

Article

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

Daniel L. Mendoza ^{1,2,3,*}, Tabitha M. Benney ⁴, Ryan Bares ⁵, Benjamin Fasoli ¹, Corbin Anderson ⁶, Shawn A. Gonzales ⁶, Erik T. Crosman ⁷ and Sebastian Hoch ¹

¹ Department of Atmospheric Sciences, University of Utah, 135 S 1460 E, Room 819, Salt Lake City, UT 84112, USA; daniel.mendoza@utah.edu; benfasoli@gmail.com; sebastian.hoch@utah.edu

² University of Utah School of Medicine, Pulmonary Division, 26 N 1900 E, Salt Lake City, UT 84132, USA

³ Department of City & Metropolitan Planning, University of Utah, 375 S 1530 E, Suite 220, Salt Lake City, Utah 84112, USA

⁴ Department of Political Science, University of Utah, 260 S Central Campus Drive, Salt Lake City, UT 84112, USA; tabitha.benney@poli-sci.utah.edu

⁵ Utah Department of Environmental Quality, Division of Air Quality, 195 N 1950 W, Salt Lake City, UT 84116, USA; rbares@utah.gov

⁶ Salt Lake County Health Department, Air Quality Bureau, Environmental Health Division 788 East Woodoak Lane, Murray, UT 84107, USA; canderson@slco.org; shgonzales@slco.org

⁷ Department of Life, Earth and Environmental Sciences, West Texas A&M University, Natural Sciences Building 324, Canyon, TX 79016, USA; etcrosman@wtamu.edu

* Correspondence: daniel.mendoza@utah.edu

Abstract: 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. Due to the pandemic, however, ventilation of buildings using outdoor air has become an important safety technique to prevent the spread of COVID-19. With the mounting evidence suggesting that air pollution is impactful to human health and educational outcomes, this contradictory guidance may be problematic in schools with higher air pollution levels, but keeping kids COVID-19 free and in school to receive their education is now more pressing than ever. To understand if all schools in an urban area are exposed to similar outdoor air quality and if school infrastructure protects children equally indoors, we installed research grade sensors to observe PM_{2.5} 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. Based on this approach, we found that during atmospheric inversions and dust events, there was a lag ranging between 35 to 73 minutes for the outdoor PM_{2.5} concentrations to follow a similar temporal pattern as the indoor PM_{2.5}. This lag has policy and health implications and may help to explain the rising concerns regarding reduced educational outcomes related to air pollution in urban areas. These data and resulting analysis show that poor air quality may impact school settings, and the potential implications with respect to environmental inequality.

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. However, with the onset of COVID-19, ventilation of buildings using outdoor air has become an important safety technique to prevent or slow the spread of the pandemic⁵. This contradictory guidance may be problematic in schools because higher ventilation rates result in greater outdoor air pollution being brought indoors during times of high outdoor air pollution concentrations. There is also mounting evidence that suggests that air pollution can also be impactful to educational outcomes⁶⁻⁸ and human health⁹, but keeping kids COVID-19 free and in school to receive their education is now more pressing than ever.

It is well-established that the health impacts of air pollution can be significant, with disadvantaged populations being disproportionately impacted. While research has demonstrated the mechanisms that produce this inequality, less is understood about these effects in school settings. Children are especially vulnerable to the health and developmental impacts of environmental inequality due to their unique biological vulnerabilities, age-related patterns of exposure, and lack of control over their own environmental circumstances¹⁰. In addition, air pollution aggravates inequality through its connection with a variety of educational and economic outcomes. Currie, 2011¹¹ and others have demonstrated links between poor health at birth, lower educational attainment¹², and poorer adult outcomes¹³. Economic research in this area has also illustrated how air quality impacts labor supply, productivity, and cognition¹⁴. Isen et al., 2017¹⁵, 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 impact teacher and school performance also, which may result in lower funding levels federally, further compounding the problem.

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. Environmental inequality is 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 birth¹⁶⁻²⁰. The impacts of this exposure, however, go well beyond simple health outcomes. Prior research has found disparities associated with air quality based on economic standing, language minority status, immigration status, race, and ethnicity²¹. 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, our research explores how unequal exposure to indoor and outdoor air pollution (e.g., fine particulate matter [PM_{2.5}]) impacts indoor air quality among high- and low-income schools in Salt Lake City (SLC), Utah.

Since indoor air quality is affected by outdoor²² and indoor sources of pollution, environmental conditions, housing characteristics, and behavioral factors²³, we installed research grade sensors to observe PM_{2.5} 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, income level, etc.). 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 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). Utah as a state is renowned for its majestic natural sites and pristine mountains, but the air quality in its urban centers and the Uintah Basin 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 pollution²⁴. This dubious standing has many contributing factors.

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) has been increasing around ten percent or more annually²⁵, making this and other urban areas increasingly susceptible to transportation related air pollution. Additionally, SLCo also has 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 ozone²⁶ and PM_{2.5}²⁷.

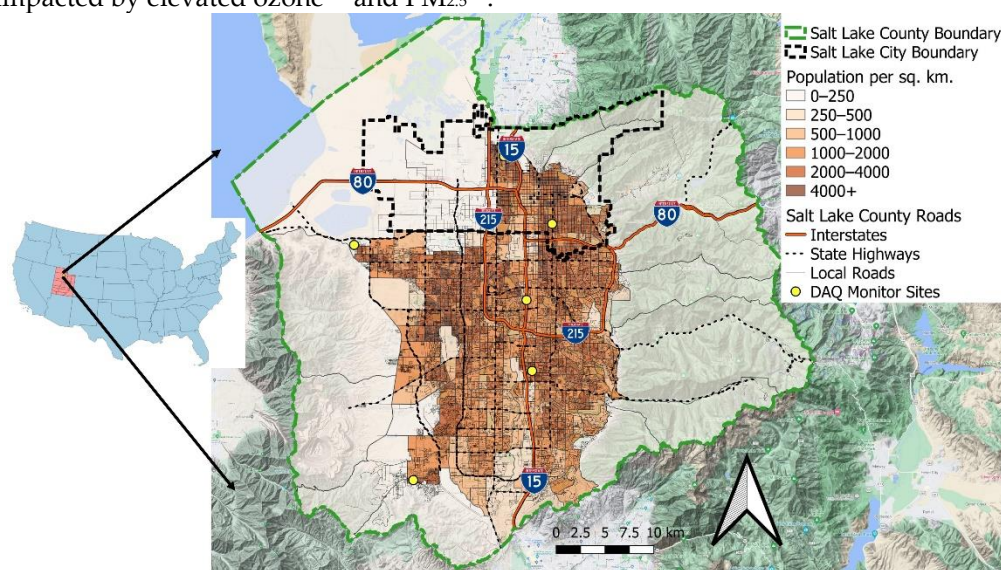


Figure 1. Salt Lake City and Salt Lake County within Utah and the United States (left inset).

This study deployed research-grade sensors, which are demonstrated to be comparable to regulatory grade instrumentation in accuracy and precision²⁸ and significantly more robust and reliable than commonly used low-cost or citizen science sensors²⁹. We installed Met One Instruments (Met One Instruments Inc., Grants Pass, OR 97526) ES-642 Remote Dust Monitors, with inlet sharp cut cyclones to measure PM_{2.5}, with a manufacturer's stated uncertainty of $1\mu\text{g m}^{-3}$ ³⁰ at schools on opposite sides of SLC. The schools, appropriately named "East High School" (East High) (40.75230 N, 111.85527 W³¹, Elevation 1373 MASL³²) and "West High School" (West High) (40.77433 N, 111.90040 W, Elevation 1302 MASL), are located approximately 4.5 kilometers 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: North east corner of East Gym; West High: Inside of commons area on north west beam) and each was approximately 3.5 meters above ground). 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.

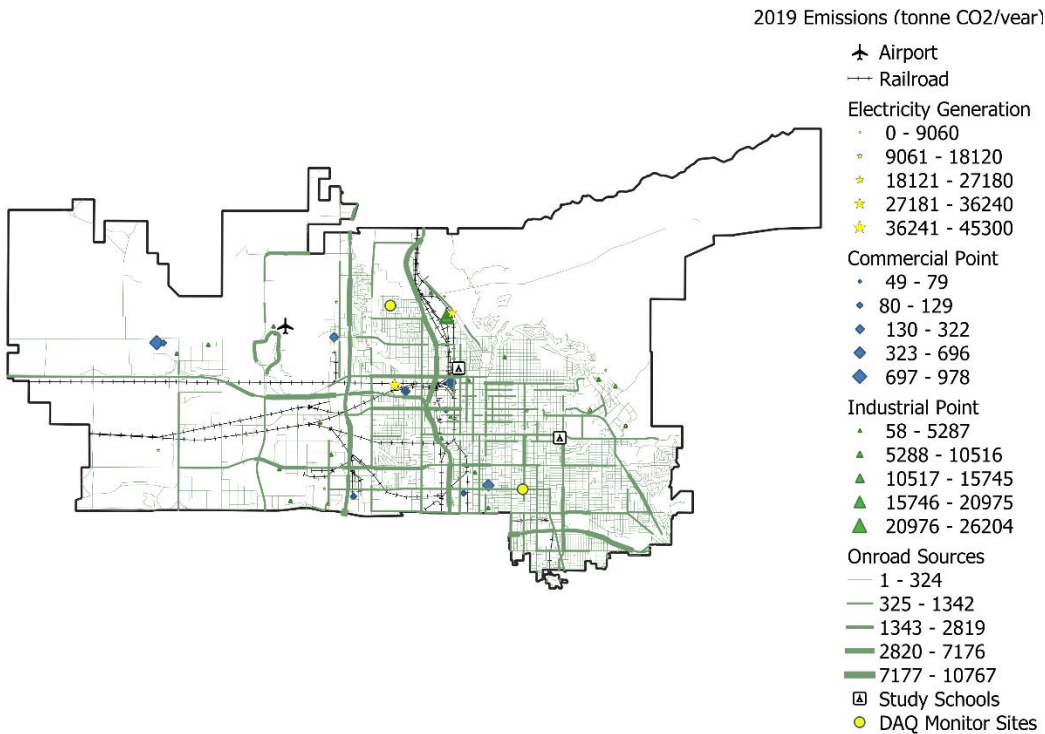


Figure 2. Study area showing Salt Lake City’s emission sources (2019 tonne CO₂/year), study schools, and regulatory air quality monitoring sites.

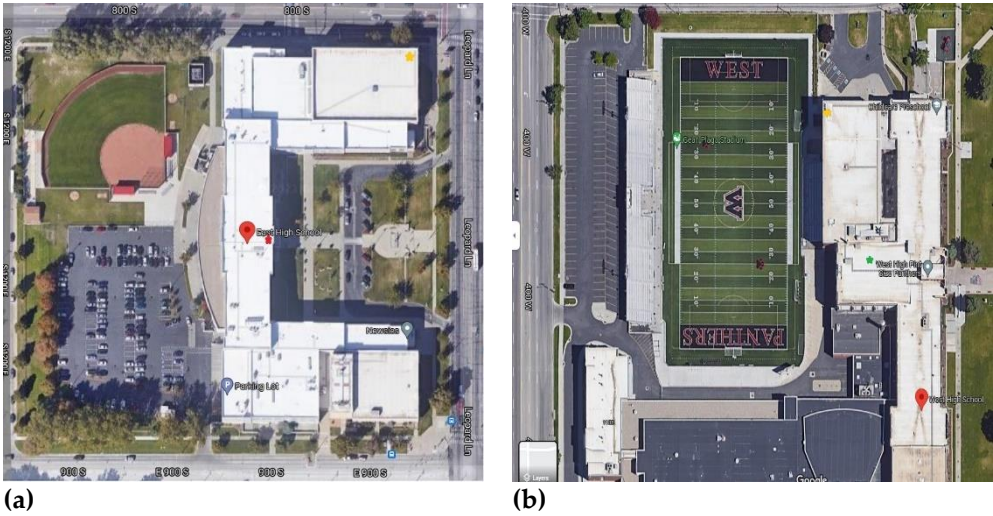


Figure 3. Study area showing the PM_{2.5} instrument locations at (a) East High and (b) West High. The location of the inlet for the indoor sensors are denoted by the yellow stars, while the red symbol denotes the location of the outdoor rooftop sensor.

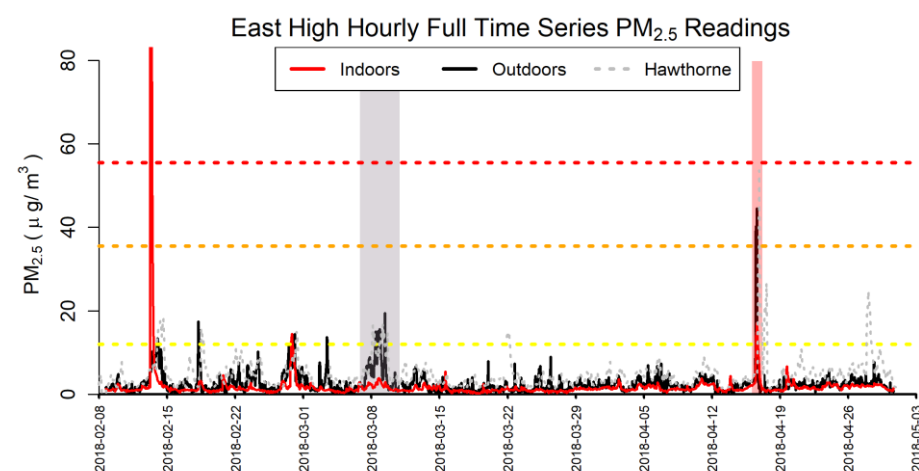
The study period for this research spanned from February 8 to April 30, 2018. Between November and February each year, the SLC experiences periodic temperature inversions where pollutants accumulate in the stable boundary layer for several days to several weeks³³. These temperature inversions weaken 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 year, with April being the dustiest month of the year³⁴. The study period in this paper (February – April 2018) is thus representative of both the end of the winter inversion season as well as the springtime dust season.

The instruments record data at 1-second intervals which was 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 to 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 one-minute 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 minutes to quantify the most impactful lag period as estimated by r^2 value as further described in Section 3.5.

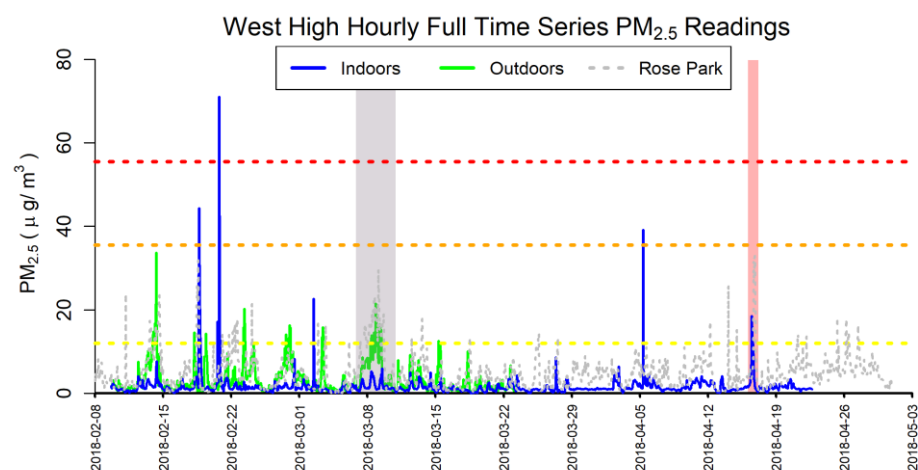
3. Results

3.1. Full Time Series

The full study period time series of PM_{2.5} for both the indoor and outdoor sensors is shown in Figure 4. Figure 4.a displays the hourly indoor and outdoor PM_{2.5} readings for East High as well as the Hawthorne regulatory sensor while Figure 4.b 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 cutoffs³⁵. The associated temperature, relative humidity, and pressure values are found in Appendix A, Figures A.1-6.



(a)



(b)

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.

As illustrated in Figures 4.a,b, PM_{2.5} 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_{2.5} readings than East High. This demonstrates, for this case study period, the potential environmental inequality effects, which could lead to lower overall standardized testing scores in low-income schools, even when controlling for other factors (e.g., economic or language status) ⁷.

In addition to the averages over the study period, there are three notable anomalies where the PM_{2.5} concentrations were substantially higher indoors than outdoors. Although we contacted the schools, they were unable to provide explanations for these events. On Tuesday, February 13th from 6-9 am, East High recorded indoor hourly readings of up to 376 µg/m³. 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 February 18th from 5-8pm and Tuesday February 20th from 6-8pm at West High. These elevated events peaked at 71 µg/m³ and are consistent with cleaning activity. As the indoor instrument was in the cafeteria and commons area, these readings could indicate the effects of vacuuming and kitchen cleaning or cooking activities.

3.2. School Outdoor vs. Regulatory Sensor PM_{2.5}

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_{2.5} concentrations than their corresponding regulatory instrument. This is likely due to the location of the schools near lower traffic roads compared to larger roads near the regulatory sensors. As noted in the previous section, the outdoor PM_{2.5} readings for West High are generally higher than for East High.

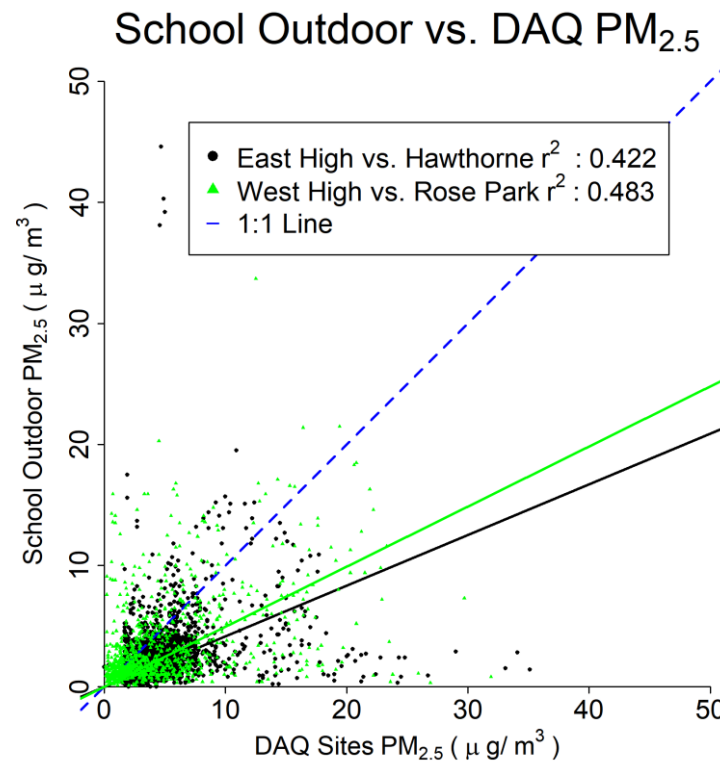


Figure 5. School outdoor sensor readings compared to nearest regulatory sensor.

3.3. School Indoor vs. Outdoor PM_{2.5}

The school indoor and outdoor sensor readings are compared in Figure 6. 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_{2.5} observed indoors at West High relative to East High compared to the outside readings. The indoor PM_{2.5} readings are generally consistent across both schools and the slope difference is attributable to the higher outdoor concentrations observed at West High.

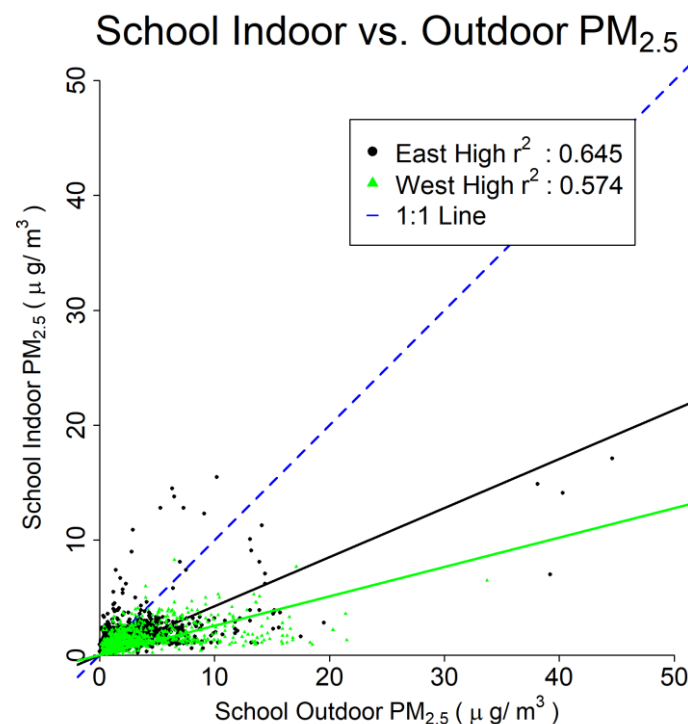


Figure 6. School indoor vs. outdoor PM_{2.5} sensor reading.

3.4. Weekday Diurnal Cycle

The weekday diurnal cycle $PM_{2.5}$ concentrations and outdoor/indoor ratio at the four sites is 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 as well as combustion activity from commercial and industrial buildings (Figure 7.a). Additionally, the atmospheric boundary layer is lowest in the early morning hours leading to the substantial increase. 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 to the outside ones. This is likely due to building infiltration rates as well as contamination from indoor sources (Figure 7.b).

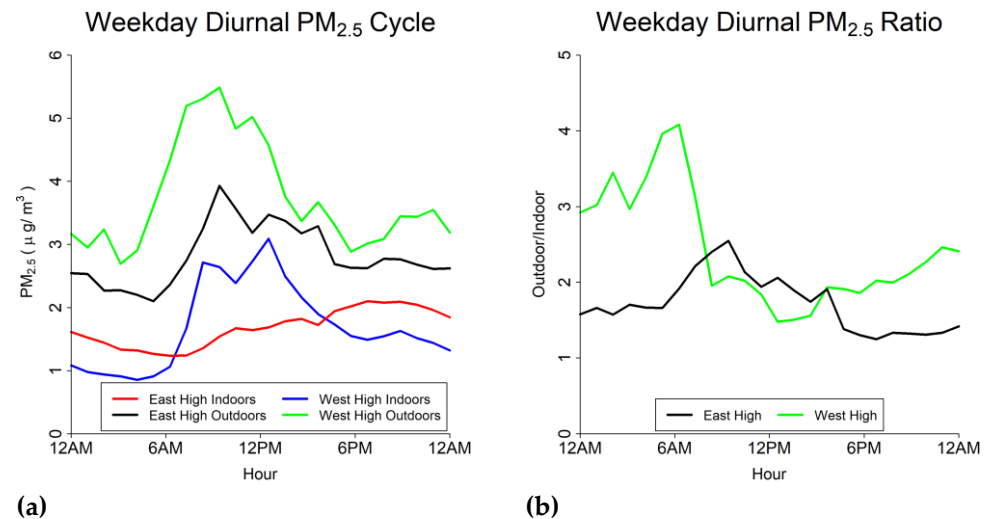


Figure 7. Weekly diurnal cycle (a) and diurnal $PM_{2.5}$ outdoor/indoor ratio for study schools.

3.5. March 7-9th Pollutant Accumulation – Atmospheric Inversion Event

A multi-day 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 $PM_{2.5}$ outside compared to inside schools. To capture the potential range of possible lags, the minute-resolved indoor data was lagged with respect to the outdoor readings by 1 to 180 minutes. The best fit was determined as the lag that produced the highest r^2 value.

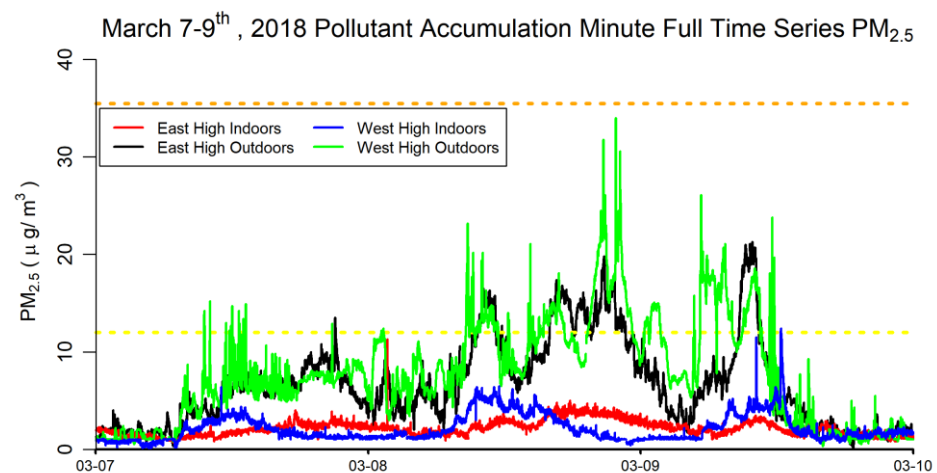


Figure 8. Pollution accumulation event from March 7-9th.

The coefficient of determination comparing lagged indoor measurements and outdoor measurement as well as the comparison between the lagged values is shown in Figure 9. The highest r^2 value (0.878) for East High was at a lag of 57 minutes (Figure 9.a,b). West High had its highest r^2 value (0.646) at a lag of 35 minutes, but there was another similar peak at 135 minutes (Figure 9.c,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. As can be seen in Appendix A, East High has markedly lower temperature and relative humidity variability than West High (Appendix A, Figures A.1-6). This larger stability could also be affected by ventilation within the indoor locations in addition to outdoor conditions.

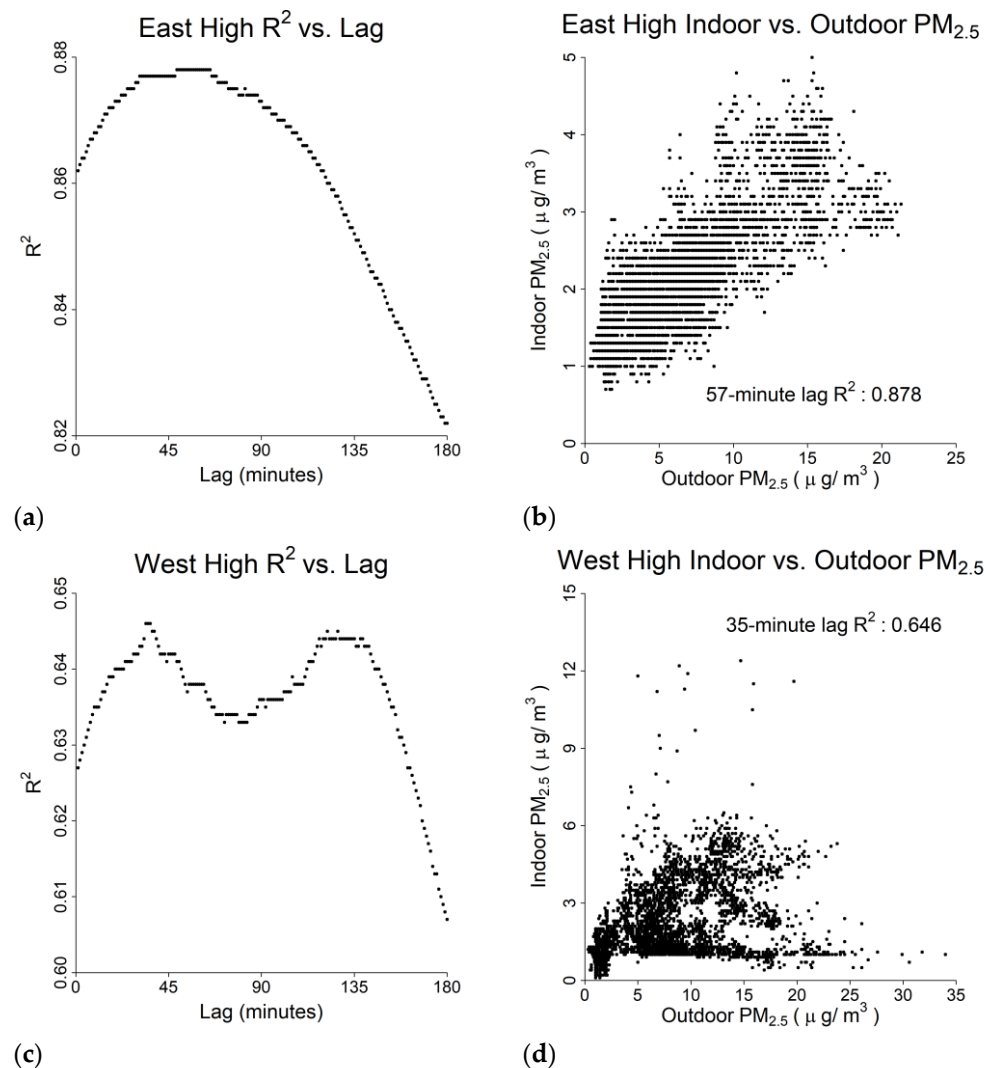


Figure 9. Coefficient of determination and comparison between lagged indoor and outdoor $PM_{2.5}$ readings at the highest coefficient of determination: (a) Coefficient of determination for East High; (b) East High 57-minute lagged indoor and outdoor $PM_{2.5}$; (c) Coefficient of determination for West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

3.6. April 16th Dust Event

The resulting indoor and outdoor $PM_{2.5}$ 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.

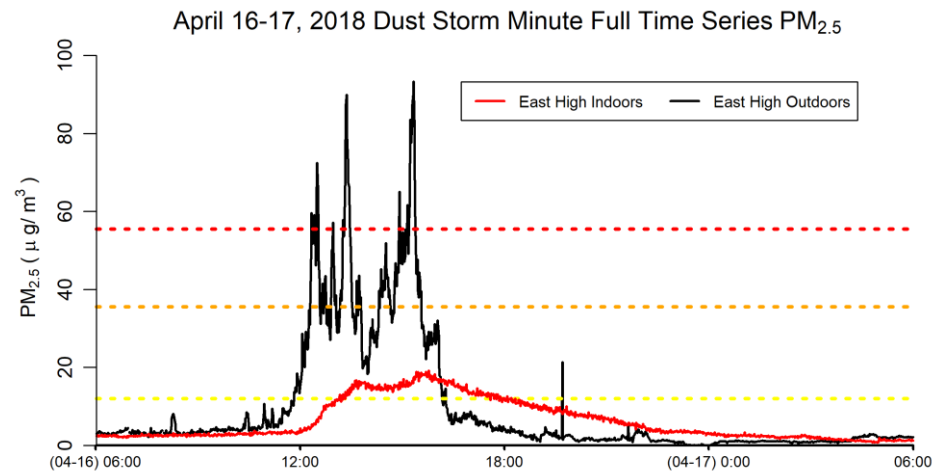


Figure 10. Dust storm event on April 16th.

The coefficient of determination comparing lagged indoor measurements and outdoor measurement as well as the comparison between the lagged values is shown in Figure 11. An interesting feature is the shape of the distribution compared to 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 be larger on average than during the earlier event). Therefore, the building air handling system was involved in filtering the $\text{PM}_{2.5}$ as outside air was brought into the building. It seems that the efficiency limit was reached which led to indoor $\text{PM}_{2.5}$ 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 storm³⁶ during which most of the observation above $30 \mu\text{g}/\text{m}^3$ occurred. Furthermore, the lag (73 minutes) is comparable to the lag found in the previous section (57 minutes) for East High.

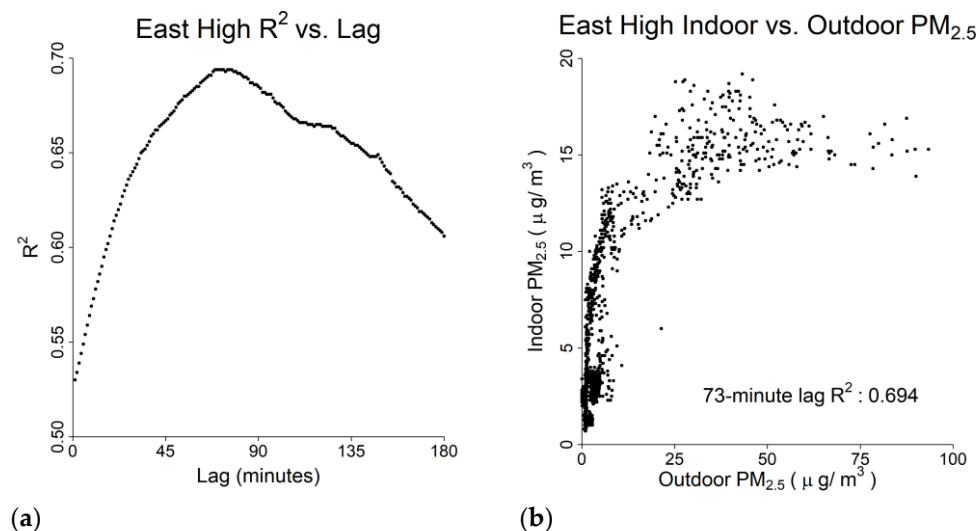


Figure 11. Coefficient of determination and comparison between lagged indoor and outdoor $\text{PM}_{2.5}$ readings at the highest coefficient of determination: (a) Coefficient of determination for East High; (b) East High 73-minute lagged indoor and outdoor $\text{PM}_{2.5}$.

4. Discussion

Inversions 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 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 way²². Since we found notable differences between outdoor air quality at the two schools, this may be a source of concern for other elevated pollution events such as wildfires. Deng and Lau, 2019³⁷ also found temperature and humidity to be correlated to indoor air quality and the relationship was consequential for the resulting particle count – CO₂ in this case. 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 done periodically across the whole school year to comprehensively describe the conditions. 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 schools in Salt Lake City, Utah. While higher levels of outdoor pollutants were observed at the low-income West High school, more research is needed to understand why indoor pollutants were lower, potentially providing some good news with respect to potential environmental inequality at the West High school. 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 – especial when used in low-income communities where infrastructure might be older. As Utah school-aged children spend at least 900 hours 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, especially in lower-income and rural communities.

5. Conclusions

5.1. Implications

This study compared indoor and outdoor PM_{2.5} 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 to 73 minutes for the outdoor PM_{2.5} concentrations to follow a similar temporal pattern as the indoor PM_{2.5}. This lag has policy and health implications and may help to explain the 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.

5.2. Future Work

The differences in outdoor and indoor 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 concentrations. For example, do differences in air intake and filtration systems, chemical properties and size of outdoor pollutants (e.g., primary versus secondary particulates), or outdoor humidity levels impact the indoor pollutant concentrations?

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 the fine filters, such as F8 (MERV14) filter, on indoor air quality merits additional research.

Author Contributions: Conceptualization, B.F., C.A., D.L.M., R.B. and S.A.G.; methodology, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; software, B.F., C.A., D.L.M., R.B. and S.A.G.; validation, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; formal analysis, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; investigation, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; resources, B.F., C.A., D.L.M., R.B. and S.A.G.; data curation, B.F., C.A., D.L.M., R.B. and S.A.G.; writing—original draft preparation, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; writing—review and editing, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; visualization, D.L.M.; supervision, B.F., C.A., D.L.M., E.T.C., R.B., S.A.G., S.H. and T.M.B.; project administration, B.F., C.A., R.B. and S.A.G.; funding acquisition, B.F., C.A., D.L.M., R.B. and S.A.G. All authors have read and agreed to the published version of the manuscript.

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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.

Acknowledgments: Charles Snow, Technical Assistant on project.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

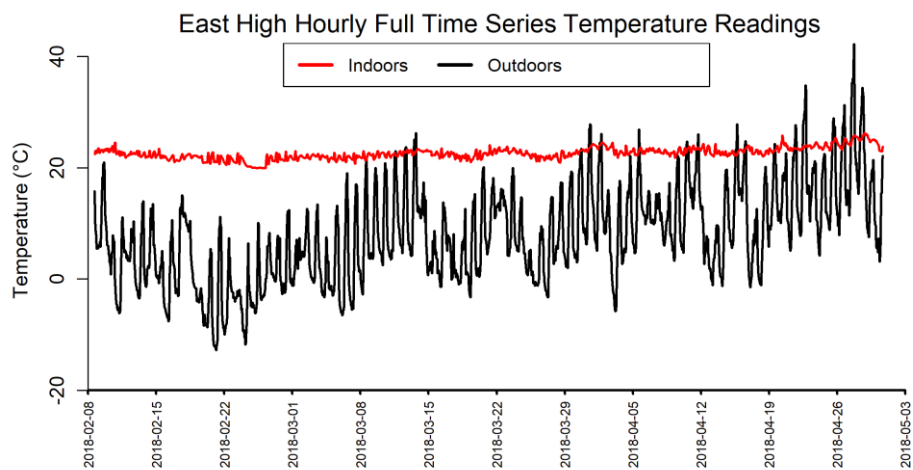


Figure A.1. Indoor and outdoor temperature at East High.

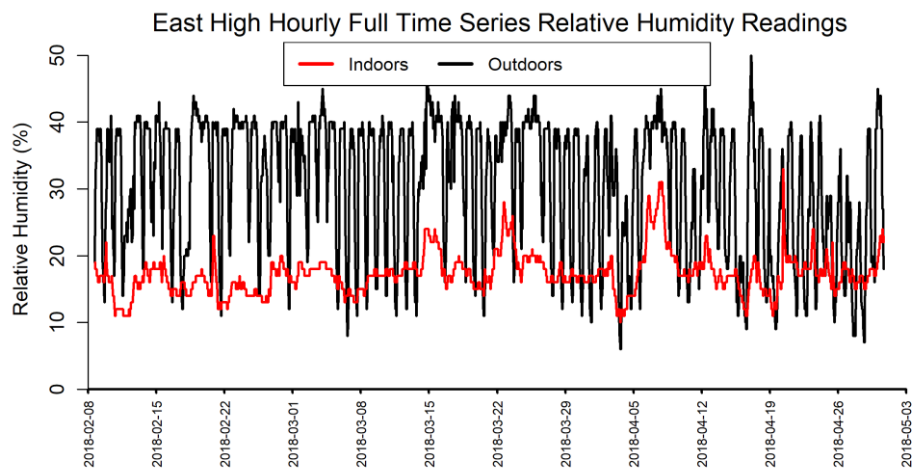


Figure A.2. Indoor and outdoor relative humidity at East High.

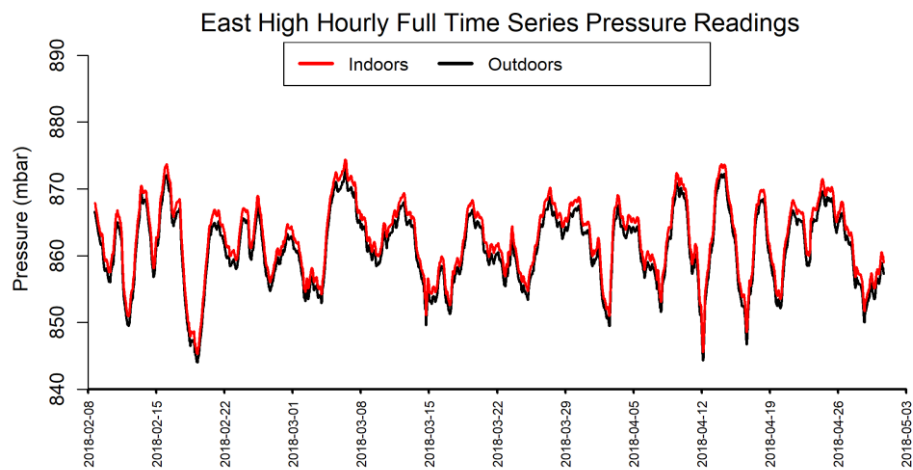


Figure A.3. Indoor and outdoor atmospheric pressure at East High.

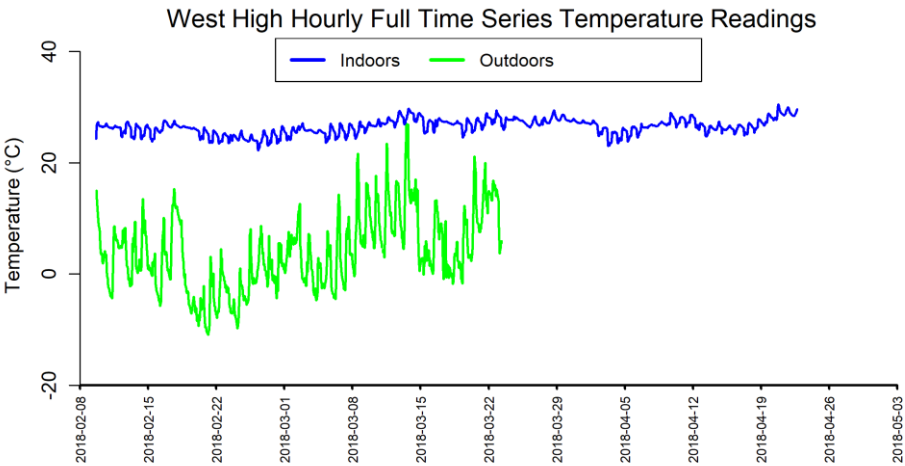


Figure A.4. Indoor and outdoor temperature at West High.

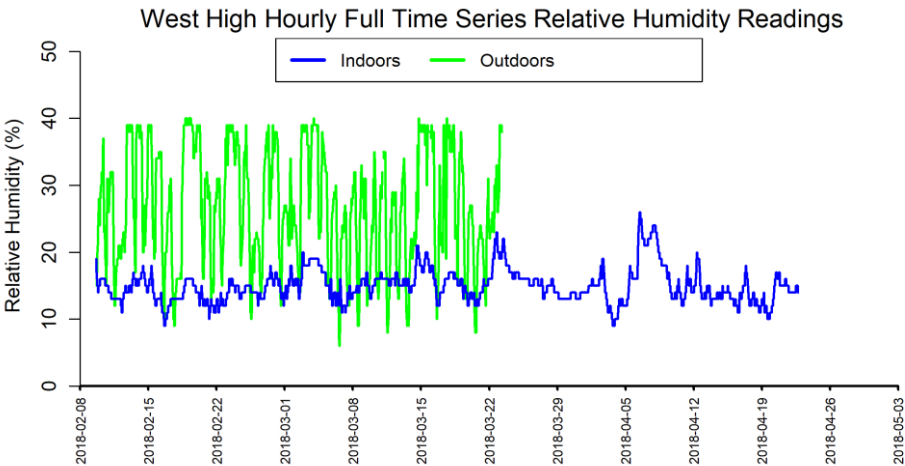


Figure A.5. Indoor and outdoor relative humidity at West High.

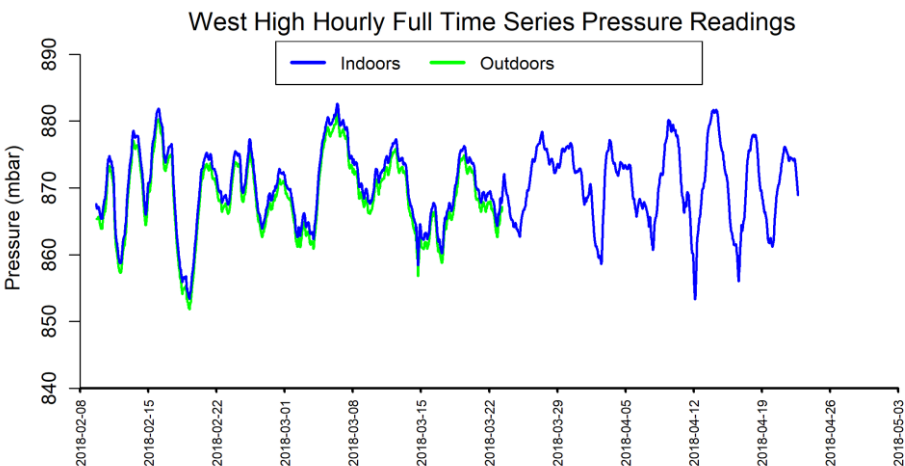


Figure A.6. Indoor and outdoor atmospheric pressure at West High.

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