Wisconsin Department of Natural Resources

2019 PurpleAir Comparison Study Report

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Overview

Low-cost air quality sensor availability, along with public interest in air quality impacts on health have contributed to a worldwide increase in air quality sensor deployment. The PurpleAir PA-II Dual Laser Air Sensor (referred to as PurpleAir or PA, pictured in *Figure 1*) is a particulate air quality sensor that is relatively inexpensive and easy to install. The PurpleAir sensor contains a "dual laser" technology, meaning that it has two separate particulate sensing elements in one unit, which can contribute to quality assurance of data outputs. These features, along with its low cost and ease of use have contributed to the PurpleAir Sensor being increasingly utilized by citizens to monitor and better understand their local air quality.

Figure 1: *Individual purple air sensor unit containing two independent "Dual Laser" measurement sensors*

Nationwide comparisons of PurpleAir data with data from regulatory monitors indicate the PA sensor data has a positive bias, meaning the sensor typically reports higher particulate concentrations than regulatory monitors. During an experimental period the PurpleAir sensor occasionally reported concentrations that nearly doubled those reported by regulatory monitors measuring the same air mass.

A correction factor is a mathematical equation that can be applied to raw sensor data to allow greater regulatory data comparability. To better understand the capabilities of the PurpleAir sensor and potential methods for developing a correction factor, the Wisconsin Department of Natural Resources (DNR) purchased five PurpleAir units and conducted a PurpleAir comparison study with a goal of developing a correction factor to improve the accuracy and utility of these sensor data. Details of the study are outlined step-wise in order of DNR completion.

Study design and goals

The PurpleAir comparison study was conducted by deploying PurpleAir sensors for approximately one year at spatially distributed DNR-operated monitoring sites where they were paired with established regulatory (Federal Equivalent Method) PM2.5 monitors. Teledyne T640/T640x (referred to as T640) regulatory instruments were used in the comparison study and are certified to meet federal criteria for comparison with the National Ambient Air Quality Standards (NAAQS).

Figure 2: *PurpleAir sensor collocated with T640 FEM at Appleton.*

The DNR's PurpleAir comparison study was drafted and eventually formalized in a quality assurance project plan (QAPP). Objectives of this study included:

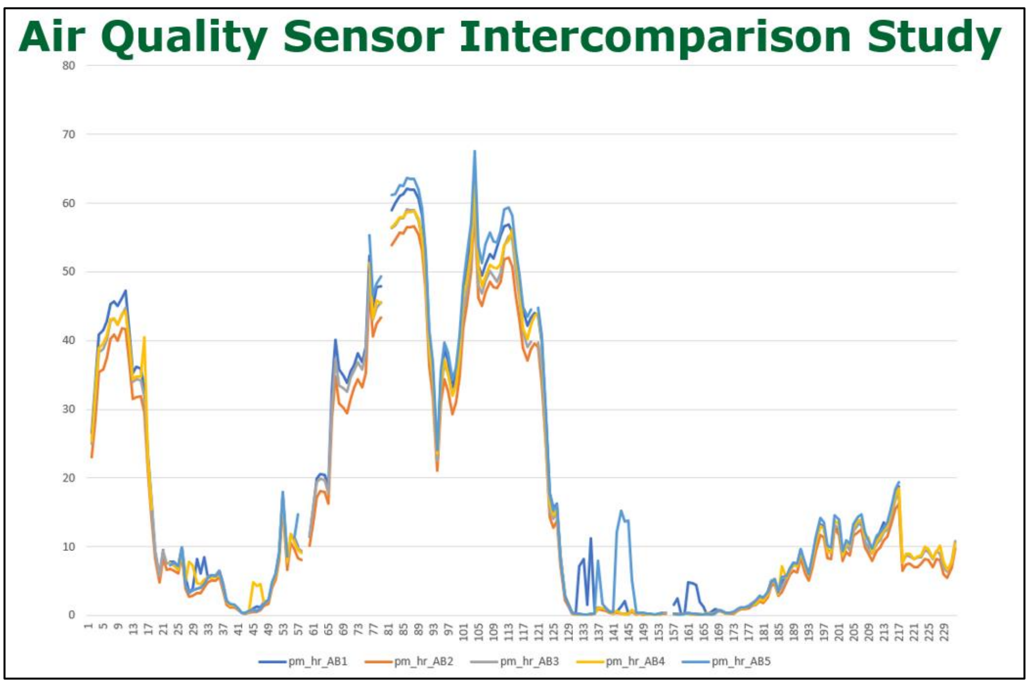
- Perform similarity assessment among PurpleAir sensors by evaluating periods where all sensors were at the same location
- Perform PurpleAir and T640 data trend correlation assessment at DNR-operated sites
- Assess how closely PurpleAir data matched T640 data at DNR-operated sites
- Develop a statewide correction factor for PurpleAir data and assess whether there are differences in how well corrected and uncorrected PurpleAir data match T640 data at DNR-operated sites
- Compare site-based versus statewide correction factors to determine sensitivity of the correction factors to Wisconsin regionality
- Compare seasonal versus statewide correction factors to determine sensitivity of the correction factors to Wisconsin seasonality

Intercomparison evaluation of PurpleAir units

To evaluate comparability among PurpleAir sensors, five sensors were located together at one DNR monitoring site (*Figure 3)* for a 7+ day period beginning in December 2018. Due to variability in raw data time scales, data was averaged to a 1-hour time base and were compared among sensors (*Figure 4*).

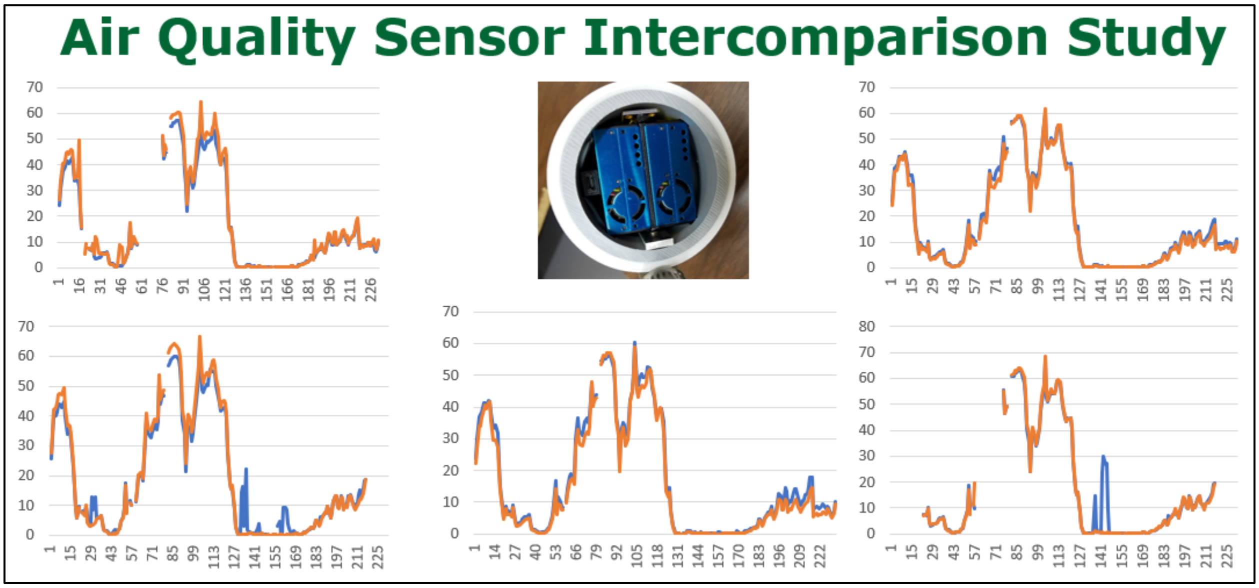
Figure 3: *PurpleAir sensors collocated for intercomparison evaluation*

Figure 4: *Results of one-hour averages of five PurpleAir air quality sensor intercomparison evaluation*



One PurpleAir sensor unit utilizes two separate particulate sensing elements resulting in two separate data outputs known as the "A" and the "B" channels. Data from the "A" and "B" channels were compared to each other for consistency and to allow for informed decision making on how to proceed with data interpretation (*Figure 5*).

Figure 5: *Results of intercomparison evaluation from five individual PurpleAir sensors comparing each sensor's individual A and B sensor channels.*



The two initial PurpleAir intercomparison evaluations lead to the following conclusions:

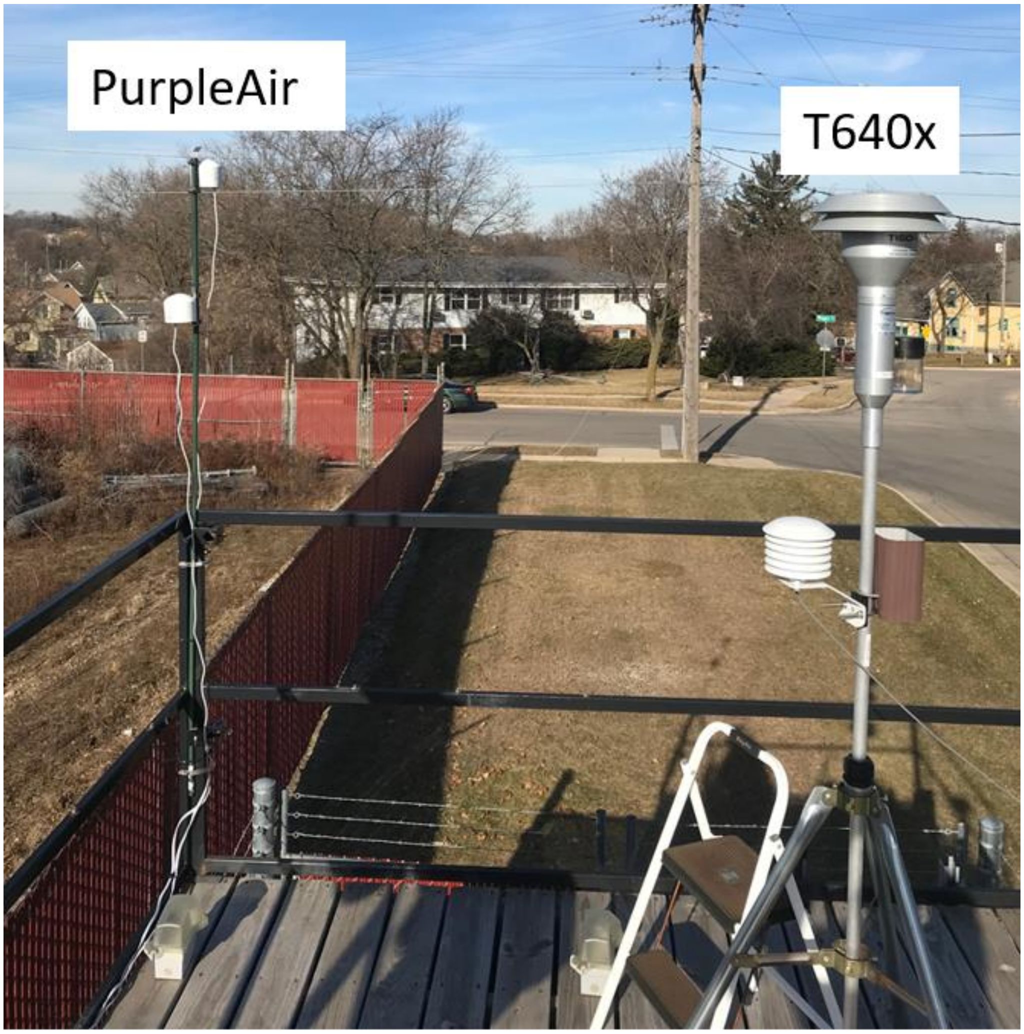
- The sensors generally had good overall agreement among units (*Figure 4*)
- Upward and downward trends generally tracked well (*Figure 4*)
- Two sensors of the five had some periods of disagreement with the other sensors (*Figure 4*)
    - A/B channel agreement was poor for these two sensors during periods of disagreement with other sensors (*Figure 5*)
    - A/B channel agreement was identified as a screening tool for abnormal sensor performance
- All sensors were operational and producing similar results

Site deployment and data collection

After the PurpleAir intercomparison evaluation, four of the five PurpleAir sensors were deployed to DNR monitoring sites in Appleton, Eau Claire, Madison and Waukesha to collect data alongside T640 regulatory monitors for a time period of one year (December 2018 – December 2019). Sites throughout the state were chosen based on their spatial distribution and historic PM2.5 concentrations. Sites with historic PM2.5 concentrations that measured higher concentrations relative to other statewide sites were prioritized to contribute to a data set with a wider range.

The fifth PurpleAir sensor was designated as the quality assurance (QA) sensor. The QA sensor was primarily deployed at Waukesha, but also traveled to three additional sites (Appleton, Eau Claire and Madison) to collect additional sensor collocation data throughout the study. QA sensor collocations lasted approximately one week each quarter.

Figure 6: *Two PurpleAir sensors collocated with T640x FEM at Waukesha Monitoring site.*



In order to retrieve data from the PurpleAir sensors an account was created with PurpleAir for access to the PurpleAir website for both the A and B channels. The downloads included data labeled as:

- CF_ATM: intended for outdoor sampling; these values are the ones that appear on the PurpleAir website map
- CF_1: intended for indoor air sampling

The DNR study used the CF_ATM values which are intended by the sensor manufacturer for outdoor air and is what is displayed on the PurpleAir website.

The PurpleAir data downloaded over the course of this one-year study was recorded in data intervals of 80 or 120 seconds. For five sensors, this totaled over one million lines of data requiring processing. To interpret this volume of data, DNR utilized RStudio; an application that employs the R programming language, widely used for statistical computing and graphing. For each site, data from PurpleAir sensors were aggregated into hourly averages and assessed for completeness. The PurpleAir and T640 hourly averages were then aggregated into daily averages and assessed for completeness. Using daily averages allowed the PurpleAir data to be compared to the T640 data using tools and techniques similar to regulatory method comparisons.

Initial expectations set by DNR established that the PurpleAir hourly data would be considered complete if 75 percent of the expected A and B channel readings were present. After reviewing the first quarter of data it was discovered that two of the five sensors had substantial shortfalls in meeting the data capture goal (incomplete data). As a result, study completeness targets were modified, and included in the final version of the QAPP, so hourly averages could be calculated using data from a single channel if necessary (A or B), rather than requiring data from both channels be used (A and B). The PurpleAir manufacturer adjusted the data telemetry interval from 80 to 120 seconds to improve performance which resolved most of the data completeness issues for the remainder of the study.

The DNR added additional weekly data screening practices to proactively identify data telemetry issues. This additional screening focused on the particulate data produced by the sensors and helped minimize losses of particulate data moving forward.

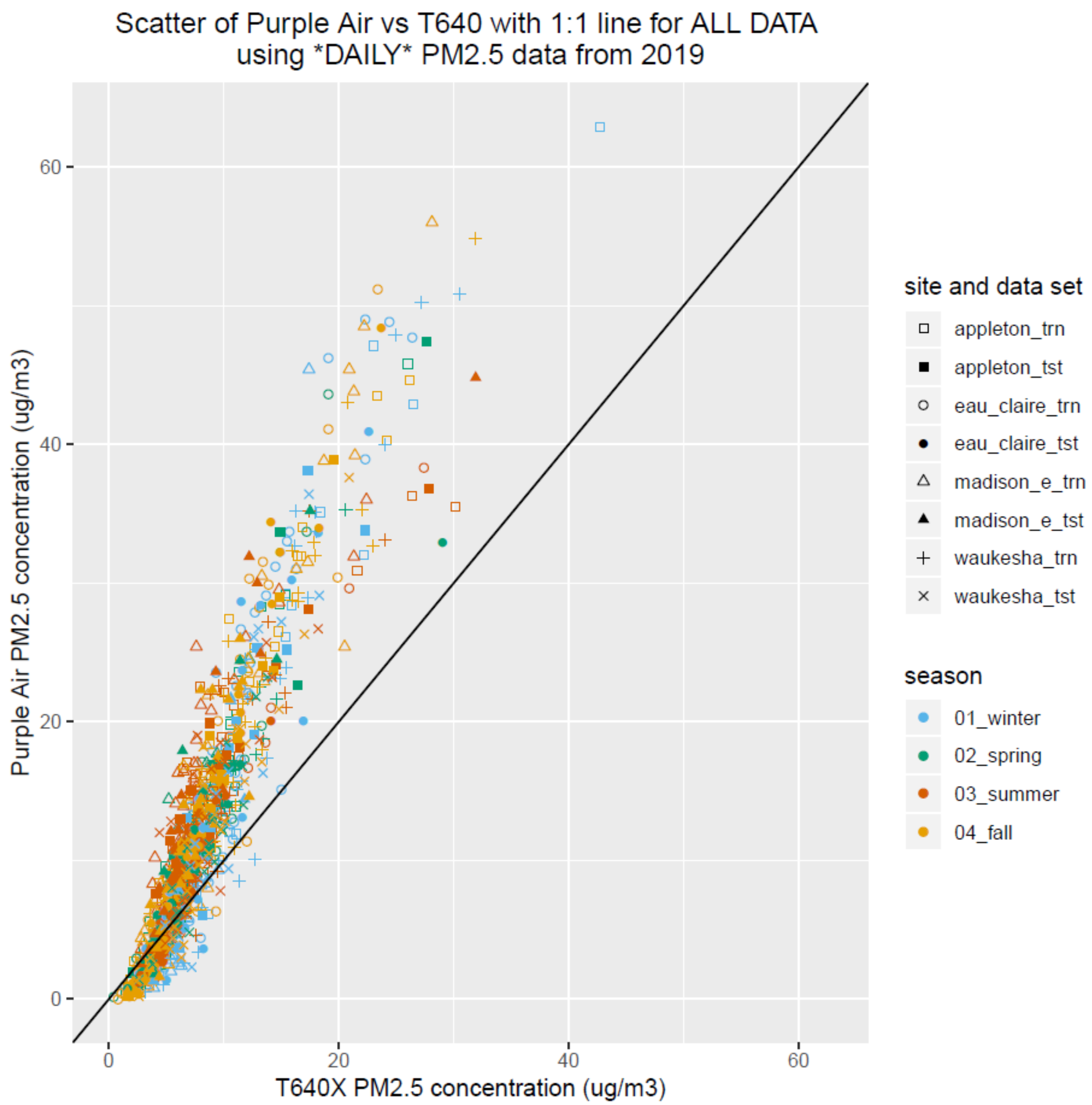
Based on the evaluation of A/B channel agreement, which is generally good, observed during the study and discussions with U.S. EPA Office of Research and Development personnel, data screening rules were established. For this study, DNR screened data based on:

- Hourly-average data outliers (higher reading of the A or B channel based on the initial intercomparison evaluation) were removed from the dataset if <u>both</u>:
    - (A channel – B channel) ≥ ±5 ug/m^3
      AND
    - (A channel – B channel) / (average of A and B channels) ≥ ±50%
- If only one channel was complete, data were not screened using this rule and the data from the single channel were allowed to remain in the data set.

Qualitative comparisons

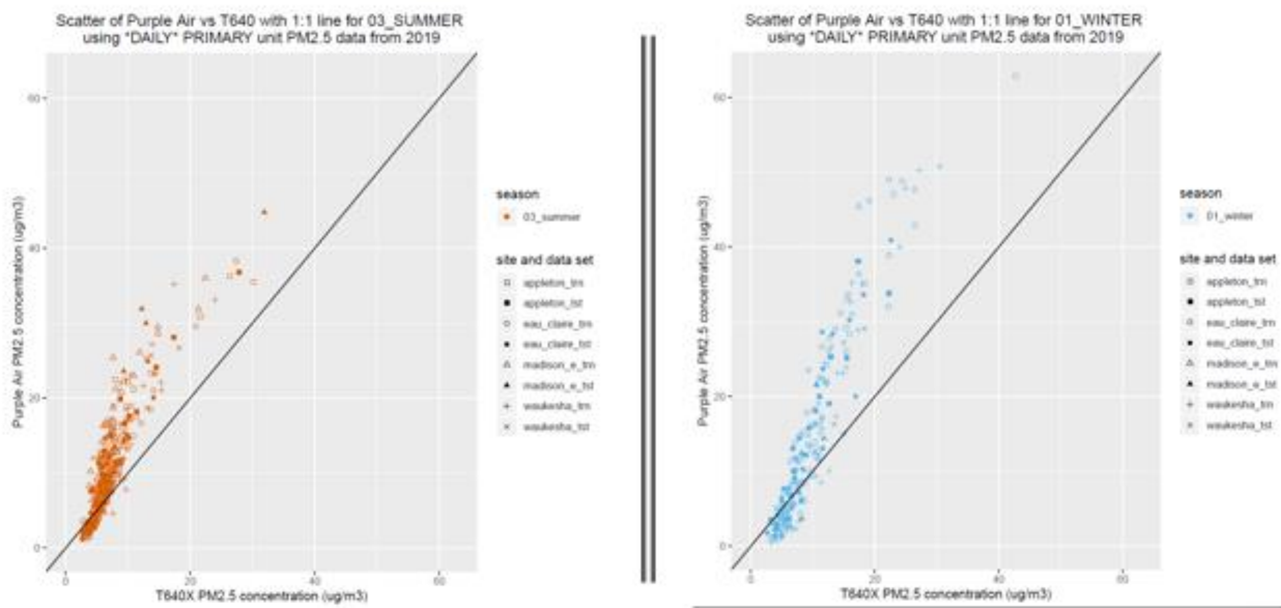
Initial exploration of the data included plotting the PurpleAir/T640 data pairs from all sites/seasons against a 1:1 line. This indicates the relationship between the two data sets is not ideally linear (*Figure 7*) and suggests that while linear relationships tend to be relatively simple to establish and use, a more sophisticated model could provide a correction equation that would outperform a linear model. It is also possible that a more complex model would improve the correction over a larger range of concentrations since the data pairs tend to become less linear at larger concentrations. Overall, at low concentrations (<5 ug/m^3) the PA sensors tended to measure lower than the T640. As concentrations grew (>5 ug/m^3), the PA overestimated, and recorded increasing disagreement and variability (*Figure 7*).

Figure 7: *PurpleAir daily data graphed against T640 daily data for all sites*



Similarly, when broken down by season it is apparent that the curvature of the summer data is more pronounced than the winter data (*Figures 8a/8b*). This may be due to meteorological variables like humidity on particulate sensor data.

Figure 8: *PurpleAir daily data graphed against T640 daily data for all sites for (a) summer data only (b) winter data only.*

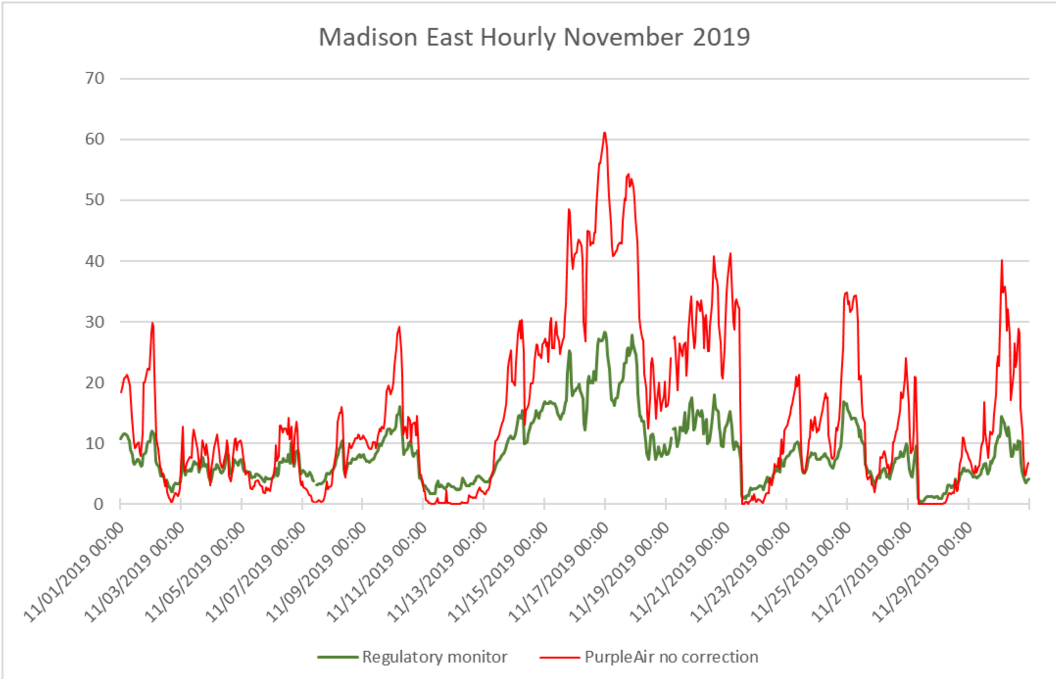


Correction factor development and evaluation

The DNR developed PurpleAir correction factors based on simple linear relationships between particulate matter concentrations measured by the PurpleAir sensor package and the T640 regulatory monitor. The correction factors developed did not utilize additional meteorological variables such as temperature, relative humidity or barometric pressure. While DNR evaluation of the data suggested that both non-linear models and accounting for meteorological conditions may result in a more refined correction factor with improved performance over a wider range of concentrations, it was determined to be beyond the scope of the current study’s time and resources. Additionally, DNR was able to provide input and data for a nationwide study by the U.S. Environmental Protection Agency to explore these models.

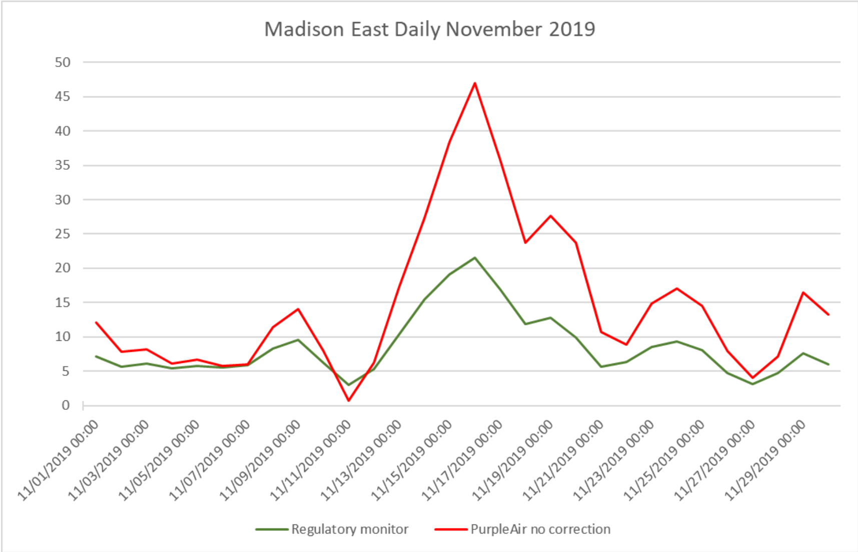
A correction factor is valuable for sensor data because the raw data produced by sensor packages has a strong bias compared to regulatory monitors. For the PurpleAir sensor, higher concentrations can be reported about twice as high as those reported by regulatory monitors measuring the same air mass. A one-month time series graph of the data from Madison (*Figure 9*) illustrates how the PurpleAir and T640 data compare over the month of November (other site/month graphs show similar performance). Like the plot of data pairs in *Figure 7*, at low concentrations (< 5 ug/m3) the PurpleAir data tends to be lower than the T640 but as concentrations increase the PurpleAir data tends to shift to a high bias with the overall bias increasing as concentrations increase. Overall the data tends to show similar upward and downward trends.

***Figure 9:** Comparison of hourly average data between PurpleAir and T640 at Madison East DNR monitoring site*



For the development of correction factors, DNR used data aggregated to 24-hour averages. Daily averages were used instead of hourly averages for two reasons. First, the National Ambient Air Quality Standards (NAAQS) for particulate matter are based on daily concentrations. Second, method evaluation techniques and metrics developed by U.S. EPA utilize daily averages. When the same data is taken from *Figure 9* and aggregated to daily averages, much of the variability is smoothed out, but the same overall trends are still evident and are more easily visualized (*Figure 10*).

Figure 10: *Comparison of daily average data between PurpleAir and T640 at the Madison East DNR monitoring site*



The daily average data from the PurpleAir and T640 were split into a training data set to develop correction factors and a testing data set to evaluate correction factors. The DNR study also evaluated whether site-specific or season-specific correction factors would perform significantly better than a year-round/statewide (Wisconsin) correction factor (Figure 11).

Figure 11: *DNR developed correction factors for application to raw PurpleAir data to allow greater comparability to regulatory PM2.5 monitors. PAc is the corrected value for that day, PA is the daily PurpleAir particulate concentration and type indicates statewide, site-specific, or season-specific correction factors.*

PAc = PA * Slope + Intercept

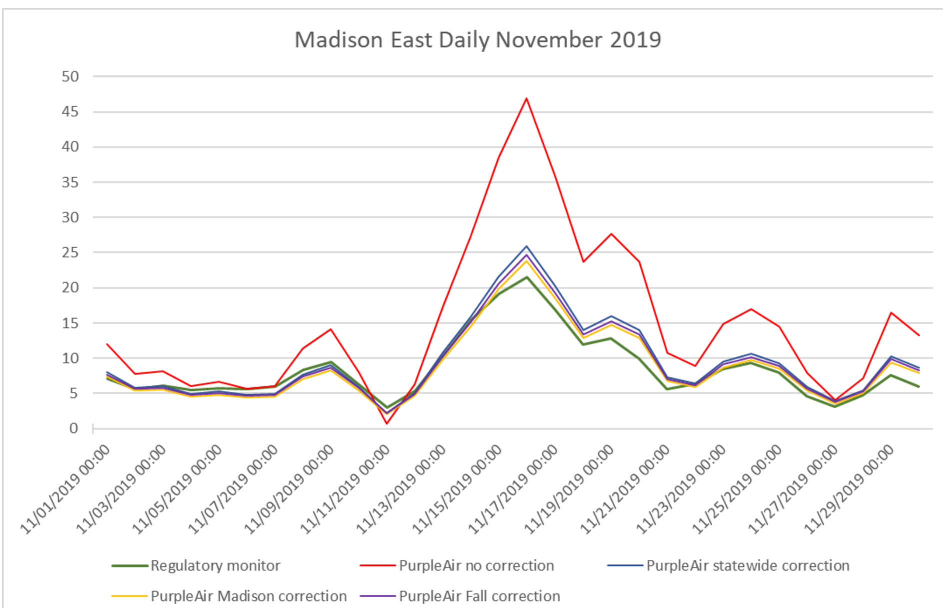
Type	Slope	Intercept
statewide	0.5140	1.8304
appleton	0.5668	1.1882
eau_claire	0.4698	2.4493
madison_e	0.4697	1.7169
waukesha	0.5170	2.1206
01_winter	0.4896	2.7182
02_spring	0.4975	2.0540
03_summer	0.6093	0.7733
04_fall	0.4873	1.8478

Some specific notes regarding DNR's correction factor development include:

- Utilized daily average data; hourly and instantaneous data evaluations are more variable
- Utilized a linear regression model
- PurpleAir meteorology data was not incorporated into correction factors
- Correction factors are expected to perform optimally within a 0-20 ug/m^3 range which is typical for most daily concentration averages in Wisconsin; reasons for this include:
    - Most daily average particulate concentrations evaluated in the study were in the 0-20 ug/m^3 range and had very few averages > 40 ug/m^3
    - Curvature of the data pairs suggests a weaker linear relationship at higher concentrations

To visualize an example of how correction factors can translate raw PurpleAir data into corrected daily values and how the raw and corrected data compare to the T640 values a time series of the Madison data from November is displayed in *Figure 12*.

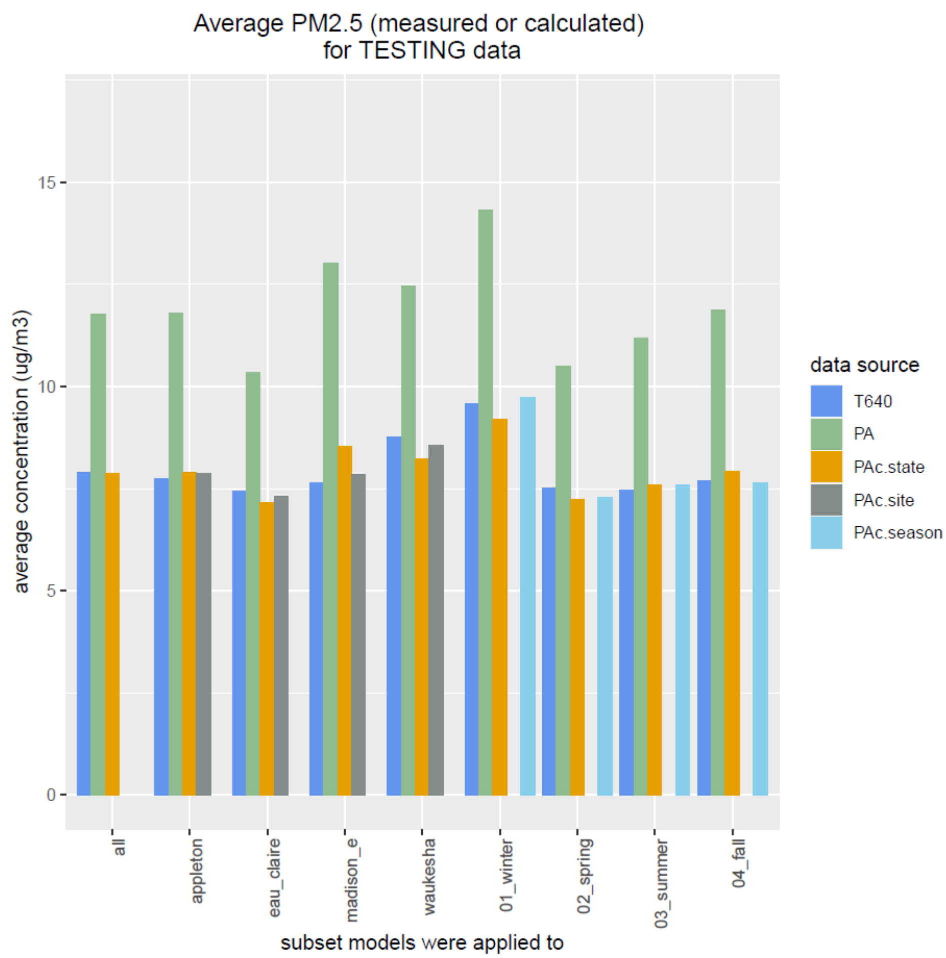
Figure 12: *Comparison of performance of various correction factors on daily average data between PurpleAir and T640*



When applied to the PA raw data, all DNR developed correction factors produced substantial improvement in the agreement between PurpleAir and T640 concentrations (*Figure 11*). Site-specific and seasonal correction factors often provided a slight improvement over the statewide correction factor. While the site specific or season specific correction factors may perform better at times than the statewide correction factor, the difference may not justify the use of a more complicated correction model.

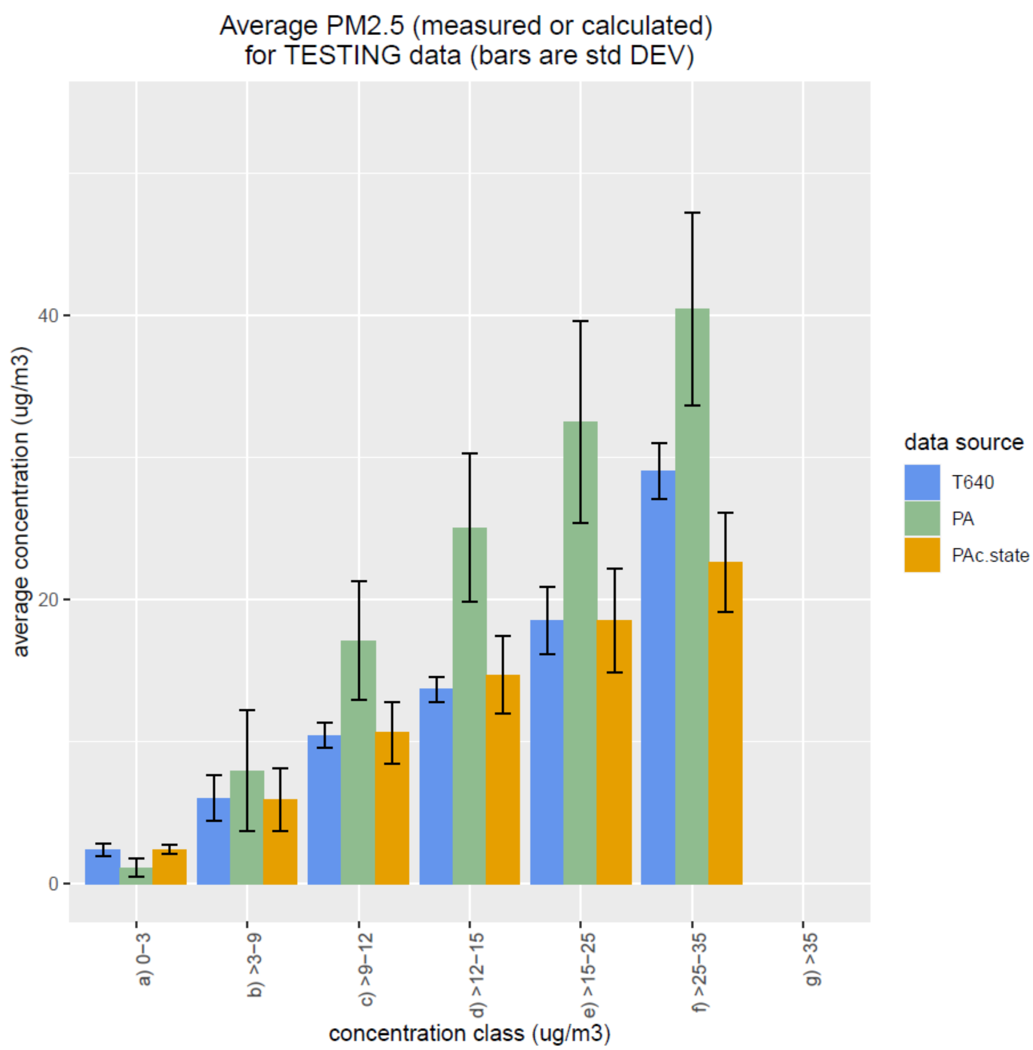
Performance of the various correction factors was also examined for the entire testing data set; broken down into all, site-specific, and season-specific groupings with the applicable correction factors applied (*Figure 13*). Here again, DNR results indicate that the site and season-specific corrected data typically yields only minor improvement over the statewide correction factor.

Figure 13. *Comparison of T640 daily data with raw PurpleAir (PA) data, and various corrected PurpleAir values by data set by all, site specific and season specific groupings. Each grouping begins with the T640 data.*



Finally, DNR evaluated the performance of the statewide correction factor over different concentration classes of T640 concentrations (*Figure 14*). The first five concentration classes show good overall correction, but the sixth class for >25-35 ug/m3 data indicates that the correction factor overcorrects raw data significantly. This was expected due to limited number of data pairs available to be evaluated in this range and the curvature seen in the upper range of the observed data pairs.

Figure 14: *Comparison of T640 daily data with raw PurpleAir (PA) data, and statewide corrected PurpleAir values broken down by particulate concentration class*



Conclusions

The DNR significantly expanded its knowledge of sensor use, performance and evaluation through the course of the study. Key takeaways include:

- Raw PurpleAir sensor data can be much different than data produced by regulatory monitors
  - If the relationship is carefully studied, correction factors can be developed to improve this agreement
- The dual sensors of the PurpleAir allow for simplified identification of outlier data and potential sensor malfunction; this can be used to exclude questionable data
- Correction factors that are more region-specific or season-specific can outperform more general correction factors; however, the degree of improvement may not warrant the added difficulty in applying a more complex strategy
- The relationship between T640 data and PurpleAir data suggests a linear model may not be ideal for developing correction factors
  - Models that are developed with a limited data range may see declining performance outside the range of values that were evaluated or most heavily represented
  - Models that incorporate meteorological data into their correction factors may be able to better compensate for potential meteorological influences on particulate sensor data
- While the online telemetry is typically sufficient for real-time data observations and communication, it is recommended that sensor units configured for research purposes include options for local data storage when available to reduce potential data loss.

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