Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-973
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 17 November 2017

Atmospheric Chemistry and Physics Discussions

Mass concentration, optical depth and carbon composition of particulate matter in the major Southwestern Africa cities of Cotonou (Benin) and Abidjan (Côte d'Ivoire).

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Abstract

Air quality degradation is a major issue in the large conurbations on the shore of the gulf of Guinea. We present for the first time PM2.5 time series collected in Cotonou, Benin and Abidjan, Cote d'Ivoire from February 2015 to March 2017. Measurements were performed in the vicinity of major combustion aerosol sources: Cotonou/Traffic (CT), Abidjan/Traffic (AT), Abidjan/Waste Burning (AWB) and Abidjan/Domestic Fires (ADF). We report the weekly PM2.5 mass and carbonaceous content as Elemental (EC) and organic (OC) carbon concentrations. We also proceed to the measurements of the Aerosol Optical Depth (AOD) and the Angström exponent in both cities. The average PM2.5 mass concentrations were 32 ± 32 µg/m^3, 32 ± 24 µg/m^3, 28 ± 19 µg/m^3 at traffic sites CT and AT and waste burning site AWD, respectively. The domestic fire site shows concentration of 145 ± 69 µg/m^3 due the contribution of smoking and grilling activities. The highest OC and EC concentrations were also measured at ADF at 71 ± 29 µg/m^3 and 15 ± 9 µg/m^3, respectively. While the other sites present OC concentration between 8 and 12 µg/m^3 and EC concentrations between 2 and 7 µg/m^3. The OC/EC ratio is 4.3 at CT and 2.0 at AT. This difference highlighs the influence of 2-wheels vehicles using 2-stoke mix in Cotonou compared to Abidjan. AOD were rather similar in both cities with a mean value of 0.58 in Cotonou and 0.68 in Abidjan. The seasonal cycle is dominated by the large increase in surface mass concentration and AOD during the main dry season (Dec.-Feb.) as expected due to mineral dust advection and biomass burning activities. The lowest concentrations are observed during the minor dry season (Aug.-Sept.) due to an increase in surface wind speed leading to a better ventilation. On the other hand, the high PM2.5 /AOD ratio in the minor wet season (Oct.-Nov.) indicates the stagnation of local pollution.

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Introduction

Many epidemiological studies have concluded that particulate pollution is directly related to serious human health risks such as respiratory tract infections, cardiovascular diseases and premature deaths (Dockery and Pope, 1994). This atmospheric pollution due to airborne fine particles is an environmental issue of a worldwide increasing concern (Kacenelenbogen et al., 2006; West et al., 2016). The impact of this anthropogenic pollution has been the subject of numerous studies in Europe and North America, where are implemented emission reduction policies, in particular on combustion. This is really different in West Africa. The cities of Africa are facing increasing air pollution problems. According to Liousse et al., 2014, Africa is an intense anthropogenic emitter (biomass fires, domestic fires, increasing car traffic, oil and mining industries in the open rise) in conjunction with exceptional population growth on the Earth, massive urbanization and rapid economic growth: one is expected a tripling anthropogenic emission in Africa between 2000 and 2030. Particulate pollution in African megacities (e.g. Lagos, Nigeria, Johannesburg, South Africa) is expected to have strong implications on population health. According to Dieme et al., (2012) and Val et al., (2013), the aerosol particles in West African cities have strong implications for population health, due to high aerosol concentration levels (Liousse and Galy-Lacaux, 2010) with inflammatory impacts directly linked to pollutant emission sources. Val et al., (2013) highlighted high toxicity of fine particles in Bamako and Dakar, with stronger impact than European cities such as Paris.

Carbonaceous aerosols are one of the major components of fine particulate matter (PM2.5) in urbanized areas as a result of combustion emissions (Zhang et al., 2007). Carbonaceous matter is usually classified into organic carbon (OC) and elemental carbon (EC). Elemental carbon is a primary pollutant emitted from combustion sources and does not undergo chemical transformations, while OC can be either released directly into the atmosphere from combustion and biogenic sources or formed within the atmosphere through gas-to-particle conversion of volatile organic compounds through photochemical reactions (Cao et al., 2003; Turpin and Huntzicker, 1995). At the global scale, last estimates for the year 2000 (Lamarque et al., 2010) have shown that anthropogenic combustions and biomass burning roughly generate about 65% and 35% of element carbon (EC) emissions respectively and 35% and 65% of primary organic (OC) carbon emissions. OC and EC not only contribute to the overall PM2.5 load, but these components have specific public health concerns because of their interactions with the human body (Dou et al., 2015; Shi et al., 2015). The presence of carbonaceous aerosols in West Africa region are known to result from biomass burning, traffic and burning emissions and to a lesser extent from other combustion sources such as industries, power plants and flaring (Doumbia et

al., 2012; Liousse et al., 1996, 2014; and Liousse and Galy-Lacaux, 2010). However, very little information exists on aerosols in West African cities. Indeed, since 1994 many aerosol observations occur in African rural sites in the frame of INDAAF network and different international programs such as DECAFE94, EXPRESSO98, SAFARI92, SAFARI2000 and AMMA2005. Therefore, observations for fine particle (PM2.5) and particulate carbon species are needed for African cities.

For this reason, the DACCIWA program of research and especially the work package 2 started in 2014 and dealing with air pollution and health issues was constructed, aiming to characterize the health impact of atmospheric pollution on West African populations. One of the objectives was to conduct an enhanced observation period (EOP) from February 2015 to March 2017 for the characterization of the physico-chemical properties of particulate matter (PM2.5) and particulate carbon species in two coastal cities of West Africa: Abidjan in Ivory Coast and Cotonou in Benin. Such cities are representative of, West African cities with strong population growth are impacted by emission sources above mentioned. For this reason, three sites were chosen in Abidjan focusing on domestic fires, traffic and waste burning sources and one in Cotonou on traffic emissions again. Indeed, in Cotonou, PM2.5 anthropogenic emissions are principally due to traffic from 2-wheel vehicles whereas in Abidjan, cars and buses are expected to dominate road traffic emissions. Note that such pollution linked to domestic fires, traffic or waste burning, should occur all along the year whereas transported biomass burning and Saharan dust are expected to have an impact during dry seasons around March and April respectively.

This paper focuses on fine particle mass, particulate carbon species and aerosol optical depth measurements performed over these four sites. Weekly-averaged data will be first presented followed by seasonal variation analysis. Then discussion will deal with comparison with worldwide measurements. This paper is the first contribution to aerosol source identification within the two cities.

1. Sites and sampling

Our experimental strategy is based on sampling the polluted atmosphere of different source environments in two majors southwestern African cities of Abidjan in Ivory Coast and Cotonou in Benin from February 2015 to March 2017 (Fig. 1).

Abidjan (5° 20’ N, 4° 1’ W) is the most important economical city of Ivory Coast. It had 6.5 million inhabitants in 2016. Similarly, Cotonou (6° 21’ N, 2° 26’ E) is the most important

economical city of Benin. It had about 1.5 million inhabitants in 2016. Both cities have a sub-equatorial climate characterized by two dry and two wet seasons. The main rainy season extends from April to July and the small rainy season from October to November (Ernest et al., 2013). These two seasons are interspersed with two dry periods that extend from December to March and from August to September (Djossou et al., 2017; Dossou and Glehouenou-Dossou, 2007; Ernest et al., 2013). The main rainy season is dominated by the West African monsoon (Sultan and Janicot, 2003) corresponding to the southwestern prevailing winds advecting humidity and precipitation to the continent. The main dry season from December to March is dominated by the Northeasterly Harmattan wind (Sauvage et al., 2005) carrying mineral dust emitted from arid areas (Adetunji et al., 1979).

The particles were collected on 47mm diameter filters on a weekly basis. The sampling system uses a PM2.5 inlet and a 5L/min pump. Two types of filters are used depending of analysis performed. Teflon filters were used for gravimetric measurements while quartz fiber filters were used for carbonaceous aerosol analysis. The use of different types of filter involves the installation of two filtration lines operating in parallel. Both lines are stored in a same box (Fig. 2). The air is sampled for 15-min every hour, leading to a total volume of sampled air of about 12.6 m^3 by week. Due to power failure, some weeks were not sampled. The samples are stored in packs before sampling and then individually in Petri dishes once the sample has been collected.

In Abidjan, we set up the instrumentation in 3 sites representative of traffic (hereinafter called AT), waste burning (AWB) and domestic fires (ADF) emissions. In Cotonou (hereinafter called CT), one site representative of traffic emission has been investigated. The CT site is located in Dantokpa area, one of the biggest market in western Africa. The area is well-known (Ayi Fanou et al., 2006) to be largely affected by emissions from 2-wheel motorcycles as shown in Fig. 3.a. The instrument is located on a balcony at 4 m height above a major crossroad. In Abidjan, ADF is located in Yopougon area at the Bracodi market (5° 19.746' N; 4° 6.353' W) on a 3-m height tower. Domestic fire emissions due to smoking meat and fish or grilling of peanuts, dominate the particulate matter emissions associated to domestic cooking at ADF. Fig. 3.c gives an overview of the smoking conditions in ADF. AT is located at Adjamé bus station (5° 21.252' N; 4 ° 1.095' W) and more precisely on the roof of the pharmacy "220 logements" (Fig. 3.b). Adjamé bus station is one of the major traffic areas for small buses called "baka" in Abidjan and so this area is largely influenced by 4-wheel vehicles emissions. AWB is near the public dump of Akouédo (5 ° 21.215' N; 3° 56.277' W) on a 3-level building flagstone about 12 m above ground. The public dump receives the totality of waste produced in the district of Abidjan

since 50 years, currently more than 1.000.000 tons of waste by year (Adjiri et al, 2015). It negatively affects the environment and the living environment of the populations of Abidjan in general. Waste burning in the Akouedo dump occurs mainly during the dry season. Fig. 3.d shows a combustion plume rising from the dump.

Additionally, the aerosol optical depth (AOD) was measured downtown Cotonou and Abidjan at about 13:00 UTC every day using a lightweight handheld sun photometer measuring the solar irradiance at 465, 540 and 619 nm. Measurements are performed only for cloud-free field of view.

2. Methods

2.1. Gravimetric analysis

Teflon filters were weighed before and after sampling using a high precision scale (SARTORIUS MC21S). Before weighing, the samples were kept for about 24-h in the weighing room at ambient relative humidity of 30 ± 15%.

2.2. Carbonaceous aerosols

Carbonaceous aerosols organic carbon (OC), elemental carbon (EC) and total carbon (TC, calculated by the sum of OC and EC) were measured on a 0.55 cm² punch from each quartz filter by thermo/optical reflectance following the Interagency Monitoring of Protected Visual Environments (IMPROVE) protocol. The quartz fiber filters are burned 48 hours at 480° C before sampling to reduce the carbon content on the blank filter (filter blanks about 0.8 µgC for OC and 0.2 µgC for EC). The analyzis are performed using a DRI model 2001 Thermal/Optical Carbon Analyser (Atmoslytic Inc., Calabasas, CA) (Chow et al., 1993, 1994a, 2004, 2006). In pure Helium (He) atmosphere, OC fractions are obtained in the four first stages of temperature (OC1, OC2, OC3 and OC4 at 120°C, 250°C, 450°C and 550°C respectively). After pyrolysis, a rise of 2% of oxygen is added in 98% inert He and EC fractions are obtained from three temperature steps (EC1, EC2, EC3 at 550°C, 700°C and 800°C respectively). Sum of OC fractions added to pyrolyzed carbon fraction (OP) gives the concentration of OC in the sample, whereas EC concentration is the difference between sum of EC fractions and OP. The detection limits are 122.4 ± 59.7, 9.0 ± 59.7, and 131.4 ± 59.7 $ng.m^{-3}$ for OC, EC and TC, respectively.

2.3. Sun photometer

Handheld sun photometer is a well-known scientific instrumentation for measuring atmospheric transmission (Porter et al., 2001; Volz, 1959, 1974). We have used in this study a lightweight

handheld sun photometer manufactured by TENUM (http://www.calitoo.fr). The sun photometer measures the Sun irradiance at 3 wavelengths, 465 nm, 540 nm and 619 nm. The atmospheric optical depth is retrieved following the Beer-Lambert law knowing the calibration constant for each instrument and the relative air mass. Sun photometers are calibrated prior to site deployment using the Langley-plot method (Schmid and Wehrli, 1995; Soufflet et al., 1992). The AOD is then retrieved after subtracting the Rayleigh and trace gases optical depth. The Angström exponent (ÅngstrÖm, 1961) is computed between wavelengths 465 and 540 nm and measurements are reported as daily values at 550 nm.

2.4 Ancillary data

Two sets of ancillary data were used to better understand our results.

- The meteorological data provided by the NOAA Integrated Surface database (ISD) and available at https://www.ncdc.noaa.gov/isd.
- The daily burned surface area MCD64A1 satellite product derived from MODIS on AQUA and TERRA at a spatial resolution of 500 m (Roy et al., 2008; Roy and Boschetti, 2009).

3. Results

3.1 Aerosol optical depth

Fig. 4 presents the AOD measurements obtained in Abidjan and Cotonou from December 2014 to April 2017. The AOD in Cotonou ranges between 0.05 and 3.5 with a mean value of 0.68 and in Abidjan between 0.12 and 1.77 with a mean value of 0.58, respectively. This difference is not expected if we consider the size of each city, Abidjan having more than 3 times more inhabitants than Cotonou. Many reasons may explain such a difference. First, the precipitation regime can partly explain that AOD is higher in Bénin than in Ivory Coast. Indeed, during the two years, Abidjan receives the mean Angström exponent in Abidjan (Table 1) is 0.82 while it is 0.65 in Cotonou.much more precipitation (1763 mm) than Cotonou (1084 mm), which implies more aerosol deposition. Second, as Angström exponent is lower for dusty atmosphere, this difference could suggest that Cotonou is more affected by dust transport than Abidjan and so the higher AOD reflects a higher contribution of mineral dust.

3.2. Mass and carbon concentrations

Fig. 5 shows the time series of PM2.5 obtained at the 4 different sites for the 2-year period. CT, AT and AWB are plotted together while ADF is on a separated panel because of the large

difference in the range of concentrations. The PM2.5 concentrations at the 3 "urban-like" sites CT, AT and AWB presents indeed a very similar time behavior. Large spikes above 100 µg/m3 during between December and April characterize the time series. The main feature of the ADF PM2.5 time series is totally different, showing a bell shape in the annual cycle with maxima during July-August.

PM2.5 varies from 11 to 174 µg/m^3 at AT, 8 to 226 µg/m^3 at CT, 7 to 112 µg/m^3 at AWB, and 18 to 436 µg/m^3 at ADF, respectively. At AT, CT, and AWB sites, higher weekly concentrations have been observed in dry seasons and lower in wet season. We found that the average PM2.5 mass concentrations at CT, AT and AWB are very similar. The mean weekly PM2.5 mass concentration is 32 ± 32 µg/m^3 at CT, 32 ± 24 µg/m^3 at AT and 28 ± 19 µg/m^3 at AWB. However, it is 145 ± 69 µg/m^3 at ADF, clearly highlighting the strong impact of nearby smoking activities. As a comparison, the World Health Organization recommends a threshold value of 10 µg/m^3 as a guideline for annual PM2.5. On average, AWB remains at the same level as the traffic sites CT and AT, showing that probably the waste burning activities didn't affect as much as expected our sampling because the site wasn't exactly located downwind the dump.

As a consequence of the vicinity of ADF to emission sources, the TC content is higher than the other sites. TC is at 86 µg/m^3 (± 35) at ADF while it is 19 µg/m^3 (± 12) at AT, 10 µg/m^3 (± 7) at CT and 14 µg/m^3 (± 8) at AWB. The OC/EC ratio in Abidjan is 2.0 at AT and 3.3 at AWB (see Fig. 6, discussed later in the text). However, it is 4.3 at Cotonou. This difference could be expected since Cotonou traffic emissions are dominated by 2-wheels vehicles using 2-stoke mix using lubricating oil. The highest OC/EC ratio of 5.3 is observed at ADF in the relation with biomass combustion for fish and meat smoking.

3.3 Seasonal variations

Hereinafter, we have separated the 2-year period in 8 seasons: 2 major dry seasons labeled D1 (December 2015 to March 2016) and D2 (December 2016 to March 2017), 2 major wet seasons labeled W1 (April to July 2015) and W2 (April to July 2016), 2 minor dry seasons labeled D1' (August to September 2015) and D2' (August to September 2016), and 2 minor wet seasons labeled W1' (October to November 2015) and W2' (October to November 2016). Fig. 7 reports the weekly average of precipitation rate and temperature for both Cotonou and Abidjan. For both cities, the weekly mean amplitude of the air temperature is between 25° and 30° C, reaching a minimum during the minor dry season (D1' and D2'). The precipitation pattern is also similar for both cities although Abidjan receives more rain than Cotonou in W1. Yearly and seasonal average meteorological parameters are reported in Table 1.

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The Table 2 shows the seasonal average of PM2.5 concentrations and carbonaceous matter (OC and EC), considering both the first and the second year. The three urban sites (CT, AWB and AT) show similar seasonal variation as expected from Fig. 5. The maximum average concentrations of PM2.5 are measured during the major dry season D at about 50 µg/m^3. The minimum PM2.5 concentrations are observed during the minor dry season (D') for all the three sites around 18 µg/m^3. The average PM2.5 concentration is always higher during W' than W. A decrease in the PM2.5 concentration is expected due to wet scavenging as the precipitation rate in both cities is much higher during W than during W'. The highest average concentrations of PM2.5 at ADF are measured during D'. PM2.5 remains also high during W' and W. Those high concentrations measured during the seasons W, D' and W' at the ADF site could be due to the humidity of wood leading to poor combustion and high smoke emission during these seasons.

The ratio between PM2.5 and AOD is given in Table 2. This ratio is an indicator of the link between surface level pollution and the atmospheric column. The highest PM2.5/AOD ratio is observed during the minor wet season W', between 88 and 133 µg/m^3/AOD at 550 nm for CT, AT and AWB. It indicates a change in the atmospheric vertical distribution of aerosols towards lower altitudes, highlighting the possible stagnation of pollution during this periods. On the opposite, lowest ratio are observed during W and D', which tends to indicate aloft transport of aerosols.

We also determined the seasonal averages of wind speeds in both cities. Seasonal averages of wind speeds are between 2.9 and 3.5 m/s in Abidjan and between 3.6 and 5.0 m/s in Cotonou. We noticed that the wind intensity is the highest in D' (Table 1). This increase in the wind intensity during the minor wet season corresponds also to a minimum in the air temperature (Fig. 7). The increase in the wind intensity favors the dispersion of pollutant during D' seasons and may explain the decrease in the PM2.5 concentrations. Inversely, the wind intensity is the lowest during the major dry season D1 and D2, while the PM2.5 concentration is the highest.

However, the contribution of advected mineral dust and biomass burning aerosol by northerly winds is also high during season D. Indeed, we can infer the massive presence of dust over the cities by looking at the Angstrom exponent on Fig. 8. A low value (typically below 0.8) of the Angstrom exponent indicates a significant contribution of coarse dust-like particles to the AOD. Fig. 8 shows that during the largest peak values (above 100 µg/m^3) in the dry season D1 and D2 are associated with Angstrom exponent close to 0.5, which means that advected dust might sporadically contribute to the increase in the ground-level PM2.5 concentration. Regarding the possible contribution of biomass burning emissions, we have also reported on Fig. 8, the

MDC64A1 surface burnt in the geographical area 7°W to 4°E and 10°N to 4°N. As expected, the largest part of the vegetation is burning during the dry season. However, we observe that a significant part of biomass burning emissions occurs during the minor wet season. Indeed, the percentage of the total surface burnt during W' is 21% and 79% for D, respectively. It shows that biomass burning emissions may have a large relative impact on PM2.5 during the minor wet season and could explain the increase in the PM2.5 concentrations from after the minor dry season D'.

As shown in Fig. 6 the OC/EC ratio has a seasonal variability, showing higher values during the major dry season, except during the first year for ADF, which has high OC/EC ratio during the wet season. This striking feature could be linked to a drastic change in the wood type or wood humidity. As seen on Fig. 7, the precipitation rate in Abidjan for W1 and W1' are much higher than for W2 and W2' and on average Abidjan receives 40% less precipitation during the first year of than the second year (Table 1). As wood fuel is stored without shelters, it is so expected that the humidity content of the wood is also higher and thus generated poor combustion leading to increase in the OC emission rate. The OC and EC average concentrations measured at the AT, CT and AWB sites are high in season D and W' (see Table 2) as expected from higher emission from biomass fires. The low mean values of OC and EC are measured in season D' at the AT, CT and AWB sites in conjunction with low PM2.5 concentrations.

Carbonaceous aerosols contribute significantly to the PM2.5. We remark after analysis of particulate carbon species at the four sites that OC is the predominant contributor to TC. During the study period, TC at the AT, CT, AWB and ADF sites accounted for an averaged 64%, 37%, 55% and 62% of PM2.5, respectively. PM2.5 at the AT, CT, AWB and ADF consisted of 24%, 8%, 17% and 11% element carbon and 39%, 29%, 38% and 51% organic carbon, respectively. These percentages of particulate carbon species obtained indicated that more carbonaceous species in PM2.5 particles. In comparing the percentages of carbonaceous species at the AT and CT sites, it can be seen that the percentage of particulate carbon species obtained at the AT site was about 1.7 times higher than the percentages obtained at the CT site. From the percentages obtained on the traffic sites, we can say that emissions of particulate carbon species are very important at the AT. These results allow us to confirm the domination of diesel and fuel at the AT and CT site, respectively.

4. Discussion

Our results show that the average concentration of PM2.5 in our urban sites is around 30 $\mu g.m^{-3}$, precisely 28 $\mu g.m^{-3}$ for the waste burning site (AWB), and 32 $\mu g.m^{-3}$ for both traffic sites in

Benin (CT) and Cote d'Ivoire (AT) whereas 145 µg.m^{-3} for domestic fire site (ADF). Such values except for ADF are in agreement with those measured by van Donkelaar et al., (2010) (35 µg.m^{-3}) in Sub-Saharan western Africa. Our observations are above the ones found for European cities. Indeed, Querol et al., 2004 have reported a range of urban background PM2.5 concentrations between 20 and 30 µg.m^{-3}. The review paper of Naidja et al., 2017 on road traffic sites gives higher values than our traffic values: 41 µg.m^{-3} for Harare, Zimbawe (Kuvarega and Taru, 2008), 51 µg.m^{-3} for Kenitra, Marocco (Zghaid et al., 2009) and 58 µg.m^{-3} for Constantine, Algeria (Terrouche et al., 2016). Mkoma et al., (2014) give a value of 33 µg.m^{-3} for Morogoro, Tanzania. In their study in Accra, Ghana Dionisio et al., 2010b reveal that the geometric mean of PM2.5 concentration is 21 µg.m^{-3} in the neighbourhood. PM2.5 concentrations of the order of our domestic fire sites are reported for China. Zhang et al., 2011 reports a value of 72 µg.m^{-3} for Xiamen while Zhang et al., 2015 give 125 µg.m^{-3} for Whanzou. Gu et al., 2010 also report an average concentration over 100 µg.m^{-3} for Tianjin. In Dakar, Senegal Dieme et al., 2012b and Doumbia et al., 2012 reports PM2.5 at 75 and 50 µg.m^{-3} respectively close to the one found by Zakey et al., 2008 85 µg.m^{-3} in Cairo, Egypt. It has been noted that those latter sites are largely influenced by mineral dust. Fig. 9 summarizes the different above-mentioned measurements existing in Africa for different cities. It is interesting to underline that all the values including our measurements in Abidjan and Cotonou are higher with a factor of 2 to 14 than the WHO norms.

In terms of the carbonaceous species, the OC concentration in PM2.5 at CT, AT, AWB and ADF site is 8 µg.m^{-3}, 12 µg.m^{-3} 10 µg.m^{-3} and 71 µg.m^{-3}, respectively. This OC concentration is higher than the one found for European Cites like Paris, France (5.9 µg.m^{-3}) (Favez, 2008), or Helsinki (3 µg.m^{-3}) (Viidanoja, 2002). For CT and AT, it is similar to the one found in Milan, Italy (9.2 µg.m^{-3}) (Lonati et al., 2007) and about twice lower than the OC in Cairo, Egypt (22.4 µg.m^{-3}) (Favez, 2008), Agra, India (22.8 µg.m^{-3}) (Tripti et al., 2013), or Taiyuan, China (28.9 µg.m^{-3}) (Meng et al., 2007). Note that our measurements in the ADF site are much higher than all the values observed in other sites.

However, the EC concentration at CT and AT sites is 2 µg.m^{-3} and 7 µg.m^{-3}, respectively. This EC concentration at our urban traffic sites show a larger variability, reflecting the large contribution of diesel engine in Abidjan. It was similar than those in Dakar (10.5 µg.m^{-3}) (Doumbia et al., 2012), in Cairo, Egypt (7.8 µg.m^{-3}), Beijing, China (7.8 µg.m^{-3}) (Favez, 2008), Los Angeles in 90's (7.3 µg.m^{-3}) (Chow et al., 1994b) but higher and lower than those in Xiamen, China (3.5 µg.m^{-3}) (Zhang et al., 2011) and Agra, India (19.4 µg.m^{-3}) (Pachauri, 2013). The EC concentration in Cotonou is close to the one found in European cities like Milan, Italy

(1.4 µg.m^{-3}), Paris, France (1.7 µg.m^{-3}) or Yokohama (1.9 µg.m^{-3}) (Khan et al., 2010) but higher than Helsinki (1.1 µg.m^{-3}).

We compared the OC and EC concentrations measured during the dry and wet seasons of this study to those measured by Mkoma et al., (2013) in Tanzania (OC: 3.9 µg.m^{-3} and 6 µg.m^{-3} in wet season and dry season, respectively; EC: 0.5 µg.m^{-3} and 1 µg.m^{-3} in wet season and dry season, respectively). OC and EC concentrations measured during the dry and wet seasons at the AT, CT, ADF and AWB sites were higher than those measured in Mkoma et al., (2013**).**

OC/EC ratios obtained at our sites are within the common ranges reported in the literature. Indeed, following the above-mentioned literature data, OC/EC ratio ranges from 2.7 in Helsinki, 3.5 in Paris, 2.87 in Cairo to 6 in Tanzania during the dry season, 6.7 in Agra and 6.6 in Milan. In our study, average of OC/EC ratio is 2 ± 1 at AT, 4 ± 1 at CT, 3 ± 2 at AWB and 5 ± 3 at ADF. Moreover, either in our study or in literature data, highest values are due to the predominant influence of sources with incomplete combustion such as domestic fires, 2-wheel vehicle traffic, biomass burning whereas lowest OC/EC ratios are typical of much more complete combustion such as diesel engines (Mmari et al., 2013).

Conclusion

In this study, the mass concentrations and particulate carbon species of PM2.5 samples collected in coastal cities in West Africa (Abidjan and Cotonou) were investigated at two traffic sites (AT and CT), one waste burning site (AWB) and one domestic fire site (ADF) from February 2015 to March 2017. We have analyzed the weekly mean concentration of PM2.5, EC and OC concentrations. AOD measurements were also made in Abidjan and Cotonou. Note that the AOD dataset is the first one obtained in this area.

We observe large similarly between both urban site in Abidjan (AT) and Cotonou. Moreover, the waste-burning site follows the same pattern at the traffic. The mean PM2.5 concentration for AT, CT and AWB of about 30 µg.m^{-3} is coherent with previous studies for sub-Saharan western Africa and is 3 times higher than the concentrations recommended by the World Health Organization. The samples collected at the domestic fire site shows a large pollution by smoking activity with an average PM2.5 concentration of 145 µg.m^{-3}, 5 times as high as that those of the traffic background.

The seasonality of PM2.5 is affected by the contribution of desert dust and biomass burning emissions that is clearly observed from the AOD time series. We observe that dust events contribute sporadically to large amount of PM2.5, above 100 µg.m^{-3}, during the dry seasons of the observation period. Moreover, the biomass burning activity at the regional scale is also

maximum during the dry season and contributes to increase the PM2.5 concentration. The biomass burning contribution is possibly larger during the minor wet season before the dry season. The low PM2.5 concentrations observed during the minor dry season could be explained by an enhancement of the atmospheric dispersion due to the increase in the wind intensity and the absence of biomass burning activity.

Even of PM2.5 concentrations are of the same order of magnitude, we observe a significant difference in the carbonaceous aerosol composition between the traffic site in Abidjan and Cotonou. The mean OC/EC ratio is on average 4 at CT and 2 at AT, clearly indicating the larger contribution emission by the 2-wheel motorcycles in Cotonou compared to Abidjan, mostly dominated by diesel vehicle park. We also remark that the particulate carbon species at the ADF site was higher to those at the traffic site and has a totally different seasonal pattern, showing higher concentration during the minor dry season, which occurs after the rainy period. We infer that the increase in the PM2.5 and OC emission at ADF can be due to the humidification of wood fuel during the wet season.

To conclude, this study suggests that emissions of carbonaceous aerosol could have a significant impact on the air quality in the atmosphere in Abidjan and Cotonou. This study could also provide a first element of expertise for urban and environmental policies in these two capitals.

Acknowledgements

This work has received funding from the European Union 7th Framework Programme (FP7/2007-2013) under Grant Agreement no. 603502 (EU project DACCIWA: Dynamics-aerosol-chemistry-cloud interactions in West Africa). The author would like to thank the AUF (Agence Universitaire de la Francophonie) for funding his stays in Laboratoire d'Aérologie of Toulouse (3 months per year during 3 years).

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Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-973
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 17 November 2017

Atmospheric Chemistry and Physics Discussions

651 **Table 1.** Seasonal average of precipitations, wind speed, Aerosol Optical Depth (AOD) and
652 Angstrom exponent for Abidjan and Cotonou sites. W and W' are the long and short rainy
653 seasons and D and D' are the long and short dry seasons, respectively.
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City	Season	Precipitation (mm)	Wind Speed (m/s)	AOD_{550nm}	$\alpha_{465-619}$
Abidjan	W	911	3.4	0.5±0.2	0.7±0.3
	D'	75	3.5	0.3±0.1	1.1±0.2
	W'	332	3.2	0.3±0.1	1.2±0.2
	D	244	2.9	0.7±0.2	0.8±0.2
	Year 1	2214	3.3	0.5±0.3	0.9±0.3
	Year 2	1312	3.2	0.5±0.2	0.9±0.2
	Total	5780	3.2	0.6±0.2	0.9±0.3
Cotonou	W	607	4.3	0.5±0.2	0.8±0.4
	D'	130	5.0	0.4±0.2	1.3±0.3
	W'	303	3.3	0.3±0.2	1.2±0.4
	D	80	3.6	1±0.4	0.8±0.3
	Year 1	1148	4.1	0.6±0.4	0.9±0.4
	Year 2	1092	4.0	0.5±0.3	1.1±0.4
	Total	3886	4.0	0.6±0.4	0.9±0.4

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Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-973
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 17 November 2017

Atmospheric Chemistry and Physics Discussions

665 **Table 2.** Seasonal average of PM2.5 concentrations, carbonaceous matter and ratio between
666 PM2.5 and AOD for Abidjan/Domestic Fires (ADF), Abidjan/Traffic (AT) Abidjan/Waste
667 Burning (AWB) and Cotonou/Traffic (CT) sites, respectively.

Sites	Season	PM2.5 (µg.m^{-3})	TC (µg.m^{-3})	OC (µg.m^{-3})	EC (µg.m^{-3})	OC/EC	PM2.5/AOD
	W	159.5±3	94±11	76±8	17.5±3	5.5	318
	D'	190.5±59	109.5±20	91.5±25	18±4	5.5	633
	W'	139.5±22	91.5±12	76±16	15.5±3	5.0	465
ADF	D	119±27	66.5±9	54±8	12.5±1	5.0	170
	Year 1	161±54	92.5±27	78.5±26	14±1	6.0	322
	Year 2	143±16	88±13	70±10	18±4	4.5	286
	Total	145±69	86±35	71±29	15±9	5.2	242
	W	27.5±6	17±4	10±3	6.5±1	2.0	55
	D'	18.5±2	12±1	8±1	4.5±1	2.0	62
	W'	40±11	19.5±3	11.5±1	7.5±2	1.7	133
AT	D	52±22	28.5±5	20±7	8.5±2	2.5	74
	Year 1	40±20	20±9	14±9	6±1	2.2	80
	Year 2	28.7±9	18.5±6	11±3	7.5±2	1.8	57
	Total	32±25	19±12	12±10	7±4	2.0	53
	W	21±4	11±5	7.5±1	4.5±1	2.5	42
	D'	18±6	10±4	6.5±3	4.5±1	1.5	60
	W'	26.5±2	12.5±6	9±4	4±1	2.0	88
AWB	D	48±1	21±4	15.5±2	6±1	3.0	69
	Year 1	29±14	11±5	8±4	4±1	2.0	58
	Year 2	28±14	16±6	11.5±4	5±2	2.5	56
	Total	28±19	14±8	10±6	4±3	2.2	47
	W	19±7	8.5±2	7±1	2±1	4.0	38
	D'	14±3	5.5±2	4±1	1±1	3.5	35
	W'	29.5±5	9±1	7±1	2±1	3.2	98
CT	D	57±52	16±11	12±10	3±2	3.5	57
	Year 1	29±21	9±5	7±4	2±1	3.2	48
	Year 2	31±18	11±4	8±3	2±1	3.8	62
	Total	32±32	10±7	8±6	2±1	3.5	53

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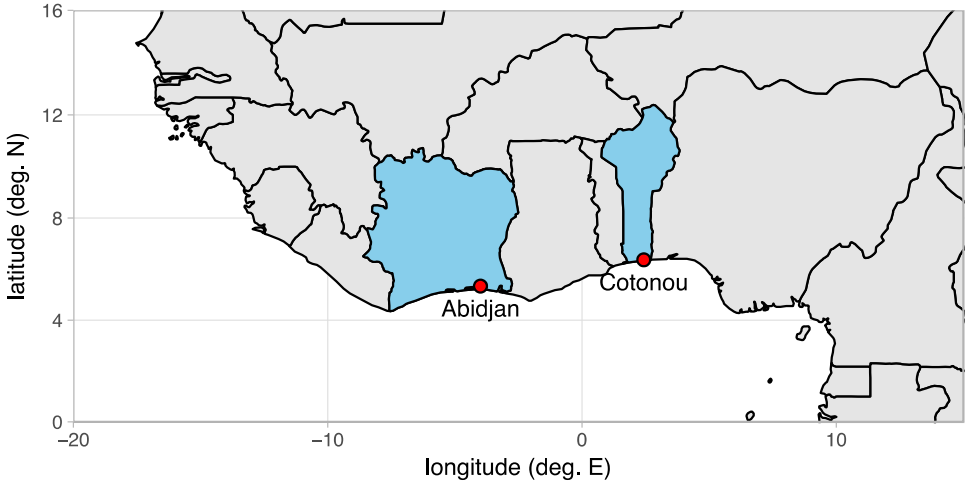

669
670 **Fig. 1.** Geographical locations of Abidjan and Cotonou cities in the gulf of Guinea.

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673 **Fig. 2.** Sampling box with the 2 lines.

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676

a) Cotonou/Traffic (CT)

b) Balcony in Abidjan/Traffic (AT)

c) Abidjan/Domestic fires (ADF)

d) Abidjan/Waste burning (AWB)

677

678 **Fig. 3**. Description of the instrumentation and the measuring sites: (a) Cotonou/Traffic (CT),
679 (b) Balcony in Abidjan/Traffic (AT), (c) Abidjan/Domestic fires (ADF) and (d) Abidjan/Waste
680 burning (AWB)

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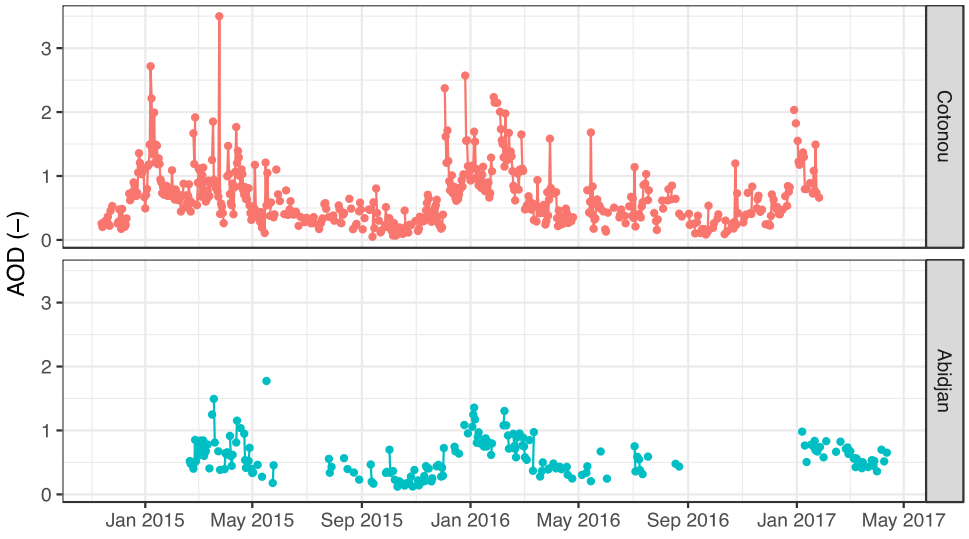

682

683 **Fig. 4.** Daily sun photometer aerosol optical depth at 550nm from December 2014 to April 2017
684 at Cotonou (Benin) and Abidjan (Ivory Coast).

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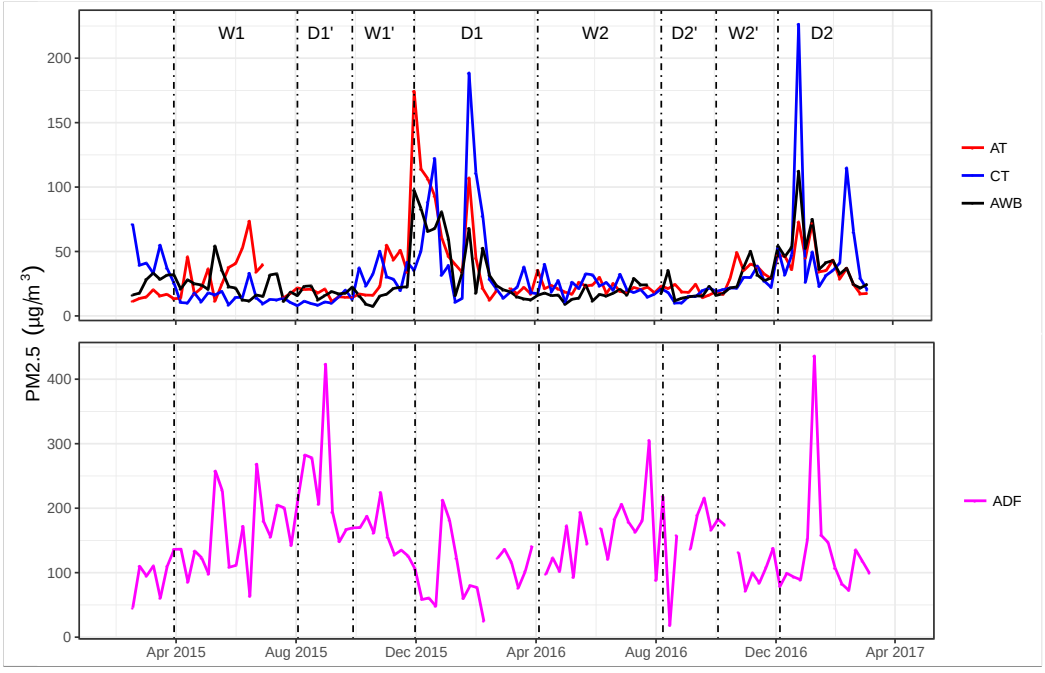

Fig. 5. Time series of the PM2.5 concentrations at the 4 sites from February 2015 to March 2017. Dashed lines show the different seasons (see text). W1 and W2, the long rainy seasons; D1' and D2', the short dry seasons; W1' and W2'; the short rainy seasons; and D1 and D2, the long dry seasons, on all the study period.

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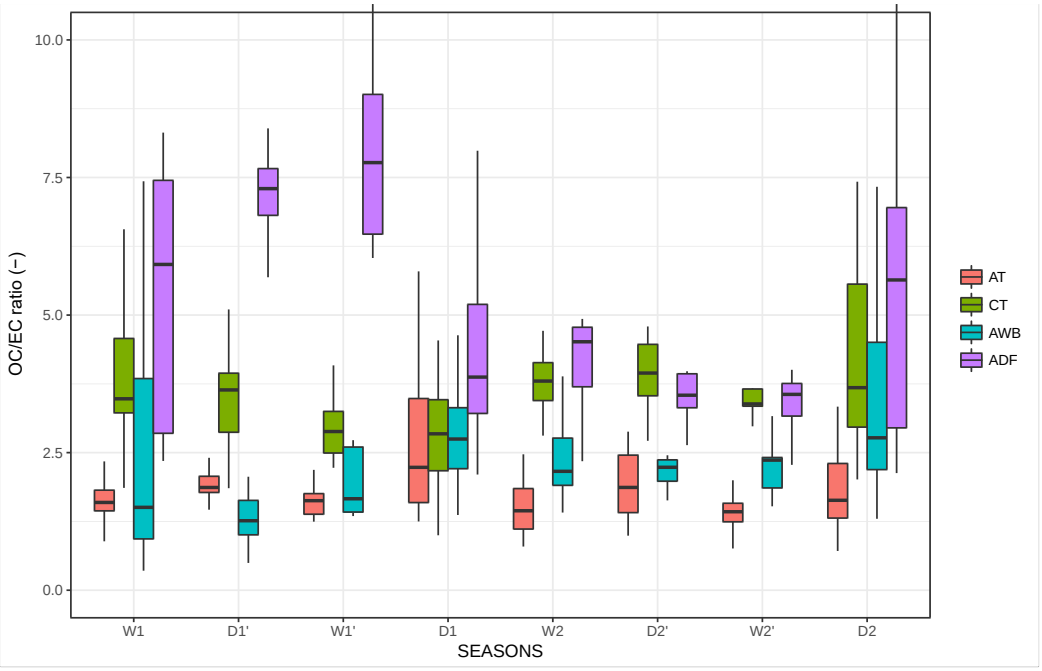

Fig. 6. Seasonal variation of the OC/EC ratio for the experimental sites.

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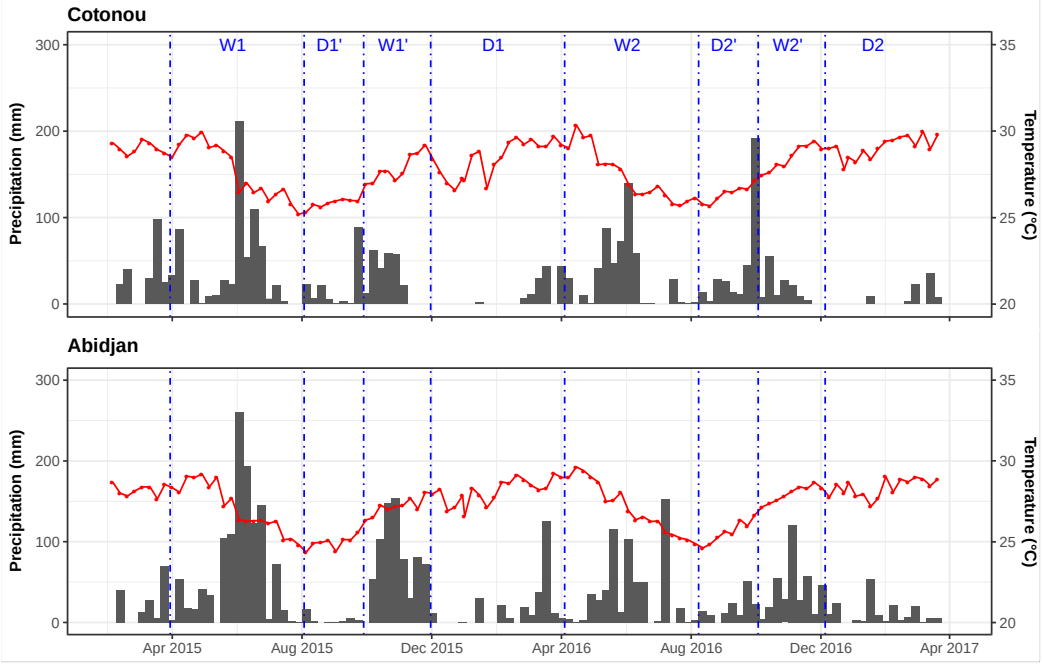

716

717 **Fig. 7.** Weekly precipitation rate and mean temperature for Cotonou and Abidjan from February
718 2015 to March 2017. W1 and W2, the long rainy seasons; D1' and D2', the short dry seasons;
719 W1' and W2'; the short rainy seasons; and D1 and D2, the long dry seasons, on all the study
720 period.

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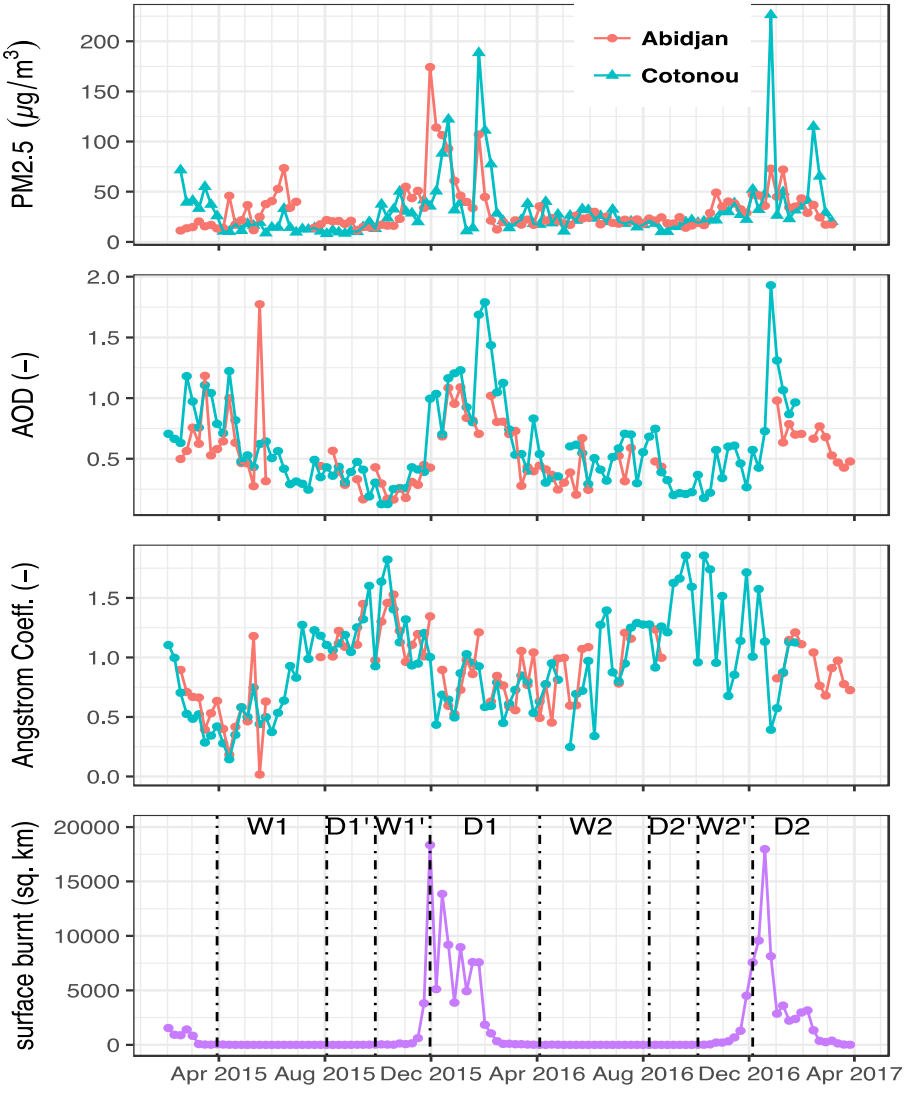

Fig. 8. Weekly mean PM2.5, AOD and Angstrom exponent observed at CT and AT from February 2015 to March 2017. The surface burnt is the weekly total of the MODIS MCD64A1 product burnt surface areas for the region from 7°W to 4°E and 4°N to 10°N.

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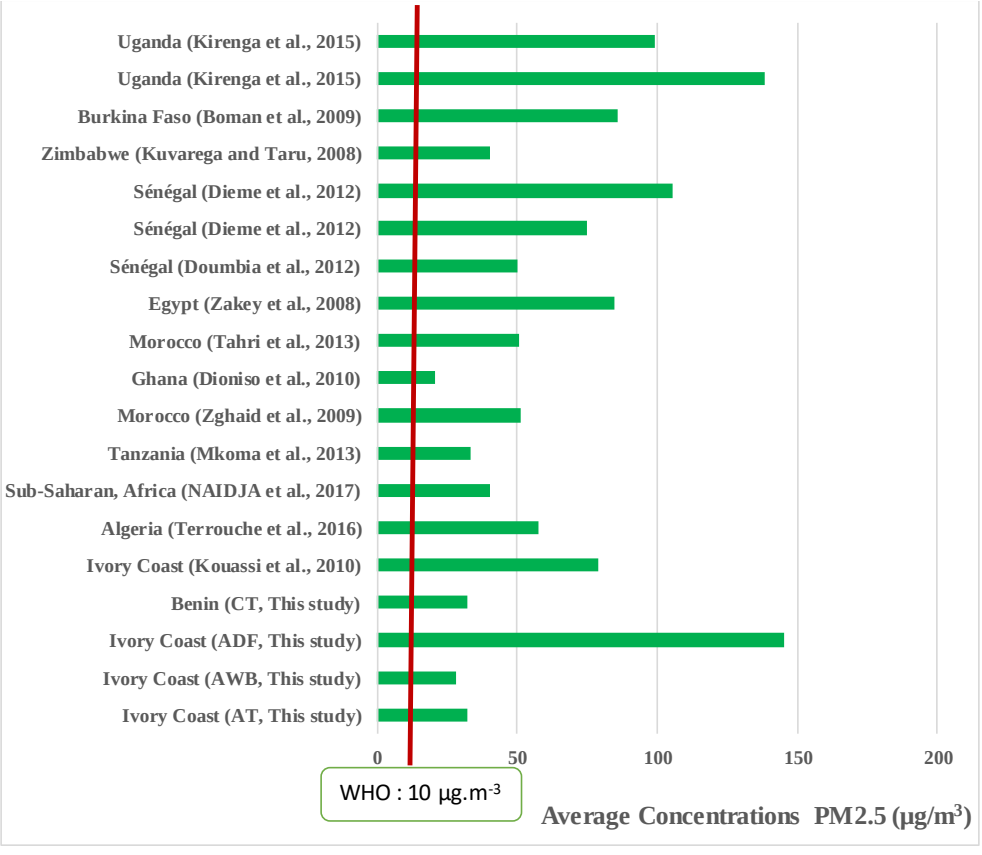

Fig. 9. Comparison of PM2.5 mass concentrations at the four sites with other African cities. Red vertical line illustrates current WHO guideline.