

## Article

# Investigation of Indoor and Outdoor Fine Particulate Matter Concentrations in Schools in Salt Lake City, Utah

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**Abstract:** Although there is mounting evidence that suggests that air pollution is impactful to human health and educational outcomes, this is especially problematic in schools with higher air pollution levels. To understand whether all schools in an urban area are exposed to similar outdoor air quality and whether school infrastructure protects children equally indoors, we installed research-grade sensors to observe PM<sub>2.5</sub> concentrations in indoor and outdoor settings to understand how unequal exposure to indoor and outdoor air pollution impacts indoor air quality among high- and low-income schools in Salt Lake City, Utah. These data and resulting analysis show that poor air quality may impact school settings and the potential implications with respect to environmental inequality. Based on this approach, we found that during atmospheric inversions and dust events, there was a lag ranging between 35 and 73 min for the outdoor PM<sub>2.5</sub> concentrations to follow a similar temporal pattern as the indoor PM<sub>2.5</sub>. This lag has policy and health implications and may help to explain rising concerns regarding reduced educational outcomes related to air pollution in urban areas.

**Keywords:** air quality; fine particulate matter; high schools; building ventilation; environmental inequality; research-grade sensors; indoor air quality; atmospheric inversions; dust events; urban

## 1. Introduction

Every day, around 93% of children under the age of 15 (1.8 billion children) breathe outdoor air that is so polluted it puts their health and development at serious risk [1]. In the US, this problem is compounded by uneven monitoring of air quality, which can vary dramatically from state to state or even within different areas of a single metropolitan area. In many cases, higher pollutant concentrations noted near industrial and near-road locales result in economically disadvantaged and minority populations facing a disproportionate exposure to air pollutants. In fact, exposure rates in the US are more likely determined by economic structures (e.g., socioeconomic status) [2] and race [3,4] than any other factor. There is also mounting evidence that suggests that air pollution can be impactful to educational outcomes [5–7] and human health [8], but research has not completely demonstrated the mechanisms that produce these outcomes, and less is understood about these effects

in school settings. This uneven exposure to environmental risks and hazards is known as environmental inequality, which is created by social, economic, and political processes that intensify or worsen economic and social inequality. This form of inequality exposes already-disadvantaged populations to the increased harms of air pollution.

When considering environmental inequality in urban areas, schools are an important setting. Children are especially vulnerable to the health and developmental impacts of pollution exposure due to their unique biological vulnerabilities, age-related patterns of exposure, and lack of control over their own environmental circumstances [9]. In addition, air pollution aggravates inequality through its connection with a variety of educational and economic outcomes. Currie [10] and others demonstrated links between poor health at birth, lower educational attainment [11], and below-average adult outcomes [12]. Economic research in this area has also illustrated how air quality impacts labor supply, productivity, and cognition [13]. Isen et al. [14], for instance, found that a higher pollution level in the year of birth is associated with lower labor force participation and lower earnings by age 30. These outcomes can also impact teacher and school performance.

The factors of environmental inequality are also associated with increased all-cause mortality and respiratory morbidity, including exacerbations of asthma, COPD, bronchitis, pneumonia, and cardiovascular conditions, creating an unequal starting point from birth [15–20]. The impacts of this exposure, however, go well beyond simple health outcomes. Prior research found disparities associated with air quality based on economic standing, language minority status, immigration status, race, and ethnicity [21]. Despite this, it is often assumed that all schools in an urban area are exposed to similar outdoor air quality and that school infrastructure protects children equally to produce similar indoor air quality. To extend our understanding of environmental inequalities in urban settings, our research explores how unequal exposure to indoor and outdoor air pollution (e.g., fine particulate matter (PM<sub>2.5</sub>)) impacts indoor air quality among high- and low-income schools in Salt Lake City, UT, USA.

Since indoor air quality is affected by outdoor [22] and indoor sources of pollution, environmental conditions, housing characteristics, and behavioral factors [23], we installed research-grade sensors to observe PM<sub>2.5</sub> concentrations in indoor and outdoor settings at two high schools with a range of geographic and demographic compositions, (e.g., elevation, distance to pollution source, minority status, and income level). These data and resulting analysis show that poor air quality may impact school settings and the potential implications with respect to environmental inequality. We expect that the results of this study will invigorate debates about the unequal distribution of air pollution and identify what risks, if any, such factors have on the protective properties of schools.

## 2. Materials and Methods

The two high schools included in this study are both located in SLC, Utah (Figures 1 and 2). The state of Utah is well known for its majestic mountains and natural sites, but the air quality in its urban centers can be exceptionally poor during pollution episodes, especially in the lower elevation areas. According to a 2021 report by the American Lung Association, Salt Lake City is the 12th most polluted city nationwide for ozone pollution and 17th most polluted city in the US for short-term particulate pollution [24]. This dubious standing has many contributing factors.

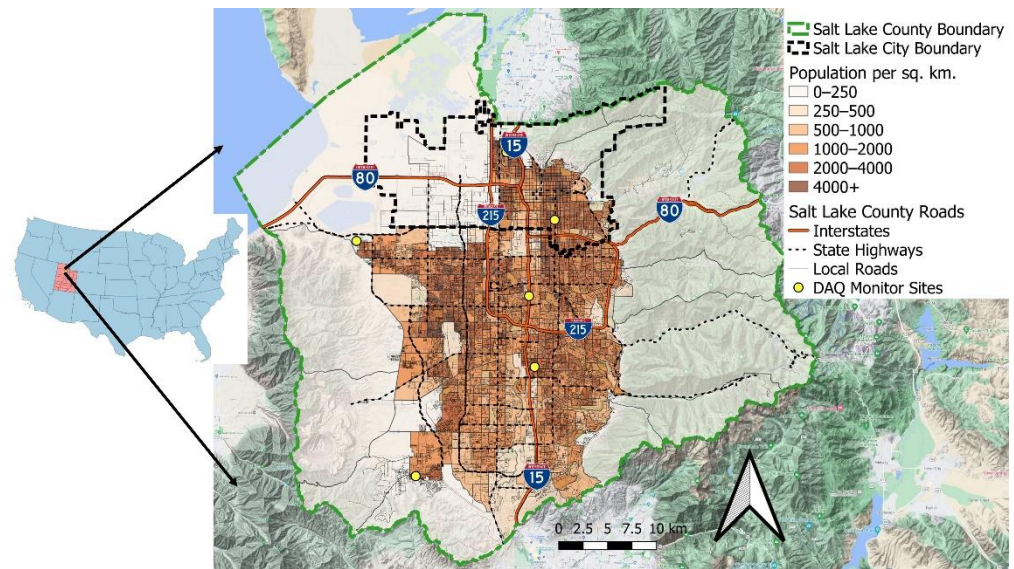


Figure 1. Salt Lake City and Salt Lake County within Utah and the United States (left inset).

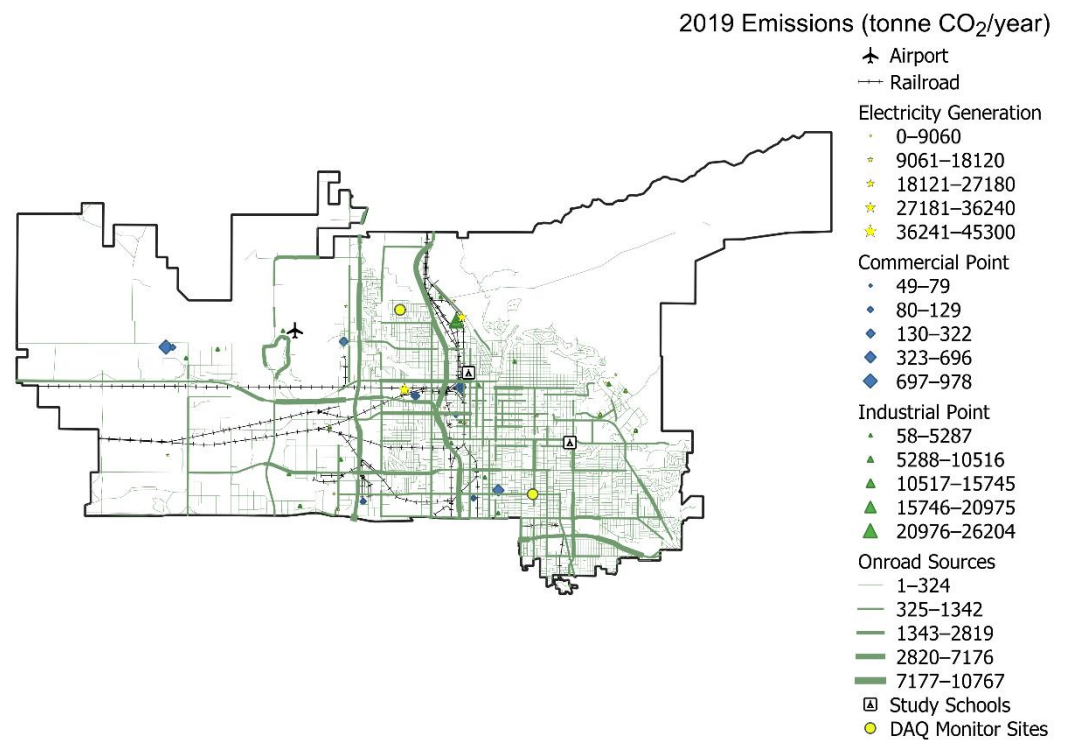
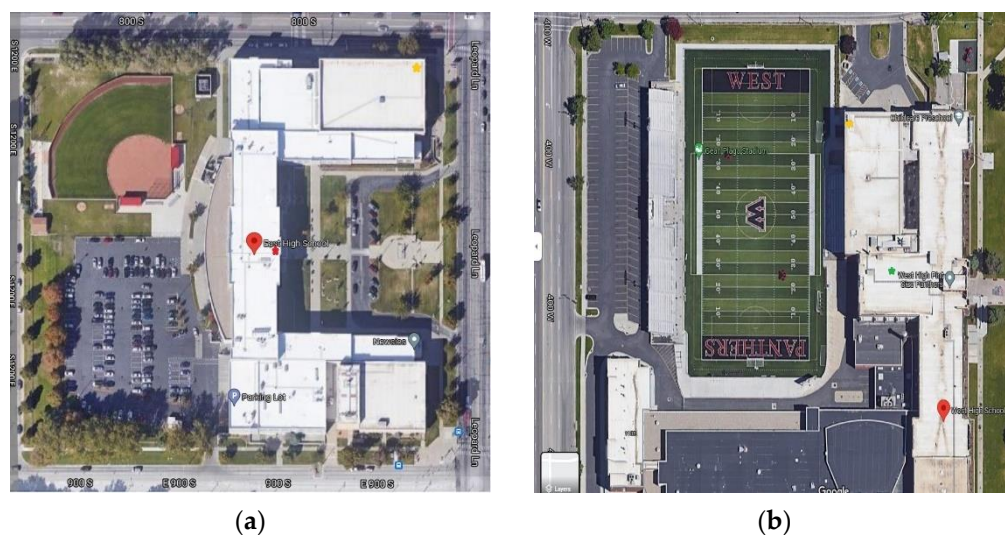


Figure 2. Study area showing Salt Lake City’s emission sources (2019 tonne CO<sub>2</sub>/year), study schools, and regulatory air quality monitoring sites.

As illustrated in Figure 1, SLC is located at the intersection of two major highways (e.g., I-80 and I-15), and therefore, transportation-related emissions are an important contributor to poor air quality. Like many urban areas, traffic density and congestion in Salt Lake County (SLCo) have been increasing by around 10% or more annually [25], making this and other urban areas increasingly susceptible to transportation-related air pollution. Additionally, SLCo has a unique geography with multiple intersecting high mountain ranges and the Great Salt Lake, surrounding expansive residential housing and a range of heavily polluting industries (Figure 1). The local air pollution problems are further exacerbated by distant and local pollution produced by local and regional dust storms and

wildfires in the Western United States. As a result, both the summer and winter months are impacted by elevated ozone [26] and  $PM_{2.5}$  [27].

This study deployed research-grade sensors, which are demonstrated to be comparable to regulatory-grade instrumentation in accuracy and precision [28] and significantly more robust and reliable than commonly used low-cost or citizen science sensors [29]. We installed Met One Instruments (Met One Instruments Inc., Grants Pass, OR 97526, USA) ES-642 Remote Dust Monitors, with inlet sharp cut cyclones to measure  $PM_{2.5}$ , with the manufacturer's stated uncertainty of  $1 \mu\text{g}/\text{m}^3$  [30] at schools on opposite sides of SLC. The schools, appropriately named "East High School" (East High) ( $40.75230^\circ \text{ N}$ ,  $111.85527^\circ \text{ W}$  [31], Elevation 1373 MASL [32]) and "West High School" (West High) ( $40.77433^\circ \text{ N}$ ,  $111.90040^\circ \text{ W}$ , Elevation 1302 MASL), are located approximately 4.5 km apart (Figure 2). At each school (Figure 3), one sensor was located outside the building (East High: south end on roof; West High: northwest corner on roof), and one was inside (East High: northeast corner of East Gym; West High: inside of common area on northwest beam), and each was approximately 3.5 m aboveground. The western part of SLC, as seen in Figure 2, has a substantial set of emission sources, including two interstate highways, Salt Lake City International Airport, the largest power plant in the city, regional railroad lines, and numerous point sources. The eastern part of SLC is primarily residential and has comparatively smaller roads with few point sources.



**Figure 3.** Study area showing the  $PM_{2.5}$  instrument locations at (a) East High and (b) West High. The locations of the inlets for the indoor sensors are denoted by the yellow stars, while the red symbol denotes the location of the outdoor rooftop sensor.

The study period for this research spanned from 8 February to 30 April 2018. Between November and February each year, SLC experiences periodic temperature inversions, where pollutants accumulate in the stable boundary layer for several days to several weeks [33]. These temperature inversions weaken into spring but are still observed in March for a few days. By April and May, solar insolation is strong enough that generally only nocturnal inversions are noted, and pollution does not build up in the valleys to the extent it does earlier in the year. However, strong winds associated with spring storm systems can bring large dust storms to the region at this time of the year, with April being the dustiest month of the year [34]. The study period in this paper (February–April 2018) is thus representative of both the end of the winter inversion season and the springtime dust season.

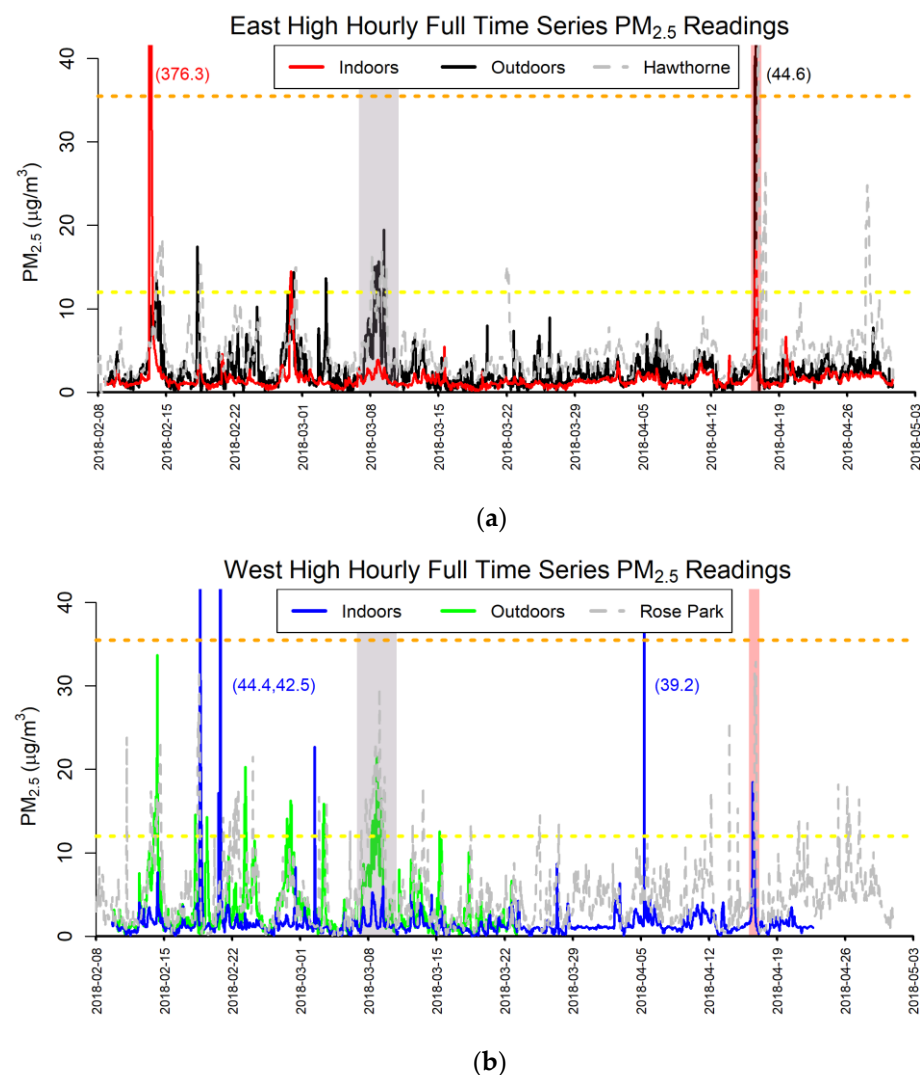
The instruments record data at 1 s intervals, which were later aggregated to average minute and hourly resolutions for  $PM_{2.5}$  concentration, temperature, relative humidity, and pressure. The hourly outdoor readings were compared against regulatory air quality sensor data from the closest Utah Division of Air Quality station (Rose Park and Hawthorne, Figure 2) for each school. The hourly indoor and outdoor readings were compared with

each other for the duration of the study period. Weekday diurnal cycles were derived for each environment to show the impact of emissions on indoor air quality. Finally, two elevated pollution events (an inversion episode and a dust storm) were studied at 2 min resolution to understand the rate of pollutant infiltration. To study the infiltration rates of the two pollution types (e.g., inversions and dust), the outdoor reading times were kept fixed, and the indoor readings were lagged from 1 to 180 min to quantify the most impactful lag period as estimated by the  $r^2$  value as further described in Section 3.5.

### 3. Results and Discussion

#### 3.1. Full Time Series

The full time series of  $PM_{2.5}$  of both the indoor and outdoor sensors for the full study period is shown in Figure 4. Figure 4a displays the hourly indoor and outdoor  $PM_{2.5}$  readings for East High and the Hawthorne regulatory sensor, while Figure 4b presents the indoor and outdoor  $PM_{2.5}$  readings for West High and the Rose Park regulatory sensor. The dashed horizontal lines represent air quality index (AQI) level cutoffs [35]. The associated temperature, relative humidity, and pressure values are found in Appendix A, Figures A1–A6.



**Figure 4.** Hourly full study period time series of  $PM_{2.5}$  readings for (a) East High and (b) West High and the closest regulatory observations. The horizontal lines correspond to AQI levels. The shaded grey and pink time periods denote an atmospheric inversion and a dust storm period. Outlier values are listed next to their occurrence.

As illustrated in Figure 4a,b, PM<sub>2.5</sub> readings are generally higher outside than indoors at both East High and West High. West High, being in a higher traffic area, shows on average approximately 25–50% higher outdoor PM<sub>2.5</sub> readings than East High. This demonstrates, for this case study period, the potential environmental inequality impacts. For instance, higher rates of outdoor air quality could lead to lower overall standardized testing scores in low-income schools, even when controlling for other factors (e.g., economic or language status) [6]. It could also lead to higher rates of student absenteeism, which has been shown to impact long-term learning in students [7].

In addition to the averages over the study period, there are three notable anomalies where the PM<sub>2.5</sub> concentrations were substantially higher indoors than outdoors. Although we contacted the schools, they were unable to provide explanations for these elevated pollution events. On Tuesday, 13 February, 6:00–9:00 a.m., East High recorded indoor hourly readings of up to 376 µg/m<sup>3</sup>. These values are too high for too long to be the result of instrument failure, which might be indicated by high values for only a few 1 min observations. As discussed in the Methods section, the instrument was in the gymnasium, and the school buses park and idle outside the door of the gymnasium. As it was a relatively cold day, it is possible that the buses were located close enough to the air intake to directly emit their exhaust, which could then infiltrate the building. It is also possible that vaping activities by students could result in this signal. The prevailing wind during that time was from the southeast; therefore, the outdoor sensor would not have registered the signal as it was upwind from the buses and gymnasium.

The two other indoor spikes occurred on Sunday, 18 February, 5:00–8:00 p.m., and Tuesday, 20 February, 6:00–8:00 p.m. at West High. These elevated events peaked at 71 µg/m<sup>3</sup> and are consistent with cleaning activity. As the indoor instrument was in the cafeteria and common area, these readings could indicate the effects of vacuuming and kitchen cleaning or cooking activities.

### 3.2. School Outdoor vs. Regulatory Sensor PM<sub>2.5</sub>

Figure 5 compares the outdoor data with the nearest regulatory instrument. The regulatory instruments are located approximately 2.5 (East High to Hawthorne) and 3.5 (West High to Rose Park) kilometers from the school. Therefore, their readings are not expected to be wholly representative of the localized school air quality. Both schools generally read lower PM<sub>2.5</sub> concentrations than their corresponding regulatory instrument. This is likely due to the location of the schools near lower traffic roads compared with larger roads near the regulatory sensors. As noted in the previous section, the outdoor PM<sub>2.5</sub> readings for West High are generally higher than for East High.

### 3.3. School Indoor vs. Outdoor PM<sub>2.5</sub> Overview

The school indoor and outdoor sensor readings are compared in Figure 6. The comparisons are for the available study dates for each site on 8 February–30 April for East High and 9 February–22 March for West High. We performed analysis using data from 9 February to 22 March, and the results for East High did not vary enough to warrant exclusion. The indoor readings are generally lower than the outdoor readings, and the slope is higher for East High than West High, indicating generally proportionately lower concentrations of PM<sub>2.5</sub> observed indoors at West High relative to East High compared with the outside readings. The indoor PM<sub>2.5</sub> readings are generally consistent across both schools, and the slope difference is attributable to the higher outdoor concentrations observed at West High since the indoor readings are similar across both schools. When evaluated more closely, interesting variations between indoor and outdoor PM<sub>2.5</sub> concentrations are observed as a function of time (Section 3.4). Diurnal cycles and type of pollutant episode (winter inversion vs. dust event) are discussed in the next section.

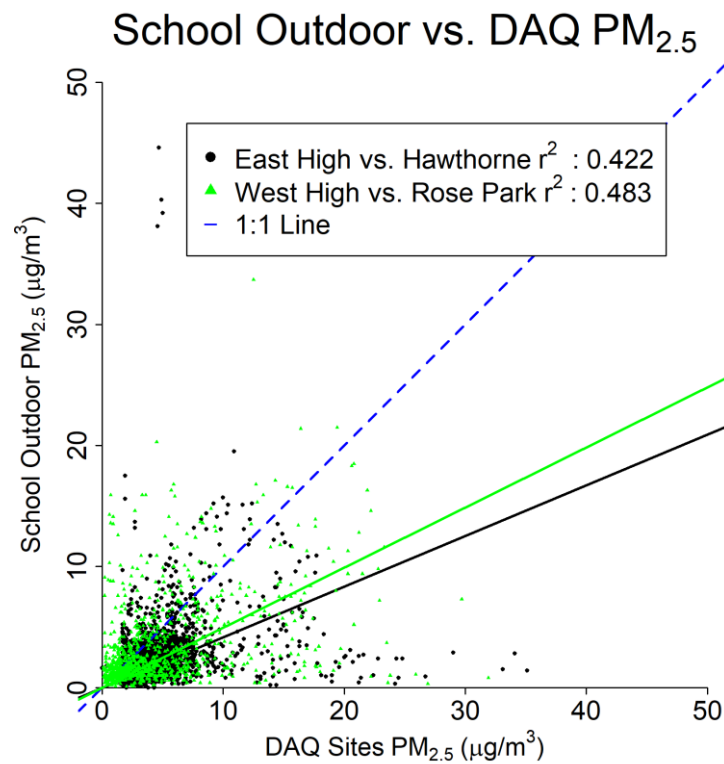


Figure 5. School outdoor sensor readings compared with the nearest regulatory sensor.

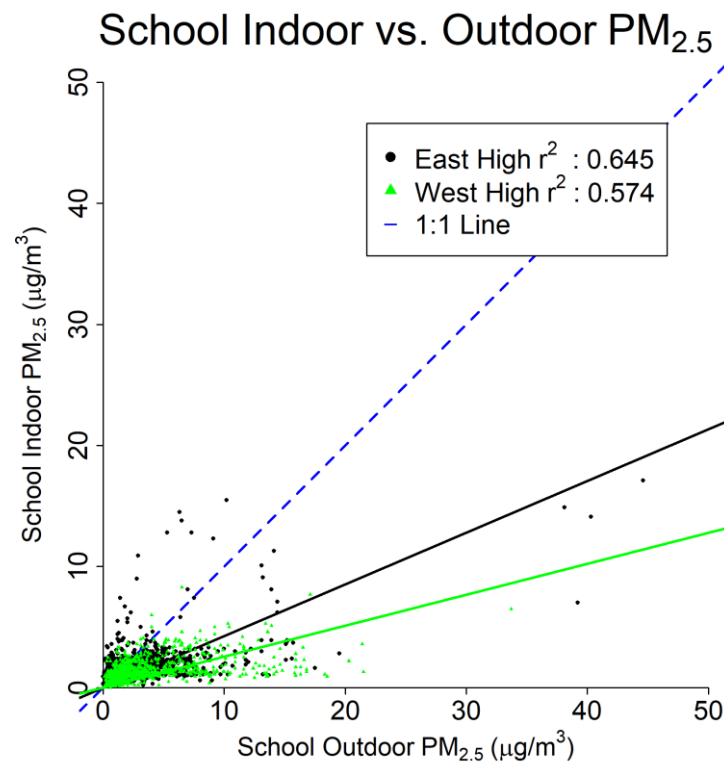
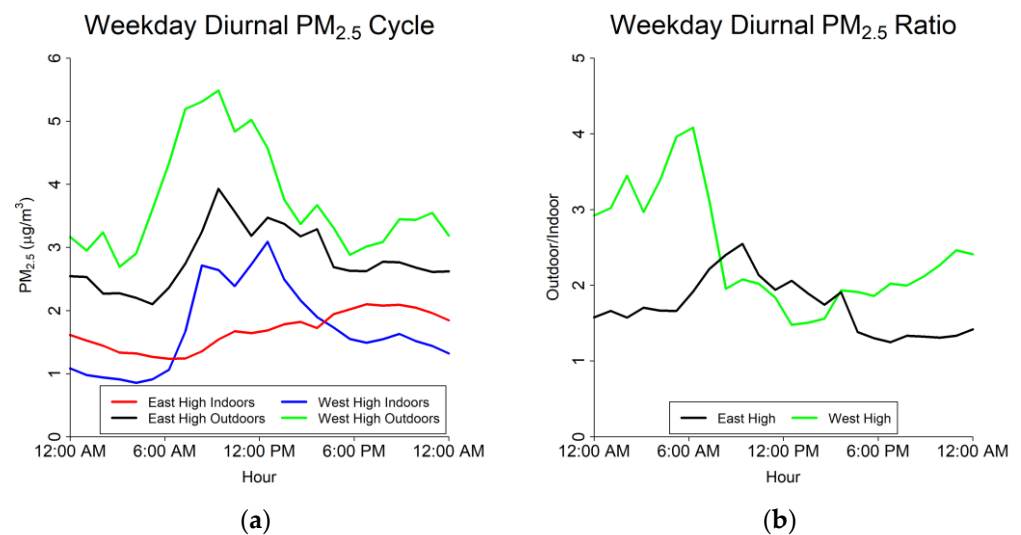


Figure 6. School indoor vs. outdoor PM<sub>2.5</sub> sensor reading.

### 3.4. School Indoor vs. Outdoor PM<sub>2.5</sub> and Weekday Diurnal Cycle

The weekday diurnal cycle PM<sub>2.5</sub> concentrations and outdoor/indoor ratio at the four sites are shown in Figure 7. The diurnal cycle is highlighted by the rapid increase

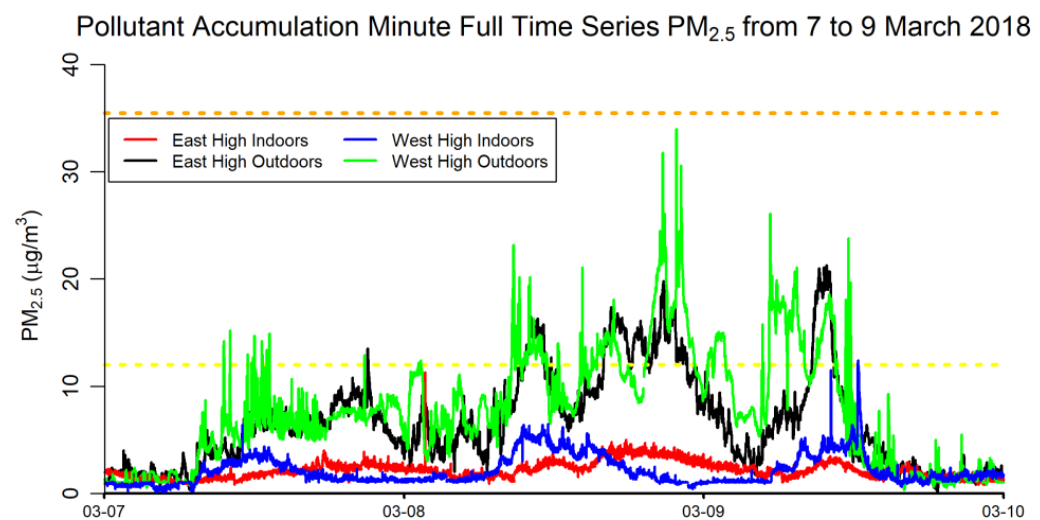
in the early morning hours due to the morning rush hour vehicular emissions and combustion activity from commercial and industrial buildings (Figure 7a). Additionally, the atmospheric boundary layer is lowest in the early morning hours. As the day progresses,  $PM_{2.5}$  becomes more well mixed in the atmosphere, leading to a decline in the outdoor concentration. There is a notable lag in the concentration readings for the indoor instruments compared with the outside ones. This is likely due to building infiltration rates and contamination from indoor sources (Figure 7b).



**Figure 7.** Weekday diurnal cycle (a) and diurnal  $PM_{2.5}$  outdoor/indoor ratio (b) for study schools.

### 3.5. Pollutant Accumulation from 7 to 9 March—Atmospheric Inversion Event

A multiday pollution accumulation event due to a weak inversion episode [27] is shown in Figure 8. As discussed in the previous section, there appeared to be a lag between elevated  $PM_{2.5}$  inside compared with outside of schools. To capture the potential range of possible lags, the minute-resolved indoor data were lagged with respect to the outdoor readings by 1 to 180 min. The best fit was determined as the lag that produced the highest  $r^2$  value.

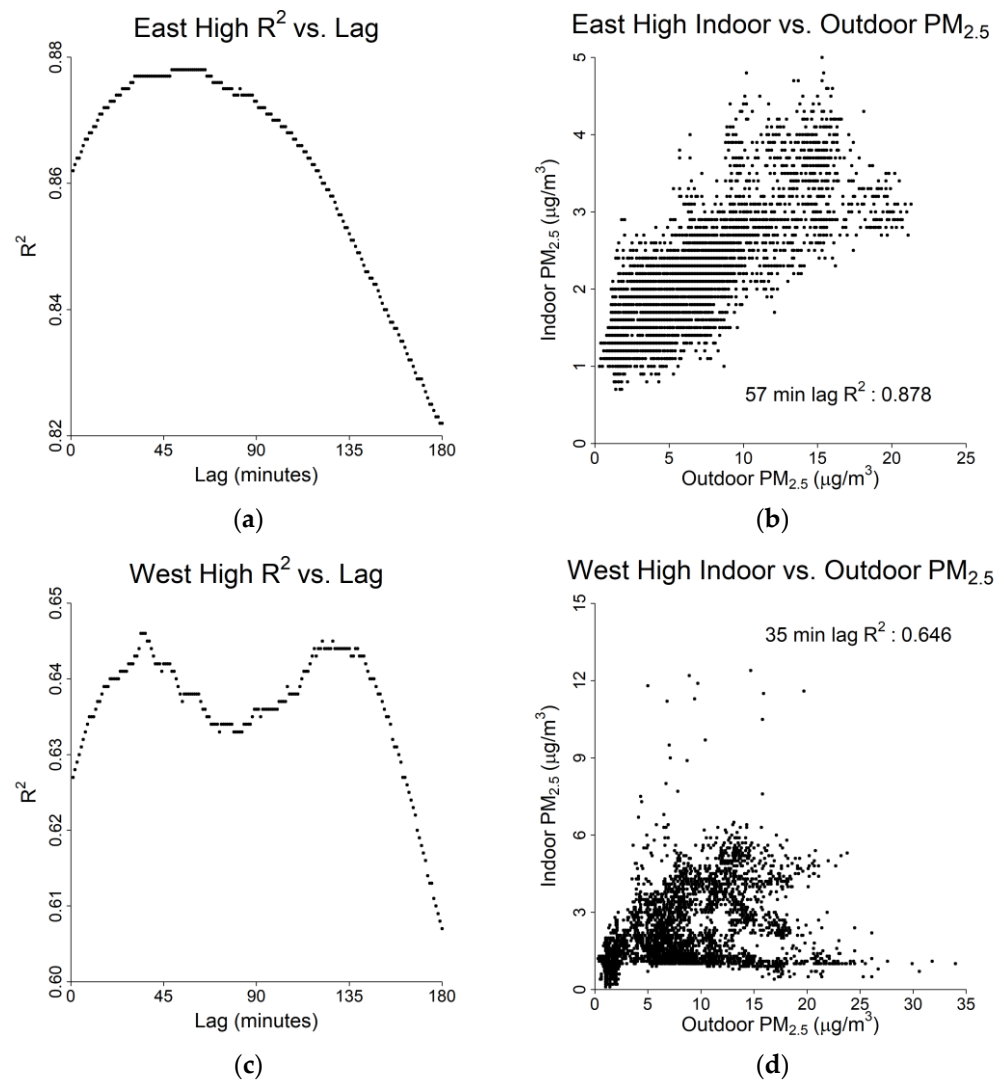


**Figure 8.** Pollution accumulation event from 7 to 9 March 2018.

The coefficient of determination comparing lagged indoor measurements and outdoor measurement and the comparison between the lagged values are shown in Figure 9. The



highest  $r^2$  value (0.878) for East High was at a lag of 57 min (Figure 9a,b). West High had its highest  $r^2$  value (0.646) at a lag of 35 min, but there was another similar peak at 135 min (Figure 9c,d). However, the variability in the  $r^2$  value was minimal between minutes 35 and 135. A potential explanation for the difference in lag values between the two schools is the air handling activity.



**Figure 9.** Coefficient of determination and comparison between lagged indoor and outdoor  $PM_{2.5}$  readings at the highest coefficient of determination: (a) coefficient of determination for East High, (b) East High 57 min lagged indoor and outdoor  $PM_{2.5}$ , (c) coefficient of determination for West High, and (d) West High 35 min lagged indoor and outdoor  $PM_{2.5}$ .

Table 1 lists the meteorological conditions, both indoor and outdoor, during the elevated pollution event for both sites. The  $PM_{2.5}$  difference between the indoor and outdoor concentrations is nearly 25% larger at West High compared with East High. While the outdoor temperature is similar at both schools, the indoor temperature is over 4 °C higher at West High, and the standard deviation is nearly twice that of East High. The mean and standard deviation of the indoor relative humidity at both schools are nearly identical, with a similar pattern for the pressure. Therefore, the indoor temperature is associated with the indoor  $PM_{2.5}$  readings.

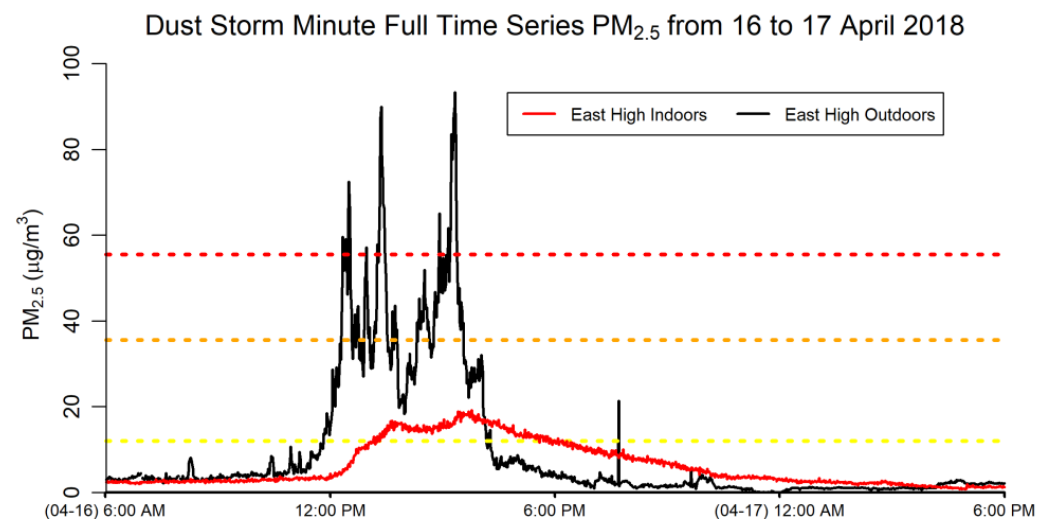
**Table 1.** Meteorological conditions during elevated pollution event.

Study Site	Metric	Mean	Standard Deviation
East High Indoors	PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )	1.84	0.83
	Temperature ( $^{\circ}\text{C}$ )	22.01	0.49
	Relative Humidity (%)	15.60	1.53
	Pressure (mbar)	866.12	4.56
East High Outdoors	PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )	4.89	4.30
	Temperature ( $^{\circ}\text{C}$ )	6.58	8.27
	Relative Humidity (%)	29.92	10.49
	Pressure (mbar)	864.65	4.45
West High Indoors	PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )	1.79	1.26
	Temperature ( $^{\circ}\text{C}$ )	26.02	0.93
	Relative Humidity (%)	14.15	1.49
	Pressure (mbar)	874.12	4.69
West High Outdoors	PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )	5.61	5.19
	Temperature ( $^{\circ}\text{C}$ )	6.61	6.35
	Relative Humidity (%)	21.90	7.33
	Pressure (mbar)	872.66	4.70

Inversions, such as the case highlighted in this section, are composed of mostly (70%+) secondary pollutants, which dissipate indoors due to the changing ambient conditions (e.g., warmer temperatures and lower relative humidity). As will be shown in the next section, the indoor school environment during these inversion episodes is more protective against the secondary pollutants, following a short lag, than during other situations, such as the dust storm highlighted next.

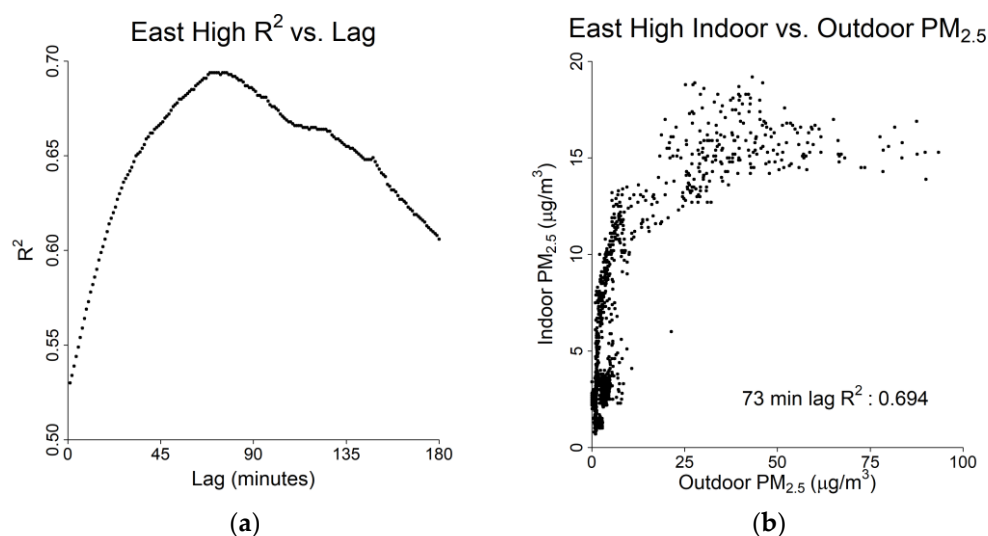
### 3.6. Dust Event on 16 April

The resulting indoor and outdoor PM<sub>2.5</sub> measurements during a dust storm is shown in Figure 10. Only East High had both sensors available during this event as the outdoor sensor at West High was not operational during this event.

**Figure 10.** Dust storm event from 16 to 17 April 2018.

The coefficient of determination comparing lagged indoor measurements and outdoor measurement and the comparison between the lagged values are shown in Figure 11. An interesting feature is the shape of the distribution compared with the near-linear relationship found in Figure 6. At concentrations below  $10 \mu\text{g}/\text{m}^3$ , the relationship is relatively linear, but at higher concentrations, there is a substantial slope change. This may

be explained by the filtration system used in the school. Unlike the March event, which was mainly attributable to secondary particulate matter from an inversion event, the April dust event was composed of primary windblown particulate matter (these dust particles would also be likely larger on average than during the earlier event). Therefore, the building air handling system was involved in filtering the  $PM_{2.5}$  as outside air was brought into the building. It seems that when the efficiency limit was reached, it led to indoor  $PM_{2.5}$  readings of  $20 \mu\text{g}/\text{m}^3$  or below regardless of the outside readings. It is also possible that the larger particles settled or deposited more associated with the dust storm [36] during which most of the observation above  $30 \mu\text{g}/\text{m}^3$  occurred. Furthermore, the lag (73 min) is comparable to the lag found in the previous section (57 min) for East High.



**Figure 11.** Coefficient of determination and comparison between lagged indoor and outdoor  $PM_{2.5}$  readings at the highest coefficient of determination: (a) coefficient of determination for East High; (b) East High 73 min lagged indoor and outdoor  $PM_{2.5}$ .

## 4. Conclusions

### 4.1. Implications

This research sought to understand how environmental inequality impacts schools in Salt Lake City, Utah. Outdoor sited sensors at both high schools produced similar results to regulatory sensors, suggesting that research-grade sensors are useful for providing protective information for schools—especially when used in low-income communities where infrastructure might be older. As Utah school-aged children spend at least 900 h a year inside schools, it is imperative to quantify and understand the potential protectiveness of these buildings. Furthermore, schools are often gathering spaces and provide recreational opportunities during off-school hours, especially in lower-income and rural communities.

In this study, we found that inversions were composed of mostly (70%+) secondary pollutants, which dissipated indoors due to the changing ambient conditions (e.g., warmer temperatures and lower relative humidity). As a result, schools were shown to be more protective against the secondary pollutants that dominate inversion episodes, following a short lag, than during other situations. What remains concerning is that outdoor air during other pollution events has not been found to behave this way [22]. Since we found notable differences in outdoor air quality between the two schools, this may be a source of concern for other elevated pollution events, such as wildfires. Deng and Lau [37] also found temperature and humidity to be correlated to indoor air quality, and the relationship was consequential for the resulting particle count in their study on  $CO_2$ . They also found large seasonal variations in humidity level, ventilation rate, particle counts, and formaldehyde concentration. It was, therefore, suggested that the monitoring of classroom indoor air

quality (IAQ) and thermal comfort (TC) should be performed periodically across the whole school year to comprehensively describe the conditions.

This study compared indoor and outdoor PM<sub>2.5</sub> readings at high- and low-income schools located in different parts of Salt Lake City, Utah, a rapidly growing urban community. It was found that there was a lag ranging between 35 and 73 min for the outdoor PM<sub>2.5</sub> concentrations to follow a similar temporal pattern as the indoor PM<sub>2.5</sub>. This lag has policy and health implications and may help to explain rising concerns regarding reduced educational outcomes related to air pollution in urban areas. Interventions could be created to narrow this unhealthy period in the lag, and supplementary equipment could be used to offset the lag during atmospheric inversion events as well as dust events. This raises the question of what the lag means for COVID-19 conditions, where drawing air in is essential for protecting students from COVID-19, but more of that air is harmful for other reasons. Resolving this dilemma is especially important in lower-income communities, where other situational factors may compound these outcomes over the long term.

#### 4.2. Future Work

This study provides a preliminary framework for evaluating environmental inequality in two high schools (East High, a high-income school, and West High, a low-income school) in Salt Lake City, Utah. While higher levels of outdoor pollutants were observed at the low-income school (e.g., West High), more research is needed to understand why indoor pollutants were lower, potentially providing some good news with respect to environmental inequality at West High school. The differences in outdoor and indoor particulate pollutants found in this study at the two high schools warrant future research to better understand some of the driving factors over multiple seasons and a larger range of pollutant types (e.g., ozone, NO<sub>2</sub>, CO<sub>2</sub>) and concentrations. For example, do differences in air intake and filtration systems, chemical properties, and size of outdoor pollutants (e.g., primary vs. secondary particulates) or outdoor humidity levels impact the indoor pollutant concentrations? Additionally, how much do the indoor particulate pollutants vary between different locales in the same school? In this study, the indoor sensors were placed in the cafeteria and gymnasium by necessity. Future studies could focus on observing those indoor locations that were most visited by students (individual classrooms).

In addition, future research could include comonitoring the differences in indoor and outdoor pollution for additional criteria pollutants, such as ozone or nitrogen dioxide. For example, in airtight buildings ozone can be lower than outside, whereas in poorly sealed buildings it can be higher than outside [38].

To account for larger particle sizes and the lag, future studies could resolve the indoor particle components and compare them with the event type (e.g., inversions, dust storms, and wildfires). Future studies could also compare the filtration system of the schools and make some recommendations to account for different lag events in the light of confounding factors (e.g., COVID-19). Furthermore, the impact of the use of fine filters, such as F8 (MERV14) filter, on indoor air quality merits additional research.

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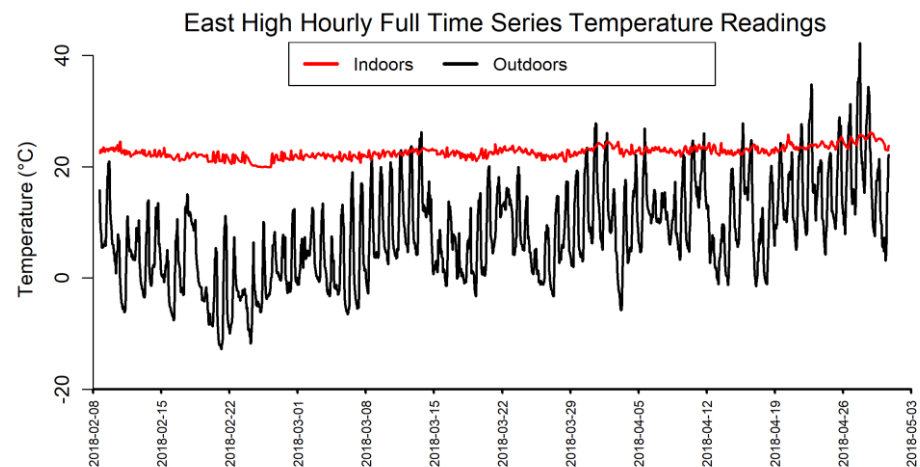
**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to this section due to school privacy concerns.

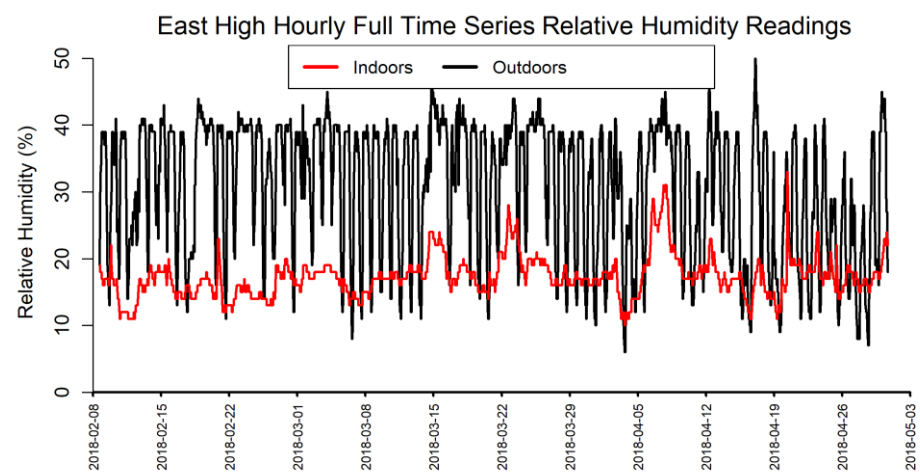
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## Appendix A



**Figure A1.** Indoor and outdoor temperature at East High.



**Figure A2.** Indoor and outdoor relative humidity at East High.

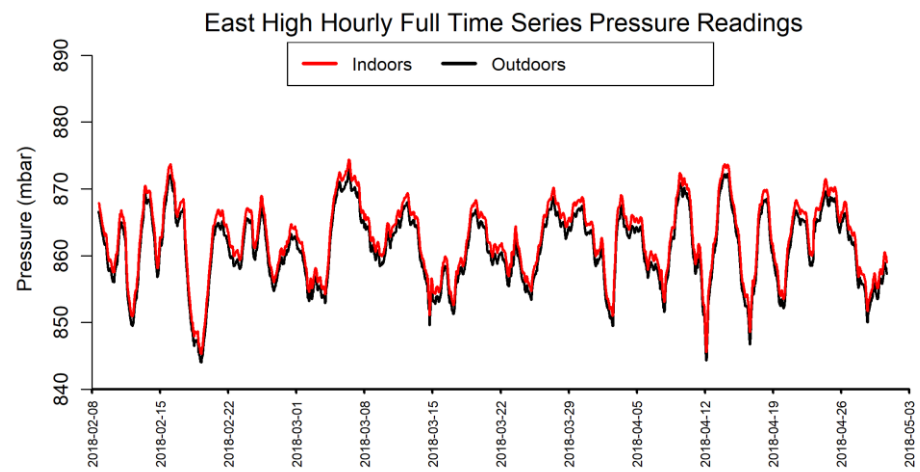


Figure A3. Indoor and outdoor atmospheric pressure at East High.

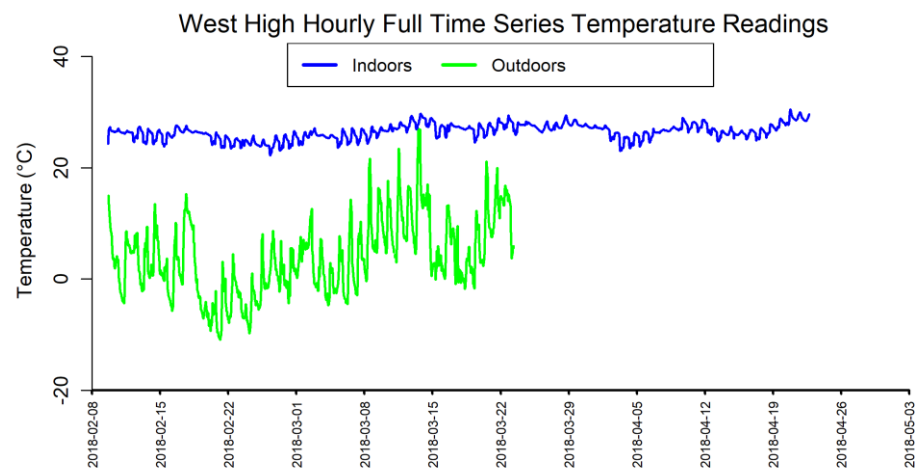


Figure A4. Indoor and outdoor temperature at West High.

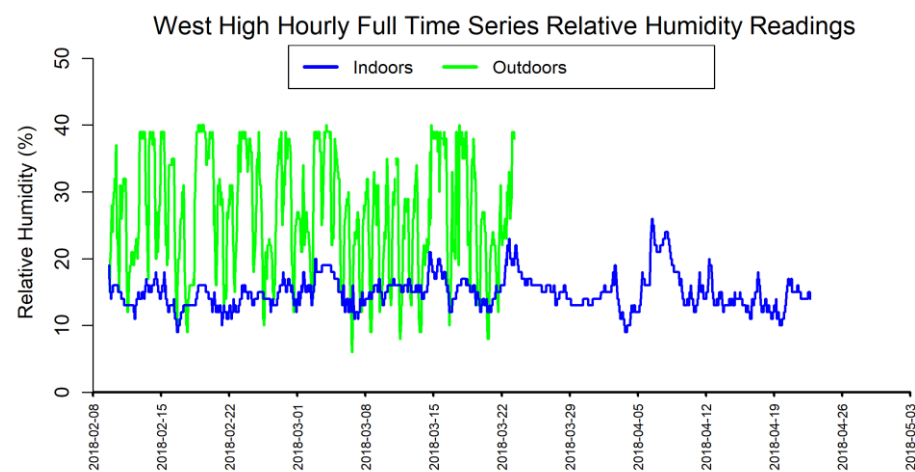


Figure A5. Indoor and outdoor relative humidity at West High.

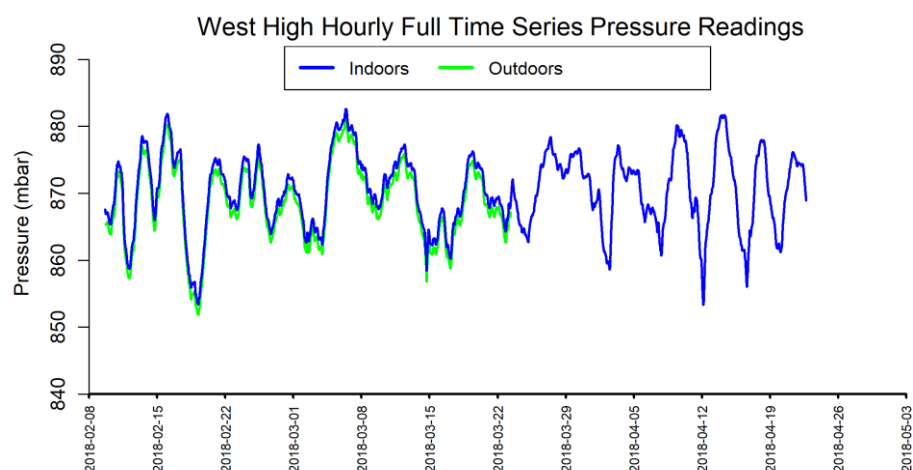


Figure A6. Indoor and outdoor atmospheric pressure at West High.

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