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1 Particulate pollution in Korhogo and Abidjan (Cote d'Ivoire) during 2 the dry season.

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11 12 Abstract

13 Particulate pollution in West African cities seriously impacts public human health. Assessing
14 the levels of pollution to which populations are exposed is problematic, as to date very few
15 countries in Africa have an air quality monitoring network in place. However, given the specific
16 anthropogenic sources present in West African countries and the increase in their projected
17 emissions in the coming years if no regulations are put in place, solutions must be found. This study
18 evaluates with a simple existing methodology particulate air pollution in two West African cities
19 (Korhogo and Abidjan in Cote d'Ivoire) which have different population practices and local
20 meteorology.

21 From two measurement campaigns at about ten sites during the dry season and using the inverse
22 distance-weighted interpolation method, maps of spatial variation in PM₁₀ and PM_{2.5}
23 concentrations are obtained at the scale of each of these cities, which provide a snapshot of the
24 concentration levels to which populations are actually exposed. The results of this study showed
25 that populations in low- and middle-income areas are exposed to higher concentrations than those
26 in high-income areas. The analysis of the relative contribution of fine particles to coarse particles
27 shows that PM_{2.5} contributes to PM₁₀ at less than 40% in Korhogo but more than 50% in Abidjan.
28 Daily average concentrations of PM_{2.5} are all above WHO standards, and are 2 to 8 times higher in
29 Korhogo, while in Abidjan they are up to 4 times higher. The daily profiles of the mean hourly
30 concentrations of the sites are similar across all sites in Korhogo, while in Abidjan, that of some
31 sites show some differences.

32 This study, by the methodology used, offers an opportunity for different research teams to assess
33 at lower cost the population's exposure levels to urban particulate pollution.

34
35 **Keywords:** Urban air quality; Aerosols; Africa cities; PASMU project.

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36 INTRODUCTION

37 Air pollution is a global public health problem and its extent in the cities of many developing
38 countries is still poorly known (Kirenga *et al.*, 2015). Among all pollutants, particulate pollution is
39 highly harmful to health, especially in low- and middle-income countries (Kalisa *et al.*, 2019).
40 Recent studies have shown alarming levels of particulate pollutants in West African cities (Dieme
41 *et al.*, 2012 and Djossou *et al.*, 2018), due to various sources of pollution that are generally
42 uncontrolled and relatively close to living areas Val *et al.*, (2013) and Adon, (2019) highlighted the
43 inflammatory nature of particles rich in organic carbon (OC) and small in size emitted by urban
44 west African sources. Also, a few studies (Cohen *et al.*, 2005 and Liousse *et al.*, 2019) have shown
45 the importance of premature death estimations for cardiovascular, lung cancer and respiratory
46 diseases causes, due to anthropogenic fine particles in West Africa.

47 Anthropogenic sources are harmful in developing countries because of the absence or
48 ineffectiveness of regulations on pollutant emissions. The typical anthropogenic sources in sub-
49 Saharan Africa are domestic fires (biomass and gas for cooking), road traffic (combustion
50 emissions and dust resuspension), waste combustion, industrial activities (petrochemicals,
51 agriculture, construction. More precisely, air quality in Cote d'Ivoire and in West Africa, is
52 impacted by emissions from a very old vehicle fleet, on average 20 years according to the Ministry
53 of Transports, (2017), using poor quality fuel and from the use of traditional stoves with wood
54 and/or charcoal incomplete consumption. Furthermore, open burning of waste in urban areas of
55 Africa is a very common phenomenon due to the ineffectiveness of municipal waste collection and
56 management policies (Keita *et al.*, 2020). In addition to these local sources, there are important
57 imported sources of aerosols: (1) desert dust and natural savannah fire sources from prevailing
58 Harmattan wind (north wind) as well as (2) marine aerosols brought by monsoon flow (southwest
59 wind).

60 Unlike developed countries, most cities in the developing countries do not have the capacity to
61 monitor urban air concentrations in order to effectively solve the problem of air pollution. In West
62 Africa, Dakar (in Senegal), is the only city with an air quality monitoring network. Considering the
63 anthropogenic source diversity and their strength which is expected to increase if no regulation is
64 taken (Lioussé *et al.*, 2014), it is necessary to expand pollution studies in African cities.

65 Studies carried out in West Africa have shown high concentrations of PM_{2.5} and PM₁₀ in several
66 cities: Accra in Ghana (Dionisio *et al.*, 2010 and Arku *et al.*, 2008); Dakar in Senegal (Dieme *et*
67 *al.*, 2012 and Val *et al.*, 2013) and Bamako in Mali (Val *et al.*, 2013 and Antonel and Chowdhury,
68 2014). In the European program DACCIWA (Dynamic-Aerosol-Chemistry-Cloud Interactions in
69 West Africa), Djossou *et al.*, (2018) observed average concentrations (February 2015 to March
70 2016) in Abidjan (Cote d'Ivoire) and Cotonou (Benin), well above WHO standards. Similarly, in
71 the POLCA program (POLlution of African Capitals), Doumbia *et al.*, (2012) measured PM_{2.5}
72 concentrations at an urban site in Dakar from June 2008 to May 2009, which were above the WHO
73 standard. These various studies highlight overexposure of populations to atmospheric particles
74 whose economic impacts were assessed by Stern and van Dijk, (2017), and mortality by Cohen *et*
75 *al.*, (2005) and in Global Burden of Disease Study 2010 by Murray *et al.*, (2012). Also, within the
76 framework of DACCIWA, Keita *et al.*, (2020) have calculated emission factors (EF) for particulate
77 pollutants based on sources and considering the specificities of African regions in order to improve
78 emission inventories for these pollutants. These results showed very high EF values, highlighting
79 the importance of particulate pollutant emissions from sources such as domestic fires and traffic,
80 which are very important sources of pollution in West Africa. These different results are a challenge
81 for us and we must act.

82 The lack of air pollution monitoring networks, even in the most urbanized cities, due to the high
83 cost of acquiring and maintaining air quality measurement equipment can be offset by the

84 installation of low- and medium-cost sensors offering simple and inexpensive alternatives.
85 Although accessible, these sensors cannot be deployed always and everywhere. To overcome this
86 problem, an experimental existing methodology based on the use of low-cost sensors during
87 intensive measurement campaigns and a geostatistical treatment tool is used to assess particulate
88 air pollution in two cities of Cote d'Ivoire. Specifically, this study quantifies the level of PM₁₀ and
89 PM_{2.5} concentrations and their spatial and temporal distribution in these cities of different
90 geography and morphology (Korhogo and Abidjan). This work is carried out within the framework
91 of the project Air Pollution and Health in Urban Areas, Cote d'Ivoire (PASMU).

92 93 **METHODOLOGY**

94 95 **Description of the experimental sites**

96 In this study, two measurement campaigns were conducted successively in Korhogo (January
97 3rd to January 16th) and in Abidjan (January 20th to February 10th, 2019), whose economic activities,
98 transport specificities and types of roads, cooking fuels, population practices and local meteorology
99 differ. As shown in Fig. 1, the population densities of these two cities are also very different, with
100 a population of Abidjan 10 times that of Korhogo. It can also be noticed that population densities
101 from south to center of Cote d'Ivoire are generally higher compared to areas further north. The
102 population density of Korhogo remains high for a northern region due to agricultural industries. In
103 each city, the measurement sites are chosen to allow representative mapping of the variability of
104 pollution including different districts. Generally, measurement sites can be of 3 types: (1) *Local*
105 *stations*, generally used to control classified establishments, are located in proximity of the polluted
106 source to be monitored and therefore under the direct influence of this pollution source; (2) *Urban*
107 *background stations*, used to monitor urban pollution, are located in an urban environment but

108 under the indirect influence of pollution sources, and (3) *Background stations*, are located in a peri-
109 urban environment. It is important to note that local stations are therefore not included in this study
110 as they only provide very local information (Jeannée *et al.*, 2006). In our study, urban background
111 stations are mainly influenced by major west-African urban sources, i.e. the domestic fires, the
112 waste burning and the road traffic (from combustion or non-combustion). In addition, dust
113 resuspension of particulate matter is also important because of road conditions and urban
114 developments. In this study, 14 non-permanent sites in Korhogo and 20 in Abidjan were sampled
115 for 3 days (2 working days and 1 weekend day). The 2 cities and their sampling sites are described
116 below.

117 ***Korhogo sampling sites***

118 Korhogo is the third largest city in Cote d'Ivoire in terms of population. A large part of the city's
119 area is not built. Korhogo is a city still marked by agricultural activities with a few rare agricultural
120 product factories for processing and packaging. The principal sources of anthropogenic emissions
121 in Korhogo are traffic sources with intense activities of heavy vehicles, national bus line but also
122 motorcycle traffic, which is a particularity of Korhogo. Furthermore, in this city, only main roads
123 are paved and represent, 10% of the urban roads (AGEROUTE, 2020). This implies important road
124 resuspension of aerosols which is also a major source of PM emissions. Another important
125 anthropogenic source is the domestic fire with the use of firewood for economic reasons or for
126 convenience as because these resources are still available in the surrounding villages. In addition
127 to the local anthropogenic sources present in Korhogo, the harmattan wind is a major contributor
128 of PM in the dry season with desert dust, biomass burning and aerosol transport. Fig. 2 shows the
129 geographical distribution of the 14 measurement sites as well as the boundaries of the city of
130 Korhogo. Also, the specificities of each sites are summarized in Table S1 (in Supplementary files),
131 where are mentioned site localizations as well as roads infrastructure and possible sources of

132 pollution around. Additional information like that geographic positions of Korhogo measurement
133 sites is given in Table S2 (in Supplementary files). Sites K₂, K₁₀, K₁₁ and K₁₄ are surrounded by
134 paved roads (i.e. under the influence of the traffic source) and far from other urban sources. The
135 other sites are located in residential areas where wood is used extensively for cooking, with the
136 exception of K₁ site which is in a peri-urban area but close to a major traffic road.

137

138 *Abidjan sampling sites*

139 Abidjan is the economic capital regrouping the main industrial activities with a population of
140 4,707,404 inhabitants for an area of 2,119 km² according to the General Census of Population and
141 Housing (RGPH, 2014).

142 Abidjan is an Autonomous District with different levels of urbanization and includes
143 populations of different social classes. Its principal anthropic sources are also traffic, domestic fires
144 and waste burning sources with different practices depending on the communes. For instance, wood
145 is intensively used in the commune of Yopougon whereas the use of gas dominates in Cocody.
146 Less road dust particles compared to Korhogo are expected since more than 50% of roads are paved
147 according to MCLAU, (2015), (MCLAU for *Ministère de la Construction, du Logement, de*
148 *l'Assainissement et de l'Urbanisme*). However, this value also depends on the communes. In
149 Cocody, Le Plateau and Marcory, a higher percentage of paved roads are observed compared to
150 Abobo and Yopougon, where a large part of the city population lives.

151 Fig. 3 shows the geographical distribution of the measurement sites in Abidjan and boundaries
152 of the sampled communes, which represent the study area of this city. In Supplementary files, Table
153 S5 provides information on the 20 sites sampled in Abidjan. In this study, only the sub-prefecture
154 of Bingerville (Abidjan peripheral municipality) is associated with the 10 municipalities of Abidjan,
155 because Bingerville city is completely integrated into Abidjan. As shown in, in Supplementary files,

156 in Table S5, measurement sites are located in neighborhoods inhabited by high-income populations
157 (A1, A2, A11, A20, A4, A6, A8, A14, A15), middle (A18) and low (A3, A5, A7, A9, A10, A12, A13, A16,
158 A17, A19). The latter sites are generally close to unpaved roads. In addition, Table S6 (in
159 Supplementary files), give latitude and longitude of Abidjan measurement sites.

160

161 ***Meteorological data and surrounding pollution***

162 To assess the impacts of weather parameters on PM concentration levels measured at each site
163 during the 3-day sampling period, temperature, wind intensity and direction are analyzed at local
164 and regional scales. These meteorological parameters are obtained from the data of the synoptic
165 stations managed by the Agency for the Safety of Air Navigation in Africa and Madagascar
166 (ASECNA) at Korhogo Airport (station No. 65536) and at Felix Houphouet-Boigny Airport in
167 Abidjan (station No. 65578).

168 Average daily temperatures (available on [https://www.accuweather.com/fr/ci/cote-divoire-
169 weather](https://www.accuweather.com/fr/ci/cote-divoire-weather)) show a range of 32 to 36 °C in Korhogo and 31 to 35 °C in Abidjan. These daily averages
170 do not vary by more than one degree over several consecutive days. This may suggest stability of
171 the atmosphere.

172 Wind roses presented in Fig. 4 highlight important north (N) and north-east (NE) winds in
173 Korhogo (Fig. 4 (a)) and south-west (SW) winds in Abidjan (Fig. 4 (b)). The regional climate is
174 defined by the position of the Intertropical Convergence Zone (ITCZ), which regulates the
175 succession of weather seasons (Nouaceur and Murarescu, 2020). During measurement campaign,
176 the ITCZ is located above the latitude of Abidjan, favoring the arrival of air masses from the south
177 to Abidjan and air masses from the north to Korhogo where high temperature and low relative
178 humidity are typical for dry seasonal conditions. Such features are confirmed by the use of
179 HYSPLIT trajectories (https://www.ready.noaa.gov/HYSPLIT_traj.php) as shown by Fig. S1 (in

180 Supplementary files). HYSPLIT trajectories represent the movement of air masses arriving at the
181 study areas during the measurement campaigns. Fig. S1 shows 14- and 21-days back-trajectories
182 before the end dates of each measurement campaign respectively for Korhogo and Abidjan
183 respectively. It gives an overview of the dominant air mass origins over the measurement period.
184 As expected, Korhogo is under the influence of northern trajectories whereas Abidjan is under the
185 influence of southern air masses, associated to air masses coming from the Nigerian coast.

186 In order to identify which aerosols could be advected into Korhogo and Abidjan using these
187 trajectories, emphasis was put on MODIS active fire maps and Aerosol Optical Thickness data
188 (AOD), obtained from <https://neo.sci.gsfc.nasa.gov>. Figs. S2 present actives fires (a and b) and
189 Aerosol Optical Depth (c and d) in January (a and c) and February (b and d) 2019, representative
190 of the study period. Associated with Figs. S1, this shows that Korhogo is under the influence of
191 regional winds that carry desert dust and biomass burning aerosols coming from the north and south
192 of the city. While at Abidjan these regional winds show that only marine aerosols are expected.

193

194 **Material and Methods**

195 *Measurement campaigns and equipment*

196

197 The first step of the methodology deals with intensive data collection through measurement
198 campaigns conducted at sites in the two cities, as presented in previously. The measurement
199 campaigns of PM₁₀ and PM_{2.5} concentrations were carried out with 4 portables PM measuring
200 devices (Aeroqual monitor S500 with PM₁₀/PM_{2.5} sensor). Particulate pollution is measured over
201 3 days at each site, with 2 consecutive working days and 1 weekend day, because these 2 periods
202 (working and weekends days) present different activities levels in urban areas. Indeed, studies have
203 shown different levels of pollution at these 2 periods of the week (Adame *et al.*, 2014; Doumbia *et*

204 *al.*, 2012; Adon *et al.*, 2020). During the campaigns, the measurements are not simultaneous on all
205 sites of each city because rotations are organized. During the campaigns, the measurements are not
206 simultaneous on all sites of each city. Rotations are organized with at maximum 4 sites running in
207 parallel. This is possible due to atmospheric stability detailed in the meteorological paragraph. This
208 technique of measuring on non-permanent sites during short periods allows to maximize
209 measurements on a large number of non-permanent sites with a small number of equipment.

210 In this study, optical PM₁₀/PM_{2.5} sensor on S500 Aeroqual monitor is used to measure
211 particulate pollution, because it is easy to use and take up very little space. This sensor covers a
212 concentration range from 0 to 1000 µg m⁻³, and simultaneously measures PM₁₀ and PM_{2.5}. These
213 types of sensors are based on light scattering and have an accuracy that can be influenced by the
214 physical and chemical characteristics of aerosols (Wang *et al.*, 2015). The measuring device has
215 been placed in a box to protect it from natural elements. The device is installed at a height of
216 between 2 and 3 m. The time step chosen is 3 minutes, in order to allow fine sampling and to store
217 the data over the entire measurement period. After data retrieval, the data logger of the equipment
218 is formatted before being installed at another site.

219 *Quality Control data:* The evaluation of the uncertainties associated with low- and middle-cost
220 sensor measurements is the subject of several studies, as shown by Wang *et al.*, (2015) who tested
221 3 low-cost sensors in combustion chambers with different results. Consequently, it is necessary to
222 evaluate and correct optical sensor concentration measurements against a reference method
223 (Clements *et al.*, 2017). The reference method here proposed, is the gravimetric method. At some
224 of the selected sites, aerosol sampling lines are installed, including a fixed flow pump, a volume
225 meter, a valve, an aerosol size selection system (cane or cut-off head). These lines allow sampling
226 by filtration of aerosols on quartz filters, over the same periods the same sites than the low-cost
227 sensor measurements. The filters are weighed on a submicron balance before and after exposure in

228 order to deduce the collected aerosol masses. This reference method has been used and validated
229 in several research projects and programs such as the International Network to study Deposition
230 and Atmospheric chemistry in Africa (INDAAF) program (ref.) and the DACCIWA program
231 (Djossou, 2018).

232 Geometrical means of the measurements obtained with low-cost sensors are compared with
233 those obtained by the gravimetric method (reference method). Geometrical means concentrations
234 of optical sensors are consistently lower than the gravimetric concentrations of 2.7 ± 1.1 and 3.5 ± 0.9
235 for PM_{10} and $PM_{2.5}$ respectively. The standard deviation of these coefficients is higher for PM_{10}
236 than for $PM_{2.5}$, the latter having more points of comparison. It is worth noting that these values are
237 in agreement with those of Zuidema *et al.*, (2019) who showed the need for a correction factor of
238 2.9 for an optical photometric sensor (GP2Y1010AU0F, Sharp Electronics, Osaka, Japan)
239 compared to the gravimetric method. Similarly, Egondi *et al.*, (2016) also showed overestimated
240 concentration values given by the DustTrak II 8532 portable samplers compared to a reference
241 method. These factors (2.7 and 3.5) are then applied to PM_{10} and $PM_{2.5}$ concentrations at all
242 measurement sites.

243

244 ***Spatial mapping***

245 Geographic Information System (GIS) provide a robust method of spatial analysis through
246 interpolation. The most commonly used methods, kriging (geostatistical method) and reverse
247 weighting of IDW (deterministic method), have already been compared in works. For example,
248 Shukla *et al.*, (2020) in the Delhi megacity showed that kriging and IDW methods are associated
249 to errors close to 22% and 24% respectively. In addition, Bahino *et al.*, (2018) carried out a spatial
250 distribution of gaseous pollutants (NO_2 , SO_2 , NH_3 , HNO_3 and O_3) in Abidjan (Cote d'Ivoire) and
251 Cotonou (Benin) during the dry season within DACCIWA Program. The latter study included also

252 a comparison between kriging and IDW, and showed that IDW method is associated to lower
253 uncertainty than kriging method. In addition, our measurement network (number of points and
254 geographic locations) is developed on the basis of the network of Bahino *et al.*, (2018); therefore,
255 in this study, the IDW method is chosen and applied to the collected data.

256 ArcGIS version 10.3 software (ESRI Inc.) is used because it combines geostatistical data
257 processing and map edition. The shapefiles for map editing are available for free on OpenStreetMap
258 (<https://www.openstreetmap.org>). Briefly, IDW interpolation allows to predict the concentrations
259 around a sampled point from the following formula presented in Eq. (1).

$$260 \quad Z_{pj} = \sum_{i=1}^N \lambda_i * Z_{O_i} \quad (1)$$

261 where,

262 Z_{O_i} is the observed value at location i ; form geometrical mean of measured values at each site
263 during the different measurement campaigns. These geometrical means, averages deviation,
264 minimums and maximum are available, for Korhogo in Table S3 (for PM₁₀) and Table S4 (for
265 PM_{2.5}) and for Abidjan in Table S7 (for PM₁₀) and Table S8 (for PM_{2.5}), in Supplementary files for
266 each site.

267 Z_{pj} is the predicted value for location j ;

268 N is the number of measured sample points surrounding the predicted location that will be used in
269 the prediction;

270 λ_i are weighting factors applied at each measured value at location O_i . They decrease according
271 to the separation distance.

272 The geostatistical analysis of the data enables the values to be evaluated in order to develop the
273 spatial variation maps. Thus, the IDW method calculates values from the collected data for each
274 point (unsampled and sampled) and gives average predicted values everywhere (Rivera-González
275 *et al.*, 2015; Zamri *et al.*, 2012; Bahino *et al.*, 2018).

276 The Root Mean Square Error (RMSE) (McKeen *et al.*, 2005; Savage *et al.*, 2013; Chai and Draxler,
277 2014) and the Mean Absolute Error (MAE) (Taylor *et al.*, (2013); Chatterjee *et al.*, (2013) and
278 Jerez *et al.*, (2013) are the two parameters widely used to evaluate the quality of the predictions of
279 interpolation methods. In order to assess the quality of the prediction in the two cities, both RMSE
280 and MAE values are calculated for each measurement campaign following the formulas present in
281 Eqs. (2) and (3).

$$282 \quad RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Z_{P_i} - Z_{O_i})^2} \quad (2)$$

$$283 \quad MAE = \frac{1}{N} \sum_{i=1}^N |Z_{P_i} - Z_{O_i}| \quad (3)$$

284 where,

285 Z_{P_i} and Z_{O_i} are respectively the predicted and observed value for a location i ;

286 N is the number of measured sample point.

287 Table 1 presents such values for the 2 cities as well as the coefficient of variation of error. In
288 Abidjan, the MAE values are lower than the RMSE values due to the high uncertainties associated
289 with some sites whereas no marked differences appear in Korhogo. Also, both coefficients are
290 higher in Korhogo than in Abidjan: that could be due to the high concentration values found in
291 Korhogo. As shown in Table 1, the coefficients of variation of error in Abidjan are higher than in
292 Korhogo. These low values obtained in Korhogo may be due to a smaller study area than in Abidjan.
293 This analysis highlights the impact of the distance between measurement sites on the uncertainties.

294

295 **RESULTS AND DISCUSSIONS**

296

297 **Spatial distribution of PM concentrations**

298 *Korhogo PM concentrations maps*

299 As previously described, the PM₁₀ and PM_{2.5} concentrations obtained by geographical averages
300 allowed the mapping of spatial variations for the Korhogo study area. These maps are presented in
301 Figs. 5(a) and 5(b), respectively for the PM₁₀ and PM_{2.5}. Concentrations are very high, between
302 212.2 $\mu\text{g m}^{-3}$ and 534.7 $\mu\text{g m}^{-3}$ for PM₁₀ and 54.3 $\mu\text{g m}^{-3}$ and 218 $\mu\text{g m}^{-3}$ for PM_{2.5} and well above
303 the World Health Organization (WHO) standards which stipulate that PM_{2.5} should not exceed 25
304 $\mu\text{g m}^{-3}$ 24-hours mean and that PM₁₀ not exceed 50 $\mu\text{g m}^{-3}$ 24-hours mean.

305 As shown in Fig. 5(a), the measurement sites in the city downtown have higher PM₁₀ concentrations,
306 namely K₂ with 534.7 $\mu\text{g m}^{-3}$, K₆ with 374.4 $\mu\text{g m}^{-3}$, K₁₁ with 475.1 $\mu\text{g m}^{-3}$ and K₁₄ with 446.7 $\mu\text{g m}^{-3}$
307 m^{-3} compared to the sites in the northern and southern outskirts of the city such as K₁ with 241.4
308 $\mu\text{g m}^{-3}$, K₈ with 245.1 $\mu\text{g m}^{-3}$ and K₁₂ with 261.2 $\mu\text{g m}^{-3}$. This can be explained by the economic
309 activities mainly occurring in Korhogo downtown, associated with intense road traffic dominated
310 by 2-wheel vehicles and the presence of the urban bus stations. The highest concentrations observed
311 in K₂, K₁₁ and K₁₄ sites are also due to the proximity of busy highways.

312 K₁₃ and K₅ sites have also high PM₁₀ concentrations because they are in neighborhoods with
313 unpaved roads. Moreover, even if downtown roads are mostly paved, a high resuspension of dust
314 by intense traffic is also observed. Indeed, as mentioned earlier, dust deposition on roads are also
315 observed at Korhogo due to northerly air masses transporting desert dust aerosols at the period of
316 this study (Fig. S1). Such aerosols significantly contribute to the pollution level of Korhogo.

317 Finally, Fig. 5(a) shows that in Korhogo, PM_{2.5} and PM₁₀ spatial variation maps roughly present
318 the same pattern of high and low concentrations despite some differences which are detailed in the
319 following section.

320

321 *Abidjan PM concentrations maps*

322 The spatial variation maps of PM₁₀ and PM_{2.5} concentrations (obtained from the geographical
323 averages of the measured concentration time series) in Abidjan study area are given respectively
324 in Figs. 6(a) and 6(b). The average concentrations are between 38.1 $\mu\text{g m}^{-3}$ and 160.4 $\mu\text{g m}^{-3}$ for
325 PM₁₀ and 23.8 $\mu\text{g m}^{-3}$ and 113.4 $\mu\text{g m}^{-3}$ for PM_{2.5}. For PM₁₀, the highest concentrations are found
326 at sites A₇ (160.4 $\mu\text{g m}^{-3}$), A₁₈ (125.3 $\mu\text{g m}^{-3}$) and A₂₀ (120.7 $\mu\text{g m}^{-3}$). The A₇ and A₂₀ sites are
327 located nearby unpaved roads (Table S2) therefore, dust from road resuspension contribute to the
328 increase of concentrations. In A₁₈ site, the high concentrations may be explained by the proximity
329 of important road traffic and industrial activities. In addition, A₁₈ and A₁₉ sites are located on the sea
330 front, and are therefore subject to a high contribution of marine aerosols.

331 Sites included in areas with better quality infrastructures and with middle- or high-class
332 populations, have generally lower PM₁₀ concentrations (e.g. A₂, A₁₁) compared to sites in
333 neighborhoods with poor quality infrastructures (e.g. A₃, A₅, A₇, A₈, A₁₆, A₁₈ and A₂₀).

334 Compared to PM₁₀, PM_{2.5} spatial variation (Fig. 6(b)) presents high concentrations over most of
335 the study area, despite some very localized low concentrations in A₁ (32.9 $\mu\text{g m}^{-3}$), A₂ (24.9 $\mu\text{g m}^{-3}$),
336 A₅ (30.8 $\mu\text{g m}^{-3}$), A₁₄ (23.8 $\mu\text{g m}^{-3}$) and A₁₉ (24.5 $\mu\text{g m}^{-3}$). PM_{2.5} concentrations in northern
337 Abidjan are higher than in southern Abidjan. Indeed, the wind rose of Abidjan shows a dominance
338 of south, southwest winds, which could lead to a transport and an accumulation of pollutants in the
339 northern area of the city, as for Bahino *et al.*, (2018). Values for these sites (A₇ with 113.4 $\mu\text{g m}^{-3}$,
340 A₉ with 91.7 $\mu\text{g m}^{-3}$, A₁₂ with 73.2 $\mu\text{g m}^{-3}$ and A₂₀ with 91 $\mu\text{g m}^{-3}$) are 2 to 6 times higher than the
341 WHO daily standard (25 $\mu\text{g m}^{-3}$). Moreover, these sites mainly appear in low income neighborhood.
342 Indeed, in such areas, high concentrations result from the combination of the use of wood for
343 cooking, the proximity of public transport (small bus: gbaka, municipal taxis: wôrô-wôrô) with
344 very old and poorly maintained vehicles and the burning of solid domestic waste due to collection

345 failure. In contrary, the less densely populated areas (high-class districts) have lower concentrations
346 (sites A₁, A₂, A₁₄) than the medium and low-class districts. In these areas (sites A₁, A₂, A₁₄), people
347 have higher incomes and are more likely to use gas for cooking than wood and charcoal for cooking
348 activities. Lower concentrations are observed in A₅ and A₁₉ sites, although located in popular
349 districts. That may be due to less intensive combustion activities than usually observed in these
350 districts for the A₅ site and to the proximity of the sea front for A₁₉ site.

351

352 **Relative importance of fine particles**

353 In order to highlight the relative contribution of particulate size and aerosol sources, spatial
354 variation maps of the percentage of relative contribution of PM_{2.5} to PM₁₀ are presented in Figs. 7
355 and 8 for Korhogo and Abidjan respectively. Low values represent a high contribution of PM_{2.5} to
356 PM₁₀, while high percentages represent a low contribution of PM_{2.5} to PM₁₀. It is important to note
357 that these figures show totally different values for the two cities. In Korhogo, more than 50% of
358 PM₁₀ are coarse particles, with the highest values in the north and south of the city and the lowest
359 values in the city center, where most urban activities take place. In Abidjan, the situation is totally
360 different: coarse particles in PM₁₀ represent less than 40%, with the highest values in A₄, A₅, A₁₄,
361 A₁₈ and A₁₉ sites and the lowest values in A₆, A₉, A₁₁, A₁₂, A₁₃ and A₁₅.

362 In both cities, the lowest values associated with high PM_{2.5} are found particularly in densely
363 populated sites or in economically very active neighborhoods with intense combustion sources and
364 fine particle emissions. In addition, the percentages of coarse particles (PM_{2.5-10}) relative to PM₁₀
365 are high near unpaved roads and sometimes in areas with heavy traffic.

366 In Abidjan, low contributions of PM_{2.5} to PM₁₀ are also observed in industrial areas (site A₁₈).
367 In these areas, heavy truck traffic damages the roads and causes dust resuspension. In addition, a
368 contribution from marine aerosols is possible due to the south-westerly (SW) wind direction. These

369 values are in line with our expectations and confirm the good representation of the measurement
370 sites and the good performance of the spatial distribution, because they reflect the main sources of
371 pollution that influence each city.

372

373 **Daily distribution of PM concentrations**

374 Daily profiles of fifteen minutes average concentrations of PM are shown in Fig. 9. The average
375 daily profiles of PM₁₀ and PM_{2.5} concentrations in Korhogo are presented in Figs. 9(a) and 9(b)
376 respectively. For Abidjan, Figs. 9(c) and 9(d) represent the sites with similar patterns of PM_{2.5}
377 concentrations and the other sites respectively. Since PM₁₀ and PM_{2.5} daily profiles are similar in
378 Abidjan, only PM_{2.5} concentrations are presented here. Note that the daily profiles of PM₁₀
379 concentrations in Abidjan are shown in Figs. S5(a) and S5(b).

380 In Korhogo, all the sites show the same daily average concentration profiles for PM₁₀ and PM_{2.5}
381 respectively in Figs. 9(a) and 9(b), with two very important daily peaks. One peak in the morning
382 and one in the evening. These peaks are due to the mix of several local sources: mainly, household
383 sweepings (twice a day), use of firewood (morning and evening), and road traffic (dominated by
384 2-wheelers). Focusing on these peaks, PM_{2.5} morning and evening peaks are of similar importance
385 whereas PM₁₀ peak is higher in the evening than in the morning. This could be due to favorable
386 conditions for dust resuspension due to the higher dryness of the soil in the evening caused by
387 sunshine during the day. According to Cheng and Li (2010) and Gualtieri *et al.*, (2015),
388 meteorological parameters such as temperature and relative humidity influence particulate matter
389 concentrations. Moreover, the low values observed during the day, twenty times lower than in
390 morning could be due to a decrease of urban activities. However, it is interesting to note that such
391 low average concentrations observed in Korhogo are still higher than the WHO daily standard.

392 In Abidjan, Fig. 9(c) shows morning peaks of concentrations which are more important than
393 those of the evening. Traffic source are mainly responsible of these peaks. The difference between
394 the morning and evening peaks can be explained by the fact that the flow of road traffic in the
395 evening is more spread out in time compared to that of the morning. In Fig. 9(d), some sites show
396 no clear daily variation. For example, A₁₈ and A₂₀ sites show high concentrations throughout the
397 day, characteristic of local economic activities. Indeed, the A₈, A₁₈ and A₂₀ sites are respectively
398 located in a low-income neighborhood (mainly using wood and charcoal for cooking), in a
399 neighborhood under construction and in an industrial area respectively. The daily minimum
400 average concentrations are 19.3 $\mu\text{g m}^{-3}$ for PM₁₀ and 14 $\mu\text{g m}^{-3}$ for PM_{2.5}. These low values are
401 compensated by the high values observed during peaks (beyond 350 $\mu\text{g m}^{-3}$ as well as PM₁₀ and
402 PM_{2.5}), thus providing a daily average concentration well above WHO standards. To conclude, this
403 data collection methodology provides daily profiles of PM concentrations, which are important in
404 the analysis of population exposure levels.

405

406 **Comparison with other Sub-Saharan Africa cities**

407 Concentrations of PM₁₀ and PM_{2.5} in Korhogo and Abidjan are generally above the WHO daily
408 exposure standard. As shown previously the local variability of these concentrations is strongly
409 related to the predominant local sources.

410 Concentrations vary on average from 212.2 $\mu\text{g m}^{-3}$ to 534.7 $\mu\text{g m}^{-3}$ for PM₁₀ and from 57.4 μg
411 m^{-3} to 230.4 $\mu\text{g m}^{-3}$ for PM_{2.5} in Korhogo and in Abidjan, from 38.1 $\mu\text{g m}^{-3}$ to 160.4 $\mu\text{g m}^{-3}$ for
412 PM₁₀ and from 23.8 $\mu\text{g m}^{-3}$ to 113.4 $\mu\text{g m}^{-3}$ for PM_{2.5}. The mean standard deviations of measured
413 concentrations are of 89 $\mu\text{g m}^{-3}$ and 23.5 $\mu\text{g m}^{-3}$ for PM₁₀ and of 41.5 $\mu\text{g m}^{-3}$ and 17.9 $\mu\text{g m}^{-3}$ for
414 PM_{2.5} respectively in Korhogo and Abidjan. The standard deviation values are lower in Abidjan
415 compared to Korhogo, which shows a greater variability in the latter. The maximum concentrations

416 in Korhogo are respectively more than 3 to 5 times higher than in Abidjan whereas the minimum
417 are 2 to 3 times higher. As already mentioned, this may be explained by additional aerosol sources
418 occurring in Korhogo such as dust aerosol coming from northern African areas and/or from
419 unpaved roads and the 2-wheel emissions.

420 Table 2 presents the daily concentrations measured in African urban areas by this study,
421 compared to literature results for Sub-Saharan Africa. PM_{2.5} concentrations measured in this study
422 are lower than those measured with the individual exposures of Xu *et al.*, (2019) in Abidjan.
423 Personal exposure measurements are generally closer to the emission sources than our sites.

424 The PM₁₀ measurements performed by Ana *et al.*, (2014) from January to March 2008 in Ibadan
425 (Nigeria) are on the same order of magnitude as the concentrations measured at Korhogo in January
426 2019. These PM₁₀ concentration levels are characteristic of the dry season in West Africa. For the
427 same period of the year, Antonel and Chowdhury (2014) found lower PM₁₀ concentrations (105 µg
428 m⁻³) in Bafossam (Cameroon), which is further south, in a forest area, therefore less exposed to
429 dust. Furthermore, the results obtained by Dionisio *et al.*, (2010) showed that concentrations in
430 low-income areas are higher than in high-income areas in Accra, which is in agreement with the
431 results of this study. Finally, the ranges of concentrations obtained at Korhogo (in Tables S3 and
432 S) and Abidjan (in Tables S7 and S8) measurement sites are on the same order of magnitude as
433 those obtained in other studies carried out in Sub-Saharan Africa. Values from other studies
434 conducted in Africa are presented in Table S9 and agree very well with the results of this study.

435

436 **CONCLUSIONS**

437

438 This study provides an assessment of air quality in the cities of Korhogo and Abidjan in Cote
439 d'Ivoire by proposing for the first time to our knowledge, spatial variation maps of PM₁₀ and PM_{2.5}

440 concentrations. It is part of the objectives of the PASMU project, which aims to characterize urban
441 air pollution and its impact on health in Cote d'Ivoire.

442 The use of low-cost sensors at 14 sites in Korhogo and 20 in Abidjan resulted in daily average
443 PM₁₀ concentrations ranging from 212.2 $\mu\text{g m}^{-3}$ to 534.7 $\mu\text{g m}^{-3}$ in Korhogo and from 38.1 $\mu\text{g m}^{-3}$
444 to 160.4 $\mu\text{g m}^{-3}$ in Abidjan. PM_{2.5} concentrations range from 57.4 $\mu\text{g m}^{-3}$ to 230.4 $\mu\text{g m}^{-3}$ and from
445 23.8 $\mu\text{g m}^{-3}$ to 113.4 $\mu\text{g m}^{-3}$ in Korhogo and Abidjan respectively.

446 The spatial variation maps obtained through the application of GIS in Korhogo show that the
447 high activity areas (market and national bus station) have higher PM₁₀ and PM_{2.5} concentration
448 levels than other areas. Our study also highlights that the relative contribution of PM_{2.5} to PM₁₀ is
449 very different in Korhogo and Abidjan, varying from 50 to 100% in Abidjan, while 20 to 50% in
450 Korhogo. In Abidjan, a difference between the concentrations is observed in high- and low-income
451 neighborhoods, with higher concentration levels in low- and middle-income neighborhoods. One
452 likely reason is that, high-income areas have better services (roads, waste collection, ...), and also
453 use less polluting cooking methods (e.g. gas). This result can be also explained by the status of the
454 city: (1) in Korhogo, the higher presence of coarse particles is due to anthropogenic (road dust
455 resuspension) and natural sources (desert dust transport); (2) Abidjan is an economic capital with
456 a higher population density, road traffic and generally a higher activity density than in Korhogo.
457 The concentrations measured in this work are comparable to previous studies conducted in Abidjan
458 and in Africa.

459 In conclusion, this study indicates that this simple and reproductive method provides a quality
460 assessment of particulate pollution at the city level. Note that this method could be also used for
461 other purposes such as performing a quick assessment of the impact of a new industrial unit or
462 infrastructure on the surrounding air quality. Finally, the original results obtained on urban

463 particulate pollution in Korhogo and Abidjan, relative contribution of fine particle to coarse and
464 daily variations of PM concentrations will be very useful for urban modelling in West African cities.
465

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478 479 **DISCLAIMER**

480
481 The authors decline any commercial link with the companies producing equipment or software
482 used in this study.

483

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List of Table titles

Table 1. Interpolation error statistics, where RMSE is root mean absolute error in $\mu\text{g m}^{-3}$; MAE is mean average error in $\mu\text{g m}^{-3}$ and CV is mean of coefficient of variation of error in %.

Table 2. Comparison between PM_{10} and $\text{PM}_{2.5}$ daily concentrations obtained in this study and other studies Sub-Saharan Africa.

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Table 1.

Pollutants	Korhogo		Abidjan	
	PM₁₀	PM_{2.5}	PM₁₀	PM_{2.5}
Root Mean Absolute Error (RMSE)	97.0	43.2	41.5	24.9
Mean Average Error (MAE)	105.6	40.0	31.0	19.98
% Coefficient of Variation of error	33.4 ± 12.6	36.7 ± 31.7	42.5 ± 41.8	39.7 ± 29.2

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Table 2.

City, Country	Site characteristic	Samplings period	PM _{2.5} (µg m ⁻³)	PM ₁₀ (µg m ⁻³)	Reference
Korhogo, Cote d'Ivoire	14 urban sites	Jan-2019	54.3 to 218	212.2 to 534.7	This study
Abidjan, Cote d'Ivoire	20 urban sites	Jan. to Feb-2019	23.8 to 113.4	38.1 to 160.4	
Abidjan, Cote d'Ivoire	Urban (WB ^a)	Jan. and July-2016	494.3	-	Xu <i>et al.</i> , (2019)
	Urban (DF ^b)		358.8	-	
Cotonou, Benin	Traffic		335.1	-	
Accra, Ghana	Traffic-highest SES ^c	2007	21	49	Dionisio <i>et al.</i> , (2010)
	Traffic-lowest SES		39	96	
Dakar, Senegal	Urban	Jun-2008 to Jun-2009	44.4	-	Doumbia <i>et al.</i> , (2012)
	Commercial area		-	422.3	
Ibadan, Nigeria	Traffic	Jan. and Mar-2008	-	328.1	Ana <i>et al.</i> , (2014)
	Industrial		-	319.7	
	Residential		-	257.4	
Bamako, Mali	Urban	Sep. to Oct-2012 and Jul-2013	43	210	Garrison <i>et al.</i> , (2014)
Ouagadougou, Burkina Faso	Urban	Nov. to Dec-2017	86	-	Boman <i>et al.</i> , (2009)
	Suburban		69	-	
Accra, Ghana	Traffic	Jun. to Jul-2006	27.4	71.8	Arku <i>et al.</i> , (2008)
Bafoussam, Cameroun			67	105	
Bamenda, Cameroun	Urban	Jan. to Mar-2012	132	141	Antonel and Chowdhury (2014)
Yaoundé, Cameroun			49	65	
Libreville, Gabon			35.8	-	
Port-Gentil, Gabon	Urban	Jun. to Jul-2015	60.9	-	Ngo <i>et al.</i> , (2019)

(^a) WB: Waste Burning; (^b) DF: Domestic Fire; (^c) Social Economic Status; "-": not measured

Figure Captions

Fig. 1. Map of the population density of Cote d'Ivoire, the position of two application cities in Cote d'Ivoire is shown by green diamond. Green diamond represents each measurement cities. Data from <https://www.diva-gis.org/gdata>.

Fig. 2. Localization of measurement sites in Korhogo (Cote d'Ivoire). Green diamond represents each measurement site with its corresponding ID, described in the Table S1 and S3 and the black lines represent the boundaries of Korhogo city.

Fig. 3. Localization of measurement sites in Abidjan (Cote d'Ivoire). Green diamond represents each measurement site with its corresponding id site, described in the Table S2 and S4 and black lines represent the boundaries of communes included in this study.

Fig. 4. Wind rose from synoptic station measurements during the study periods in Korhogo (a) and Abidjan (b) in Cote d'Ivoire.

Fig. 5. Spatial variation of PM₁₀ (a) and PM_{2.5} (b) concentrations in Abidjan (Cote d'Ivoire). Black diamond represents each measurement site, line represent the main roads of Abidjan and dotted line represent administrative boundaries.

Fig. 6. Spatial variation of PM₁₀ (a) and PM_{2.5} (b) concentrations in Abidjan (Cote d'Ivoire). Black diamond represents each measurement site, line represent the main roads of Abidjan and dotted line represent administrative boundaries.

Fig. 7. Spatial variation of relative difference between PM₁₀ and PM_{2.5} in percentage in Korhogo (Cote d'Ivoire). Black diamond represents each measurement site.

Fig. 8. Spatial variation of relative difference between PM₁₀ and PM_{2.5} in percentage in Abidjan (Cote d'Ivoire). Black diamond represents each measurement site.

Fig. 9. Daily averages of PM₁₀ and PM_{2.5} concentrations in Korhogo (a, b) and PM_{2.5} concentrations in Abidjan (c, d).

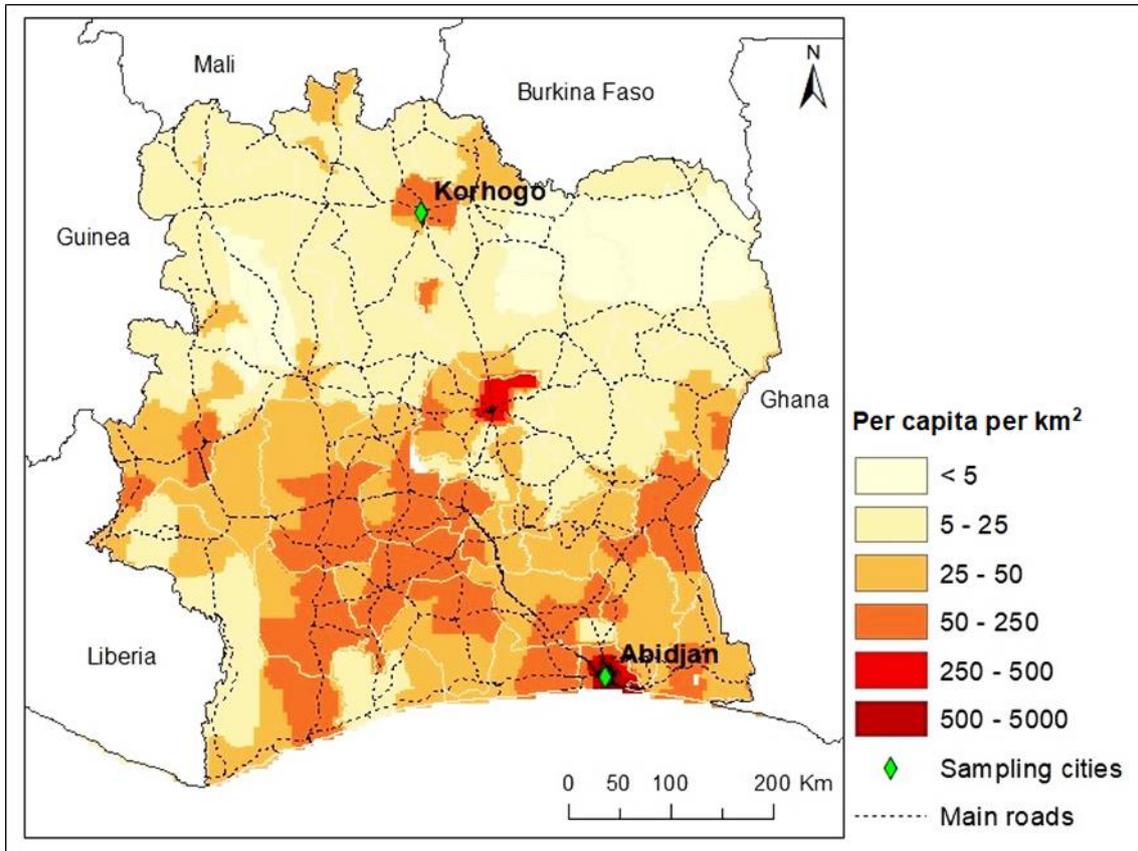


Fig. 1.

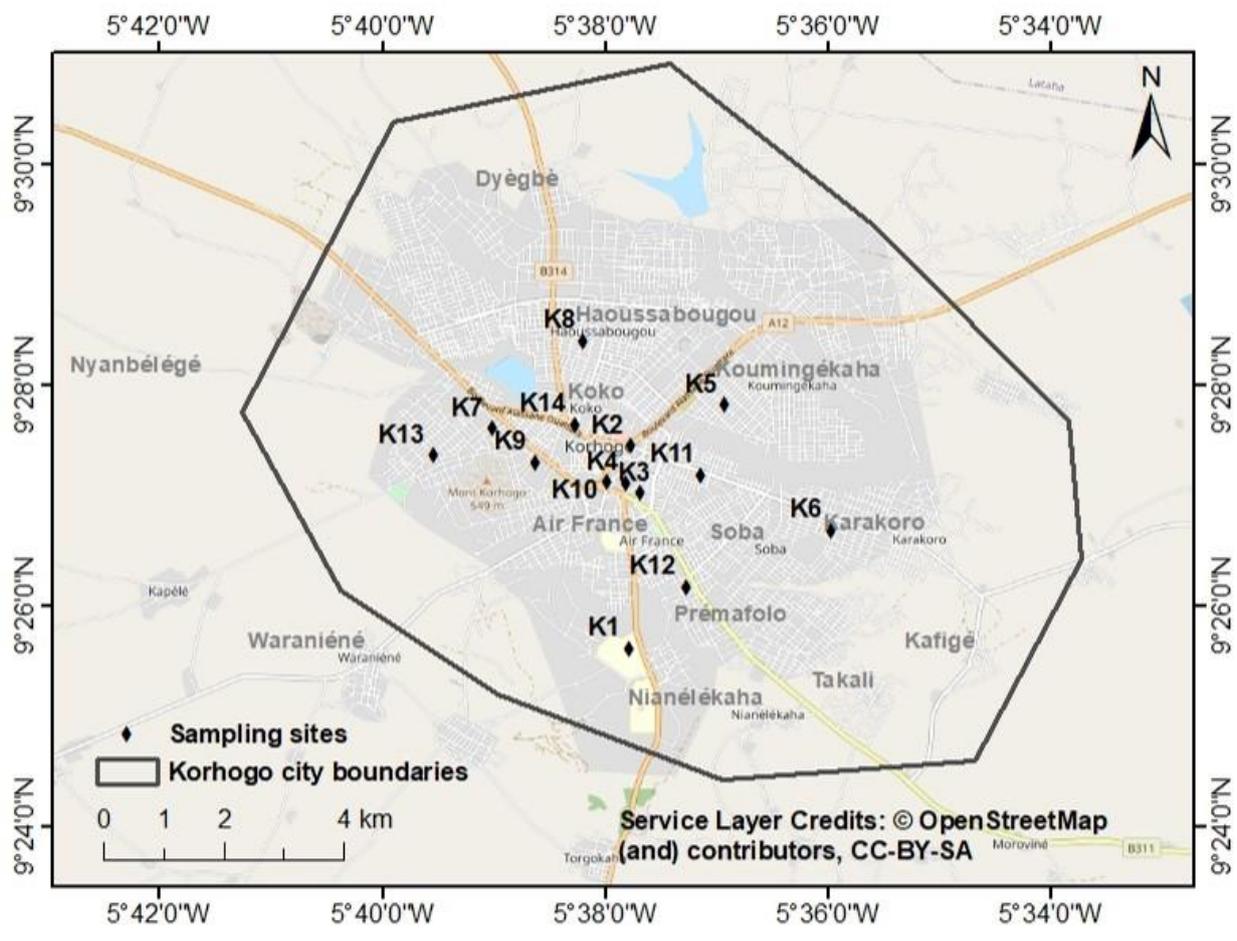


Fig. 2.

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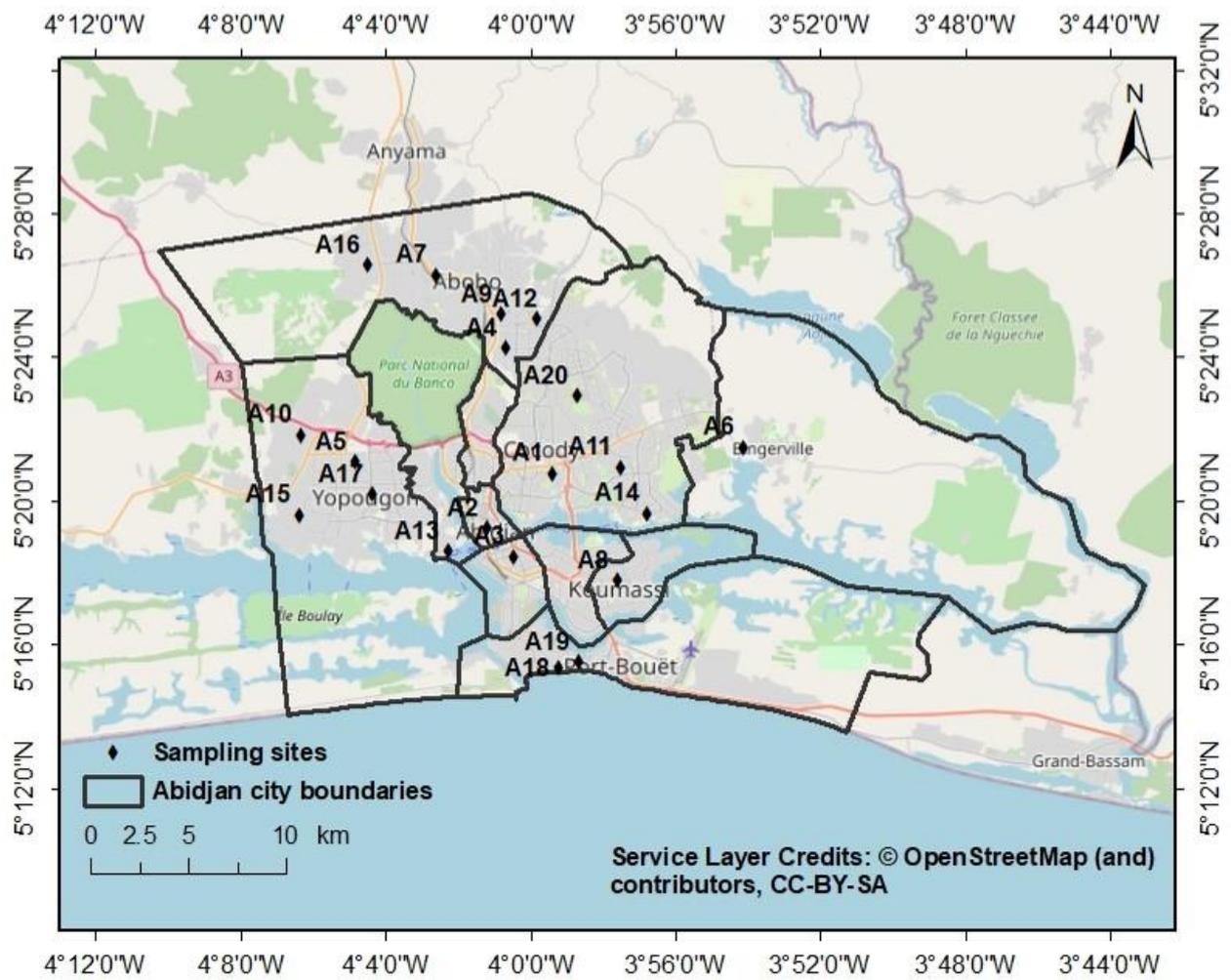


Fig. 3.

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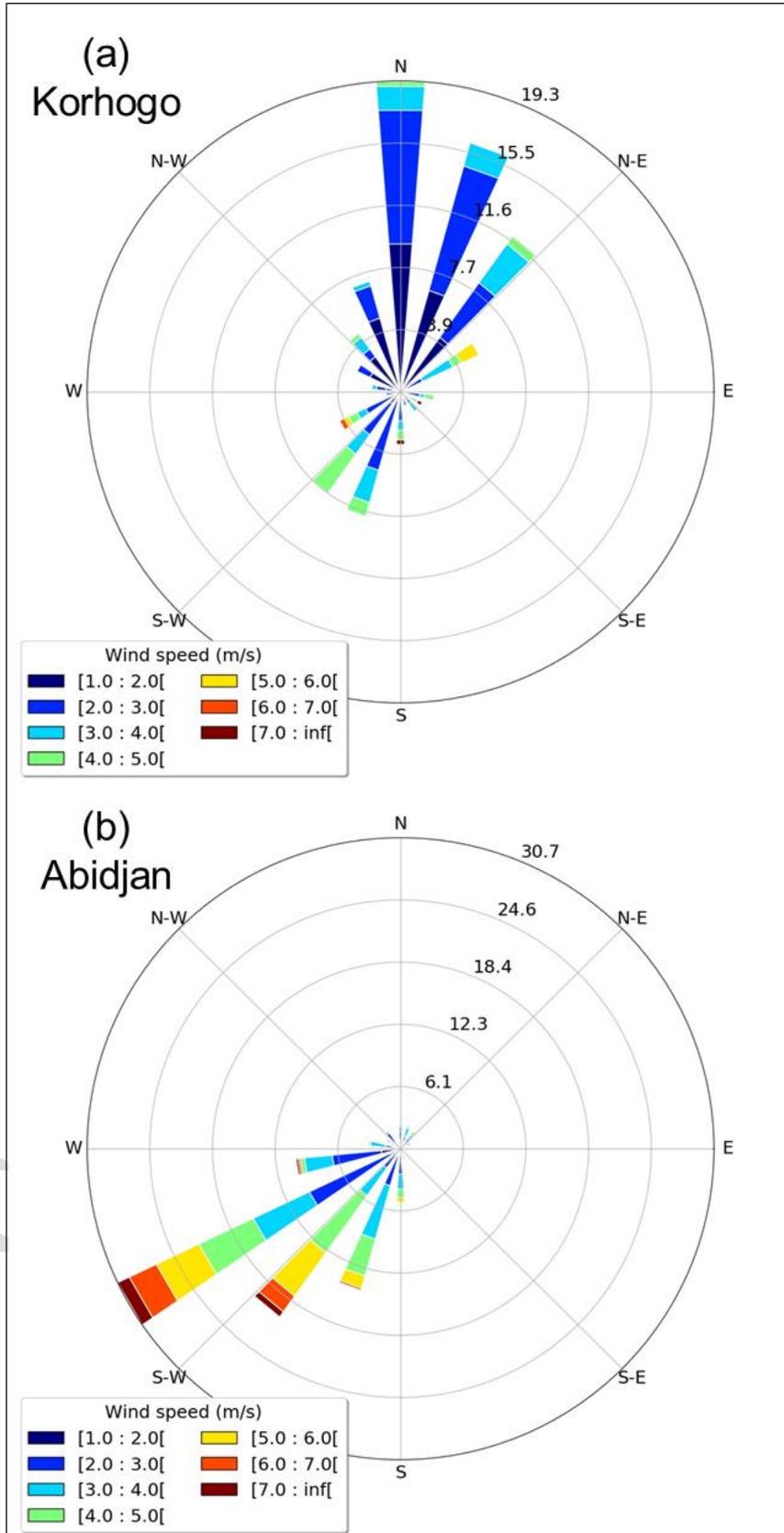


Fig. 4.

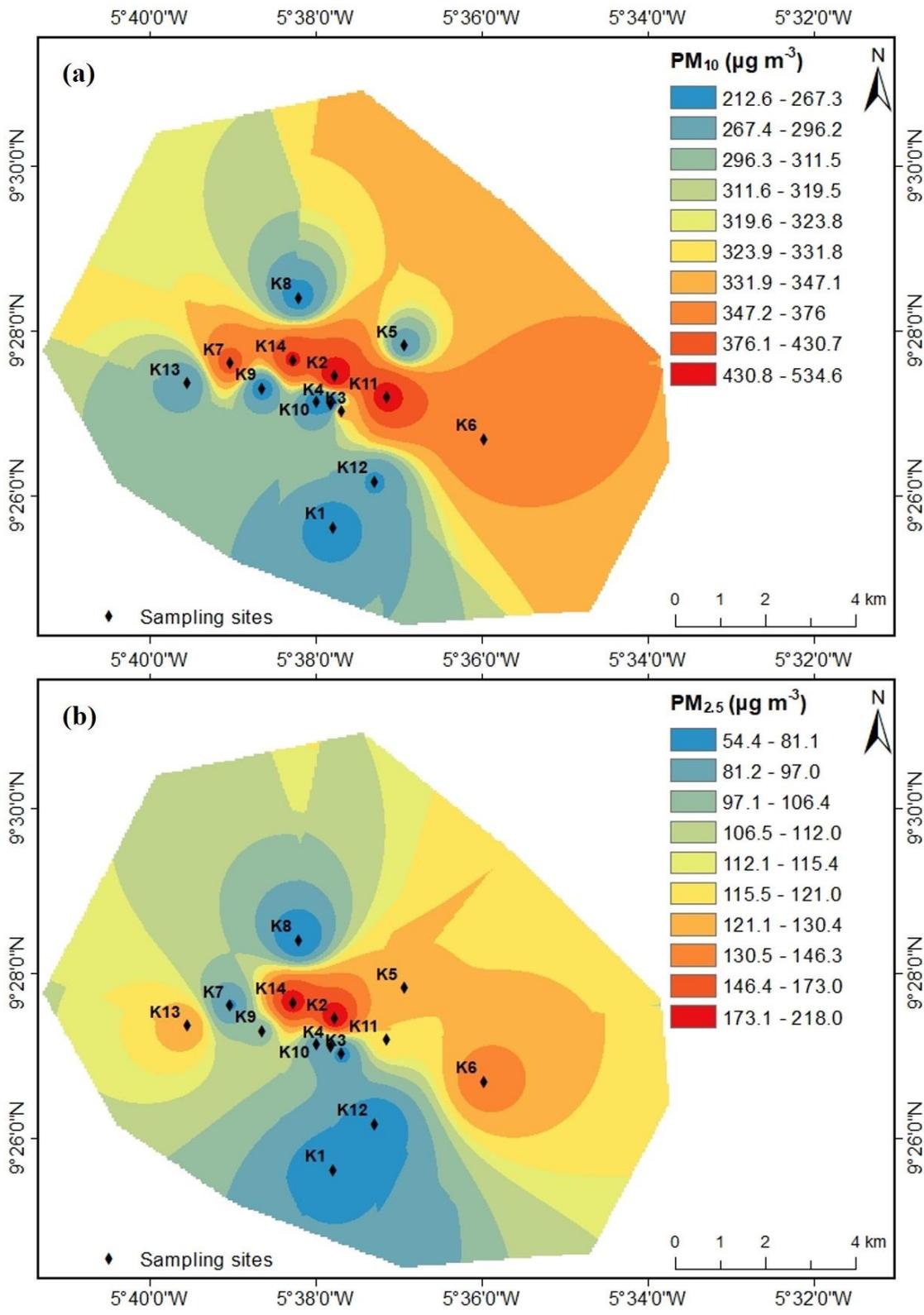


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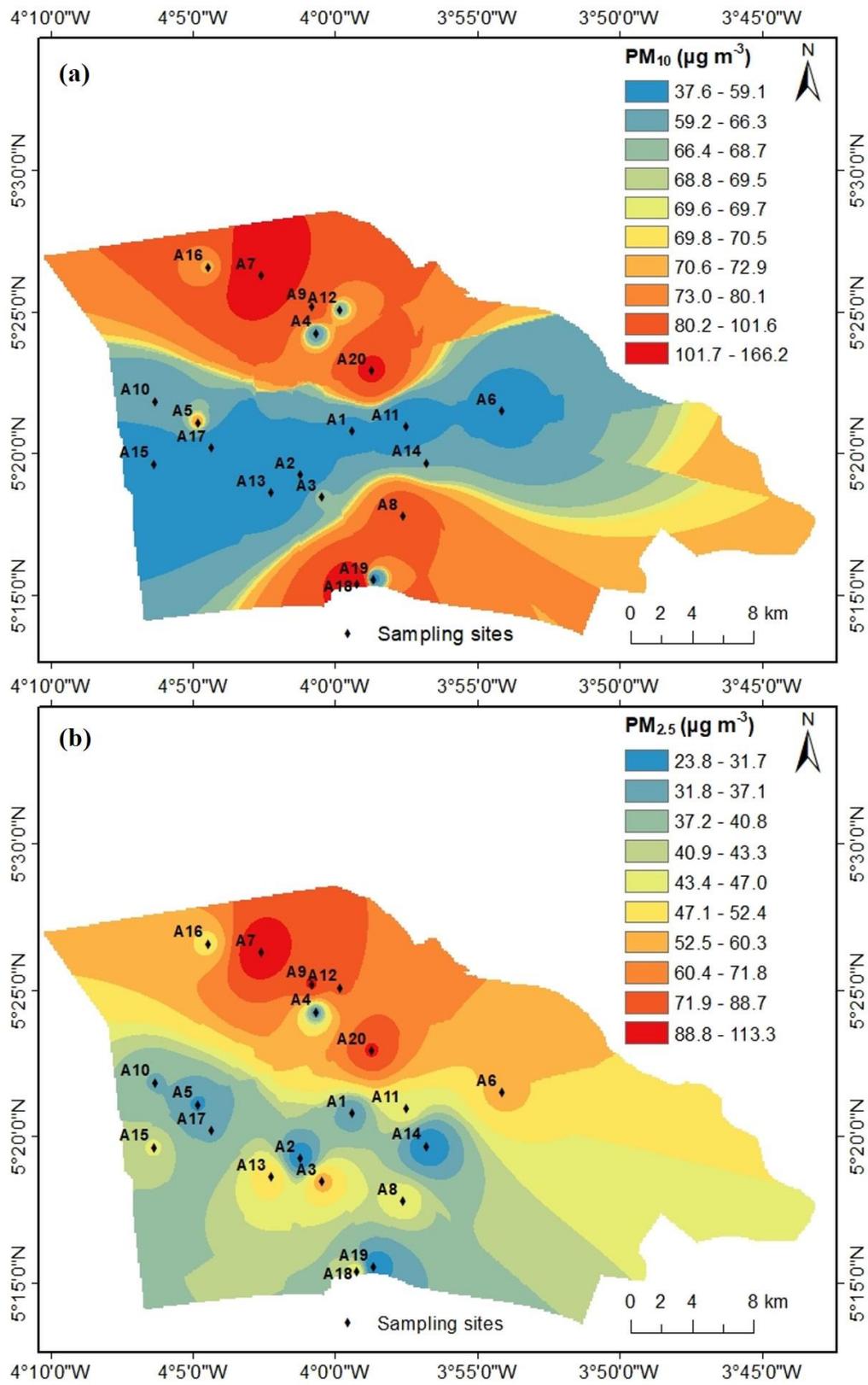


Fig. 6.

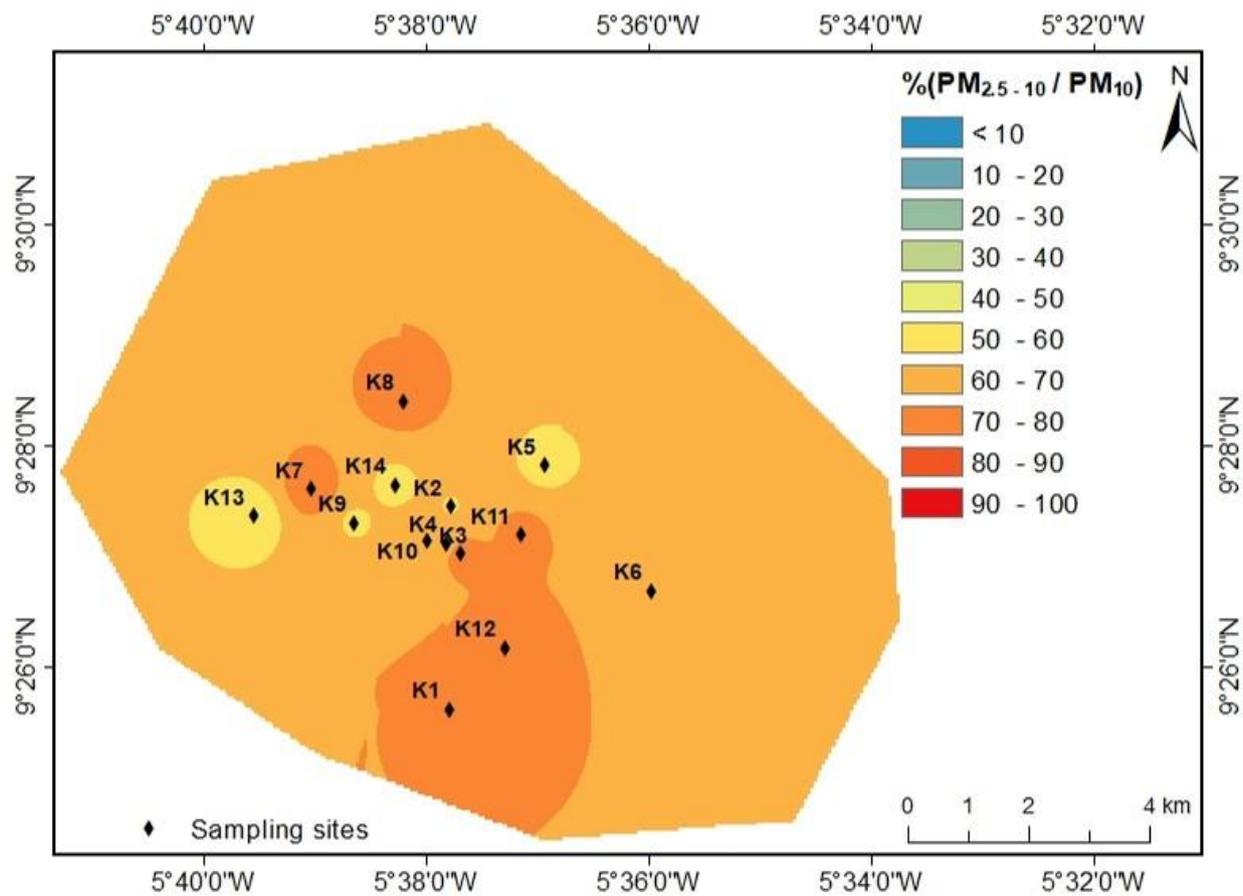


Fig. 7.

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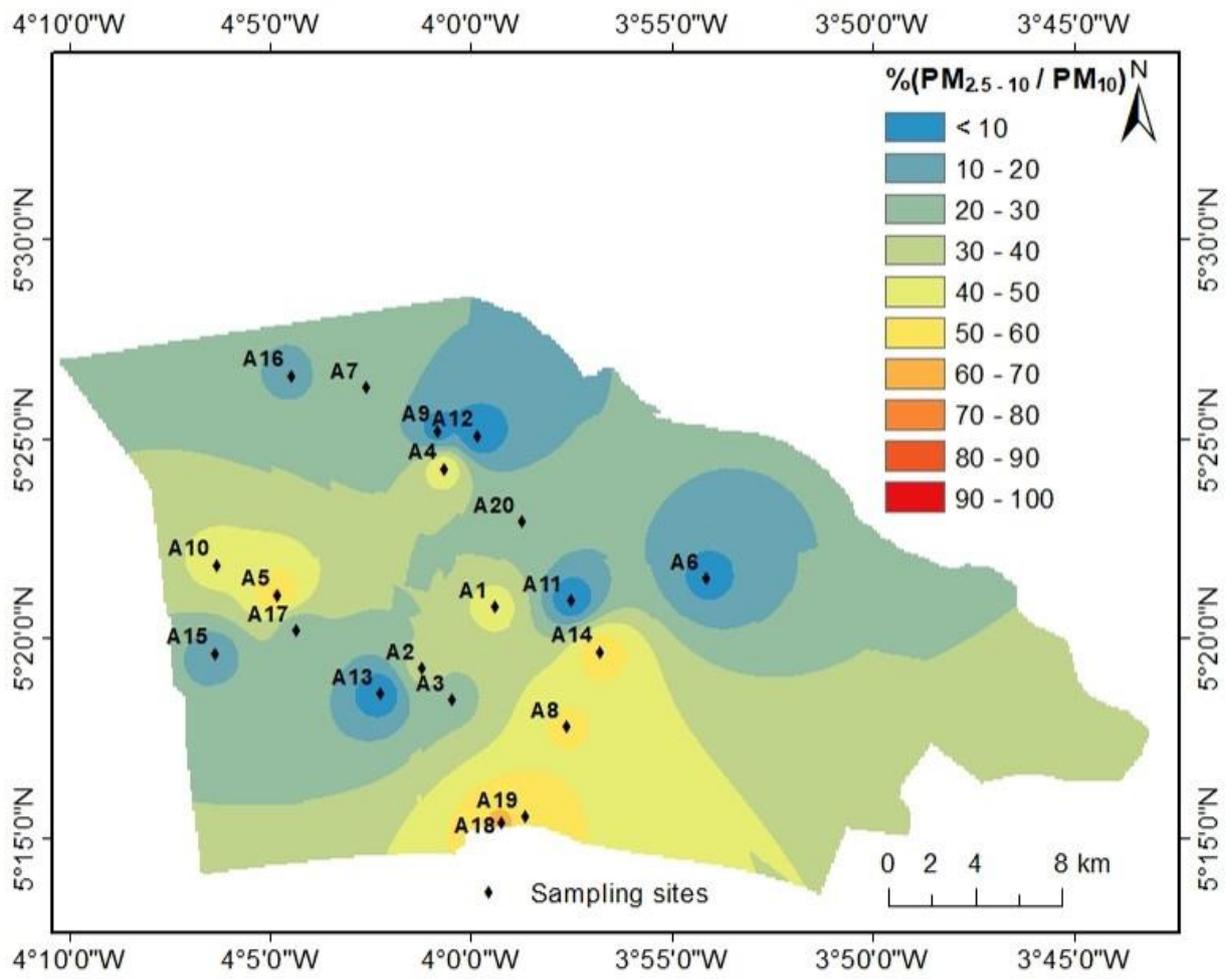


Fig. 8.

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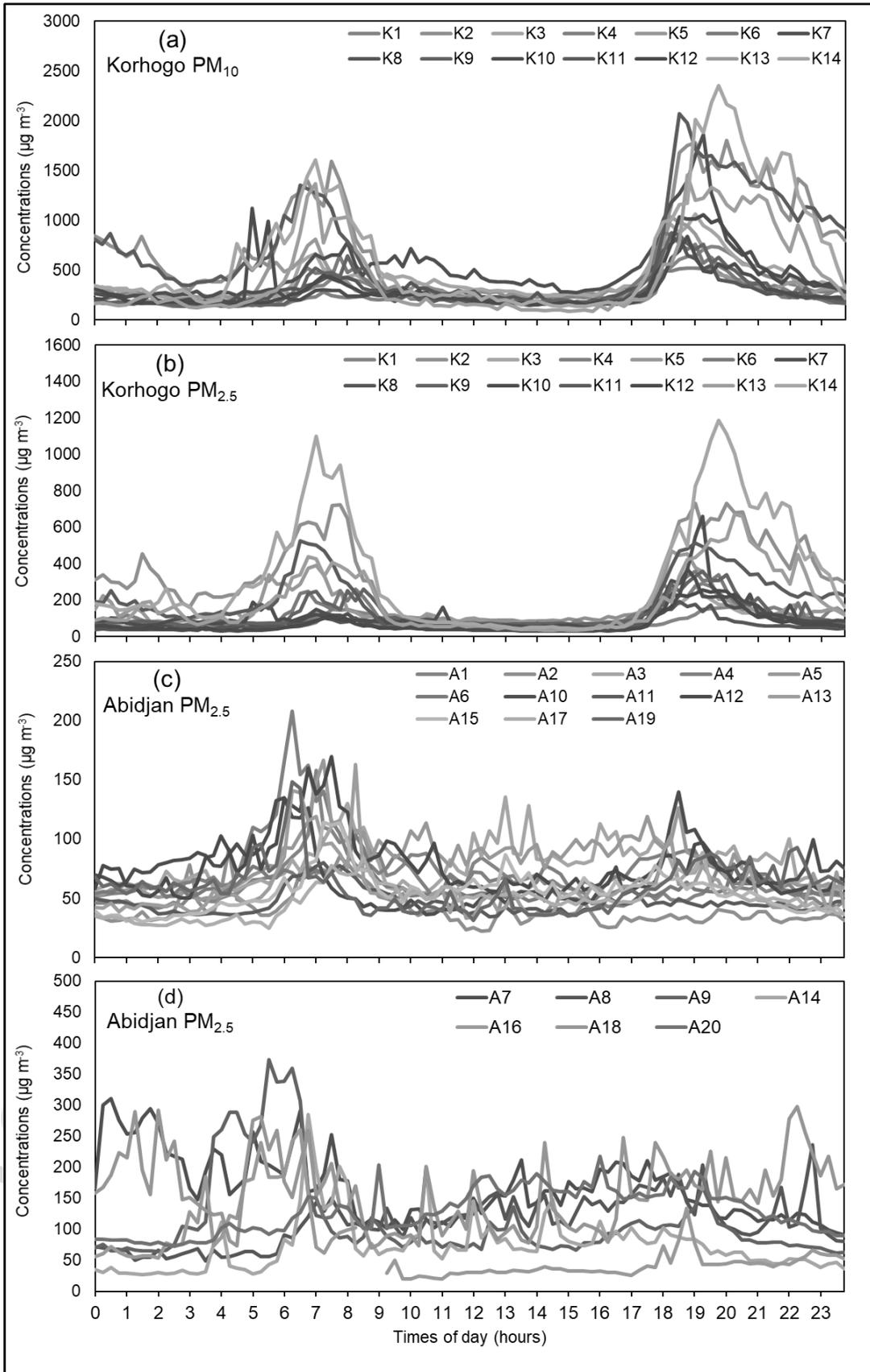


Fig. 9.