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Assessment of Pollution Levels of Suspended Particulate Matter on an Hourly and a Daily Time Scale in West African Cities: Case Study of Ouagadougou (Burkina Faso)

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Abstract

In Western countries, research works on air quality have reinforced in recent years because of the links between the level of particulate pollution in numerous cities and the appearing of various health disorders including cardio-respiratory pathologies, acute bronchopneumonia, lung cancer, etc. In sub-Saharan Africa countries, particularly Burkina Faso, there is very few similar research. In the present work, the pollution levels of airborne particle in the city of Ouagadougou have been assessed through two campaigns of in situ measurements of suspended particulate matter concentrations. These measurements which have concerned PM_1, $PM_{2.5}$ and PM_{10} were performed using a portable device (AEROCET531S) at nine sites in 2018 and at ten sites in 2019. These sites are located on roadside, administrative services, secondary education establishments and outlying districts. The results show that: 1) the PM_1 concentrations values presented no significant variation between days, seasons or sampling sites; 2) the 24-hour $PM_{2.5}$ concentrations often exceeding WHO recommended concentrations and, 3) the 24-hour PM_{10} concentrations exceed WHO recommended concentrations regardless of the season or the sampling site. In indeed, the average 24-hour concentrations are 20 ± 4, 87 ± 16 and 951 ± 266 $\mu g \cdot m^{-3}$ for the PM_1, $PM_{2.5}$ and PM_{10}, respectively. They are 17 ± 3, 29 ± 5 and 158 ± 43 $\mu g \cdot m^{-3}$, respectively, in 2018 dry season and, 12 ± 1, 22 ± 9 and 187 ± 67 $\mu g \cdot m^{-3}$, respectively, in 2019 rainy season.

Keywords

Urban Air Pollution, PM_1, $PM_{2.5}$, PM_{10}, AEROCET, Ouagadougou

1. Introduction

Air pollution is a serious problem that affects the life of billions of people every year (Louati, Son, and Chabchoub, 2018); (Son and Louati, 2016). Africa has been singled out by UN HABITAT as the fastest urbanizing continent in the world (UN-HABITAT, 2010). This fact is accompanied by pollutions, particularly those of air by particulate matter (PM) emission that can cause multiple adverse long-term as well short-term effects on the human wellbeing such as increased health problems (Li et al., 2018) (Chen et al., 2019) (Cassee et al., 2013) (Beltrando, 2014) (Chang, Peng, and Dominici, 2011). In the same vein, and according to the World Health Organization (WHO), more than 25% of deaths around the world may directly be linked to pollution.

By the aerodynamic diameter (Di), PM can be divided into nanoparticles or $PM_{0.01}$ (Di < 0.01 μm), ultrafine particles or PM_1 (Di < 0.1 μm), fine particles or $PM_{2.5}$ (Di < 2.5 μm), and fine particles or PM_{10} (Di < 10 μm) (Duan et al., 2015). The composition and size distribution of particles depend on their formation processes, including their source that has been explored in numerous studies (Tsai et al., 2015).

According to Chatoutsidou and Lazaridis (Chatoutsidou and Lazaridis, 2019), PM may be classified into two groups based on their sources: 1) naturally originated PM and 2) anthropogenic originated PM. The first group includes PM that are emitted by natural sources such as sea spray, volcanoes, forests, and deserts. On the other hand, common anthropogenic sources are power plants, industries, aviation, vehicles, re-suspension, processes that utilize combustion (the use of biomass as domestic energy, common waste burning practices in residential areas). Previous studies showed that road dust emissions can increase PM_{10} by 21% - 35% at traffic stations, 17% - 34% at urban administrative sites, 17% - 22% at industrial sites and 9% - 22% at rural sites (Amato et al., 2016).

Meteorological parameters such as temperature, humidity, wind speed and direction play a crucial role in air pollution mitigating (Radaideh, 2017) (Kliengchuay et al., 2018) (Janae et al., 2014). In normal weather conditions, the temperature decreases with altitude so that the pollutants emitted on the ground rise and disperse. This physical phenomenon fades as soon as there is a temperature inversion that favors an accumulation of pollutants in the air, especially in urban environment because at the ceiling of inversion, the pollutants will not be able to disperse any more (Sarr et al., 2018). This would result in containment of pollutants and an increase in concentration at the beginning of the night (Petäjä et al., 2016). Lindén and coauthors (Lindén, Thorsson, and Boman, 2012) have highlighted the relationship between atmospheric stability and pollutant levels in

Ouagadougou's climate. It was pointed out that PM_{10} levels were substantially higher during unstable weather conditions compared to moderately stable atmospheric conditions across selected locations with various land cover, land use, and traffic density. A similar relationship in the morning is discussed by Etyemezian and coauthors (Etyemezian et al., 2005) which links the largest peak of air pollution to Addis Ababa to a higher atmospheric stability in the morning caused by temperature inversions at the surface during the night. The different intra-urban trends in PM concentrations between day and night can be explained by the difference between the sources of PM. Indeed, there is probably a greater influence of traffic dust suspension on paved and unpaved roads, the exhaust emissions in the morning to that adds the effect of using biomass as a source of energy as we move forward in the day. In addition to these sources, we can list the contribution of the dry season by the Harmattan of Sahara dust and local dust. More stable night conditions favor a mixture of suspended dust with particles generated by combustion and circulation, resulting in more uniform levels of $PM_{2.5}$ in the evening.

Meteorological parameters of Ouagadougou are described in section 2.1. In general, wind speeds are low and stable and this is favorable for a stagnation of pollutants in the air, especially after 6:00 pm (Eliasson, Jonsson, and Holmer, 2009). However, the main origin of air pollutants and air pollution, is urban such as re-suspension related to traffic on paved and unpaved roads (Boman et al., 2009). Indeed, according to Boman and coauthors (Boman et al., 2009), most of the geological material found in PM_{10} is due to dust suspension from roads related to the prevalence of unpaved roads, the use of biomass as domestic energy and waste incineration. Some natural sources contribute also to PM such as the Saharan desert, which is the world's largest source of wind dust (Goudie and Middleton, 2001), the Bodélé's depression in Chad, which contributes to inject an important quantity of dust transported by Harmattan in the atmosphere of West Africa. A study of long-range dust transport shows that West Africa is the region the most affected by dust transported from the Saharan desert but the least studied (De Longueville et al., 2010).

Some studies on air pollution in the city of Ouagadougou show that this pollution is mainly due to PM and hydrocarbons (Eliasson, Jonsson, and Holmer, 2009) (Boman et al., 2009) (Nana et al., 2012) (Lindén et al., 2012). The PM concentrations exceed two or three times the recommended concentrations. Eliasson and coauthors (Eliasson, Jonsson, and Holmer, 2009) were assessed the PM_{10} concentrations to 578 $\mu g \cdot m^{-3}$ in central business district, 1123 $\mu g \cdot m^{-3}$ in high standing residential and 1884 $\mu g \cdot m^{-3}$ in traditional residential. Nana and coauthors (Nana et al., 2012) have obtained PM_{10} concentrations of 135.8 $\mu g \cdot m^{-3}$ in February 2007, 302.9 $\mu g \cdot m^{-3}$ in March 2007, 116.5 $\mu g \cdot m^{-3}$ in April 2007, 183 $\mu g \cdot m^{-3}$ in May 2007 and 92.9 $\mu g \cdot m^{-3}$ in June 2007. Lindén and coauthors (Lindén et al., 2012) have measured PM_{10} concentrations to 162 ± 144 $\mu g \cdot m^{-3}$ and 69.0 ± 46.6 $\mu g \cdot m^{-3}$ for extreme and moderate pollution situations, respectively, in dry season 2007. These concentrations exceed the 24-hour PM_{10} concentrations recommended by the WHO and European Environment Agency (EEA) (50 $\mu g \cdot m^{-3}$), as well as United States Environmental Protection Agency US EPA (150 $\mu g \cdot m^{-3}$). However, these concentrations are lower than the 24 hours total suspended particles recommended limit of 200 - 300 $\mu g \cdot m^{-3}$ by Burkina Faso authorities (Presidence du Faso, 2001). It will be noticed that there are no recommended limits especially for $PM_{2.5}$, PM_{10} and other in Burkina Faso.

In this paper, we present an analysis of PM (PM_1, $PM_{2.5}$ and PM_{10}) concentrations in Ouagadougou for measurement campaigns in 2018 (dry and rainy season) and 2019 (rainy season). PM mass concentrations were analyzed by hour, day and location. The characterization of traffic fleet composition was also described. The overall objective of this study was to address the present status of air pollution due to suspended particulate matter in Ouagadougou's city, ten years after the last status. It should be noted that this study covered more measurement sites than any previous study and was conducted over two years.

2. Material and Methods

2.1. Description of Study Area and Sampling Points

Ouagadougou the capital of Burkina Faso, located at 12˚22 North, 1˚31 West, 300 m above sea level, is situated in Sahelian region of West Africa. Its population was estimated at 1,700,000 in 2010 and 2,684,052 in 2020 by National Institute of Statistics and Demography. This corresponds to a population increase of 57.9%. Thus, UN-HABITAT (UN-HABITAT, 2010) has renamed it the most dynamic city in the world. As the city is located in a warm semi-arid climate of Sahel, the climate consists of a dry season from October to May and a rainy season from June to September. During the rainy season, the rainfall ranged between 600 - 900 mm, while the dry eight-month period generally receives less than 100 mm of rain (Lindén et al., 2012). Stable night-time atmospheric conditions are common at the beginning of the dry season in Ouagadougou (Lindén and Holmer, 2011), which are favorable to higher pollution levels (Boman et al., 2009). A study of the local wind field by (Lindén and Holmer, 2011) showed that wind speeds are generally very low in Ouagadougou, thus preventing good ventilation of urban air followed by the dispersion of pollutants emitted locally.

During the dry season, the influence of dust carried by Harmattan winds from Saharan desert in the North and North-East affects the entire Sahelian region and creates important seasonal differences in suspended particulate concentrations. The highest levels of airborne particulate matter are generally observed in February and the lowest levels in August (Prasad, 2011), (Titcombe and Simcik, 2011). According to Ouagadougou Meteorological Office, visibility is generally reduced by almost half during the dry season compared to the rainy season (DMN, 201AD).

PM measurements were carried out at fourteen (14) sampling sites (**Figure 1**) in 2018 and 2019 years. These sites can be divided into five (5) groups: 1) scholar sites (C3 and H6), 2) peripheral district sites (Kar, BV and G2), 3) industrial sites

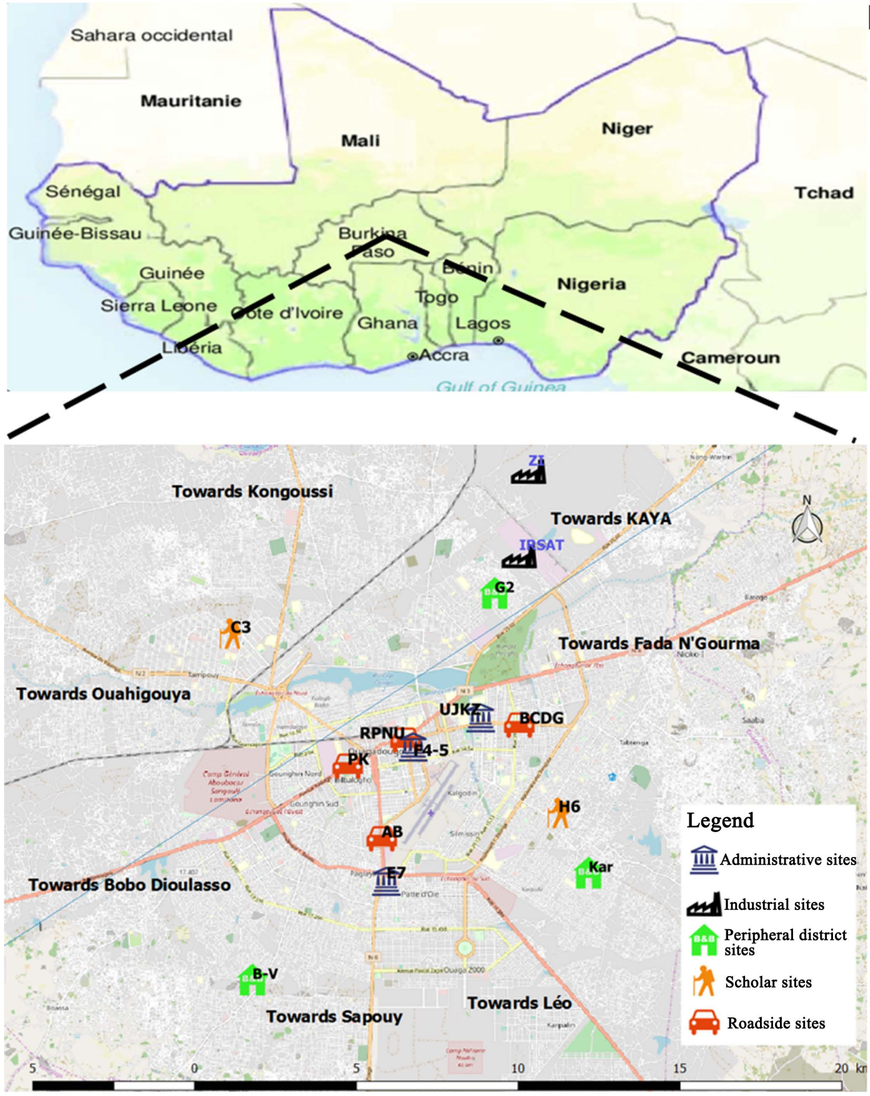

Figure 1. Particulate monitoring sites in Ouagadougou.

(IRSAT, ZI), 4) roadside sites with heavy traffic on paved roads (BCDG, PK, RPNU, AB), and 5) administrative sites (F4-5, E7, UJKZ). Three sites of 2018 campaign (F4-65, PK and RPNU) have not been not monitored in 2019 campaign. Data of G2's site were insufficient to represent 24 hours of measurement. Five sites (IRSAT, ZI, BV, Kar and UJKZ) were added in 2019 campaign. Sites were selected to cover as much of the city as possible. Table 1 presents the geographic coordinates of the sampling locations in Ouagadougou city.

2.2. Road Traffic Characteristic

In 2016, the Ouagadougou town hall has carried out a characterization of road traffic in the city of Ouagadougou by manual counting (Somda, 2018). About 1,003,997 of daily displacements of people that enter and leave downtown. The distribution of vehicles is as follows: 74% motorized two-wheeled vehicles, 18% private vehicles, 7% transit vehicles and 1% heavy trucks.

Table 1. Geographic coordinates of the sampling sites.

N°	Sampling site	Longitude	Latitude	Site type	Measurement period
1	E7*: ONATEL SUD	−1.524834347	12.33149065	Administrative	2018-03-21 2018-08-27 2019-07-10
2	F4-5*: Ministère de l'Environnement de l'Économie Verte et du Changement Climatique (MEEVCC)	−1.517218554	12.36967226	Administrative	2018-03-15 2018-08-24
3	UJKZ: (Université Joseph KI-ZERBO)	−1.498053	12.377978	Administrative	2019-09-17
4	AB*: SONABEL Bassawarga	−1.526194454	12.3431663	Roadside	2018-03-28 2018-08-22 2019-08-08
5	PK*: Pont Kadiogo	−1.53587835	12.3638069	Roadside	2018-03-30 2018-08-09
6	RPNU*: Rond-point des Nations Unies	−1.5194297	12.37120785	Roadside	2018-04-03 2018-07-31
7	BCDG*: Boulevard Charles De Gaulle	−1.4871354	12.37549121	Roadside	2018-04-10 2018-08-07 2019-09-12
8	C3*: Complexe scolaire Notre dame de l'espérance	−1.569103003	12.40132924	Scholar	2018-19-04 2018-08-23 2019-09-04
9	H6*: Complexe scolaire Bon BERGER	−1.47595143	12.35034032	Scholar	2018-17-04 2018-08-20 2019-08-26
10	BV: Bonheur-ville	−1.56288300	12.30300500	Peripheral district	2019-10-03
11	Kar: Karpala	−1.46738100	12.33341900	Peripheral district	2019-06-10
12	G2: Plateau omnisports de somgandé	−1.49405834	12.4129417	Peripheral district	2018-03-27 2018-08-14 2019-10-01
13	IRSAT: Institut de Recherche en sciences appliquées et technologies (Kossodo)	−1.48709400	12.42494500	Industrial	2019-07-05
14	ZI: Zone industrielle (Kossodo)	−1.484449	12.448949	Industrial	2019-06-30

*These names were used in previous similar studies.

2.3. Measurement Equipment

An analyzer AEROCET 531S has been used. It is a mass profiler and particle counter combined in a small portable battery-powered unit. This analyzer measures particulate matter with diameters between 0.3 and 10.0 µm and some others (total suspended particles). Its detection limit is 1.0 µg·m^{-3}.

2.4. Measurement Methods

Measurements of ambient air particulates concentrations were made at each sampling point during at least 12-hours and 48-hours during the measurement campaigns of 2018 and 2019, respectively. The AEROCET-531S was placed at a height of between 1.5 and 2 meters, which corresponds to the average position of the human airways. Each measurement consisted of one-minute concentrations of PM_{10}, $PM_{2.5}$ and PM_1 and was recorded on a data storage card. Hourly and daily average concentrations reported here are arithmetic means of the respective 1-min readings in µg·m^{-3}. The measurement relative uncertainties are deduced from the AEROCET measurement accuracy of ±5%. The calculations of the average concentrations and the measurement relative uncertainties were done by Microsoft Excel.

The Origin software, version 9 and the QSIS software, version 2.18.28, have been used for graphs and map, respectively.

It should be noted that in 2018 all measures lasted 12 hours. In 2019 at the sites (UJKZ, H6, ZI and B-V), measurements were taken during 48 hours continuously, 72 hours at the sites (BCDG, C3, Kar and G2), 96 hours at the sites (E7, AB and IRSAT). F4-5, RPNU and PK were not sampled in 2019.

3. Results and Discussion

Limit values for human exposure to particles recommended by the WHO, EEA or US EPA concern the 24-hour concentrations of $PM_{2.5}$ and PM_{10}. The results that will be presented and discussed will focus on these particles. Results concerning PM_1 were also presented with respect to the fact that they have more significant human health effects. However, there are not recommended limits values.

The results will be discussed and will take into account the grouping made in the material and methods section.

3.1. Hourly Concentrations Profiles

3.1.1. Hourly PM_1 Concentrations

Figure 2 presents the hourly concentration profiles obtained in 2019 campaign for PM_1 in Ouagadougou city. These profiles are characterized by two obvious peaks between 3:00 - 8:00 am and 5:00 - 9:00 pm, respectively. These peaks can be explained on the one hand by the hours of heavy road traffic linked to the activities of the population and on the other hand by industrial activities on in there. It is important to note that large vehicles circulate in the city of Ouagadougou from 10 pm to 5 am (time allowed for these types of track vehicles). There is also the dynamics of the boundary layer (BL), which results in high dilution rates during the day and low dilution rates at night (Lee et al., 2019). The peaks between 5:00 - 9:00 pm are more important than those between 5:00 - 8:00 am in

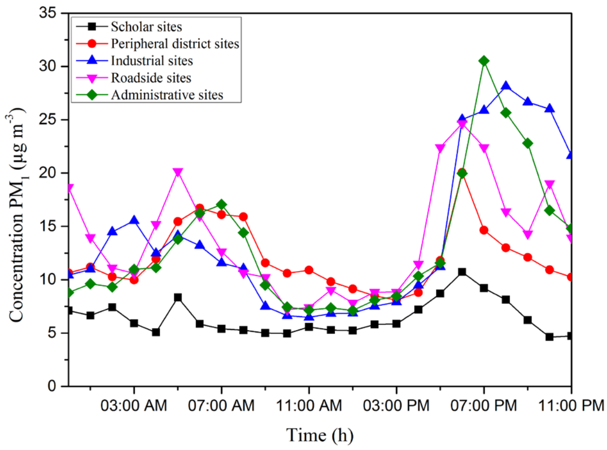

Figure 2. Profiles of 1-hour concentrations of PM_1 obtained in rainy season (June-September) in 2019 (hours in local time HLT).

some sites. This could be explained by the increase in emissions during the evening, which stretches in a period when the BL is shallow as compared to the morning situation in which the height of the BL increases rapidly after sunrise. The PM_1 concentration was 20 ± 4 and 17 ± 3 $\mu g \cdot m^{-3}$ for 2018 dry season and 2018 rainy season, respectively. These values were similar to those obtained by Talbi and coauthors (Talbi, Kerchich, and Kerbachi, 2017) for Alger city. The hourly PM_1 concentrations for educational institutions sites ranged from 5 to 11 $\mu g \cdot m^{-3}$, for peripheral district sites ranged from 8 to 20 $\mu g \cdot m^{-3}$, for industrial sites ranged from 6 to 28 $\mu g \cdot m^{-3}$, for roadside sites ranged from 7 to 25 $\mu g \cdot m^{-3}$ and for administrative sites ranged from 7 to 30 $\mu g \cdot m^{-3}$. These results highlight the importance of the activities of these sites except scholar ones on ultrafine particulates.

3.1.2. Hourly $PM_{2.5}$ Concentrations

Figure 3 presents the profiles of 1-hour concentrations of $PM_{2.5}$ obtained during the rainy season (June-September) in 2019 for the five sampling groups of sites. The profile of each group of sites exhibits two peaks: one during the morning (6:00 - 8:00 am) and the other during the afternoon (5:00 - 8:00 pm) except industrial sites and traffic sites which are marked by two morning peaks located respectively around 3:00 and 11:00 a.m. and 5:00 and 11:00 a.m. and afternoon's one. These observations are linked to the heavy traffic due to the start and end times of the administration's work and industrial activities. It should be noted that the populations of Ouagadougou have not yet adopted public transportation. The majority of them use single motorized two-wheeled vehicles. The 11:00 am peaks at the traffic sites can be explained on the one hand by the high level of traffic in connection with market and shop traffic, delivery activities and the activities of the various construction and demolition sites. On the other hand, the dynamics of the atmospheric boundary layer.

For scholar sites which holiday's period is in rainy season, the 1-hour concentrations don't vary practically from hour to hour. It should be noted that in the

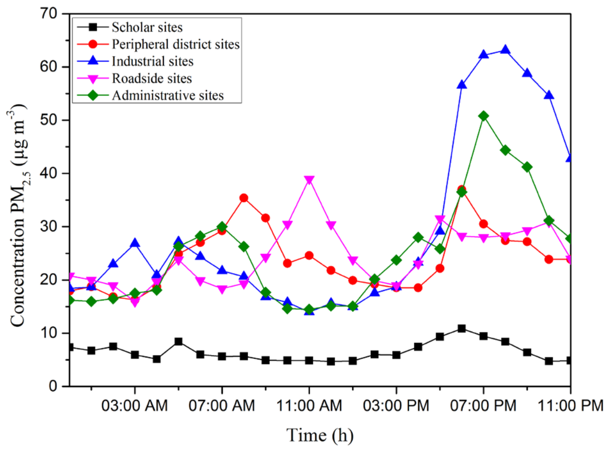

Figure 3. Profiles of 1-hour concentrations of $PM_{2.5}$ obtained in rainy season (June-September) in 2019 (hours in local time HLT).

configuration of school sites, there is always a sports ground that serves as a sports training area. These playgrounds are even used by local residents during the holidays for sports. Hence, the observed concentrations, the low concentrations at the educational institutions sites can also be explained by the higher relative humidity and monthly rainfall observed during the measurement periods (70% in August and 67% in September) and (5 mm/day in August and 2 mm/day in September) respectively compared to the other months of the year. High concentration values are observed for industrial sites at 8 pm with a peak around 9:00 - 10:00 pm. This may be explained by the heavy traffic of large trucks in the industrial zone at these hours. Also, it should be noted that the roads in these areas are virtually unpaved. It must be added that in the industrial areas, some activities are (cement works, breweries, sawmills) done in the night coinciding with the measurement schedules. This contributes to the increase of the level of pollution in fine particles. Concerning residential dusty sites, $PM_{2.5}$ concentration levels are high between 8:00 - 11:00 am and this is explained by the traffic and overcrowding in some areas of the city. For the case of administrative sites (E7 and UJKZ), it should be noted two peaks of the morning and evening rush hours corresponding to the morning work start time (7:00 am) and the evening work descent time around 5:00 pm. This gradual evolution can be explained by the increase in traffic related to the increased number of people visiting the administrative services. This finding is general with respect to African cities as pointed out by Petkova and coauthors (Petkova et al., 2013).

3.1.3. Hourly PM_{10} Concentrations

Figure 4 presents the profiles of 1-hour concentrations of PM_{10} obtained during the rainy season (June to September) 2019. Each of the sites exhibits scattered peaks in time. This is relatively linked to the different phenomena involved in the processes of emission and dispersion of the pollutants.

As previously, concentrations variation from hour to hour at scholar sites vary slightly. The profile of peripheral district sites exhibits an important peak of

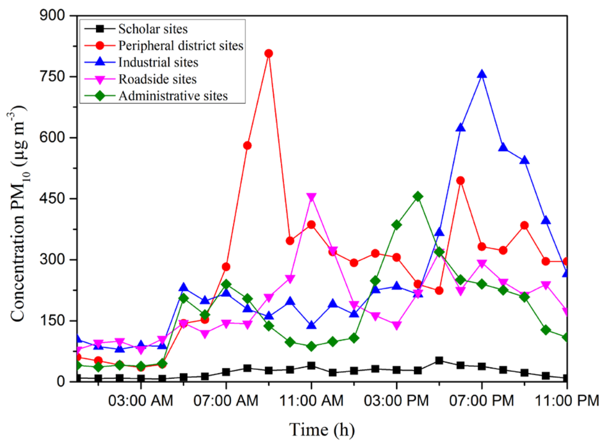

Figure 4. Profiles of 1-hour concentrations of PM_{10} obtained in rainy season (June-September) in 2019 (hours in local time HLT).

PM_{10} concentration between 8:00 - 11:00 am. Another peak, less important, is observed between 6:00 - 7:00 pm. These results are explained by the resuspension due to traffic on unpaved roads in these sites and high (respectively low) wind speed during the morning (respectively the evening). Residential dusty sites located near unpaved roads are characterized by important PM_{10} emissions. These areas are also characterized by extensive construction and demolition work, resulting in the re-suspension of dust. The profile of industrial sites shows peak around 9:00 - 10:00 pm corresponding to the heavy traffic of large trucks at these hours. The great gear causes a great re-suspension of dust. Roadside sites and administrative ones exhibited low PM_{10} concentration because they are associated to paved roads that not generate significant dust resuspension. However, a peak is observed around 11:00 am (respectively 4:00 pm) for roadside sites (respectively administrative sites) and related to worker's movements for lunch (respectively for worker's movement to home).

3.2. 24-Hour Concentrations

Table 2 presents the 24-hour (daily) PM concentrations obtained during the rainy season (June to September) 2019. The results show that excepted scholar sites and despite the rainy season campaign, $PM_{2.5}$ concentrations are close to recommended values whereas PM_{10} concentrations exceed three to five time the recommended limit by the WHO and European Environment Agency (EEA) and around two times the recommended limit by US EPA.

3.3. Seasonal and Spatial Pollution Variability

Tables 3-6 present results of descriptive statistics of hourly (or daily) of PM pollution levels for sampling sites. The percentage of hours in which recommended limits by US EPA, EEA, WHO and Burkina Faso (BFA) were exceeded is also presented.

The arithmetic means of hourly concentrations of PM are higher in dry season than rainy season (see lines 1 and 2 of **Table 3** and **Table 4**). Indeed, the data in

Table 2. 24-hour concentrations in 2019 rainy season.

PM	24-hour PM concentrations (μg·m^{-3})					
	Scholar sites	Peripheral district sites	Industrial sites	Roadside sites	Administrative sites	Recommended limits
PM_1	6 ± 1	12 ± 3	14 ± 6	14 ± 4	13 ± 5	-
$PM_{2.5}$	6 ± 1	24 ± 5	29 ± 14	25 ± 5	25 ± 9	25[a], 35[b]
PM_{10}	23 ± 11	281 ± 154	263 ± 156	195 ± 77	171 ± 95	50[a,c], 150[b]

[a]World Health Organization (WHO, 2006); [b]US Environmental Protection Agency (USEPA, 2011); [c]European Environment Agency (EEA, 2012).

Table 3. Descriptive statistics of 1-hour concentrations of $PM_{2.5}$ obtained from measurements in Ouagadougou, Burkina Faso, and percent of hours in which recommended limits of 35 μg·m^{-3} by USEPA, of 25 μg·m^{-3} by WHO and of 300 μg·m^{-3} by BFA were exceeded. sd = standard deviation; nd = not determined. For each site, the data of the first line corresponds to measurements results of 2018 dry season (March-May); the second line to measurements results of 2018 rainy season (June-September); and the third line to measurements results of 2019 rainy season (June-September).

Site (type)	Mean ± sd (μg·m^{-3})	Minimum (μg·m^{-3})	Maximum (μg·m^{-3})	Median (μg·m^{-3})	Number of measures	Measurement duration	Percentage of 1-hour concentrations higher than recommended limit		
							USPEA	WHO	BFA
E7: ONATEL SUD (Administrative)	46.3 ± 2.7 11.2 ± 0.8 29.3 ± 0.9	26.7 3.1 13.9	144.3 42.2 121.5	42.3 10.5 24.6	517 606 428	12 h 12 h 4 days	82.8 0.2 20.7	100 0.3 47.3	88.4 0.2 23.2
F4-5: MEEVCC (Administrative)	39.6 ± 5.6 19.8 ± 1.5 nd	15.0 6.7 nd	706.1 115.0 nd	30.2 16.5 nd	774 748 nd	12 h 12 h nd	68.0 8.4 nd	38.6 23.9 nd	74.3 21.3 nd
UJKZ: Université Joseph KI-ZERBO (Administrative)	nd nd 21.5 ± 0.8	nd nd 5.7	nd nd 86.1	nd nd 19.4	nd nd 3121	12 h 12 h 2 days	nd nd 13.5	nd nd 28.9	nd nd 21.3
AB: SONABEL Bassawarga (roadside)	61.3 ± 5.8 21.1 ± 2.0 14.9 ± 0.7	16.3 7 0.8	256.1 187 291.9	51.1 19.2 11.6	516 568 6.21	12 h 12 h 5 days	74.0 7.2 8.5	90.7 25.5 18.3	98.6 14.4 7.9
PK: Pont Kadiogo (roadside)	79.5 ± 4.5 25.6 ± 2.1 nd	53.5 8.3 nd	227.8 68.7 nd	73.5 24 nd	484 543 nd	12 h 12 h nd	100 21.2 nd	100 43.5 nd	99.8 17.5 nd
RPNU: United Nation roundabout (roadside)	182.9 ± 6.2 34.1 ± 1.4 nd	143.4 20.3 nd	296.6 63.4 nd	167.5 32.5 nd	499 476 nd	12 h 12 h nd	99.8 35.7 nd	100 93.3 Nd	100 21.2 nd
BCDG: Bd. Charles De Gaulle (roadside)	57.9 ± 2.7 14.6 ± 1.4 25.4 ± 1.1	33.9 5.0 6.5	122.7 42.4 604.0	55.1 11.8 22.3	491 437 4565	12 h 12 h 3 days	99.4 3.2 17.7	100 11.2 41.5	83.5 0.7 15.7
C3: Complexe scolaire Notre dame de l'espérance (scholar)	56.2 ± 4.4 15.8 ± 1.2 8.4 ± 0.3	30.7 5.7 0.9	333.9 68.2 39.1	43.2 13.3 7.2	766 964 3863	12 h 12 h 3 days	87.1 3.4 0.2	100 10.8 1.8	98.4 4.6 0.8
H6: Complexe scolaire Bon BERGER (scholar)	88.3 ± 10.8 15.2 ± 1.3 4.9 ± 0.2	31.6 5.4 0.3	395.7 52.4 13.2	55.1 11.8 22.3	491 437 4565	12 h 12 h 2 days	98.3 3.8 0.0	100 14.4 0.0	97.3 2.0 0.0
B-V: Bonheur-ville (peripheral district)	nd nd 22.6 ± 1.1	nd nd 7.1	nd nd 177.3	nd nd 19.3	nd nd 1899	12 h 12 h 2 days	nd nd 9.7	nd nd 27.8	nd nd 32.5

Continued

Kar: Karpala (peripheral district)	nd nd 23.6 ± 0.7	nd nd 11.1	nd nd 277	nd nd 21.5	nd nd 2712	12 h 12 h 5 days	nd nd 6.3	nd nd 33.0	nd nd 39.0
G2: Plateau Omnisportde Somgandé (Residential)	57.7 ± 6.2 18.8 ± 1.7 27.0 ± 1.4	20.3 27.2 10.5	228.9 59.9 113.8	46.4 15.7 19.4	481 535 2457	12 h 12 h 3 days	77.8 8.2 26.5	95.0 22.8 35.1	96.5 8.4 19.1
IRSAT-Kossodo (industrial)	nd nd 28.9 ± 1.0	nd nd 8.9	nd nd 355.4	nd nd 22.4	nd nd 5339	12 h 12 h 4 days	nd nd 20.1	nd nd 39.9	nd nd 23.8
ZI: Zone Industrielle-Kossodo (industrial)	nd nd 26.0 ± 0.9	nd nd 11.6	nd nd 236.4	nd nd 23.5	nd nd 2879	12 h 12 h 5 days	nd nd 18.0	nd nd 41.5	nd nd 14.7

Table 4. Descriptive statistics of 1-hour concentrations of PM_{10} obtained from measurements in Ouagadougou, Burkina Faso, and percent of hours in which recommended limits of 150 $\mu g \cdot m^{-3}$ by USEPA, of 50 $\mu g \cdot m^{-3}$ by EEA, of 50 $\mu g \cdot m^{-3}$ by WHO and of 300 $\mu g \cdot m^{-3}$ by FA were exceeded. sd = standard deviation; nd = not determined. For each site, the data of the first line corresponds to measurements results of 2018 dry season (March-May); the second line to measurements results of 2018 rainy season (June-September); and the third line to measurements results of 2019 rainy season (June-September).

Site (type)	Mean ± sd ($\mu g \cdot m^{-3}$)	Minimum ($\mu g \cdot m^{-3}$)	Maximum ($\mu g \cdot m^{-3}$)	Median ($\mu g \cdot m^{-3}$)	Number of measures	Measurement duration	Percentage of 1-hour concentrations higher than recommended limit		
							USPEA	WHO	BFA
E7: ONATEL SUD (Administrative)	545.1 ± 71.3 55.2 ± 5.1 223.7 ± 10.5	95.9 10 27.8	3676.9 244.2 2787.2	426.7 49.2 171.5	517 606 4276	12 h 12 h 4 days	95.9 1.0 57.2	100 49.5 96.8	88.4 0.2 23.2
F4-5: MEEVCC (Administrative)	435.6 ± 102.4 163.4 ± 18.9 nd	104.8 48.6 nd	13,484 2260.5 nd	293 140.85 nd	744 748 nd	12 h 12 h nd	91.8 44.1 nd	100 99.9 nd	74.3 21.3 nd
UJKZ: Université Joseph KI-ZERBO (Administrative)	nd nd 211.1 ± 16.8	nd nd 16.6	nd nd 2337.9	nd nd 129.2	nd nd 3121	12 h 12 h 2 days	nd nd 43.9	nd nd 86.4	nd nd 21.3
AB: SONABEL Bassawarga (roadside)	859.5 ± 97.2 127.6 ± 16.3 104.3 ± 8.7	155.2 23.1 1	4433.4 754.4 6097.2	753.9 99.55 39.6	516 568 6214	12 h 12 h 5 days	100 24.8 24.8	100 88.0 47.1	98.6 14.4 7.9
PK: Pont Kadiogo (roadside)	613.5 ± 102.1 143.7 ± 16.4 nd	259.9 28.1 nd	3433.6 565.6 nd	445.9 113.6 nd	484 543 nd	12 h 12 h nd	100 36.1 nd	100 89.0 Nd	99.8 17.5 nd
RPNU: United Nation roundabout (roadside)	1311.3 ± 69.1 231.7 ± 17.0 nd	711.6 74.2 nd	2553.8 710 nd	1148.8 207.55 nd	499 476 nd	12 h 12 h nd	100 84.5 nd	100 100 Nd	100 21.2 nd
BCDG: Bd.Charles De Gaulle (roadside)	487.3 ± 57.3 60.9 ± 7.6 188.2 ± 24.3	120.9 11.8 24.9	2242.8 420 17,811.4	377.8 50.3 115.9	491 437 4565	12 h 12 h 3 days	98.9 3.9 40.8	100 50.8 85.5	83.5 0.7 15.7
C3: Complexe scolaire Notre dame de l'espérance (scholar)	671.3 ± 83.2 103.7 ± 7.2 41.1 ± 1.5	196.6 29.9 1.2	6357.6 523.8 873.5	477.6 95.8 24.4	766 964 3,863	12 h 12 h 3 days	100 13.5 4.9	100 85.6 22.5	98.4 4.6 0.8
H6: Complexe scolaire Bon BERGER (scholar)	1278.8 ± 220 100.6 ± 5.8 12.8 ± 1.0	179.8 25.3 05	10,200.5 276.1 305.6	648.3 91.3 8.3	715 758 3160	12 h 12 h 2 days	100 10.0 0.1	100 96.2 1.4	97.3 2.0 0.0

Continued

B-V: Bonheur-ville (peripheral district)	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	270.6 ± 28.6	22.1	6420.5	202.6	1899	2 days	59.0	85.7	32.5
Kar: Karpala (peripheral district)	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	226.6 ± 45.4	27.9	29,300.3	191.95	2712	5 days	61.8	86.6	39.1
G2: Plateau Omnisport de Somgandé (Residential)	766.8 ± 118.8	176	4532.4	559	481	12 h	100	100	96.5
	88.2 ± 14.0	18.4	694.1	57.9	535	12 h	15.7	58.7	8.4
	177.6 ± 12.3	18.5	687.2	117.8	2457	3 days	39.0	86.6	19.1
IRSAT–Kossodo (industrial)	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	250.7 ± 16.4	21.9	11,031.9	157	5339	4 days	52.3	90.1	23.8
ZI: Zone Industrielle–Kossodo (indsutrial)	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	nd	nd	nd	nd	nd	12 h	nd	nd	nd
	191.8 ± 17.2	28.4	6122.2	139	2879	5 days	46.0	89.5	14.7

Table 5. Descriptive statistics of 24-hour concentrations of $PM_{2.5}$ obtained from measurements of 2019 rainy season (June to September) in Ouagadougou, Burkina Faso, and percent of hours in which recommended limits 35 μg·m^{-3} by USEPA, of 25 μg·m^{-3} by EEA, of 25 μg·m^{-3} by WHO and of 300 μg·m^{-3} by BFA were exceeded. sd = standard deviation.

Site (type)	Mean ± sd (μg·m^{-3})	Minimum (μg·m^{-3})	Maximum (μg·m^{-3})	Median (μg·m^{-3})	Number of measures	Percentage of 24-hour concentrations higher than recommended limit		
						USPEA	WHO	BFA
E7: ONATEL SUD (Administrative)	27.5 ± 8.0	17.7	54.0	24.7	24	20.8	50	0.0
UJKZ: Université Joseph KI-ZERBO (Administrative)	22.6 ± 10.6	7.9	47.6	22.5	24	12.5	45.8	0.0
AB: SONABEL Bassawarga (roadside)	27.2 ± 11.0	10.5	66.7	22.7	24	20.8	45.8	0.0
BCDG: Bd. Charles De Gaulle (roadside)	21.7 ± 9.4	9.5	41.1	17.3	24	20.8	37.5	0.0
C3: Complexe scolaire Notre dam de l'espérance (scholar)	7.8 ± 2.1	2.3	12.0	7.5	24	0.0	0.0	0.0
H6: Complexe scolaire Bon BERGER (scholar)	5.2 ± 1.4	2.8	9.7	5.0	24	0.0	0.0	0.0
B-V: Bonheur-ville (peripheral district)	23.1 ± 7.2	13.5	48.8	20.3	24	12.5	29.2	0.0
Kar: Karpala (peripheral district)	24.8 ± 5.7	17.0	42.9	22.9	24	4.2	37.5	0.0
IRSAT-Kossodo (industrial)	35.0 ± 24.2	12.5	100.0	21.7	24	25	41.7	0.0
ZI: Zone industrielle-Kossodo (industrial)	23.8 ± 9.4	13.5	60.3	20.7	24	8.3	33.3	0.0
All	**21.9 ± 8.9**	**2.8**	**100.0**	**18.5**	**24**	**12.5**	**32.1**	**0.0**

Table 6. Descriptive statistics of 24-hour concentrations of PM_{10} obtained from measurements of 2019 rainy season (June to September) in Ouagadougou, Burkina Faso, and percent of hours in which recommended limits of 150 μg·m^{-3} by USEPA, of 50 μg·m^{-3} by EEA, of 50 μg·m^{-3} by WHO and of 300 μg·m^{-3} by BFA were exceeded. sd = standard deviation.

Site (type)	**Mean ± sd (μg·m^{-3})**	**Minimum (μg·m^{-3})**	**Maximum (μg·m^{-3})**	**Median (μg·m^{-3})**	**Number of measures**	**Percentage of 24-hour concentrations higher than recommended limit**		
						USPEA	**WHO**	**BFA**
E7: ONATEL SUD (Administrative)	50.0 ± 7.8	31.5	102.6	45.2	24	0.0	37.5	0.0

Continued

UJKZ: Université Joseph KI-ZERBO (Administrative)	293.0 ± 92.7	35.7	866.2	255.5	24	75	83.3	45.8
AB: SONABEL Bassawarga (roadside)	199.5 ± 64.5	23.0	741.2	156.0	24	58.3	95.8	16.7
BCDG: Bd. Charles De Gaulle (roadside)	190.3 ± 65.3	38.2	529.7	113.1	24	41.7	87.5	25
C3: Complexe scolaire Notre dame de l'espérance (scholar)	31.1 ± 7.5	9.4	83.3	31.7	24	0.0	8.3	0.0
H6: Complexe scolaire Bon BERGER (scholar)	15.9 ± 4.4	4.0	44.8	16.3	24	0.0	0.0	0.0
B-V: Bonheur-ville (peripheral district)	309.4 ± 95.5	21.2	873.1	330.8	24	70.8	83.3	54.2
Kar: Karpala (peripheral district)	253.5 ± 98.6	43.3	1224.7	241.0	24	70.8	91.7	16.7
IRSAT-Kossodo (industrial)	318.1 ± 120.8	34.6	1009.7	232.1	24	70.8	87.5	29.2
ZI: Zone industrielle-Kossodo (industrial)	208.6 ± 81.9	34.6	779.6	141.2	24	45.8	91.7	12.5
All	**186.9 ± 63.9**	**4.0**	**1224.7**	**148.6**	**240**	**25**	**68.8**	**38.8**

the second column show that the concentrations in the 2018 dry season are higher than the concentrations of the two measurements in 2018 and 2019 rainy seasons for all sampled sites. This result shows a seasonal variability of PM pollution level. Concentration values significantly vary from a site category (scholar, roadside, administrative, peripheral district or industrial) to another (see **Figures 2-4**) and **Table 3** and **Table 4**. As previously, this result shows a spatial variability of PM pollution level.

Concerning the daily concentration, where only measurements realized during the rainy season in 2019 (**Table 5** and **Table 6**), the arithmetic means of $PM_{2.5}$ (respectively PM_{10}) concentrations varied from 5.2 to 35.0 $\mu g \cdot m^{-3}$ (respectively 15.9 to 318.1 $\mu g \cdot m^{-3}$) overall sites. For all sites, the average percentage of 24-hour concentrations higher than the WHO recommended limit of $PM_{2.5}$ (respectively PM_{10}) is about 32% (respectively 69%). This means that the PM_{10} pollution in Ouagadougou is more acute than the $PM_{2.5}$ pollution. Concerning the PM_{10}, 69% means that each people of Ouagadougou is each day exposure to 16 hours of pollution level higher than the WHO recommended limit.

Based on **Table 2**, except scholar sites, the other ones (roadside, administrative, peripheral district or industrial) are significantly influenced by combustion and resuspension processes resulting in relatively higher concentrations of $PM_{2.5}$ and PM_{10}. The traffic proximity sites are influenced by traffic exhaust emission which is a significant source of fine and ultra-fine particles. In the whole city during the dry season other sources come into play such as the dust carried by Harmattan from Sahara and the Bodélé's depression in Chad, the suspension by the wind of local dust, during all seasons the use of biomass as domestic energy and the incineration of waste in open spaces. During the rainy season, the scenario does not change for fines and ultra-fines but the traffic proximity sites will be more polluted with PM_{10} than those of urban administrative ones. From the dry season to the rainy season the ultra-fine particles undergo a very low variability. This may suggest that they come mainly from traffic. Indeed, the activity of this source may not change significantly from a season to another. For $PM_{2.5}$ and PM_{10}, their concentrations are subject to different degrees of variability. This would suggest attenuation, extinguishment, or reduction of the contribution of some sources of these sizes of particles, and that these two categories of particulate matter would be added by all other sources in addition to those cited above. It has been observed the effect of the season on particulate matter concentrations over the city of Ouagadougou. Particulate matter concentrations are attenuated by rainfall by leaching air from a large part of these particles especially coarse.

During the dry season, the influence of dust carried by Harmattan winds from the Sahara Desert in the North and North-East affects the entire Sahelian region and creates important seasonal differences in suspended particulate concentrations.

The results also indicate that the PM concentrations vary depending on the type of site and from the rainy to the dry season. It appears that PM pollution levels are higher in the dry season than in the rainy season. These results show the seasonal and spatial variability of PM pollution levels. There are several reasons for these results. On the one hand, the road network on the outskirts of the city (unpaved roads), the mode of transport of the inhabitants on the outskirts (individual transport) and the lack of rain that enhances the activity of other sources including the re-suspension of local dust by the wind. It is important to note that these pollution levels change with particle size. The amplitudes of concentrations are not the same but the fine particles whatever are their amplitudes have the greatest impact on human health.

The highest concentrations were observed in the dry season. Apart from the site of the E7 which is at the limit of the daily standard all other sampling sites exceed the WHO standard for $PM_{2.5}$ by at least a coefficient of two. This may be explained by the fact that over this site there are many trees, which particles are deposited by impact. The high values observed at the RPNU can also be attributed to traffic congestion and heavy traffic at this site which is a road intersection where a long wait for vehicles was observed at the time of sampling and the difference in meteorology. Several studies in the literature found a significant relationship between emissions from high-traffic vehicles and air pollution concentrations (Akpan and William, 2014) (Gobo et al., 2012). According to Marticorena and coauthors (Marticorena et al., 2010), the minimum concentration of PM_{10} coincides with the maximum of rain falls which reduces dust emission by increasing soil moisture and the effect of scavenging.

The industrial activity of the region and even the country is mainly concentrated in the city of Ouagadougou. This explains the dynamics of the population of Burkina Faso towards the city of Ouagadougou. Also, the activity centers are concentrated in the city center and in a few peripheral districts, hence the massive daily movement of residents towards the activity areas. In addition, the

Ouagadougou road network extends over a distance of 2700 kilometers with 200 km of paved roads, 400 km in laterite and 2100 km on the track (mixture of laterite, sand and clay), on which the traffic contributes by the suspension to the particles. All these parameters associated with an aging vehicle fleet explain the high concentrations PM recorded. The high values observed in rainy season can be attributed to winds that precede the rain by suspending important quantity of mineral dust.

Table 7 reports the PM concentrations of Sub-Saharan cities, from Bamako, Mali (Garrison et al., 2014), Accra, Ghana (Dotse et al., 2012), Dakar, Senegal (Demay, 2011) and Ouagadougou, Burkina Faso (Lindén et al., 2012) (Boman et al., 2009). PM concentrations vary between cities, even for those with similar climate and precipitation levels. It is well-known that PM emissions are strongly and negatively correlated with the Harmattan winds from the Sahara Desert and unpaved roads. As an illustration, Garrison and coauthors (Garrison et al., 2014) obtained for one day measurement, a 24-hour concentrations of 43 and 210 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ and PM_{10}, respectively, in Bamako where the Harmattan winds are similar to those of Ouagadougou. Dotse and coauthors (Dotse et al., 2012) measured a 24-hour concentrations of 23.3 and 96.6 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ and PM_{10}, respectively, in Accra where the Harmattan winds are lower than those of Ouagadougou. $PM_{2.5}$ pollution levels obtained in 2018 for the city of Ouagadougou (57.9 ± 10.5 $\mu g \cdot m^{-3}$) are close to those for Bamako (43 ± 21 $\mu g \cdot m^{-3}$). This seems

Table 7. Comparison of PM concentrations from sub-Saharan cities. Data in brackets correspond to the range of variation.

City, Country	Site type	Measurements Period	24-hour concentrations ($\mu g \cdot m^{-3}$)		Ref.
			$PM_{2.5}$	PM_{10}	
Bamako, Mali	Urban	12/09/2012-09/07/2013	43 ± 21 [8 - 123]	210 ± 93 [35 - 505]	Garrison et al., 2014
Accra, Ghana	Urban	14/02/-23/05/2008	23.3 [3.9 - 46.4]	96.6 [37.1 - 193.1]	Dotse et al., 2012
Dakar, Senegal	Urban	Jan-Dec 2010	-	[59.3 - 388.0]	Demay, 2011
Ouagadougou, Burkina Faso	Urban Suburban Rural	2007	-	[16.8 - 1010.1] [10.0 - 2006.8] [15.2 - 1177.7]	Lindén et al., 2012
	Urban Suburban	29 Nov. and 11 Dec. 2007	[27 - 164]	-	Boman et al., 2009
	Urban	March-May 2018	87 ± 16*	951 ± 266*	Present study
	Urban	July-August 2018	29 ± 5*	158 ± 43*	
	Urban	June-September 2019	22 ± 9	187 ± 64	

*These values correspond to 12-hour concentration.

logical in view of similar climates. However, it should be noted that the PM_{10} are more important in Ouagadougou and this is certainly linked to the traffic which is more important. These pollution levels are higher than recommended limits. These values are in the same order than those generally obtained on air pollution in West African cities. The reasons are also more or less identical, namely the high density of the population, the evolution of the vehicle fleet and the major part of the road network which is not subject to a limit.

4. Conclusion

PM monitoring campaigns were carried out in 2018 and 2019 in Ouagadougou, in order to investigate pollution levels and seasonal and spatial variability of these pollutants. It was found that no sites in Ouagadougou are exempt from PM pollution and this situation threatens comfort, human existence and the ecosystem, especially during the dry season. PM_1 concentration values showed no significant variation between days, seasons and type of sampling sites, in opposite to $PM_{2.5}$ or PM_{10} concentration values. These results are consistent with those of similar works in other African cities reported.

The concentration mean value of $PM_{2.5}$ (respectively PM_{10}) obtained during the 2019 rainy season is 22 ± 9 $\mu g \cdot m^{-3}$ (respectively 187 ± 64 $\mu g \cdot m^{-3}$). Concerning the $PM_{2.5}$, the obtained value is relatively lower than the tolerable threshold value of 25 $\mu g \cdot m^{-3}$ of the WHO recommendations, whereas this for PM_{10} is higher than the tolerable threshold value of 50 $\mu g \cdot m^{-3}$ of the WHO recommendations. These high PM_{10} concentrations can be attributed to local dust (suspension linked to traffic and wind suspension of local dust), as shown in previous works. Modeling is a current perspective of traffic emission calculations and imputed traffic suspension on paved and unpaved roads. The dispersion of gaseous and particulate pollutants in the city of Ouagadougou are carried out using an urban model of dispersion of pollutants (MUNICH). This modeling will help to partially answer the following questions: what is the contribution of road traffic to $PM_{2.5}$ exhaust emissions in the city? What is the contribution of road traffic to suspension of $PM_{2.5}$ in the city? What is the contribution of road traffic to the resuspension of PM_{10} in the city? What are the predominant sources in modeling?

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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