms of economy and
119 population (Fig 1). It has a warm and humid subtropical climate with four distinct seasons (Nguyen, 2009).
120 The month of March (sample period) is generally cloudy and hazy, with an average of about 1.5 hours of

121 clear-sky sunshine per day (Hien et al., 2022). HCMC, located in the south of Vietnam (Fig 1), generally
122 experiences more solar irradiance throughout the year. It has two distinct seasons, a dry season from
123 December to April and a wet season from May to November (Nguyen, 2009) with an average of 7.7 and 5.3
124 hours per day clear-sky conditions, respectively (Hien et al., 2022).

125

126 **2.1 Sampling strategy**

127 Online VOC observations were made from roof top locations in Hanoi and HCMC and are described in detail
128 by Hien et al. (2021). Both sampling locations were near busy highways that experienced a large volume of
129 light and heavy-duty vehicle traffic (Figure 1). Intensive field campaigns were carried out in HCMC in
130 September-October 2018 (Hien et al., 2022) and simultaneously in both cities in March 2019. In Hanoi, direct
131 source emission measurements were also carried out to obtain VOC emission profiles from selected sources.
132 The study targeted the main anthropogenic sources in the city and are thought to be representative of other
133 urban locations in Vietnam.

134

135 **2.2 Online ambient measurements**

136 A detailed description of the on-line observations of VOCs are included in Hien et al. (2021). Briefly, VOCs
137 in Hanoi were measured using an online dual-channel Gas Chromatograph coupled with Flame Ionization
138 Detection (DC-GC-FID, Agilent 7890) and a Selected-Ion Flow-Tube – Mass Spectrometer (SIFT-MS Voice
139 2000). A total of 40 compounds (some of them grouped into similar families, i.e. monoterpenes, C₈ and C₉
140 aromatics) were reported and shown in table S2 of the Supplementary Information. A similar setup was
141 deployed in HCMC, where a dual GC-FID and a Proton Transfer Reaction – Mass Spectrometer (PTR-MS)
142 were used to measure more than 30 VOCs. Concurrent observations of carbon monoxide (CO) and ozone
143 concentrations were made to support VOCs data analysis and their interpretation. More details can be found in
144 the Supplementary Information. In this work, we revisited and reanalysed the ambient VOC data obtained in
145 Hanoi and HCMC (Hien et al., 2022) together with source emissions measurements performed in Hanoi.

146

147 **2.3 Source emission measurements**

148 Direct source emission measurements were carried out to obtain VOC emission profiles from Hanoi's main
149 anthropogenic sources. Samples were collected using 1.2-liter evacuated canisters (dual-valve electropolished
150 stainless-steel canisters) and later analyzed using the DC-GC-FID described in section 2.2 to quantify up to
151 thirty-eight VOC species (including eleven alkanes, eight alkenes (including isoprene), eight aromatics, eight
152 terpenes, and acetylene). All the canister samples were analysed within a day of their collection to assure the
153 preservation and stability of VOCs measured.

154 Measurements of CO and carbon dioxide (CO₂) were simultaneously made at the emission sources using a
155 QTRAK-7575 sensor (TSI) (Keita et al., 2018). The instrument relies on an electrochemical sensor with a

156 range between 0.1 and 500 ppm for the CO measurements with an accuracy of $\pm 3\%$. CO₂ concentrations were
157 obtained using a non-dispersive infrared detector ranging between 0.1 and 5000 ppm (accuracy of $\pm 3\%$). The
158 sensor was calibrated in the laboratory before each emission measurement using a cylinder of ambient air and
159 following the procedures detailed in a previous study (Keita et al., 2018). The CO and CO₂ concentrations
160 obtained were used to estimate EF from different samples and sources.

161 Emission sources were targeted to investigate emissions from the road transportation sector and domestic
162 waste combustion, coal burning, and cook fuel burning emissions considering the specific practices in the SEA
163 (Cao et al., 2016, Hai and Kim Oanh, 2013; Hang et al., 2014; Hien et al., 2019, Sakamoto et al., 2018) (Table
164 S1). The samples were obtained in emission plumes, approximately 1 m from the source.

165 • Road transportation: The most common vehicle types were chosen for investigation: heavy-duty vehicles
166 (diesel vehicles including trucks and public buses - five samples); light-duty vehicles (two samples of each
167 diesel and non-diesel cars); three-wheeled motorcycles (3W, three samples); and four-stroke motorcycles (4S
168 motorcycles, five samples). Differences in fuel type (petrol, ethanol content, and diesel) and fleet age were
169 also considered. All transport-related samples were taken while the vehicle engine was idling.

170 • Waste burning (WB): samples were obtained near the road in spontaneous fires ignited by locals (two
171 samples). Sampling was carried out within the waste combustion plume integrating the different combustion
172 processes involved.

173 • Charcoal burning (CB) is a common cooking practice, from morning until late evening, at food stalls in
174 Hanoi and other Vietnamese urban areas. The samples were collected within the smoke plume of the food
175 stands.

176 **2.4 Data analysis**

177 **2.4.1 Calculation of emission ratios**

178 To establish VOC enhancement emission ratios from ambient measurements (referred to as ER in this work),
179 the chemical removal of reactive compounds must be considered. The VOC enhancement ER refers to the
180 ratio of a selected VOC to a vehicular tracer compound (CO or acetylene) in fresh emissions without
181 undergoing photochemical processing. Air masses reaching the sampling site contain emissions from various
182 sources. Those close to the sampling site will be dominated by primary emissions and therefore suitable for
183 ER calculations, while other sources, further away, may have had sufficient time for chemical processing to
184 have occurred which could perturb the ER calculation.

185 CO and acetylene (C₂H₂) are combustion tracers commonly used in the literature (Borbon et al., 2013;
186 Dominutti et al., 2020; Salameh et al., 2016b; Warneke et al., 2007) due to their relatively low reactivity in the
187 atmosphere ($k_{OH} = 1.4 \times 10^{-13} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ and $0.90 \times 10^{-12} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ respectively) (Atkinson
188 and Arey, 2003). Overall, we found better correlation coefficients for VOC versus C₂H₂ (Figure S4c, S5c, and
189 S6c). Nevertheless, we used both tracers to ensure rigor of the calculations and because ratios to CO are most

190 regularly reported in the literature for urban and traffic emissions (Borbon et al., 2013; Dominutti et al., 2020;
191 de Gouw et al., 2017; Salameh et al., 2016b; Simpson et al., 2014b; Thera et al., 2019; Wang et al., 2014),
192 which provide valuable constraints for further comparisons.

193 A commonly applied method to determine these ratios is the Linear Regression Fit (LRF) which uses the slope
194 of the scatter plot between a selected VOC and a tracer (Dominutti et al., 2020; Warneke et al., 2007). To
195 evaluate the effects of chemical transformation on the observations, the scatterplots are coloured by morning
196 and nighttime ambient measurements. In cases where photochemistry is sufficient to perturb the correlation,
197 we would expect to see differences between those periods since photochemistry will be more prevalent during
198 the daytime (Borbon et al., 2013; de Gouw et al., 2017). No significant difference was observed between the
199 nighttime and daytime VOC data (Figure S2) which suggests photochemistry does not affect the data
200 presented here. This is further supported by the strong correlation between benzene and 1,2,4-trimethyl
201 benzene. These compounds are known to be co-emitted by urban sources, but have vastly different lifetimes
202 in the atmosphere (k_{OH} (benzene) = 1.4×10^{-12} cm³ molecule⁻¹ s⁻¹, k_{OH} (124-TMB) = 33×10^{-12} cm³
203 molecule⁻¹ s⁻¹). If chemical processing were impacting the data then we would expect to see a more rapid
204 decrease in 1,2,4-trimethyl benzene and a curvature in the scatter plot. These results indicate that the distance
205 and time between the primary emission and sampling point are short enough for the chemical processing of
206 VOCs in both cities to be insignificant and would not affect the ER calculations.

207 Consequently, we applied the LRF method to all the data obtained without filtering to determine enhancement
208 ER. Good correlations were also obtained between CO and acetylene at both sites, suggesting their emission
209 from similar sources (Figure S2). Thus, enhancement ERs were calculated as parts per billion by volume
210 (ppbv) of VOC per parts per million by volume (ppmv) of CO and per ppbv of C₂H₂ (Table S2).

211 2.4.2 Calculation of emission factors

212 The EFs were estimated from the concentrations measured from all the emission sources. EFs can be
213 determined using the carbon balance method (Ferek et al., 1998; Keita et al., 2018; Radke et al., 1991; Ward
214 and Radke, 1993). The amount of carbon emitted into the atmosphere from each source allows an estimate of
215 the amount of fuel burned during the combustion processes. As a result, EFs are obtained using the method
216 developed by Keita et al. (2018) as follows:

$$217 \quad EF(VOC) = \frac{\frac{\Delta VOC}{\Delta CO + \Delta CO_2} \times MW_{VOC}}{12} \times fc \times 10^3 \quad (1)$$

218 where EF (VOC) is the specific emission factor of the VOC in gram per kilogram of burned fuel (g kg⁻¹);
219 $\Delta VOC = [VOC]$ emission – $[VOC]$ background are the mixing ratio of the VOC in the emission and
220 background atmosphere, respectively, in ppbv, MW_{VOC} represents the molar weight of each specific VOC (in g
221 mol⁻¹), 12 denotes the molar weight of carbon (g mol⁻¹), and fc is the carbon mass fraction in the fuel
222 responsible for emissions, which were obtained from the literature and applied to each source (Ban-Weiss et
223 al., 2010; IEA-AMF, 2019; Keita et al., 2018; Lundin et al., 2013). Thus, EFs for each VOC specific to each

224 emission source were estimated using equation (1). In order to obtain total VOC emissions, the equivalent
225 vehicular fleet was calculated by integrating the differences in fuel type, fleet age, and distribution. The
226 average VOC EFs are detailed in Table S3.

227 For the road transport sector, the average equivalent fleet was calculated considering the fleet characteristics in
228 Hanoi and Vietnam. For example, in Hanoi, 96% of the total fleet comprises light-duty vehicles, 89% is
229 composed of motorcycles (General Statistics Office, 2020). Fuel types and vehicle standards in Vietnam have
230 changed over the past decade. For example, in 2017, new cars and motorcycles had to meet the EURO 4 and
231 EURO 3 standards, respectively (Huu and Ngoc, 2021; Le and Yang, 2022; Vietnam, 2011). Most of these
232 motorcycles are four-stroke engines, but only 6% are equipped with catalysts (Ly et al., 2020a), and 35% of
233 the vehicle fleet did not meet any EURO standard (Kim Oanh et al., 2012). A similar vehicular fleet
234 composition is reported at the national level, with a dominant fraction of motorcycles accounting for around
235 90% of the fleet. Octane rating (RON, research octane number) measures the fuel's ability to withstand an
236 explosion caused by its premature combustion in the combustion chamber. Aromatic compounds like benzene
237 are added to gasoline to meet the required octane rating, limited to 2.5% in 2017 by a Vietnamese government
238 regulation (Vietnam, 2009).

239 In 2015, Hanoi introduced the 5% ethanol-blended gasoline, E5 RON 92, which replaced the RON 92 in 2018.
240 After the conversion, consumers gradually adopted this fuel, bringing the E5 RON 92 gasoline usage rate up to
241 45% of total gasoline consumption in Hanoi (PVOIL, 2018). However, this consumption percentage dropped
242 to 38% in 2019 due to its higher prices than RON 95 (Evnexpress, 2019).

243 **2.4.3 Comparison with a global emission inventory**

244 We estimate the total annual emission of thirty-eight VOCs from the EF obtained near sources in Hanoi.
245 Additionally, the EFs were crossed with the activity data available from International Energy Agency (IEA)
246 for the different sources in Vietnam. The total emission obtained from our estimations was then compared to
247 the global VOC inventory, EDGAR v4.3.2 (<http://edgar.jrc.ec.europa.eu/>, last accessed 15/05/2022). For
248 comparison purposes, VOC species were aggregated into fifteen VOC families (VOC2 to VOC16), as detailed
249 in the inventory. The VOCs emissions related to Hanoi urban area integrate 7 points of the inventory grid,
250 covering a spatial resolution of 0.1° x 0.1° each (EDGAR database, Huang et al., 2017). Finally, our total
251 VOC and VOC group estimations from the road transport sector are compared to the annual total VOC
252 emissions provided by the EDGAR inventory for Hanoi.

253 **3. Results and discussion**

254 **3.1 VOC concentrations in Vietnam**

255 The mixing ratios of different VOC species measured in both Vietnamese cities are discussed in a recently
256 published article (Hien et al., 2022), where the VOC profiles in both cities were dominated by alkanes (31–
257 35%) and OVOCs (27–33%), followed by alkenes (13–17%) and aromatics (12–19%) in similar proportion.

258 Even though a similar contribution of VOC groups has been found during sampling periods and cities,
259 significant differences were observed in the mixing ratios measured at HCMC during the two sampling
260 periods (Figure S5a, S6a). Average VOC mixing ratios, nighttime (22:00–5:00 LT), and daytime (10:00–18:00
261 LT) levels measured at Hanoi (2019) and HCMC (2019) and HCMC (2018) are presented in the SI (Figures
262 S4a, S5a, and S6a respectively). Hanoi's highest average mixing ratios were obtained for OVOCs (ethanol and
263 methanol), C₆–C₉ aromatics, i-pentane, C₅-alkenes, and acetylene. The highest average mixing ratios in
264 HCMC were observed for C₇–C₉ aromatics, i-pentane, and C₂–C₄ alkenes. OVOCs also presented high
265 concentrations, particularly during 2018 measurements. Generally, greater concentrations were observed
266 during the rainy season at HCMC (2018, Figure S6). These differences indicate that local meteorology and
267 regional dynamics impact air pollution in HCMC. The concentration ratios between daytime and nighttime
268 averages give a good idea about emission sources and atmospheric photochemical processing (Figure S4b,
269 S5b, S6b). As can be seen, higher concentration ratios (by a factor of 1.5 or more) were observed for traffic-
270 related VOCs such as heavy alkanes (C₇–C₈), ethene, propene, 1,3-butadiene, acetylene, C₈- and C₉-aromatics
271 (also SIFT-MS m/z 107 and m/z 121) at Hanoi. A similar profile was also detected in HCMC in 2019, with
272 higher diurnal concentrations of alkenes and aromatics. The main differences between the cities are related to
273 the OVOC concentration ratios, which presented higher diurnal values at HCMC for methanol (PTR-MS m/z
274 33), acetaldehyde (m/z 45), and acetone (m/z 59). The concentration ratios observed in HCMC in 2018
275 showed a similar profile with a higher contribution of the same species except for toluene and methanol;
276 however, day-to-night ratios were lower than those observed in 2019. These concentration ratios suggest
277 higher VOC emissions during the day being offset by a deeper mixing layer compared to nighttime, resulting
278 in relatively constant mixing ratios between day and night.

279 Isoprene was much higher during the day at HCMC because its biogenic emissions are light- and temperature-
280 dependent. This result is also observed for the mixing ratios of isoprene-oxidation products (MVK+MACR,
281 m/z71), which also presented a higher contribution during daytime at HCMC. Substantial seasonal differences
282 are observed in HCMC, with day-to-night ratios higher by a factor of 3 during the dry season. Isoprene
283 showed a strong correlation with CO and acetylene at Hanoi but a weak correlation at HCMC during both
284 sampling periods. On the one hand, these results indicate a higher contribution of the biogenic sources of
285 isoprene in HCMC due to more sunshine and warmer temperatures. On the other hand, the strong correlation
286 in Hanoi evidences the contribution of anthropogenic sources of isoprene as reported previously (Borbon et
287 al., 2001; dos Santos et al., 2022).

288 Figure S3 displays the average mixing ratio concentrations of a selected number of VOC measured in Hanoi
289 and HCMC and compared with those reported in the literature for other cities worldwide. The distribution of
290 VOC in Hanoi and HCMC is similar to those observed in other megacities. Despite this distribution
291 agreement, the average mixing ratios of most VOCs were higher in the Vietnamese cities compared to those in
292 the other megacities (by a factor of 1.2 to 14).

293

294

3.2 Seasonal and spatial variability of ER in Vietnam

295 As previously discussed, some seasonal differences were observed in the VOC concentrations at HCMC
296 between the two field campaigns performed in 2018 and 2019. In order to determine if seasonality also
297 affected ERs, the two campaigns were evaluated separately. Figure 2 shows the ERs of VOC relative to CO
298 and acetylene obtained at HCMC for each compound measured during each season and then grouped into
299 compound types, namely: aromatics, alkanes, alkenes, CO, acetylene, and OVOCs. No strong seasonality was
300 observed for either approach and similar ERs were observed at HCMC within a factor of 2, except for
301 isobutene, which exhibited a higher ER in 2018 by a factor of 4. Other minor differences are observed for
302 isoprene (with higher ER in 2019) and some oxygenated compounds (butanone, acetone, and methanol higher
303 in 2018).

304 The stability of ER over the year indicates that ERs are not strongly affected by seasonality and that emission
305 sources do not change over the year in HCMC. These results are in line with those observed in previous
306 studies in Beirut (Salameh et al., 2015) and Sao Paulo (Dominutti et al., 2020), where no intense seasonality
307 was observed in the ER.

308 In the case of Hanoi, measurements were only performed in 2019, not allowing the analysis of seasonality.
309 The spatial distribution of ER in Vietnam is analyzed by comparing the ER obtained in both cities during the
310 same period. Figure 3 shows the average ER obtained relative to acetylene and CO in both cities during the
311 2019 campaign. Higher ER of CO, acetylene, and octane have been observed in Hanoi than in HCMC,
312 suggesting differences in the fuel used or the contribution from other sources, such as domestic fuel
313 combustion. In recent years, Vietnam has started a transition toward cleaner fuels, banning RON 92 and
314 encouraging the use of biofuels, such as ethanol-containing fuels (E5 RON92) or RON 95 gasoline. However,
315 this shift to new fuels is not completely adopted by the population, and most vehicles are still fueled with
316 gasoline as opposed to the recent ethanol-containing fuels. Therefore, the greater octane ratios observed in
317 Hanoi could be related to the greater consumption of RON 92 in the city than in HCMC during this study. This
318 could also explain Hanoi's larger ratios observed for acetylene and CO.

319 Other VOC species also show slightly higher differences than a factor of 2 in the comparison between the
320 Vietnamese cities. As is the case of some alkenes (pentene, cis-2-butene, trans-2-pentene and isoprene) and
321 oxygenated VOCs (methanol and butanone). The differences in the alkenes could be associated with the
322 difference in seasonality since those compounds present a higher sensibility to photochemical reactions and
323 evaporative processes which are dependent on ambient temperature and solar radiation. In the case of
324 oxygenated VOCs, they could be related to the influence of other emission sources.

325 Nevertheless, despite the minor discrepancies observed, a good agreement in the ER between both cities is
326 globally observed within a factor of 2. These similarities indicate that similar emission sources regulate the
327 release of VOCs in the two most populous cities of Vietnam, with a high contribution of vehicular-related
328 emission, even if the presence of other VOC sources cannot be neglected.

3.3 Comparison of Vietnamese ER with other places worldwide

329
330 This section compares the average VOC/CO ERs obtained in both Vietnamese cities in 2019 with other places
331 worldwide. This choice was made based on the availability of ER reported from other studies, which mainly
332 calculate the ER relative to CO. Figure 4 shows the ER obtained at Hanoi and HCMC versus those obtained at
333 Sao Paulo (Dominutti et al., 2020), Beijing, and Beirut (Salameh et al., 2016a; Wang et al., 2014), as those
334 cities are all within developing countries, at different stages of development.

335 Generally, a good consistency (within a factor of 2) is observed between ER in all the cities evaluated. There
336 are, however, several larger-scale differences which highlight interesting features in the emissions occurring in
337 each of the cities investigated. Some aromatics, such as trimethyl benzenes, presented higher ER at Hanoi. In
338 the case of Beijing, higher OVOCs (methanol and acetone) are observed in the ER compared to both cities and
339 light alkanes (propane and ethane) compared to HCMC. However, more significant ER of C₉-aromatics, iso-
340 pentane, n-octane, and 1,3-butadiene are revealed in Vietnamese cities (Figure 4). Compared to Beirut, a
341 similar result is obtained, with greater ER of C₉-aromatics, n-octane, and isoprene observed at Hanoi.

342 The ethane and propane enrichment in Sao Paulo (by a factor of 4 to 7) and Beirut revealed a stronger
343 influence of LPG and/or NG emissions, which is also observed in Hanoi compared to HCMC. In a previous
344 study, the influence of emissions from China was observed to affect the ambient concentrations of ethane and
345 propane in Hanoi during our sampling campaign in 2019 (Hien et al., 2022). Thus, the influence of the long-
346 range transport of these species could have an impact on the differences in ER observed in both Vietnamese
347 cities. Nevertheless, this contribution could also change over the year under the influence of different air
348 masses. Longer-term measurements are then needed to better characterise the contribution from these sources.

349 The lower ER of ethanol observed in Hanoi than in Sao Paulo could be related to the difference in fuel
350 formulation in both countries and the fleet composition. In Hanoi, the incorporation of ethanol in fuels is
351 relatively recent and not fully adopted by all vehicles. In contrast, in the Brazilian city, different biofuels are
352 available and consumed more significantly by the fleet. Similarly, the higher ERs observed for aromatics and
353 pentanes in Vietnamese cities indicate the specificities of local fleet composition and technologies and the
354 fuels used in the country.

355 An additional comparison between Hanoi, HCMC, and other cities can be found in Figure S8. A moderate
356 consistency with northern mid-latitude cities (Los Angeles and Paris) was found, especially for aromatics and
357 alkenes. However, there are significant differences for alkanes (except octane) and oxygenated with higher ER
358 obtained in the northern cities by factors of 2 to 13 and 2 to 11, respectively. These differences could be
359 related to the lower levels of CO observed in Vietnamese cities, resulting in lower ERs. Furthermore, diesel-
360 powered cars are more frequently used in European cities, with heavy alkanes and toluene making larger
361 contributions. ERs reported in Mecca (Simpson et al., 2014a) presented a good agreement when compared
362 with those obtained in Vietnam, but still higher contributions of light alkanes (C₂-C₄) and alkenes are reported
363 in the Middle East city.

364 This evaluation discloses the differences in the spatial variability of VOC ER, with the lower impact of those
365 NG/LPG-related compounds and similar to higher contribution of traffic-related ones, indicating that specific
366 fleet/fuel characteristics could have consequences in the ER observed in Vietnam.

367

368 **3.4 VOC Emission profiles from combustion sources**

369 Figure 5 compares the average relative species concentration profiles to the total VOC mass measured from
370 different emission sources together with samples from a traffic site and the profile from the ambient site where
371 online measurements were obtained in Hanoi.

372 The comparison between the ambient and traffic sites reveals quite a good agreement, with higher contribution
373 observed for acetylene, toluene, monoterpenes, and ethene near traffic emissions. Except for acetylene, all the
374 other species have atmospheric lifetimes of less than two days, and a lower contribution in the ambient site can
375 be expected. In contrast, a higher contribution of light alkanes is observed in the ambient site, suggesting the
376 contribution of non-traffic related sources, such as cooking emissions using LPG/NG, in the release of these
377 compounds. The average profiles of each emission source reveal differences between them and are mainly
378 related to the fuel burned and the age of the vehicles. They all, however, present a chemical profile dominated
379 by pentanes, light alkenes, acetylene, and aromatics. In the case of heavy-duty vehicles (buses and trucks), the
380 profiles between the diesel vehicles agree well albeit with some differences in the toluene contribution (higher
381 contribution in the truck profile).

382 Light-duty vehicles can burn all types of fuels in Hanoi, including different grades of petrol (for example, RON
383 95 and E5 RON 92) and diesel, consequently, we have selected a range of vehicles to capture this diversity. It
384 can be noted that passenger cars fueled with diesel have a toluene contribution which represents more than 50 %
385 of the total VOCs measured, followed by ethene. For ethanol and petrol-fueled passenger cars, a good
386 agreement ($R^2= 0.82 - 0.97$) is observed between both profiles, with a higher contribution of toluene in gasoline-
387 fueled cars.

388 Motorcycles dominate the vehicular fleet in Hanoi (89%) and Vietnam (86%) and should, therefore, have an
389 impact in terms of emissions by the road transport sector. Most are 4-stroke motorcycles, and only a small
390 fraction have a catalytic converter (Ly et al., 2020a). Light alkanes, mainly pentanes, dominate the VOC profiles
391 from motorcycles emissions and reveal a more significant contribution of heavy alkanes from older
392 motorcycles. Motorcycles were found to emit a large amount of acetylene which, given the large number of
393 motorcycles in the city, may explain the high levels measured at the ambient site (Figure 5). For 3-wheeled
394 motorcycles, most used for transporting goods, a similar profile is observed to those from diesel vehicles, with a
395 higher contribution of butanes in their emissions.

396 Regarding other combustion sources, we have also measured the emissions from coal-burning and waste-
397 burning sources. Their profiles are quite different since the emissions will depend on the age of the coal or the

398 content of waste being burned. In general, a higher contribution of heavy alkanes is observed (>C₆ alkanes) in
399 waste burning, providing a different signature to the coal combustion source.

400 Interestingly, monoterpenes were systematically detected in all the emission sources in different content,
401 contributing up to 11% to the total VOC mass measured (Figure 5). The presence of monoterpenes, traditionally
402 perceived as a solely biogenically released compound, has already been discussed in a recent study in West
403 Africa, where monoterpenes represent 20 and 47% of road transport and waste-burning sources, respectively
404 (Dominutti et al., 2019).

405 Generally, a higher contribution of light alkanes than heavy ones is noticed, with pentanes representing the
406 largest fraction of total VOC mass, responsible for up to 34% of emissions. These results align with the ambient
407 profile, and the ER observed in Hanoi and HCMC, where C₉ aromatics and pentanes presented the most
408 significant contribution in ambient air dominated by iso-pentane, pentane, propene, and aromatic compounds
409 (Imamura et al., 2006; Ly et al., 2020a; Sakamoto et al., 2018).

410 We believe the emission sources investigated here give a representative view of emissions from the transport
411 sector in Vietnam, representing the diversity of the vehicle fleet in the country. To the best of our knowledge,
412 this is the first time a detailed study combining emission sources and continuous ambient VOC measurements
413 has been developed in Vietnam and even the SEA region.

414 **3.5 VOC emission factors from the road transport sector**

415 Emission factors (EFs) are defined as the amount of a pollutant emitted per kilogram of burned fuel. Previous
416 studies have shown that during fuel combustion, approximately 95% of carbon is emitted into the atmosphere as
417 CO₂ and CO (Chen et al., 2007; Hall et al., 2012; Keita et al., 2018). The EF calculation method estimates the
418 released amount of carbon from CO and CO₂ concentrations, hinting at a minor misestimation of EF values
419 (Dominutti et al., 2019; Hall et al., 2012; Keita et al., 2018; Pant and Harrison, 2013; Yokelson et al., 2007).
420 Therefore, we compare here the ER obtained from continuous ambient measurement with the EF observed from
421 emission sources (coal burning, trucks, diesel, and petrol cars, motorcycles, buses, etc.) (Figure 6). This
422 comparison allows us to investigate which profiles fitted best with the VOC ratios in ambient air, considering
423 that ER represents all the combustion sources (mainly traffic-related ones) affecting the atmospheric
424 composition in the urban area.

425 Overall, both datasets have consistency, with the main discrepancies in truck emissions. This difference could
426 be related to the low fraction of trucks in the urban areas, representing approximately 1% of the fleet during rush
427 hours (Ly et al., 2020b). A relatively good agreement between ambient ER and petrol ($R^2 = 0.64$) and diesel (R^2
428 $= 0.75$) passenger car emissions is observed (Figure 6). Diesel cars denote higher emissions of benzene and 123-
429 TMB within the aromatics, isopentane and n-heptane for alkanes, and slightly higher contribution of propene
430 and isobutene in the alkene group. Petrol cars, however, present only minor differences with ambient ER but
431 greater emissions of 123-TMB and pentenes. Buses' profile was relatively consistent with the ER, with two

432 main differences observed: the pretty significant contribution of 123-TMB and the low levels of n-heptane. As
433 for motorcycles, higher isopentane and 224-TMP and lower toluene ethylbenzene, propane, and butane
434 emissions are depicted (Figure 6). A poor contribution of toluene is also displayed in the emission profile of
435 coal burning. These results suggest that the high ratios of toluene and C₉-aromatics in Hanoi are mainly related
436 to the emissions from cars and buses diesel-fueled vehicles. The higher levels of pentenes are associated with
437 the emission from petrol-fueled cars and motorcycles, which are largely the most significant contributors to
438 pentanes emissions in Hanoi. This agrees with the profile obtained in another recent study in Hanoi, where a
439 good accord was observed between near-road traffic ambient measurements and motorcycle emissions
440 (Sakamoto et al., 2018).

441 **3.6 Road Transport emission estimations and comparison with a global emission** 442 **inventory**

443 This section evaluates the differences in the magnitude of VOC emissions and speciation between
444 observations and estimation from global inventories for the road transport sector in Hanoi. For that, the
445 composition of the circulating fleet was considered, as well as the consumption of gasoline and diesel in the
446 city. Additionally, a downscaling of the road transport emissions of the global inventory was performed,
447 integrating an extended region around the city of Hanoi.

448 Figure S9 illustrates the VOC relative contribution of the road transport profile obtained from observations
449 and that estimated by the global inventory. Substantial differences are observed in chemical speciation
450 between both profiles, except for ethane (VOC2), propane (VOC3), and benzene (VOC13). Aromatics and
451 alkanes are the main contributors in both profiles but in different proportions. Our estimates disclose the most
452 significant contributions in pentanes (VOC5), C₈ aromatics (VOC15), and C₉ aromatics (VOC16), with 17.5
453 %, 12 %, and 11%, respectively. In comparison, EDGAR reports a contribution of 6% for VOC5, 3 % for
454 VOC15, and 1.5% for VOC16 (Figure S9). Discrepancies are also associated with heavy alkanes' contribution
455 (>C₆ alkanes, VOC6), which dominated the road transport profile of the inventory, counting for 54% of the
456 total VOCs. These dissimilarities between the profiles could be related to the compounds considered for the
457 speciation of the groups. In our estimation, VOC6 (2,3- methyl pentanes, n-hexane, n-heptane, octane, and
458 2,2,4- trimethyl pentane), VOC12 (1-butene, trans-2-butene, isobutene, cis-2-butene, pentene, trans-2-pentene
459 and 1,3- butadiene) are integrated by a fixed number of species, while those of the inventory combine several
460 unknown species. Due to this limitation in the number of VOCs accounted, we have removed those groups for
461 the following comparisons.

462 Figure 7 displays the absolute VOC emissions (in Tn year⁻¹), estimated by the EDGAR inventory and our
463 measurements. Significant differences are noted for several species, including pentanes (VOC5), acetylene
464 (VOC 9), aromatics (VOC14-VOC16), isoprene (VOC10), and monoterpenes (VOC11) (Figure S9,7).
465 Overall, our results show that except for VOC 7 and VOC8, all the VOC groups present higher emissions than
466 the estimations of EDGAR.

467 As mentioned before, pentanes presented the highest VOC levels in both cities, and they also dominated the
468 emission profile (23%), 3.5 times higher than the inventory estimation (Figure 7a). Aromatics also display an
469 underestimation by a factor of 2.5 to 9 (VOC14, 15 and 16). This discrepancy is likely due to the EFs used in
470 the inventory estimation not being representative of the local characteristics of the Vietnamese fleet. These
471 differences are substantial, with total aromatics found to be three times higher than those calculated by the
472 EDGAR inventory.

473 Isoprene and monoterpenes (VOC10 and 11) are the groups depicting the greatest underestimation, by a factor
474 of 47 in the case of isoprene and entirely absent for monoterpenes (Figure S9,7b). Despite biogenic emissions
475 dominating the global contribution of isoprene, it can also be released by traffic-related sources, as
476 documented in previous studies, which can exceed the biogenic ones depending on the season (Borbon et al.,
477 2001; Brito et al., 2015; dos Santos et al., 2022). There is an increasing volume of evidence about the presence
478 of monoterpenes in anthropogenic emissions. Recent studies have evaluated the contribution of these species
479 from personal care and volatile consumer products, suggested as the main emission sources in northern urban
480 areas (Coggon et al., 2021; Gkatzelis et al., 2021; McDonald et al., 2018). In addition, the presence of
481 monoterpenes in roadside concentrations has been highlighted in a recent study in Hanoi, where ocimene
482 related-compounds reach up to 0.95 ppb and show a similar trend to traffic-related tracers (Ly et al., 2020a).
483 The strong correlations of acetylene and CO with isoprene and its presence in emission profiles of several
484 sources in Hanoi reinforce its emission from anthropogenic sources (Figure S2). Nevertheless, the contribution
485 from other sources cannot be neglected. Ethanol and other oxygenated compounds, such as aldehydes, are
486 not present in the road transport profile of the inventory. The introduction of ethanol-blended fuels in Vietnam
487 was done after the development of the inventory, which could explain its absence in the profile. A recent study
488 in Sao Paulo has shown that oxygenated VOCs can contribute considerably to the traffic-related emission
489 profiles where ethanol or other biofuels are frequently burned (Dominutti et al., 2020). Unfortunately, our
490 study did not include the evaluation of EF for oxygenated VOCs, and they should be included in future studies
491 in Vietnam.

492 Regarding the total calculated VOC emissions, a discrepancy by a factor of 3 (more than 6000 Tn year⁻¹) is
493 disclosed between the estimation and the observations (Figure 7d). Even if these differences are not as
494 substantial in other places (i.e., West Africa), they can have implications on the oxidative capacity of the
495 atmosphere at the regional scale. Furthermore, since major underestimations are related to highly reactive
496 VOCs, such as alkenes, monoterpenes, and aromatics, the inaccuracies in the speciation could also have
497 consequences on the estimation of their impacts on the formation of secondary pollutants.

498 The scarcity of source profile measurements and long-term ambient data in regions such as the SEA,
499 reinforces the need for further research on VOCs and their representation in EIs. Our results provide relevant
500 information on individual EFs of VOC from in situ observations, which can help develop accurate EIs in the
501 SEA region.

3.7 Limitations of this study and recommendations

This study focused on VOC ERs established from ambient measurements and EFs estimated from individual sources in Vietnam, limiting our study in some aspects. Despite the advantages offered in the measurement of online VOCs in urban traffic sites, focus on the transport sector limits the discussion on the contribution from other potential sources that may be relevant for other urban sites in Vietnam but less dominated by traffic. In addition, other sources such as industrial, biomass burning, residential, ship transportation, and volatile consumer products should be assessed to have a complete picture of the VOC emissions in Vietnam and to better evaluate population exposure to air pollution.

We recommend that future studies include an expanded number of vehicles to better estimate the uncertainties from the measurements obtained. Moreover, our measurements were performed under real-world but also uncontrolled conditions. Therefore, further work should include the estimation factors from controlled emission chambers, mainly for estimating coal and other burning emissions.

Restrictions in access to data were found during our research, mainly due to the lack of reliable information available. The estimation of total emissions can benefit from improving the availability of activity data from consumption and source characteristics to develop more reliable EIs.

Finally, long-term VOC data was unavailable over the year and these observations would help evaluate the contribution of VOC emission sources over the whole year in Vietnam.

4. Conclusions

This work presents, for the first time, a comprehensive study on EFs and ERs of ambient VOC and total VOC emissions from the road transport sector in Vietnam. Our ER estimations show no substantial differences between the dry and rainy seasons in HCMC and a relatively homogeneous spatial distribution within the two cities (Hanoi and HCMC), suggesting that similar emission sources are presented in both areas.

Globally, the comparison with other cities worldwide shows a reasonable consensus with higher emissions ratios in Hanoi than in other places. These findings disclose the differences in the global variability of VOC ER, with a higher contribution of traffic-related ones, indicating that specific fleet characteristics and fuels could impact the ER observed in Vietnam.

The total VOC emissions calculated for the road transport sector were compared with a downscaled global inventory. Substantial differences are observed in chemical speciation between the two profiles. Our estimates reveal the most significant contributions in pentanes, C₈ aromatics, and C₉ aromatics, while heavy alkanes' contribution dominated the road transport profile of the inventory. Oxygenated compounds are not represented in the inventory for the area, as well as isoprene and monoterpenes depict the more contrasting underestimation by a factor of 47. Regarding absolute VOC emissions, a discrepancy of a factor of 3 between

534 inventory and our estimations in Hanoi is observed. Those discrepancies could have consequences on the
535 estimation of the effects that road transport can have on regional air quality.

536 Thus, at a local and regional level, comprehensive measurements integrating ambient levels and regional-
537 specific sources are of great interest in providing more reliable information to improve the VOCs magnitude
538 and speciation of emission estimations in the SEA region.

539 Author contributions.

540 PAD conceptualized and drafted the paper, analysed the data and produced the figures with help from JRH,
541 HAL, GLF, SK, and DEO. Experimental design and project planning was carried out by DEO, HTT and HAL.
542 Field measurements were performed by PAD, JRH, MS, GPM, DHH, GLF, and DEO. Reviewing and editing
543 were carried out by JRH, HAL, DEO and GLF.

544 Declaration of competing interest.

545 The authors declare that they have no known competing financial interests or personal relationships that could
546 have appeared to influence the work reported in this study.

547 Acknowledgments.

548 This study was funded by the RCUK (Research Councils UK)- NAFOSTED (Vietnam National Foundation
549 for Science and Technology Development) Newton Fund Research Partnership under grant number
550 NE/P014771/1.

551 Acknowledgement is made to Dr Katie Read from the Atmospheric Measurement and Observation Facility
552 (AMOF), National Centre for Atmospheric Science (NCAS) for the support of the ozone and carbon monoxide
553 measurements. The authors would like to kindly thank the dedicated efforts of Nguyen Viet Thanh, Nguyen
554 Doan Thien Chi and Tran Anh Ngan for collecting samples and participating in the field campaigns.

555 **References**

- 556 Atkinson, R.: Atmospheric chemistry of VOCs and NO, *Atmos. Environ.*, 34, 2063–2101, 2000.
- 557 Atkinson, R. and Arey, J.: Atmospheric Degradation of Volatile Organic Compounds, *Chem. Rev.*,
558 103(12), 4605–4638, doi:10.1021/cr0206420, 2003.
- 559 Ban-Weiss, G. A., Lunden, M. M., Kirchstetter, T. W. and Harley, R. A.: Size-resolved particle
560 number and volume emission factors for on-road gasoline and diesel motor vehicles, *J. Aerosol Sci.*,
561 41(1), 5–12, 2010.
- 562 Borbon, A., Fontaine, H., Veillerot, M., Locoge, N., Galloo, J. C. and Guillermo, R.: An investigation
563 into the traffic-related fraction of isoprene at an urban location, *Atmos. Environ.*, 35(22), 3749–3760,
564 doi:10.1016/S1352-2310(01)00170-4, 2001a.
- 565 Borbon, A., Gilman, J. B., Kuster, W. C., Grand, N., Chevaillier, S., Colomb, A., Dolgorouky, C.,
566 Gros, V., Lopez, M., Sarda-Estevé, R., Holloway, J., Stutz, J., Petetin, H., McKeen, S., Beekmann,
567 M., Warneke, C., Parrish, D. D. and de Gouw, J. A.: Emission ratios of anthropogenic volatile organic
568 compounds in northern mid-latitude megacities: Observations versus emission inventories in Los
569 Angeles and Paris, *J. Geophys. Res. Atmos.*, 118(4), 2041–2057, doi:10.1002/jgrd.50059, 2013.
- 570 Brito, J., Wurm, F., Yáñez-Serrano, A. M., de Assunção, J. V., Godoy, J. M. and Artaxo, P.: Vehicular
571 Emission Ratios of VOCs in a Megacity Impacted by Extensive Ethanol Use: Results of Ambient
572 Measurements in São Paulo, Brazil, *Environ. Sci. Technol.*, 49(19), 11381–11387,
573 doi:10.1021/acs.est.5b03281, 2015.
- 574 Cao X., Yao Z., Shen X., Ye Y., Jiang X. On-road emission characteristics of VOCs from light-duty
575 gasoline vehicles in Beijing, China. *Atmos. Environ.*, 124, pp. 146-155,
576 <https://doi.org/10.1016/j.atmosenv.2015.06.019>, 2016.
- 577 Chen, L.-W. A., Moosmüller, H., Arnott, W. P., Chow, J. C., Watson, J. G., Susott, R. A., Babbitt, R.
578 E., Wold, C. E., Lincoln, E. N. and Hao, W. M.: Emissions from Laboratory Combustion of Wildland
579 Fuels: Emission Factors and Source Profiles, *Environ. Sci. Technol.*, 41(12), 4317–4325,
580 doi:10.1021/es062364i, 2007.
- 581 Coggon, M. M., Gkatzelis, G. I., McDonald, B. C., Gilman, J. B., Schwantes, R. H., Abuhassan, N.,
582 Aikin, K. C., Arend, M. F., Berkoff, T. A., Brown, S. S., Campos, T. L., Dickerson, R. R., Gronoff,
583 G., Hurley, J. F., Isaacman-VanWertz, G., Koss, A. R., Li, M., McKeen, S. A., Moshary, F., Peischl,
584 J., Pospisilova, V., Ren, X., Wilson, A., Wu, Y., Trainer, M. and Warneke, C.: Volatile chemical
585 product emissions enhance ozone and modulate urban chemistry, *Proc. Natl. Acad. Sci.*, 118(32),
586 doi:10.1073/pnas.2026653118, 2021.
- 587 Coll, I., Rousseau, C., Barletta, B., Meinardi, S. and Blake, D. R.: Evaluation of an urban NMHC
588 emission inventory by measurements and impact on CTM results, *Atmos. Environ.*, 44(31), 3843–
589 3855, doi:10.1016/j.atmosenv.2010.05.042, 2010.
- 590 Dominutti, P., Keita, S., Bahino, J., Colomb, A., Liousse, C., Yoboué, V., Galy-Lacaux, C., Morris,
591 E., Bouvier, L., Sauvage, S. and Borbon, A.: Anthropogenic VOCs in Abidjan, southern West Africa:
592 from source quantification to atmospheric impacts, *Atmos. Chem. Phys.*, 19(18), 11721–11741,
593 doi:10.5194/acp-19-11721-2019, 2019.
- 594 Dominutti, P., Nogueira, T., Fornaro, A. and Borbon, A.: One decade of VOCs measurements in São
595 Paulo megacity: Composition, variability, and emission evaluation in a biofuel usage context, *Sci.*
596 *Total Environ.*, 738, 139790, doi:10.1016/j.scitotenv.2020.139790, 2020.
- 597 Dunmore, R. E., Hopkins, J. R., Lidster, R. T., Lee, J. D., Evans, M. J., Rickard, a. R., Lewis, a. C.
598 and Hamilton, J. F.: Diesel-related hydrocarbons can dominate gas phase reactive carbon in
599 megacities, *Atmos. Chem. Phys.*, 15(17), 9983–9996, doi:10.5194/acp-15-9983-2015, 2015.

600 Evnexpress: Biofuel fails to make a difference in Vietnam, consumption drops, [online] Available
601 from: [https://e.vnexpress.net/news/business/economy/biofuel-fails-to-make-a-difference-in-vietnam-](https://e.vnexpress.net/news/business/economy/biofuel-fails-to-make-a-difference-in-vietnam-consumption-drops-3922777.html)
602 [consumption-drops-3922777.html](https://e.vnexpress.net/news/business/economy/biofuel-fails-to-make-a-difference-in-vietnam-consumption-drops-3922777.html) (Accessed 28 May 2022), 2019.

603 Ferek, R. J., Reid, J. S., Hobbs, P. V., Blake, D. R. and Liousse, C.: Emission factors of hydrocarbons,
604 halocarbons, trace gases and particles from biomass burning in Brazil, *J. Geophys. Res.*, 103(32),
605 107–32, 1998.

606 Fuzzi, S., Andreae, M. O., Huebert, B. J., Kulmala, M., Bond, T. C., Boy, M., Doherty, S. J.,
607 Guenther, A., Kanakidou, M., Kawamura, K., Kerminen, V.-M., Lohmann, U., Russell, L. M. and
608 Pöschl, U.: Critical assessment of the current state of scientific knowledge, terminology, and research
609 needs concerning the role of organic aerosols in the atmosphere, climate, and global change, *Atmos.*
610 *Chem. Phys. Discuss.*, 6(7), 11729–11780, doi:10.5194/acpd-5-11729-2005, 2006.

611 General Statistics Office: The statistical yearbook of Vietnam 2020, edited by S. P. House, Hanoi.
612 [online] Available from: [https://www.gso.gov.vn/en/data-and-statistics/2021/07/statistical-yearbook-](https://www.gso.gov.vn/en/data-and-statistics/2021/07/statistical-yearbook-of-2020/)
613 [of-2020/](https://www.gso.gov.vn/en/data-and-statistics/2021/07/statistical-yearbook-of-2020/), 2020.

614 General Statistics Office of Vietnam: Population and Employment, [online] Available from:
615 <https://www.gso.gov.vn/en/data-and-statistics/2020/> (Accessed 28 May 2022), 2020.

616 Gkatzelis, G. I., Coggon, M. M., McDonald, B. C., Peischl, J., Gilman, J. B., Aikin, K. C., Robinson,
617 M. A., Canonaco, F., Prevot, A. S. H., Trainer, M. and Warneke, C.: Observations Confirm that
618 Volatile Chemical Products Are a Major Source of Petrochemical Emissions in U.S. Cities, *Environ.*
619 *Sci. Technol.*, 55(8), 4332–4343, doi:10.1021/acs.est.0c05471, 2021.

620 Goldstein, A. H. and Galbally, I. E.: Known and Unexplored Organic Constituents in the Earth's
621 Atmosphere, *Environ. Sci. Technol.*, 41(5), 1514–1521, doi:10.1021/es072476p, 2007.

622 de Gouw, J. A., Gilman, J. B., Kim, S.-W., Lerner, B. M., Isaacman-VanWertz, G., McDonald, B. C.,
623 Warneke, C., Kuster, W. C., Lefer, B. L., Griffith, S. M., Dusanter, S., Stevens, P. S. and Stutz, J.:
624 Chemistry of Volatile Organic Compounds in the Los Angeles basin: Nighttime Removal of Alkenes
625 and Determination of Emission Ratios, *J. Geophys. Res. Atmos.*, 122(21), 11,843–11,861,
626 doi:10.1002/2017JD027459, 2017.

627 Hai, C. D. and Kim Oanh, N. T.: Effects of local, regional meteorology and emission sources on mass
628 and compositions of particulate matter in Hanoi, *Atmos. Environ.*, 78, 105–112,
629 doi:10.1016/j.atmosenv.2012.05.006, 2013.

630 Hall, D., Wu, C.-Y., Hsu, Y.-M., Stormer, J., Engling, G., Capeto, K., Wang, J., Brown, S., Li, H.-W.
631 and Yu, K.-M.: PAHs, carbonyls, VOCs and PM_{2.5} emission factors for pre-harvest burning of
632 Florida sugarcane, *Atmos. Environ.*, 55, 164–172, doi:10.1016/j.atmosenv.2012.03.034, 2012.

633 Hang, N. T., Thi, N. and Oanh, K.: Chemical characterization and sources apportionment of fine
634 particulate pollution in a mining town of Vietnam, *Atmos. Res.*, 145–146, 214–225,
635 doi:10.1016/j.atmosres.2014.04.009, 2014.

636 Hester, R. and Harrison, R.: Volatile organic compounds in the atmosphere., 1995.

637 Hien, P. D., Bac, V. T., Thinh, N. T. H., Anh, H. L., Thang, D. D. and Nghia, N. T.: A comparison
638 study of chemical compositions and sources of pm_{1.0} and pm_{2.5} in hanoi, *Aerosol Air Qual. Res.*,
639 21(10), doi:10.4209/AAQR.210056, 2021.

640 Hien, T. T., Chi, N. D. T., Nguyen, N. T., Vinh, L. X., Takenaka, N. and Huy, D. H.: Current Status of
641 Fine Particulate Matter (PM_{2.5}) in Vietnam's Most Populous City, Ho Chi Minh City, *Aerosol Air*
642 *Qual. Res.*, 19(10), 2239–2251, doi:10.4209/aaqr.2018.12.0471, 2019.

643 Hien, T. T., Huy, D. H., Dominutti, P. A., Thien Chi, N. D., Hopkins, J. R., Shaw, M., Forster, G.,
644 Mills, G., Le, H. A. and Oram, D.: Comprehensive volatile organic compound measurements and their
645 implications for ground-level ozone formation in the two main urban areas of Vietnam, *Atmos.*

- 646 Environ., 269(November 2021), 118872, doi:10.1016/j.atmosenv.2021.118872, 2022.
- 647 Ho, B. Q. and Clappier, A.: Road traffic emission inventory for air quality modelling and to evaluate
648 the abatement strategies: A case of Ho Chi Minh City, Vietnam, Atmos. Environ., 45(21), 3584–3593,
649 doi:10.1016/j.atmosenv.2011.03.073, 2011.
- 650 Huang, G., Brook, R., Crippa, M., Janssens-Maenhout, G., Schieberle, C., Dore, C., Guizzardi, D.,
651 Muntean, M., Schaaf, E. and Friedrich, R.: Speciation of anthropogenic emissions of non-methane
652 volatile organic compounds: A global gridded data set for 1970-2012, Atmos. Chem. Phys., 17(12),
653 7683–7701, doi:10.5194/acp-17-7683-2017, 2017.
- 654 Huu, D. N. and Ngoc, V. N.: Analysis Study of Current Transportation Status in Vietnam’s Urban
655 Traffic and the Transition to Electric Two-Wheelers Mobility, Sustainability, 13(10), 5577,
656 doi:10.3390/su13105577, 2021.
- 657 IEA-AMF: Ethanol properties, [online] Available from: [https://www.iea-](https://www.iea-amf.org/content/fuel_information/fuel_info_home/ethanol/e10/ethanol_properties)
658 [amf.org/content/fuel_information/fuel_info_home/ethanol/e10/ethanol_properties](https://www.iea-amf.org/content/fuel_information/fuel_info_home/ethanol/e10/ethanol_properties) (Accessed 28 May
659 2022), 2019.
- 660 Imamura, K., Maeda, Y., Takenaka, N., Hung Viet, P. and Thi Ngoc Lan, T.: Investigation on Air
661 Pollution in Vietnam -Volatile Organic Compounds in Hanoi and Ho Chi Minh, Annu. Rep. FY 2006,
662 core Univ. Progr. between Japan Soc. Promot. Sci. Vietnamese Acad. Sci. adn Technol., (January
663 2015), 47–54, 2006.
- 664 Keita, S., Liousse, C., Yoboué, V., Dominutti, P., Guinot, B., Assamoi, E.-M., Borbon, A., Haslett, S.
665 L., Bouvier, L., Colomb, A., Coe, H., Akpo, A., Adon, J., Bahino, J., Doumbia, M., Djossou, J., Galy-
666 Lacaux, C., Gardrat, E., Gnamien, S., Léon, J. F., Ossohou, M., N’Datchoh, E. T. and Roblou, L.:
667 Particle and VOC emission factor measurements for anthropogenic sources in West Africa, Atmos.
668 Chem. Phys., 18(10), 7691–7708, doi:10.5194/acp-18-7691-2018, 2018.
- 669 Kim Oanh, N. T., Thuy Phuong, M. T. and Permadi, D. A.: Analysis of motorcycle fleet in Hanoi for
670 estimation of air pollution emission and climate mitigation co-benefit of technology implementation,
671 Atmos. Environ., 59, 438–448, doi:10.1016/j.atmosenv.2012.04.057, 2012.
- 672 Kim, S.-W., McKeen, S. A., Frost, G. J., Lee, S.-H., Trainer, M., Richter, A., Angevine, W. M., Atlas,
673 E., Bianco, L., Boersma, K. F., Brioude, J., Burrows, J. P., de Gouw, J., Fried, A., Gleason, J., Hilboll,
674 A., Mellqvist, J., Peischl, J., Richter, D., Rivera, C., Ryerson, T., te Lintel Hekkert, S., Walega, J.,
675 Warneke, C., Weibring, P. and Williams, E.: Evaluations of NO_x and highly reactive VOC emission
676 inventories in Texas and their implications for ozone plume simulations during the Texas Air Quality
677 Study 2006, Atmos. Chem. Phys., 11(22), 11361–11386, doi:10.5194/acp-11-11361-2011, 2011.
- 678 Koppmann, R.: Volatile organic compounds in the atmosphere, Blackwell Pub., 2007.
- 679 Le, H. and Yang, Z.: Using policy and regulation to pave the way for two-wheeler electrification in
680 Vietnam., 2022.
- 681 Lelieveld, J., Haines, A. and Pozzer, A.: Age-dependent health risk from ambient air pollution: a
682 modelling and data analysis of childhood mortality in middle-income and low-income countries,
683 Lancet Planet. Heal., 2(7), e292–e300, doi:10.1016/S2542-5196(18)30147-5, 2018.
- 684 Lundin, L., Gullett, B., Carroll, W. F., Touati, A., Marklund, S. and Fiedler, H.: The effect of
685 developing nations’ municipal waste composition on PCDD/PCDF emissions from open burning,
686 Atmos. Environ., 79, 433–441, doi:10.1016/j.atmosenv.2013.06.040, 2013.
- 687 Ly, B. T., Kajii, Y., Nguyen, T. Y. L., Shoji, K., Van, D. A., Do, T. N. N., Nghiem, T. D. and
688 Sakamoto, Y.: Characteristics of roadside volatile organic compounds in an urban area dominated by
689 gasoline vehicles, a case study in Hanoi, Chemosphere, 254(1), 126749,
690 doi:10.1016/j.chemosphere.2020.126749, 2020a.
- 691 Ly, B. T., Kajii, Y., Nguyen, T. Y. L., Shoji, K., Van, D. A., Do, T. N. N., Nghiem, T. D. and

692 Sakamoto, Y.: Characteristics of roadside volatile organic compounds in an urban area dominated by
693 gasoline vehicles, a case study in Hanoi, *Chemosphere*, 254(1), 126749,
694 doi:10.1016/j.chemosphere.2020.126749, 2020b.

695 McDonald, B. C., de Gouw, J. A., Gilman, J. B., Jathar, S. H., Akherati, A., Cappa, C. D., Jimenez, J.
696 L., Lee-Taylor, J., Hayes, P. L., McKeen, S. A., Cui, Y. Y., Kim, S.-W., Gentner, D. R., Isaacman-
697 VanWertz, G., Goldstein, A. H., Harley, R. A., Frost, G. J., Roberts, J. M., Ryerson, T. B. and Trainer,
698 M.: Volatile chemical products emerging as largest petrochemical source of urban organic emissions,
699 *Science* (80-.), 359(6377), 760–764, doi:10.1126/science.aaq0524, 2018.

700 Nguyen, C. (2021). Do weather extremes induce people to move? Evidence from Vietnam. *Economic*
701 *Analysis and Policy*. 69. 118-141. 10.1016/j.eap.2020.11.009.

702 Pant, P. and Harrison, R. M.: Estimation of the contribution of road traffic emissions to particulate
703 matter concentrations from field measurements: A review, *Atmos. Environ.*, 77, 78–97,
704 doi:10.1016/j.atmosenv.2013.04.028, 2013.

705 Phung, D., Hien, T. T., Linh, H. N., Luong, L. M. T., Morawska, L., Chu, C., Binh, N. D. and Thai, P.
706 K.: Air pollution and risk of respiratory and cardiovascular hospitalizations in the most populous city
707 in Vietnam, *Sci. Total Environ.*, 557–558, 322–330, doi:10.1016/j.scitotenv.2016.03.070, 2016.

708 PVOIL: Hanoi: E5 gasoline use has increased to 45%, [online] Available from:
709 <https://www.pvoil.com.vn/en-US/media/related-news/hanoi-e5-gasoline-use-has-increased-to-45>
710 (Accessed 28 May 2022), 2018.

711 Radke, L. F., Hegg, D. A., Hobbs, P. V., Nance, J. D., Lyons, J. H., Laursen, K. K., Weiss, R. E.,
712 Riggan, P. J. and Ward, D. E.: Particulate and trace gas emissions from large biomass fire in North
713 America, 1991.

714 Sakamoto, Y., Shoji, K., Bui, M. T., Phạm, T. H., Vu, T. A., Ly, B. T. and Kajii, Y.: Air quality study
715 in Hanoi, Vietnam in 2015–2016 based on a one-year observation of NO_x, O₃, CO and a one-week
716 observation of VOCs, *Atmos. Pollut. Res.*, 9(3), 544–551, doi:10.1016/j.apr.2017.12.001, 2018a.

717 Salameh, T., Sauvage, S., Afif, C., Borbon, A., Leónardis, T., Brioude, J., Waked, A. and Locoge, N.:
718 Exploring the seasonal NMHC distribution in an urban area of the Middle East during ECOCEM
719 campaigns: Very high loadings dominated by local emissions and dynamics, *Environ. Chem.*, 12(3),
720 316–328, doi:10.1071/EN14154, 2015.

721 Salameh, T., Borbon, A., Afif, C., Sauvage, S., Leonardis, T., Gaimoz, C. and Locoge, N.:
722 Composition of gaseous organic carbon during ECOCEM in Beirut, Lebanon: new observational
723 constraints for VOC anthropogenic emission evaluation in the Middle East, *Atmos. Chem. Phys.*
724 *Discuss.*, (August), 1–32, doi:10.5194/acp-2016-543, 2016a.

725 Salameh, T., Sauvage, S., Afif, C., Borbon, A. and Locoge, N.: Source apportionment vs. emission
726 inventories of non-methane hydrocarbons (NMHC) in an urban area of the Middle East: local and
727 global perspectives, *Atmos. Chem. Phys.*, 16(5), 3595–3607, doi:10.5194/acp-16-3595-2016, 2016b.

728 dos Santos, T. C., Dominutti, P., Pedrosa, G. S., Coelho, M. S., Nogueira, T., Borbon, A., Souza, S. R.
729 and Fornaro, A.: Isoprene in urban Atlantic forests: Variability, origin, and implications on the air
730 quality of a subtropical megacity, *Sci. Total Environ.*, 824, 153728,
731 doi:10.1016/j.scitotenv.2022.153728, 2022.

732 von Schneidmesser, E., Monks, P. S. and Plass-Duelmer, C.: Global comparison of VOC and CO
733 observations in urban areas, *Atmos. Environ.*, 44(39), 5053–5064,
734 doi:10.1016/j.atmosenv.2010.09.010, 2010.

735 Seinfeld, J. H. and Pandis, S. N.: *Atmospheric Chemistry and Physics. From Air Pollution to Climate*
736 *Change*, Second edi., John Wiley & Sons., 2006.

737 Simpson, I. J., Aburizaiza, O. S., Siddique, A., Barletta, B., Blake, N. J., Gartner, A., Khwaja, H.,

738 Meinardi, S., Zeb, J. and Blake, D. R.: Air Quality in Mecca and Surrounding Holy Places in Saudi
739 Arabia During Hajj: Initial Survey, *Environ. Sci. Technol.*, 48(15), 8529–8537,
740 doi:10.1021/es5017476, 2014a.

741 Simpson, I. J., Aburizaiza, O. S., Siddique, A., Barletta, B., Blake, N. J., Gartner, A., Khwaja, H.,
742 Meinardi, S., Zeb, J. and Blake, D. R.: SM_Air quality in Mecca and surrounding holy places in Saudi
743 Arabia during Hajj: Initial survey, *Environ. Sci. Technol.*, 48(15), 8529–8537,
744 doi:10.1021/es5017476, 2014b.

745 Thera, B. T. P., Dominutti, P., Öztürk, F., Salameh, T., Sauvage, S., Afif, C., Çetin, B., Gaimoz, C.,
746 Keleş, M., Evan, S. and Borbon, A.: Composition and variability of gaseous organic pollution in the
747 port megacity of Istanbul: Source attribution, emission ratios, and inventory evaluation, *Atmos. Chem.*
748 *Phys.*, 19(23), 15131–15156, doi:10.5194/acp-19-15131-2019, 2019.

749 Trang, T. T., Van, H. H. and Oanh, N. T. K.: Traffic emission inventory for estimation of air quality
750 and climate co-benefits of faster vehicle technology intrusion in Hanoi, Vietnam, *Carbon Manag.*,
751 6(3–4), 117–128, doi:10.1080/17583004.2015.1093694, 2015.

752 Tung, H. D., Tong, H. Y., Hung, W. T. and Anh, N. T. N.: Development of emission factors and
753 emission inventories for motorcycles and light duty vehicles in the urban region in Vietnam, *Sci. Total*
754 *Environ.*, 409(14), 2761–2767, doi:10.1016/j.scitotenv.2011.04.013, 2011.

755 Uherek, E., Halenka, T., Borken-Kleefeld, J., Balkanski, Y., Bernsten, T., Borrego, C., Gauss, M.,
756 Hoor, P., Juda-Rezler, K. and Lelieveld, J.: Transport impacts on atmosphere and climate: Land
757 transport, *Atmos. Environ.*, 44(37), 4772–4816, doi:10.1016/j.atmosenv.2010.01.002, 2010.

758 Vietnam, G. of S. R. of: QCVN 01: 2009/BKHCN, National technical regulation on gasoline, diesel
759 fuel oils and biofuels, Vietnam (in Vietnamese), 2009.

760 Vietnam, G. of S. R. of: Decision No.49/2011/QĐ-TTg Decision about Progression on the Application
761 of Standard for Emission of Gaseous Pollutants from Manufactured, Assembled, and New Imported
762 Mo- torcycles and Mopeds, Vietnam (in Vietnamese), 2011.

763 Wang, M., Shao, M., Chen, W., Yuan, B., Lu, S., Zhang, Q., Zeng, L. and Wang, Q.: A temporally
764 and spatially resolved validation of emission inventories by measurements of ambient volatile organic
765 compounds in Beijing, China, *Atmos. Chem. Phys.*, 14(12), 5871–5891, doi:10.5194/acp-14-5871-
766 2014, 2014.

767 Ward, D. E. and Radke, L. F.: Emissions measurements from vegetation fires: A comparative
768 evaluation of methods and results, *Fire Environ. Ecol. Atmos. Clim. Importance Veg. Fires*, 1993.

769 Warneke, C., McKeen, S. a., de Gouw, J. A., Goldan, P. D., Kuster, W. C., Holloway, J. S., Williams,
770 E. J., Lerner, B. M., Parrish, D. D., Trainer, M., Fehsenfeld, F. C., Kato, S., Atlas, E. L., Baker, A. and
771 Blake, D. R.: Determination of urban volatile organic compound emission ratios and comparison with
772 an emissions database, *J. Geophys. Res.*, 112(D10), D10S47, doi:10.1029/2006JD007930, 2007.

773 Warneke, C., de Gouw, J. A., Holloway, J. S., Peischl, J., Ryerson, T. B., Atlas, E., Blake, D., Trainer,
774 M. and Parrish, D. D.: Multiyear trends in volatile organic compounds in Los Angeles, California:
775 Five decades of decreasing emissions, *J. Geophys. Res. Atmos.*, 117(D00V17),
776 doi:10.1029/2012JD017899, 2012.

777 WHO: WHO Global air quality guidelines. Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen
778 dioxide, sulfur dioxide and carbon monoxide, Geneva. [online] Available from:
779 https://www.who.int/airpollution/data/AAP_BoD_results_May2018_final.pdf?ua=1, 2021.

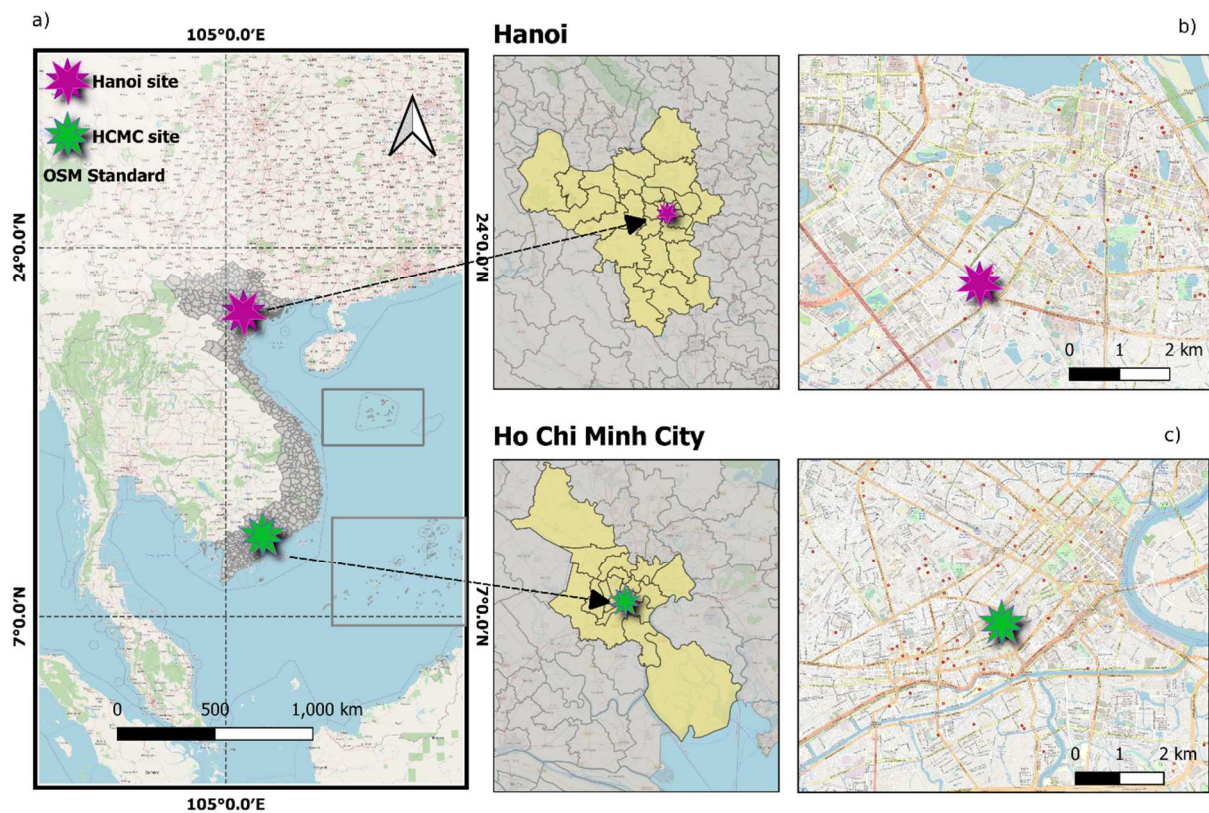
780 Wilde, S. E., Dominutti, P. A., Allen, G., Andrews, S. J., Bateson, P., Bauguitte, S. J.-B., Burton, R.
781 R., Colfescu, I., France, J., Hopkins, J. R., Huang, L., Jones, A. E., Lachlan-Cope, T., Lee, J. D.,
782 Lewis, A. C., Mobbs, S. D., Weiss, A., Young, S. and Purvis, R. M.: Speciation of VOC emissions
783 related to offshore North Sea oil and gas production, *Atmos. Chem. Phys.*, 21(5), 3741–3762,

784 doi:10.5194/acp-21-3741-2021, 2021.

785 Yokelson, R. J., Karl, T., Artaxo, P., Blake, D. R., Christian, T. J., Griffith, D. W., Guenther, A. and
786 Hao, W. M.: The Tropical Forest and Fire Emissions Experiment: overview and airborne fire emission
787 factor measurements, *Atmos. Chem. Phys.*, 7(19), 5175–5196, 2007.

788

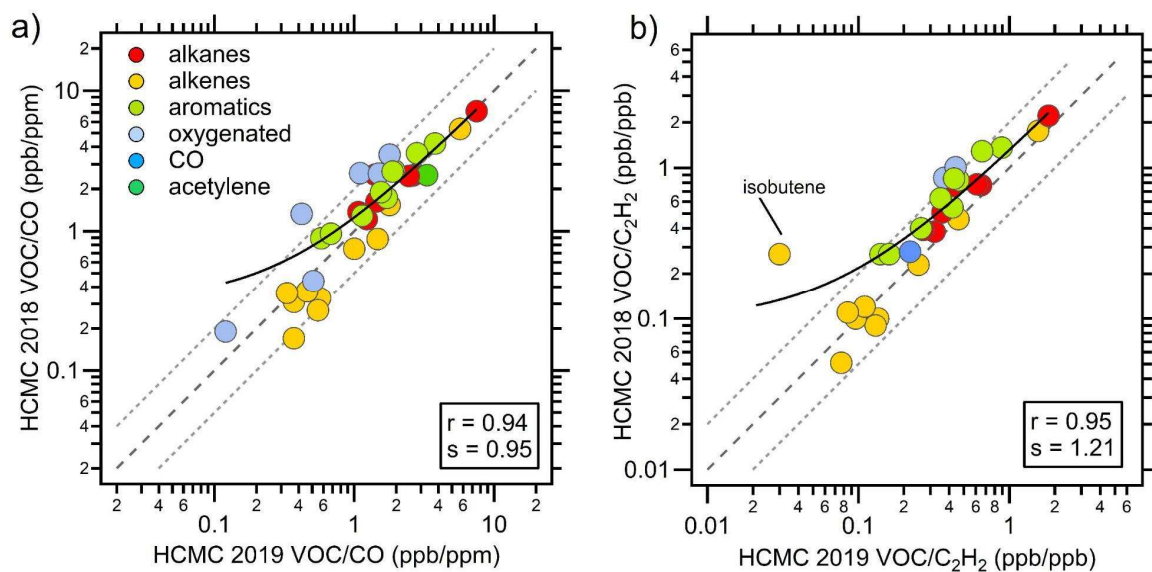
789



791

792 **Figure 1. Location of sampling points in Hanoi (purple star) and HCMC (green star) and their location**
 793 **in Vietnam. © OpenStreetMap contributors, 2021. a) location of Hanoi and HCMC in Vietnam, b)**
 794 **location of the sampling point in Hanoi and zoom to the Hanoi sampling area and c) location of the**
 795 **sampling point in HCMC and zoom to the HCMC sampling area.**

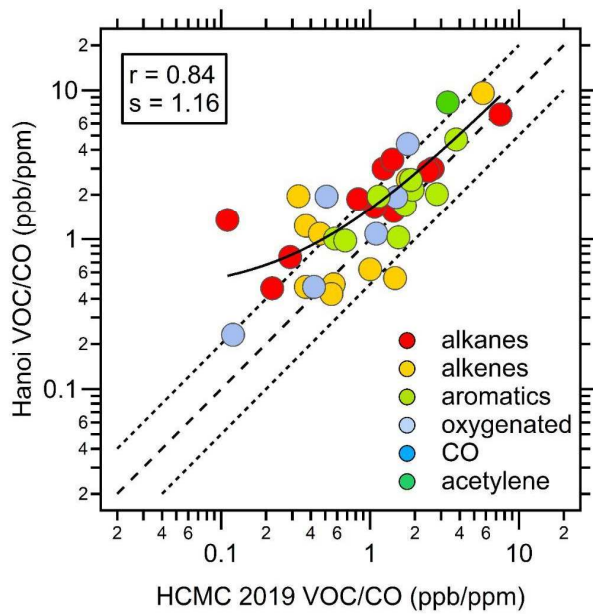
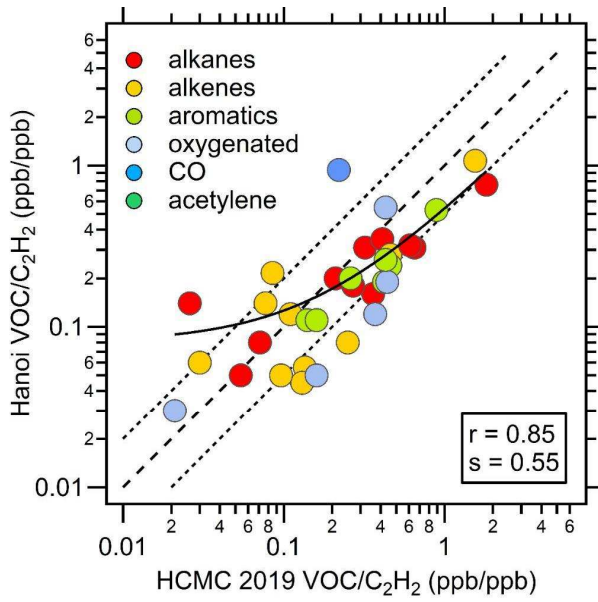
796



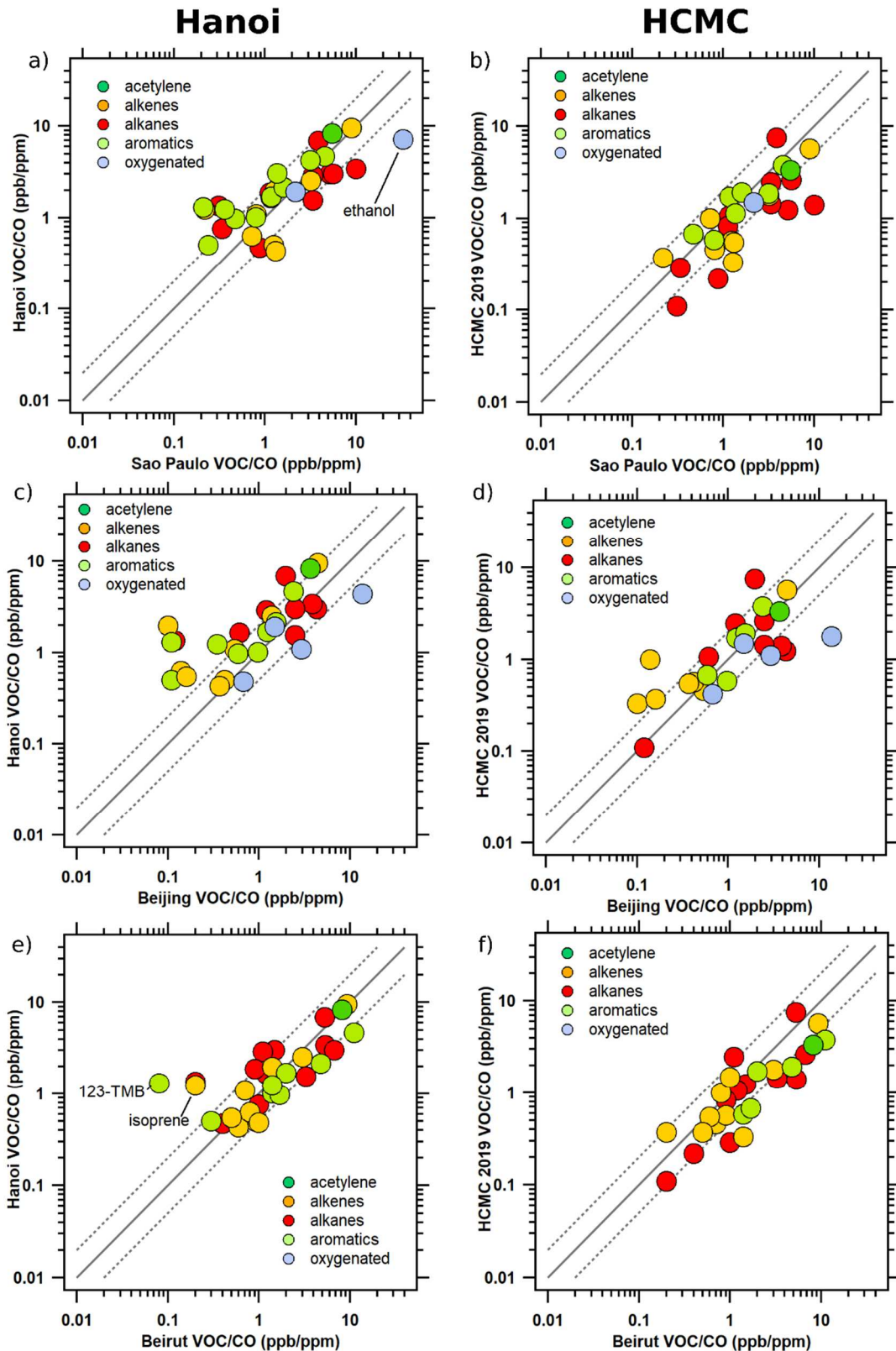
798

799 **Figure 2. Seasonal average emission ratios of VOC/CO (a) and VOC/C₂H₂ (b) obtained in HCMC in 2018**
 800 **and 2019, during rainy and dry seasons, respectively. Color-coded markers represent VOC families. The**
 801 **solid line represents the 1:1 relationship between sampling sites compared, and the dashed lines represent**
 802 **the difference within a factor of 2.**

803



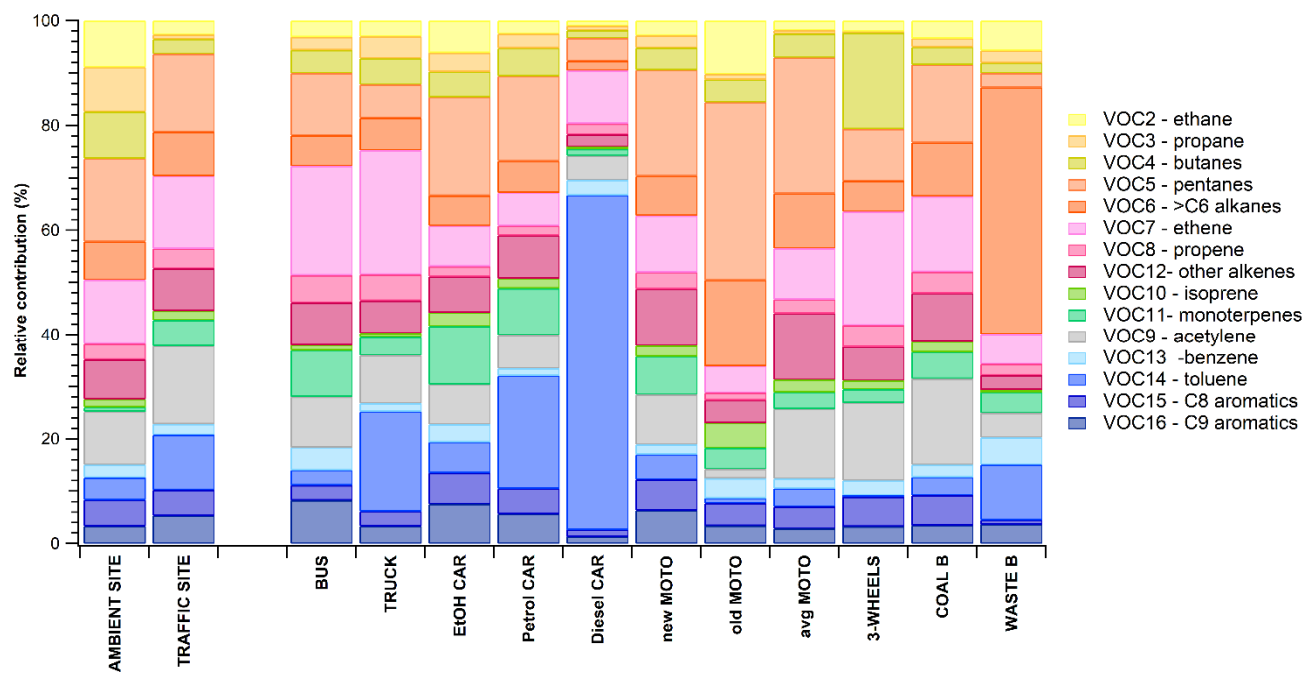
804
 805 **Figure 3.** Average emission ratios of VOC/C₂H₂ (a) and VOC/CO (b) were derived for each VOC species at both
 806 sampling sites in Hanoi and HCMC for 2019. Color-coded markers represent VOC families, the solid line
 807 represents the 1:1 relationship between sampling sites compared, and the dashed lines represent the difference by
 808 a factor of 2.
 809



810

811 **Figure 4.** Comparison of VOC to CO (ppb/ppm) emission ratios obtained at urban sites in Hanoi and HCMC and
 812 compared with those reported in the literature for a)-b) Sao Paulo, c)- d) Beijing, and e)- f) Beirut.

813

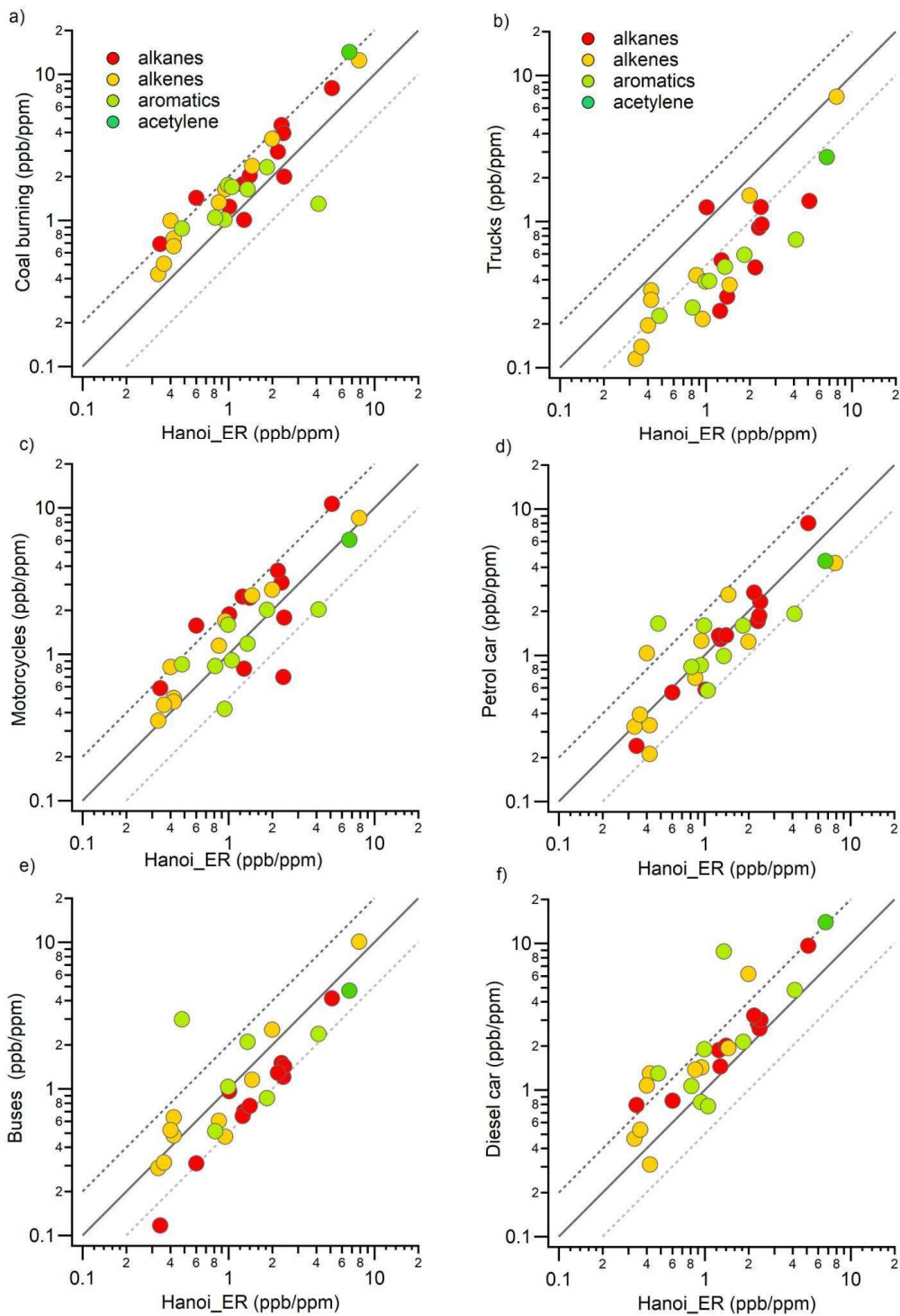


814

815 **Figure 5. The relative contribution of VOC group concentrations from emission sources to the total VOC**
 816 **mass measured and compared to the ambient and near-road traffic site profiles observed in Hanoi.**

817

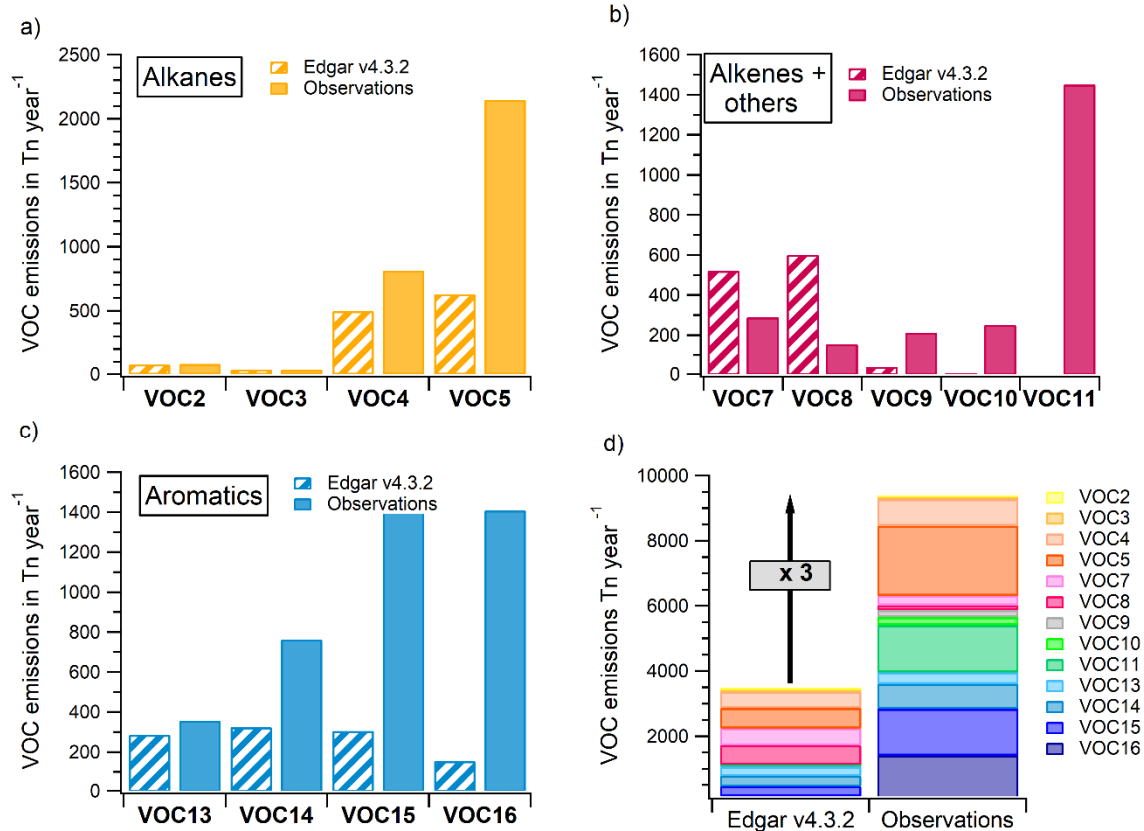
818



819

820 **Figure 6. Emission ratios comparison between the LRF method from ambient measurements and the**
 821 **averaged ones obtained near-source emissions in Hanoi for a) coal burning, b) trucks, c) motorcycles,**
 822 **d) petrol cars, e) buses, and f) diesel cars.**

823



824

825 **Figure 7. Absolute VOC emissions from the road transport sector estimated by the global inventory,**
 826 **EDGAR4.3.2, and our emission factors in Hanoi. a), b), and c) represent the emissions per group of VOC**
 827 **(alkanes, alkenes+others, and aromatics) estimated by the inventory in stripped bars and by our EF in**
 828 **solid bars. d) represent the total VOC emissions comparison between both estimations. Colors represent**
 829 **the VOC group following the methodology used in the inventory. Only the VOC groups with species in**
 830 **common were considered in this evaluation.**

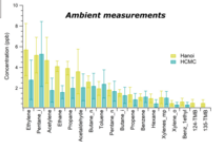
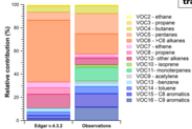
831

Sources vs Inventory

Chemical transformations



Ambient measurements



Road Transport emissions

Ambient VOC concentrations