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Article

Monitoring of $PM_{2.5}$ Using Well-Calibrated Low-Cost Sensors over One Year in Burkina Faso

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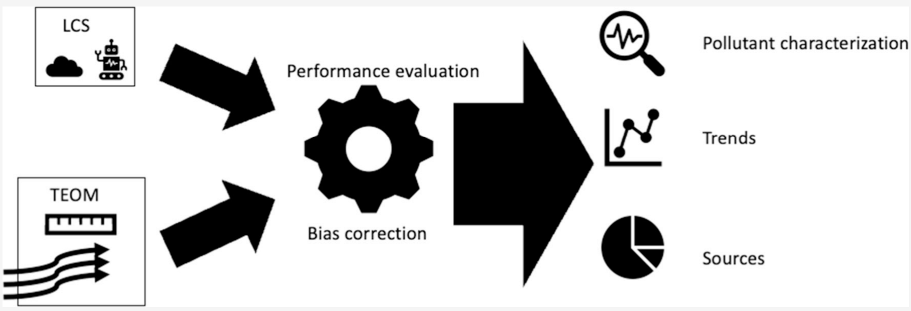

ABSTRACT: Air pollution causes more than 8.34 million premature deaths worldwide. Most of these deaths occur in the Global South, particularly in Africa. However, the means of observing this air pollution in these countries are lacking. Knowledge of pollutant concentration levels and their distribution in time and space is inadequate or nonexistent in most African countries. This study focuses on the temporal and spatial distribution of $PM_{2.5}$ in Burkina Faso, a country of more than 22 million residents yet with very scarce air pollution literature. The study used Clarity low-cost sensors. The sensors were placed at 19 sites throughout the country, including 13 in Ouagadougou, the capital, and three in Bobo-Dioulasso and three in Koudougou, the second and third largest cities in Burkina Faso, respectively. The measurements were taken over a one year period (November 2021 to November 2022). The data was corrected using a Gaussian Mixture Regression trained on a 2-month colocation of a TEOM with a Clarity monitor in Ouagadougou. The corrected mean daily concentrations measured at all of the sites ranged from 17 to 68 $\mu g/m^3$, with an overall daily average of 46.7 $\mu g/m^3$. The city averages are 48.5 $\mu g/m^3$ for Ouagadougou, 46.9 $\mu g/m^3$ for Bobo-Dioulasso, and 38.7 $\mu g/m^3$ for Koudougou. These concentrations are significantly higher than the World Health Organization's recommended safe daily guideline, 15 $\mu g/m^3$. Measurement values are highest during the dry season, which is dominated by the Harmattan winds from the Sahara desert. At all sites, between 61% and 87% of the measured days exceeded the WHO daily guidelines for $PM_{2.5}$. These measurements show the need to undertake an action plan to reduce air pollution in general in Burkina Faso in order to better protect the population health.

KEYWORDS: *air pollution, particulate matter, air sensor, $PM_{2.5}$, Burkina Faso*

1. INTRODUCTION

Air pollution causes nearly 8.34 million premature deaths per year worldwide.[1] In fact, air pollution is one of the leading causes of death, ahead of alcohol and malnutrition.[2] The majority of these deaths are attributable specifically to ambient fine particulate matter air pollution or $PM_{2.5}$ (particles with aerodynamic diameters less than 2.5 μm).[3] In Africa, estimates of the annual mortality due to air pollution are about 1.1 million per year,[2] though that estimate is hampered by a lack of on-the-ground air quality observations. Like many African countries, Burkina Faso's cities are expected to have high levels of $PM_{2.5}$, due to (i) urbanization and industrial operations in association with rapid population growth, (ii) transportation using dirty engines such as on motorcycles (80% of individual trips) or imported used vehicles on unpaved roads, and (iii) dust from the Sahara Desert. To date, in Ouagadougou (population 2.5 million), the capital of Burkina Faso (population 22 million), there has been little to no known continuous monitoring of $PM_{2.5}$. There have also been very few published peer-reviewed studies, far less than North American or European cities with similar population sizes such

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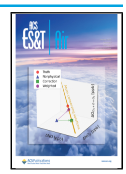

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Table 1. Characteristics of Clarity Low-Cost Sensors (LCS)

Parameter	Technology	Range
$PM_{2.5}$	Laser light scattering	0 to 1000 $\mu g/m^3$ 1 $\mu g/m^3$ of resolution
Temperature	Band-gap	−20 to 70 °C
Relative Humidity (RH)	Capacitive	0% to 100%

Table 2. Criteria for Selecting Measuring Stations

Name of station	Description of the station
Traffic stations	Measures population exposure in the vicinity of major roads and intersections
Industrial stations	Measures the exposure of populations around industrial zones.
School and administrative stations	Measures exposure of people working in offices and students in classrooms and outside buildings
Residential stations	Measures the exposure of populations located in densely populated areas far from Ouagadougou city center. These are peri-urban stations.
Urban peripheral stations	Stations located on the outskirts of Ouagadougou. They measure the population's exposure to background pollution, far from major pollution sources.

Table 3. Sampling Locations, Durations, and Data Retrieval[a]

No.	Site name	Site code	Longitude	Latitude	Site type	Number of days
1	SONABEL Bassawarga (cite An II)	O-ABO	−1.526004	12.343267	Traffic	305
2	Mairie Centrale Ouagadougou	O-MCO	−1.527301	2.368048	Traffic and administrative	325
3	Ministere de l'Environnement	O-MEV	−1.516225	12.369816	Administrative	295
4	Universite Joseph Ki-ZERBO	O-UJKZ	−1.498053	12.377978	Administrative	358
5	Complexe scolaire Notre dame de l'Esperance	O-CSNDE	−1.569392	12.401732	School	314
6	Karpala (château d'eau)	O-KAR	−1.480344	12.339747	Residential	289
7	Institut de Recherche en Sciences Appliquees et Technologies	O-IRSAT	−1.487094	12.424945	Industrial	360
8	Universite Thomas Sankara	O-UTS	−1.342478	12.473833	Peripheral urban	82
9	Bonheur-ville	O-BVO	−1.562883	12.303005	Residential	355
10	INERA Kamboinsin	O-INERA	−1.551195	12.460542	Peripheral urban	252
11	Echangeur de l'Ouest	O-ECO	−1.558931	12.349318	Traffic	180
12	Universite Virtuelle du Burkina Faso	O-UVBF	−1.503361	12.308167	Peripheral urban	251
13	Universite Saint Thomas D'Aquin	O-USTA	−1.418294	12.384318	Peripheral urban	180
14	Hôpital de l'amitie	K-HAK	−2.359525	12.261095	Administrative	255
15	Mairie Centrale de Koudougou	K-MCK	−2.365665	12.250602	Traffic and Administrative	255
16	Universite Norbert ZONGO	K-UNZ	−2.396487	12.241014	Administrative	255
17	IRSAT Bobo	B-IRSAT_B	−4.272473	11.176823	Traffic and Administrative	254
18	Mairie Centrale de Bobo	B-MCB	−4.296195	11.175681	Administrative	254
19	Universite NAZI Boni	B-UNB	−4.314889	11.164605	Industrial and Administrative	254

[a]Site codes are preceded by city codes (O-Ouagadougou, K-Koudougou, and B-Bobo-Dioulasso).

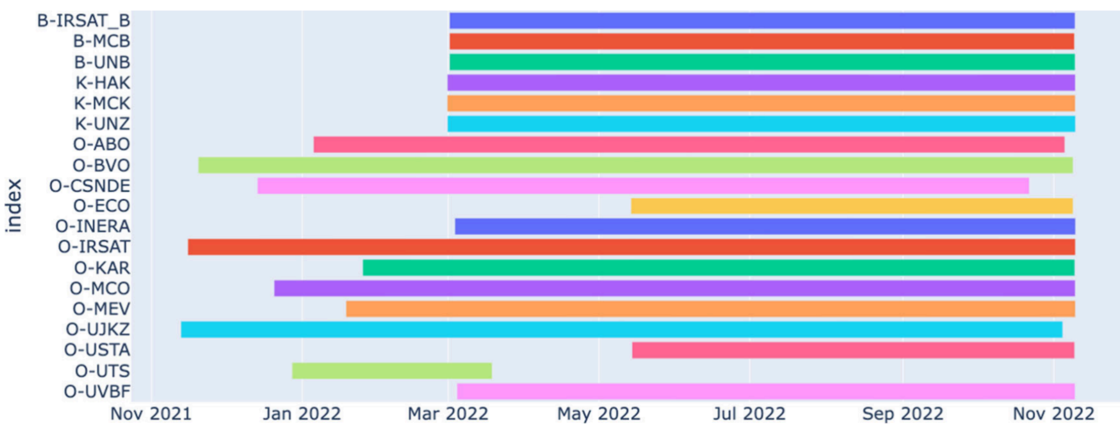

Figure 1. Timeline of data measurement by each node in Ouagadougou, Koudougou, and Bobo- Dioulasso.

as Chicago (population 2.6 million) or Paris (population 2.1 million).[4] This data scarcity is partially due to the high cost of traditional air pollution monitoring using reference equipment (between USD$10,000 and USD$100,000). The alternative is low-cost sensors (LCS), which cost between USD$250 and USD$6,000.

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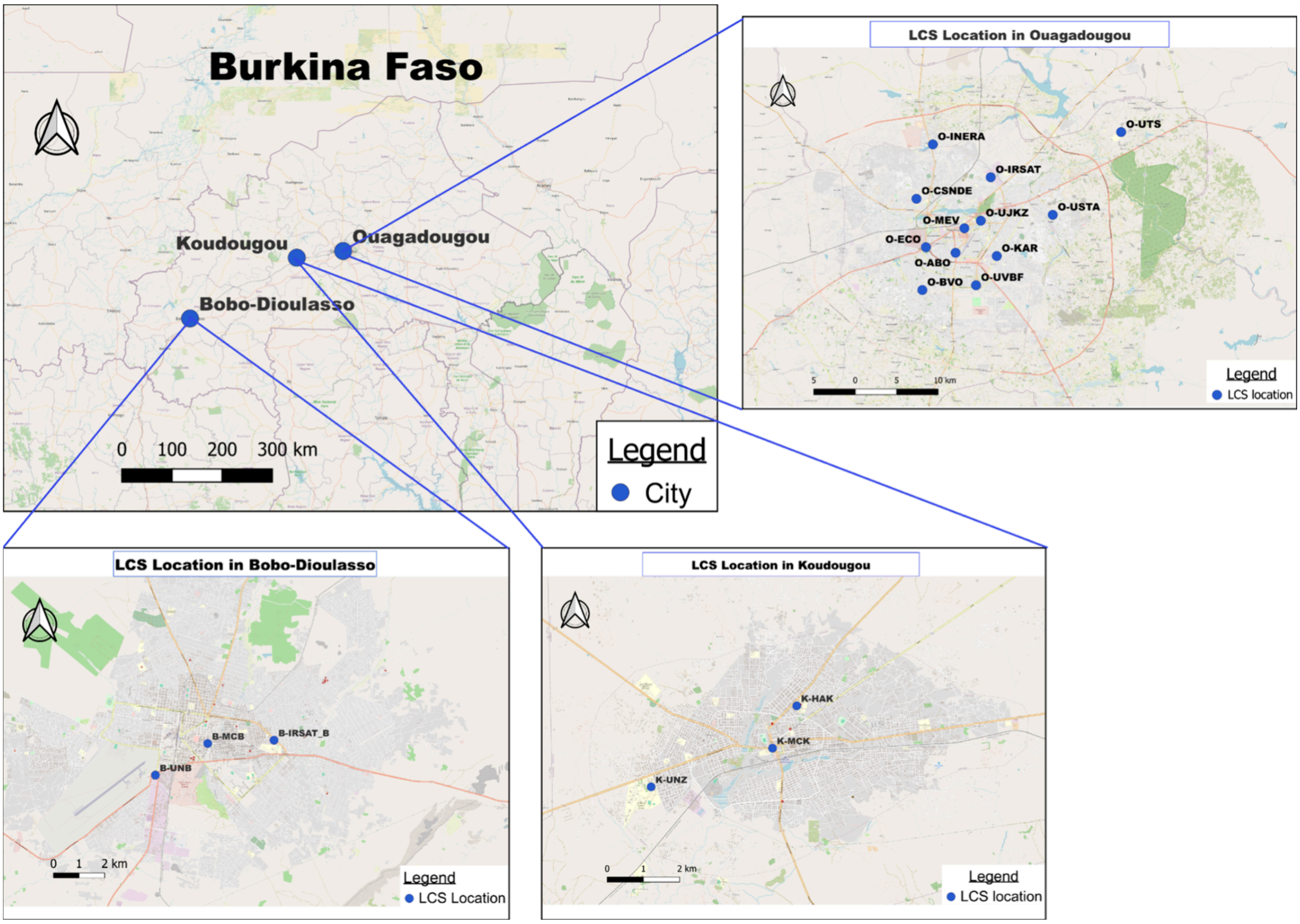

Figure 2. Location of measurement sites in Ouagadougou, Koudougou, and Bobo-Dioulasso. Map is reproduced with permission from OpenStreetMap.

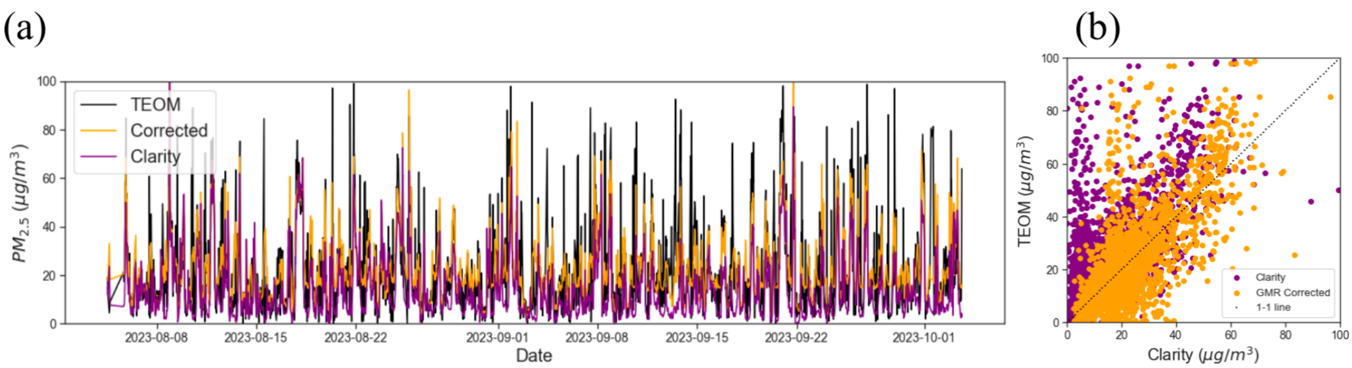

Figure 3. Colocation of Clarity monitor (LCS) and TEOM 1400a (Reference-grade) at Joseph Ki-ZERBO University in Ouagadougou, Burkina Faso.

A challenge regarding the use of LCS remains data quality. Several studies in recent years have developed a playbook for extracting useful, actionable data from LCS, while accounting for their limitations.[5−14] In particular, a side-by-side colocation in which a sensor is placed next to a certified reference monitor (such as the US EPA Federal Equivalent Method designation) for a length of time is strongly recommended to improve the accuracy and precision of LCS. These colocation campaigns have occurred frequently in Global North cities but have been less common in the Global South. Localized colocation efforts are critical because emissions sources, aerosol size, aerosol composition, and environmental conditions, all of which impact the reliability of low cost optical air sensors, are not always similar between locations.

Within West Africa, low cost air sensors have gained traction in many major cities. Raheja et al. presented some of the first air quality monitoring in Togo, using a network of well-calibrated air sensors.[15] Similar work has taken place in Accra, Ghana,[16] and Lagos, Nigeria.[17] Hybrid reference and air sensor monitoring networks also exist in Kinshasa, DRC.[11,18] Around the African continent, sensor studies are also taking place in cities like Kampala, Uganda,[19] and Nairobi, Kenya.[20]

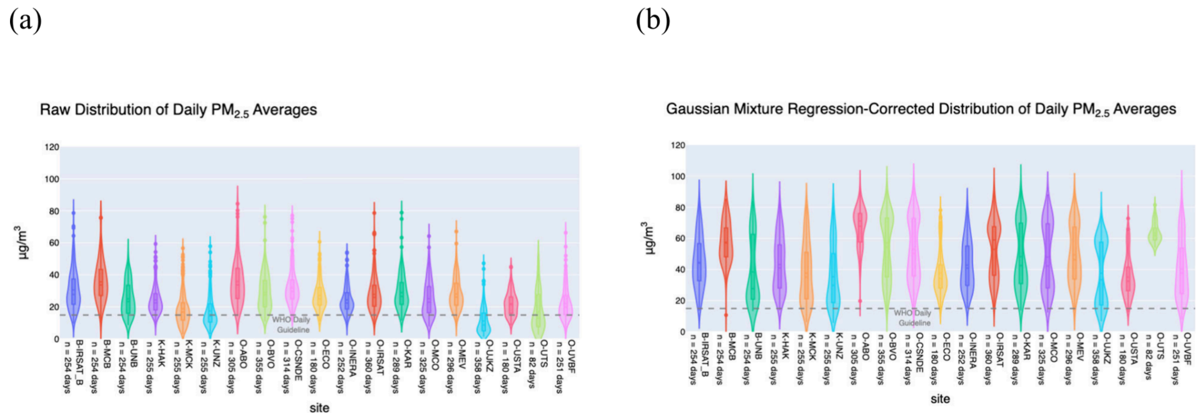

Figure 4. (a) Distributions of daily averaged $PM_{2.5}$ as output from LCS at each site and (b) distributions of daily averaged $PM_{2.5}$ corrected using Gaussian mixture regression. Box and whisker plots are shown within the violin.

Specifically within Ouagadougou, air quality studies have been limited. Lindén et al. conducted a study of urban air quality in 2007 and 2010 during two month periods.[21] Some other short-term studies included PM_{10} and other pollutant monitoring in recent years.[22,23]

Here we analyze a 19-node hybrid network consisting of low-cost sensors and reference monitors mostly in Ouagadougou, Burkina Faso, a rapidly growing city with a current estimated population of around 2.5 million, with limited current air quality monitoring capacity. Our work represents the first, to our knowledge, long-term $PM_{2.5}$ monitoring efforts in Ouagadougou, Bobo-Dioulasso, and Koudougou.

2. MATERIAL AND METHODS

2.1. Instrumentation. The devices used to measure $PM_{2.5}$ particles in Burkina Faso are low-cost sensors (LCS) developed by Clarity (https://www.clarity.io). These devices incorporate a laser particle counter which uses a light scattering method to size and count the particles and then convert them into a mass fraction. The data is recorded every 15 min and stored in the cloud. These sensors measure $PM_{2.5}$ ($\mu g/m^3$), temperature and relative humidity.[24,25] We use the Clarity-reported $PM_{2.5}$ and develop a calibration correction using Gaussian Mixture Regression.[26] The characteristics of a sensor are given in Table 1 below. We also deployed a Tapered Element Oscillating Microbalance (TEOM) 1400a reference monitor outfit with a $PM_{2.5}$ cyclone in Ouagadougou. The TEOM is a gravimetric estimate of $PM_{2.5}$ using an oscillating glass tube that changes the frequency of oscillation as particles are deposited onto a filter at the end of the tube. The frequency change can be converted into a particle mass change, which results in a high quality measurement.[27] The TEOM is located at the Universite Joseph Ki-Zerbo site (O-UJKZ, see Section 2.3 and Table 3) where a Clarity node was also placed in order to establish a colocation to develop a correction factor. The colocation time period was approximately 2 months, from August to October of 2023.

2.2. Climate, Description of Measurement Sites, and Periods. *2.2.1. Climate of Burkina Faso.* Burkina Faso is located in West Africa in the Sahel zone, at latitude 13° North and longitude 2° West. The terrain consists mainly of a plateau with an average altitude of 250 to 350 m. The climate is Sudano-Sahelian, a tropical semiarid hot climate with a long dry period from October to April and 3000 h of sunshine. The Harmattan occurs from the end of November through the middle of March, accompanied by strong dust-laden winds that bring elevated dust concentrations.[16] The lowest temperatures are recorded in December (around 16° or 17 °C) and the highest in April (between 40° and 42 °C) with an average temperature of around 30 °C. In May and June, the first showers from the south are often accompanied by whirlwinds and tornadoes. Between July and September, with the onset of the monsoon, the temperature drops throughout the country.[28] Lindén et al. reported that nighttime inversion layers are frequent in the early dry season, in which atmospheric stability and calm horizontal winds limit the ventilation in the airshed around Ouagadougou, resulting in higher concentrations.[29]

2.2.2. Description of the Sites and Measurement Period. The measurement campaign took place in three cities in Burkina Faso: Ouagadougou, the capital (in the center), Bobo-Dioulasso (in the southwest), and Koudougou (in the center-west). Thirteen sensors were placed in Ouagadougou, three in Bobo-Dioulasso, and three in Koudougou. The measurement campaign ran from November 2021 to November 2022. The TEOM was acquired in 2023, and thus, the colocation period took place after the initial deployment of the sensor network. The choice of measurement sites was based on the criteria described in Table 2 below. We aimed to have as diverse a set of locations by type as possible given practical limitations such as site security and access. Table 3, Figure 1, and Figure 2 show the different measurement sites in the three cities.

2.3. Calibration and Correction. A Python script was used to clean data as per generally established protocol,[16] namely, to filter out $PM_{2.5}$ concentrations below 0 $\mu g/m^3$ and above 100 $\mu g/m^3$, temperature values below 0 °C and above 150 °C, and relative humidity values below 0% and above 100%. Clarity data at 15 min resolution was averaged up to hourly, with a requirement that 50% of the hourly data exist in order to represent a valid daily data point.

Data measured by low-cost sensors are often corrected by placing a reference grade monitor next to them. In our case, a reference instrument, a TEOM 1400a, was used. A Clarity monitor was placed side-by-side with a TEOM 1400a at the measurement site of the Joseph Ki-Zerbo University (UJKZ). Co-located measurements were carried out from August 7, 2023, to October 3, 2023, which is the tail end of the wet season. Development of correction factors during primarily the wet season may imply that our corrected $PM_{2.5}$ estimates are conservative in nature and may be slightly higher than what we present. Figure 3a shows the results of the evaluation of the

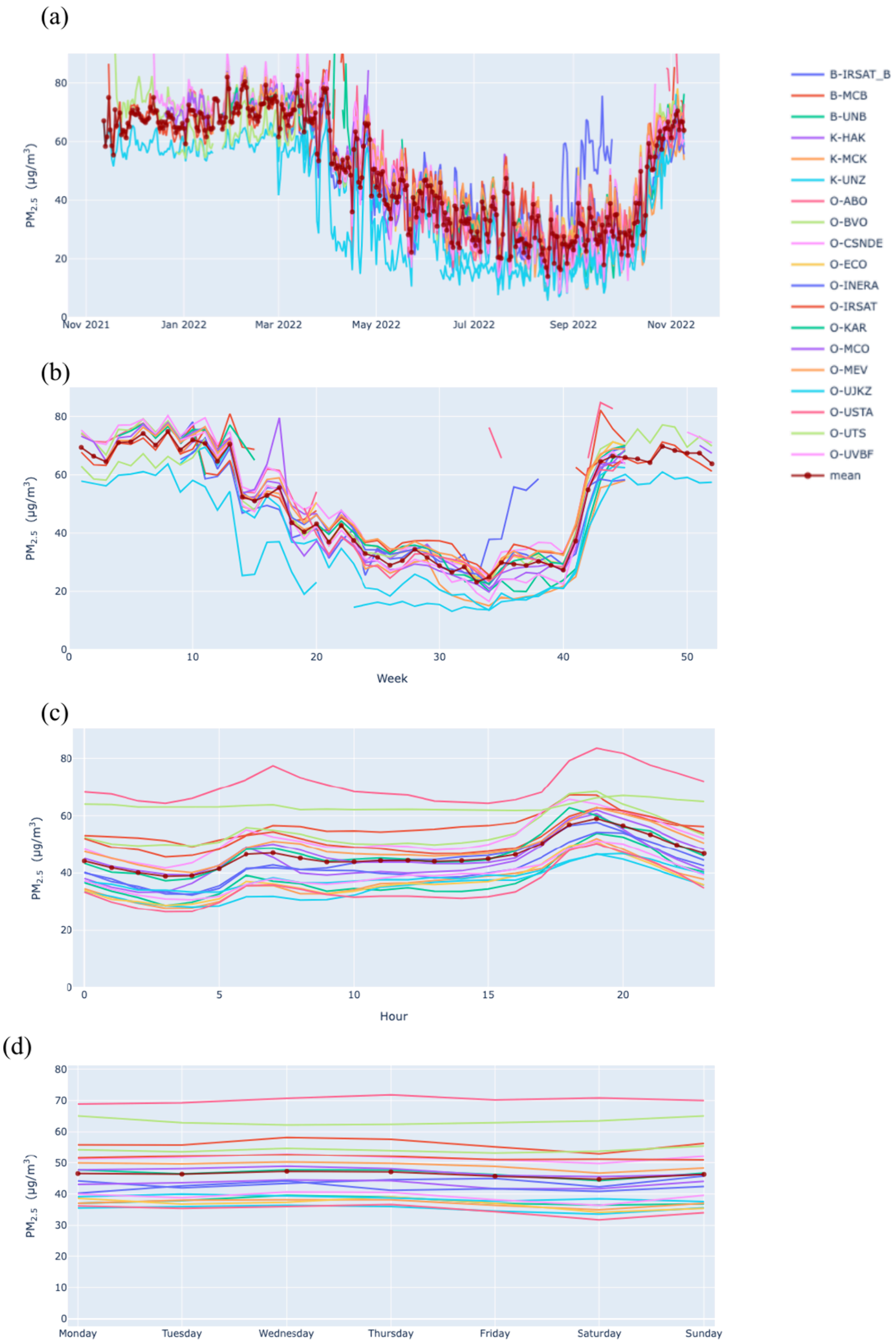

Figure 5. GMR-corrected temporal distributions of $PM_{2.5}$ concentrations at 19 sites in Burkina Faso. (a) Daily averaged GMR-corrected $PM_{2.5}$, (b) weekly averaged GMR-corrected $PM_{2.5}$ (Week 0 = January 1). (c) Diurnal concentration over entire data set in GMR-corrected $PM_{2.5}$ (hour 0 = midnight). (d) Weekday−weekend concentration over the entire data set in GMR-corrected $PM_{2.5}$ by day of week.

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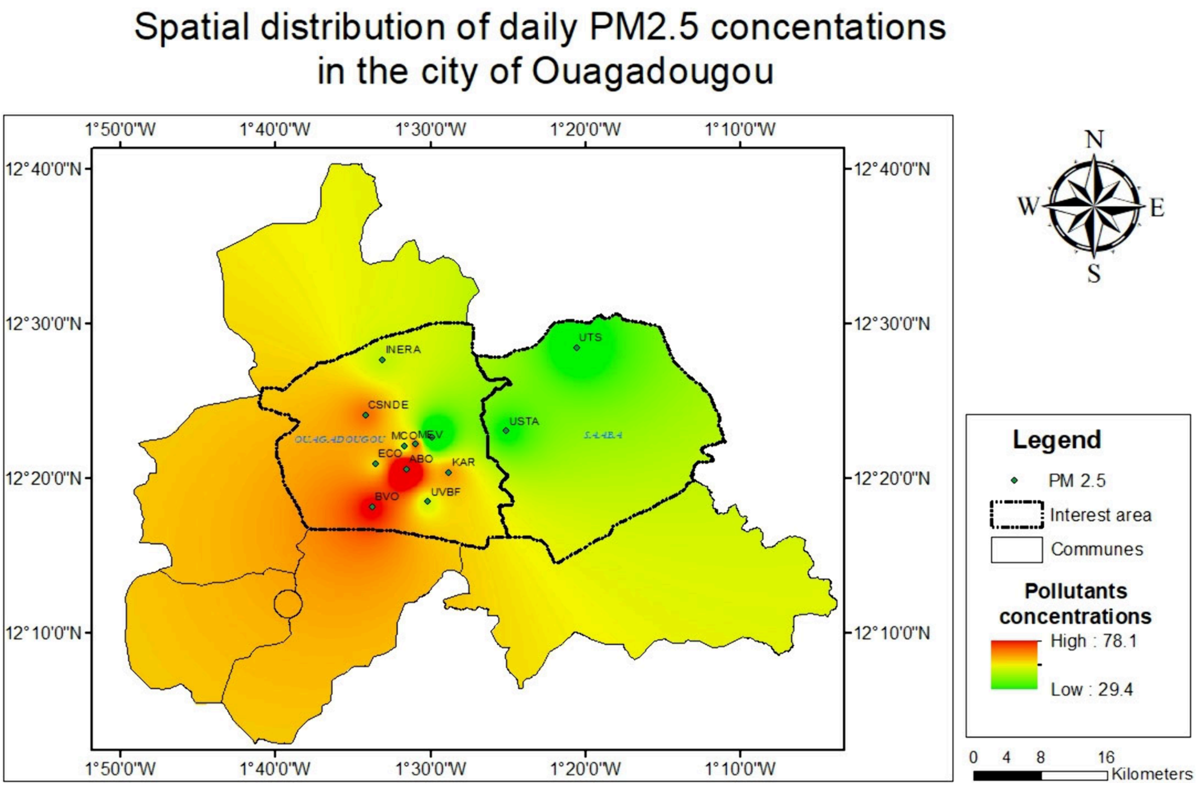

Figure 6. Spatially interpolated distribution of $PM_{2.5}$ concentration, measured by Clarity nodes and corrected by GMR, in the city of Ouagadougou, Burkina Faso.

raw (as-reported) Clarity monitor (purple lines) versus the TEOM (black lines), while Figure 3b shows the scatterplot of the raw Clarity data and the corrected Clarity data against the TEOM. The raw (as-reported) data during the evaluation period had a Mean Absolute Error (MAE) of 12.0 $\mu g/m^3$ and a coefficient of determination (R^2) of 0.31. A Gaussian Mixture Regression (GMR) model[26] was trained on 80% of the colocation data (randomly sampled) with 20% held out for evaluation and testing and then applied to the data from all of the deployed sensors. It has been shown in several studies that data from LCS are influenced by temperature and humidity.[5,30] We also present in Figure 3 the data set corrected by the GMR method: this regression takes into account temperature and relative humidity, which gave the best coefficient of determination (R^2 = 0.54) and the lowest Mean Absolute Error (MAE = 7.70 $\mu g/m^3$) following the methods of McFarlane et al. using the 20% testing data set aside for evaluation of the correction model. GMR has been shown to be more accurate and provide higher correlation and lower bias, compared to linear regression, in sensor studies in West Africa, including Accra, Ghana.[16,26] Key advantages of GMR include ability to handle missing inputs, deal with nonlinear relationships between variables, and produce components that identify different data regimes (e.g., high relative humidity) under which regression can be classified.

Note that nephelometric PM sensors (such as the Plantower sensors inside Clarity nodes) demonstrate poor performance for supermicrometer particles and therefore significantly underestimate $PM_{2.5}$ in dusty conditions.[6,31] Therefore, the general pattern is that the corrected $PM_{2.5}$ data values are higher than the measured values from low-cost sensors.

3. RESULTS AND DISCUSSION

3.1. Analysis of the $PM_{2.5}$ Data in Burkina Faso.

Figure 4a shows the distributions of raw data collected from the Clarity nodes in the Burkina Faso network. The violin plot in Figure 4b shows that for all of the sites, the mean corrected concentrations are all above the WHO Daily Guideline for safe $PM_{2.5}$ exposure (15 $\mu g/m^3$). Corrected daily mean values range from a low value of 35.1 $\mu g/m^{-3}$ (O-USTA) to a high value of 67.9 $\mu g/m^3$ (O-ABO), with the network-wide daily mean between all three cities being 46.7 $\mu g/m^3$. The study by Ouarma et al. obtained an average of 87 $\mu g/m^3$ in the city of Ouagadougou.[22] Our concentration is lower than this value, but it should be noted that the Ouarma et al. study does not take into account other cities in Burkina Faso. Recent studies found mean daily concentrations of 23.5 $\mu g/m^3$ for the city of Lomé[15] and 23.4 $\mu g/m^3$ for Accra, Ghana.[16] Accra is of similar size to Ouagadougou (2.7 million people), but Both Lomé and Accra are located in the south, which is coastal and farther from the Sahara, potentially allowing for clean oceanic air masses to mix in with anthropogenic pollution and Saharan dust. We therefore expect a lower concentration in Accra and Lomé than in Ouagadougou.

Annual averages are possible at some sites where data collection began in November 2021 and ended in November 2022 (Figure 1). At those sites, the annual average greatly exceeds the WHO annual guideline of 5 $\mu g/m^3$. Note that Annual averages range from 34.8 $\mu g/m^3$ (O-UJKZ) to 73.0 $\mu g/m^3$ (O-CSNDE).

Figures 5a-b show the variation of $PM_{2.5}$ over the course of the calendar year, showing a clear rise in $PM_{2.5}$ concentrations during the Harmattan (end of November to middle of March) and the lowest during the rainy season (June−October). The

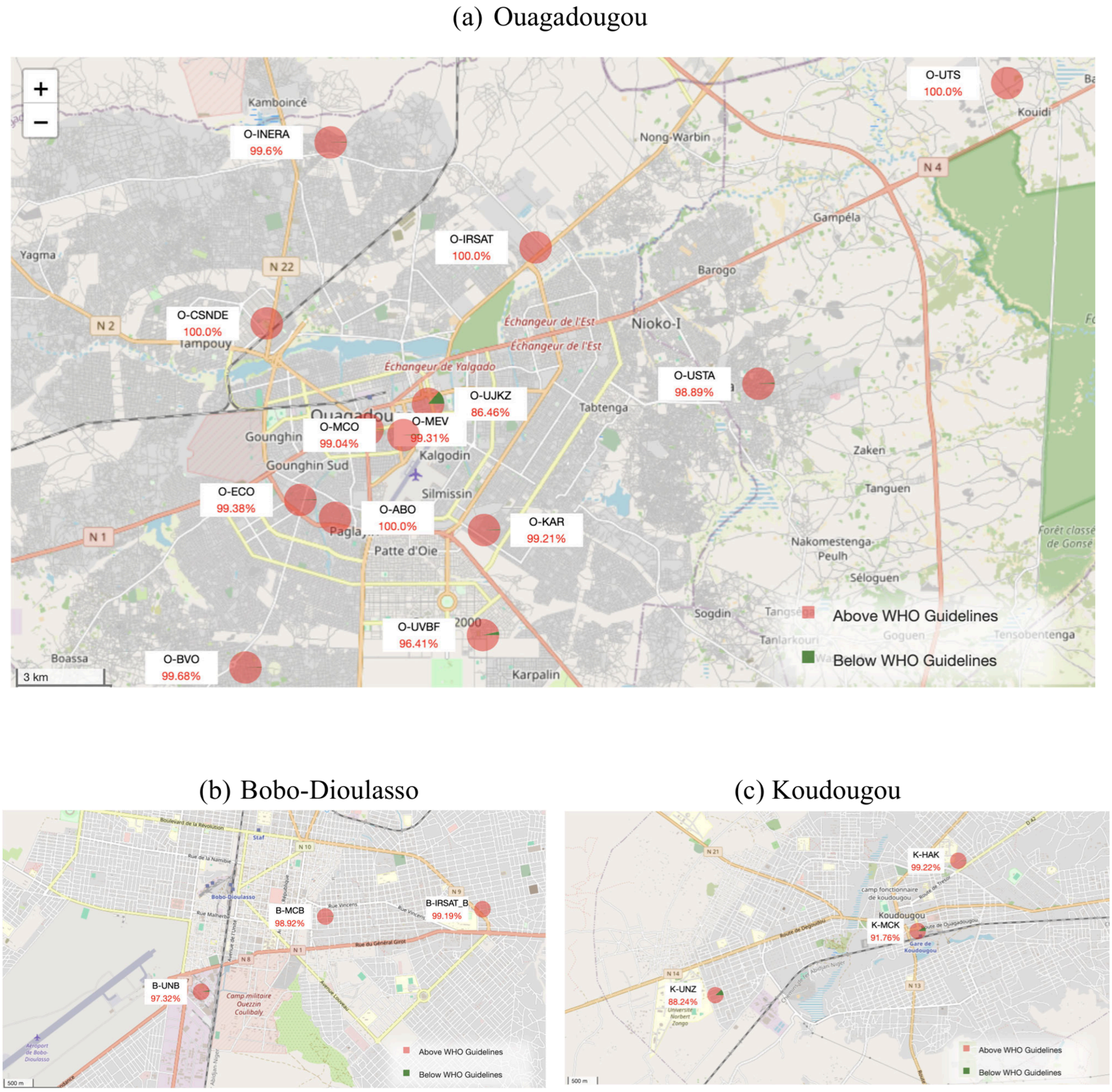

Figure 7. Pie charts of WHO exceedance at all sites (red text shows the percent of measured days above WHO guidelines of 15 $\mu g/m^3$). Map is reproduced with permission from OpenStreetMap.

Harmattan is a period of dry, dusty winds blowing Saharan dust into Burkina Faso. This adds to the existing air pollution from vehicle traffic on unpaved roads and other sources in Ouagadougou. For the specific case of Ouagadougou, the general state of the road network is poor, with many roads being unpaved and made of undeveloped earth, with rising numbers of vehicles on the roads.[32] Paving the road system and managing traffic would be helpful measures for reducing $PM_{2.5}$ emissions in Ouagadougou.

Figure 5c shows two daily peaks: a morning peak between 6 and 8 AM and an evening peak between 7 and 8 PM, which could be explained by increased residential cooking or rush hour traffic. These results are consistent with those of Nanaa et al. and Ouarma et al.[22,33] However, in Figure 5d, we see little change in average concentrations between weekdays and weekends. In Ouagadougou, Saturday is generally a working day rather than a true weekend day, and Sunday is characterized by heavy traffic associated with leisure and social activities, which may explain the lack of a clear difference between weekend and weekday concentrations.[34]

3.2. Spatial Distribution of $PM_{2.5}$ Concentrations in Cities. Figure 6 shows that $PM_{2.5}$ concentrations are lowest in the outlying districts throughout the year, as seen by the O-UTS (caveat that this sensor had a short collection period due to sensor malfunction) and O-USTA sites, and highest in the middle of the city, as seen at the O-ABO. For a few sites such as the O-UTS, the O-UTSA, and the O-ECO, the total number of daily mean data points was less than 200 due to sensor malfunction, constituting much less than a full year, which can skew the spatial averages at those locations. For example, the Saint Thomas D'Aquin University (O-USTA) site, which is located on the outskirts of the city and has low concentrations, can be partially explained by the fact that the sensor was mainly in operation during the period from May to October 2022, which is a rainy period and therefore a time of low particle concentration. The pie charts in Figure 7 show that the exceedance of the WHO standard varies from 86% to 100% of the time.

4. CONCLUSION

Cities in Africa have high levels of air pollution yet very low levels of monitoring. Ouagadougou, Burkina Faso, is a major urban area in West Africa. A network of 19 low-cost air pollution Clarity monitors, corrected using a Gaussian Mixture Regression technique based on a colocation with a reference-grade TEOM1400a, found that $PM_{2.5}$ concentrations are higher in the densely populated city center with unpaved roads and heavy traffic, and lower in the outlying districts. There are two daily peaks in concentrations, namely, one in the morning (6−8 AM) and one in the evening (7−8 PM). Daily mean $PM_{2.5}$ concentrations are consistently higher than 60 $\mu g/m^3$ in the dry Harmattan season (end of November through middle of March) and lower in the winter season (May−October). Over the study period, daily mean concentrations of $PM_{2.5}$ in Ouagadougou exceed the World Health Organization's recommended daily safe guideline of 15 $\mu g/m^3$ in 86−100% of the measured days. The city-specific daily mean $PM_{2.5}$ concentrations are 48.5 $\mu g/m^3$ for Ouagadougou, 46.9 $\mu g/m^3$ for Bobo-Dioulasso, and 38.7 $\mu g/m^3$ for Koudougou. These concentrations are much higher than other West African cities of similar sizes such as Accra, Ghana, and Lomé, Togo, indicating a greater need for mitigation measures such as road pavement and decarbonization of electricity generation as well as increased monitoring of air pollution and associated health impact assessments.

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Notes

The authors declare no competing financial interest.

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