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Roadside PM2.5 concentrations measured with low-cost sensors and student science in Arba Minch, Ethiopia

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ABSTRACT

Exposure to PM2.5 poses one of the biggest health threats, with traffic and biomass burning as dominant sources in urban areas of low-income countries. In Ethiopia, the combination of these two sources suggests a high roadside exposure. Because of a lack of resources for data collection, only few studies were conducted on roadside exposure in Ethiopia. Using low-cost sensors and student science could partially remedy this lack of resources. Students collected PM2.5 data in Arba Minch at four stationary locations and inside two public transport tricycles during a period of six weeks with self-made low-cost sensors. Data was analyzed to gain insight into concentration levels, temporal variation, spatial variation, and difference between next to the road and on-road concentrations. Average concentrations ranged from 13-36 µg/m^3. Concentrations were highest during morning hours (42 ±12 for hours 6:00-10:00, versus 20 ± 1 and 32 ± 4 for 10:00-17:00 and 17:00-21:00, respectively), and concentrations were highest at the local bus station (36.2 µg/m^3). On-road concentrations showed the highest variation and were on average higher than concentrations next to the road (33 ± 25 and 30 ± 22 µg/m^3 versus 23.3 ± 18 and 22.6 ± 18 µg/m^3). On a daily average level, concentrations at different locations showed a high correlation (R^2 0.8-0.95) amongst each other. This suggests the possibility to interpolate concentrations from one location to other locations. Moreover, the PM2.5 concentrations exceeded air quality guidelines. In Ethiopia, more than ten cities have higher populations and traffic flows than Arba Minch. In those cities, similar or higher exceedances are expected. With this study as an example, other universities could likewise conduct research with low-cost sensors and student science in their cities. Cooperation across course instructors and universities in applying these methods will increase the insight in PM2.5 exposure in Ethiopian cities.

Keywords: ambient air pollution; traffic; Sensirion SPS30; student measurements; Particulate Matter

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1. INTRODUCTION

Air pollution poses one of the biggest threats to health worldwide (Babatola, 2018; Gakidou et al., 2017; Shaddick et al., 2018). Ambient (outdoor) air pollution is estimated to cause 4.2 million premature deaths worldwide each year, especially owing to exposure to particles with a diameter smaller than 2.5 µm ($PM_{2.5}$) (World Health Organization [WHO], 2021b). Exposure to PM2.5 tends to be higher in low-income countries (Institute for Health Metrics and Evaluation, 2020). Dingemanse et al. (2022) found the bus station in Arba Minch, southern Ethiopia, exposed to high concentrations of PM2.5. This suggests that exposure related to motorized traffic is an important aspect of total exposure. Indeed, for urban areas in low-income countries, traffic is a major source of air pollution (Kim Oanh et al., 2013). Tefera et al. (2021) apportioned 31% of PM2.5 to traffic at one location in Addis Ababa. Furthermore, locations in low-income countries have the added burden of PM2.5 originating from biomass burning. Biomass is a common source for cooking, and open waste burning is a widespread practice as well. 18.3% of PM2.5 originated from biomass burning in the case of Addis Ababa (Tefera et al., 2021). Roadside exposure is potentially an important study area. However, to our knowledge in Ethiopia there are only three published studies on ambient or traffic related PM2.5 exposure. Two of these are conference abstracts which are not publicly available. These studies reveal that traffic-related concentrations in Addis Ababa and Adama exceed WHO air quality guidelines (Isaxon et al., 2019; Kumie, 2020; Tefera et al., 2020). They also reveal that the concentrations vary over time within days, between days and over seasons (Kumie, 2020; Tefera et al., 2020). Furthermore, they reveal that concentrations vary across different locations within the same city (Isaxon et al., 2019). Additionally, studies in other countries show variations in exposure between neighborhoods (next to the road) versus traffic participants (on-road) (Al-sareji et al., 2022; Jinsart et al., 2012; Kim Oanh et al., 2013). This aspect is not yet studied in Ethiopia. Arba Minch is smaller than Addis Ababa, with less vehicles and related traffic jams. Addis Ababa, Adama and Arba Minch were placed 1, 4 and 14 respectively based on the latest census and projections (Central Statistics Agency (Ethiopia) [CSA], 2013; Population Census Commission, 2007). The single measurement at the bus station in Arba Minch suggests high concentrations nearby traffic. It is unknown whether this is the case for other roadside (next to the road or on the road) locations as well. If this would be the case, this would have ramifications for more cities in Ethiopia. The possibility of high roadside concentrations with variation over time and space in potentially more than ten cities suggests a high need for research. However, a lack of resources has resulted in low research undertaking. This can be partially remedied with low cost sensors (Dingemanse, 2022a; Isaxon et al., 2019) and student science (Dingemanse & Dingemanse-de Wit, 2022). This study has applied both methods. Undergraduate students of Arba Minch University measured PM2.5 at the bus station, next to traffic hot spots in town, and inside the most common public transport mode (Bajaj: public transport tricycle). They conducted measurements with a self-built set-up including a Sensirion SPS30. With the use of these methods, this study contributes to knowledge on roadside PM2.5 concentrations. The objectives of our study are to compare Arba Minch roadside concentration levels to guideline values, to distinguish temporal patterns on an hourly and daily level, to find whether concentrations vary significantly across distinct locations, and to evaluate the difference between on-road and next to the road concentrations.

2. MATERIALS AND METHODS

2.1 Study area

2.1.1 Characteristics

Arba Minch town is the administrative center of Gamo Zone in the Southern Nations, Nationalities and People's Regional State (SNNPR) of Ethiopia. It is situated between 1,200 and 1,400 meters above sea level, surrounded by mountains to the west and lakes (Abaya and Chamo) to the east. This topography causes wind flows towards the mountains during daytime and towards the lakes during nighttime (Minda, 2014). On a wider scale, the topography of the Grand Rift Valley also determines the wind direction, which results in a variety of wind directions. Local fishermen from the nearby lake identify four winds (Weiß et al., 2022). Arba Minch is mostly dominated by low-rise buildings. The natural wind movement from various directions and the presence of few high-rise buildings cause the dispersion of air pollutants. This decreases air pollution concentrations in comparison to a situation where there would not be such wind circulation. The annual rainfall is between 800 and 1,000 mm. 70-90% of this is accounted for by two seasonal rainfall periods: September-November and March-May (Shalishe et al., 2022).

According to the latest projection, the population of Arba Minch town is 210,255 (CSA, 2023). Sources for PM2.5 are household cooking, traffic, and open waste burning. According to the census in 2007, 0.2% of the households used electricity for cooking, while 90% of the households used firewood (Population Census Commission, 2007). We do not have access to more recent figures. While electricity use has increased since 2007, use of biomass for cooking is still a common practice in Ethiopian cities (Dingemanse et al., 2022; Tefera et al., 2021). Minda (2014) hypothesized that for the town as a whole household biomass burning is the largest air pollution source. This will however be different at locations close to roads. Regular cooking hours are 05:30 – 9:00 and 17:00 – 21:00. These are also busy traffic hours. Arba Minch Town Road Transport Service has estimated the number of vehicles to be 9,356 of which 77.8% constitute motorcycles, 17.1% Bajajs (public transport tricycles), and only 5% cars and buses. In reality, these numbers will be different. We have witnessed that most cars and buses have an Addis Ababa license plate. Hence, the percentage of cars and buses might be higher than the locally registered 5%. However, the high skew of Bajaj and motorcycles is supported by their biggest share in road traffic accidents (33 and 40%) (Misker et al., 2017).

2.1.2 Measurement locations

Students conducted measurements at locations next to or on the road. They installed four instruments at fixed locations (A1-A4), and two instruments inside a Bajaj (B1-B2). Figure 1 shows the measurement locations.

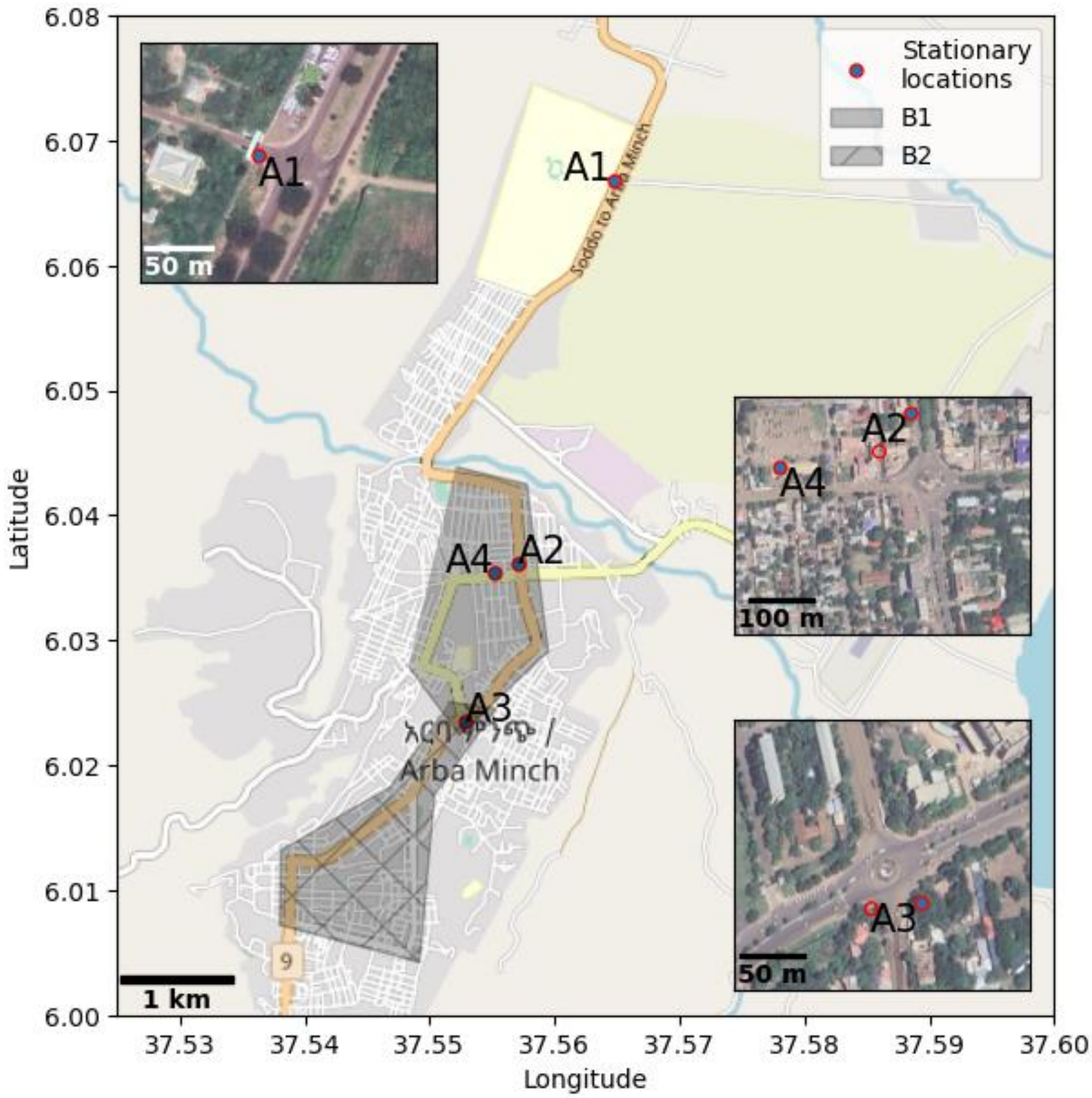

Figure 1. Locations of stationary measurements (A1-A4) and the normal working area for Bajaj with mobile measurements (B1, B2).

Locations A1-A3 were all 10-20 meters from the road, while location A4 was at an office with a window facing the bus waiting area of the bus station. Locations A2 and A3 were both near a traffic square. At both locations the instruments shifted to another orientation of the square during the measurement period. The waiting position for Bajaj B1 was close to location A2, while that of B2 was close to location A3. Table 1 shows an overview of the six locations.

Table 1. Measurement locations. Measurements took place between 8 April and 15 May 2022. See Section 2.3 for more information.

ID	Location	Measurement type	Description
A1	University Student Gate	Stationary	Main road for inter-city travel, Bajaj waiting for student customers
A2	Sikela Gamo Square	Stationary	Main road, business center, starting- and stopping travel for shops
A3	Nech Sar Square	Stationary	Main road, starting- and stopping travel for shops
A4	Bus station	Stationary	Short- and long distances buses arrival and departure
B1	Bajaj Sikela	Mobile	Driving with customers, standing idle when there are no customers
B2	Bajaj Nech Sar	Mobile	Driving with customers, standing idle when there are no customers

2.2 Measurement instrument

The instrument to collect data for this study is a self-built PM2.5 low-cost sensor, based on the Sensirion SPS30. The Sensirion SPS30 measures the PM2.5 concentration based on scattered IR light (Sousan et al., 2021). The SPS30 is a particle sensor that needs to be connected to either a computer or a microprocessor together with other components for data storage and access. For this study, the SPS30 was connected to an Arduino Mega microprocessor, together with a micro-SD module, a DS3231 real-time clock and a power bank. We refer to this full set-up as SPSA. The SPSA is low-cost because of its measurement principle and being self-built. The price of all components combined was approximately $50.00. The data quality of the SPSA was evaluated in Arba Minch at different ambient and high-exposure (kitchen) locations. Amongst itself, variation at ambient locations was small (coefficient of variation 4-6%, R^2 = 0.98-1). Based on comparison with a reference instrument, a calibration factor of 2 for ambient concentrations was found (Dingemanse, 2022a).

2.3 Data collection

Data was collected with the student science method: letting students conduct research as part of their curriculum (Dingemanse & Dingemanse-de Wit, 2022). As part of a course, students in groups of 5-6 studied traffic air pollution. They produced a measurement plan, collected and analyzed data, and wrote a measurement report. Seven student groups selected six locations and got an instrument for 6 weeks. The instruments were set at either 10-second or 1-minute measuring frequency. Students took the instruments once a week to the lecturer to retrieve data from the SD card. At that moment, the lecturer performed quality checks such as the time setting, availability of data, and students having noted start and end times.

At location A1, the students placed the instrument in the morning and collected it in the evening. At locations A2 and A3, the instrument was placed inside for safety and charging during nighttime and placed outside during daytime. Students only discontinued measurements when they took the instrument for data retrieval. At locations A2 and A3, after two weeks the specific location changed to another place: at the same distance but another orientation relative to the nearby traffic square. We treated two locations at the same square as one location. At location A4, the instrument was placed in an office whose windows were open windows during daytime. At this location, less data was collected as the office holders were less dependable in connecting the instrument to a power source. For this location, we used only data between 6:00 and 21:00. Outside these times the power supply was irregular. For locations B1 and B2, the drivers placed the instrument in their Bajaj during their working hours.

Table 2 gives an overview of the amount of collected data per station.

Table 2. Available data.

Location	Days with data	Hours of data	Remark
A1	28	321	Only daytime
A2	35	643	Day and night (night inside)
A3	32	687	Day and night (night inside)
A4	20	258	Only daytime
B1	28	265	Only daytime
B2	23	259	Only daytime

Figure 2 visualizes the data collection times.

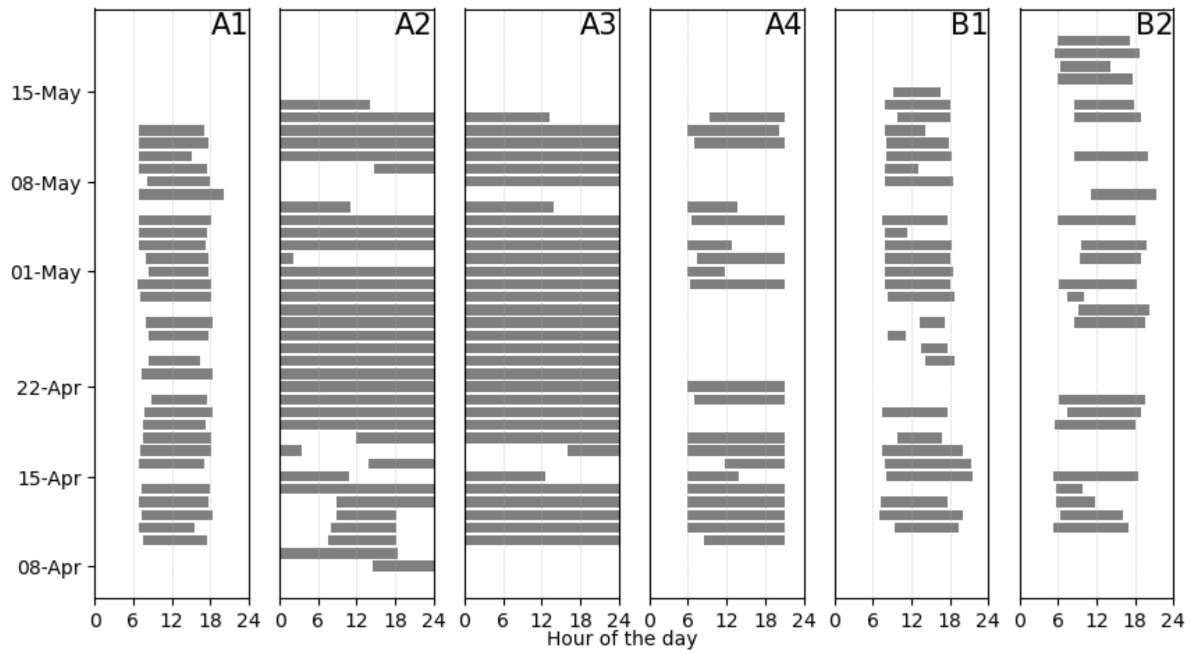

Figure 2. Data collection times for all measurement locations.

2.4 Data corrections

The real time clock of the SPSA failed in five occasions. Three times there was a full reset (two times at location B1, one time at location A4). Twice there was a 2-to-3-hour lag (location A2). In all incidents, we corrected the time during data retrieval, based on the time difference witnessed at that moment. A calibration factor of 2 is used based on comparisons of the SPSA with a reference method at an ambient location in Arba Minch (Dingemanse, 2022a). Grubb's Test was used to remove outliers at 99% level. This led to the removal of 2, 0.9, 2.3, 2.1, 4.4 and 3.5% of the data for locations A1, A2, A3, A4, B1 and B2, respectively.

2.5 Data analysis

The data analysis was based on 5-minute averaged data. All hour- and daily averages presented in this study are based on this 5-minute averaged data. Data is analyzed with respect to four topics: the concentration levels measured at the different locations, the temporal variation (hourly and daily), the spatial variation (difference amongst locations, whether those differences were significant, can be attributed to specific times, and have a correlation), and the difference between on-road and roadside concentrations.

3. RESULTS

3.1 General concentration levels

Figure 3 shows the daily averaged concentrations for all measurements combined (with hourly 5-95 percentile), and bar charts for the mean concentrations over time by location. Besides, the figure shows the 24-hour average guideline value of the WHO (15 µg/m^3).

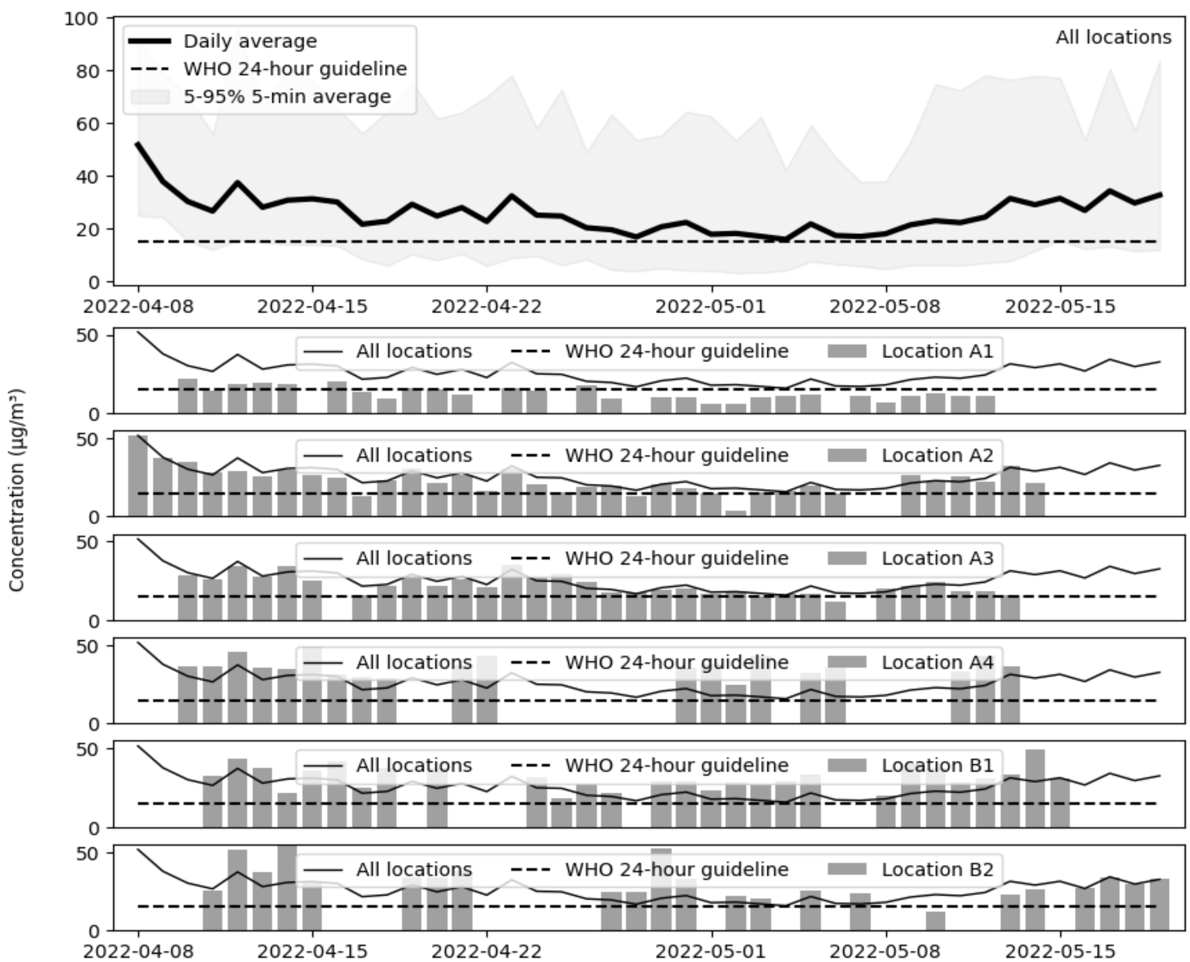

Figure 3. Daily averaged concentrations for all locations combined and individually. The shaded area shows 5-95% of five-minute averaged data for the corresponding day.

Concentrations varied between 10-50 µg/m^3 on a daily level, and between 5 and 100 µg/m^3 on 5-minute level. Averages for locations A1 through B2 were 13.0 ± 9.6, 23.3 ± 18.0, 22.6 ± 18.1, 36.2 ± 25.9, 32.6 ± 24.5 and 29.8 ± 22.3 µg/m^3, respectively. Night-time measurements were only available for locations A2 and A3. Concentrations between 6:00-21:00 at those locations were on average 25.9 ± 19.1 and 26.9 ± 19.5 µg/m^3. Daily average concentrations for days with at least 20 hours of measurements ranged from 14.4 to 35.6 µg/m^3. These concentrations were close to up to well over the WHO 24-hour guideline of 15 µg/m^3.

3.2 Temporal analysis

Figure 4 shows the average concentration per hour of the day.

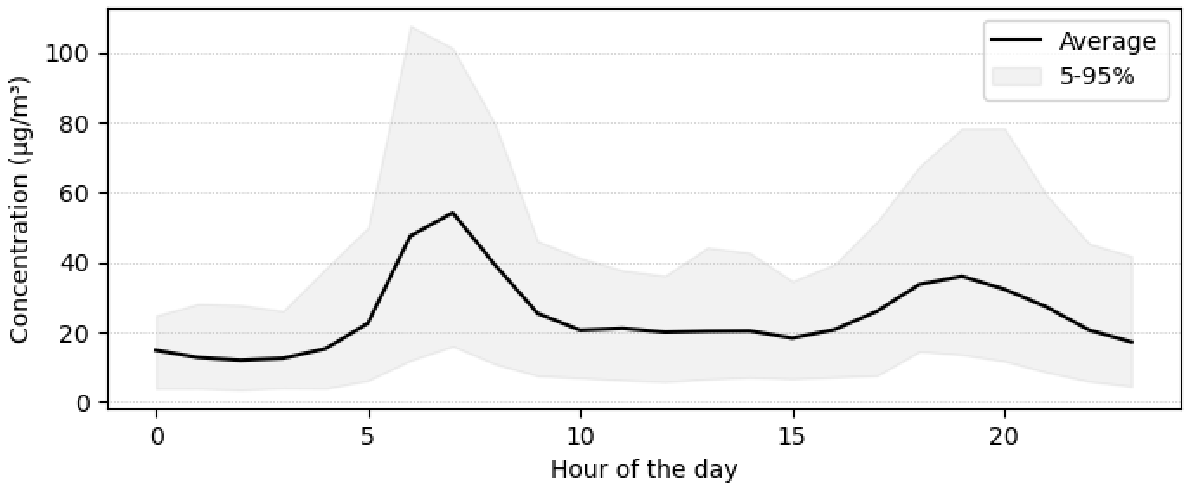

Figure 4. Concentrations averaged per hour of the day for all locations combined. Concentrations shown at hour x are those measured between hour x and x+1.

Based on figure 4, the day is split up in four distinct concentration periods. Concentrations peak in the morning and evening (6:00-10:00 and 17:00-21:00), and lowest concentrations are witnessed between those peaks (10:00-17:00 and 21:00-6:00). We call these two periods of lowest concentrations ‘afternoon’ and ‘night’. The periods morning, afternoon, evening, and night had average concentrations of 42 ± 12, 20 ± 1, 32 ± 4, and 17 ± 5 µg/m^3, respectively. On average the morning and evening peaks reached up to 50 and 35 µg/m^3, with the top 5% of the data ranging up to 100 and 80 µg/m^3, respectively. The morning and evening peaks matched with times of higher traffic intensity (people leaving or coming back home) and morning and evening food preparation times. During daytime, solar energy heating results in vertical transport of air (convective mixing). Convective mixing disperses available air pollution. The pollutants are dispersed over a larger volume of air, which results in lower concentrations. The evening peak was lower than the morning peak because there was more convective mixing owing to the preceding hours of solar energy heating. The afternoon and night periods showed similar concentrations with their average mostly around 20 µg/m^3. Emission of PM2.5 is lower during nighttime than during the afternoon. However, there is more convective mixing in the afternoon than during nighttime. These effects balance each other: despite lower emissions, during nighttime concentrations are not much lower.

Figure 5 shows the average daytime concentration for different days of the week (6:00-21:00) and the three distinct daytime periods. We excluded nighttime hours because there were nighttime measurements only at two locations.

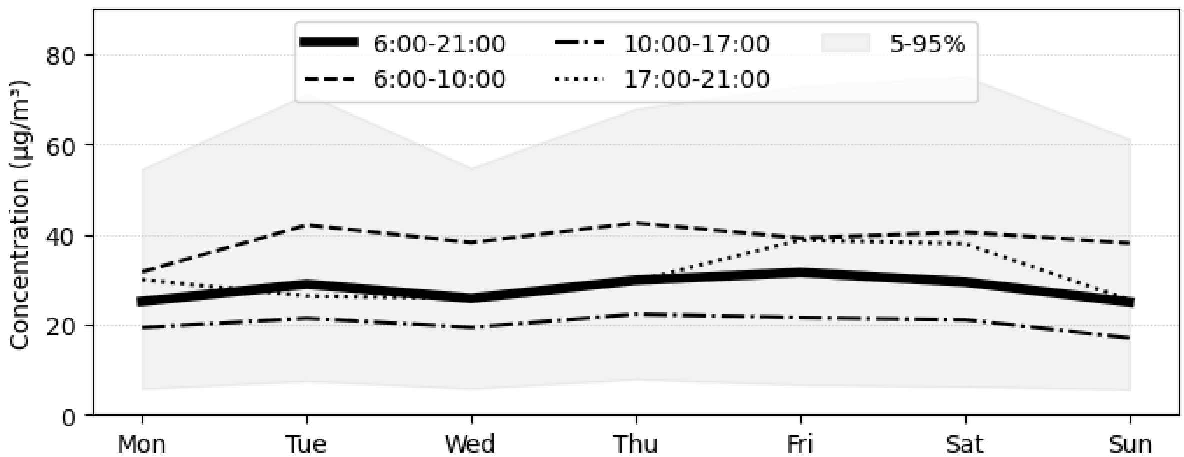

Figure 5. Concentrations averaged per day of the week for different time periods, for all locations combined.

The average day concentrations (from 6:00-21:00) did not vary significantly per day of the week. The evening peak was highest on Friday and Saturday (35 µg/m^3), while it was lowest on Sunday and Tuesday (20-25 µg/m^3). Highest concentrations were noted in the evenings of Friday and Saturday because of high traffic activities during weekends. The morning peak was lowest on Monday. On a Monday morning, many shops open late. Therefore, there is less traffic and a lower PM2.5 concentration. In between peak times (10:00-17:00), there is no significant variation across days of the week.

3.3 Spatial analysis

Figure 6 shows a boxplot of 5-minute averaged data for the six measurement locations. Only data measured between 6:00-21:00 is included. Nighttime hours were excluded as there were only nighttime measurements at two locations.

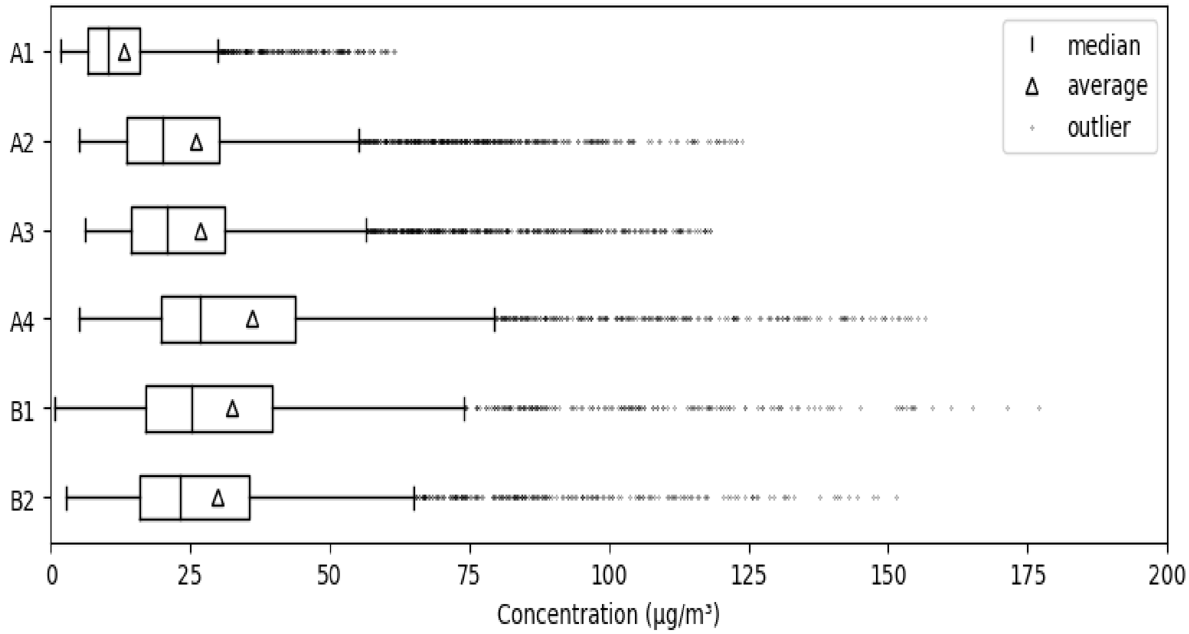

Figure 6. Boxplot of 5-minute average concentrations for all locations from 6:00-21:00. Outliers are all values outside the range of 1.5*(Q75-Q25) separated from the Q25 to Q75 box.

The variation was high at all locations. A high variation implies that concentrations were largely affected by nearby sources and dispersed soon after the moment of emission. If concentrations primarily originated from sources far away, the concentration would be more stable. Also, if concentrations would not disperse soon, the concentration would be more stable. A relatively fast dispersion of emitted PM2.5 results from the natural ventilation because of the surrounding topography of Arba Minch.

Location A1 had the lowest concentration. This location is in the periphery of Arba Minch. The traffic at this location has a steady flow, with fewer instances of starting and stopping. Also, there are not many houses near this location. The highest average concentrations were noted at location A4 (bus station). The locations with the highest variation were the mobile locations (B1, B2): they had the most outliers. Table 3 compares concentrations at hourly and daily averaged level with an independent samples t-test to evaluate whether differences are significant.

Table 3. Independent samples t-test between all locations for hourly averaged data and daily averaged data. Cells with insignificant results ($p \geq 0.1$) are shaded.

Hourly average concentration comparison <---	Daily average concentration comparison ---->					
	A1	t = -8.24 p<0.001	t = -9.69 p<0.001	t = -11.56 p<0.001	t = -10.47 p<0.001	t = -5.88 p<0.001
	t = -7.46 p<0.001	**A2**	t = -1.16 p=0.25	t = -4.97 p<0.001	t = -2.41 p=0.02	t = -1.47 p=0.23
	t = -10.88 p<0.001	t = -2.35 P=0.02	**A3**	t = -5.03 p<0.001	t = -1.64 p=0.11	t = -1.22 p=0.23
	t = -10.67 p<0.001	t = -5.35 p<0.001	t = -4.26 p<0.001	**A4**	t = 3.13 p=0.004	t = 1.37 p=0.19
	t = -13.62 p<0.001	t = -7.65 p<0.001	t = -3.66 p<0.001	t = -0.5 p=0.62	**B1**	t = 0.28 p=0.78
	t=-9.37 p<0.001	t=-2.03 p=0.04	t=-1.63 p=0.10	t=1.78 p=0.08	t=4.2 p<0.001	**B2**

Concentrations at hourly and daily averaged levels were significantly different ($p<0.1$) for most locations, except for location B2. At daily level, variation at location B2 was too big, relative to its average, to significantly distinguish it from concentrations at locations A2-A4 and B1. Interestingly, at an hourly averaged level, there was a significant difference. In other words, the hourly pattern over the day at location B2 was significantly different while overall (on a daily average) difference was insignificant.

A significant difference between the locations underlines the need for measurements at separate locations. Possibly, however, concentrations at one location can be estimated based on the concentrations at another location. Figure 7 shows the correlation coefficient (R^2) for ordinary least square regression without intercept between all stations on a daily and hourly averaged level.

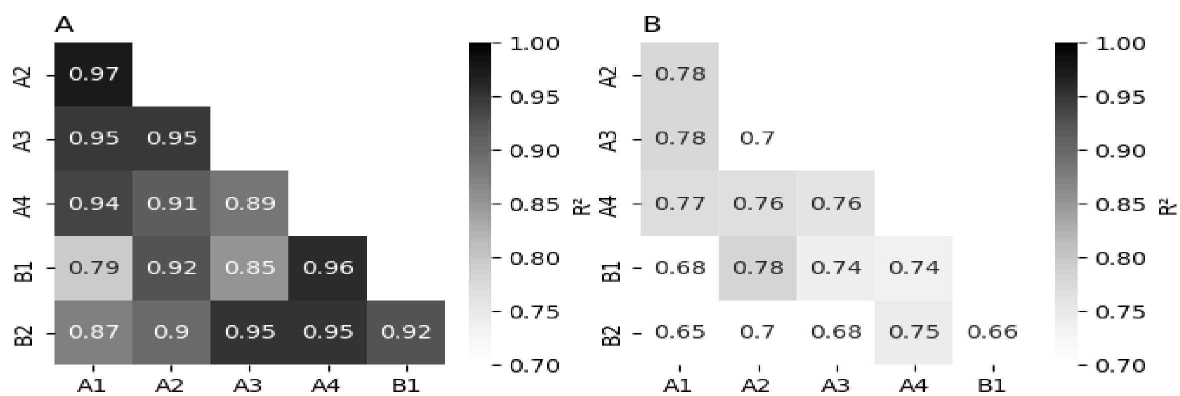

Figure 7. R^2 of data between all locations for daily averaged (A) and hourly averaged (B) concentrations. We used only the data for hours between 6:00-21:00.

On a daily level, strong correlations were noted between some of the measurement locations. Interestingly, location A4 strongly correlated with the mobile measurement locations ($R^2 \geq 0.94$). The stationary city locations A2 and A3 showed strong correlation with each other and with the out-of-town location (A1). In other words, concentrations could be predicted on a daily level for other locations based on one location. Concentration differences between locations were linear as differences in sources are linear as well. On an hourly level, however, correlations were much lower (R^2 = 0.66-0.79). To evaluate the difference between locations across hours of the day, figure 8 shows the hourly average concentration for all locations individually.

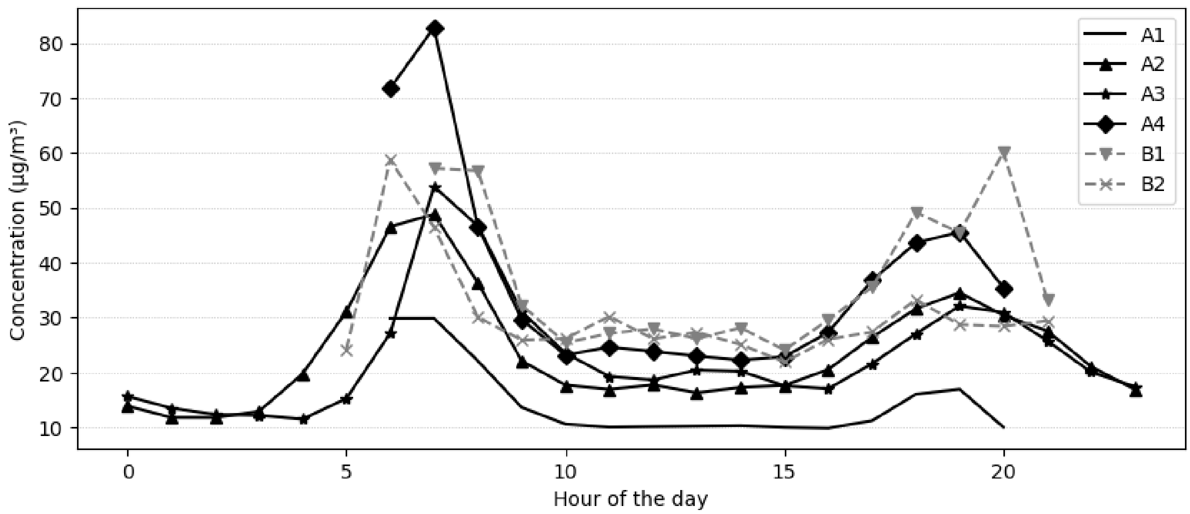

Figure 8. Concentrations averaged per hour of the day for all locations.

Figure 8 shows that concentration differences between locations were not the same across the day. This explains why the correlations at an hourly level were weaker. On a daily level, a linear difference in concentrations was observed between locations. However, this difference varied at hourly level. The highest average concentration at location A4 was due to concentrations during the morning period. The morning peak was distinctly highest at location A4 (bus station) while at other hours the concentration was the same to other locations. In the morning, long distance buses wait for passengers, running the motor. For the mobile stations, B1 concentrations were higher than B2 concentrations throughout most of the day. The work area of B1 was closer to the city center than B2. Hence, B1 was exposed to higher sources.

3.4 Next to the road versus on-road concentrations

Concentrations inside the Bajaj experienced the highest variation. On the road, variable concentrations are experienced due to nearby sources. At 10-20 meters from these sources, the concentrations become more diffuse, resulting in lower variability. Average on-road concentrations between 6:00-21:00 (33 and 30 $\mu g/m^3$ for B1 and B2) were lower than bus station concentrations (36 $\mu g/m^3$), but higher than the concentrations at the two locations next to the road (26 and 27 $\mu g/m^3$ for A2 and A3). The morning peak concentrations were in the same order of magnitude (38, 40, 45 and 38 $\mu g/m^3$ for locations A2, A3, B1 and B2, respectively). However, the concentrations on-road between 10:00-17:00 were higher than those next to the road (18, 19 $\mu g/m^3$ at A2, A3 versus 26, 27 $\mu g/m^3$ at B1, B2). Higher on-road concentrations imply traffic is a dominant source of roadside concentrations. If biomass burning was instead the main source for roadside locations, on-road concentrations would be lower than concentrations next to the road.

4. DISCUSSION

4.1 General concentration levels

Concentration levels ranged from 13.0 to 36.2 $\mu g/m^3$, and averages for days with at least 20 hours of measurements ranged from 14.4 to 35.6 $\mu g/m^3$. In Addis Ababa, average concentrations of 43.3 and 53.8 $\mu g/m^3$ were found at two locations (Kumie, 2020; Tefera et al., 2020). Daily averages ranged from 19.1 to 127.0 $\mu g/m^3$ (Tefera et al., 2020). Concentrations in Arba Minch are lower than those in Addis Ababa because Arba Minch is significantly smaller than Addis Ababa and has lower traffic flows and less household cooking. Still, multiple daily averages in Arba Minch exceeded the WHO guideline of 15 $\mu g/m^3$ as 24-hour average. With cities having higher populations than Arba Minch, we expect these cities to exceed the WHO guidelines. Even more, the topography around Arba Minch results in a natural ventilation. Cities with the same level of emission, but not a topography promoting ventilation, will experience higher concentrations. Therefore, it is advisable to conduct measurements in other cities of Ethiopia as well.

4.2 Temporal variation

We did not find a prominent pattern for days of the week in our study. In Addis Ababa lowest concentrations were witnessed on Sundays (Kumie, 2020). In Addis Ababa, while the contribution of traffic with respect to biomass burning is higher, traffic is lower on Sundays. However, biomass burning related to cooking may not necessarily be lower on Sundays. In Arba Minch, a relatively higher share of biomass burning might mask lower emissions of traffic. We did find a clear temporal pattern during the day, with highest concentrations during the morning hours. Minda (2014) found distinct peaks of black carbon (BC) concentrations during these hours as well. BC originates from combustion sources and is part of PM2.5. Traffic and household biomass burning are important sources for both PM2.5 and BC. BC concentrations during morning and evening hours reached up to 20 $\mu g/m^3$ while afternoon and nighttime concentrations were mostly below 5 $\mu g/m^3$. The morning and evening hours match with cooking times and traffic rush hours. With respect to roadside exposure, a higher number of people on the road during morning and evening hours is a double problem: exposure concentrations are high, but the number of people experiencing this exposure is also high.

Another temporal aspect is seasonal variation. Measurements in this study were all conducted in April/May, which are the wettest months within the bimodal rainfall pattern in Arba Minch (Mulugeta et al., 2017; Shalishe et al., 2022). In Addis Ababa, highest concentrations were reported during the wet season (Kumie, 2020; Tefera et al., 2020), but studies in other countries reported highest concentrations during dry seasons (Jinsart et al., 2012; Kim Oanh et al., 2013). Tefera et al. (2020) hypothesized that concentrations during the wet season in Addis Ababa were higher owing to heating-related emissions. Temperatures in Arba Minch are higher than those in Addis Ababa. Heating during the wet season is therefore not a common phenomenon. Data at a background location in Arba Minch show highest concentrations in November and December (dry season), and lowest concentrations in April/May (Dingemanse, 2022b). Compared to the findings of our study, concentrations are expected to be higher in other months that experience less rainfall. Based on this, we conclude that measurement results in our study were the bottom line for concentrations in Arba Minch, and yearly average concentrations are expected to be higher. Therefore, most likely WHO and Ethiopian yearly average guideline values of respectively 5 and 15 µg/m^3 (Environmental Protection Authority, 2003; WHO, 2021a) are exceeded.

4.3 Spatial variation

The findings suggested that the bus station was a hotspot. Cheng et al. (2011) found average concentrations of 50-70 µg/m^3 PM2.5 at a bus terminal in Taiwan, approximately 1.5 times higher than inside the buses in the same area, and about 10 times higher than urban background. Likewise, Salama et al. (2017) found concentrations exceeding air quality standards at three different bus stations in Saudi Arabia. Like us, they found that concentrations were distinctly higher during the morning than during the afternoon. Bus travel is an important means of transport in Ethiopia. As bus stations are located at a central location, for other cities of Ethiopia it is also expected that a bus station is an important contributor to urban air pollution. At other locations in Arba Minch, concentrations also exceed guideline values. It was found that concentration differences at distinct locations were statistically significant. Although PM2.5 concentration differences within the same city have not been adequately researched, the findings of Kumie, 2020 and Tefera et al., 2020 suggested a significant difference as well. At a daily averaged level, this study found strong correlations between some of the locations. Measurements are needed at separate locations for insight in roadside exposure in cities of Ethiopia. The strong correlations suggest, however, that with a short period of measurements at multiple locations, measurements can be changed to a limited number of locations in combination with extrapolation of those concentrations to other locations. Spatial variation can also be mapped if mobile measurements are combined with GPS measurements.

4.4 Next to the road versus on-road

It was found that on-road concentrations had a higher variation and are higher than concentrations next to the road, especially in the afternoon (10:00-17:00). Kim Oahn et al. (2013) measured concentrations of 21-30 and 52-60 µg/m^3 next to the road during respectively wet and dry season, respectively, while inside a vehicle during those seasons concentrations of 35 and 47 µg/m^3, respectively, were measured. In their study, on-road concentrations were not continuously higher than concentrations next to the road. Still, other studies found high concentrations for road users. Jinsart et al. (2012) compared exposure of different drivers in Bangkok: the highest exposure was recorded for tricycle drivers and vehicles with open windows. Similarly, in a city in Iraq Al-sareji et al. (2022) found that out of four transportation modes the car with open windows experienced the highest exposure, while motorcycles experienced the lowest exposure. Those studies found that PM2.5 concentrations were 86-350 $\mu g/m^3$ for these highest exposure modalities. The fact that tricycles and open-window vehicles experience the highest exposure suggests that for Arba Minch the Bajaj is the transport modality with highest exposure. Next to that, a common public transport mode in Arba Minch is a minibus, which drives with open windows as well. This suggests a similar high exposure.

4.5 Sources

High concentrations result from traffic and surrounding biomass burning. Concentrations getting higher on-road than next to the road suggested that traffic was a dominant source. Likewise, morning concentrations at bus stations came from buses waiting in the morning. If the dominant source was biomass, we would not see a distinction in morning and evening peak for that location. Whatever the source, there are ramifications for other cities. Other cities of Ethiopia have traffic and biomass burning as well. More than ten cities in Ethiopia have a higher population than Arba Minch. A higher population means an increase in both sources. The 2007 census reported that use of firewood was around 89% while electricity was only 0.2% in SNNPR and at country level (Population Census Commission, 2007). Since then, the use of electricity for cooking might have increased. However, there is no reason to expect that SNNPR will significantly differ from country average. The concentrations measured in Arba Minch are therefore not likely to be an overestimation relative to other cities.

4.6 Student science as method

The application of the student science method resulted in the limitation of sampling time to the course duration and a lower cooperation of location managers at the bus station. The measurements gave a good reflection of relative differences between locations. Insight in year-round and genuine 24-hour average concentrations was missing. Data collection during day and night at multiple locations and over different seasons requires a higher investment in supervision and course load, or dedicated measurement stations. Sharing a measurement project across multiple courses may result in higher course load and more supervision. However, the application of student science in the current study brought about relevant insight into city concentrations. The findings of this study conformed with concentration patterns found in other studies, pointed to peaks in time and locations, and underlined the burden of exposure above guidelines. In a situation with limited resources for data collection, student science fills the gap in knowledge on PM2.5 exposure in Ethiopian cities.

5. CONCLUSIONS AND RECOMMENDATIONS

In an application of student science and low-cost sensors, students conducted measurements at four stationary and two mobile stations in Arba Minch for six weeks. Daily average roadside concentrations in Arba Minch ranged from 10-50 $\mu g/m^3$, with 5-minute averages up to 100 $\mu g/m^3$. Daily averages exceeded air quality standards. This study revealed a distinct morning- and evening concentration peak at all measurement locations. Concentrations during 6:00-10:00 were twice as high as those during daytime. The two mobile stations showed the highest variation in concentration while the measurement location at the bus station showed both highest average concentrations and high variations. Highest concentrations at the bus station were primarily due to high concentrations during morning hours (6:00-10:00). On a daily average level, strong correlations were found between some of the locations; however, this was not the case on an hourly level. Apart from the bus station, on-road concentrations on average were higher than concentrations next to the road primarily owing to higher afternoon concentrations.

Results for Arba Minch imply exposures exceeding air quality guidelines in multiple cities of Ethiopia. This underlines the need for increased data collection across Ethiopia. With limited resources, it is important to find ways to make research cheaper. We found that, on a daily level, it was possible to monitor at one location and extrapolate it to some other locations within the same city. Furthermore, this study showed that student science and low-cost sensors were useful for increasing the availability of data collection. Limitations originating from student science, such as locations not trusting the data collectors, can be resolved by more active involvement of staff. While this study was limited to the duration of one course, data collection across different seasons becomes possible through student science if there is cooperation amongst different course instructors and universities.

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Data availability

All data used and code created in this study is made available on the OSF repository, https://doi.org/10.17605/OSF.IO/WHU6A.

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