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Article

The Relationship between Indoor and Outdoor PM_{2.5} in a High-Rise Building in Chicago Monitored by PurpleAir Sensors

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Abstract: In urban areas like Chicago, daily life extends above ground level due to prevalence of high-rise buildings where residents and commuters live and work. This study examines the variation in fine particulate matter (PM_{2.5}) concentrations across building stories. PM_{2.5} levels were measured using PurpleAir sensors, installed between April 8 and May 7, 2023, on floors one, four, six, and nine of an office building in Chicago. Additionally, data were collected from a public outdoor PurpleAir sensor on the fourteenth floor of a condominium located 800 meters away. Results show that outdoor PM_{2.5} concentrations peak at 14 meters height, then decline by 0.11 µg/m³ per meter elevation, especially noticeable from midnight to 8 AM under stable atmospheric conditions. Indoor PM_{2.5} concentrations increase steadily by 0.02 µg/m³ per meter elevation, particularly during peak work hours, likely caused by greater infiltration rates at higher floors. Both outdoor and indoor concentrations peak around noon. We find that indoor and outdoor PM_{2.5} are positively correlated, with indoor levels consistently remaining lower than outside levels. These findings align with previous research suggesting decreasing outdoor air pollution concentrations with increasing height. The study informs decision-making by community members and policymakers regarding air pollution exposure in urban settings.

Keywords: fine particulate matter; PM_{2.5}; indoor air pollution; Chicago; high-rise buildings; PurpleAir; low-cost sensors; vertical variation

1. Introduction

Nearly 120 million people in the United States experience unhealthy levels of ozone and particulate pollution, and among them over five million are residents or commuters in the city of Chicago [1]. Fine particulate matter (PM_{2.5}) is one of the most harmful air pollutants, as these particles are small enough to enter the lungs and bloodstream [2]. PM_{2.5} is also an important topic of study for its relevance to climate change, as a type of aerosol that can have cooling or warming effects on the climate [3]. It is also important for its relevance to environmental justice, as neighborhoods of low-income or high-minority residents tend to experience higher concentrations of and exposure to PM_{2.5} [1,4,5].

In general, PM_{2.5} concentrations in Chicago have decreased in recent years, though the proportion of those concentrations attributable to vehicles and other local sources has increased [6]. Concentrations vary widely across the city and vary significantly by season [7,8]. Additionally, though particulate matter originating from outdoor sources has been widely studied, indoor PM_{2.5} levels have received less attention and are important because outdoor air pollution can infiltrate inside buildings, and indoor sources of particulate matter exist as well. Most Americans spend about 90% of their time indoors [9], so studying indoor PM_{2.5} is important to assess peoples' overall air pollution exposure.

When examining the variation of PM_{2.5} in an urban setting, elevation is a factor to consider, given the prominence of high-rise apartments and office buildings in which many people live and work daily. Chicago is ranked the second “tallest” city in North America, based on the number of skyscrapers – 308 buildings in the city over 60 meters tall [10]. Furthermore, residents in high-rise buildings tend to be white, young, college-educated, and in higher income brackets [11]. These patterns are a continuation of Chicago’s history of residential segregation. Interestingly, the people living on the highest floors in a given high-rise building are generally those with the highest incomes of all the tenants in the building, with individuals with lower incomes living toward the bottom [12], as units on higher floors offer residents better views and more access to natural light and are therefore more expensive. This is highly relevant to the intersection of environmental justice with the topic of urban air pollution.

Past studies have indicated that air pollutant concentrations tend to decrease with increasing altitude, as demonstrated, for example, by Bisht et al. [13] studying black carbon and particulate matter in Delhi, India; KAILA [14] studying NO₂ and PM_{2.5} in Helsinki, Finland; and Liu et al. [15] studying PM_{2.5} in two neighborhoods in Nanjing, China. As explained by Liao et al. [16], who studied PM_{2.5} in Taipei, Taiwan, this decrease in many cases may be due to increased distance at higher altitudes from ground-level sources such as traffic emissions. A particular area of concern in urban areas is the problem of street canyons, when buildings lined up on both sides of a road prevent ventilation and dilution of pollutants. According to Liu et al. [15], within street canyons there often exists a specific height at which peak pollutant concentration occurs, which may not be at ground level. How PM_{2.5} varies with height around high-rise buildings in Chicago is not well studied. Therefore, we conducted a project in an office building in the Edgewater neighborhood of Chicago, Illinois.

2. Materials and Methods

2.1. Sampling Location

To increase our understanding about vertical variations of PM_{2.5} in urban areas, we installed eight PurpleAir sensors (four PA-II outdoor sensors and four PA-I indoor sensors) between April 8 and May 7, 2023, in an 11-floor office building in Edgewater, Chicago. The building and the period of the data collection were decided based on the availability of volunteering office occupants who allowed us to temporarily install an indoor sensor inside their office and an outdoor sensor on the exterior wall of their office. All four offices are located on the side of the building that faces away from a major road. The Edgewater neighborhood, located on the north side of the city, is situated next to Lake Michigan, containing several parks, beaches, and major roadways. According to the Chicago Metropolitan Agency for Planning [17], in 2023 there were about 56,296 residents in Edgewater, and about 56% are White, 17% Hispanic, 13% Black, 13% Asian, and 1% “Other.” The median age is 37.7 years old, the median annual income is \$61,872, and the employment rate is 93.5%. Edgewater was a good test neighborhood for its urban location and proximity to roadways and sufficiently tall buildings from which to measure air pollution levels as they vary by height.

2.2. PurpleAir Data

PurpleAir is a network of sensors that measure indoor and outdoor PM_{2.5}. Data are collected by PurpleAir sensors using a beam from a laser counter that reflects off particles present in an air sample. The reflections translate to estimates of real-time mass concentrations of particulate matter present in the air sample. Each PurpleAir sensor contains two channels, which alternate reading air samples every five seconds, corresponding to an average reading of the sensor every two minutes [18]. We used PA-II outdoor sensors and PurpleAir Touch indoor sensors to monitor outdoor and indoor air quality, respectively. These sensors measure PM_{2.5} and record temperature, relative humidity, and barometric pressure.

PurpleAir sensors were chosen because their data are already integrated into experimental maps (<https://fire.airnow.gov>) developed by the U.S. Environmental Protection Agency (EPA) and the U.S.

Forest Service. Prior work has evaluated the performance of monitors in the PurpleAir network, and newly established correction factors can be used to correct reported $PM_{2.5}$ values to better agree with Federal Equivalent Method (FEM) measurements [19–22]. Following the recommendation for outdoor air quality monitors in the U.S., as used in O'Dell et al. [23], we used the correction factor developed by Barkjohn et al. [22], as shown below:

$$\text{For } PA_{cf,1} < 343 \mu\text{g}/\text{m}^3: PM_{2.5} = 0.52 \times PA_{cf,1} - 0.086 \times RH + 5.75 \quad (1)$$

$$\text{and for } PA_{cf,1} \geq 343 \mu\text{g}/\text{m}^3: PM_{2.5} = 0.46 \times PA_{cf,1} + 0.000393 PA_{cf,1}^2 + 2.97 \quad (2)$$

in which $PA_{cf,1}$ is the average of the $PM_{2.5}$ values in $\mu\text{g}/\text{m}^3$ measured by Channels A and B over a two-minute interval with the conversion factor equal to 1, and RH is relative humidity in percent. According to O'Dell et al. [23], this correction factor can be applied to indoor sensors as well, and therefore we applied it to measurements taken by both outdoor and indoor sensors. In addition, we discarded data points whose $PM_{2.5}$ values were less than $0 \mu\text{g}/\text{m}^3$ or greater than $80 \mu\text{g}/\text{m}^3$. According to more reliable data retrieved from EPA air quality monitors, in this location there were no days during our study period in which the average $PM_{2.5}$ levels exceeded $80 \mu\text{g}/\text{m}^3$.

2.3. The Correlation between Outdoor and Indoor $PM_{2.5}$

We analyzed the correlation between outdoor and indoor $PM_{2.5}$ to examine the infiltration of outside air into the building following the method of Lv et al. [24], expressed with the following equation:

$$C_{in} = F_{in}C_{out} + C_s \quad (3)$$

where C_{in} is the actual indoor $PM_{2.5}$ concentration, C_{out} is the actual outdoor $PM_{2.5}$ concentration, C_s represents the concentration of $PM_{2.5}$ generated from indoor sources. F_{in} is the infiltration coefficient, representing the factor by which $PM_{2.5}$ generated outdoors enters into the building, which depends on the ventilation system and permeability of the building. In the most efficiently ventilated buildings, F_{in} should theoretically be zero, indicating that the building is not “leaky” or vulnerable to pollutant infiltration from the outdoors.

2.4. Colocation and Data Collection

We co-located our four outdoor sensors by placing them side-by-side together outside the office building for a week between March 29 and April 4, 2023, to determine to what extent the sensors' readings agreed with each other. To correct the differences observed between sensors during this co-location, we used these data to calculate how much the mean $PM_{2.5}$ concentration of each sensor deviated from the mean across all four sensors. These amounts of deviation were added to all future data points for each respective sensor. The same process was done for the four indoor PurpleAir sensors co-located inside over the same week-long period.

We then installed a pair of indoor and outdoor sensors for an office on each floor (one, four, six, and nine) of the building (Table 1). They were positioned on the inside and outside of the office's exterior wall that faces away from the roadside. The four offices were selected based on the voluntary willingness of occupants to allow installation for one month, i.e., between April 8 and May 7, 2023. In addition to the data provided by the sensors we installed, we obtained data from another outdoor PurpleAir sensor in Edgewater, situated on the fourteenth floor of a condominium about 800 m away from the office building. Even though this sensor was on a different building, we decided it would be beneficial to examine its data as well because of the higher elevation of the sensor.

Table 1. The information of the sensors used in this study, including their PurpleAir sensor identification number, location, elevation, latitude, and longitude.

Sensor IDs	Location	Elevation (m)	Latitude	Longitude
175445 (outdoor); 171081 (indoor)	Office Building 1 st Floor	2.0	41.9979	-87.6566
175417 (outdoor); 171015 (indoor)	Office Building 4 th Floor	13.5	41.9980	-87.6567
175457 (outdoor); 171075 (indoor)	Office Building 6 th Floor	19.6	41.9979	-87.6563
175419 (outdoor); 171079 (indoor)	Office Building 9 th Floor	28.7	41.9980	-87.6564
123003 (outdoor)	Condominium 14 th Floor	40	41.9911	-87.6546

3. Results

We conducted co-location tests for both indoor and outdoor sensors for a week between March 29 and April 4, 2023. Raw PM_{2.5} measurements taken by each sensor were corrected based on the relative humidity values using Equations 1 and 2. We then interpolated the corrected PM_{2.5} to regularly gridded two-minute intervals to perform a comparative evaluation of the sensors. Our results show that each outdoor sensor agreed closely with the other outdoor sensors (the R-squared value between any two sensors is between 0.97 and 0.99) (Figure 1). The same was true for the co-location results of the indoor sensors (the R-squared value between any two sensors is between 0.96 and 0.97) (Figure 2). The average PM_{2.5} concentration of each outdoor sensor during the week displayed biases that ranged between -0.16 and +0.15 mg/m³ from the mean value of all the four outdoor sensors combined. The biases for the four indoor sensors ranged between -0.10 and +0.22 mg/m³. These biases were removed from the observations before we compared PM_{2.5} levels at different floors in the office building. The co-location test did not include the public outdoor sensor installed on the 14th floor of the condominium. Therefore, we did not remove any potential bias for this 14th floor sensor.

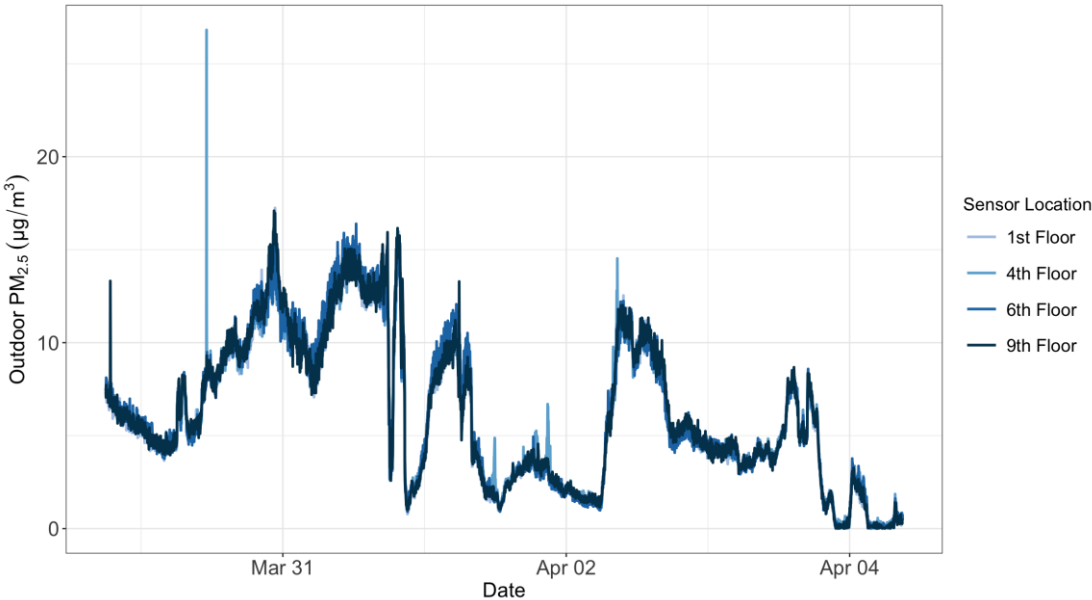


Figure 1. PM_{2.5} concentrations of the four outdoor PurpleAir sensors when they were co-located between March 29 and April 4, 2023, before they were later installed on the outside walls of the four floors of an office building.

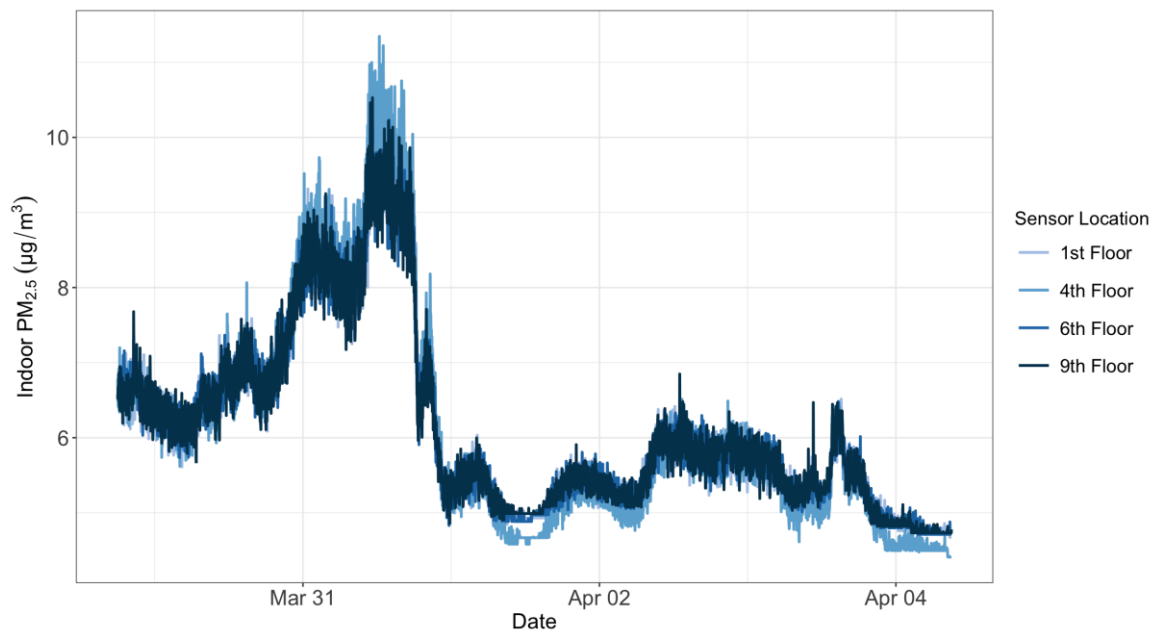


Figure 2. PM_{2.5} concentrations of the four indoor PurpleAir sensors when they were co-located between March 29 and April 4, 2023, before they were later installed inside offices on the four floors of an office building.

During the one-month study period between April 8 and May 7, 2023, data collected by the outdoor sensors were first corrected based on the relative humidity value using Equations 1 and 2 and then their biases were removed based on the co-location results. The results indicated that the median PM_{2.5} concentration increased with increasing height between the 1st and 4th floors (Figure 3). The median outdoor PM_{2.5} concentrations decreased for each successive level of altitude beyond the 4th floor by 0.11 µg/m³ per meter elevation. Statistical tests (Kruskal-Wallis test and Dunn test) showed significant differences between every outdoor sensor compared to every other outdoor sensor, except for one pair (the 1st and 9th floors). For indoor air quality, the median PM_{2.5} concentration increased with increasing height (+0.02 µg/m³ per meter elevation) for all levels (Figure 4). Although small, these differences between every indoor sensor were statistically significant.

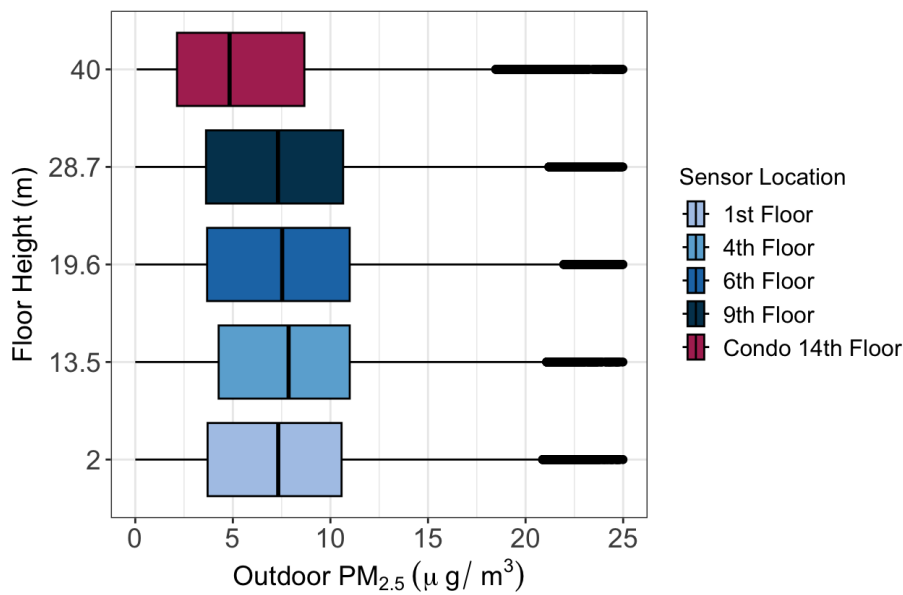


Figure 3. Distributions of outdoor PM_{2.5} concentrations at different floor heights between April 8 and May 7, 2023.

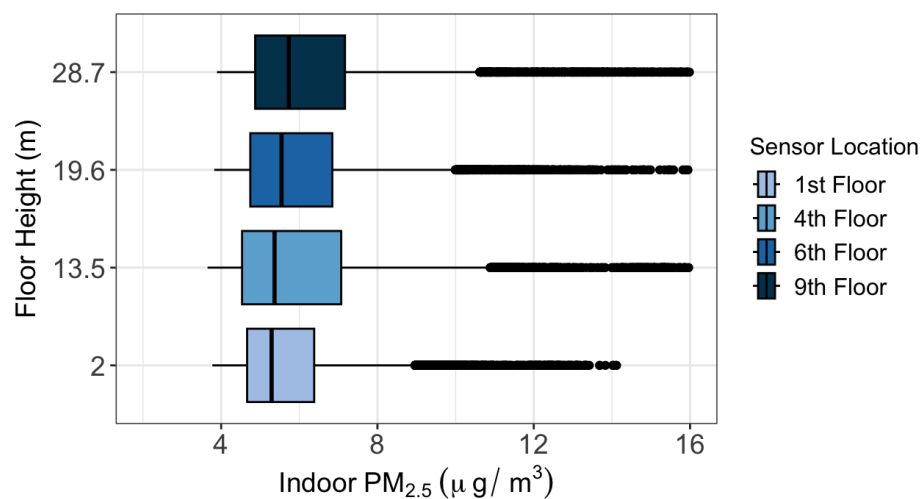


Figure 4. Distributions of indoor PM_{2.5} concentrations at different floor heights between April 8 and May 7, 2023.

We calculated the hourly average PM_{2.5} concentrations to study the diurnal cycles of the indoor and outdoor PM_{2.5} at different floors. Outdoor PM_{2.5} concentrations displayed a similar daily cycle at all floor heights (Figure 5). They all decreased in the afternoon until 8 PM, then increased throughout the night and early morning followed by a drop between 9 AM and 10 AM and increased again until peaking at noon. Such variations are controlled not only by the diurnal changes in PM_{2.5} emissions from traffic but also by the dynamics of the atmospheric boundary layer [25]. The vertical mixing in the boundary layer is weak at night and strongest in the mid-afternoon causing air pollutants to accumulate at night and disperse in the afternoon. The most pronounced differences of PM_{2.5} by floor height occurred between 12 AM and 8 AM when the atmospheric condition is stable and vertical mixing is weak. Figure 5 also shows that PM_{2.5} concentrations decreased as the height of the sensor increased except for the 1st floor. That the 1st floor PM_{2.5} concentrations are lower than those at the 4th floor is because the sensor at the 1st floor is situated above bushes and surrounded by trees, which could have helped to clean the air by removing PM_{2.5} from the air. Indoor PM_{2.5} concentrations, however, remained relatively constant over a day (Figure 6), though with a late-morning spike in the concentration on the 9th floor. The greatest variation of indoor PM_{2.5} by floor height appeared between the hours of 9 AM and 3 PM likely caused by the activities of office occupants during their work hours.

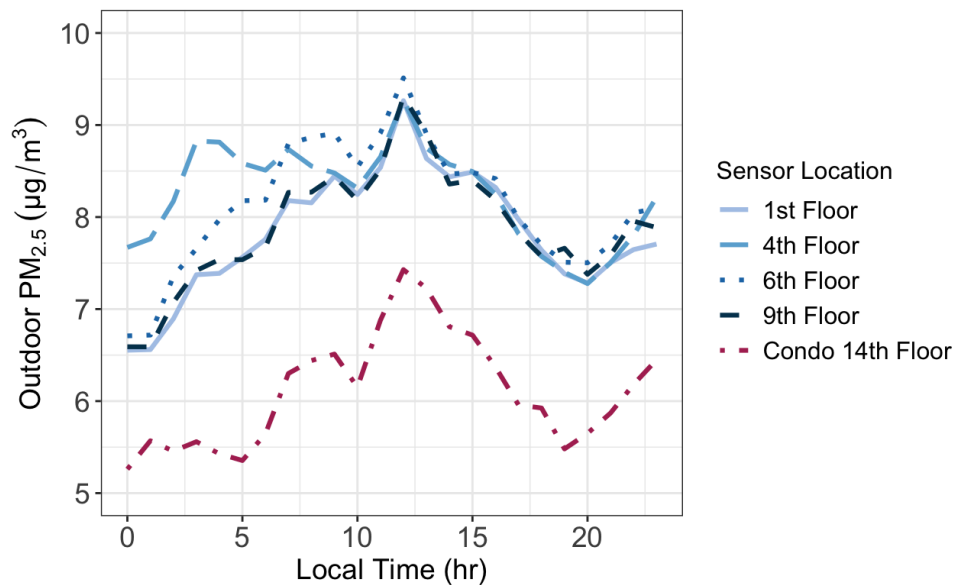


Figure 5. The average hourly $PM_{2.5}$ concentrations over a 24-hour day observed by outdoor sensors at five different floor heights between April 8 and May 7, 2023.

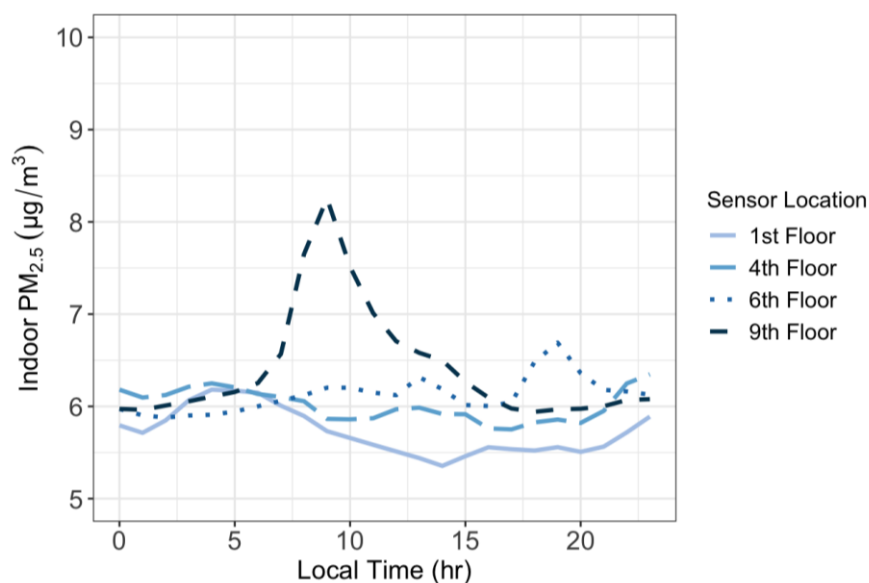


Figure 6. The average hourly $PM_{2.5}$ concentrations over a 24-hour day observed by the indoor sensors at four floor heights between April 8 and May 7, 2023.

To understand what caused the indoor air quality to change, we compared the indoor and outdoor daily average $PM_{2.5}$ concentrations observed by the four paired indoor and outdoor sensors. By conducting a linear regression test, our results show a positive correlation between the indoor $PM_{2.5}$ and the outdoor $PM_{2.5}$ (Figure 7 and Table 2), indicating the influence of outside air on the indoor air quality through infiltration. The infiltration factors, represented by the slope of the linear fitted line (F_{in}), vary between 0.22 and 0.29. The intercept of the linear fitted line represents the average amount of $PM_{2.5}$ attributable to indoor sources (C_s), and it ranges between $3.91 \mu\text{g}/\text{m}^3$ and $4.23 \mu\text{g}/\text{m}^3$ across the four floors. In comparison, the C_s and F_{in} values for office buildings in Daqing, China, were $4.83 \mu\text{g}/\text{m}^3$ and 0.72, respectively [24]. We then estimated the contribution of outdoor $PM_{2.5}$ to indoor $PM_{2.5}$ using the method in Lv et al. [24] by calculating $C_{out}F_{in}/C_{in}$. Our results show the

contributions of outdoor PM_{2.5} to the mean indoor PM_{2.5} are between 30% and 40% across the four floors, which are lower than the contribution rate of 79% in Lv et al. [24].

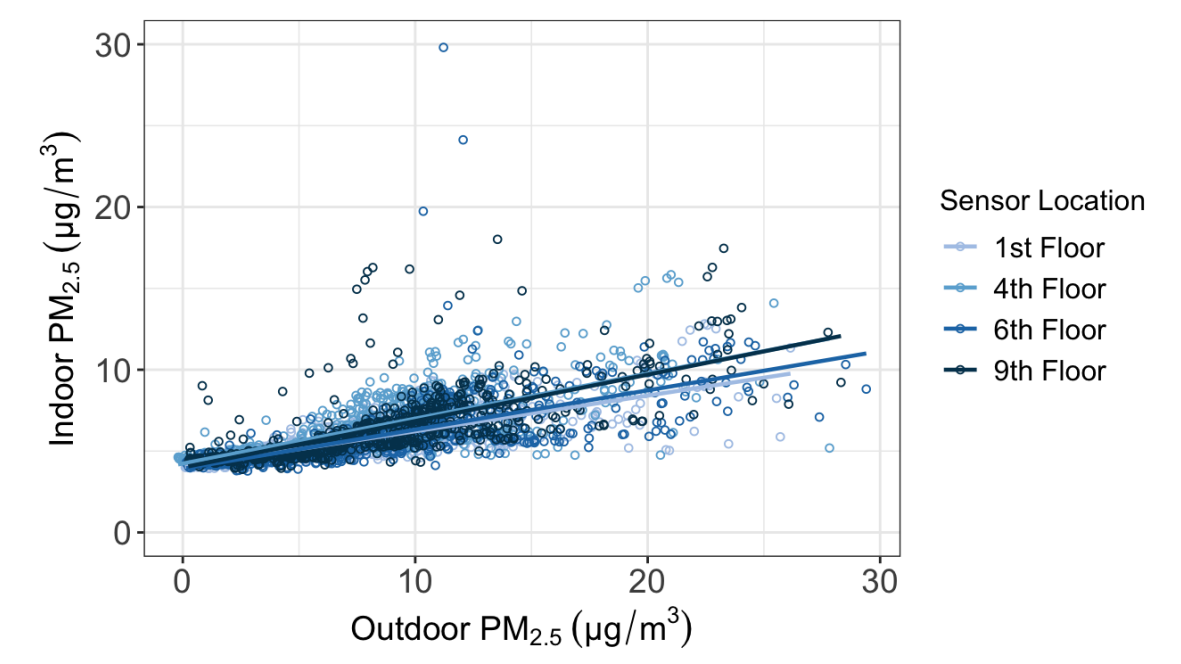


Figure 7. Indoor versus outdoor daily average concentrations of PM_{2.5} at four floor heights between April 8 and May 7, 2023.

Table 2. Results of the linear regression model between indoor (C_{in}) and outdoor (C_{out}) PM_{2.5}, $C_{in} = F_{in}C_{out} + C_s$.

Sensor Location	Indoor Median PM _{2.5}	Outdoor Median PM _{2.5}	Intercept (C_s)	Slope (F_{in})	R-squared	p-value
1 st Floor	5.29 µg/m ³	7.36 µg/m ³	4.0197 µg/m ³	0.2196	0.6125	<2.2e-16
4 th Floor	5.37 µg/m ³	7.90 µg/m ³	4.2349 µg/m ³	0.2762	0.5261	<2.2e-16
6 th Floor	5.55 µg/m ³	7.59 µg/m ³	3.9101 µg/m ³	0.2411	0.4346	<2.2e-16
9 th Floor	5.75 µg/m ³	7.37 µg/m ³	3.9936 µg/m ³	0.2853	0.5059	<2.2e-16

4. Discussion

This study conducted in Edgewater, Chicago, focused on analyzing the vertical profile of PM_{2.5} concentrations in both outdoor and indoor environments of high-rise buildings using PurpleAir sensors. The near-ground layer of the atmosphere is typically not probed by conventional instruments such as satellites, lidar, or air balloons. The PurpleAir sensors offer a low-cost method to investigate the fine vertical resolution of PM_{2.5} concentration change in the area.

We found good agreement among PurpleAir sensors during the one-week co-location period between March 29 to April 4, 2023, indicating the reliability of the sensors for the study. The findings revealed that PM_{2.5} concentrations decreased at 0.11 µg/m³ per meter for each successive level beyond the 4th floor. This trend may be attributed to the increasing distance from ground-level pollution sources, such as traffic, as elevation increased. That PM_{2.5} on the 1st floor is lower than on the 4th floor is likely due to the fact that the outdoor sensor was situated above bushes and there are trees nearby. The vegetation could have helped to increase the dry deposition of PM_{2.5}. Indoor PM_{2.5} concentrations increased with increasing height at 0.02 µg/m³ per meter elevation, from 5.3 µg/m³ at the first floor to 5.8 µg/m³ at the 9th floor, which is mostly likely caused by the greater infiltration coefficient which is 0.22 at the 1st floor and 0.29 at the 9th floor.

Hourly averages of outdoor PM_{2.5} concentrations showed the clearest variation by height between the hours of 12 AM and 8 AM. The same pattern of outdoor PM_{2.5} concentration increasing between the 1st and 4th floors, then decreasing after the 4th floor, still holds over this period. Mornings exhibit the most variation due to the low atmospheric boundary layer overnight, resulting in little atmospheric mixing and more distinct stratification with height. For the indoor sensors, the clearest variation in air quality by height appeared to be between 9 AM and 3 PM. This could be due to this period being the peak of the workday with the most activity in the building occurring.

Comparing outdoor to indoor PM_{2.5}, for each floor their concentrations were positively correlated; the indoor air pollution stayed at a concentration lower than outside. This follows logically given that we expect most of the PM_{2.5} sources in this setting to originate outdoors. The F_{in} values, or the slopes of the regression lines, are low and indicate that there are low factors of infiltration of outdoor PM_{2.5} penetrating inside the building. The C_s values, or the indoor intercepts of the regression lines, indicated that the sources of indoor air pollution were low, around 4 $\mu\text{g}/\text{m}^3$.

A potential limitation of this study was that the sensors at different floor heights were not placed exactly above one another, but distributed along the same wall of the building according to the location of the office in which an occupant was willing to host a sensor. Additionally, the chosen condominium building is a few blocks away and may experience slightly different primary emission sources of PM_{2.5} compared to the office building.

This project serves as a case study for two buildings in Edgewater, Chicago, for one month in spring. A full understanding of the vertical profile of PM_{2.5} concentration requires a longer and more extensive period of study, incorporating greater temporal and spatial coverage and greater vertical extent. Future research could include a greater number of different sensor heights and could incorporate a greater degree of control between heights, with data collection periods spanning multiple seasons of the year and examining how weather impacts outdoor air quality and how building type influences infiltration indoors.

Research on this topic will provide a greater nuance to our understanding of how people in urban areas may be exposed to different levels of air pollution while on different building floors, as air quality is an important topic for its relevance to climate science, public health, and environmental justice.

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Data Availability Statement: All raw data are publicly available from the PurpleAir website (<https://www2.purpleair.com/>) using the PurpleAir API (<https://api.purpleair.com/>). All analyzed data available on request from the corresponding author.

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