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Fine particulate pollution concentration in Addis Ababa exceeds the WHO guideline value

Results of 3 years of continuous monitoring and health impact assessment

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Background: Real-time monitoring of fine particulate matter ($PM_{2.5}$) concentrations and assessing the health impact are limited in Ethiopia. The objective of this study is to describe current levels of $PM_{2.5}$ air pollution in Addis Ababa and examine temporal patterns and to consider the health impact of current $PM_{2.5}$ exposure levels.

Methods: $PM_{2.5}$ concentrations were measured using a centrally-located Beta Attenuator Monitor (BAM-1022) for 3 years (1 April 2017 to 31 March 2020), with data downloaded biweekly. Deaths attributable to current $PM_{2.5}$ concentration levels were estimated using the AirQ+ tool. The daily average was estimated using hourly data.

Results: The daily mean (SD) $PM_{2.5}$ concentration was 42.4 μg/m³ (15.98). Two daily extremes were observed: morning (high) and afternoon (low). Sundays had the lowest $PM_{2.5}$ concentration, while Mondays to Thursdays saw a continuous increase; Fridays showed the highest concentration. Seasons showed marked variation, with the highest values during the wet season. Concentration spikes reflected periods of intensive fuel combustion. A total of 502 deaths (4.44%) were attributable to current air pollution levels referenced to the 35 μg/m³ WHO interim target annual level and 2,043 (17.7%) at the WHO 10 μg/m³ annual guideline.

Conclusion: $PM_{2.5}$ daily levels were 1.7 times higher than the WHO-recommended 24-hour guideline. The current annual mean $PM_{2.5}$ concentration results in a substantial burden of attributable deaths compared to an annual mean of 10 μg/m³. The high $PM_{2.5}$ level and its variability across days and seasons calls for citywide interventions to promote clean air.

Keywords: Fine particulate matter; Ambient air pollution; Beta Attenuation Mass Monitor; Impact of air pollution

Introduction

Air pollution is one of the single largest determinants of environmental health risks, causing substantial premature mortality and morbidity. Worldwide, about one in every nine deaths annually are attributable to air pollution.[1] Household and ambient air pollution were responsible for about 7 million deaths in 2016, which is about 16% of all global deaths. Air pollution is a known risk factor for noncommunicable diseases.[2] About 94% of the attributable deaths occurred in low-and middle-income countries where the impact of air pollution has received insufficient attention. In urban areas of low-income countries, particulate matter and the gaseous pollutants result from the use of biomass and fossil fuels by households, vehicles, power generation, manufacturing plants, boilers, and local microenterprises.[3]

Ambient air pollution affects the poor and vulnerable population groups such as children and older people to a larger extent,[4]

What this study adds

Our study contributes novel primary data on levels and trends of ambient air pollution (focusing on fine particulate matter, $PM_{2.5}$) in a time series design in a Sub-Saharan African country where exposure to air pollution is not routinely monitored but has become a serious health threat. The study is ground-breaking in using high quality and continuous measurement and has the potential to inform policy makers so that they can make evidence-based decisions toward the mitigation of excess exposure. Our findings showed that levels of $PM_{2.5}$ exceeded the daily WHO guideline value almost two-fold, also exceeding four times the annual value. Our data showed significant proportion of premature death that is attributable to the current level of $PM_{2.5}$ air pollution. The novel findings from this study about high daily $PM_{2.5}$ concentrations and their temporal patterns, as well as the health impact assessment findings, have great potential to inform policy, hopefully leading to interventions to achieve clean air for the urban population.

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particularly those living in big cities of low- and middle-income countries. Worldwide, most cities in these poorer countries did not meet the World Health Organization (WHO) air quality guideline for the annual mean concentration of $PM_{2.5}$ (atmospheric particulate matter with diameter of 2.5 μm or smaller) in 2018, compared with at least half of cities in high-income countries.[5] However, there has been limited monitoring for $PM_{2.5}$ in the cities of Africa, particularly in Sub-Saharan Africa. The 2018 WHO air pollution database for Africa includes only 10 countries with 41 monitoring sites.[6] This database includes reports on annual mean $PM_{2.5}$ concentrations only for Kenya, Uganda, and Tanzania among countries in Eastern Africa; for these countries, there was only 1 fixed monitoring station in each capital city. The expected trend of rapid growth in urban populations and urbanization in general is likely to lead to substantial increases in pollution levels, as urbanization inherently demands growing service sectors in energy use, increased transportation, additional industries, and energy production, all leading to worsening air pollution.[3] WHO has raised concern about increasing air pollution in cities of developing countries.[7] It has developed the AirQ+ tool to estimate the likely impact of air pollution on disease burden due to the existing level of air pollution.[8] The tool has been used in cities of Europe.[9]

Here, we report $PM_{2.5}$ concentrations measured over 3 years in Addis Ababa, the capital of Ethiopia, where air quality measurements have been limited. Due to rapid urban growth, increase in vehicles, and physical factors such as high altitude and hills/valleys causing temperature inversions, air quality management in Addis Ababa is challenging and real-time monitoring is needed. As part of the activities of the Eastern Africa GEOHealth Hub, a monitor for airborne particulate matter was placed centrally in Addis Ababa to describe air quality in the city and to support a program of epidemiological research. We will also report findings from a related health impact assessment based on the AirQ+ tool described earlier.

Methods

Study site

Addis Ababa is the largest city in Ethiopia regarding size and population. An estimated 4.6 million people lived there in 2019,[10] in an area of around 527 km^2 and at an estimated population density of 5,165 per square kilometer.[10] It has two distinct seasons characterized by high and low rainfalls. The wet season usually starts in June and ends in September, while the dry season extends between October and May. Wet months in 2020 had an average of 340.5 mm precipitation, while the dry season had 64 mm.[11] Addis Ababa is located at a latitude of 9° 0’ 19” N, and a longitude of 38° 45’ 48” E at an average altitude of 8,000 feet above sea level.[12]

The $PM_{2.5}$ sampling site is located on the premises of Tikur Anbessa Specialized Referral Hospital (TASH) in an urban zone of the city located at a latitude of 9° 1’ 13” N, and a longitude of 38° 44’ 58” E.

Study design and $PM_{2.5}$ measurement

The study data came from continuous real-time measurement of $PM_{2.5}$ concentration. The ambient air pollution data were generated by a Beta Attenuation Monitor (BAM-1022) installed in March 2017 at a central site in the City. The instrument is manufactured by MetOne Instruments, Inc. (Grant Pass, OR), and is designated as an automated equivalent $PM_{2.5}$ mass monitor by the United States Environmental Protection Agency.[13,14] The site selection for the BAM-1022 followed recommended site specification criteria.[14,15] In addition, availability of sustained power, height from the ground, instrument safety, and lack of any physical barrier that may restrict the free flow of air were considered (Figure 1). Data were logged at 1-hour intervals, yielding 24 data points daily. This interval was set after exploring the variability of $PM_{2.5}$ concentration over 1-hour intervals. The BAM-1022 has an internal working environment that maintains a steady flow rate (at $15.8 < FR < 17.5$ liters per minute) and a range of meteorological conditions: relative humidity ($10\% < RH < 80\%$), temperature ($1 < T < 40$ °C), and barometric pressure ($525 < BP < 640$ mm Hg). For quality control, the instrument provides error messages so that problems could be addressed when needed. The study used data for the period 1 April 2017 to 31 March 2020.

Two BAM-1020 $PM_{2.5}$ monitors are managed by the US Embassy as part of the US State Department’s monitoring program, one at the site of the embassy and the other at the site of an international school. We used the concentration data from these monitors to compare with our results. The BAM-1020 on the premises of the US Embassy in Addis Ababa is located at a relatively “clean” site, whereas the second BAM-1020, at the US Embassy-International Community School, is located in downtown Addis Ababa, presenting a more polluted site regarding air pollution. The locations of the three BAMs are shown in Figure 2. The daily $PM_{2.5}$ concentrations measured by the two US BAMs were accessed freely at the website https://aqicn.org/city/ethiopia/addis-ababa/us-embassy/.

Data management

Data were downloaded biweekly from the BAM-1022 and evaluated according to a standard operating procedure. For analysis, we used data for days with at least 18 of 24 hours available, for example, 75% of the 24 hours. The missing data primarily came from power outages and periods of routine maintenance. Missing data were detected in the system software records by a signal for a sampling error resulting from data outside of the acceptable ranges for the following selected parameters: flow rate, concentration, temperature, barometric pressure, relative humidity, and sampling time interruption.

Among the techniques proposed in the literature for replacing missing values, we selected substitution of the mean, an imputation technique often used for air pollution data.[16] We adapted the “before-after-mean” method, which replaces all missing values with the mean of one datum before the missing value and one datum after the missing value. If at least one of the before-and-after data points were not available, we moved to a 2-day window to complete the data. We recovered 77 days (11%) of the expected data, while we had 7.4% of days missed in the 3 years of analyzed data. Log-transformed data were used to compare the $PM_{2.5}$ concentration by days (normality Kolmogorov Smirnov test, $P = 0.234$). With regard to the US Embassy data, a few negative concentrations were removed from the dataset.

Data quality assurance

Data quality was evaluated on an ongoing basis using an established protocol. The data manager validated the downloaded $PM_{2.5}$ data by manually checking the set parameters of flow rate, temperature, barometric pressure, and relative humidity, and the $PM_{2.5}$ concentration itself. A comprehensive quality check of the raw data was conducted to reduce the impact of uncertain data points, including duplicated data records, missing measurements, and implausible values. In particular, extremely high $PM_{2.5}$ concentrations (>700 μg/m^3) were considered as implausible, and, therefore, such data points were removed from the analysis. This was based on the routine reviews.[17] In addition, any data points with accompanying error messages were set aside. The final data set included the variables date (year, date, hour/minute/second), hourly average $PM_{2.5}$ concentration (μg/m^3), relative humidity (%), ambient temperature (°C), and barometric pressure (mm Hg).

Figure 1. BAM 1022, Tikur Anbessa Hospital site, GEOHealth Hub, Addis Ababa, Ethiopia.

Data analysis

The averaged continuous ambient $PM_{2.5}$ measurements were used for statistical analysis. The R statistical software (R 3.6.2; https://www.r-project.org/) was used to conduct descriptive analyses, including time series plots and box-plots. The 1-hour BAM-1022 data were aggregated to create the daily averaged data sets for $PM_{2.5}$. Time series line graphs were used to explore the daily pattern and seasonality.

Assessing the impact/effect of the current level of $PM_{2.5}$ concentration

We used the WHO AirQ+ tool[8,18] to calculate the attributable deaths to the exposure levels of the three BAMs separately. We employed averaged concentrations over a 3-year period from our BAM-1022 and the US-Embassy BAM-1020 on embassy premises, while an average for 2 years was available for the BAM-1020 at the international school site. The total population of Addis Ababa in 2020 was taken from UN population data sources (4.8 mln).[10] We considered that 34% of the total population was adult of 30 years old and above (Addis Ababa Health Bureau, personal communication, February 2, 2021). The annual mortality for the year 2020 was taken from Addis Ababa Mortality Surveillance Program.[19] A 7% of the incidence of injury was taken from published articles addressing the mortality surveillance program.[20,21] We used the three WHO annual interim target options and the WHO annual mean air quality guideline as cut-off reference values to estimate the excess deaths because of $PM_{2.5}$ pollution as measured by the three BAMs separately.[3]

Ethical considerations

This study had an ethical clearance from the Institutional Review Board of the College of Health Science at Addis Ababa University. The clearance followed a yearly renewal.

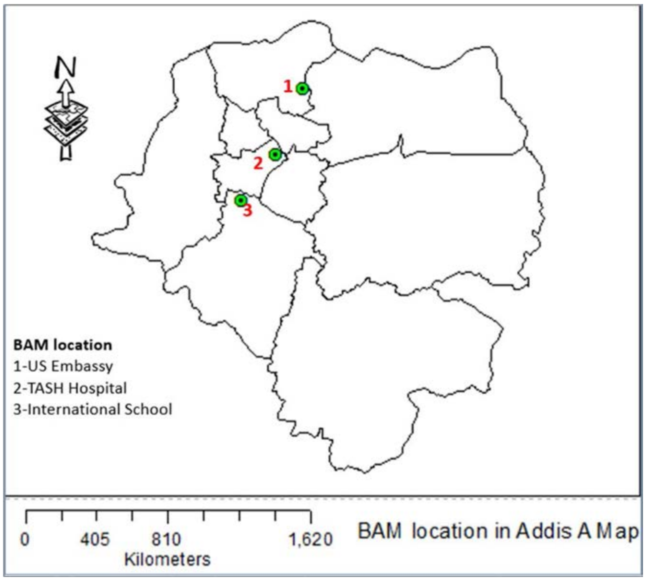

Figure 2. Locations of BAM in Addis Ababa.

Results

Data description

Over the 3 years of the study, data were available for 1,012 days (Table 1).

Hourly and daily variability of $PM_{2.5}$ concentration

The hourly $PM_{2.5}$ concentrations in Addis Ababa exhibited distinct diurnal, day-of-week, and seasonal patterns of variation. The overall diurnal $PM_{2.5}$ concentration patterns (with bootstrap 95% confidence intervals) showed morning and afternoon

Table 1.

The number of observed/available daily $PM_{2.5}$ concentrations per month monitored by BAM-1022, Addis Ababa, Ethiopia, 2017–2020.

		Month												
Site	**Year**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
TASH	2017				30	31	30	31	31	30	31	24	29	267
	2018	28	28	31	30	31	25	31	31	26	24	30	31	346
	2019	29	28	6	1	31	30	31	31	30	31	30	31	309
	2020	31	28	31										90
	Total	88	84	68	61	93	85	93	93	86	86	84	91	1012
US Embassy	2017				30	31	30	31	26	29	31	30	29	267
	2018	28	24	22	30	27	30	31	31	28	31	30	31	343
	2019	31	28	31	28	31	23		23	23	31	30	13	292
	2020	30	28	30										88
	Total	89	80	83	88	89	83	62	80	80	93	90	73	990
School	2017				30	31	12	1		19	30	22	27	172
	2018	16	9	5	28	31	11	29	5	12	24	4		174
	Total	16	9	5	58	62	23	30	5	31	54	26	27	346

TASH: "Tikur Anbessa Hospital" with BAM 1022; Central-location BAM-1020 in the premises of US Embassy; School-International School hosting BAM-1020.

peaks (Figure 3). The wider confidence intervals in the afternoon reflect a substantial variation of $PM_{2.5}$ levels. On Sundays, the diurnal variation was less prominent compared with the other 6 days of the week (Figure 4).

Table 2 provides summary statistics for $PM_{2.5}$ concentrations across the day, highlighting the far higher morning hourly values and increased variability. The substantial variability of levels is described by the standard deviation.

Daily time series: BAM-1022

A daily time series of $PM_{2.5}$ values is plotted in Figure 5. Line interruptions indicated days with missing $PM_{2.5}$ values. The daily $PM_{2.5}$ levels varied between 11.8 and 131.1 μg/m^3 with an arithmetic mean (SD) of 42.4 ± 15.9 μg/m^3 represented by the horizontal broken blue line in the plot. Most values (90% of days) are above the WHO $PM_{2.5}$ daily guideline of 25 μg/m^3.[3] About 27.3% of the observed days were above 50 μg/ m^3—twice the WHO daily guideline. As shown in Figure 5, the maximum 24-hour average $PM_{2.5}$ value of 131.1 μg/m^3 was observed on 10 September 2017, aligned with the eve of Ethiopian New year. A second spike was evident on 7 April 2018, with a peak value of 118.1 μg/m^3, while smaller peaks were observed on other days without a clear pattern. The rainy months, including July, August, and September, had relatively high levels of $PM_{2.5}$, while the lowest levels were in April and May.

The 3-year average $PM_{2.5}$ values for working (weekdays) and nonworking (weekend) days, showing the distribution of $PM_{2.5}$ values across the days, are displayed in box plots in Figure 6. The average $PM_{2.5}$ is represented by the blue dot. In general, the ambient $PM_{2.5}$ concentration during working days was higher than during nonworking days. The lowest values were often observed on Sundays and Mondays. Relatively increased $PM_{2.5}$ values were observed on Fridays and Saturdays, but the increases were not statistically significant (data not shown). The Sunday low level was followed by an increase on Monday and a further increase across the week to a Friday maximum, followed by a weekend decline.

Comparison of $PM_{2.5}$ levels across monitors in Addis Ababa

We compared the findings of the GEOHealth Hub BAM-1022 with the data from the two monitors maintained by the US Embassy, located 4.5 and 3.6 km (aerial distance) from our BAM-1022, respectively. The temporal patterns of variation in the $PM_{2.5}$ concentrations across the three $PM_{2.5}$ monitors were consistent. The concentrations were lower at the Embassy sites compared to those at the GEOHealth Hub BAM-1022, and were consistently the lowest for the US Embassy BAM-1020 located within the "clean" US Embassy premises. With regard to peaks, the findings at the three BAMs were consistent, capturing peak values of $PM_{2.5}$ on 10 September 10, 7 April 2018, and other, smaller peaks.

Daily time series plots for $PM_{2.5}$ are shown for all three monitoring sites in Addis Ababa in Figure 7.

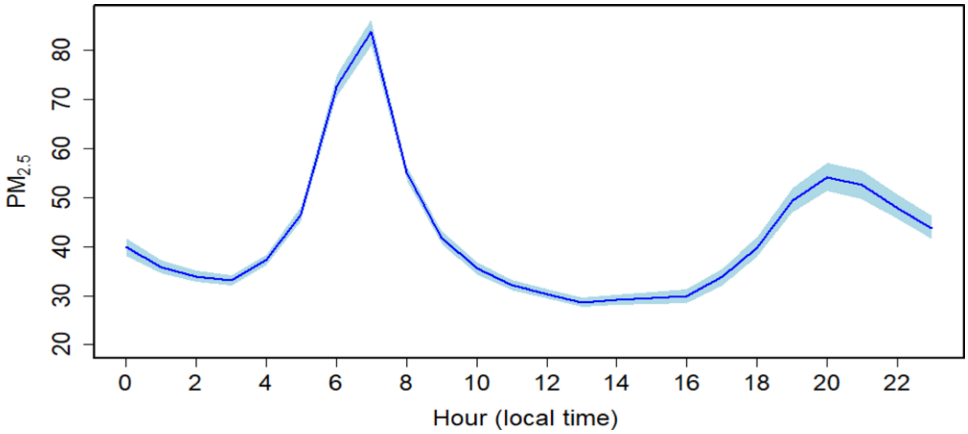

Figure 3. Overall diurnal pattern of $PM_{2.5}$ concentrations monitored by BAM, Addis Ababa, Ethiopia, 2017–2020.

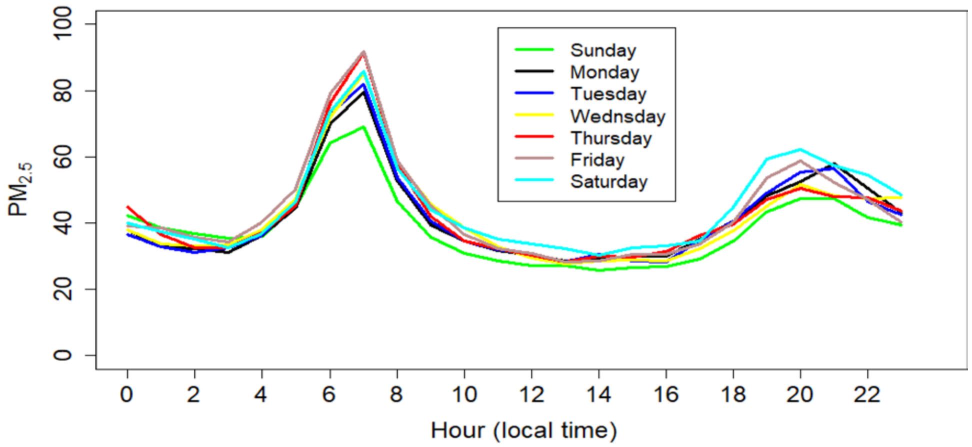

Figure 4. Diurnal pattern of $PM_{2.5}$ concentration by day of the week, Addis Ababa, Ethiopia, 2017–2020.

The health impact of long-term exposure to $PM_{2.5}$ pollution

The calculated attributable death to air pollution is presented in Table 3. A substantial number of deaths can be prevented by achieving the WHO annual $PM_{2.5}$ guideline (10 µg/m^3), given the high level of current level of pollution (42.4 µg/m^3).

Discussion

In this study, we have documented high levels of $PM_{2.5}$ in Addis Ababa and characterized the diurnal, weekly, and longer-term variation in $PM_{2.5}$ concentration. The observed daily mean of $PM_{2.5}$, 42.4 µg/m^3, exceeds the 2005 daily WHO Air Quality Guideline of 25 µg/m^3 and is between the interim target 2 and 3 levels of 50 and 37.5 µg/m^3, respectively.[3] Over the 3-year period, there was no clear upward trend. The findings from the health impact assessment that have been conducted in this study demonstrate that effective policy-driven interventions to reduce $PM_{2.5}$ concentrations in Addis Ababa have the potential to lead to appreciable reduction in premature deaths.

Fine particulate pollution concentrations in African cities with ground monitoring stations exceeding the WHO guidelines have been documented previously.[22] Visibility, a proxy index of particulate matter air pollution, continually decreased, indicating worsening air pollution since the 1970s in Addis Ababa, as well as in Kampala and Nairobi.[23] The trend of worsening air pollution can likely be attributed to increasing sources of air pollution such as daily traffic density and other sources. The scarcity of data on air pollution in African cities is an inherent challenge, but available data indicate that many cities in Africa exceed the WHO annual guideline value, as in other large cities in low- and middle-income countries. The 3 years of data provided in our study exceeded this guideline as well.

The relatively high $PM_{2.5}$ concentrations on weekdays are likely to reflect the number of vehicles on the road during these days. The number of newly registered vehicles in Addis Ababa increased by 185% on average during 2010–2015,[24] which reflects the trend in most capital cities in Sub-Saharan Africa. The number of vehicles in Addis Ababa increased at the rate of 10% per year from 2012 to 2016[25] and about 13% per annum from 2014 to 2019.[26] This increase undoubtedly impacts $PM_{2.5}$ concentration and has implications for the trend of air pollution in the city. Diesel vehicles are a particular concern. Based on tailpipe emissions, it is estimated that 55% and 33% of the total vehicular $PM_{2.5}$ emissions come from heavy-duty vehicles (diesel users) and passenger cars (petrol fuel users), respectively, in use on the roads of Addis Ababa.[24]

The daily profile of $PM_{2.5}$ concentration was characterized by two peaks, observed during morning and afternoon with the morning peak about 50% greater than the afternoon peak. The morning peak reflects the contribution of household pollution and vehicular emissions from the preceding day. Pollution from these sources stays close to the ground because of the morning temperature inversion.[27,28] At the city's high altitude, the ground surface after midnight consistently cools faster than the upper atmospheric layer, thereby creating a layer of relatively warmer and stable air mass sitting over a layer of colder air. This process slows and, sometimes in severe cases, prevents the vertical mixing of air. The temperature inversion may also increase the relative humidity at the surface, which may accelerate particulate matter suspension and formation. The temperature inversion keeps the inversion layer close to the ground, thereby reducing the mixing volume available to pollutants and reducing dilution. This phenomenon is well described elsewhere.[29,30] This context creates sufficient time for increased exposure to high level of $PM_{2.5}$ pollution, including other air pollutants in the morning times.

The increasing trend of $PM_{2.5}$ usually starts at about 1 AM, reaching its highest point at 7 AM and declining after 10 AM. The $PM_{2.5}$ concentration usually decreases after 9 AM once the morning sunlight radiation breaks the inversion layer by heating that allows the vertical mix of air in the atmosphere. The temperature change allows an upward movement of air pollution, hence improving vertical air ventilation. Although not as high as the morning peak, the peak in the afternoon is likely explained by the increased level of traffic, with the period after 3 PM marked by the return of schoolchildren and workers to their homes. A study in Addis Ababa in 2005, which used portable PM_{10} dust monitors, showed a similar pattern for PM_{10}.[31] We noted that the diurnal behavior of particulate matter pollution in Addis Ababa is consistent with that in Nairobi, Kenya,[32] Ethiopia's neighbor to the south.

In addition, we cannot exclude the possible effect of the study monitor's location (i.e., TASH) being along the path of air mass movement so that the $PM_{2.5}$ mass is trapped at our sampling site. The local wind moves often from East to West and North East to West.[33]

The seasonal variability is likely to be explained by the presence of moisture in the air mass and hence attributed to meteorological differences, more evident due to rains during the wet season in Ethiopia. The natural cloud cover during most of the day, accompanied by rain that leaves suspended droplets in the air, increases the relative humidity, which is likely to hamper the vertical aeration of suspended fine $PM_{2.5}$. This stagnation increases the relative concentration of $PM_{2.5}$ because of the continuous influx of air pollutants from household and vehicular emissions. Studies in India,[34] Mongolia,[35] and California/United States[36] showed similar variability in $PM_{2.5}$ by season. In these

Table 2.

Summary statistics of $PM_{2.5}$ concentration monitored by BAM-1022 across the hours of the day, Addis Ababa, Ethiopia, 2017–2020.

	Time	Time description[a]	Minimum	Median	Mean	Maximum	SD
TASH	Before 5h00	Midnight	1	35	37.8	366	23.4
	6h00 to 9h00	Early morning	3	54	63.4	295	37.6
	10h00 to 15h00	Day time	0	26	30.9	260	18.5
	16h00 to 19h00	Late afternoon	0	26	38.2	234	33.5
	After 20h00	Night	1	34	49.6	452	31.4
US Embassy	Before 5h00	Midnight	0	15	17.5	246	11.1
	6h00 to 9h00	Early morning	0	23	27.3	354	18.2
	10h00 to 15h00	Day time	0	20	24.6	248	15.9
	16h00 to 19h00	Late afternoon	0	19	24.3	375	18.5
	After 20h00	Night	1	24	29.7	402	16.5
School	Before 5h00	Midnight	0	32	35.9	332	22.5
	6h00 to 9h00	Early morning	4	48	52.6	309	27.6
	10h00 to 15h00	Day time	0	18	21.5	98	12.3
	16h00 to 19h00	Late afternoon	1	21	26.0	203	19.0
	After 20h00	Night	5	30	44.1	347	24.0

[a] This is to customize the daily profile $PM_{2.5}$ concentration in reference to Figure 3 in order to show the likely of exposure given human mobility according the context of local time. The increased PM concentration was indicative during early morning (6:00-9:00 AM) and relatively low peaks during late afternoon, around 20:00 PM.

countries, $PM_{2.5}$ concentration during the wet months exceeded concentrations during months when rainfall and/or relative humidity were high.

Our data showed lower levels of $PM_{2.5}$ concentrations in the months of April and May when the daily temperature was high relative to other months. The presence of improved air mixing relative to wet months could be a factor in the background of continued emissions from vehicles and households. Variation in the $PM_{2.5}$ profiles comparing dry and wet seasons was similar to data from the US Embassy BAM monitors. However, we found two local studies reporting that the $PM_{2.5}$ concentration was higher during dry months compared with wet months.[31,37] Two factors might explain this difference related to the number of vehicles in Addis Ababa and the methods of measuring particulate pollution. First, the number of vehicles in 2019 was 4.6 times that of 2005, and twice that of 2010 (2019, n = 596,084).[26] Assuming the proportion of diesel engine vehicles is at least 50% of the available fleet and that about 50% of the vehicles are at least 20 years old, the amount of $PM_{2.5}$ emission in the air is substantial: it can be easily trapped and suspended for a period of time in the presence of temperature inversion which plays a synergistic role. Second, local studies had limited duration of sampling time, while our study used a reference equivalent instrument with real-time measurements over 3 years. The real-time measurement over 24 hours in a day provides an opportunity to document the profile of the concentration by time and weighted averages.

The occurrence of different levels of peaks on particular days can be linked to high levels of use of household fuels. Biomass fuel is used extensively as an energy source in 70% of households in urban communities in Ethiopia.[38] The peak during 10 September 2018, for instance, corresponds to the Ethiopian New Year's Eve when cooking is intensive throughout the city, and neighborhoods hold campfire ceremonies. These traditions involve almost every household in the Ethiopian community. Smaller peaks may be explained by local changes in traffic density in the proximity of our monitoring stations.

Continued growth of Addis Ababa has resulted in a demand for energy use that also increases air pollution. For example, fuel consumption in Addis Ababa in 2016 doubled that of 2012.[25] The development of road network Addis Ababa is getting improved from time to time.[39] We believe that the quality of the roads, many unpaved, and widespread construction activity have increased the level of inert dust in the urban atmosphere.

Our health impact assessment demonstrated variations in the number and proportion of premature deaths in reference to the

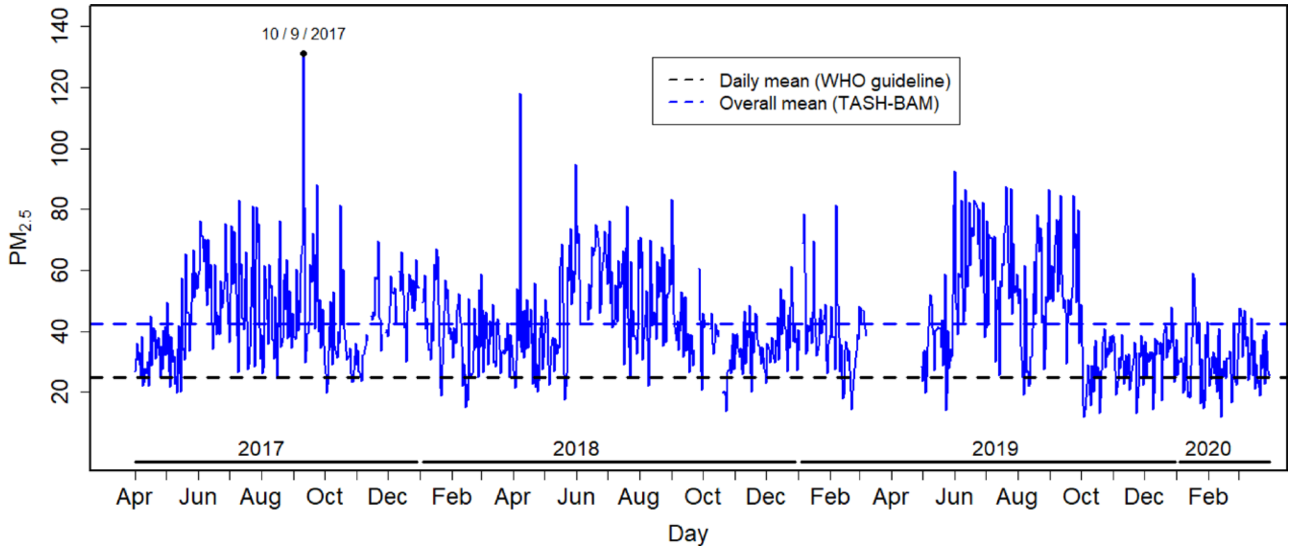

Figure 5. Daily pattern of 24-hour average $PM_{2.5}$ concentrations in Addis Ababa, Ethiopia, 2017–2020.

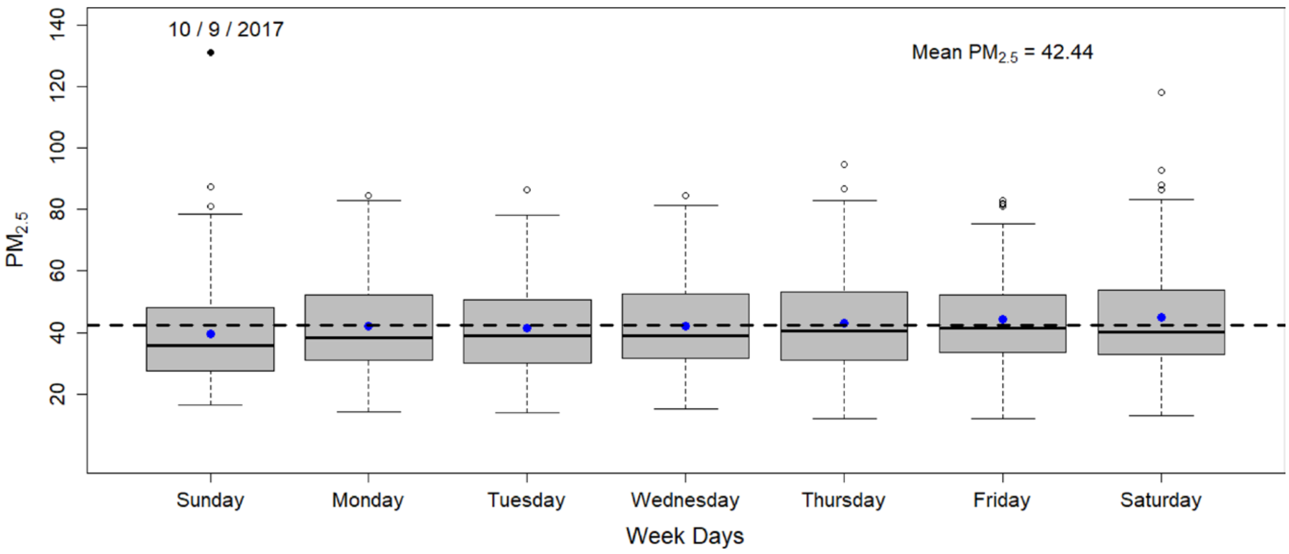

Figure 6. Distribution of $PM_{2.5}$ concentrations across weekdays in Addis Ababa, Ethiopia, 2017–2020.

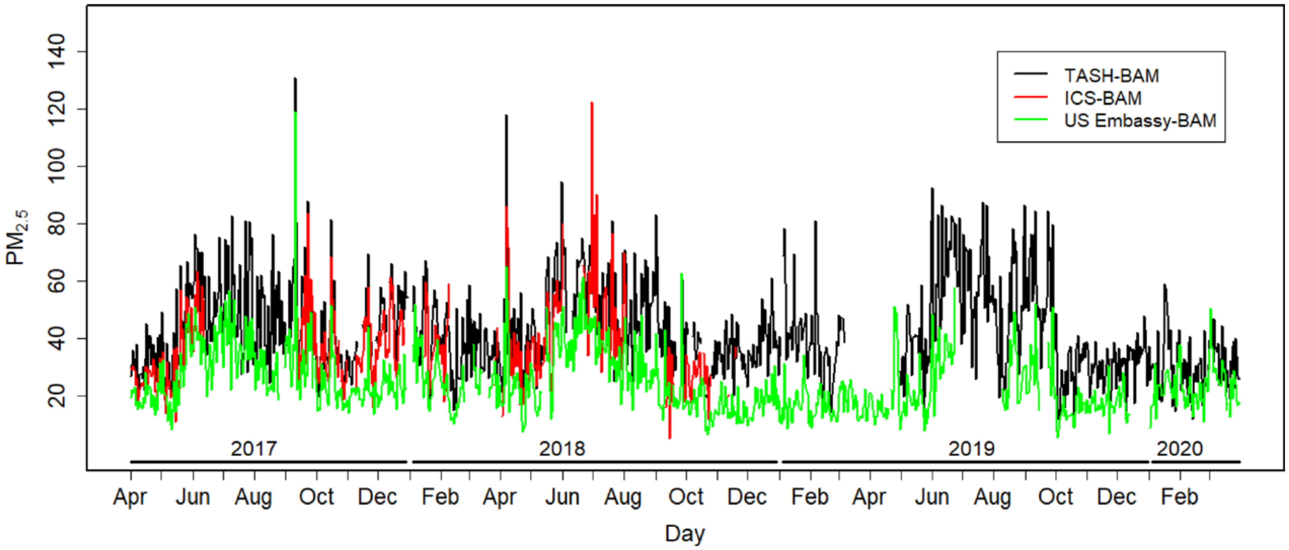

Figure 7. Time series patterns of $PM_{2.5}$ based on BAMs at TASH, the US Embassy-ICS and the US Embassy-Center Addis Ababa, Ethiopia, 2017–2020. ICS indicates International Community School.

different targets of WHO guideline, the highest being at the 10 μg/m^3 cut-off. The percentage of annual attributable deaths due to present $PM_{2.5}$ pollution levels varied between an excess of 8% and 18%. The calculations from the study monitoring site at TASH are most likely to represent the $PM_{2.5}$ concentration to which the city's residents are exposed, implying that there are substantial excess annual attributable deaths. Ambient air pollution could be a factor as a contributor to the changes from communicable to noncommunicable diseases in Addis Ababa.[20] The impact of air pollution will continue as long as the quality

Table 3.

Estimated annual attributable deaths from long-term exposure to $PM_{2.5}$ air pollution in 2020.

		Annual attributable deaths with 95% CI							
		N (%)							
		WHO annual Interim 1 (35 μg/m^3)		WHO annual Interim 2 (25 μg/m^3)		WHO annual Interim 3 (15 μg/m^3)		WHO annual Mean (10 μg/m^3)	
BAM location	Annual mean $PM_{2.5}$ concentration, μg/m^3 (2017–2020)	N (95% CI)	%	N (95% CI)	%	N (95% CI)	%	N (95% CI)	%
"TASH"	42.4	502 (330, 661)	4.4	1147 (761, 1495)	9.9	1753 (1176, 2265)	15.2	2043 (1377, 2627)	17.7
School	34.7	0	0	654 (431, 859)	5.7	1290 (858, 16770)	11.2	1598 (1065, 2063)	13.8
US Embassy	24.2	0	0	0	0	613 (403, 805)	5.3	936 (620, 1225)	8.1

"0" shows that the current level is below the WHO cut off with zero risk.
CI indicates confidence interval.

of vehicles and roads do not improve. Health matters need to be addressed in conjunction with development efforts, including new and/or improved roads and policies that affect vehicle importation and handling. The Ethiopian government has taken important steps to allow new vehicles to be imported into the country at reduced taxes, as well as promoting the assembly of new cars.[40]

This study has several strengths. Using US EPA–approved $PM_{2.5}$ monitors, the real-time temporal measurements and rigorous quality control have contributed to the collection of 3 years of valid data. The validity of our data is supported by comparability with data from the US Embassy's BAM 1020. Our monitor's location downwind relative to the wind's easterly direction resulted in higher measurements than the Embassy BAM, but with a similar temporal profile.

Unfortunately, we lack data on traffic flow and do not have an up-to-date emissions inventory. This limits our ability to place our findings in the context of the present distribution of sources. We also acknowledge that there are substantial uncertainties in the estimates of disease burden. We have acknowledged the limited use of traffic flow in evaluating the trend of $PM_{2.5}$ concentration.

Overall, the findings show that particulate matter air pollution in Addis Ababa is well above the WHO Air Quality Guideline values and at concentrations known to be associated with increased risk for adverse health effects. We have also shown the feasibility of implementing high quality monitoring in Sub-Saharan Africa. While further monitoring is needed, there is a clear imperative for air quality control as cities grow and have ever-increasing vehicle fleets.

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Conflicts of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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