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A pilot study of gaseous pollutants' measurement (NO_2, SO_2, NH_3, HNO_3 and O_3) in Abidjan, Côte 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 Côte d'Ivoire. Measurements of inorganic gaseous pollutants, i.e. NO_2, SO_2, NH_3, HNO_3 and O_3 were performed in Abidjan during an intensive campaign within the dry season (15 December 2015 to 16 February 2016), using INDAAF (International Network to study Deposition and Atmospheric chemistry in AFrica) passive samplers exposed in duplicate for 2-week 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 the highest O_3 concentration at the two coastal sites of Gonzagueville and Félix-Houphouët-Boigny International Airport located in the southeast of the city, with average concentrations of 19.1 ± 1.7 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 showing concentrations ranging between 0.4 and 1.9 ppb. The HNO_3 average concentration ranged between 0.2 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 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, in this work we propose 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 to 3662 $\mu g\,m^{-3}$. Annual NO_2 concentrations ranged from 2 to 175 $\mu g\,m^{-3}$, which 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 an 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.

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1 Introduction

For several years, urban areas have experienced a deterioration in air quality and an 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; 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. A total of 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 for 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 major cities of Europe, Asia and northern America. These studies underlined the emergency of taking action to reduce the emission of pollutants into the atmosphere in order to mitigate health and environmental impacts. Air quality networks have been set up in major cities of the United States and Europe with the purpose of informing the public authorities 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, an air quality monitoring network is almost non-existent (Roy Rana, 2016). Very few studies on air pollution have been carried out over the African continent; this is particularly true for the western African region (Norman et al., 2007).

The western 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 a massive rural exodus and significant migration of western African populations (Denis and Moriconi-Ebrard, 2009). This intense economic activity, associated with a rapid population growth, strong urbanization and the perpetual uncontrolled expansion of cities, causes increasingly significant 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 datasets related to the levels of pollutants' concentrations are available for African cities. Through some research programs and projects such as AMMA (African Monsoon Multidisciplinary Analysis), 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, Yaoundé, 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 western 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, Côte 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 Ebrié Lagoon along the Gulf of Guinea on the south-east coast of Côte d'Ivoire. Abidjan, the economic capital of Côte d'Ivoire is a cosmopolitan city in sub-Saharan Africa and the second most populated western African city. According to the National Institute of Statistics, the population of Abidjan was estimated to be 4.7 million in 2014, with an average annual population growth of 2.6 % (INS, 2015). The autonomous district of Abidjan is composed of 10 municipalities in the city (Abobo, Adjamé, Attécoubé, Cocody, Koumassi, Marcory, Plateau, Port-Bouët, Treichville and Yopougon) and three neighbouring municipalities (Anyama, Bingerville and Songon). The cumulative area of these municipalities is 2119 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 centre, not only for the country, but also for the entire western African subregion. The port of Abidjan is of the first rank in western Africa in terms of merchandise traffic, with 21.5 million tons in 2013 and a prospect of 27 million tons in 2018. Abidjan hosts 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 Côte d'Ivoire, which is estimated to be USD 31.76 billion (Country Economy, 2016). The annual growth rate of GDP in Côte 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 Côte d'Ivoire are real estate, road transport, road building, manufacturing and mining industries. Abidjan has experienced strong economic growth in recent years that contributes to different environmental issues such as air pollution. This is one of the main issues in western 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 15 December 2015 to 16 February 2016. This work, part of the WP2, aims to characterize urban air pollution in Abidjan through the measurement of the concentrations of gaseous pollutants (NO_2, SO_2, NH_3, HNO_3 and O_3). 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 the contribution of each source of pollution to be established as well as the concentrations of inorganic gaseous species in Abidjan to be compared 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. For the purpose of obtaining a good spatial coverage of the Abidjan district, several measurement sites have chosen across the different municipalities.

In this work, a network of experimental measurement sites was built. Measurement sites were chosen based on criteria of land use, orographic effects and the objectives of the DACCIWA program (i.e. (1) population density of each municipality is considered as a 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. Three sites are considered to be representative of industrial areas (A_9 to A_{11}). Industrial sites are often influenced by traffic. Four sites are representative of the residential district (A_7, A_8, A_{12} and A_{13}). Four 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-month 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 (Airport FHB) are shown in Fig. 2. Mid-term measurement 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

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, last access: 3 April 2018) passive sampler method. These passive samplers developed by the 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 major African ecosystems over the past 15 years (Adon et al., 2010). Validation and inter-comparison studies have been performed according to comparisons with active analysers. Results presented in Adon et al. (2010) assure the quality and the 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 indoor and outdoor pollution monitoring in all environments (Salem et al., 2009) and provide 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 and reliable, and they do not need electricity. The sampling technique is based on the 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 the gaseous pollutant average concentration in ppb using the following formula given by Adon et al. (2010) Eq. (1):

$$C_{\mathrm{amb}}\,(\mathrm{ppb}) = \frac{(L/A)\cdot X\cdot R\cdot T}{t\cdot D\cdot P}, \tag{1}$$

where 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) and R (constant gas) = $0.08206\,\mathrm{L\,atm\,mol^{-1}\,K^{-1}}$. T is the average temperature during the sampling period (K), P is the mean atmospheric pressure during the sampling period, D is the

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	Adjamé	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 taxis and buses); 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 Dabou Road; heavy goods vehicles; minibuses (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 centre; surrounded by forests; human activities
A5	Pharmacy Cadre Blvd	Plateau	5°19′33″ N	4°01′26″ W	Traffic/ administrative centre	City centre; crossroad; traffic jams; personal vehicles; train station
A6	Airport FHB	Port-Bouët	5°16′26″ N	3°55′21″ W	Traffic	Airport weather station; open space; a lot of wind; air traffic
A7	Town hall Attécoubé	Attécoubé	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 goods 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-Bouët	5°16′12″ N	4°00′07″ W	Industrial/ harbour	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; new personal vehicles; use of liquefied petroleum gas (LPG) for cooking
A13	Angré	Cocody	5°23′27″ N	3°59′34″ W	Residential district	New 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 to Ebrié Lagoon; university residence
A18	Songon health centre	Songon	5°19′6″ N	4°12′06″ W	Suburban background	Far from city centre; hospital
A19	Niangon Adjamé	Yopougon	5°20′15″ N	4°07′08″ W	Suburban background	Human activities; firewood, charcoal
A20	Gonzagueville	Port-Bouët	5°14′31″ N	3°53′09″ W	Suburban	Near to Atlantic Ocean, human activities
A21	Ecological research centre	Treichville	5°18′41″ N	4°00′10″ W	Green area	Near to Ebrié Lagoon; a lot of wind;

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

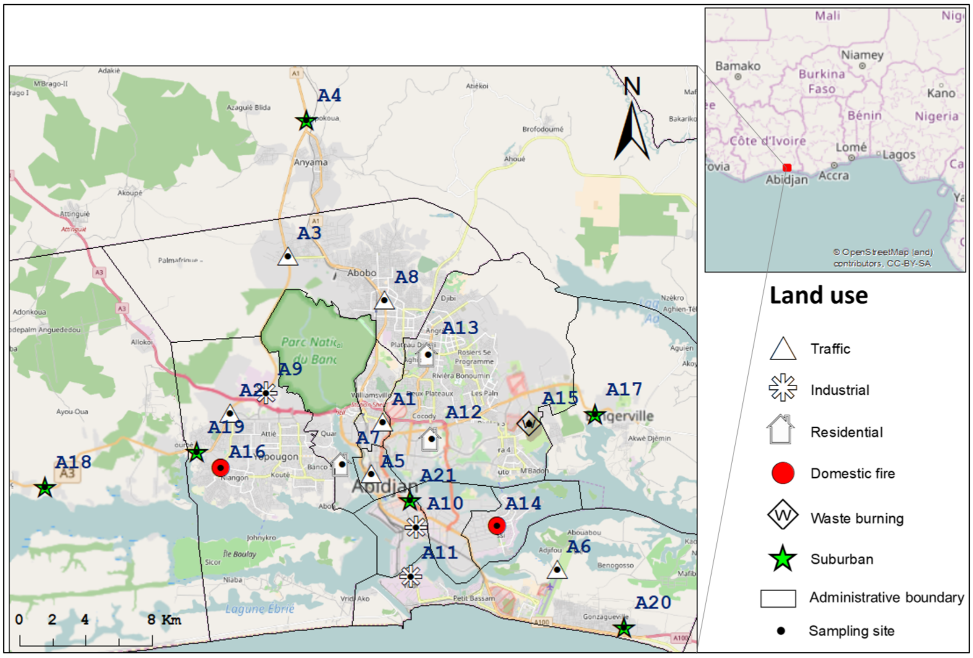

Figure 1. Spatial distribution of the 21 sampling sites (A_1–A_{21}) and major sources of air pollution nearby in the district of Abidjan.

molecular diffusion coefficient of the specific gas in the atmosphere, t is the exposure duration time (s) and the ratio $L/A = 47.5\,\mathrm{m}^{-1}$ is the air resistance coefficient for the INDAAF passive sampler (Adon et al., 2010).

The passive samplers were prepared by the LA in Toulouse and dispatched in Abidjan (Côte d'Ivoire) from 15 December 2015 to 16 February 2016 during the dry season. For each set of passive samplers, blank samples were 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 2-week periods over the 2-month study period. Passive samplers were mounted on stainless steel rails in duplicate and placed at a height of at least 2.5 m above the ground, corresponding to the 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 were kept refrigerated before being shipped to the LA for analysis. Over the study period, 672 passive samplers were exposed and 2 were damaged. A total of 670 samples and 48 blanks (12 for each gas) were analysed (24 blanks kept in the 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 the LA in Toulouse by performing a quality control inter-comparison program organized by the World Meteorological Organization/Global Atmospheric Watch (WMO/GAW) twice a year (Laouali et al., 2012). Results of the WMO/GAW quality assurance program for the year 2016 show 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, the 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 interference between HNO_3 and NO_2 passive samplers was estimated and found to be negligible. For the traffic site A_1, our results presented in Supplement Table S1 show that nitrate (NO_3^-) concentrations are very low compared to nitrite (NO_2^-) ions, with a ratio around 2 %. Other NO_y species such as peroxyacetyl nitrate (PAN) and nitrous acid (HONO), which can be deposited as nitrite and oxidize to nitrate, may

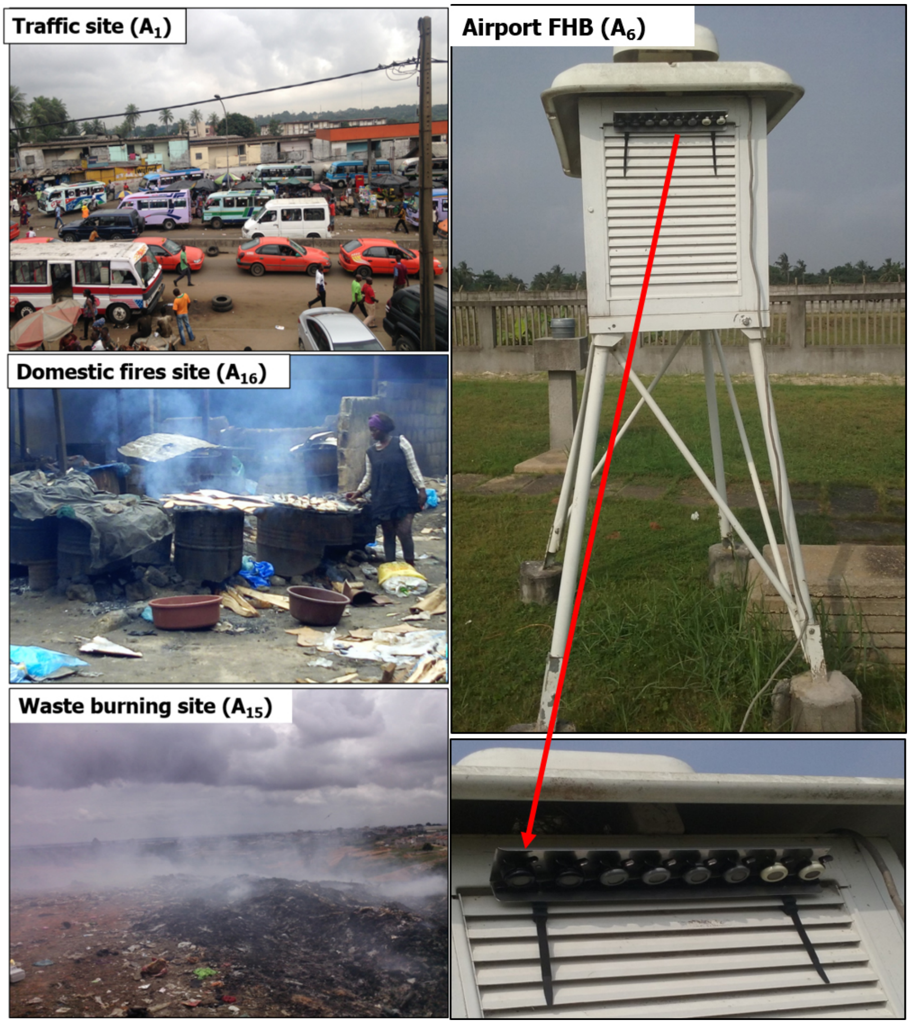

Figure 2. Photos of different sampling sites using INDAAF passive samplers installed in duplicate: traffic (A$_1$), domestic fires (A$_{16}$) waste burning (A$_{15}$) and airport FHB (A$_6$).

interfere with the determination of NO_2 and HNO_3 concentration (Cape, 2009). The choice of the coating solution in the INDAAF passive sampler aims to reduce this interference. The average concentration of two samples is used in all the cases 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 Houphouët-Boigny International Airport (Airport FHB, 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 (15 December 2015 to 16 February 2016) are presented in Fig. 3. Daily average temperature ranged between 25 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) wind directions. Wind velocity presents values ranging between 1 and 9 $\mathrm{m\,s^{-1}}$, with an average of $2.75 \pm 0.6\,\mathrm{m\,s^{-1}}$. These observed meteorological parameters are characteristic of the major dry season in Côte d'Ivoire (Konate et al., 2016).

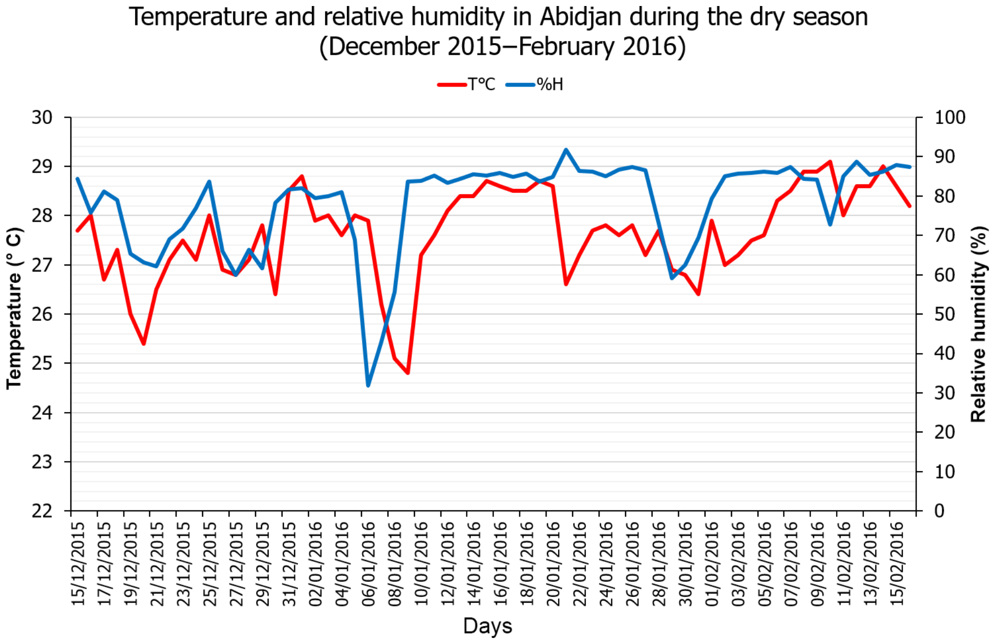

Figure 3. Temperature and relative humidity measured by ASECNA in Abidjan during the dry season (15 December 2015–16 February 2016).

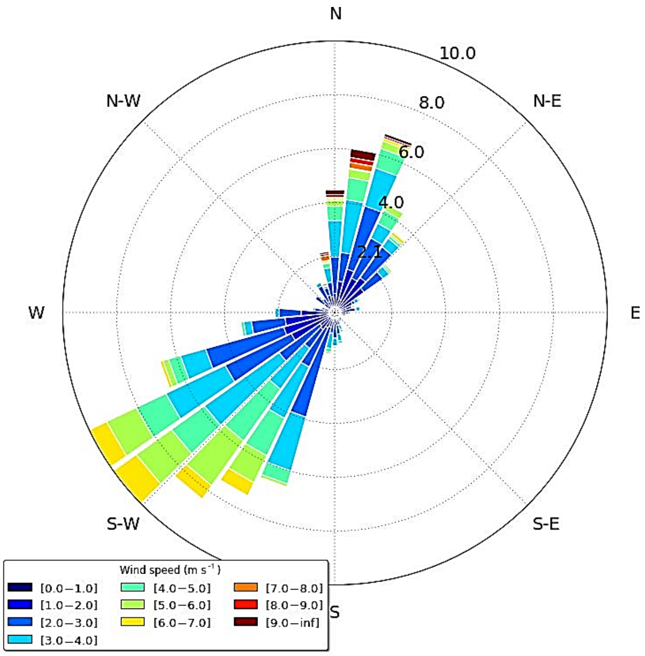

Figure 4. Hourly wind rose diagram of Abidjan during the dry season (15 December 2015–16 February 2016).

2.4 Spatial analysis

In this study, we interpolated the inorganic gaseous species' concentrations measured at the 21 sites to obtain the 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. These are inverse distance weighting (IDW) and kriging. The general formula for both interpolators is formed as a weighted sum of the data Eq. (2):

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

where $\hat{Z}(S_0)$ 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 only depends 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 reality. The 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 the kriging method, the weight λ_i is not only based on the distance but also on the overall spatial arrangement of the sampling sites. Kriging is the method of interpolation derived

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

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).

2.4.1 Data analysis

The empirical semivariograms provide information on the spatial autocorrelation of datasets. The semivariograms necessary for kriging were estimated for each pollutant and are 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 autocorrelation of NH_3 concentration.

2.4.2 Cross-validation

Ordinary kriging with a Gaussian semivariogram model and IDW was used to perform the spatial interpolation. To validate the interpolation model, 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). The RMSE and MAE are regularly employed in model evaluation studies (Chai and Draxler, 2014). Lower MAE and RMSE values and a 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 the kriging method is presented in Fig. 6, while statistical parameters calculated for each interpolation method are presented in Table 3. Results indicate that the lowest MAE and RMSE values and the highest R^2 value are always obtained for the 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 2 weeks for each gaseous pollutant is shown in Table S2. The average concentrations calculated from the four 2-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 in the spatial distribution of the sites are examined in the following discussion.

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

3.1 Spatial distribution of gaseous pollutants in Abidjan

In order to present the spatial distribution of gaseous pollutants investigated in this work, the centre of the district of Abidjan is divided into a rectangle of 35 km × 30 km between 5°14′ and 5°31′ N, and 3°53′ 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) (Figs. 7 to 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.

3.1.1 Nitrogen dioxide (NO_2)

The spatial distribution of NO_2 concentrations in the district of Abidjan is represented in Fig. 7. This map reveals that NO_2 average concentrations vary between 2.7 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 and 2.7 ppb respectively. The 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 the A_5 site, characterized by traffic, with a mean concentration of 23.9 ppb. This site, located in the administrative centre of Abidjan, is characterized by traffic jams every working day. Sites A_1 and A_8, representative of traffic sites, and A_9, representative of industrial sites, present comparable mean concentrations ranging between 19.9 and 21 ppb. Moreover, the 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

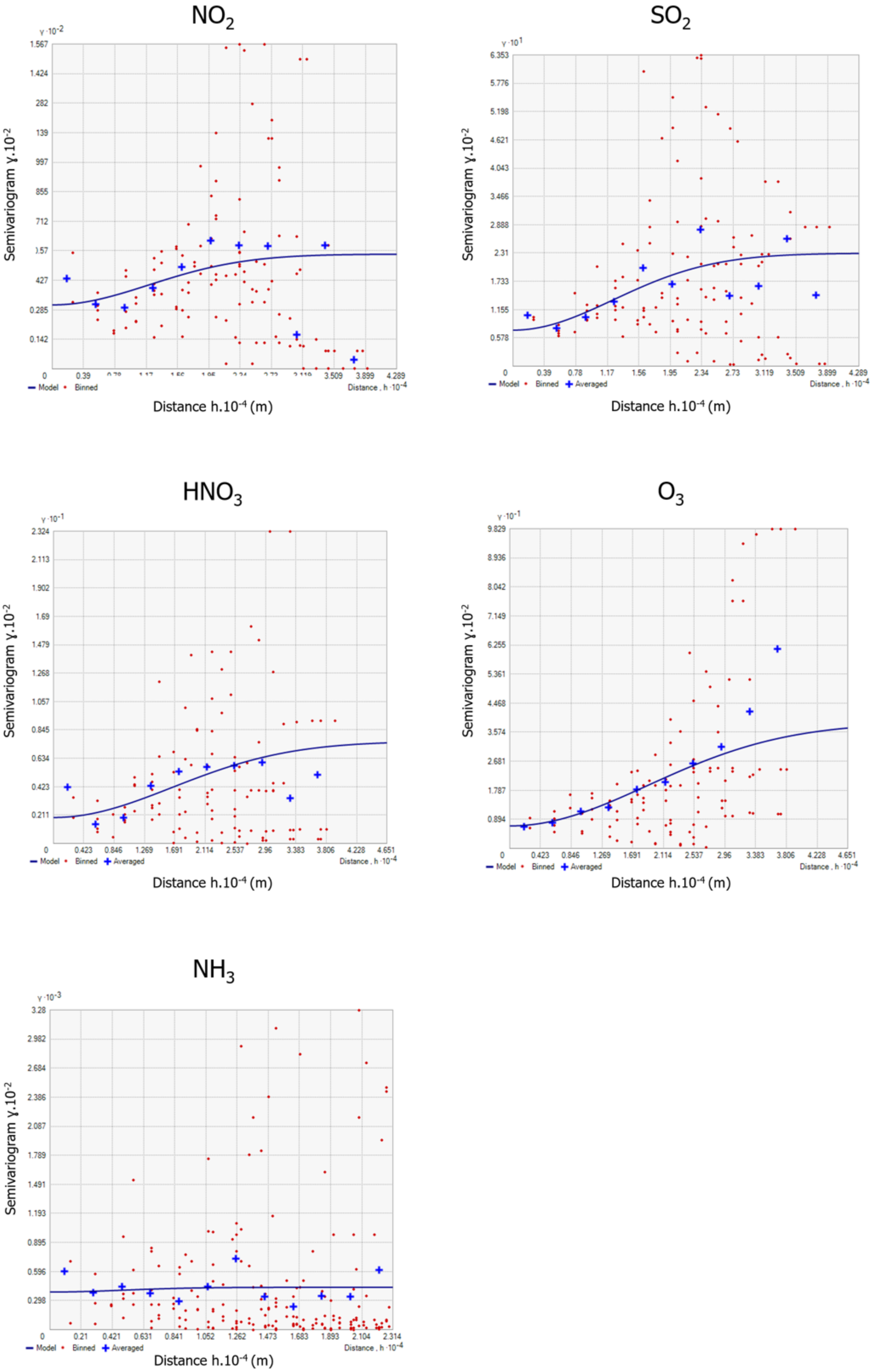

Figure 5. Empirical semivariogram for each pollutant.

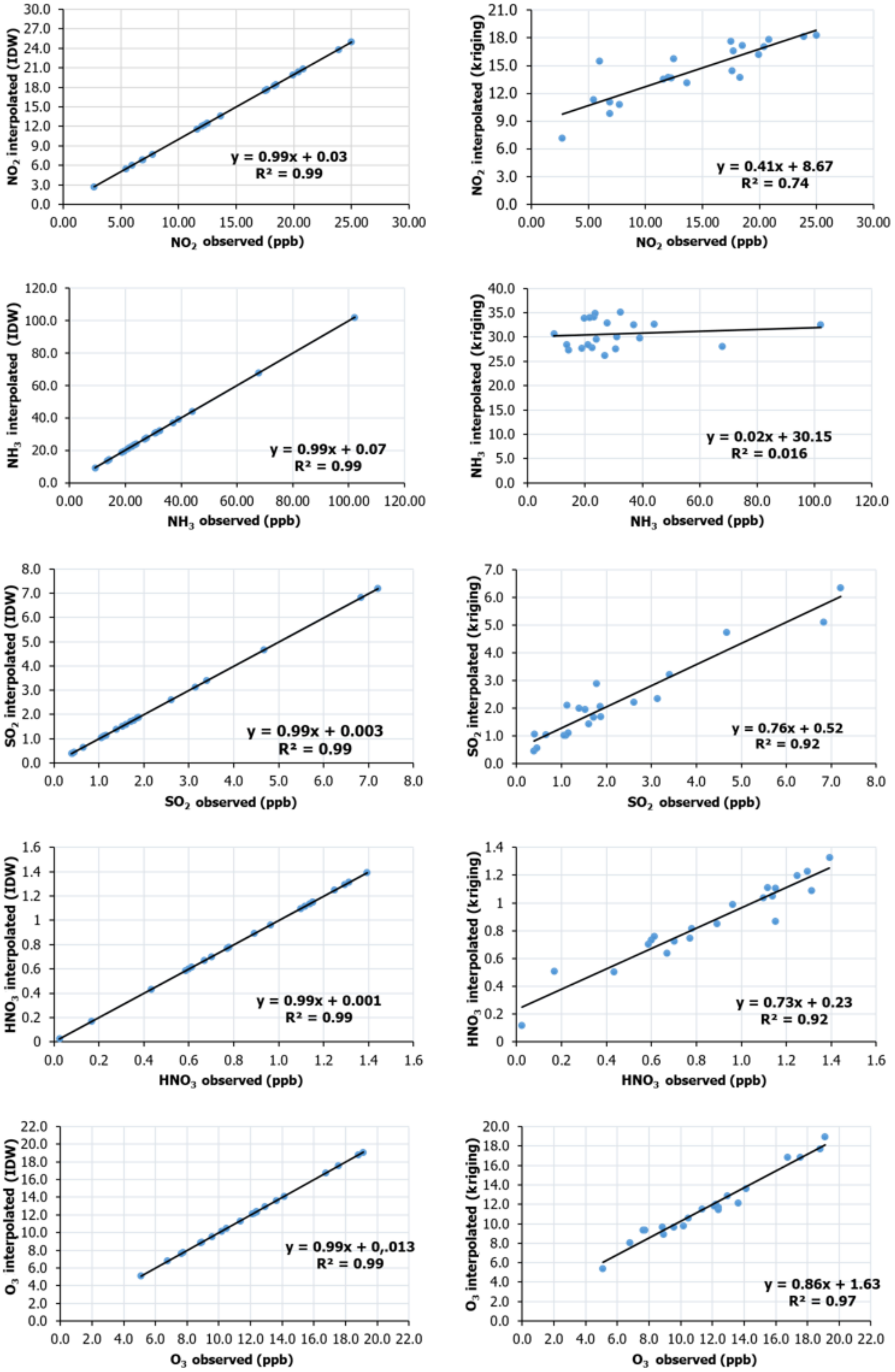

Figure 6. Regression between interpolated data and observed data using IDW and the kriging method.

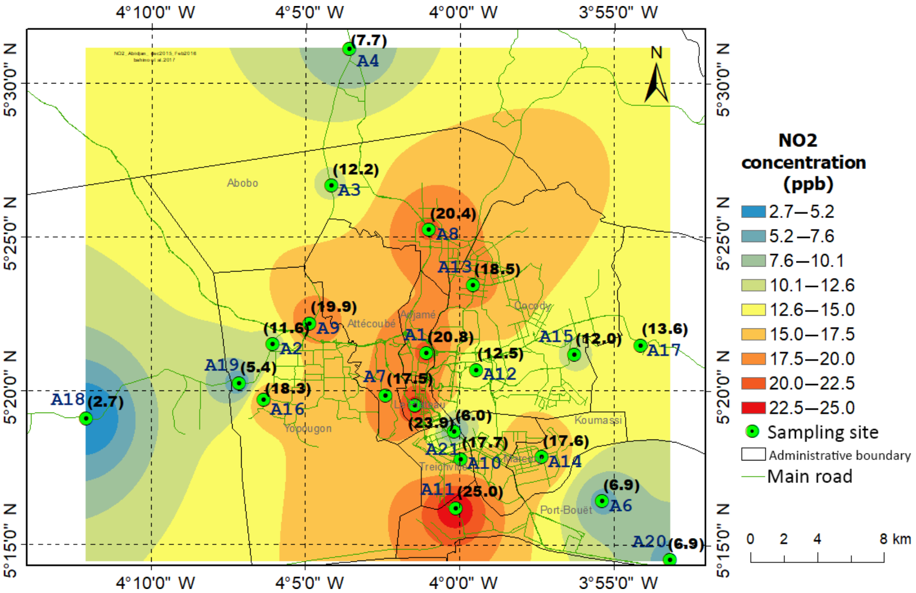

Figure 7. Spatial distribution of NO_2 in the district of Abidjan during the dry season (15 December 2015–16 February 2016). Measured concentrations in ppb are in brackets.

Côte 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 are more than 20 years old (Ministry of Transport, 2012). These vehicles do not comply with European Union (EU) air quality standards and are mostly used because of their moderate price.

Besides the road traffic, the industrial sector seems to be another great contributor to the 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 currently has three industrial zones covering 885 ha, and the fourth is under construction. The biggest one is located in the municipality of Yopougon (645 ha), followed by the industrial areas of Vridi in the municipality of Port-Bouët (120 ha) and of Koumassi (120 ha) (MI, 2015). 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, a thermal power station and the processing and storage of petroleum product 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).

3.1.2 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 a maximum of 7.2 ppb measured at the A_3 traffic site (Table 2). The highest concentrations were generally obtained at the five traffic sites (A_3, A_2, A_4, A_{19}, A_5) and at the A_1 suburban site, with respective values of 7.2, 6.8, 4.7, 3.4, 3.1 and 2.6 ppb. We notice a decrease of SO_2 concentrations from the northwest of the city where the main roads (North 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 %) show 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 yet have desulfurization units. 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 Côte 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 developed countries (50 ppm or below). There is also 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 Côte d'Ivoire, charcoal production increased by 22 % between 2003 (400 850 t) and 2012 (488 128 t). During the same pe-

Table 4. Gaseous pollutants' concentrations and standard deviation (SD) at 21 sampling sites in Abidjan during the dry season (15 December 2015–16 February 2016).

Sampling site		Concentration in ppb														
ID code	Site name	NO_2			NH_3			SO_2			HNO_3			O_3		
		Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD
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 centre	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 centre	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

riod, 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 areas in Côte 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).

3.1.3 Ammonia (NH_3)

The main source of NH_3 emissions is biomass 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 western 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 from domestic fires in Bamako (Mali) and Dakar (Senegal) have been estimated for 2005 to be 1.6×10^{-3} and $7.0 \times 10^{-4}\,\mathrm{TgNH_3\,yr^{-1}}$ respectively (Adon et al., 2016). In Abidjan, NH_3 concentrations were much higher compared to other gaseous pollutants. 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 and their contributions to this source. The second most significant concentration of NH_3 was measured at the site A_{14} located on the east of the city and characterized by domestic

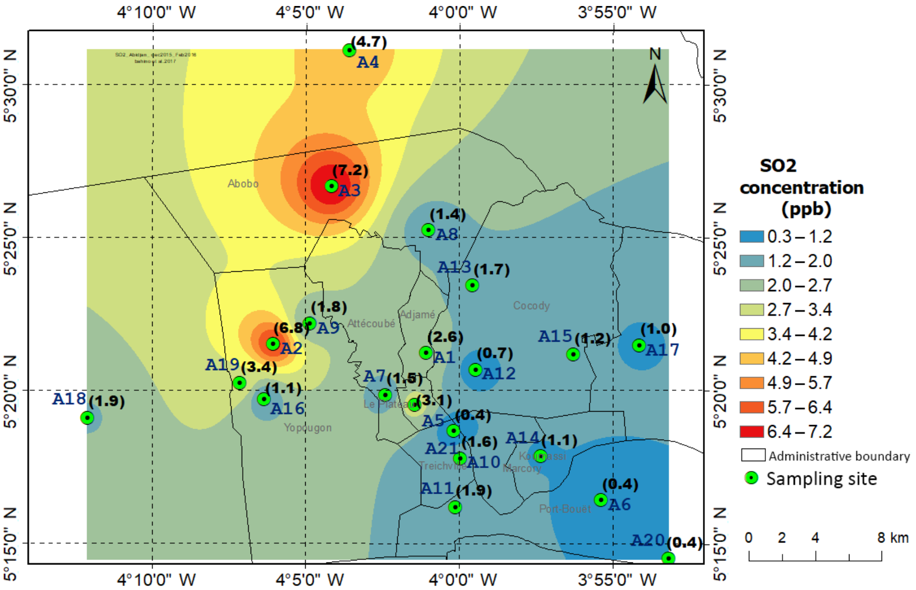

Figure 8. Spatial distribution of SO_2 in the district of Abidjan during the dry season (15 December 2015–16 February 2016). Measured concentrations in ppb are in brackets.

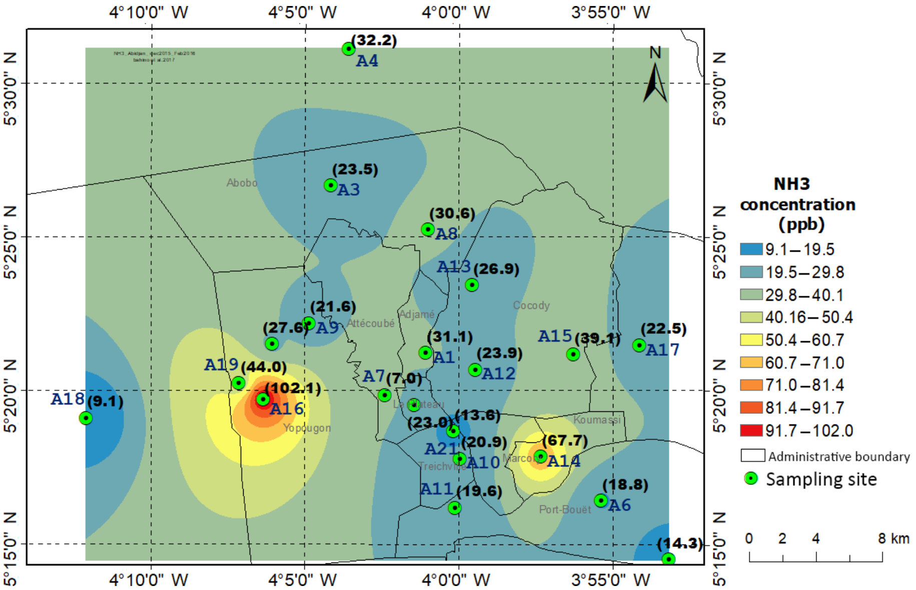

Figure 9. Spatial distribution of NH_3 in the district of Abidjan during the dry season (15 December 2015–16 February 2016). Measured concentrations in ppb are in brackets.

fires and the residential sector (67.7 ± 8.3 ppb). It should be noted that these two sites presenting very high concentrations correspond 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 to 44.0 ± 2.2 ppb. High concentrations about 36.6 ± 4.1 ppb are measured in the west and the north-east of the city where most of the domestic fires, residential sector 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} regrouped 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 this breeding 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 due

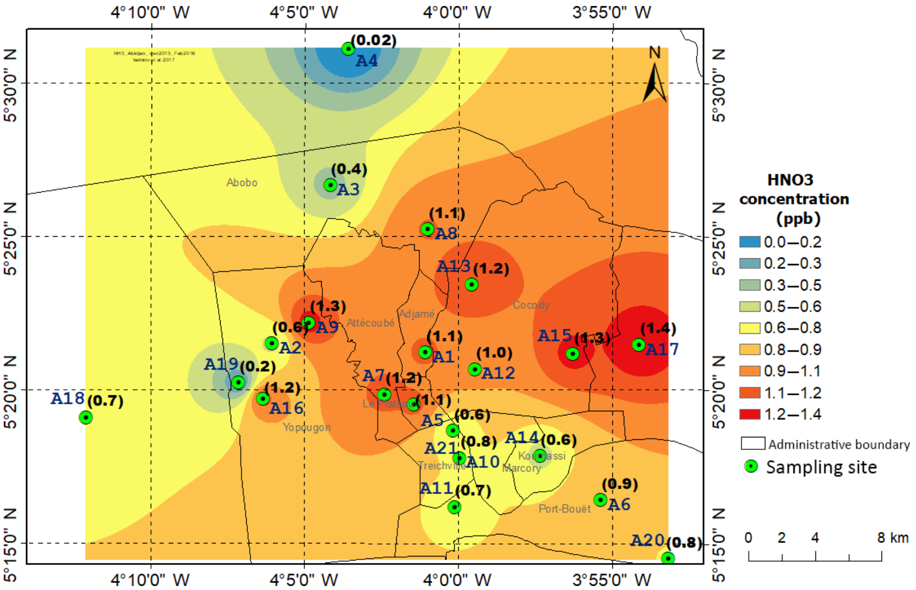

Figure 10. Spatial distribution of HNO_3 in the district of Abidjan during the dry season (15 December 2015–16 February 2016). Measured concentrations in ppb are in brackets.

to poultry dejections (Gac et al., 2007). In the global NH_3 anthropogenic source budget, Bouwman et al. (2002) indicated that the animal excreta source represents 21.7 Mt yr^{-1} of the total 53.6 Mt yr^{-1}. In addition to breeding, this urban area combines large industrial and individual plantations of hevea and banana. These plantations often make excessive use of chemical fertilizers rich in urea, which therefore lead 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 a size of 153 ha, it has received 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.

3.1.4 Nitric acid (HNO_3)

HNO_3 is believed to be a major end product in the oxidation of gaseous nitrogen compounds. It is one of the mineral acid contributors to 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 ranged between 0.2 ± 0.0 and 1.4 ± 0.3 ppb. Approximately half of the sampling sites have concentrations between 1.1 ± 0.3 and 1.4 ± 0.3 ppb. These sites are mainly located in the centre and in the west of the city. The highest concentrations of HNO_3 were 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 in the east of the city. This could be explained by the fact that gaseous HNO_3 is the result of several chemical transformation processes of NH_3 and NO_x ($NO_2 + NO$) guided by the presence of oxidants such as H_2O_2, O_3 and OH radicals (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 centre in an easterly direction, and ageing in the air masses leads to the production of HNO_3 far from their source.

3.1.5 Ozone (O_3)

O_3 is often associated in urban areas with adverse effects on human health and natural environment (Hagenbjörk et al., 2017). It is well known that this secondary pollutant depends on photochemical interactions of gaseous precursors composed of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (Duan et al., 2008; WHO, 2006). At a specific location, the level of O_3 concentration depends on emission of its precursors (VOCs and NO_x), 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 NO_x-saturated (or VOC-limited) regime and the NO_x-limited regime. In urban areas with high NO_x concentrations (NO_x-saturated) and a low ratio of VOCs / NO_x, the ozone production rate is generally low and

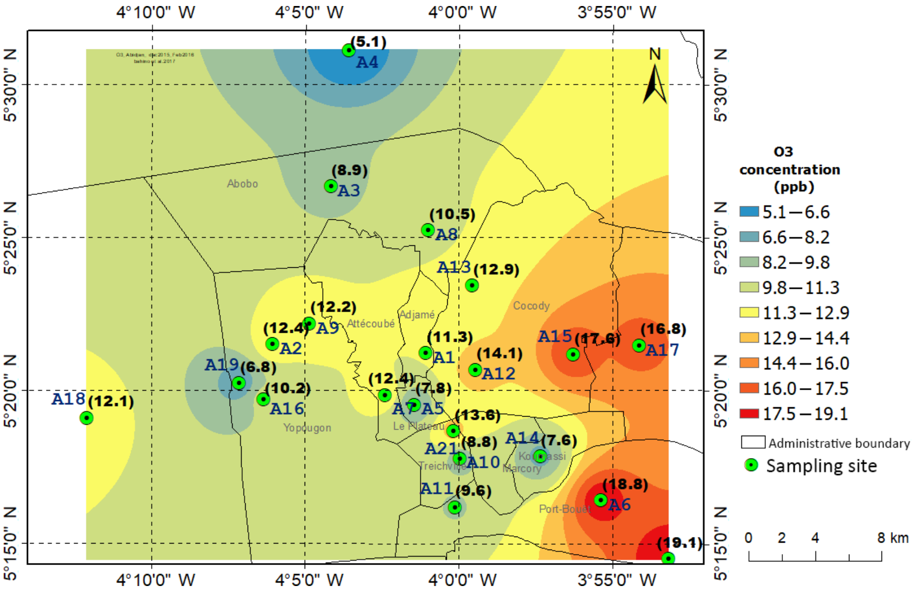

Figure 11. Spatial distribution of O_3 in the district of Abidjan during the dry season (15 December 2015–16 February 2016). Measured concentrations in ppb are in brackets.

concentrations are on the order of a 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 centre, in the peri-urban areas, we notice an increase of the VOC / NO_x ratio and a high O_3 production because of the absence of major sources of NO_x, the dilution of air mass and the presence of biogenic VOCs. We measured O_3 concentration at different locations 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. The 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 and 18.8 ppb respectively. These two sites on the eastern outskirts of the city are characterized by monthly sunshine ranging between 117 and 224 h (Messou et al., 2013) and by a high relative humidity in the air due to the presence of water vapour from the marine spray. OH radicals are the major oxidant of the atmosphere. OH directly controls the lifetime of VOCs and NO_x (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 and 16.76 ppb respectively. As in the case of HNO_3, the highest concentrations measured in the east of the city may be due to the ageing of precursor pollutants transported in an easterly direction by SW prevailing winds. At 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 and 12.9 ppb. The lowest O_3 concentration in Abidjan was measured in the north of the city at 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 concentration 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 the activity sectors' source of pollution. Six different groups were formed. The main activities' sources of pollution have been identified in Sect. 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 and 17.8 ± 4.7 ppb respectively. However, domestic fires and res-

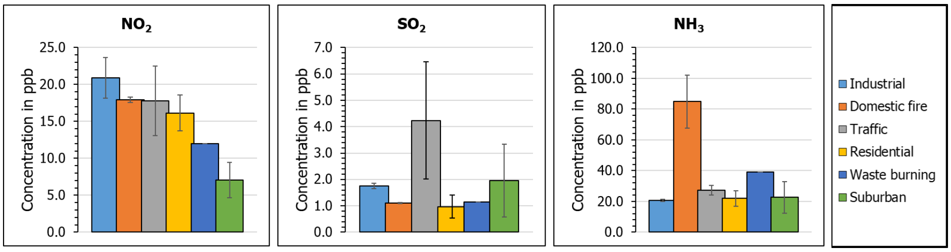

Figure 12. Concentration of gaseous pollutants by anthropogenic sectors of activity in the district of Abidjan.

idential sites present very comparable levels of NO_2 concentrations of 17.9 ± 0.3 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 m far from roadways. This could explain the near-similar concentration 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 concentrations of NO_2. Nevertheless, these concentrations are not negligible and can be due, on the one hand, to the limited traffic of the garbage collection vehicles and also on the other hand to the circulation of minibuses called "gbaka", which connect 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 Côte d'Ivoire, diesel sulphur content is generally significant. The average concentration of SO_2 in suburban and industrial sites is 2.0 ± 1.4 and 1.7 ± 0.1 ppb, respectively.

Ammonia (NH_3)

NH_3 concentrations are significantly higher at domestic fires sites, with an average concentration 2 to 4 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 households of Abidjan. The high standard deviation is due to the location of two of the domestic fires sites near the source, while the other domestic fires sites are much further away from the source. The other 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 are similar to concentrations 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 subregional and international context, in Table 5 we have listed some experimental studies using passive samplers to obtain a comparable measurement technique and also comparable temporal integration. Table 5 presents a comparison between gas 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 3 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. (2017). 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 (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) 2 times higher than that obtained in Abidjan.

The average SO_2 concentrations at the traffic and urban sites range from 1.56 to 15.9 ppb. In comparison with the Abidjan traffic site (4.2 ppb), the average SO_2 concentrations in Bamako (3.6 ppb) and St John's (1.56 ppb) are much lower. The concentration of SO_2 in Abidjan is comparable to those measured at the polluted urban sites of Shenzhen (4.9 ppb) in China and Al Ain (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).

Table 5. Gaseous pollutants' concentrations (ppb) at 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, Côte 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, UAE**	Traffic	Feb 2005–Feb 2006	31.5	17.1	5.8	Salem et al. (2009)
Shenzhen, China	Urban	Mar 2013–Feb 2014	20.7	–	4.9	Xia et al. (2016)
St. John's. India	Urban	Jul 1999–Jun 2001	4.8	9.5	1.56	Kumar et al. (2004)

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

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

Suburban sites

The average concentration of NO_2 at the Abidjan suburban site (7 ppb) is more than 2 times higher in comparison with that measured at the 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, at 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 adapted to each country. If some synthesis of air quality measurements for particulate matter concentrations exists 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 found in the literature. As this study shows, one of the main gaseous sources of air pollution in African cities is traffic roads emitting NO_2 and SO_2.

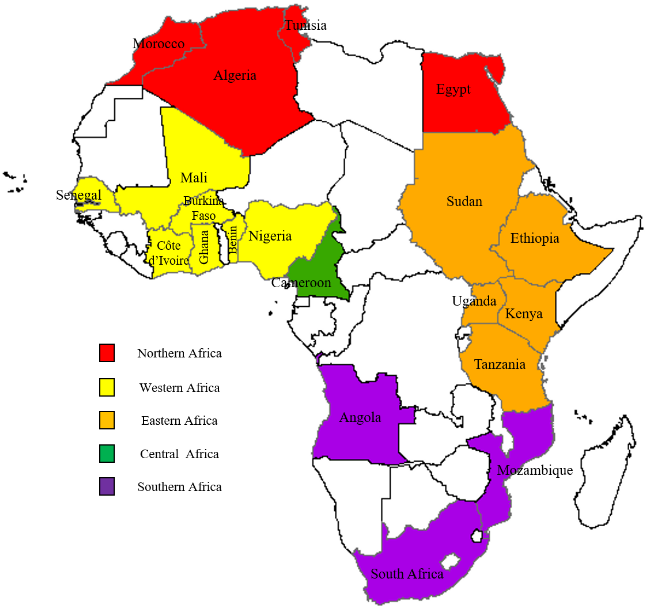

Figure 13. African countries coloured by UN subregion for which NO_2 and SO_2 studies were identified and included in this publication.

This section aims to report the main studies on NO_2 and SO_2 conducted at different timescales (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 reports were clearly described were selected and listed in Tables S3 and 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 subregion, for which NO_2 and SO_2 monitoring studies were identified and included in this work.

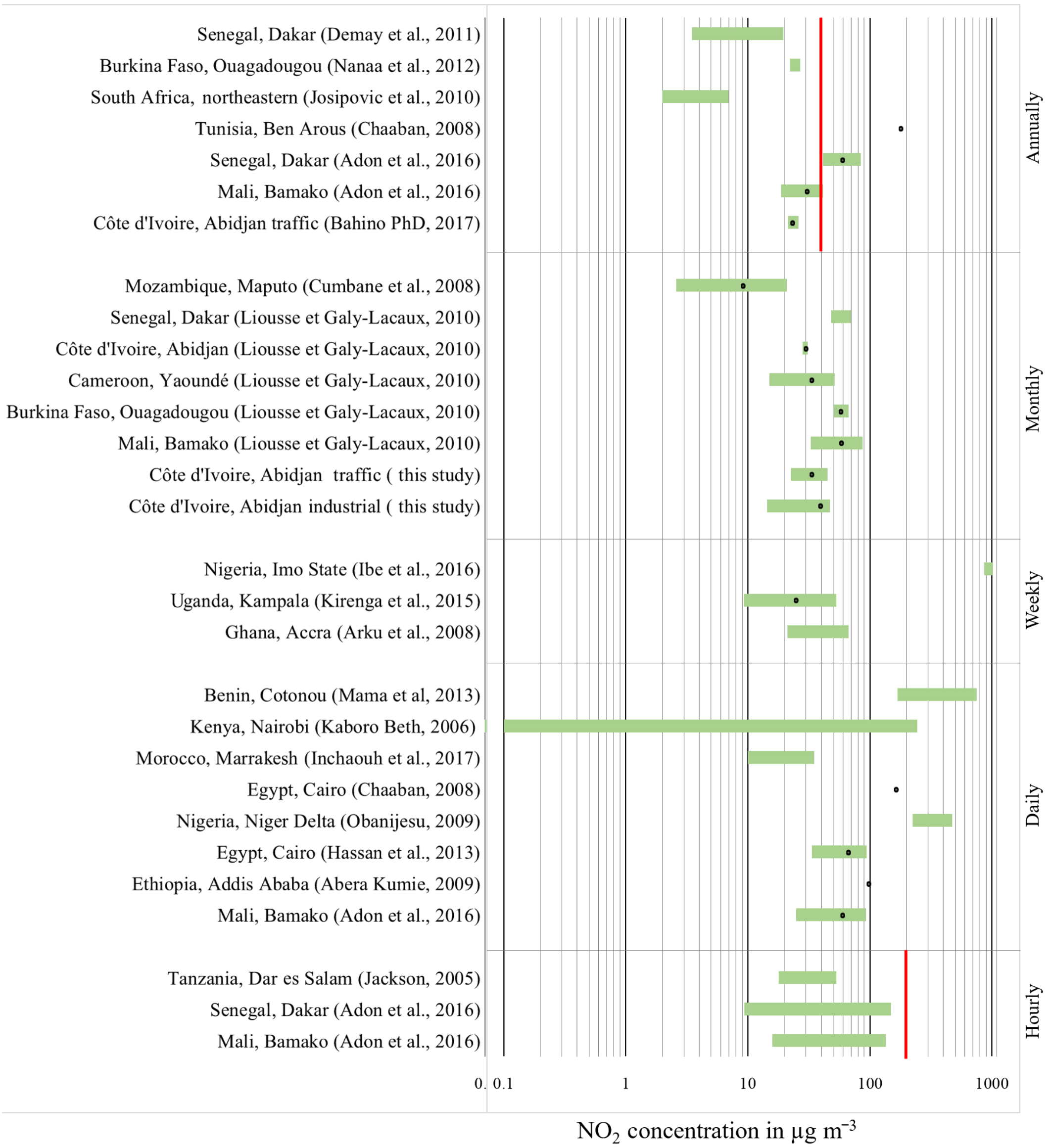

Figure 14. NO$_2$ concentration levels in µg m^{-3} in African capitals at different timescales (hourly, daily, weekly, monthly and annually) as reported in literature. Green bars represent lower and upper range of means if reported. Black points represent average concentration of NO$_2$. Red vertical lines illustrate current WHO guidelines at different timescales.

We found NO$_2$ and SO$_2$ measurements conducted in at least 20 African countries. Most of those measurements were located in seven western African countries (Senegal, Mali, Burkina Faso, Côte d'Ivoire, Nigeria, Ghana and Benin) and in five eastern 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. Figures 14 and 15 represent NO$_2$ and SO$_2$ levels in African cities as reported in the various studies. 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 satellites) and over short periods. Thus, only few studies allow the comparison with WHO standards.

Nevertheless, this section represents, to the best of our knowledge, the state of the art of urban NO$_2$ and SO$_2$ concentrations measured in African cities and leads to a contextualization of our results in Abidjan.

Figure 15. SO_2 concentration levels in $\mu g\, m^{-3}$ in African capitals at different timescales (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 SO_2. Red vertical lines illustrate current WHO guidelines at different timescales.

3.3.1 Nitrogen dioxide (NO_2)

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

The WHO air quality guideline value for annual exposure to NO_2 concentration is $40\, \mu g\, m^{-3}$. Seven studies were carried out during at least 1 year in Dakar (Senegal), Ouagadougou (Burkina Faso), Bamako (Mali), Abidjan (Côte d'Ivoire), South Africa and Ben Arous (Tunisia) (Julien Bahino, personal communication, 2017; Chaaban, 2008; Demay et al., 2011; Josipovic et al., 2010; Nanaa et al., 2012). The average annual concentrations of NO_2 in Ben Arous, Tunisia ($178\, \mu g\, m^{-3}$), and in Dakar, Senegal ($59.6\, \mu g\, m^{-3}$), exceed the WHO threshold value ($40\, \mu g\, m^{-3}$). Annual average concentrations measured in Dakar, Ouagadougou and South Africa are lower and ranged from 3.5 to $19.6\, \mu g\, m^{-3}$, 22 to $27\, \mu g\, m^{-3}$ and 2 to $7\, \mu g\, m^{-3}$ respectively.

Almost 19 studies were conducted at daily, weekly and monthly scales. Eight studies were conducted on a daily basis. Average 24 h concentrations ranged from $0.1\, \mu g\, m^{-3}$ along Juja Road in Nairobi (Kaboro, 2006) to $752\, \mu g\, m^{-3}$ on the traffic site of Dantokpa market in Cotonou (Mama et al., 2013). Only three studies measuring NO_2 on a weekly scale were identified. The maximum concentration ($1015.34\, \mu g\, m^{-3}$) 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 ranges from 2.6 to 87.2 µg m^{-3} for eight studied sites. The lowest values were measured in Maputo (Mozambique) in a residential site and in a green area. The monthly average concentration in Maputo is 9.13 µg m^{-3} and varies between 2.6 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 at traffic and industrial sites in Abidjan (33.5 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, 2017) in the DACCIWA mid-term experiment (2015–2017) present values about 25 µg m^{-3} for the traffic site (A_1) that are in the same range of other African capitals studied. However, the table emphasizes the lack of NO_2 measurements in Abidjan at hourly and annual scales 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 timescales and with recommended methods to obtain reliable results.

3.3.2 Sulfur dioxide (SO_2)

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

Twenty-four hour SO_2 levels are significantly associated with daily mortality rates (Burnett et al., 2004). The WHO 24 h guideline for SO_2 is 20 µg m^{-3}. Nine daily (24 h) studies are reported in Fig. 14. Measurements in Cotonou (Benin) have been performed at the crossroads of Dantokpa market, characterized by a large circulation of two-wheeled vehicles. Daily average concentrations range between 784.8 and 3662.4 µg m^{-3} (Mama et al., 2013). These concentrations are 39 to 183 times higher than the threshold value. In Dakar (68.54 µg m^{-3}), Cairo (34 µg m^{-3}) and Bamako (29.03 µg m^{-3}), SO_2 mean daily concentrations are greater than 20 µg m^{-3}. It is found that only two studies conducted in Marrakesh (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 ranges from 9.14 to 1385 µg m^{-3}. In western Africa (Mali and Burkina), concentrations are much lower (9–136 µg m^{-3}).

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

The annual average concentrations of SO_2 are reported for 11 studies. The concentrations measured in northern Africa are the highest. Average levels of SO_2 range between 8 µg m^{-3} in Rabat (Morocco) and 325 µg m^{-3} in Alger (Algeria). In western Africa, concentrations are lower and range from 0.5 µg m^{-3} in Ouagadougou (Burkina Faso) to 80 µg m^{-3} in Dakar (Senegal). The annual average SO_2 concentration in Abidjan (3.66 µg m^{-3}) is one of the lowest of western African cities reported in this study (Julien Bahino, personal communication, 2017). Measurements of SO_2 at smaller timescales (i.e. 10 min, 24 h) do not exist in Abidjan or are not published. As for NO_2, studies should be carried out regularly and according to WHO standards.

Air pollution from human activities has been a long-standing environmental issue. Human activities have led to an unprecedented increase in atmospheric abundance 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 the burden of cancer in western Africa in recent years (Val et al. 2013). Premature death in the world in 2010, resultant 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 economic loss associated with these crop losses is estimated to represent an economic value of USD 14–26 billion for the year 2000 (van Dingenen et al., 2009).

Data provided by this kind of study can help as follows:

- 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;
- 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 western African subregion. The new urban master plan of the city foresees its extension and the construction of many types of infrastructure, which will certainly increase environmental and sanitary problems.

The present study reports the gaseous concentrations' measurements using passive samplers performed during an intensive experimental field campaign 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 measured at 21 representative sites. This database allows the levels of gaseous concentration to be characterized and a spatial distribution of gaseous pollution at the scale of the city during the dry season (15 December 2015 to 16 February 2016) to be presented for the first time.

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

The spatial distribution of gaseous pollutants has been studied according to 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 significant at some sites. On the one hand, it highlights the predominance of the domestic fires source with the use of wood and charcoal that emits a large amount of NH_3. On the other hand, it shows the significant impact of traffic roads on NO_2 and SO_2 emissions.

The average gas 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 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 and 39.1 ppb respectively. In addition to the high concentration of NO_2, the traffic sites also have the highest SO_2 average concentration (4.2 ppb).

In this study, for the first time we propose an overview of gaseous SO_2 and NO_2 pollutants, which allows a global picture of gas concentrations to be given 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 western 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 timescales 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 (9.4–135 $\mu g\,m^{-3}$) is lower than the WHO standards. Abidjan annual NO_2 concentration is 23.25 $\mu g\,m^{-3}$, with a range on the scale of African cities from 2 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 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 Marrakesh and Tunis.

These scarce datasets should draw the attention of African public authorities to the urgent need of measuring NO_2 and SO_2 emissions. The results indicate the need of other studies including VOCs and NO_x measurements to better understand the production processes of secondary pollutants such as O_3. In the framework of the DACCIWA WP2 (Air Pollution and Health) program, bi-monthly measurements have been ongoing since December 2014 over three supersites. These measurements will make it possible to estimate the impact of pollutants' concentrations on the population's 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 western Africa based on modelling, the university Félix Houphouët-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 modelling studies to predict air quality for Africa on regional to urban scales.

Data availability. The pollution data used in this study are original and are publicly available in Table S2 in the Supplement.

The Supplement related to this article is available online at https://doi.org/10.5194/acp-18-5173-2018-supplement.

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