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Measuring students' exposure to particulate matter (PM) pollution across microenvironments and seasons using personal air monitors

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Abstract Particulate matter (PM) pollution is a significant concern in public health, yet children's exposure is not adequately characterized. This study evaluated PM exposures among primary school-aged children in NYS across different microenvironments. This study helps fill existing knowledge gaps by characterizing PM exposure among this population across seasons and microenvironments. Sixty students were recruited from randomly selected public primary schools representing various socioeconomic statuses. Individual real-time exposure to $PM_{2.5}$ was measured continuously using AirBeam personal monitors for 48 h. Children were consistently exposed to higher $PM_{2.5}$ concentrations in the fall (median: fall = 2.84, spring = 2.31, winter = 0.90 μg/m^3). At school, 2.19% of $PM_{2.5}$ measurements exceeded the EPA annual fine particle standard, 12 μg/m^3 (winter = 7.38%, fall = 2.39%, spring = 1.38%). In classrooms, $PM_{1\text{-}4}$ concentrations were higher in spring and overnight, while $PM_{7\text{-}10}$ concentrations were higher in fall and school hours. At home, 37.2% of fall measurements exceeded EPA standards (spring = 10.39%, winter = 4.37%). Overall, $PM_{2.5}$ levels in classrooms and during transportation never rose above the EPA standard for any significant length of time. However, $PM_{2.5}$ levels routinely exceeded these standards at home, in the fall, and the evening. More extensive studies are needed to confirm these results.

Keywords Primary school · Indoor environment · Children's exposure · Personal monitor · Seasonal variation · Particulate matter

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Introduction

Particulate matter (PM) pollution is significant due to its ability to penetrate and lodge in alveolar tissue (EPA, 2021). PM, especially particles with a diameter of 2.5 μm and smaller ($PM_{2.5}$), is implicated in respiratory diseases (Hopke et al., 2019), heart attacks (WHO, 2013; Huxley-Reicher et al., 2021), cognitive impairment (Calderón-Garcidueñas et al., 2011; Clifford et al., 2016; Mohai et al., 2011), and premature death (Caiazzo et al., 2005).

Unfortunately, many adverse health outcomes associated with $PM_{2.5}$ are exacerbated in children because; compared to adults, they breathe more rapidly (Fleming et al., 2011), and their immunological systems are still developing (MacNaughton et al., 2017). A systematic assessment of sources of $PM_{2.5}$ in classrooms showed that most in-classroom $PM_{2.5}$ comes from secondary pollution and motor vehicles that infiltrate indoor spaces (Carrion-Matta et al., 2019). While some studies report that US classrooms experience $PM_{2.5}$ concentrations well below EPA standards (Sánchez-Soberón et al., 2019), other literature provides compelling evidence that concentrations of many air pollutants in schools are often outside of healthy recommendations, mainly due to the lack of adequate ventilation (Fisk, 2017). Since US children spend most of their time inside, including over 1000 h in school every year, improving air quality in schools can prevent disease and promote health in this population (Cohen, 2010; Csobod et al., 2014).

Although it is well established that $PM_{2.5}$ harms human health, the real-time exposure to and temporal trends/seasonality of this pollutant have not been adequately characterized in primary school-aged children. One reason for this is that many studies attempting to characterize children's exposure to $PM_{2.5}$ only focused on one microenvironment and did not comprehensively depict exposure from all sources (Carrion-Matta et al., 2019; Sánchez-Soberón et al., 2019; Fisk, 2017; Stranger et al., 2008; Morawska et al., 2017). Other studies used only stationary monitors and did not accurately estimate personal exposure to the pollutant(s) of interest (Sánchez-Soberón et al., 2019; Morawska et al., 2017). Finally, the importance of seasonal variation in $PM_{2.5}$ exposure has not been established. Individuals are typically exposed to more outdoor pollution during spring and indoor pollution during winter. However, few studies on schoolchildren have separated their results by season or even taken measurements in multiple seasons (Delfino et al., 2004; Johnston et al., 2020; Morawska et al., 2017; Rabinovitch et al., 2016).

This study helps fill existing knowledge gaps by (1) characterizing the temporal distribution of children's exposure to $PM_{2.5}$, including hourly, daily, and seasonal trends; (2) comparing real-time $PM_{2.5}$ exposures in different microenvironments —school, homes, during transit, at public school, and university; and (3) using stationary monitors in classrooms to measure the temporal trends of different sized particles (PM_1, $PM_{2.5}$ PM_4, PM_7, PM_{10}, and total suspended particles [TSP]).

Materials and methods

This cross-sectional analysis was conducted from August 2017 to May 2019 and involved enrolling ten New York State (NYS) primary schools in the capital region. Schools with fourth-grade enrollment were selected from public school districts within the four greater Capital District Board of Cooperative Educational Services (BOCES) regions. A varied study sample was obtained based on school SES and greenness. School SES was measured using the percent of students eligible for a free lunch from 2005 SED data and checked against 2008 SED data. Districts with schools in the highest and lowest tertiles of SES were selected, and then, within each SES group, districts with schools in the lowest and highest GSI quartiles were chosen. Districts with schools near the GSI and SES cutoff points were included to obtain a geographically representative sample and increase the number of candidates. A total of 65 schools in 41 districts were selected from 162 and 83, respectively. A stratified random sampling method was used to choose which schools to contact first, and recruitment letters were sent to the corresponding district superintendents. The next school on the list was contacted if a school refused to participate or did not respond after three follow-ups.

Finally, nine schools in the capital region agreed to participate in the SHAPE project. Unfortunately, three schools withdrew from the study before undergoing air quality measurements, leaving six primary schools — two representing high SES urban areas, three representing low SES urban areas, and one representing low SES rural areas. Participating schools received $200 gift cards to Target for school supplies. Two departments at SUNY Albany were included in this study to compare the 11 classrooms from 6 NYS primary schools and help make up for the three schools that dropped from the study. The UAlbany School of Public Health was selected due to its proximity to a wastewater treatment plant (WWTP). WWTPs are significant sources of several air pollutants, including CO, CO2, VOCs, and PM (Widiana et al., 2019). In addition, these and other types of municipal and

industrial facilities are common in urban areas and along roads near where the study population lives and, therefore, represent a relevant exposure in this study. The UAlbany Atmospheric Sciences Research Center was selected to represent exposure to PM on the main university campus, where thousands of students spend several hours most days.

Instrumentation

This study utilized AirBeam personal air quality monitors (HabitatMap) to measure individual exposure to PM pollution. The AirBeam is a hand-sized device that measures local temperature, humidity, and $PM_{2.5}$ mass concentrations (HabitatMap, 2021). It does so by drawing in air and using a light scattering method, which allows the monitor to determine particle mass and number in real time (HabitatMap, 2021; Mukherjee et al., 2017). AirBeams have been used in many different environments (Rabinovitch et al., 2016; Johnston et al., 2020; Korto et al., 2021; Mazaheri et al., 2018; Folkerth et al., 2020; D'Eon et al., 2021), validated against several other air monitors, and typically achieve moderate correlation and high precision with reference instruments (Borghi et al., 2018; Mukherjee et al., 2017; Sousan et al., 2017). Each participant was also given a Samsung Galaxy J3 Eclipse smartphone to record data using the AirCasting app. After 48 h of continuous measuring, the data was uploaded to secure computers.

In-classroom PM concentrations were collected using a stationary Aerocet 531S Handheld Particle Counter (Met One Instruments, 2014). Each Aerocet was placed on a table at the back of each classroom behind the students on the morning of day one and removed on the morning of day 3. The Aerocet 531S measured temperature, relative humidity (RH), PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP.

All PM monitors were calibrated against laboratory samples before any school measurements were made. Before traveling to each classroom, the single stationary Aerocet monitor underwent gravimetric calibration in a laboratory setting. Specifically, the indoor monitor was tested to ensure it was within 5% of the lab sample and maintained a flow rate between 1.0 and 3.5 L/min. Before traveling to each classroom, the ten AirBeam monitors were calibrated against one another and the stationary Aerocet monitors. Specifically, the personal monitors were tested to ensure they remained within the manufacturer's calibration range. All detailed procedures regarding sampling method, equipment calibration, and PM measurement recording have been standardized in a document required by the EPA. The field staff was systematically trained by two co-investigators for this project, Dr. Thurston and Dr. Khwaja, to ensure the quality and normal functioning of AirBeam and other equipment before each field trip.

Procedure

School environments were assessed by (1) measuring $PM_{2.5}$ using a real-time personal monitor and (2) measuring in-school and classroom air quality using a real-time stationary monitor. On average, two teachers and eight students from each participating classroom were given an AirBeam for 48 consecutive hours to measure individual exposure to temperature, humidity, and $PM_{2.5}$ on weekdays. Participants were instructed to keep the devices with them throughout the day and within ten feet of their phones to maintain the Bluetooth connection. Personal monitoring occurred in spring and was repeated with the same students in either fall or winter. At the same time, the corresponding classroom underwent 48 h of monitoring using stationary monitors (described later). Everyone who participated in the personal monitoring portion of the study received a $60 Target gift card as an incentive.

At the same time, temperature, humidity, CO_2, CO, PM, and volatile organic compounds (VOCs) were measured in participating classrooms using an Aerocet. Each round of in-school air quality measurements was conducted in fall, winter, or spring. Summer was excluded because most students do not attend school during this season in the USA. A comparison of in-class measurements using AirBeams and Aerocets can be found in Fig. 4 in the Appendix.

Data analysis

Individual and in-class air monitoring data were collected for 48 consecutive hours. As air pollution concentrations were collected every minute, measurements from the closest timeslot were used to impute any missing values to help maintain data integrity. Unfortunately, due to user error (not charging phone, disconnecting bluetooth between phone and AirBeam,

leaving the AirBeam away from their person) and smartphone malfunctions (freezing, crashing), data from 12 of the 60 primary school children (20%) and 1 of the 30 college students (3.33%) was unusable. All AirBeam data were stripped of identifying information, individual and school, and aggregated according to calendar date and time. $PM_{2.5}$ concentrations retrieved from AirBeam data were then plotted using the smooth function of the "ggplot2" package in R statistical software. This function smooths the mean $PM_{2.5}$ concentration trend and removes the influence of momentary spikes above 100 µg/m^3. Aggregation and smoothing of data also allowed us to assess the overall seasonal trend of $PM_{2.5}$ exposure for NYS capital region students and helped reduce the impact of missing data in this study. All analyses and data aggregation were completed using R 4.0.0 statistical software and the "data.table" package. The "ggplot2" package was used to create all figures.

Table 1 Primary School Children $PM_{2.5}$ Concentrations by Season, 2017–2019 (AirBeam)

$PM_{2.5}$ concentrations (µg/m^3) all microenvironments combined				
Statistic	**Overall**	**Winter**	**Spring**	**Fall**
Maximum	189.25	161.05	114.29	189.25
Minimum	0.54	0.54	0.54	0.54
Median	2.31	0.90	2.31	2.84
Mean	6.35	4.20	4.93	16.02
25th percentile	0.94	0.54	1.17	0.78
75th percentile	5.11	6.65	4.43	9.40
Interquartile range (IQR)	4.17	6.11	3.26	8.62
Total measurements	56,764	7,132	41,860	7,772
Measurements > 12 µg/m^3[a]	8.69%	5.14%	7.38%	18.98%

12.0 µg/m3 is the EPA annual fine particle standard (average annual concentration) (note: no federal indoor pm standard exists)

Results and discussion

AirBeam personal air monitors

Overall trends

Table 1 shows real-time, one-min average $PM_{2.5}$ concentrations among the 77 participants by season and across microenvironments. The median $PM_{2.5}$ concentration in the fall was significantly higher than in the spring and winter (fall: median = 2.84, spring: median = 2.31, winter: median = 0.90 µm/m^3). Specifically, 18.98% of measurements taken in the fall exceeded the EPA annual fine particle standard of 12 µm/m^3, approximately 3.5 times as many measurements as in the winter (5.14%) and 2.5 times as many measurements as in the spring (7.38%). $PM_{2.5}$ concentrations also varied more in the fall than in spring and winter (fall: IQR = 8.62, winter: IQR = 6.11 µm/m^3, spring: IQR = 3.26).

Temporal trends

As shown in Fig. 1, the temporal trend of $PM_{2.5}$ daily concentrations varied by season. Interestingly, the highest spikes of $PM_{2.5}$ concentrations in fall and spring occurred at home around 9:00 pm, whereas there was no significant peak in winter. Despite these consistent temporal spikes, the only time the average $PM_{2.5}$ concentration exceeded the EPA standard was in the fall. Outside of those evening spikes, $PM_{2.5}$ concentrations stayed below the EPA standard.

Trends by microenvironment

Table 2 summarizes $PM_{2.5}$ concentrations separated by both season and microenvironment. Peak daily concentrations of $PM_{2.5}$ occurred at home (defined as 2:30 pm to 8:00 am) during the fall and spring (fall: max = 189.25, spring: max = 114.29 µm/m^3) but occurred during school hours (defined as 8:30 am–2:00 pm) in the winter (161.05 µm/m^3). $PM_{2.5}$ concentrations in the fall varied the most across the three microenvironments (in-school: IQR = 2.37, transportation: IQR = 5.85, home: IQR = 28.54 µm/m^3). Across all seasons, $PM_{2.5}$ concentrations at home varied the most (fall: IQR = 28.54, spring: IQR = 3.90, winter: IQR = 5.88 µm/m^3). During school hours, 7.38% of $PM_{2.5}$ measurements exceeded the EPA standard in winter, followed by 2.39% in fall and 1.38% in spring. In homes, 12.21% of the observations exceeded the EPA standard, followed by 4.35% during transportation and 2.19% in school. More than one-third (37.2%) of the in-home measurements in fall exceeded the EPA standard, followed by 10.39% in spring and 4.37% in winter. During transportation, 12.21% of measurements in fall exceeded

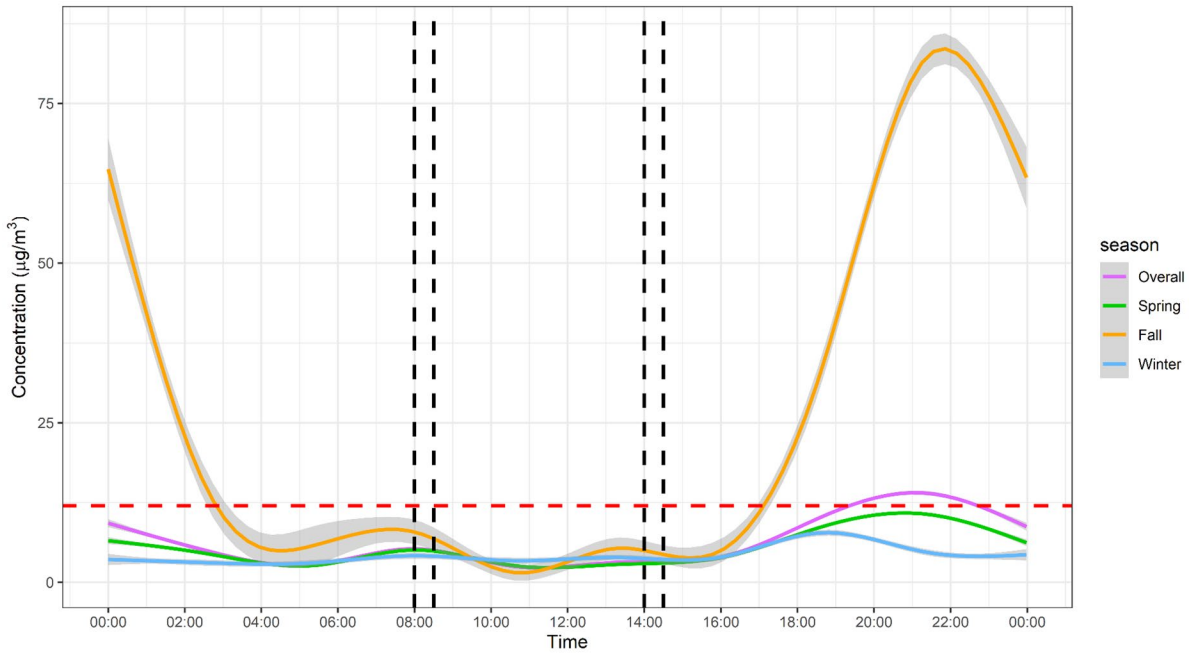

Fig. 1 Seasonal trends of primary school children's exposure to $PM_{2.5}$ (vertical black lines separate time by microenvironment (transport: 8:00–8:30, 14:00–14:30, school: 8:30–14:00, home: 14:30–8:00); the horizontal red line represents the EPA's outdoor annual average $PM_{2.5}$ standard: 12.0 µg/m.^{3} (note: no federal indoor pm standard exists)) (personal monitor)

the EPA standard, followed by 4.21% in winter and 2.54% in spring.

Trends by student type

Figure 2 presents different temporal trends of $PM_{2.5}$ daily concentrations by school type (university measurements were only taken in the spring). $PM_{2.5}$ concentrations followed the same basic trend for primary school and college students. Peak concentrations occurred in the evening (elementary school: 9:00 pm; university: 7:45 pm). In addition, a second peak occurred for both groups during morning transportation at 8:00 am. Throughout the day, $PM_{2.5}$ concentrations never rose above 12 µg/m^3 and tended to be lowest during the school hours of 10:00 am and 2:00 pm for both groups.

Aerocet stationary air monitors

Temporal trends

In addition to personal AirBeam monitors, stationary monitors measured several different diameters of PM in classrooms. As shown in Fig. 3, in-school $PM_{2.5}$ and PM_4 concentrations in spring remained slightly higher than in the fall and winter, while PM_7, PM_{10}, and TSP concentrations in the fall were significantly higher than those in the spring and winter. PM_1 concentrations, on the other hand, were much more variable during the day. Overall, the most prominent peak of PM_1 was observed at 5:00 pm, after students and staff had left for the day. Although concentrations of the different sized particles varied over time, no measurements exceeded the EPA guidelines.

PM temporal variation

Seasonal variation

This study discovered a strong seasonal trend regarding PM pollution. Fall was the only season during which $PM_{2.5}$ concentrations exceeded the EPA annual fine particle standard of 12 µg/m^3. In addition, largely due to these excessive spikes, the mean, median, and range of $PM_{2.5}$ concentrations were significantly higher in the fall than in other

Table 2 $PM_{2.5}$ concentrations among primary school children by microenvironment and season, 2017–2019 (AirBeam)

Statistic	In-school				Transportation				Home			
Season	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall	Overall	Winter	Spring	Fall
Max	161.05	161.05	110.02	124.10	127.56	14.72	29.89	127.56	189.25	114.68	114.29	189.25
Min	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Median	2.12	0.57	2.38	1.25	2.77	2.51	2.74	3.12	2.44	1.43	2.25	8.64
Mean	3.15	3.81	3.14	2.87	4.61	4.54	3.52	9.33	8.068	4.33	5.82	30.49
25th percentile	0.74	0.54	1.27	0.54	1.03	0.54	1.22	1.03	1.03	0.54	1.13	2.77
75th percentile	3.62	7.42	3.76	2.91	5.19	8.19	4.43	6.88	6.19	6.42	5.03	31.31
IQR	2.88	6.88	2.49	2.37	4.16	7.65	3.21	5.85	5.16	5.88	3.90	28.54
Total measurements	18,136	1,857	12,509	3,770	2,344	261	1,690	393	36,284	5,014	27,661	3,609
Measurements > 12 $\mu g/m^3$[a]	2.19%	7.38%	1.38%	2.39%	4.35%	4.21%	2.54%	12.21%	12.21%	4.37%	10.39%	37.20%

[a]12.0 $\mu g/m^3$ is the EPA annual fine particle standard (average annual concentration) (note: no federal indoor pm standard exists)

seasons. Similar research on inner-city schools in the Northeast reported lower indoor $PM_{2.5}$ concentrations in fall compared to spring and winter, contrary to the results in this study (Carrion-Matta et al., 2019). After conducting a literature review for this paper, it is not readily apparent why $PM_{2.5}$ levels would be so much higher in the fall compared to the spring and winter, as no other papers have noted similar results for this study population.

However, there are several reasons why this could be the case. First, researchers have noted how important outdoor sources are to indoor air pollution and seasonal variation (Rovelli et al., 2014). A systematic assessment of sources of $PM_{2.5}$ in classrooms showed that the majority of in-classroom $PM_{2.5}$ comes from secondary pollution (41%), motor vehicles (17%), and other outdoor sources that infiltrate indoor spaces (Carrion-Matta et al., 2019). In fall, motor vehicles contribute more to indoor air pollution than spring and winter due to local use of motor equipment in that season (i.e., leaf blowers and lawnmowers) (Carrion-Matta et al., 2019). A subset of participants in this study may have been exposed to significant emissions from motor vehicles and other equipment.

The data collected in this study suggest that the significantly higher PM concentrations observed in the fall occurred primarily in homes. Extreme spikes in indoor PM concentrations typically result from an acute activity, such as burning incense, candles, or cooking (Morawska et al., 2017). In addition, these concentrations may linger in the absence of adequate ventilation. Therefore, a unique exposure to one or more of the well-documented sources of indoor air pollution among a subset of participants may also be responsible for much of this statistical difference — engine exhaust, tobacco smoke, cooking activities, fireplaces, heaters, and use of fragrance products (Bruce et al., 2014; EPA, 2021; Morawska et al., 2017; Stabile et al., 2017).

Interestingly, in-class concentrations of $PM_{2.5}$ were lowest in the winter. Since ventilation plays a crucial role in reducing indoor air pollution, many studies have noted higher concentrations of various air pollutants (including PM) during colder months (Fisk, 2017; Stabile et al., 2017). For example, a study conducted in Spain found that in-classroom $PM_{2.5}$ concentrations were slightly higher than those reported in the northeastern USA in both cold (mean = 7.87 μg/

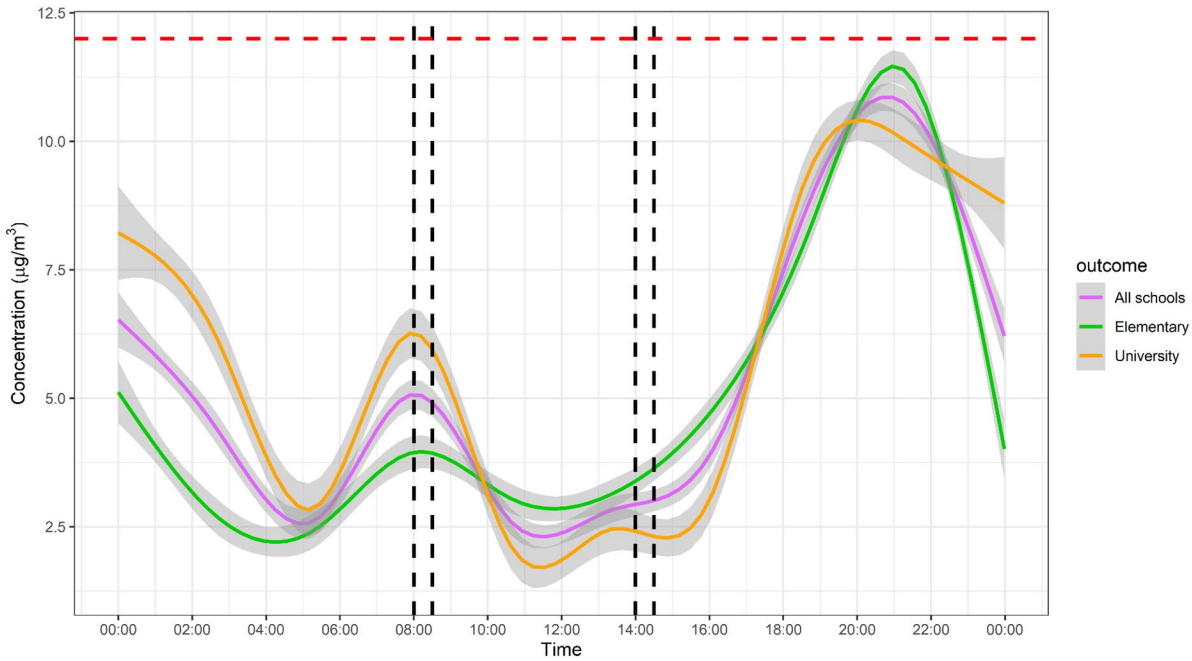

Fig. 2 Temporal trends of $PM_{2.5}$ concentration by school type (vertical black lines separate time by microenvironment (transport: 8:00–8:30, 14:00–14:30, school: 8:30–14:00, home: 14:30–8:00); the horizontal red line represents the EPA's outdoor annual average $PM_{2.5}$ standard: 12.0 µg/m.^{3} (note: no federal indoor pm standard exists)) (spring only, in-class monitor)

m^3) and warm (mean = 5.99 µg/m^3) seasons (Sánchez-Soberón et al., 2019).

Daily $PM_{2.5}$ peaks

Across all seasons, daily $PM_{2.5}$ concentrations peaked in the evening and followed the same basic pattern. Specifically, daily concentrations started under 10 µg/m^3 (8:00 am) and stayed at this level until around 4:00 pm, just after children returned home from school. The evening peak $PM_{2.5}$ concentrations were also consistent across seasons, though the magnitude of those peaks differed. These peaks are likely due to cooking, a well-documented PM source. Zhang et al. (2010) conducted a study that extensively analyzed the indoor air quality effects of several cooking modes. Their results indicate that, while TSP concentrations return to baseline within 2 h of heating elements being turned off, it takes several (4 +) hours for $PM_{2.5}$ concentrations to return to pre-cooking levels depending on the method, ingredients, and kitchen ventilation (Zhang et al., 2010). The evening peaks observed in this study are likely a combination of resuspended PM due to indoor activity, cooking, and lack of ventilation.

Temporal patterns by PM diameter

In-class PM pollution increased significantly at 7:00 am and stabilized at 9:00 am when school began. Smaller PM ($PM_{1\text{-}4}$) concentrations were relatively low during school hours and rose significantly after school. On the other hand, larger PM (PM_7, PM_{10}, and TSP) concentrations peaked during school hours. Previous research suggests that the size of PM pollution may be a significant factor in this study (Csobod et al., 2014; Gaffin et al., 2017). Specifically, larger particles are more prone to re-suspension due to movement. Figure 3 shows that PM_7, PM_{10}, and TSP concentrations are higher in classrooms during school hours than during non-school hours. These data support the hypothesis that larger particles are prone to re-suspension when children are present and active.

PM microenvironmental variation.

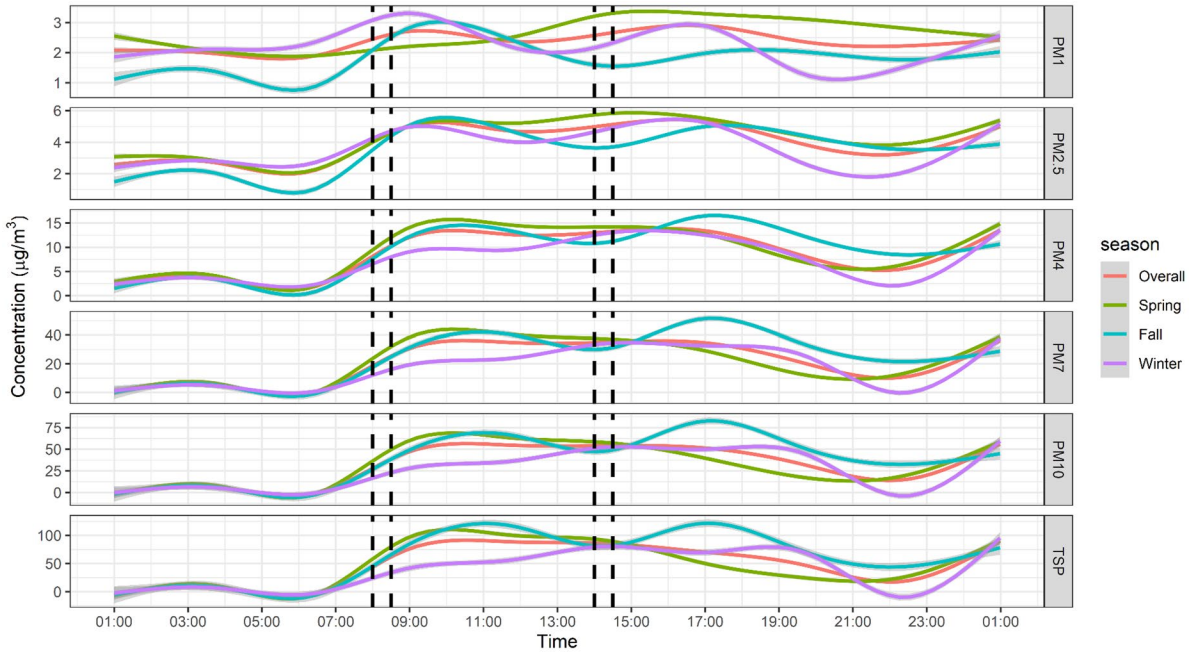

Fig. 3 Temporal trend of primary school children's exposure to different diameters of PM (vertical black lines separate time by microenvironment (transport: 8:00–8:30, 14:00–14:30, school: 8:30–14:00, home: 14:30–8:00); the horizontal red line represents the EPA's outdoor annual average $PM_{2.5}$ standard: 12.0 µg/m.^{3} (note: no federal indoor pm standard exists)) (in-class monitor)

Home, school, and transit

Approximately 12% of $PM_{2.5}$ measurements in homes exceeded EPA standards, significantly more than during transportation and school. As explained in the previous section, this large discrepancy is likely due to cooking, primarily in the home setting. Homes are also smaller and less ventilated than school buildings, meaning that PM pollution from cleaners and deodorizers is less able to disperse in this location. In addition, tobacco smoke and emissions from fireplaces are PM exposures unique to the home and are likely to occur in the evening when children have already returned from school. Rabinovitch et al. conducted a personal exposure study on thirty Denver-area school children with asthma (Rabinovitch et al., 2016). These researchers also found that children were consistently exposed to the highest $PM_{2.5}$ concentrations at home. Johnston et al. (2020) conducted a similar study on eighteen children in Southern California who lived and went to school near a freeway (Johnston et al., 2020). These children were exposed to an average concentration of 10.7 µg/m^3 and peak concentrations after school, during outdoor activities or indoor cooking.

In this study, students were rarely exposed to $PM_{2.5}$ concentrations above the EPA standard at school. Fewer than 1% of the total classroom measurements exceeded this limit. These results match those from other air quality studies conducted in classrooms. For example, a study conducted in 32 inner-city Boston schools across all relevant seasons found that indoor levels were well under EPA standards (mean = 5.2 µg/m^3) and generally lower than outdoor levels (mean = 6.5 µg/m^3) (Carrion-Matta et al., 2019). Rabinovitch et al. (2016) also found that children were exposed to the lowest overall $PM_{2.5}$ concentrations at school. In addition, in-class was the one microenvironment where children did not experience an "exposure event" where the PM concentration increased by 5 µg/m^3 rapidly (Rabinovitch et al., 2016).

During transportation, students were exposed to more PM pollution in the fall, although the concentrations in each season varied significantly. Very few measurements exceeded the EPA standard during transit, and the few that did are likely related to

car and bus exhaust. As mentioned, motor vehicles contribute more to air pollution in the fall due to the widespread usage of leaf blowers and lawnmowers (Carrion-Matta et al., 2019). These vehicles may account for the seasonal difference observed during transit.

Elementary school children vs. college students

Peak exposure to $PM_{2.5}$ varied significantly between elementary school children and university students. For instance, university students were exposed to significantly higher $PM_{2.5}$ concentrations during morning transportation than elementary school children. However, schoolchildren were consistently exposed to higher levels during and after school. A likely confounding factor is that these two groups do not share the same school hours. For example, university students may primarily drive their cars to class while younger children may primarily ride the school bus, accounting for some difference in their $PM_{2.5}$ exposure. Other potential explanations include more exposure in primary school classrooms (art supplies, printers, chalk) and smaller, more enclosed spaces than college classrooms.

Aerocet vs. AirBeam measurements

Overall, each device detected $PM_{2.5}$ concentrations rising between 12:00 and 1:00 PM (Fig. 4 in the Appendix). However, these results varied by season. For example, the AirBeams detected significant spikes in $PM_{2.5}$ concentrations between 11:30 AM and 12:00 PM in spring and fall. On the other hand, Aerocets detected significant spikes slightly later between 12:30 and 1:30 PM. Interestingly, Aerocets measured the same level of $PM_{2.5}$ in the spring and fall, while AirBeams measured significantly higher concentrations in the fall. In the winter, however, the two devices agreed almost perfectly. These results suggest seasonal differences in PM exposures and how PM tracks from outdoor to indoor environments. Another possible explanation for these differences is the technical differences between the devices. For example, AirBeams use LEDs and can only detect $PM_{2.5}$, while Aerocets use high-energy lasers and can differentiate between eight different resolutions of PM (Kumar & Foster, 2008; Nguyen et al., 2021). This and other technical differences make Aerocets more powerful and accurate when measuring particle concentrations.

Another reason the measurements recorded by these two devices may be different is their location in the room. AirBeams were, ostensibly, located adjacent to each participant, while Aerocets remained stationary at the back of each classroom throughout the study period. This difference in mobility means that the AirBeams were more frequently near environmental disturbances (activity among children) and, therefore, subject to larger spikes and more variable $PM_{2.5}$ concentrations. Finally, the differences in meteorological and seasonal factors, combined with the previously mentioned factors, may explain the differences shown in Fig. 4 in the Appendix. While Aerocets remained in consistent thermal conditions, AirBeams traveled between microenvironments and were consistently closer to active children. Therefore, the mobile AirBeams encountered elevated temperature, RH, and related obfuscation of PM measurement compared to their stationary counterparts.

Strengths and limitations

As far as the authors are aware, this is the first study to measure children's exposure to different diameters of PM across different microenvironments and seasons. However, several potential limitations must be acknowledged. One potential limitation of this study was the relatively small sample size and geographic area due to funding and resource restrictions. This study collected monitoring data from 77 individuals in 13 different classrooms in upstate NY, which may not be adequate to generalize these results. Another concern is that aerosol monitors, like the AirBeam, are prone to significant biases depending on local PM pollution's size, composition, and concentration (DeWitt et al., 2019; Sousan et al., 2017). Specifically, the accuracy of AirBeams is highly dependent on the type of aerosol detected. In addition, relative humidity can alter the shape and size of PM by absorbing moisture and encouraging agglomeration with larger particles (DeWitt et al., 2019). These factors can alter the AirBeam's

ability to accurately sense PM, particularly when it has not been calibrated. Therefore, the seasonal differences found in this study could be due to different aerosol types (i.e., pollen in the spring and leaves in the fall) (Sousan et al., 2017) and thermal conditions (DeWitt et al., 2019) across seasons. While the AirBeams were calibrated against standardized laboratory samples and the Aerocet before each trip to a school, the thermal conditions within each classroom differed and likely affected the devices' accuracy. However, given the AirBeam's high precision (coefficient of variation: 2–9%), the trend of $PM_{2.5}$ exposure reported in this study is accurate (Sousan et al., 2017).

In addition, while AirBeams have exhibited impressive precision in laboratory tests, the sensors in this device may be inaccurate when $PM_{2.5}$ concentrations exceed 100 μg/m^3 (Sousan et al., 2017). In this study, some children were exposed to momentary spikes in $PM_{2.5}$ above 100 μg/m^3 across days and microenvironments. Given the data aggregation method, the trends displayed in this study's figures likely underestimate the study population's true exposure to PM due to the AirBeams upper detection limit. Long-term studies utilizing AirBeams across different seasons are required to determine the extent to which different thermal conditions affect its accuracy.

Importantly, this study used the EPA's outdoor annual $PM_{2.5}$ standard (12 μg/m^3) as a reference point for children's exposure to indoor PM over a 2-day period, which may not seem intuitive. However, no indoor PM standard exists for the microenvironments analyzed in this study. Therefore, any reference point would not be perfectly appropriate. In addition, the selected threshold may be a good approximation in this case. Though each participant recorded their PM exposure for only 48 h, multiple subjects among the same study population (i.e., schoolchildren) were observed across multiple seasons and microenvironments. Therefore, the measurements recorded in this study can be reasonably extrapolated to similar populations in NYS and used to estimate their long-term exposure to PM. Finally, this study could not account for all important air pollutants that children may be exposed to indoors, such as NOx, due to equipment, budgetary limits, and grant commitments. The effects of exposure to other air pollutants will be studied in the future.

Conclusion

This study found that $PM_{2.5}$ levels routinely exceeded EPA standards at home and were significantly higher in the fall than in other seasons. In addition, $PM_{2.5}$ concentrations peaked after 6:00 PM in all seasons but significantly later in the fall. In classrooms, smaller particles ($PM_{1\text{-}4}$) peaked at 5:00 PM in winter and spring, but larger particles ($PM_{7\text{-}10}$) peaked during school hours, especially in the fall. Finally, PM exposure was higher among elementary schoolchildren compared to university students. This study suggests that ventilation in many homes is inadequate, especially during cooking. In addition, teachers and students have limited ability to control ventilation and air quality in classrooms, leading to variable concentrations of important pollutants. There is an urgent need to determine the primary sources of PM exposure across children's microenvironments. Installing real-time air monitors in any space children occupy may be important. Future research may monitor students' real-time exposures more accurately in different geographic areas and different types of schools, and account for seasonal variation as relevant policy changes and updating school infrastructure could improve health and academic performance for millions of students each year.

Appendix

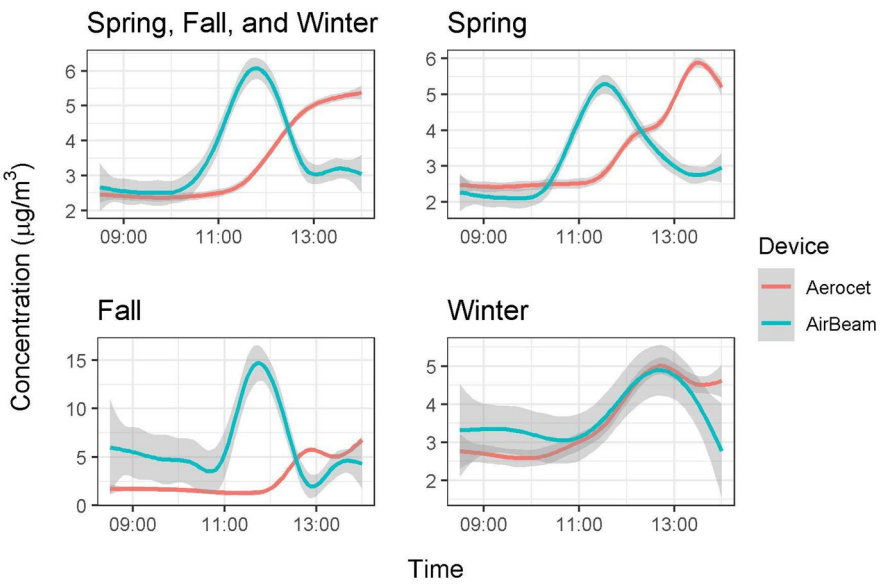

Fig. 4 Comparison between Aerocet and AirBeam measurements during school hours by season

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Importantly, the EPA prevents revealing identifiable information for students or schools.

Declarations

Human subjects' approval statement The University at Albany Institutional Review Board (IRB) approved the methods in this study, protocol number: 16-X-323–01. Each adult (college student, teacher) involved in the study and each participating child's parental guardian signed a consent form.

Conflict of interest The authors declare no competing interests.

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