A pilot study of gaseous pollutants measurement (NO$_2$, SO$_2$, NH$_3$, HNO$_3$ and O$_3$) in Abidjan, Cote d'Ivoire: contribution to an overview of gaseous pollution in African Cities.

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Abstract. This work is part of the DACCIWA FP7 project (Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa) in the framework of the work package 2 « Air Pollution and Health ». This study aims to characterize urban air pollution levels through the measurement of NO$_2$, SO$_2$, NH$_3$, HNO$_3$ and O$_3$ in Abidjan, the economic capital of Cote d'Ivoire. Inorganic gaseous, i.e. NO$_2$, SO$_2$, NH$_3$, HNO$_3$ and O$_3$ pollutants measurements were performed in Abidjan during an intensive campaign within the dry season (December 15th, 2015 to February 16th, 2016), using INDAAF (International Network to study Deposition and Atmospheric chemistry in AFrica) passive samplers exposed in duplicate for two weeks periods. Twenty-one sites were selected in the district of Abidjan to be representative of various anthropogenic and natural sources of air pollution in the city. Results from this intensive campaign show that gas concentrations are strongly linked to surrounding pollution sources and show a high spatial variability. Also, NH$_3$, NO$_2$ and O$_3$ gases were present at relatively higher concentrations at all the sites. NH$_3$ average concentrations varied between 9.1 ± 1.7 ppb at a suburban site and 102.1 ± 9.1 ppb at a domestic fires site. NO$_2$ mean concentration varied from 2.7 ± 0.1 ppb at a suburban site to 25.0 ± 1.7 ppb at an industrial site. Moreover, we measured highest O$_3$ concentration at the two coastal sites of Gonzagueville and Felix Houphouet-Boigny international airport located in the southeast of the city with average concentrations of 19.1 ± 1.7 ppb and 18.8 ± 3.0 ppb, respectively. The SO$_2$ average concentration never exceeded 7.2 ± 1.2 ppb over all the sites with 71.5 % of the sampling sites presenting concentrations ranging between 0.4 ppb and 1.9 ppb. The HNO$_3$ average concentration ranged between 0.2 ppb and 1.4 ppb. All these results were combined with meteorological parameters to provide the first mapping of gaseous pollutants on the scale of the district of Abidjan using the geostatistical analysis (ArcGIS software). Spatial distribution results emphasize the importance of the domestic fires source and the significant impact of the traffic emissions on the scale of the city. In addition, we propose in this work a first overview of gaseous SO$_2$ and NO$_2$ concentrations on the scale of several African cities by comparing literature to our values. The daily SO$_2$ standard of World Health Organization (WHO) is exceeded in most of the cities reported in the overview with concentrations ranging from 0.2 µg.m^{-3} to 3,662 µg.m^{-3}. Annual NO$_2$ concentrations ranged from 2 µg.m^{-3} to 175 µg.m^{-3} that are lower than the WHO threshold. As a conclusion, this study constitutes an original database to characterize urban air pollution and a first attempt towards presenting a spatial distribution of the pollution levels at the scale of the metropolis of Abidjan. This work should draw the attention of the African public authorities to the necessity of building air quality monitoring network in order to (1) to define national standards and to better control the pollutants emissions and (2) to investigate the impact on the health of the growing population in developing African countries.

1 Introduction

For several years, urban areas have experienced a deterioration in air quality, and increase in health and environmental impacts. Several scientific studies have shown that a large number of premature deaths, as well as respiratory and cardiovascular diseases are related to air pollution (Brook et al., 2004; Murray, 2001; Pope III et al., 2002; Pope III and Dockery, 2006; WHO, 2006). According to the World Health Organization (WHO) estimation in 2012, 11.6 % of the deaths in the world were associated with outdoor and indoor air pollution. It represents nearly 6.5 million of deaths per year among which 3 million deaths were attributable only to ambient air pollution. 88 % of these deaths occurred in low- and middle-income countries (WHO, 2016). Also, according to the Organisation for Economic Co-operation and Development (OECD) Centre, 700,000 premature deaths were linked to air pollution in Africa in 2013 (Roy Rana, 2016).

Anthropogenic activities are considered to be responsible of the main sources of gaseous and particulate pollutants emissions into the air and their concentrations measured in the urban atmosphere (Kampa and Castanas, 2008). Several studies have been carried out in the major cities of Europe, Asia and northern America. These studies underlined the emergency of taking action to reduce emission of pollutant into the atmosphere in order to mitigate health and environmental impacts. Air quality networks have been set up in the major cities of United States of America and Europe in the purpose to inform the public authorities and as well as the population in real time. However, in Africa where researchers have found that air pollution causes more premature deaths per year than either unsafe drinking water or malnutrition, air quality monitoring network is almost not-existent (Roy Rana, 2016). Very few studies on air pollution were carried out over the African continent, this is particularly true for the West African region (Norman et al., 2007).

West African region has experienced an economic upturn during the last few years characterized by an economic growth estimated at 2.7 % in 2017 with a prospect of 3.5 % in 2018 (IMF, 2017). Most of the economic activities of African countries (e.g. industries, trade, transport and real estate) are concentrated in cities. Therefore, this favoured a strong population explosion in cities due to massive rural exodus and important migrations of the West African populations (Denis and Moriconi-Ebrard, 2009). This intense economic activity associated with a rapid population growth, a strong urbanization and the perpetual uncontrolled expansion of cities involve increasingly important anthropogenic emissions of gaseous and particulate pollutants. This causes a significant deterioration of general air quality that may alter the health of populations and damage ecosystems (Fourn and Fayomi, 2006; Norman et al., 2007).

Very few qualified dataset on levels of pollutants concentrations are available for African cities. Through some research programs and projects such as AMMA (African Monsoon Multidisciplinaty Approach), INDAAF (International Network to study Deposition and Atmospheric chemistry in AFrica) and POLCA (POLlution des Capitales Africaines), some experimental studies have been carried out in certain African capitals and rural areas such as in Bamako, Dakar, Yaounde, and Amersfoort (Adon et al., 2016; Conradie et al., 2016; Liousse and Galy-Lacaux, 2010; Lourens et al., 2011; Val et al., 2013). The DACCIWA (Dynamics-Aerosols-Chemistry-Clouds Interactions in West Africa) European program follows the framework of the above-mentioned programs. The measurements implemented within the framework of DACCIWA are mainly focused on the Southern West African (SWA) region. DACCIWA has conducted extensive fieldwork in the SWA to collect high-quality observations, spanning the entire process chain from surface-based natural and anthropogenic emissions to impacts on health, ecosystems, and climate (Knippertz et al., 2015). Work package 2 (WP2) of the DACCIWA program aims to link emission sources, air pollution and health impacts in terms of lung inflammation and related diseases over representative differentiated urban sources in SWA (i.e., traffic, domestic fires and waste burning in Abidjan (Cote d'Ivoire), and two-wheel vehicle traffic in Cotonou (Benin)). The strategy in WP2 is based on a multidisciplinary approach (e.g., physics, chemistry, toxicology, epidemiology, modelling). Experimental results from WP2 rely both on intensive short campaigns and also on mid-term monitoring measurements at the different selected urban sites. Three urban supersites to represent the major urban sources mentioned above have been selected for the mid-term monitoring from December 2014 to March 2017.

Abidjan is located close to the Ebrie Lagoon along the Gulf of Guinea in the south-east coast of Cote d'Ivoire. Abidjan, the economic capital of Cote d'Ivoire is a cosmopolitan city in sub-Saharan Africa and the second most-populated West African city. According to the National Institute of Statistics, the population of Abidjan was estimated to 4.7 million in 2014, with an average annual population growth of 2.6 % (INS, 2015). The autonomous district of Abidjan is composed of ten municipalities in the city (Abobo, Adjamé, Attécoubé, Cocody, Koumassi, Marcory, Plateau, Port-Bouët, Treichville and Yopougon) and three neighboring municipalities (Anyama, Bingerville and Songon). The cumulated area of these municipalities is 2,119 km^2 (i.e., 0.66 % of the country) (Yao-Kouassi, 2010) compared to 580 km^2 in 1990 (Kopieu, 1996). Abidjan is a port city and a dynamic economic center, not only for the country, but also for the entire West African sub-region. The port of Abidjan is at the first rank in West Africa in terms of merchandise traffic with 21.5 million tons in 2013 and a prospect of 27 million tons in 2018. Abidjan is hosting 70 % of the country's industries and constitutes the main maritime facade for the hinterland countries such as Burkina Faso, Niger and Mali. In addition, Abidjan represents 60 % of the Gross Domestic Product (GDP) of Cote d'Ivoire, which is estimated to be 31.76 billion US dollars (World Bank, 2016). The annual growth rate of GDP in Cote d'Ivoire is expected to be 9 % at the end of the third quarter of 2017. The main sectors that support the economic growth of Cote d'Ivoire are real estate, road transport, road building, manufacturing and mining industries. Abidjan has experienced in recent years strong economic growth that contribute to different environmental issues such as air pollution. This is one of the main issues in West African capitals driven by explosive unplanned growth of urban conglomerations and contributing to unregulated emissions.

This study presents results of an intensive measurement campaign performed from December 15th, 2015 to February 16th, 2016. This work, part of the WP2, aims to characterize urban air pollution in Abidjan through the measurement of gaseous pollutants (NO_2, SO_2, NH_3, HNO_3 and O_3) concentrations. Twenty-one sampling sites distributed throughout the district of Abidjan were selected to be instrumented with gaseous passive samplers in order to obtain the spatial distribution of each gaseous pollutant. This study allows to establish the contribution of each source of pollution, as well as to compare the concentration of inorganic gaseous species in Abidjan with those of other cities in Africa and other developing countries.

2 Experimental design

2.1 Sampling sites

For air pollution assessment in a city, it is important to consider most of the anthropogenic activities that may constitute sources of pollution. In the purpose to get a good spatial coverage of the Abidjan district, several measurement sites have chosen across the different municipalities.

In this work, an experimental measurement sites network was built. Measurement sites were chosen based on criteria of land use, orographic effects and the objectives of DACCIWA program (i.e., (1) population density of each municipality is considered as factor highly impacting gaseous pollutants sources, (2) spatial coverage of the 13 municipalities of the district of Abidjan and (3) documentation of identified air pollution main sources). Figure 1 presents the mapping of the 21 selected sites referenced from A_1 to A_{21} and their identified major sources of pollution nearby in the district of Abidjan while Table 1 presents details of each site. So, 10 sampling sites are classified as traffic sites (A_1 - A_8, A_{10}, A_{14}) of which 5 of these sites present a combination of traffic and another pollution source (A_4, A_7, A_8, A_{10}, A_{14}). A_1 is also the DACCIWA supersite representative of traffic. 3 sites are considered to be representative of industrial areas (A_9 to A_{11}). Industrial sites are often influenced by traffic. 4 sites of residential district (A_7, A_8, A_{12} and A_{13}). 4 sites (A) have been selected as suburban and one as a green area (A_{17} to A_{21}). Finally, two DACCIWA supersites studied over a 28 months period (December 2014-March 2017) in terms of local emission sources were considered in this study to be representative of domestic fires (A_{16}) and waste burning (A_{15}). These two supersites as well as A_1 traffic site and A_6 FHB airport are shown on Fig. 2. Mid-term measurements sites

are operational. The seasonal variation of gaseous pollutants showed that the highest concentrations are measured during the dry season (December-February). This information led to the choice of the study period.

2.2 Sampling and analysis

2.2.1 Sampling procedure

5   Ambient concentrations of gaseous pollutants (NO_2, SO_2, HNO_3, NH_3 and O_3) were determined using the INDAAF (http://indaaf.obs-mip.fr) passive samplers method. These passive samplers developed by Laboratory of Aerology (LA) in Toulouse (France) using the work of Ferm, (1991) were tested and qualified in the framework of the INDAAF project for the major African ecosystems over the past fifteen years (Adon et al., 2010). Validation and inter-comparison studies have been performed according comparison with active analysers. Results presented in Adon et al., (2010) assure the quality and the
10   accuracy of the measurements. Passive samplers have also been used for the measurement of gaseous pollutants concentration in urban areas during the POLCA program (Adon et al., 2016). Passive samplers can be used for indoors and outdoors pollution monitoring in all environment (Salem et al., 2009) and provided good results (Gorecki and Namiesnik, 2002). Moreover, they are suitable to investigate the spatial distribution of gaseous pollutants in an air quality monitoring network (Carmichael et al., 2003; Cox, 2003; Cruz et al., 2004). Also, INDAAF passive samplers have the advantage of being small, silent, reliable and
15   do not need electricity. The sampling technique is based on molecular diffusion of gas molecules into the passive sampler where they are quantitatively collected on an impregnated filter (He, 2014; Galy-Lacaux et al., 2001). The calculation of gaseous pollutants concentrations in the air depends on the physical characteristics of the passive samplers, the duration of exposure and the meteorological parameters. We calculate gaseous pollutant average concentration in ppb using the following formula given by (Adon et al., 2010) Eq. (1):

20   $$C_{amb}(ppb) = \frac{(L/A).X.R.T}{t.D.P},\qquad\qquad(1)$$

C_{amb} (ppb) represents the concentration of the considered gaseous pollutant in ppb, X is the number of gas molecules trapped on the cellulose filter (µmol), R (constant gas) = 0.08206 L atm mol^{-1} K^{-1}. T is the average temperature during the sampling period (K), P is the mean atmospheric pressure during the sampling period, D is the molecular diffusion coefficient of the specific gas in the atmosphere, t is the exposure duration time (s) and the ratio L/A= 47.5 m^{-1} is the air resistance coefficient
25   for the INDAAF passive sampler (Adon et al., 2010).

The passive samplers were prepared by the Laboratory of Aerology in Toulouse and dispatched in Abidjan (Cote d'Ivoire) from December 15th, 2015 to February 16th, 2016 during the dry season. For each set of passive samplers, blank samples are kept sealed in the laboratory and others sent to the sites. Passive samplers were exposed bi-monthly at the 21 measurement sites of the Abidjan district to represent integrated two week periods over the two month of study period. Passive samplers
30   were mounted on stainless steel rails in duplicate and placed at a height of at least 2.5 meters above the ground corresponding to height of human exposure. On each rail, we installed duplicate passive samplers for each gaseous species measured (Fig. 2). Passive samplers were then exposed for 2 weeks before being replaced by new ones. Once removed, passive samplers are kept refrigerated before being shipped to the Laboratory of Aerology for analysis. Over the study period, 672 passive samplers have been exposed and 2 were damaged. 670 samples and 48 blanks (12 for each gas) were analysed (24 blanks kept in the
35   laboratory and 24 other blanks sent in the same condition with exposed passive samplers).

2.2.2 Chemical analysis

To determine and calculate the concentration of studied gaseous pollutants, ionic concentrations of ammonium (NH_4^+), nitrate (NO_3^-), sulfate (SO_4^{2-}) and nitrite (NO_2^-) are determined by ion chromatography (IC) after desorption of the filters in 10 mL (5 mL for the NH_3) of 18 MΩ deionized water by ultrasonic stirring (15 min). The IC system used for this

study has been extensively described in previous studies (Adon et al., 2010; Galy-Lacaux and Modi, 1998; Hodgkins et al., 2011). The reliability of the IC analytical results are assessed by the chemistry laboratory of Laboratory of Aerology in Toulouse by performing twice a year a quality control inter-comparison program organized by World Meteorological Organization/ Global Atmospheric Watch (WMO/GAW) (Laouali et al., 2012). Results of the WMO/GAW quality assurance program for the year 2016 shows that analytical precision is estimated to be ± 5 % for all ions (http://www.qasac-americas.org/). The reproducibility of the INDAAF passive samplers was found to be 20 %, 9.8 %, 14.3 %, 16.6 % and 10 % for HNO_3, NO_2, NH_3, SO_2 and O_3 respectively. Detection limits for each trace gas were calculated from field blanks filters and found to be 0.07 ± 0.03 ppb for HNO_3, 0.2 ± 0.1 ppb for NO_2, 0.7 ± 0.2 ppb for NH_3, 0.05 ± 0.03 ppb for SO_2 and 0.1 ± 0.1 ppb for O_3 (Adon et al., 2010). For our present study, detection limit was found to be 0.09 ± 0.00 ppb for HNO_3, 0.37 ± 0.02 ppb for NO_2, 1.4 ± 0.18 ppb for NH_3, 0.01 ± 0.00 ppb for SO_2 and 0.08 ± 0.04 ppb for O_3. Potential interferences between HNO_3 and NO_2 passive samplers were estimated and found to be negligible. For the traffic site A_1, our results presented in supplementary Table S1 show that nitrate (NO_3^-) concentration are very low compared to nitrite (NO_2^-) ions with a ratio around 2 %. Other NOy species such as Peroxyacetyl nitrate (PAN) and nitrous acid (HONO) which can deposit as nitrite and oxidize to nitrate may interfere with the determination of NO_2 and HNO_3 concentration (Cape, 2003). The choice of the coating solution in the INDAAF passive sampler aims to reduce these interferences. The average concentration of two samples is used in all the case except when contamination of one sample is suspected and when the average concentration is under the detection limit. Thus, for the present work, 4 samples (0.6 %) were removed from the whole database for contamination and/or detection threshold, making a database of 666 samples representing about 99.4 % of the total analysed samples.

2.3 Meteorological data

Meteorological parameters used for this study were collected at the site (A_6), which is located at the weather station of the Félix Houphouet-Boigny international airport (Fig.2). This weather station is managed by ASECNA (Agency for Safety of Air Navigation in Africa and Madagascar) and provides meteorological data for air navigation in the district of Abidjan. The meteorological data used in this study included wind direction and velocity, temperature and relative humidity. Daily variations in temperature and relative humidity during the study period (December 15th, 2015 to February 16th, 2016) are presented in Fig. 3. Daily average temperature ranged between 25 °C and 29 °C while mean relative humidity was about 78 % with a maximum of 92 % during the study period. In addition, this period was particularly dry with only two rainy days and a total cumulative rainfall of 32 mm. The wind rose presented in Fig. 4 shows the predominance of southwest (SW) and north-northeast (NNE) winds directions. Wind velocity presents values ranging between 1 and 9 m.s^{-1} with an average of 2.75 ± 0.6 m.s^{-1}. These observed meteorological parameters are characteristic of the major dry season in Cote d'Ivoire (Konate et al., 2016).

2.4 Spatial analysis

In this study, we interpolated the inorganic gaseous species concentrations measured at the 21 sites to build spatial distribution of gaseous concentrations of the entire city of Abidjan using geostatistical analysis (GIS). The mapping tool used was ArcGIS software version 10.2.2. The features were projected using World Geodetic System (WGS_1984) UTM_Zone_30N (Universal Transverse Mercator). Two interpolation methods are frequently used to study spatial distribution of pollutants. There are Inverse Distance Weighted (IDW) and kriging. The general formula for both interpolators is formed as a weighted sum of the data Eq. (2):

$$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i), \qquad\qquad (2)$$

$\hat{Z}(S_0)$ is the predicted concentration at S_0 location and is calculated as a linear weighted sum of N observations surrounding the predicted location. $Z(S_i)$ is the measured concentration at the S_i location, λ_i is an unknown weight for measured concentration at the S_i location, S_0 is the prediction location and N is the number of measured concentration.

In IDW, the weight, λ_i depends only on the distance between the measurement points and the prediction location. IDW computes predicted concentrations at the location as a weighted average of neighbouring measured concentrations (Ibrahim et al., 2012; Rivera-Gonzalez et al., 2015). This method provides a spatial distribution of pollutants much closer to the reality. IDW method showed better similarity between measured and interpolated concentrations of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) (Jha et al., 2011).

For kriging method, the weights λ_i are not only based on the distance but also on the overall spatial arrangement of the sampling sites. Kriging is the method of interpolation deriving from regionalized variable theory. It depends on expressing spatial variation of the property in terms of the variogram, and it minimizes the prediction errors which are themselves estimated (Oliver and Webster, 1990).

Data analysis

The empirical semivariogram provide information on the spatial autocorrelation of datasets. The semivariograms necessary for kriging were estimated for each pollutant and presented in Fig. 5. The results for NO_2, SO_2, HNO_3 and O_3 show that the Gaussian semivariogram model is fitted to empirical values. The parameters of the empirical semivariogram are presented in Table 2. The empirical semivariogram of NH_3 shows a nugget model. It represents the discontinuity at the origin due to small-scale variation and the lack of spatial auto-correlation of NH_3 concentration.

Cross-validation

Ordinary kriging with Gaussian semivariogram model and IDW was used to perform the spatial interpolation. To validate the interpolation model, an error analysis was carried out between measured and interpolated values. The free statistical software R was used to determine the mean absolute error (MAE), the root mean square error (RMSE) and the coefficient of correlation (R^2). RMSE and MAE are regularly employed in model evaluation studies (Chai and Draxler, 2014). Lower MAE and RMSE values higher value of R^2 are used for better comparison (Jha et al., 2011; Rivera-Gonzalez et al., 2015). The critical value of the Pearson's correlation coefficient at the threshold of 5 % is $R^2 = 0.42$. Regression between interpolated data and observed data using IDW and kriging method are presented in fig.6 while statistical parameters calculated for each interpolation method are presented in Table 3. Results indicate that lowest MAE and RMSE values and highest R^2 value are always obtained for IDW interpolation method. Thus, the IDW was chosen to interpolate data and represent the spatial distribution of all gaseous pollutants.

3 Results and discussion

The average concentration measured every two weeks for each gaseous pollutant is shown in supplementary Table S2. The average concentrations calculated from the four two-week periods were used to provide pollutants spatial distribution maps. The minimum, maximum and average concentrations of gaseous pollutants at each site are presented in Table 4. The differences between the sites are discussed in the spatial distribution that follows.

3.1 Spatial distribution of gaseous pollutants in Abidjan

In order to present the spatial distribution of gaseous pollutants investigated in this work, the center of the district of Abidjan is divided into a rectangle of 35 km x 30 km between 5°14' N and 5°31' N, and 3°53' W and 4°12' W. Maps of each pollutant are presented using a colour scale from blue (low concentration in ppb) to red (high concentration in ppb) (Fig. 7 to Fig. 11). Black lines present administrative boundaries. Sampling sites are represented by green points and referenced with an ID code from A_1 to A_{21}. Green lines on the spatial distribution map of NO_2 represent the main road network.

Nitrogen dioxide (NO_2)

The spatial distribution of NO_2 concentrations in the district of Abidjan is represented on Fig. 7. This map reveals that NO_2 average concentrations vary between 2.7 ppb and 25 ppb during this dry season. The highest values (25 ppb) were obtained at the Tri postal site (A_{11}) while lowest values are recorded at the suburban sites A_{19} and A_{18} with concentrations of 5.4 ppb and 2.7 ppb respectively. These highest values at A_{11}, may be explained by the presence of both the port and industrial areas around this site. Also, high concentrations were found at A_5 site characterized by traffic with a mean concentration of 23.9 ppb. This site located in the administrative center of Abidjan is characterized by traffic jams every working day. Sites A_1, A_8, representative of traffic sites and A_9 representative industrial sites present comparable mean concentrations ranging between 19.9 ppb and 21 ppb. Moreover, highest NO_2 average concentrations measured in Abidjan are usually found for sampling sites located close to an important road confirming NO_2 as a tracer of the presence of traffic (Istrate et al., 2014). Therefore, traffic appears to be one of the main sources of NO_2 emission in Abidjan. For example, in 2014, more than 82 % of vehicles in Cote d'Ivoire were in the district of Abidjan (Kouadio, 2014). The national agencies of urban transport (AGETU (AGEnce des Transports Urbains) and SONATT (SOciété NAtionale des Transports Terrestres)) counted 423,587 vehicles in 2010 (Goore Bi, 2011). Most of these vehicles are second-hand and have more than 20 year old (Ministry of Transport, 2017). These vehicles do not comply the standards of European Union (E.U) air quality standards and are most used because of their moderate price.

Beside the road traffic, the industrial sector seems to be another great contributor to highest measured NO_2 concentration. Significant concentration levels around 20.9 ppb are measured over the three industrials sites (A_{11}, A_9, and A_{10}). Abidjan has currently three industrial zones covering 885 ha and the fourth is under construction. The biggest one is located at the municipality of Yopougon (645 ha) followed by the industrial areas of Vridi in the municipality of Port-Bouet (120 ha) and of Koumassi (120 ha) (ICI, 2014). The industrial area of Vridi (A_{11}) where the highest NO_2 concentrations were measured (25 ppb) includes several activities related to the harbour area, shipyards, oil terminals, chimneys, thermal power station, and processing and storage of petroleum products factories. With the exception of oil and shipping industries, most of these activities are also found in the other industrial areas. Other activities such as cement manufacturing, chemical industries and plastic production are also present. These industrial activities are well known to be the main source of anthropogenic nitrogen oxide emissions into the atmosphere (Krzyzanowski and Cohen, 2008).

Sulfur dioxide (SO_2)

Figure 8 shows the spatial distribution of the SO_2 concentrations in Abidjan. SO_2 concentrations varied from a minimum of 0.4 ppb in the suburban site (A_{20}) to the maximum of 7.2 ppb measured at the (A_3) traffic site (Table 2). The highest concentrations were generally obtained on the five traffic sites (A_3, A_2, A_4, A_{19}, A_5) and on the A_1 suburban site with respective value of 7.2 ppb, 6.8 ppb, 4.7 ppb, 3.4 ppb, 3.1 ppb, and 2.6 ppb. We notice a decrease of SO_2 concentrations from the Northwest of the city where the main roads (Northern Highway and East source Road) and the industrial zone of Yopougon (A_9) are located to the Southeast of Abidjan near the Atlantic Ocean. The majority of the sampling sites (71.5 %) presents concentrations lower than 2 ppb. Similarly to NO_2, the highest SO_2 concentrations are observed in areas of dense traffic and

in industrial zones. It should be noted that refining companies located in the industrial zone of Vridi (A_{11}) do not have yet desulfurization unit. This kind of production unit may constitute an important source of SO_2 (Rodriguez and Hrbek, 1999; Tam et al., 1990). The sulfur content of the fuel produced and marketed in Cote d'Ivoire is higher than 2000 part per million (ppm) (CCAC and UNEP, 2016). This content is more than 40 times higher than the standards applied in most of the developed countries (50 ppm or below). There is also an intensive charcoal production through biomass burning in the northwest of the city. The large rubber plantations located in this area are regularly reconverted into charcoal using traditional ovens. According to the study NAMA (Nationally Appropriate Mitigation Action) on sustainable charcoal in Cote d'Ivoire, the charcoal production increased by 22 % between 2003 (400,850 t) and 2012 (488,128 t). During the same period, firewood production increased from 8,699,979 m^3 to 9,034,617 m^3 (UNDP, 2015). Charcoal (47 %) and firewood (35 %) are the main sources of energy for households in urban area in Cote d'Ivoire making biomass burning a significant source of SO_2 (Bates et al., 1992; Andreae, 1991). The Northeastern gradient could be also attributed to air masses circulation in the dry season with North-Northeast harmattan winds shown by the wind diagram (Fig. 4).

Ammonia (NH₃)

The main source of NH_3 emissions is biomsass burning including biofuel combustion, agriculture, animal husbandry, NH_3-based fertilizer, industrial processes and vehicular emission (Paulot et al., 2017; Whitburn et al., 2015; Behera et al., 2013; Akagi et al., 2011). In urban areas, domestic fires, traffic and industrial activity are generally considered as major sources of NH_3 (Sun et al., 2017; Teng et al., 2017; Perrino et al., 2002; Sapek, 2013; Sutton et al., 2000; Whitehead et al., 2007). In West African capitals, domestic fires and biomass burning are the main source of NH_3 emission (Liousse et al., 2014; Adon et al., 2010). Anthropogenic emissions of NH_3 for the domestic fires source in Bamako (Mali) and Dakar (Senegal) have been estimated for 2005 to be 1.6 x 10^{-3} TgNH₃ yr^{-1} and 7.0 x 10^{-4} TgNH₃ yr^{-1} respectively (Adon et al., 2016). In Abidjan, NH_3 concentration were very much higher compared to other gaseous. Figure 9 shows the spatial distribution of NH_3 in Abidjan. The domestic fires site (A_{16}) has the highest concentration of NH_3 (102.1 ± 9.1 ppb). This site is a mid-term instrumented monitoring site of the DACCIWA project located near a traditional smokehouse of food products. It was selected to investigate the concentrations of pollutants emitted by domestic fires contributions to the source. The second most important concentration of NH_3 was measured at the site A_{14} located on the east of the city and characterized by domestic fires and the residential sector (67.7 ± 8.3 ppb). It should be noted that these 2 sites presenting very high concentrations corresponds to measurements performed less than 5 m from the source of pollution. NH_3 concentrations at the other sites ranged from 9.1 ± 1.7 ppb to 44.0 ± 2.2 ppb. High concentrations about 36.6 ± 4.1 ppb are measured in the west and the northeast of the city where most of the domestic fires, residential and suburban sites are located. One part of the Songon municipality located in the south-west of Abidjan between sites A_{18} and A_{19} regroups a set of poultry and pig farms because of the availability of space and its rural character (Yapi-Diahou et al., 2011). Golly and Koffi-Didia (2015) showed the existence of 63 modern poultry farms and 9 modern pig farms in this area. Also, the liquid manure resulting from these breedings is one of the main sources of NH_3 and nitrogenous compounds emission (Degré et al., 2001; Bouwman and Van Der Hoek, 1997). Total NH_3 emissions in France in 2007 were estimated at 382 kt with 15 % of these emissions were due to poultry dejections (Gac et al., 2007). In the global NH_3 anthropogenic source budget, (Bouwman et al., 2002) indicates that animal excreta source represents 21.7 Mt yr^{-1} of the total 53.6 Mt yr^{-1}. In addition to the breedings, this urban area combine large industrial and individual plantations of hevea and banana. These plantations often make excessive use of chemical fertilizers rich in urea and leading to ammonia emissions (Degré et al., 2001). A High NH_3 concentration was also measured at the waste burning site (A_{15}). This site is located in the village of Akouedo and classified as an uncontrolled dump site of garbage (Kouame et al., 2006). With 153 ha, it receives all the vegetable, animal and industrial waste of the city of Abidjan since 1965. This huge waste is estimated at about 550,000 t per year (Kouame et al., 2006). Human waste and its management is a problem in Abidjan that can also explain the

concentration levels obtained. To summarize, NH_3 concentrations are very high, which can be attributed to domestic fires, as well as bacterial decomposition associated with agriculture (pig and poultry farming) and waste dumps

Nitric acid (HNO₃)

HNO_3 is believed to be a major end product in oxidation of gaseous nitrogen compounds. It is one of the mineral acid contributor to the acid rain (Cogbill and Likens, 1974). Figure 10 shows the spatial distribution of HNO_3 in Abidjan during the dry season. The study of the spatial distribution of HNO_3 in Abidjan showed that the concentrations are ranged between 0.2 ± 0.0 ppb and 1.4 ± 0.3 ppb. Approximately half of the sampling sites have concentration between 1.1 ± 0.3 ppb and 1.4 ± 0.3 ppb. These sites are mainly located in the center and in the west of the city. The highest concentration of HNO_3 was measured at a suburban site A_{17} (1.4 ± 0.3 ppb), a waste burning site A_{15} and an industrial area A_9 (1.3 ± 0.2 ppb), a residential site A_{13}, a domestic fires site A_{16} and a residential district A_7 (1.2 ± 0.3). Most of these sites are located at the East of the city. This could be explained by the fact that gaseous HNO_3 is the result from several chemical transformation processes of NH_3 and NOx (NO_2 + NO) guided by presence of oxidants such as H_2O_2, O_3 and OH radical (Seinfeld and Pandis, 2016; Kumar et al., 2004; Hanke et al., 2003). The prevailing SW winds can also transport the precursor pollutants from the city center in the easterly direction and aging in the air masses lead to the production of HNO_3 far from their source.

Ozone (O₃)

O_3 is often associated in urban areas to adverse effects on human health and natural environement (Hagenbjörk et al., 2017). It is well known that this secondary pollutant depends on photochemical interactions of gaseous precursors composed of nitrogen oxides (NOx) and volatile organic compounds (VOCs) (Duan et al., 2008; WHO, 2006). At a specific location, the level of O_3 concentration depends on emission to its precursors (VOCs and NOx), the long-range transport of O_3 and meteorological parameters (Hagenbjörk et al., 2017). Two chemical regimes are associated with the rate of ozone production. The NOx-saturated or (VOC-limited) regime and the NOx-limited regime. In urban areas with high NOx concentrations (NOx-saturated) and a low ratio VOCs/NOx, the ozone production rate is generally low and concentrations are in the order of few ppb. In some places, high concentrations can be observed, due to the recirculation of atmospheric air mass and specific meteorological conditions. When we leave the city center, in the peri-urban areas, we notice an increase of VOC/NOx ratio and a high O_3 production because of the absence of major sources of NOx, the dilution of air mass and the presence of biogenic VOCs. We measured O_3 concentration at different location in the district of Abidjan. Figure 11 shows the spatial distribution of ozone in the district of Abidjan during the dry season. Generally, we notice the presence of O_3 throughout the city. The levels of concentration increase considerably from the west to the east of Abidjan. Highest O_3 concentrations were observed in the two coastal sampling sites A_6 (Gonzagueville) and A_{20} (Airport-FHB) located in the southeast of the city with 19.1 ppb and 18.8 ppb respectively. These two sites on the eastern outskirts of the city are characterized by a monthly sunshine ranging between 117 hours and 224 hours (Messou et al., 2013) and by a high relative humidity in the air due to the presence of water vapor from the marine spray. The OH radical is the major oxidant of the atmosphere. It directly controls the lifetime of VOCs and NOx (Sadanaga et al., 2012). It ensures the conversion of NO to NO_2 and is therefore responsible for the net production of ozone (Camredon and Aumont, 2007). We also measured significant concentrations at two other peri-urban sites in the east of the city: the waste burning site of the village of Akouedo (A_{15}) and the suburban site of Bingerville (A_{17}) with O_3 concentrations of 17.55 ppb and 16.76 ppb respectively. As in the case of HNO_3, highest concentrations measured at the east of the city may be due to the aging of precursor pollutants transported in the easterly direction by SW prevailing winds. On the traffic sites (A_1, A_2, A_7, A_9) located near the Banco forest, ozone concentration was found to be between 11.3 ppb and 12.9 ppb. The lowest O_3 concentration in Abidjan was measured in the north of the city on the site A_4 (5.09 ppb).

3.2 Mean gaseous concentrations of the main anthropogenic activities in Abidjan and comparison with other cities of developing countries

The study of the spatial distribution of gaseous pollutants in Abidjan reveals different anthropogenic contributions to the measured levels of pollution. Therefore, we have tried to investigate the relation between the concentrations levels measured for each primary pollutant (NO_2, SO_2, NH_3) and the potential emission of each anthropogenic activity. Sampling sites were grouped by activity sectors source of pollution. Six different groups were formed. The main activities sources of pollution have been identified in section 3.1 to be traffic, industrial, residential, domestic fires, waste burning and suburban. We calculated the mean concentration of each gaseous pollutant associated with each sector (Fig. 12).

3.2.1 Average concentration of primary gaseous pollutants associated with anthropogenic activities

Nitrogen dioxide (NO_2)

The analysis shows that the industrial sector and traffic mainly explain the highest measured NO_2 concentrations with an average concentration of 20.9 ± 2.8 ppb and 17.8 ± 4.7 ppb respectively. However, domestic fires and residential sites present very comparable levels of NO_2 concentrations of 17.9 ± 0.3 ppb and 16.1 ± 2.4 ppb respectively compared to industrial and traffic sites. It should be noted that residential and domestic fires sites are strongly influenced by road traffic in Abidjan. The identified residential and domestic fires sites are never more than 10 meters far from roadways. This could explain the near-similar concentrations levels observed between traffic, domestic fires and residential sites. Waste burning (12.0 ± 0.0 ppb) and suburban (7 ± 2.4 ppb) sites present lower concentration of NO_2. Nevertheless, these concentrations are not negligible and can be due, on one hand, to the limited traffic of the garbage collection vehicles and also on the other hand to the circulation of minibus called "gbaka" which connects the city centre to the suburbs.

Sulfur dioxide (SO_2)

The road traffic sector is the main contributor to the SO_2 pollution levels measured in Abidjan (4.2 ± 2.2 ppb). This result seems to be a good indicator of the quality of fuels used in Abidjan. In countries without stringent fuel policies such as Cote d'Ivoire, diesel sulphur content is generally important. The average concentration of SO_2 in suburban and industrial sites is 2.0 ± 1.4 ppb and 1.7 ± 0.1 ppb, respectively.

Ammonia (NH_3)

NH_3 concentrations are significantly higher at domestic fires sites with an average concentration two to four times higher than for other sites (84.9 ± 17.2 ppb). This very high value highlights the use of biomass burning (firewood and charcoal) as a source of energy by most of households of Abidjan. The high standard deviation is due to the location of 2 of the domestic fires sites near the source while the other domestic fires sites are much further away from the source. The others groups of sites representative of waste burning (39.1 ppb) and traffic sources (27.2 ± 3.1 ppb) present NH_3 concentrations lower than 40 ppb. Peri-urban agriculture and intensive livestock in the Abidjan suburbs are mainly responsible for the suburban areas NH_3 concentration (22.6 ± 10.3 ppb). This value is close to concentrations measured at residential (21.9 ± 5.2 ppb) and industrial (20.7 ± 0.7 ppb) sites. Ammonia concentrations measured in Abidjan are very high compared to the concentrations measured in rural African environments where concentrations range from 1 to 9 ppb (Adon et al., 2010; Carmichael et al., 2003; Fattore et al., 2014; Martins et al., 2007) and similar to concentration found near agriculture sources.

3.2.2. Average concentrations of gases compared with other urban sites

In order to contextualize the gaseous pollution measured in Abidjan in a sub-regional and international context, we have listed in Table 5 some experimental studies using passive samplers to have a comparable measurement technique and also a comparable temporal integration. Table 5 presents a comparison between gases concentrations measured in Abidjan with literature data, with a focus on primary pollutants (NO_2, SO_2 and NH_3)

Traffic and urban sites

The average concentration of NO_2 in Abidjan (17.8 ppb) is more than three times higher than that measured in St John's in India (4.8 ppb) (Kumar et al., 2004). This concentration in Abidjan is comparable to those measured in Bamako (16.2 ppb) and Shenzhen (20.7 ppb) reported by Adon et al. (2016) and Xia et al. (2016). However, it remains lower than the concentrations obtained in Dakar (31.7 ppb) and Al Ain in the Middle East (31.5 ppb) and reported respectively by Adon et al (2016) and Salem et al (2009).

The average concentration of NH_3 measured at the Abidjan traffic site (27.2 ppb) in this study is higher than those obtained in Dakar (21.1 ppb), Al Ain city (17.1 ppb) and St John's (9.5 ppb), respectively reported by Adon et al. (2016), Salem et al. (2009) and Kumar et al. (2004). Adon et al., (2016) also reported a concentration of NH_3 in Bamako (46.7 ppb) two times higher than that obtained in Abidjan.

The average SO_2 concentrations at the traffic and urban sites ranging from 1.56 to 15.9 ppb. In comparison with Abidjan traffic site (4.2 ppb), the average SO_2 concentrations in Bamako (3.6 ppb) and St John's (1.56 ppb) are very lower. The concentration of SO_2 in Abidjan is comparable to those measured in the polluted urban sites of Shenzhen (4.9 ppb) in China and Al-Ain City (5.8 ppb) in the United Arab Emirates. The SO_2 level in Dakar is the highest with a concentration of 15.9 ppb (Adon et al., 2016).

It highlights significant differences in the sources of gaseous pollutants and their level of concentrations in West African and African cities and those in developing countries.

Suburban sites

The average concentration of NO_2 in Abidjan suburban site (7 ppb) is more than 2 times higher in comparison with that measured in Amersfoort suburban site (2.5 and 2.9 ppb), respectively reported by Martins et al., (2007) and Lourens et al., (2011). The concentrations of SO_2 in Abidjan (2.2 ppb) are lower than those measured at Amersfoort suburban site in South Africa (2.8 - 5.5 ppb). The concentration of NH_3 in Abidjan is the highest with 22.6 ppb

3.3 Overview of urban NO_2 and SO_2 monitoring studies in African cities

Air quality monitoring networks are very important in assessing the health risk associated with exposure to gaseous pollutants. They also help governments to take measures of mitigation of the levels of pollutant concentrations and to define air quality indices (AQI) adapted to each country. If some synthesis of air quality measurements for particulate matter concentrations exist in the literature at the scale of Africa (Petkova et al., 2013), there is no overview for gaseous pollutants. Nowadays, it is quite difficult to provide an overview of air quality results for gaseous pollution over Africa because of the availability of only some non-perennial studies carried out within the framework of scientific research programs. The available results are also not always communicated publicly or in the literature. As this study shows, one of the main gaseous sources of air pollution in African cities is traffic road emitting NO_2 and SO_2.

This section aims to report the main studies on NO_2 and SO_2 conducted at different time scale (hourly, daily, weekly, monthly and annually) in African urban and industrial environments. This is the result of literature searches based on studies conducted in Africa between 2005 and 2017. Publications in which methodology or data reporting were clearly described were selected and listed in Table S3 and Table S4 respectively for NO_2 and SO_2. Recent and unpublished studies have also been presented for comparison. Figure 13 presents the African countries, coloured by UN sub-region, for which NO_2 and SO_2 monitoring studies were identified and included in this work.

We found NO_2 and SO_2 measurements conducted in at least 20 African countries. Most of those measurements were located in seven West African countries (Senegal, Mali, Burkina Faso, Cote d'Ivoire, Nigeria, Ghana and Benin) and in five East African countries (Sudan, Kenya, Ethiopia, Uganda and Tanzania). Studies were also identified for four countries (Algeria, Tunisia, Morocco and Egypt) in Northern Africa and three countries (South Africa, Angola and Mozambique) in

Southern Africa. Only one study was identified in Central Africa (Cameroon). To compare the levels of gaseous concentration in Africa with WHO air quality guidelines, we present the concentration level of each pollutant for each country using the mean, the minimum and the maximum values when available. Figure 14 and Figure 15 represent NO_2 and SO_2 levels in African cities as reported in the various studies respectively. Daily or hourly routine NO_2 and SO_2 do not exist in most of the African cities. In most of the studies we found, monitoring campaigns were carried out with different methods (passive sampling, real time analysers or satellite) and over short periods. Thus, only few studies allow the comparison with WHO standards.

Nevertheless, this section represents, to our knowledge, a state of the art of urban NO2 and SO2 concentrations measured in African cities and lead to a contextualisation of our results in Abidjan

Nitrogen dioxide (NO2)

Short time exposure (1hour) at a concentration of 200 μg.m^{-3} of NO_2 is toxic and has significant health effects. The three studies at this time scale performed by Jackson, (2005) in Tanzania and Adon et al. (2016) in Senegal and Mali show that hourly NO_2 concentration range between (18 μg.m^{-3} - 53 μg.m^{-3}), (9.4 μg.m^{-3} - 150 μg.m^{-3}) and (15.8 μg.m^{-3} - 135 μg.m^{-3}) in Dar-es-Salam, Dakar and Bamako respectively (Fig. 14). These levels of concentration are under the WHO threshold.

WHO air quality guidelines value for annual exposure to NO_2 concentration is 40 μg.m^{-3}. Seven studies were carried out during at least one year in Dakar (Senegal), Ouagadougou (Burkina Faso), Bamako (Mali), Abidjan (Cote d'Ivoire), South Africa and Ben Arous (Tunisia) (Bahino PhD, 2017 pers. com; Chaaban, 2008; Claire Demay et al., 2011; Josipovic et al., 2010; Nanaa et al., 2012). The average annual concentration of NO_2 in Ben Arous, Tunisia (178 μg.m^{-3}) and in Dakar, Senegal (59.6 μg.m^{-3}) exceed the WHO threshold value (40 μg.m^{-3}). Annual average concentration measured in Dakar, Ouagadougou and in South Africa are lower and ranged between (3.5 μg.m^{-3} and 19.6 μg.m^{-3}), (22 μg.m^{-3} and 27 μg.m^{-3}) and (2 μg.m^{-3} and 7 μg.m^{-3}) respectively.

Almost nineteen studies were conducted at daily, weekly and monthly scales. 8 studies were conducted on a daily basis. Average 24-hour concentrations ranged from 0.1 μg.m^{-3} along Juja road in Nairobi (Kaboro, 2006) to 752 μg.m^{-3} on the traffic site of Dantokpa market in Cotonou (Mama et al., 2013). Only 3 studies measuring NO_2 on a weekly scale were identified. The maximum concentration (1015.34 μg.m^{-3}) was measured in the city of Oweri, the capital of the oil-rich region of Imo state in Nigeria (Ibe et al., 2016). Except this extreme value, concentrations range from 9.32 μg.m^{-3} in urban sites of Kampala (Uganda) to 60 μg.m^{-3} in low-income areas of Accra (Ghana).

Average monthly concentration is ranged from 2.6 μg.m^{-3} to 87.2 μg.m^{-3} for 8 studied sites. The lowest values were measured in Maputo (Mozambique) in a residential site and on a green area. The monthly average concentration in Maputo is 9.13 μg.m^{-3}and varies between 2.6 μg.m^{-3} and 21 μg.m^{-3} (Cumbane et al., 2008). The highest monthly average concentration of NO_2 was measured in Bamako.

In our study, concentrations measured on traffic and industrial sites in Abidjan (33.5 μg.m^{-3} and 39.3 μg.m^{-3} respectively) are of the same order of magnitude as the values obtained by (Liousse and Galy-Lacaux, 2010) at urban sites in Abidjan (29.8 μg.m^{-3}) and Yaoundé (33.3 μg.m^{-3}). Similarly, annual NO_2 concentrations measured in Abidjan (Bahino phD 2017) in the DACCIWA mid-term experiment (2015-2017) presents values about 25 μg.m^{-3} for the traffic site (A_1) that is in the same range of other African studied capitals. However, this table emphasizes the lack of NO_2 measurements in Abidjan at hourly and annual scale allowing the comparison with WHO thresholds. It would therefore be wise for public authorities in Abidjan as well as in other African cities to carry out regular studies at comparable time scales and with recommended methods to obtain reliable results.

Sulfur dioxide (SO₂)

WHO indicates that changes in pulmonary function and respiratory symptoms appear after a ten-minute exposure period to SO_2 at a concentration of 500 $\mu g.m^{-3}$. No study carried out with a minimum time interval of 10 minutes was reported in the literature.

5   Twenty-four hour SO_2 levels are significantly associated with daily mortality rates (Burnett et al., 2004). WHO twenty-four hour guideline for SO_2 is 20 $\mu g.m^{-3}$. Nine daily (24-hour) studies are reported on Fig. 14. Measurements in Cotonou (Benin) have been performed at the crossroad of Dantokpa market characterized by a large circulation of two-wheeled vehicles. Daily average concentrations range between 784.8 $\mu g.m^{-3}$ and 3662.4 $\mu g.m^{-3}$ (Mama et al., 2013). These concentrations are 39 to 183 times higher than the threshold value. In Dakar (68.54 $\mu g.m^{-3}$), Cairo (34 $\mu g.m^{-3}$), and Bamako (29.03 $\mu g.m^{-3}$), SO_2

10   mean daily concentrations are greater than 20 $\mu g.m^{-3}$. It is found that only 2 studies conducted in Marrakech (Morocco) and Tunis (Tunisia) have concentration ranges lower than the threshold. In Nairobi and Khartoum the maximum concentration can reach and exceed the threshold.

Hourly SO_2 concentration in African cities is ranged from 9.14 $\mu g.m^{-3}$ to 214514 $\mu g.m^{-3}$. In West Africa (Mali and Burkina), concentrations are much lower (9 $\mu g.m^{-3}$ - 136 $\mu g.m^{-3}$).

15   Approximately 6 studies report weekly and monthly concentrations of SO_2 (Fig. 14). Generally, weekly and monthly SO_2 concentrations in Africa range from 0.77 $\mu g.m^{-3}$ to 18.9 $\mu g.m^{-3}$. The weekly concentrations measured in the oil state of Imo State (Nigeria) are not in this range (1203 $\mu g.m^{-3}$ to 1465 $\mu g.m^{-3}$) (Ibe et al., 2016).

The annual average concentrations of SO_2 are reported for 11 studies. The concentrations measured in North Africa are the highest. Average levels of SO_2 range between 8 $\mu g.m^{-3}$ in Rabat (Morocco) and 325 $\mu g.m^{-3}$ in Alger (Algeria). In West

20   Africa, concentrations are lower and range from 0.5 $\mu g.m^{-3}$ in Ouagadougou (Burkina Faso) to 80 $\mu g.m^{-3}$ in Dakar (Senegal). The annual average SO_2 concentration in Abidjan (3.66 $\mu g.m^{-3}$) is one of the lowest of West African cities reported in this study (Bahino PhD, 2017 pers.com). Measurements of SO_2 at smaller time scales (i.e., 10 min, 24 hours) do not exist in Abidjan or are not published. As for NO_2, studies should be carried out regularly and according to WHO standards.

25   Air pollution from human activities has been a long-standing environmental issue. Human activities have led to an unprecedented increase in atmospheric abundances of key air pollutants. High concentrations of ozone and PM adversely impact human health by increasing the risk of a variety of diseases. The high concentrations of gaseous pollutants measured in Abidjan could be responsible for respiratory diseases, which could result in significant costs to human health and the economic capacity of the local workforce. Environmental changes, including air pollution, have already significantly increased

30   the burden of cancer in West Africa in recent years (Val et al. 2013). Premature death in the world in 2010, resulting of air pollution leads according to the World Health Organisation, to a combined estimate of more than 7 million premature deaths.

In addition to health impacts, anthropogenic pollutants that react with biogenic emissions can also lead to increased ozone and acid production outside urban areas (Marais et al. 2014), with adverse effects on precipitation and cloudiness that can affect animals, land area, ecosystems and crops and affect many other important socio-economic factors. The worldwide

35   economic loss associated with these crop losses is estimated to represent an economic value of \$14-26 billion for the year 2000 (van Dingenen et al., 2009).

Data provided by this kind of study can help:

- to study the expected changes in future air quality in response of various forcings such as changes in the emissions due to urbanization and industrialization, and climate change.

40   - to estimate the immediate impacts (e.g., human health effects, crop damage) and long-term effects (e.g., chronic health impacts, deposition on the biosphere, climate impacts) of air pollution (knippertrz et al., 2015)

4 Conclusion and recommendations

Abidjan is the economic capital of the West African sub region. The new urban master plan of the city foresees its extension and the construction of many infrastructures, which will certainly increase the environmental and sanitary problems.

The present study reports the gaseous concentrations measurements using passive samplers performed during an intensive experimental field campaigns in the framework of the Work Package 2 of the European DACCIWA project. This work presents an original database of bi-monthly gaseous concentrations (NO_2, SO_2, NH_3, HNO_3, O_3) in the district of Abidjan performed on 21 representative sites. This database allows for the first time to characterize the levels of gaseous concentration and to present a spatial distribution of gaseous pollution at the scale of the city during the dry season (December 15th, 2015 to February 16th, 2016).

Our results show that there is a great spatial variability of gaseous pollutants in Abidjan. The average concentrations of the main gaseous pollutants are ranged between (2.7 ppb - 25 ppb) for NO_2, (9.1 ppb - 102.1 ppb) for NH_3, (0.2 ppb - 1.4 ppb) for HNO_3, (0.4 ppb - 7.21 ppb) for SO_2 and (5.1 ppb - 19.1 ppb) for O_3.

The spatial distribution of gaseous pollutant has been studied according the main potential sources of pollution nearby the measurement sites. Results show that the concentration level of gaseous pollutants such as NH_3 and NO_2 is very important at some sites. On one hand, it highlights the predominance of the domestic fires source with the use of wood and charcoal that emits large amount of NH_3. On the second hand, it shows the significant impact of traffic road on NO_2 and SO_2 emissions.

The average gases concentrations per source of pollution, showed that industrial (20.9 ppb), domestic fires (17.9 ppb) and traffic (17.8 ppb) sites mainly contribute to the NO_2 pollution. Concerning NH_3, domestic fires and waste burning sites constitute by far the main sources of pollution with an average concentration of 84.9 ppb and 39.1 ppb respectively. In addition to the high concentration of NO_2, the traffic sites have also the highest SO_2 average concentration (4.2 ppb).

In this study, we propose for the first time an overview of gaseous SO_2 and NO_2 pollutants which allows to give a global picture of gases concentrations at the scale of several African cities. It includes 22 publications on NO_2 and SO_2 measurements conducted in 20 African countries during the period 2005-2017. This study indicates that gaseous pollution in Abidjan is comparable to other west and central African cities and also emphasizes the lack of air quality monitoring networks. Only a few studies carried out by research teams within the framework of scientific programs with various objectives give an idea of the state of air quality. These studies used different methods and time scales that do not allow comparison with WHO standards and threshold values. The comparable studies show that the hourly concentration of NO_2 in African cities (9.4 $\mu g.m^{-3}$ and 135 $\mu g.m^{-3}$) is lower than the WHO standards. Abidjan annual NO_2 concentration is 23.25 $\mu g.m^{-3}$ with a range at the African cities scale from 2 $\mu g.m^{-3}$ to 175 $\mu g.m^{-3}$. Annual NO_2 WHO standards are exceeded in Dakar and Tunis. The daily concentration of SO_2 in African cities ranges from 0.2 $\mu g.m^{-3}$ to 3662 $\mu g.m^{-3}$ and exceeds the daily SO_2 WHO standard (40 $\mu g.m^{-3}$) in most of the African cities, except in Marrakech and Tunis.

These scarce datasets should draw the attention of the African public authorities to the urgent need to measure NO_2 and SO_2 emissions. The results indicate the need of other studies including VOCs and NOx measurements to better understand the production processes of secondary pollutants such as O_3. In the framework of DACCIWA WP2 (Air Pollution and Health) program, bi monthly measurements are on-going since December 2014 over three supersites. These measurements will make possible to estimate the impact of pollutants concentrations on the population health through the calculation of real dose response functions. To guarantee the continuity of the work done in the DACCIWA work package 2 and to produce health risk maps for the different combustion sources specific to West Africa based on modeling, the university Felix Houphouet Boigny of Abidjan will manage a new project called PASMU (Pollution de l'Air et Sante en Milieu Urbain) starting in 2018. All the results presented in this work will help in the development of new projects and will serve to develop the experimental

strategy of such a network. In addition, meteorological parameters will be included to finally lead to modeling studies to predict air quality for Africa to regional to urban scale.

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Table 1: Geographical coordinates of sampling sites and majors source of air pollution nearby.

ID code°	Site Name	Municipality	Latitude	Longitude	Land Use	Observations
A1*	220 Lgts Liberté	Adjame	5°21'14″ N	4°01'04″ W	Traffic	Mid-term measurement site near a transport station; regular traffic jams; obsolete public transport vehicles; (gbaka, shared taxi and bus); human activities
A2	Gesco	Yopougon	5°21'31″ N	4°06'03″ W	Traffic	Very large intersection at the junction of an exit of the municipality of Yopougon, the North Highway and the Dabou road; heavy vehicles; minibus (gbaka); buses; personal vehicles; regular traffic jams.
A3	N'Dotré	Abobo	5°26'41″ N	4°04'10″ W	Traffic	Crossroads at the east exit of the city. traffic of heavy goods vehicles and buses; human activities
A4	Corridor Anyama	Anyama	5°31'8 ″ N	4°03'34″ W	Suburban/Traffic	Far from the city center; surrounded by forests; human activities
A5	Pharmacy Cadre Blvd	Plateau	5°19'33″ N	4°01'26″ W	Traffic/ Administrative center	City center ; crossroad; traffic jams ; personal vehicles ; train station
A6	Airport-FHB	Port-Bouet	5°16'26″ N	3°55'21″ W	Traffic	Airport weather station; open space; a lot of wind; air traffic
A7	Town hall Attecoube	Attecoube	5°19'52″ N	4°02'23″ W	Residential district / Traffic	Town hall; near traffic lanes; old shared taxis; low income population; use of wood and charcoal
A8	Town hall Abobo	Abobo	5°25'15″ N	4°01'00″ W	Traffic/Residential	Town hall; near a big crossroads and the big market of Abobo; old communal taxis and minibuses (gbaka); low income population; human activities
A9	Yopougon industrial area	Yopougon	5°22'12″ N	4°04'52″ W	Industrial	Heavy industries (cement plants) and light industries (agro-industries, plastic and iron processing, pharmaceutical and cosmetics industries); heavy vehicles, traffic jams
A10	Zone 3	Marcory	5°17'48″ N	3°59'57″ W	Industrial/Traffic	Mixture of residential, commercial and industrial land uses; wood industries, tire retreading, paint manufacturing, chemical fertilizer preparation.
A11	Tri postal-vridi	Port-Bouet	5°16'12″ N	4°00'07″ W	Industrial / harbor	Heavy industry (oil refinery, hydrocarbon depot, oil terminal, thermal power station) ; Light industry (port activities, coffee and cocoa production, metal and plastic processing, fertilizer preparation, paint, soap and oil manufacture)
A12	University FHB	Cocody	5°20'42″ N	3°59'27″ W	Residential district	University residences; electric vehicles; recent personal vehicles; use of LPG for cooking
A13	Angré	Cocody	5°23'27″ N	3°59'34″ W	Residential district	Recent personal vehicles ; use of LPG for cooking
A14	Place Inch'allah	Koumassi	5°17'52″ N	3°57'20″ W	Domestic fires/Traffic	Residential site mainly influenced by domestic activities ; firewood and charcoal; old vehicles
A15*	Akouédo	Cocody	5°21'12″ N	3°56'16″ W	Waste burning	uncontrolled landfill ; continuous burning of all types of waste
A16*	Niangon Bracodi	Yopougon	5°19'44″ N	4°06'21″ W	Domestic fires	Site for smoking meat and fish using firewood
A17	Scientific pole CNRI-UFHB	Bingerville	5°21'30″ N	3°54'07″ W	Suburban background	Far from traffic ; near from Ebrie Lagoon; university residence
A18	Songon health center	Songon	5°19'6″ N	4°12'06″ W	Suburban background	Far from city center ; hospital
A19	Niangon Adjamé	Yopougon	5°20'15″ N	4°07'08″ W	Suburban background	Human activies ; fireood, charcoal
A20	Gonzagueville	Port-Bouet	5°14'31″ N	3°53'09″ W	Suburban	Near from Atlantic ocean, human activities
A21	Ecological research center	Treichville	5°18'41″ N	4°00'10″ W	Green area	Near from Ebrie lagoon; lot of Wind ;

* Mid-term measurement sites (December 2014 - April 2017)

Table 2: Parameters of empirical semivariogram for each pollutant

	NO_2	SO_2	HNO_3	O_3
Nugget Co $(ppb)^2$	30.90	1.93	0.07	6.93
Partial sill Cs $(ppb)^2$	24.46	5.66	0.16	31.68
Major Range (km)	29.44	40.41	30.39	46.51

Table 3: Statistical parameters calculated for each interpolation method

Parameters	MAE		RMSE		R^2	
	IDW	Kriging	IDW	Kriging	IDW	Kriging
NO_2	**0.010**	3.419	**0.031**	4.064	**0.999**	0.738
NH_3	**0.029**	13.016	**0.062**	19.945	**0.999**	0.016
SO_2	**0.003**	0.437	**0.006**	0.621	**0.999**	0.916
HNO_3	**0.000**	0.093	**0.000**	0.127	**0.999**	0.916
O_3	**0.007**	0.609	**0.009**	0.815	**0.999**	0.965

Table 4: Gaseous pollutants concentrations and standard deviation (S.D) on 21 sampling sites in Abidjan during the dry season (December 15th, 2015 - February 16th, 2016).

Sampling site		Concentration in ppb															
ID code	SITE NAME	NO_2			NH_3			SO_2			HNO_3			O_3				
		min	max	mean ± S.D	min	max	mean ± S.D	min	max	mean ± SD	min	max	mean ± SD	min	max	mean ± S.D	
A1	220 Lgts Liberté	13.9	30.8	**20.8±5.0**	23.3	43.3	**31.1±6.1**	0.9	5.4	**2.6±1.4**	0.9	1.3	**1.1±0.1**	10.1	12.6	**11.3±1.0**	
A2	Gesco	10.4	13.1	**11.6±1.0**	25.1	31.6	**27.6±2.3**	4.9	8.2	**6.8±1.3**	0.6	0.7	**0.6±0.1**	10.4	13.3	**12.4±1.0**	
A3	N'Dotré	10.9	15.7	**12.2±1.8**	20.2	28.2	**23.5±2.4**	5.4	8.8	**7.2±1.2**	0.3	0.5	**0.4±0.1**	7.2	10.3	**8.9±0.9**	
A4	Corridor Anyama	7.0	8.7	**7.7±0.6**	26.2	38.5	**32.2±3.8**	3.8	6.0	**4.7±0.8**	0.2	0.3	**0.2±0.0**	4.0	5.6	**5.1±0.6**	
A5	Pharmacy Cadre Blvd	19.7	33.6	**23.9±4.9**	19.0	26.7	**23.0±2.2**	2.0	4.4	**3.1±1.1**	0.6	1.9	**1.1±0.4**	6.9	8.2	**7.8±0.4**	
A6	Airport-FHB	5.3	8.0	**6.9±0.9**	16.4	22.5	**18.8±1.9**	0.2	0.7	**0.4±0.2**	0.6	1.0	**0.9±0.1**	14.0	22.4	**18.8±3.0**	
A7	Town hall Attécoubé	13.9	23.4	**17.5±2.9**	28.2	58.8	**37.0±10.9**	0.9	2.5	**1.5±0.5**	0.6	1.8	**1.2±0.5**	8.7	15.9	**12.4±2.0**	
A8	Town hall Abobo	18.0	24.6	**20.4±2.1**	24.7	37.0	**30.6±3.6**	0.7	2.6	**1.4±0.6**	0.7	1.6	**1.1±0.3**	7.4	13.3	**10.5±1.9**	
A9	Yopougon industrial area	15.7	26.7	**19.9±3.4**	16.7	26.5	**21.6±2.8**	0.5	2.5	**1.8±0.7**	0.9	1.7	**1.3±0.2**	10.9	14.8	**12.2±1.3**	
A10	Zone 3	16.2	19.7	**17.7±1.0**	15.5	24.5	**20.9±2.9**	0.9	2.3	**1.6±0.4**	0.6	0.9	**0.8±0.1**	7.0	11.6	**8.8±1.5**	
A11	Tri postal-vridi	22.7	27.6	**25.0±1.7**	16.9	21.8	**19.6±1.6**	1.2	2.9	**1.9±0.5**	0.5	1.0	**0.7±0.2**	5.8	11.9	**9.6±1.9**	
A12	University FHB	8.4	17.3	**12.5±2.4**	18.4	33.5	**23.9±5.0**	0.5	0.8	**0.7±0.1**	0.6	1.5	**1.0±0.4**	13.4	15.1	**14.1±0.4**	
A13	Angré	15.8	22.8	**18.5±2.2**	24.4	29.6	**26.9±2.4**	1.5	1.9	**1.7±0.1**	0.8	1.8	**1.2±0.3**	9.1	16.1	**12.9±1.9**	
A14	Place Inch'allah	15.8	21.5	**17.6±1.9**	57.6	80.5	**67.7±8.3**	0.6	1.6	**1.1±0.3**	0.4	0.8	**0.6±0.1**	5.3	12.4	**7.6±2.4**	
A15	Akouédo	9.9	13.6	**12.0±1.4**	36.9	43.3	**39.1±2.1**	0.4	2.5	**1.2±0.7**	0.9	1.8	**1.3±0.2**	15.2	19.6	**17.6±1.9**	
A16	Niangon Bracodi	17.6	18.9	**18.3±0.6**	83.9	109.4	**102,1±9.1**	0.8	1.4	**1.1±0.2**	1.0	1.6	**1.2±0.2**	7.7	12.8	**10.2±1.4**	
A17	Scientific pole CNRI-UFHB	9.4	21.0	**13.6±3.7**	16.0	31.5	**22.5±6.1**	0.7	1.7	**1.0±0.3**	1.0	2.0	**1.4±0.3**	11.2	20.4	**16.8±3.0**	
A18	Songon health center	2.5	2.9	**2.7±0.1**	7.5	12.4	**9.1±1.7**	1.4	2.1	**1.9±0.2**	0.4	0.9	**0.7±0.2**	10.1	13.7	**12.1±1.3**	
A19	Niangon Adjamé	4.9	5.7	**5.4±0.3**	41.7	47.2	**44.0±2.2**	2.3	4.9	**3.4±1.0**	0.2	0.2	**0.2±0.0**	5.4	7.8	**6.8±0.7**	
A20	Gonzagueville	6.0	7.7	**6.9±0.5**	11.0	18.8	**14.3±2.6**	0.3	0.5	**0.4±0.1**	0.1	1.5	**0.8±0.4**	15.9	21.4	**19.1±1.7**	
A21	Ecological research center	5.1	7.4	**6.0±0.7**	9.9	17.5	**13.6±2.9**	0.3	0.6	**0.4±0.1**	0.4	0.8	**0.6±0.2**	10.9	15.3	**13.6±1.4**	

Table 5: gaseous pollutants concentrations (ppb) in different sites of Abidjan and in other cities of developing countries

Sites	Type	Period	NO_2 (ppb)	NH_3 (ppb)	SO_2 (ppb)	References
Abidjan, Cote d'Ivoire	Traffic	Dec. 2015-Feb. 2016	17.8	27.2	4.2	This study
	Suburban	Dec. 2015-Feb. 2016	7.0	22.6	2.0	This study
Dakar, Senegal	Traffic	Jan. 2008-Dec.2009	31.7	21.1	15.9	(Adon et al., 2016)
Bamako, Mali	Traffic	Jun. 2008 - Dec. 2009	16.2	46.7	3.6	(Adon et al., 2016)
Cairo, Egypt	Suburban	Winter of 2009-2010	35.5	50.9	13.0	(Hassan et al., 2013)
Amersfoort, SA*	Suburban, Industrialized	Aug. 2007-Jul. 2008	2.9	-	5.5	(Lourens et al., 2011)
Amersfoort, SA*	Suburban, Industrialized	1995-2005	2.5	1.2	2.8	(Martins et al., 2007)
Singapore	Urban	Sept. 2007- Aug. 2008	23.8-28.1	-	12.5-14.9	(He et al., 2014)
Al Ain City, UAE**	Traffic	Feb.2005-Feb.2006	31.5	17.1	5.8	(Salem et al., 2009)
Shenzhen, China	Urban	March. 2013-Feb.2014	20.7	-	4.9	(Xia et al., 2016)
St. John's. India	Urban	July 1999 - June 2001	4.8	9.5	1.56	(Kumar et al., 2004)

*SA: South Africa
** UAE: United Arab Emirates

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Figure 1: Spatial distribution of the 21 sampling sites (A$_1$-A$_{21}$) and major source of air pollution nearby in the District of Abidjan.

Figure 2: Photos of different sampling sites using INDAAF passive samplers installed in duplicate: Traffic (A_1), Domestic fires (A_{16}) Waste burning (A_{15}) and Airport FHB (A_6).
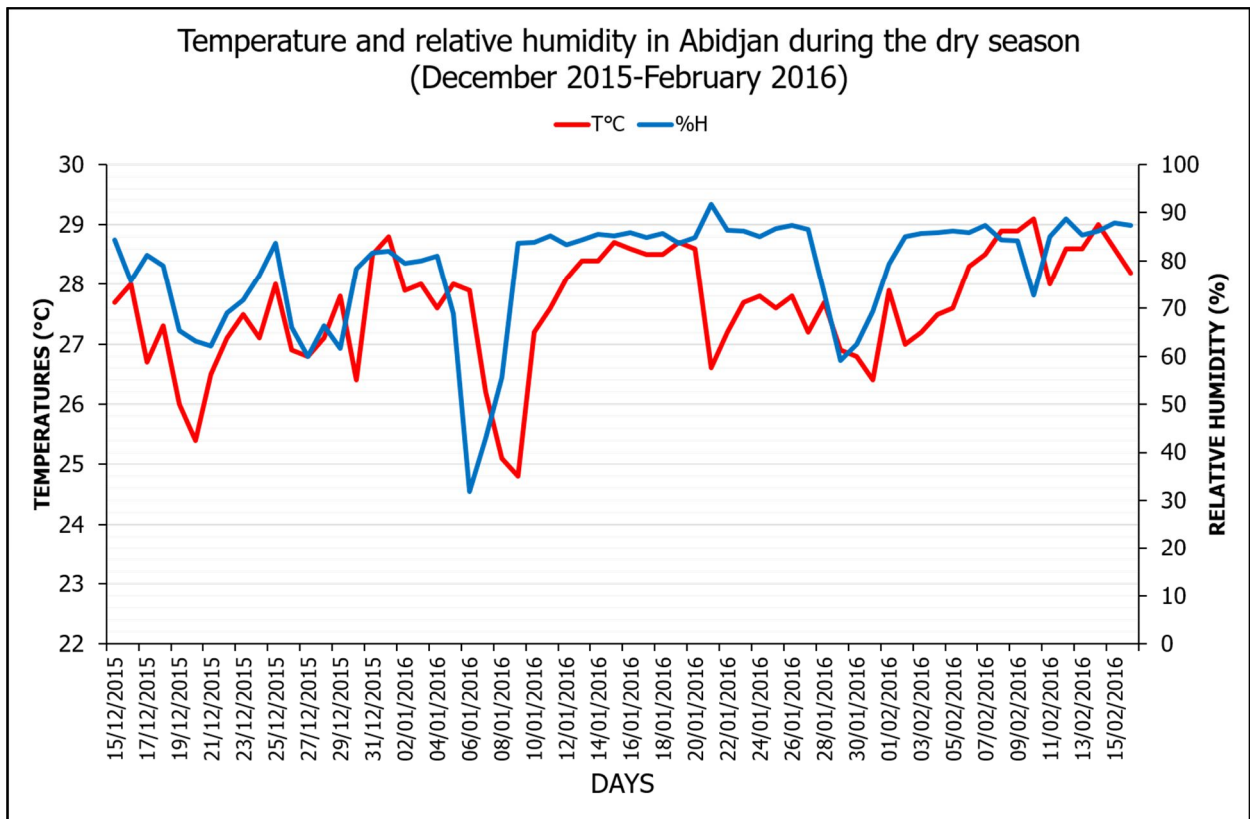
Figure 3: Temperature and relative humidity measured by (ASECNA) in Abidjan during the dry season (December 15ᵗʰ, 2015 – February 16ᵗʰ, 2016).
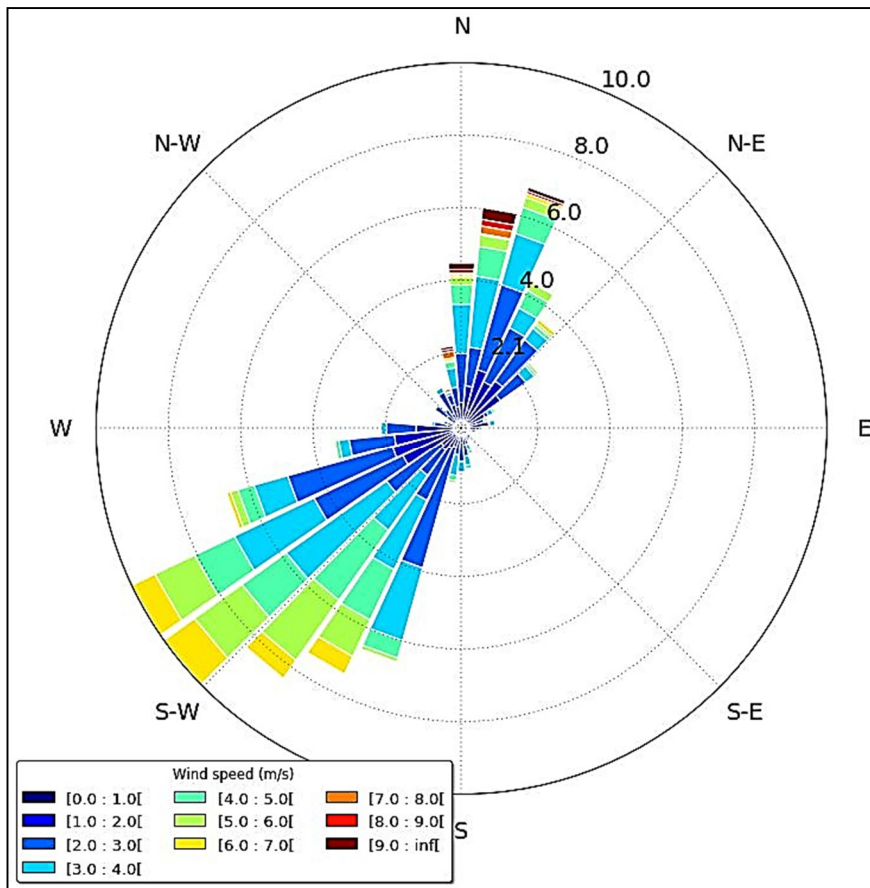
Figure 4: Hourly wind rose diagram of Abidjan during the dry season (December 15th, 2015 – February 16th, 2016)
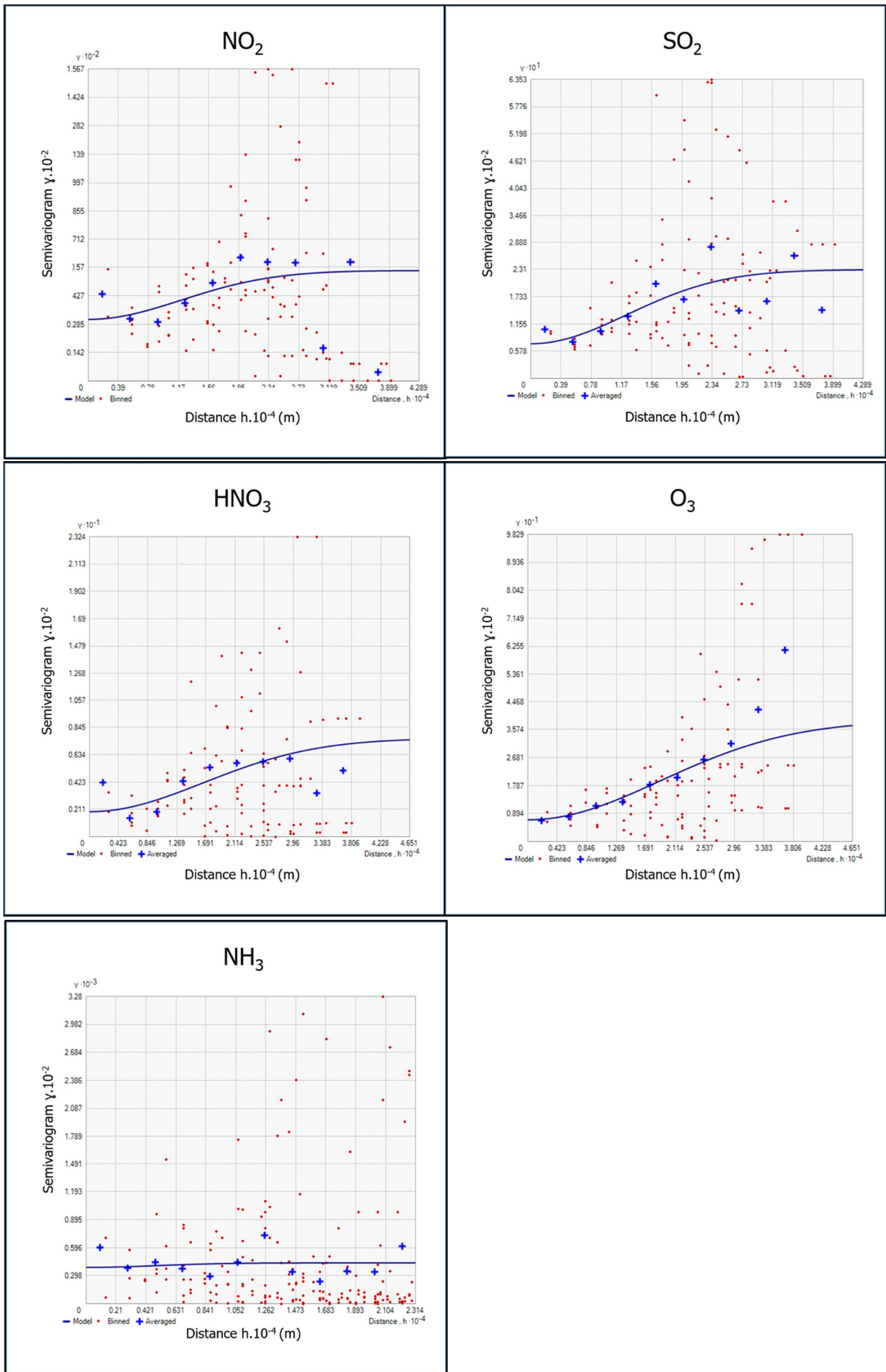
Figure 5: Empirical semivariogram for each pollutant.
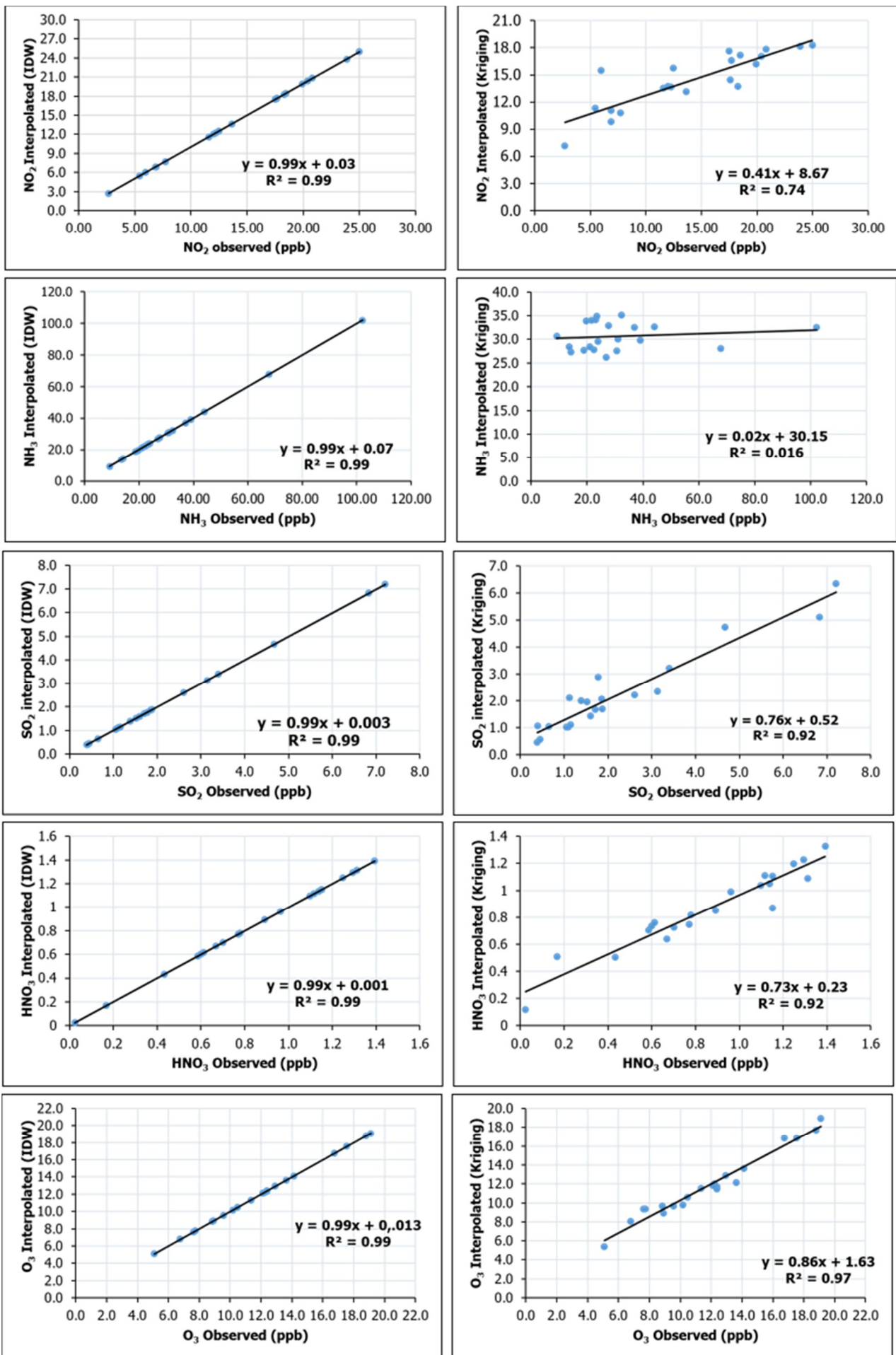
Figure 6: Regression between interpolated data and observed data using IDW and kriging method.
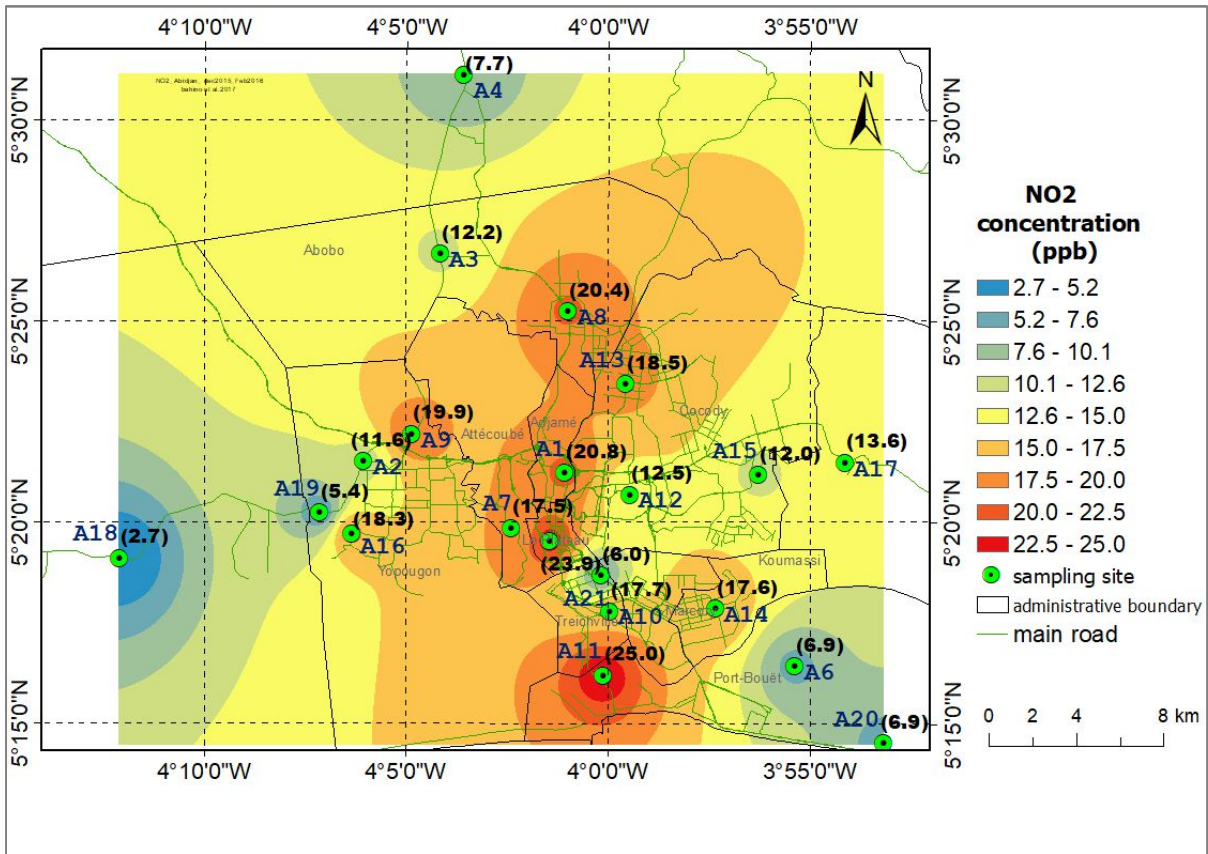
Figure 7: Spatial distribution of NO₂ in the district of Abidjan during the dry season (December 15ᵗʰ, 2015 – February 16ᵗʰ, 2016). Measured concentrations in ppb are into brackets.
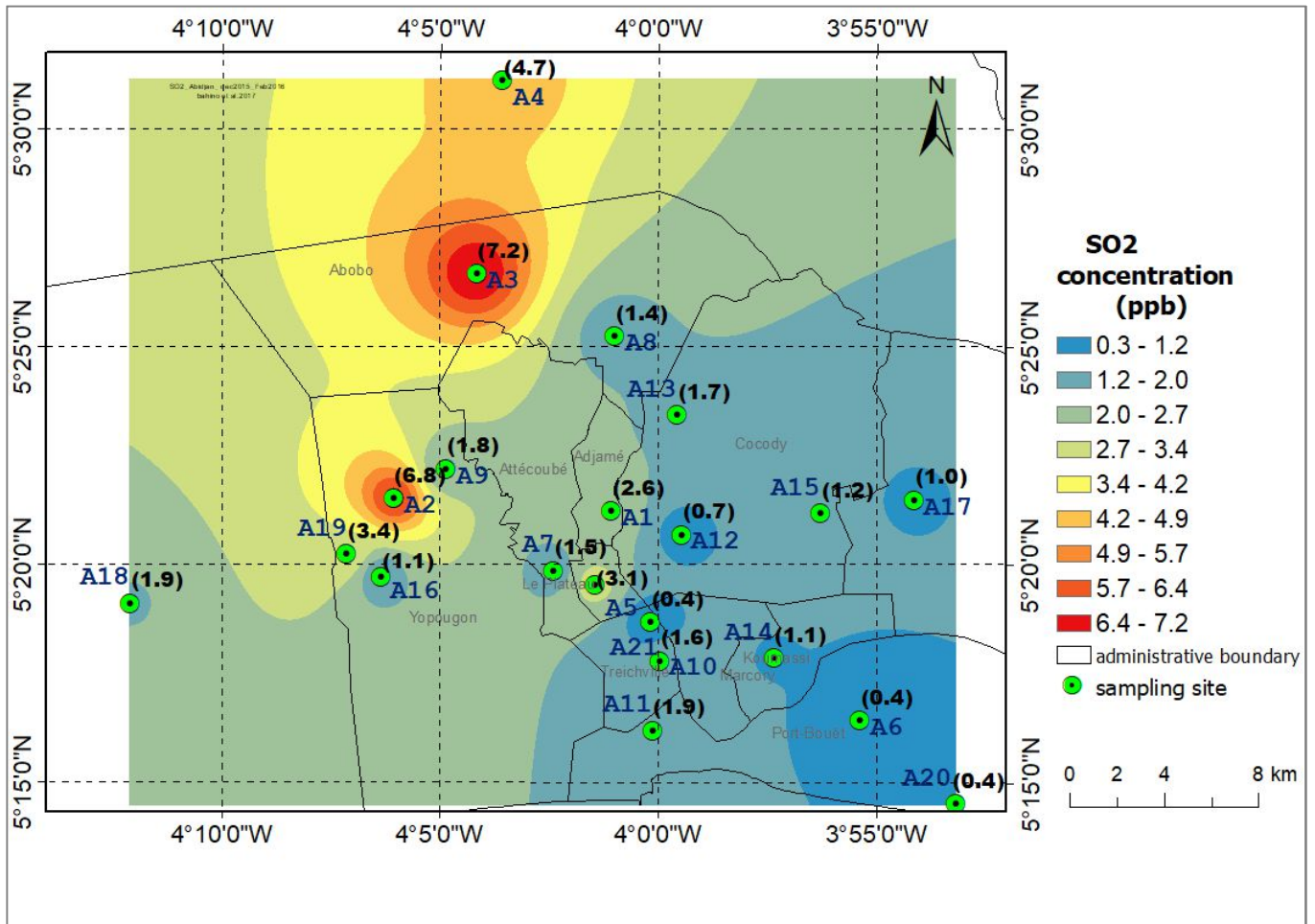
Figure 8: Spatial distribution of SO₂ in the district of Abidjan during the dry season (December 15ᵗʰ, 2015 – February 16ᵗʰ, 2016). Measured concentrations in ppb are into brackets.
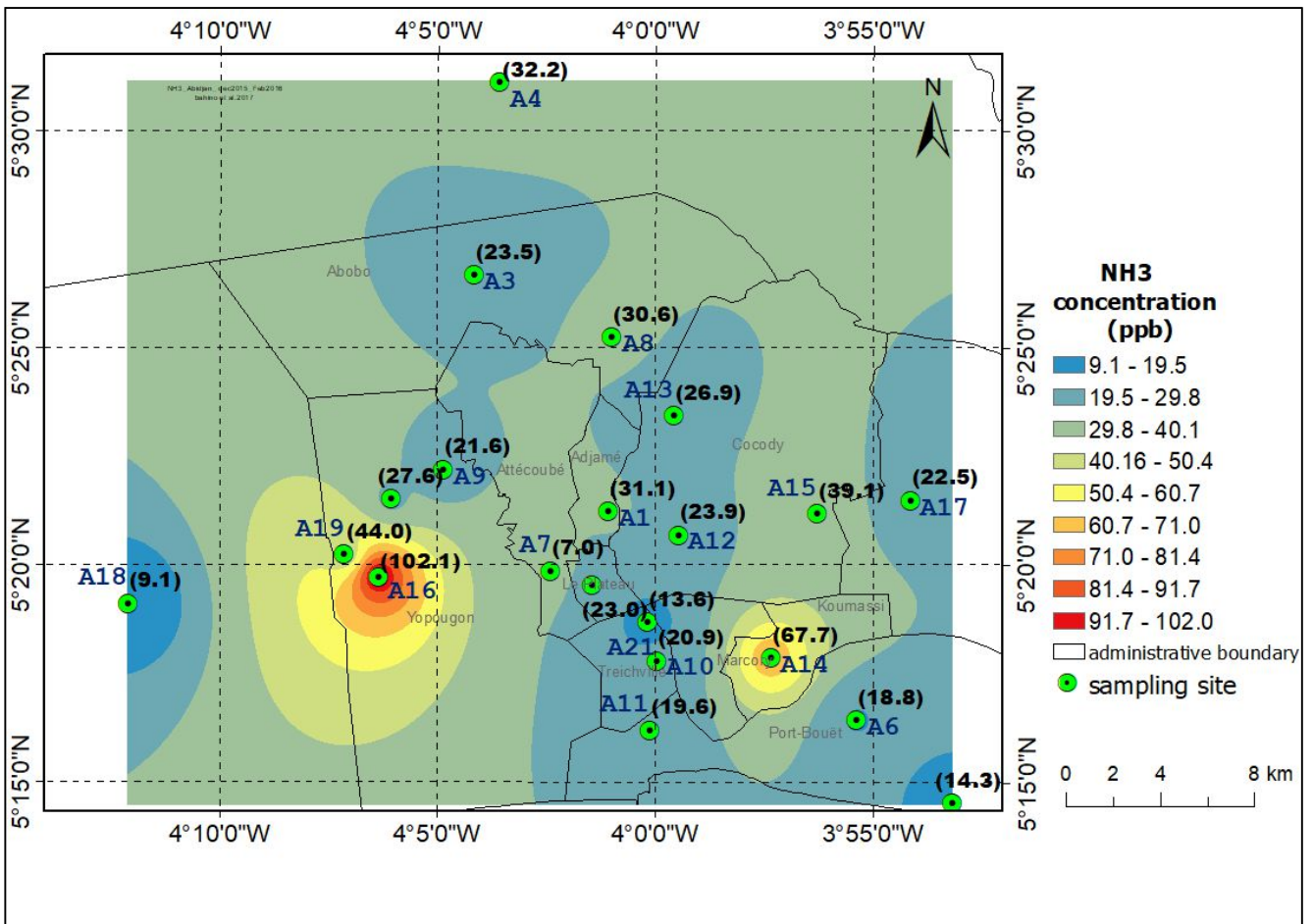
Figure 9: Spatial distribution of NH₃ in the district of Abidjan during the dry season (December 15ᵗʰ, 2015 – February 16ᵗʰ, 2016). Measured concentrations in ppb are into brackets.
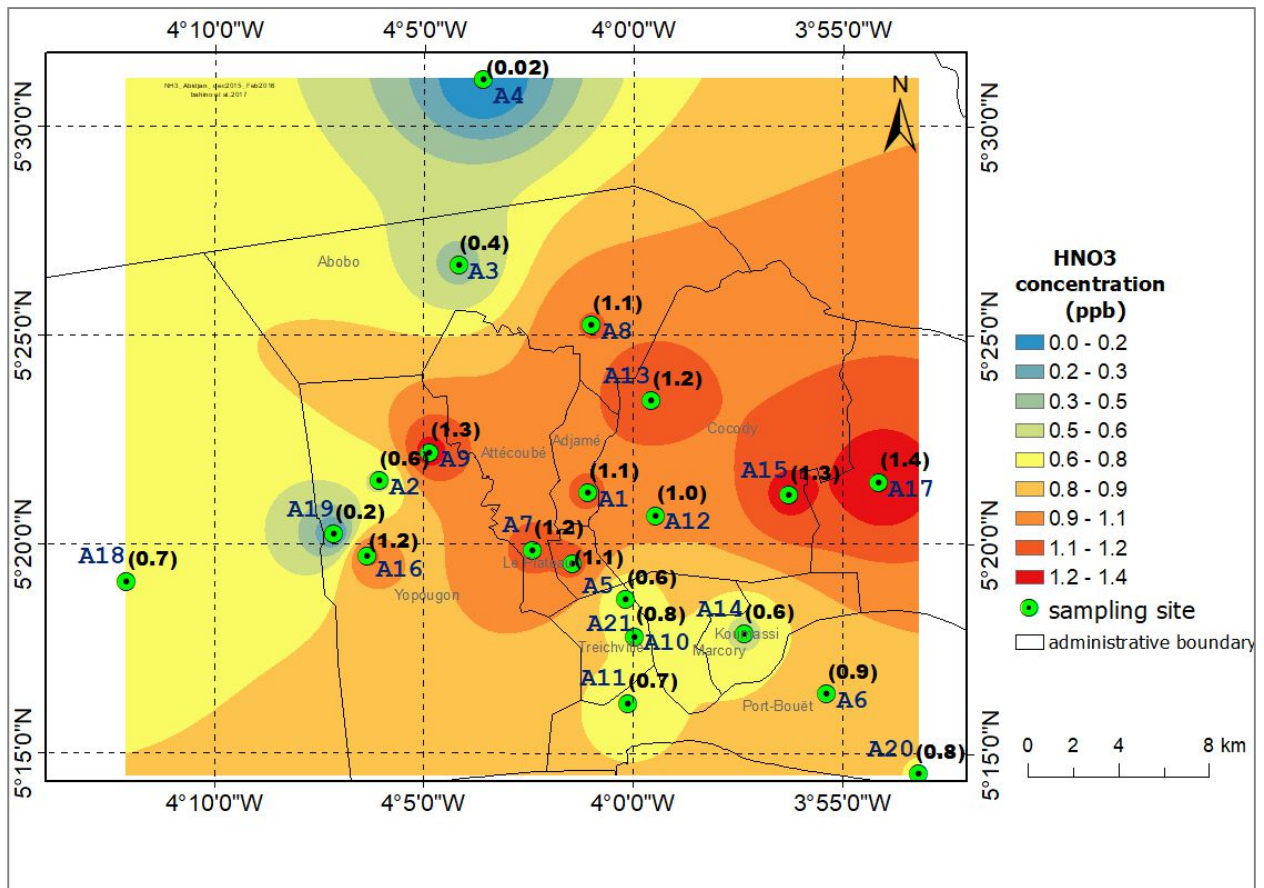
Figure 10: Spatial distribution of HNO₃ in the district of Abidjan during the dry season (December 15ᵗʰ, 2015 – February 16ᵗʰ, 2016). Measured concentrations in ppb are into brackets.
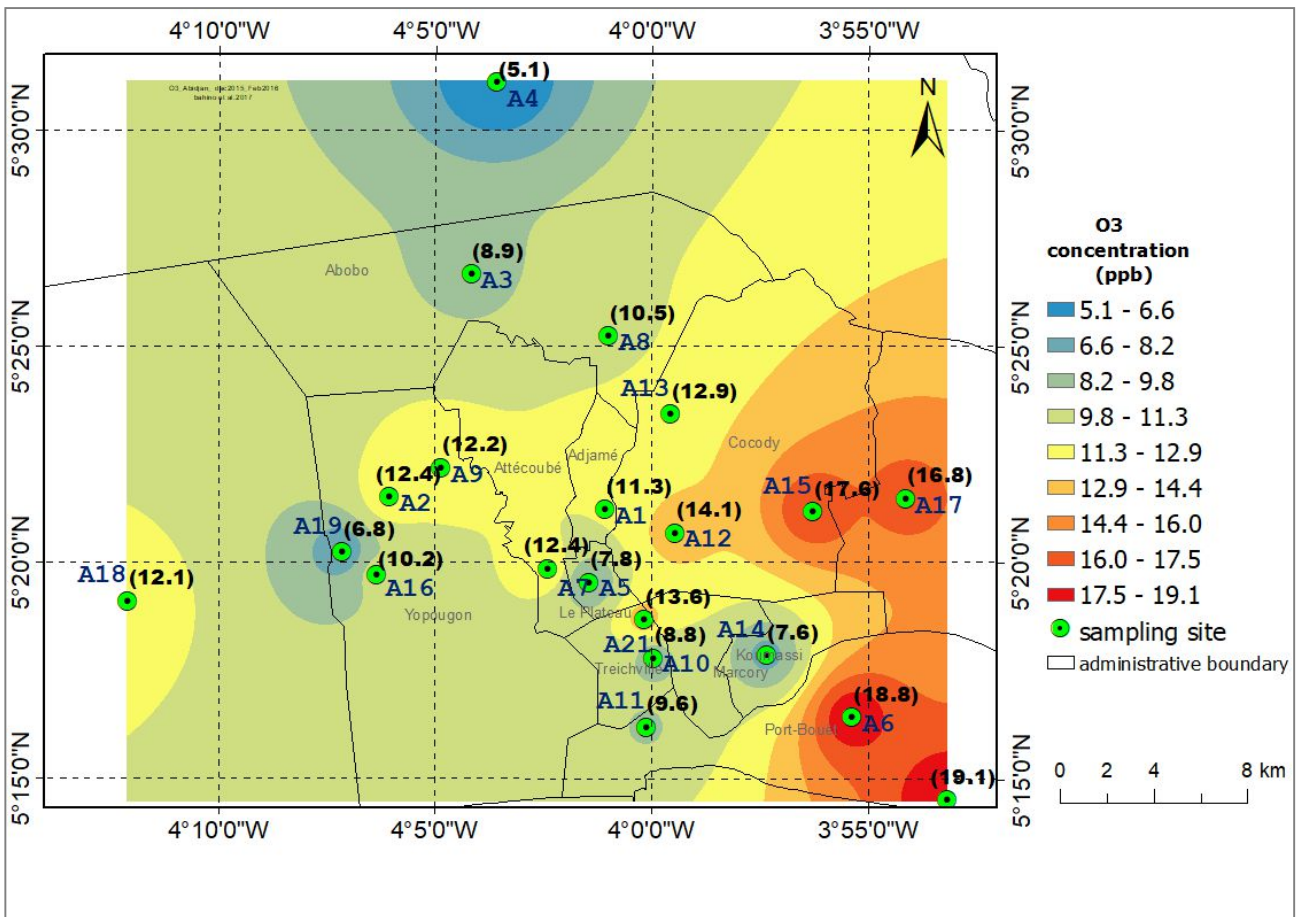
Figure 11: Spatial distribution of O₃ in the district of Abidjan during the dry season (December 15th, 2015 – February 16th, 2016). Measured concentrations in ppb are into brackets.
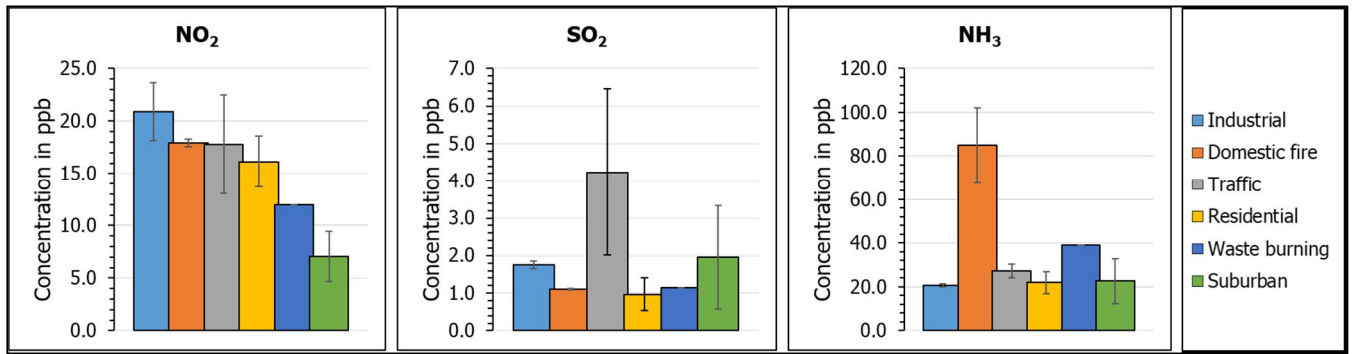
Figure 12: Concentration of gaseous pollutants by anthropogenic sectors of activity in the district of Abidjan.
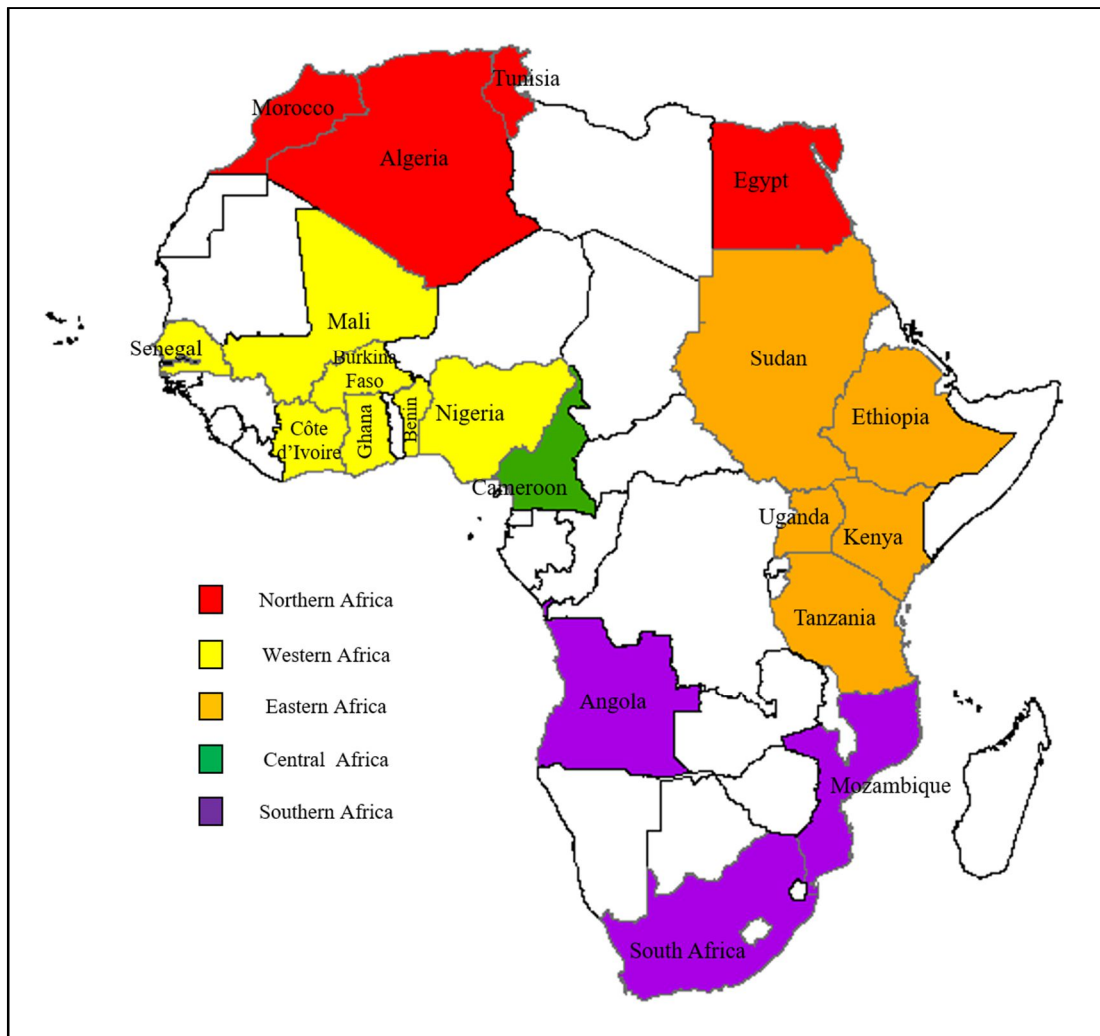
Figure 13: African countries coloured by UN sub-region for which NO₂ and SO₂ studies were identified and included in this publication.
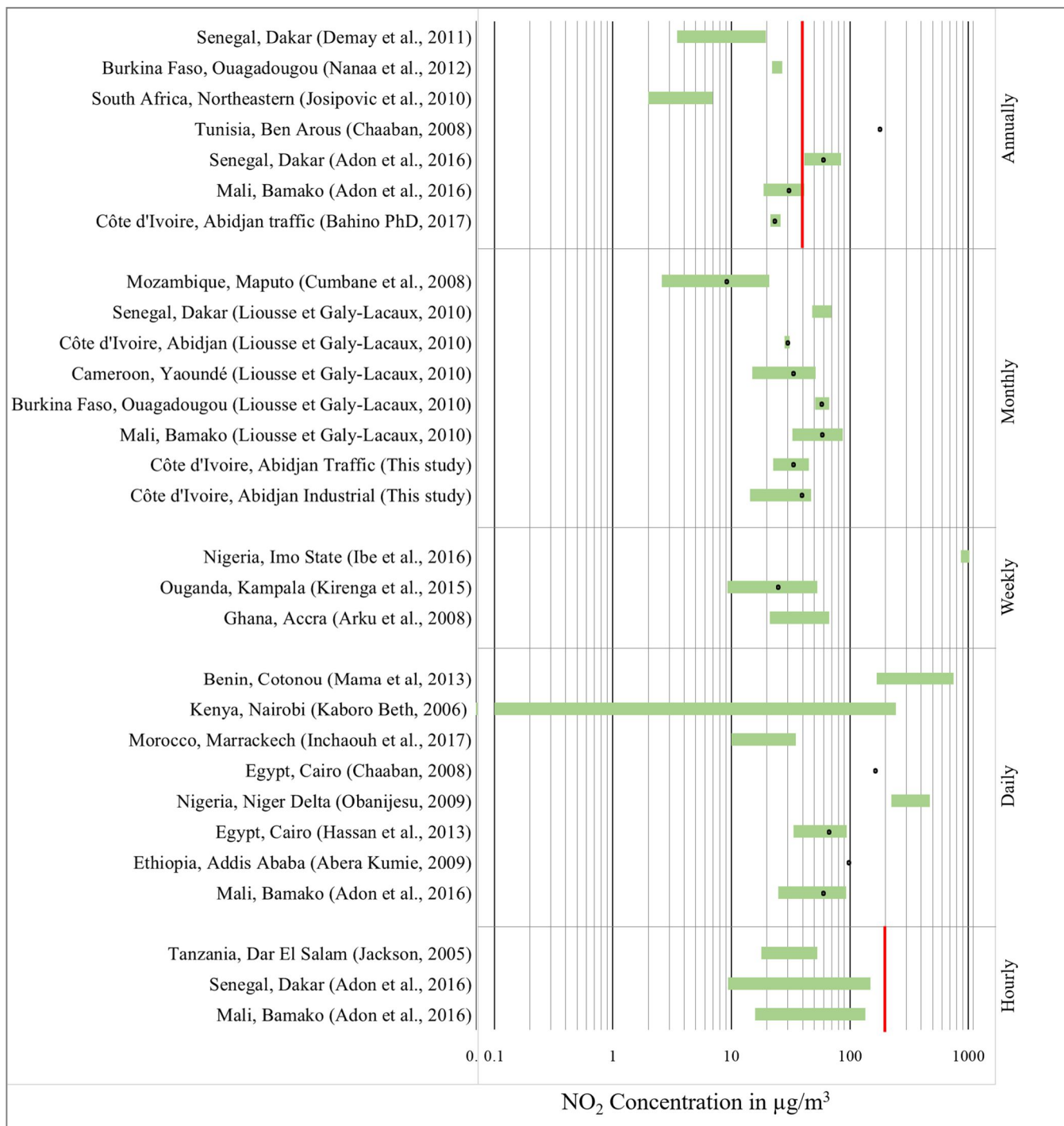
Figure 14: NO₂ concentration levels in µg.m⁻³ in African capitals at different time scale (hourly, daily, weekly, monthly, and annually) as reported in literature. Green bars represent lower and upper range of means if reported. Black points represent average concentration of NO₂. Red vertical lines illustrate current WHO guidelines at different time scale.
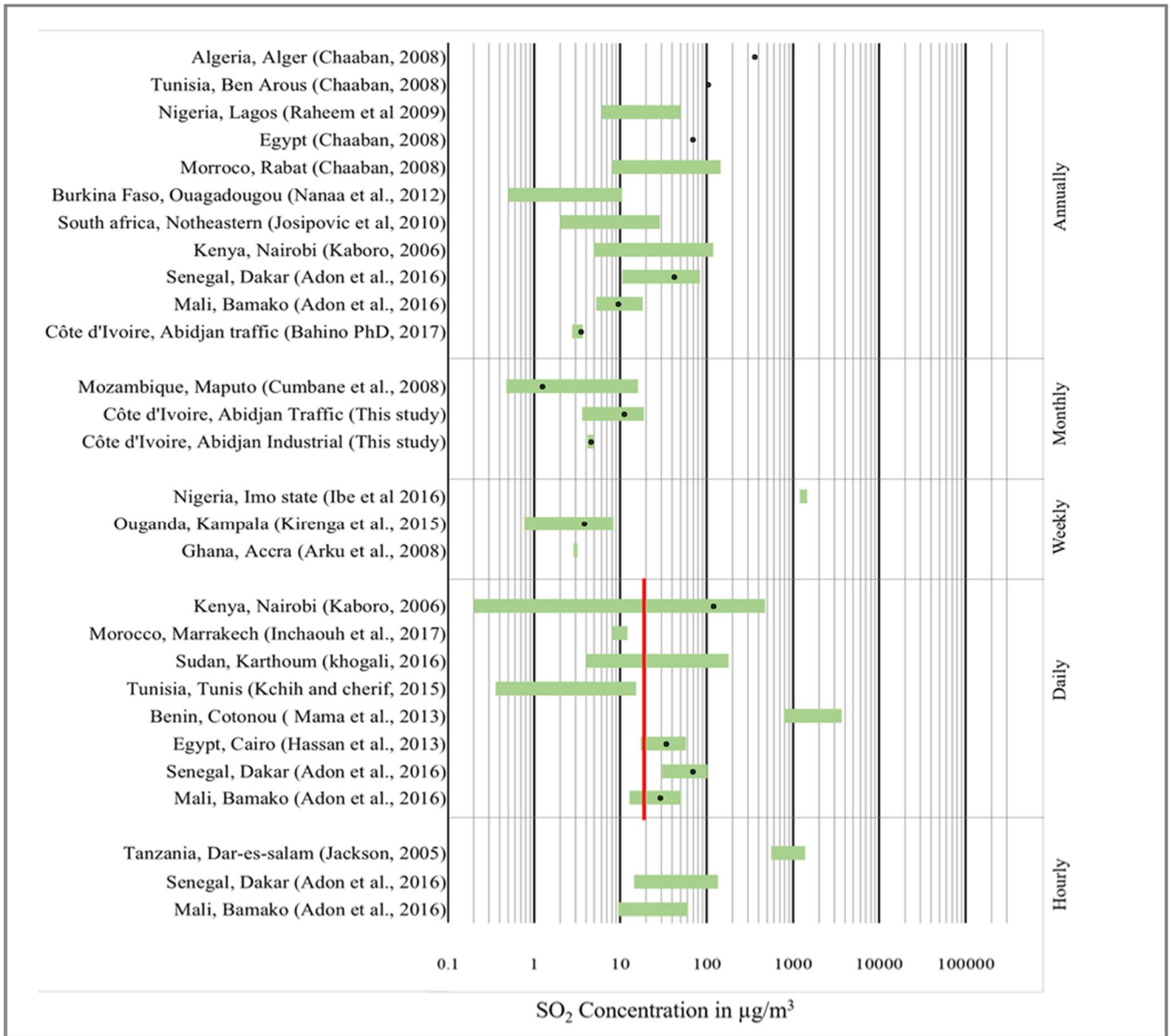
Figure 15: SO₂ concentration levels in µg.m⁻³ in African capitals at different time scale (hourly, daily, weekly, monthly, and annually) as reported in literature. Green bars represent lower and upper range of means if reported. Black points represent average concentration of SO₂. Red vertical lines illustrate current WHO guidelines at different time scale.