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Evaluation of Environmental Beta Attenuation Monitor (EBAM) Performance in Low $PM_{2.5}$ Concentrations and Higher Relative Humidity Environment: Expectations, Data Utility, and Considerations for Wildland Fire Smoke Uses

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Cover—Left photo: an environmental beta attenuation monitor (EBAM) deployed on the Fishlake National Forest, Utah; Forest Service photo by Susan O'Neill. Right photos: researchers taking measurement notes from an EBAM deployed at Eglin Air Force Base, Florida; Forest Service photos by Roger Ottmar.

Abstract

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Environmental beta attenuation monitors (EBAMs) are commonly used to measure 1-hour average particulate matter concentrations in smoke from prescribed fires and wildfires. Because relative humidity (RH) can artificially inflate particulate matter concentrations, EBAMs are equipped with an internal heater that activates when ambient RH reaches a specified setpoint. Most studies address high $PM_{2.5}$ concentration conditions, where the EBAM is well documented to perform quite well on an hourly basis (R^2 of 0.95). In prescribed fire applications, however, increases in $PM_{2.5}$ concentrations are often more subtle than those observed during wildfires, and several studies have reported that 1-hour EBAM measurements can be noisy under clean, low-$PM_{2.5}$ conditions, limiting data usability. These studies, however, do not clearly illustrate what noisy data means or show what a user can expect when viewing data on an hourly basis. These factors highlight the need to better understand EBAM performance under conditions of low $PM_{2.5}$ concentrations and elevated RH and to identify optimal operating settings for these environments.

To address these needs, we evaluated EBAM performance by colocating four EBAMs with one federal reference method (FRM) sampler and one federal equivalent method (FEM) monitor. Specifically, we examined two internal heater settings (15- and 45-percent RH setpoints) for two models of EBAMs—two EBAM-V1s (EBAM version 1, an older model) and two EBAM-WFs (EBAM wildfire, a new model). Hourly EBAM measurements exhibited substantial variability, and error (defined as the difference between EBAM and FEM measurements) occasionally exceeded 10 to 20 $\mu g/m^3$ under clean atmospheric conditions, particularly for the EBAM-V1 operated at the 45-percent RH setpoint. Overall, the EBAM-WF configured with the 15-percent RH setpoint demonstrated the best performance, with R^2 values of 0.73 for 1-hour average $PM_{2.5}$ concentrations and 0.99 for 24-hour average $PM_{2.5}$ concentrations. Although the 15-percent RH setpoint produced a slight low bias (mean bias of -1.3 $\mu g/m^3$), it was the most effective configuration for reducing hour-to-hour absolute error relative to the FEM monitor.

Keywords:

Air quality

EBAM

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Introduction

Wildland fire (both prescribed fire and wildfire) produces smoke, which can be harmful to human health (Cascio 2018, Jaffe et al. 2020, Liu et al. 2015, Reid et al. 2016, Rizzo and Rizzo 2025) and can obscure visibility of scenic vistas (Hu et al. 2018, Park et al. 2006) and transportation corridors, causing fatal accidents (Bartolome et al. 2019). Small particulates, <2.5 µm in aerodynamic diameter ($PM_{2.5}$), are a primary concern because they can bypass the body's natural barriers and migrate deep into the lungs. If they are small enough, they can enter the bloodstream and cause respiratory and cardiovascular issues (Chen et al. 2021), especially for people with pre-existing conditions, such as asthma and chronic obstructive pulmonary disease. To protect public health, state, local, and tribal agencies maintain networks of permanent $PM_{2.5}$ monitors to determine if local air quality conditions meet the National Ambient Air Quality Standards (US EPA 2025). These permanent monitors are typically in populated areas. During periods of widespread wildfires and sometimes during prescribed fires, temporary $PM_{2.5}$ monitors are deployed, often in more rural locations, to assist with smoke forecasting and public health protection.

Prescribed fires used for fuel reduction and ecological restoration and maintenance (McLauchlan et al. 2020, Ryan et al. 2013) and wildland-urban interface (WUI) wildfire protection (USDA Forest Service 2022) are typically smaller and much shorter duration fires than wildfires. Nationally, 4 to 5 million ha/year burn in prescribed fires (Larkin et al. 2020, Melvin 2018, US EPA 2023). They typically occur in the spring and fall, with a strong signature of winter burning in the Southeast, where about 67 percent of prescribed fires occur in the United States (Melvin 2018). In some regions, smoke management surrounding these fires can be complex and the effects subject to scrutiny. For example, if a 1-hour average $PM_{2.5}$ concentration is measured higher than 35 µg/m^3 at a temporary monitor in California, then the prescribed fire may be suppressed (Schweizer et al. 2016). In central Oregon, a smoke intrusion is a ground-level, 1-hour average $PM_{2.5}$ concentration of 70 µg/m^3 or higher from a verified prescribed fire (Oregon Secretary of State 2023); earlier versions of Oregon public law were much more stringent (Miller et al. 2019). When temporary monitors are deployed to support prescribed fire operations, the accuracy of a $PM_{2.5}$ monitor at these short, 1-hour timescales and at lower concentrations becomes critical.

Atmospheric water content can increase $PM_{2.5}$ concentration measurements because of aerosol water content. Different aerosol species have different affinities for water, being anywhere from hygroscopic (tending to absorb moisture from the air) to hydrophobic (tending to repel water), and the chemical composition of these aerosols can vary greatly from one region to another. This is obviously a concern in places

such as the Southeastern United States and coastal mountains of the Western United States, but what is less obvious is that relative humidity (RH) can be higher during prescribed fires even in areas typically not associated with high RH conditions. This is because RH is a parameter in many burn plans (Chiodi et al. 2019, Miller et al. 2019) and is used as a fire-control mechanism and to get the desired fire intensity (Schweizer et al. 2016). Therefore, land managers may conduct prescribed fires in higher RH conditions. To account for higher humidity conditions, many $PM_{2.5}$ monitors are equipped with an internal heater, which heats the air sample to remove aerosol water content (Met One Instruments, Inc. 2021; Patashnick and Rupprecht 1991). However, this can also drive off the semivolatile species, reducing particulate matter concentrations and changing the chemical composition of the sample (Li et al. 2012). Thus, the internal heater setting is an important parameter; it needs to be high enough to reduce the water content but not so high that significant particulate matter is lost from the sample.

Beta attenuation is a well-established technology for measuring $PM_{2.5}$ concentrations (Macias and Husar 1976). The U.S. Environmental Protection Agency (EPA) recognizes one model, the BAM-1020, manufactured by Met One Instruments, Inc., as a federal equivalent method (FEM) monitor. The EPA gives FEM and federal reference method (FRM) designations to instruments that meet quality standards for accuracy and precision. These instruments may be used with air quality classifications to see if a region meets or fails to meet the National Ambient Air Quality Standards (US EPA 2025). FEM and FRM instruments are typically expensive, nonmobile, and require climate-controlled environments. Portable monitors for wildland fire operations are necessary for quick deployment in sometimes rugged conditions and often in rural communities, therefore Met One Instruments, Inc. developed a portable version of the beta attenuation technology, the environmental beta attenuation monitor (EBAM). Beta attenuation monitors have an inlet heater to reduce the sample RH to a specified level, and it is part of the quality assurance/quality control process to check that the internal RH does not exceed the specified level. The Met One Instruments, Inc. default setting for the EBAM internal RH is 45 percent (Met One Instruments, Inc. 2021), Schweizer et al. (2016) recommend 40 percent, and standard operating procedures for the BAM-1020 specify 35 percent (California Air Resources Board 2019). Despite controlling the internal RH of the air sample, in high-RH conditions, EBAM $PM_{2.5}$ concentration measurements can still be affected (Schweizer et al. 2016).

Several laboratory and field studies evaluated and compared EBAMs with FRM and FEM monitors (Mehadi et al. 2020; Schweizer et al. 2016; Trent 2003, 2006). At high ambient $PM_{2.5}$ concentrations (about 200–1000 $\mu g/m^3$) (Mehadi et al. 2020), EBAM and FEM monitor 1-hour average $PM_{2.5}$ concentrations exhibited a strong linear relationship ($R^2 = 0.95$),

performing quite well and better than the other six monitors tested in the study. At low ambient $PM_{2.5}$ concentrations (about 0–33 µg/m^3) (Mehadi et al. 2020), this relationship was reduced ($R^2 = 0.64$), and several studies noted that at low concentrations, there was a lot of noise in the hourly data (Mehadi et al. 2020, Schweizer et al. 2016, Zheng et al. 2018). EBAM performance, in terms of R^2, was higher than 0.9 over a 24-hour averaging period in both low (e.g., clean) and high atmospheric $PM_{2.5}$ concentrations (Mehadi et al. 2020, Schweizer et al. 2016).

At low atmospheric concentrations, EBAM 1-hour average $PM_{2.5}$ concentration data exhibited high hour-to-hour variability, with measurements oscillating between 0 and 20 µg/m^3 or more. This behavior was exacerbated when relative humidity was high. Schweizer et al. (2016) investigated these behaviors and EBAM performance by colocating an EBAM with an FRM sampler in both chamber and field experiments. They used RH setpoints of 40 and 45 percent. They found that EBAM 1-hour average $PM_{2.5}$ concentration data were about 24 percent higher than FEM monitor data and that differences between the EBAM and FEM monitor became greater as ambient humidity increased, especially ≥65 percent. In terms of performance, the EBAMs had an R^2 of 0.7 for 1-hour data and 0.9 for 24-hour data. The fluctuations at low $PM_{2.5}$ concentrations were attributable to the accuracy and detection limit of the monitor, and they recommended that low $PM_{2.5}$ concentration data should be averaged to 24 hours for use. Overall, they found the monitors were effective options in smoky conditions because of their performance, portability, and cost compared to FEM monitors, but caution should be used when using them over short-term (e.g., 1-hour) periods in low $PM_{2.5}$ concentration, higher humidity conditions.

Here we report on a colocation study of four EBAMs with an FEM monitor and an FRM sampler in a higher RH and typically clean(er) (e.g., low $PM_{2.5}$ concentration) environment. Our goals were to determine if there are EBAM settings that can mitigate the effects of prolonged high RH on the measurements and to provide a benchmark of what to expect with regards to EBAM performance in low $PM_{2.5}$ concentration, higher RH environments. We also highlight details of the data and data processing to give users a clear view of what to expect when using the data (e.g., showing hourly time series). We designed this study to build on Schweizer et al. (2016) and Mehadi et al. (2020), and it is the first evaluation of the EBAM-WF (EBAM wildfire).

Methods

In 2024, we deployed four EBAMs from February 15–May 1 at the Duwamish Valley air quality monitoring site (operated by the Puget Sound Clean Air Agency) in Seattle, Washington. The Puget Sound Clean Air

Agency operates three instruments that measure $PM_{2.5}$ concentrations—a Met One Instruments, Inc. BAM-1020, a Met One Instruments, Inc. E-SEQ-FRM, and an Acoem Aurora 1000 nephelometer. The BAM-1020 is an EPA-designated FEM monitor and the E-SEQ-FRM is an EPA-designated FRM sampler. We colocated two models of EBAMs (EBAM-V1 [version 1] and EBAM-WF) that are commonly deployed to measure smoke from wildland fire with these FEM/FRM instruments to evaluate EBAM performance.

The EBAMs and the BAM-1020 operate on the principle of beta attenuation. A sample of air is pulled through an inlet at a flow rate of 16.7 L/minute. Particulate matter in the air is deposited on a filter tape that intercepts the flow. Beta particles are released towards the filter, and the resulting beta particle attenuation gives a measure of the particulate matter on the filter. The hourly concentration is based on two, 4-minute-long, beta counts, one at the beginning and one at the end of each sample hour. The difference in the two beta counts is used to calculate the particulate mass on the tape. As soon as the new hour starts, the EBAM stores the $PM_{2.5}$ concentration measurement for the previous hour and starts a new hourly measurement (Met One Instruments, Inc. 2021). The filter tape advances forward at a set timing (e.g., every 1–24 hours) to avoid impeding air flow from particulate matter overload on the filter tape. Negative concentrations can occur in clean atmospheric conditions (such as <3 $\mu g/m^3$) when the hourly change in concentration is within the noise band of the instrument (Met One Instruments, Inc. 2021). Each monitor has an internal heater to control aerosol water content. The internal heater turns on when the air sample reaches a defined RH setpoint. The EBAM is a portable version of the BAM-1020, which is large and heavy and requires a climate-controlled room. The standard unit of measure for the BAM-1020 and EBAMs is a 1-hour average $PM_{2.5}$ concentration, although during periods of high smoke concentrations, the EBAMs can be used to measure subhourly $PM_{2.5}$ concentrations.

The E-SEQ-FRM is a filter-based system configured to measure 24-hour average $PM_{2.5}$ concentrations every 3 days. Particles deposit on the filter, and the filters are analyzed in a laboratory. This method results in a highly accurate $PM_{2.5}$ concentration measurement.

The Aurora 1000 nephelometer, which is neither an FRM sampler nor an FEM monitor, uses the principle of light scattering to measure the amount of particulate matter in the air. Light at the 525 nm wavelength is directed through the air sample, and the amount of light scattering gives a measure of visibility reduction. Light scattering measurements are sensitive to (1) atmospheric water content (which can significantly increase light scattering), (2) aerosol species hygroscopicity/hydrophobia, and (3) the degree of aerosol loading in which the instrument behaves differently at low concentrations versus high concentrations (i.e., not a

linear response). Given these issues, the nephelometer requires calibration to local conditions to convert the light scattering measurements to $PM_{2.5}$ concentration. The Puget Sound Clean Air Agency has calibrated the nephelometer for local conditions making it an accurate, useful instrument, and we find that the data have less noise than EBAM data, which is particularly useful at the lower $PM_{2.5}$ concentrations.

The BAM-1020, nephelometer, and E-SEQ-FRM were all in a climate-controlled trailer, while we deployed the EBAMs outside, exposed to the elements. Table 1 summarizes instrument specifications.

Table 1—Instrument summary

Instrument	Manufacturer	Short name	Regulatory designation	Measurement range	Lower detection limit or accuracy
				$\mu g/m^3$	$\mu g/m^3$
Beta attenuation monitor 1020	Met One Instruments, Inc.	BAM-1020	Federal equivalent method (FEM)	−15 to 985	<4.9
Sequential reference method sampler	Met One Instruments, Inc.	E-SEQ-FRM	Federal reference method (FRM)	Lab analysis	Lab analysis
Aurora 1000 nephelometer	Acoem	Nephelometer	None	NA	NA
Environmental beta attenuation monitor-version 1	Met One Instruments, Inc.	EBAM-V1	None	−5 to 65,530	<6.0 (1-hour average) <1.2 (24-hour average)
Environmental beta attenuation monitor-wildfire	Met One Instruments, Inc.	EBAM-WF	None	−15 to 10,000	<10.0 (1-hour average) <2.0 (24-hour average)

NA = not applicable.

We deployed two older model EBAM-V1s and two new model EBAM-WFs, each at two internal heater settings (15- and 45-percent RH setpoints) and two tape advance settings (every 3 hours and every 24 hours). Table 2 gives the EBAM serial numbers, deployment dates, and configuration settings. The factory default RH setpoint is 45 percent, and studies in California recommend 40 percent (Schweizer et al. 2016). Prior experience with these monitors deployed in the Southeastern United States for prescribed burning indicated that a 45-percent RH setpoint may not be sufficient. Also, Schweizer et al. (2016) used 40 percent and still had issues with RH, therefore we are investigating a more stringent setting of 15 percent.

Table 2—Environmental beta attenuation monitor (EBAM) deployment information

Serial number (model)	Deployment date	Demobilization date	Relative humidity setpoint	Tape advance time
			Percent	*Hours*
C15947 (EBAM-WF)	2024-02-15	2024-02-22	15	3
C17416 (EBAM-WF)	2024-02-22	2024-05-01	15	3
H9495 (EBAM-V1)	2024-02-16	2024-05-01	15	3
C17410 (EBAM-WF)	2024-02-15	2024-05-01	45	24
G6841 (EBAM-V1)	2024-02-16	2024-05-01	45	24

EBAM C15947 was not functioning properly, so we replaced it with EBAM C17416 one week into the study. The EBAM-V1 is the version 1 monitor, and the EBAM-WF is the wildfire monitor.

The Duwamish Valley site is located south of downtown Seattle, Washington in a semi-industrial area near the Duwamish Waterway (fig. 1). Wind directions were typically from the southwest or north during the study period. Before deployment, we cleaned all monitors, performed a leak test, and calibrated them for flow rate, temperature, pressure, and beta counts per manufacturer instructions (Met One Instruments, Inc. 2021). When deployed, we performed a leak test, temperature and pressure calibration, and flow rate calibration on all monitors.

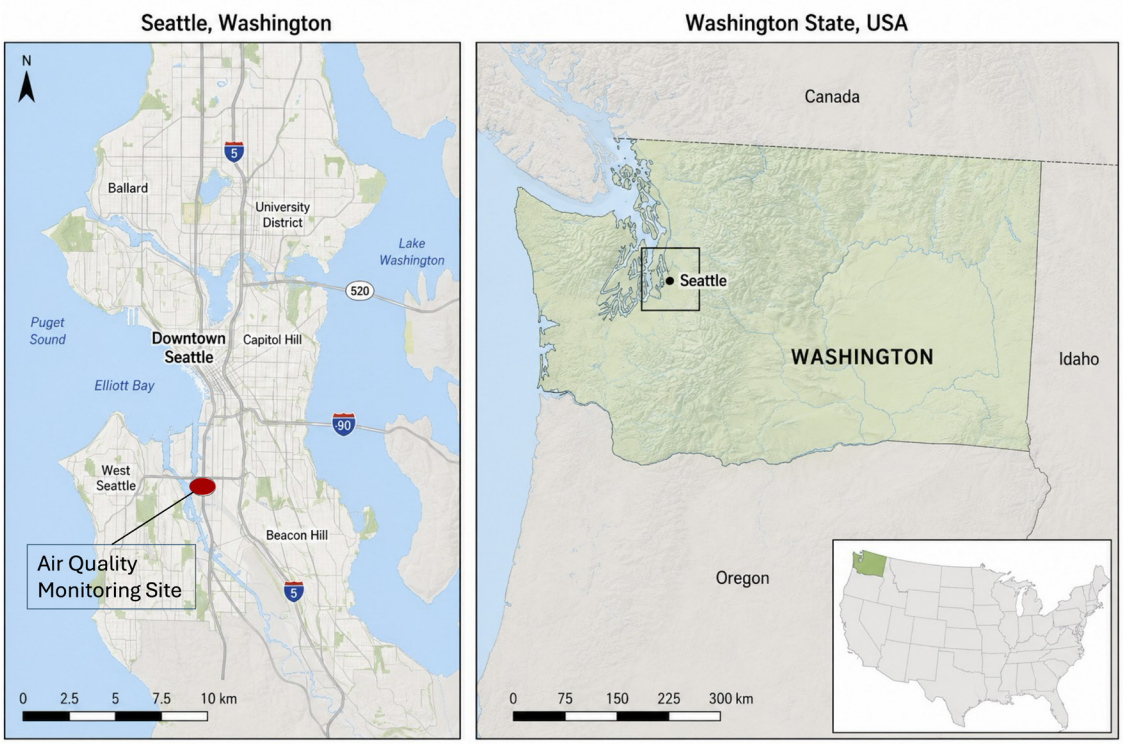


Figure 1—Location of the Puget Sound Clean Air Agency's Duwamish air quality monitoring site in Seattle, Washington.

We used several metrics to evaluate EBAM performance compared to the BAM-1020, E-SEQ-FRM, and nephelometer for both the 1-hour and 24-hour average $PM_{2.5}$ concentrations. We used linear regression (R^2) to evaluate EBAM performance compared to the FRM sampler and FEM monitor for 1-hour and 24-hour average $PM_{2.5}$ concentration data. We provide mean, median, minimum, maximum, and standard deviations over the study period. Other metrics are mean bias, fractional bias, root mean square error (RMSE), and maximum absolute error (table 3), which are pairwise analyses of experimental measurements (M_i) with actual observational measurements (O_i). Mean bias indicates how an experimentally measured value (e.g., EBAM measurement) tends to overestimate or underestimate compared to the actual observational data (e.g., BAM-1020, E-SEQ-FRM, or nephelometer measurement). Outlier or high-value data can skew the mean bias; therefore, we also calculated the fractional bias, which reduces this influence. RMSE is the standard deviation of the residuals, where residuals are a measure of how far data points are from the regression line, and is an indication of how concentrated the data are around the line of best fit. Maximum absolute error gives the maximum departure of the EBAM data from the BAM-1020, E-SEQ-FRM, or nephelometer data.

Table 3—Evaluation metrics

Metric	Equation
Mean bias	$\frac{1}{n}\sum_{1}^{n}(M_i - O_i)$
Fractional bias	$\sum_{i=1}^{n}\frac{2\times(M_i - O_i)}{(M_i + O_i)}$
Root mean square error (RMSE)	$\sqrt{\frac{1}{n}\sum_{i}^{n}(M_i - O_i)^2}$
Maximum absolute error	$Maximum(\lvert M_i - O_i\rvert,\ i = 1,\ n)$
$Error_i$	$(M_i - O_i),\ i = 1,\ n$

i = an individual sample within the dataset, *M* = experimental measurement, *n* = the number of samples, *O* = actual observational measurement.

Results and Discussion

We evaluate EBAM performance for 1-hour and 24-hour average $PM_{2.5}$ concentrations, give observations on the effects of RH on the data, and review optimal internal heater settings for the monitors for extended use in higher humidity environments. We also discuss internal heater performance and the effects of removing negative $PM_{2.5}$ concentrations when analyzing the data and averaging to 24 hours.

Evaluation of 1-Hour Average $PM_{2.5}$ Concentration Measurements

During the February 15–May 1, 2024 study period, the BAM-1020 (the FEM monitor) measured a maximum 1-hour average $PM_{2.5}$ concentration of 38 µg/m^3, with mean and median $PM_{2.5}$ concentrations of 6 and 5 µg/m^3, respectively (table 4). The two EBAM-WFs measured slightly lower maximum 1-hour average $PM_{2.5}$ concentrations at 33.8 µg/m^3, while both EBAM-V1s measured higher maximum 1-hour average $PM_{2.5}$ concentrations of 44 and 58 µg/m^3. The BAM-1020 data had a standard deviation of 3.8 µg/m^3, and data for three of the four EBAMs had higher standard deviations than the BAM-1020 data, indicating larger spread/variation in the data. See table 4 for a summary of these data.

Violin plots (fig. 2) show the distribution of the 1-hour average $PM_{2.5}$ measurements by the six instruments. Qualitatively, the data for the EBAM-WF at the 15-percent RH setpoint most closely resembles the BAM-1020 data. The data for the EBAM-WF at the 45-percent RH setpoint is similar as well but has more negative $PM_{2.5}$ concentration measurements with a longer tail into the negative range (to −15 µg/m^3). The data for the two EBAM-V1s have noticeably longer/slimmer distributions of $PM_{2.5}$ concentrations than the other instruments, indicating larger, more even spread to the data.

Table 4—Instrument 1-hour average $PM_{2.5}$ concentration mean, median, maximum, minimum, and standard deviation, February 15–May 1, 2024

Instrument	Relative humidity (RH) setpoint	Ambient RH	Mean $PM_{2.5}$	Median $PM_{2.5}$	Maximum $PM_{2.5}$	Minimum $PM_{2.5}$	$PM_{2.5}$ standard deviation	Data points	Negative $PM_{2.5}$ concentrations
	Percent	*Percent*	*µg/m³*	*µg/m³*	*µg/m³*	*µg/m³*	*µg/m³*	*Number*	*Percent*
BAM-1020	35	<65	4.8 (4.9)	4.0	20.0	−4.0 (0)	3.1 (3.0)	609	3.3
BAM-1020	35	All RH conditions	6.0	5.0	38.0	−4.0 (0)	3.9 (3.8)	1,817	1.3
BAM-1020	35	≥65	6.7	6.0	38.0	−1.0 (0)	4.1	1,192	0.3
Nephelometer	40	<65	4.9	4.7	14.7	2.8	1.4	562	0.0
Nephelometer	40	All RH conditions	5.5	4.9	25.1	2.5	2.3	1,728	0.0
Nephelometer	40	≥65	5.8	5.2	25.1	2.5	2.5	1,150	0.0
EBAM-WF	15	<65	4.0 (4.2)	4.0	19.4	−8.0 (0)	3.3 (3.0)	561	10.5
EBAM-WF	15	All RH conditions	4.6 (4.7)	4.3	33.8	−8.0 (0)	3.7 (3.5)	1,604	7.1
EBAM-WF	15	≥65	4.9 (5.0)	4.4	33.8	−6.2 (0)	3.9 (3.7)	1,043	5.3
EBAM-WF	45	<65	4.4 (4.6)	4.2	22.3	−15.0 (0)	4.0 (3.4)	613	10.4
EBAM-WF	45	All RH conditions	4.6 (4.8)	4.1	33.8	−15.0 (0)	4.3 (3.9)	1,806	10.4
EBAM-WF	45	≥65	4.7 (4.9)	4.1	33.8	−15.0 (0)	4.5 (4.2)	1,193	10.4
EBAM-V1	15	<65	2.9 (3.8)	3.0	58.0	−5.0 (0)	5.5 (4.6)	573	26.5
EBAM-V1	15	All RH conditions	3.6 (4.3)	3.0	58.0	−5.0 (0)	5.3 (4.4)	1,730	22.2
EBAM-V1	15	≥65	3.9 (4.5)	4.0	27.0	−5.0 (0)	5.1 (4.4)	1,157	20.1
EBAM-V1	45	<65	4.0 (4.6)	4.0	21.0	−5.0 (0)	5.1 (4.2)	605	19.8
EBAM-V1	45	All RH conditions	6.4 (7.0)	6.0	44.0	−5.0 (0)	7.2 (6.4)	1,781	16.8
EBAM-V1	45	≥65	7.6 (8.2)	7.0	44.0	−5.0 (0)	7.8 (7.0)	1,176	15.2

Data in parentheses are changes from setting negative concentrations to zero.

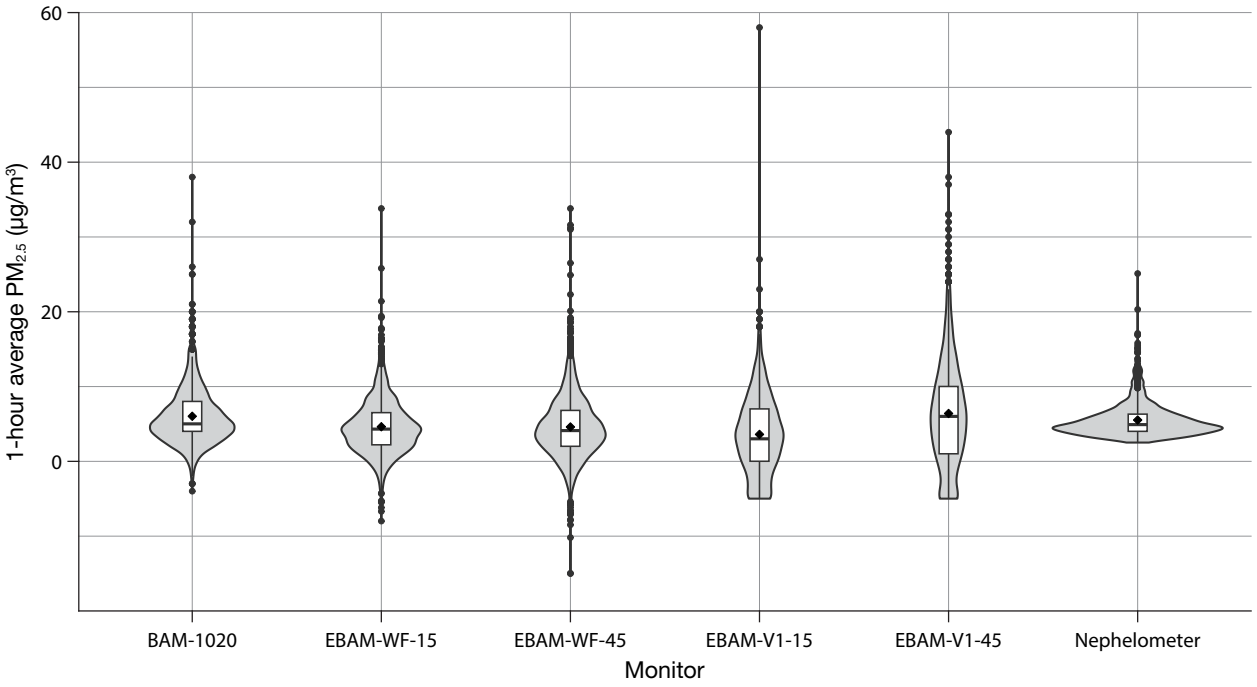


Figure 2—Violin plots of the distribution of 1-hour average fine particulate matter ($PM_{2.5}$) concentrations measured by the BAM-1020 (a federal equivalent method monitor), two environmental beta attenuation monitors—EBAM-WF and EBAM-V1 (at 15 and 45 percent relative humidity setpoints as indicated)—and the nephelometer, February 15–May 1, 2024. Center lines in the interior boxplots are the median concentrations, and diamonds are the mean concentrations. The lower and upper bounds of the boxes are the 25th- and 75th-percentile data limits. The width of the violin plot indicates how concentrated the data points are at the $PM_{2.5}$ concentration.

A land manager or smoke specialist will deploy temporary monitors, such as EBAMs, for prescribed fire and wildfire operations to monitor smoke transport. The monitors typically transmit the data every hour to satellites, and the data are available in real time on a website. Users of the data, such as land managers, smoke specialists, and local air quality personnel often scrutinize the data on an hour-by-hour basis to evaluate potential smoke effects. Time series plots, especially over short, 1- to 5-day periods, are the primary tool a data reviewer uses. Figure 3 shows a time series of data for each EBAM compared with BAM-1020 data for the entire study period, and figure 4 shows a subset of 5 days of data to more clearly illustrate what a data reviewer might see. Fluctuations of the EBAM data above and below the BAM-1020 data (black line) increase with the older EBAM-V1 model and as the RH setpoint increases from 15 to 45 percent. The BAM-1020 data are <10 µg/m^3 over the 5-day period, but some of the EBAM data fluctuate up to 20 µg/m^3 (such as in figure 4: panel D). A land manager or smoke specialist using an EBAM will not have an FEM monitor colocated with their monitor, so it is difficult to discern if these spikes indicate wildland fire smoke or if it is instrument noise at low/clean atmospheric concentration. The data for the EBAM-WF at the 15-percent RH setpoint exhibits lower occurrence and magnitude of fluctuations from the BAM-1020 data than other EBAMs.

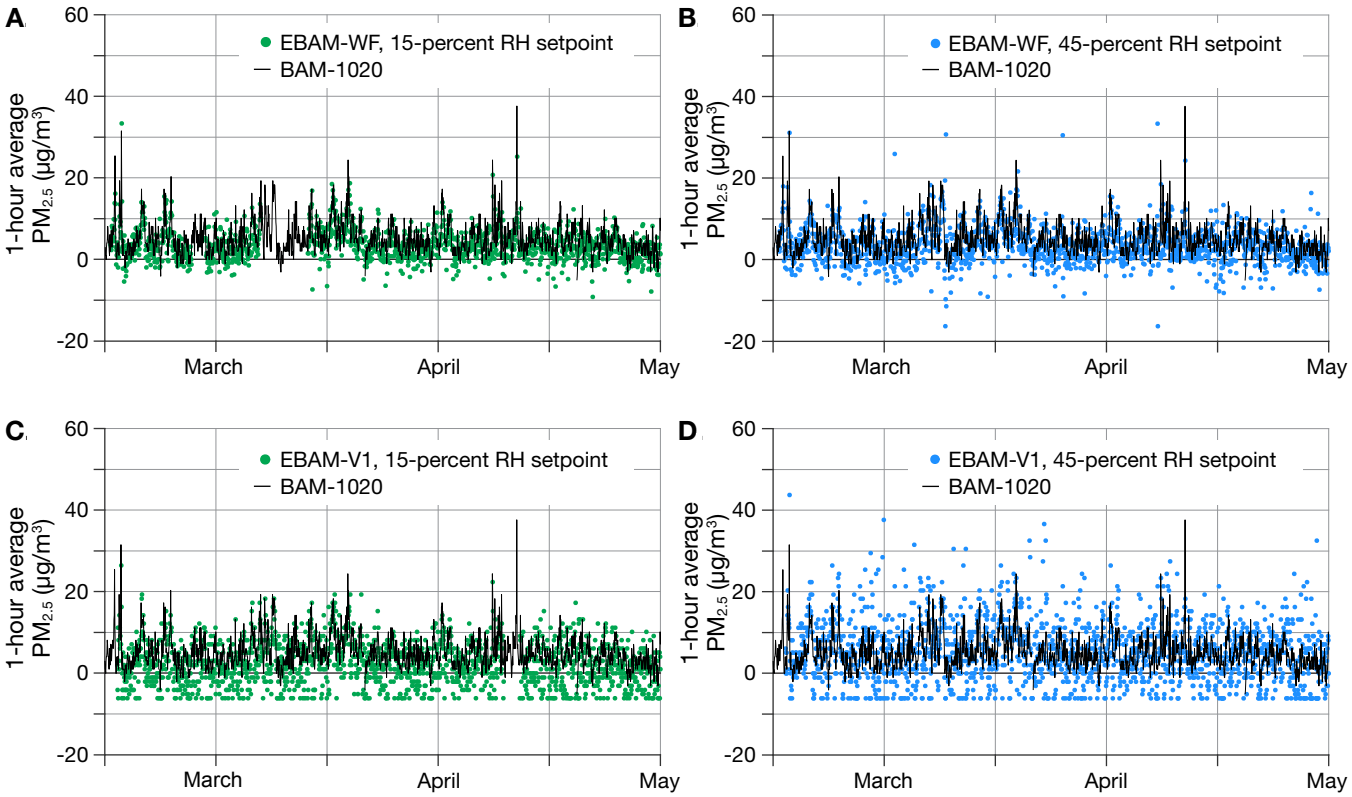


Figure 3—Time series of 1-hour average fine particulate matter ($PM_{2.5}$) concentration data for the BAM-1020 (black line) and (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint, February 15–May 1, 2024. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

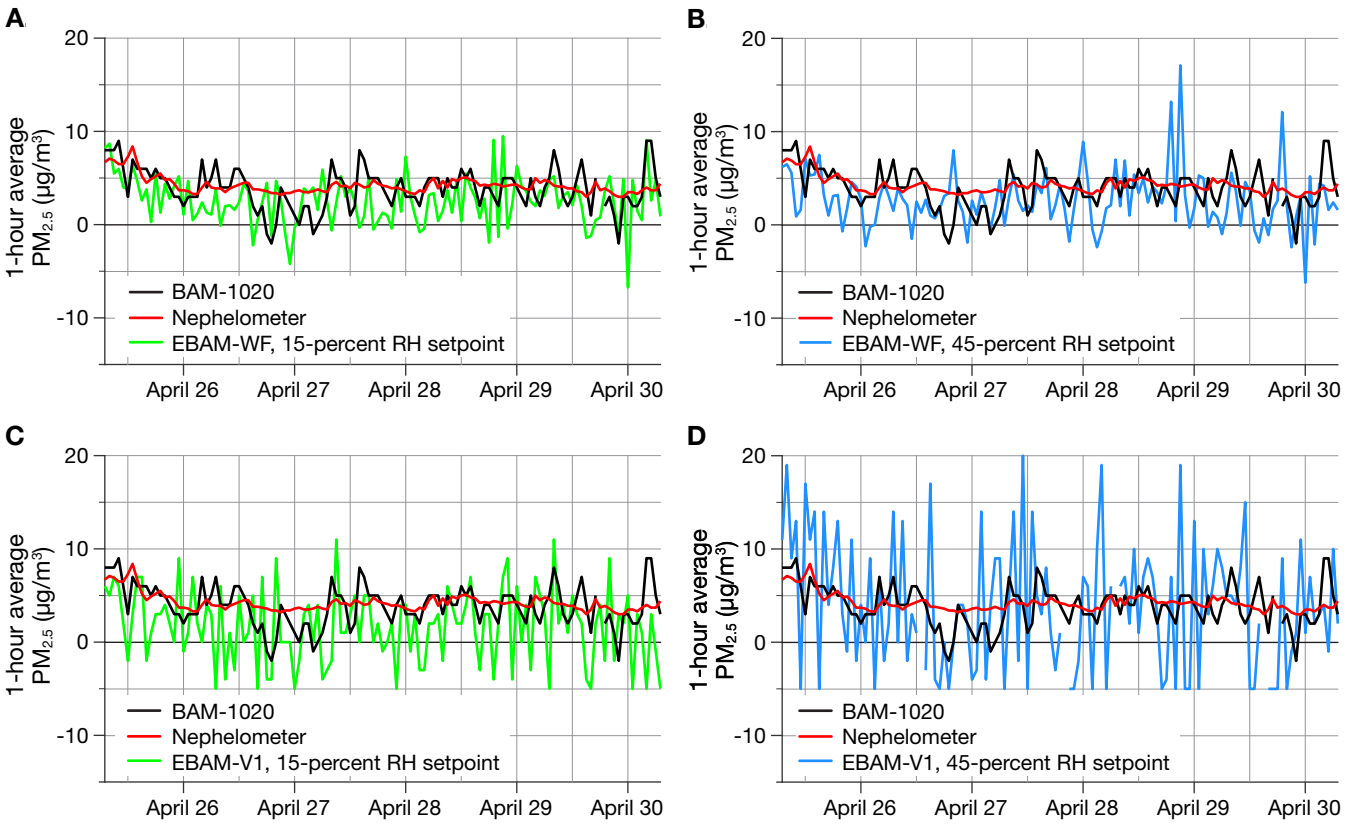


Figure 4—Time series of 5 days to further illustrate data variability on a more granular hour-to-hour and day-to-day basis. Comparison of the 1-hour average fine particulate matter ($PM_{2.5}$) concentration data for the BAM-1020 (black line), the nephelometer (red line), and (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

Mean bias and fractional bias results show how the EBAMs tended to underestimate 1-hour average $PM_{2.5}$ concentrations; however, the fractional bias is relatively small, with measurements ranging from −0.5 to −0.2 µg/m^3 across all four EBAMs (table 5). Linear regression analysis yielded R^2 values ranging from 0.45 (EBAM-V1, 15-percent RH setpoint) to 0.73 (EBAM-WF, 15-percent RH setpoint) relative to the BAM-1020 and are listed in table 6. Most of these results are within the range of both Schweizer et al. (2016: R^2 range of 0.68 to 0.82) and Mehadi et al. (2020: $R^2 = 0.64$) except for the EBAM-V1 at the 15-percent RH setpoint. Mehadi et al. (2020) measured a much improved R^2 of 0.95 under high ambient $PM_{2.5}$ conditions (200–1000 µg/m^3).

Table 5—Evaluation metrics comparing the environmental beta attenuation monitors (EBAMs) to the BAM-1020 and nephelometer for 1-hour average $PM_{2.5}$ concentrations

Experimental measurement monitor	Actual observation instrument	Mean bias	Fractional bias	Root mean square error	Maximum absolute error	Data points	Occurrence of hourly absolute error >10 µg/m³	Occurrence of hourly absolute error >10 µg/m³ RH <65 percent/ RH ≥65 percent
	µg/m³	*µg/m³*	*µg/m³*	*µg/m³*	*µg/m³*	*Number*	*Percent*	*Percent*
EBAM-WF-15	BAM-1020	−1.3 (−1.2)	−0.4 (−0.3)	**3.7** (3.5)	**27.3**	1,598	1.2	0.5/1.6
EBAM-WF-45	BAM-1020	−1.4 (−1.2)	**−0.2** (−0.4)	4.4 (4.1)	31.8	1,800	3.0	2.0/3.5
EBAM-V1-15	BAM-1020	−2.4 (−1.7)	−0.5 (−0.6)	5.5 (4.7)	51.0	1,724	4.3	3.6/4.7
EBAM-V1-45	BAM-1020	**0.4** (1.0)	**−0.2**	6.5 (5.9)	32.0	1,775	8.6	2.4/11.9
EBAM-WF-15	Nephelometer	−1.1 (−1.0)	−0.7 (−0.4)	**3.0** (2.8)	**21.6**	1,510	NC	NC
EBAM-WF-45	Nephelometer	−1.1 (−0.8)	−0.3 (−0.4)	3.1 (3.5)	30.7	1,711	NC	NC
EBAM-V1-15	Nephelometer	−2.0 (−1.3)	−0.7	5.1 (4.1)	53.5	1,640	NC	NC
EBAM-V1-45	Nephelometer	**0.8** (1.4)	**0.2** (−0.3)	6.6 (5.9)	34.7	1,686	NC	NC

The EBAM relative humidity (RH) setpoint is appended to the EBAM name (e.g., The EBAM-WF at the 15 percent RH setpoint is EBAM-WF-15). Data in parentheses are changes from setting negative concentrations to zero. Data in bold indicate the optimal performing EBAM.

NC = not calculated.

Table 6—Instrument coefficient of determination (R^2) values for 1-hour and 24-hour average $PM_{2.5}$ concentrations

Unit 1	Unit 2	R^2 (1-hour average $PM_{2.5}$)	R^2 (24-hour average $PM_{2.5}$)
BAM-1020	EBAM-WF-15	**0.73** (0.75)	**0.98**
BAM-1020	EBAM-WF-45	0.62 (0.67)	**0.98**
BAM-1020	EBAM-V1-15	0.45 (0.58)	0.95 (0.98)
BAM-1020	EBAM-V1-45	0.54 (0.61)	**0.98** (0.97)
E-SEQ-FRM	EBAM-WF-15	NA	**0.99**
E-SEQ-FRM	EBAM-WF-45	NA	0.98
E-SEQ-FRM	EBAM-V1-15	NA	0.96 (0.98)
E-SEQ-FRM	EBAM-V1-45	NA	**0.99**
Nephelometer	EBAM-WF-15	**0.75** (0.79)	0.96 (0.97)
Nephelometer	EBAM-WF-45	0.63 (0.70)	0.97
Nephelometer	EBAM-V1-15	0.43 (0.58)	0.92 (0.96)
Nephelometer	EBAM-V1-45	0.53 (0.63)	**0.98**
EBAM-WF-15	EBAM-WF-45	0.77 (0.80)	0.98
EBAM-V1-15	EBAM-V1-45	0.37 (0.49)	0.93 (0.96)
EBAM-WF-15	EBAM-V1-15	0.52 (0.66)	0.97 (0.98)
EBAM-WF-45	EBAM-V1-45	0.54 (0.60)	0.97
E-SEQ-FRM	BAM-1020	NA	1.00
E-SEQ-FRM	Nephelometer	NA	0.99
BAM-1020	Nephelometer	0.89 (0.9)	0.98

The EBAM relative humidity (RH) setpoint is appended to the EBAM name (e.g., The EBAM-WF at the 15 percent RH setpoint is EBAM-WF-15). Data in parentheses are changes from setting negative concentrations to zero. Data in bold indicate the optimal performing EBAM.

NA = not applicable.

Figure 5 shows scatterplots of 1-hour average $PM_{2.5}$ concentrations measured by each EBAM versus the BAM-1020 data. There is a high degree of scatter, which is also indicated by the RMSE data, which ranges from 3.7 to 6.5 µg/m^3, and a maximum absolute error of 51 µg/m^3 for the EBAM-V1 at the 15-percent RH setpoint. The line of best fit slopes are <1.00 for three of the four EBAMs, further illustrating how they tended to underestimate average $PM_{2.5}$ concentrations, while data for the EBAM-V1 at the 45-percent RH setpoint has a slope of almost 1.00. The EBAM-V1 at the 45-percent RH setpoint also has the second lowest R^2 with the BAM-1020 data ($R^2 = 0.54$). The EBAM-WF at the 15-percent RH setpoint has the second-best slope and the highest R^2 with the BAM-1020 data ($R^2 = 0.73$). We are likely seeing loss of semivolatile species at the lower RH setpoint of 15 percent with the tendency of both the EBAM-WF and EBAM-V1 to underestimate the mean and median concentrations. However, this setpoint was more successful at controlling the spread in

the data, as shown with lower standard deviations and fewer occurrences of the higher and lower concentration data compared to the BAM-1020. Data in bold in tables 5 and 6 indicate the best-performing EBAM for the evaluation metric. Overall, the EBAM-WF at the 15-percent RH setpoint performed the best in terms of lowest RMSE and absolute error, and highest R^2, and second best (to the EBAM-V1 at the 45-percent RH setpoint) in terms of bias.

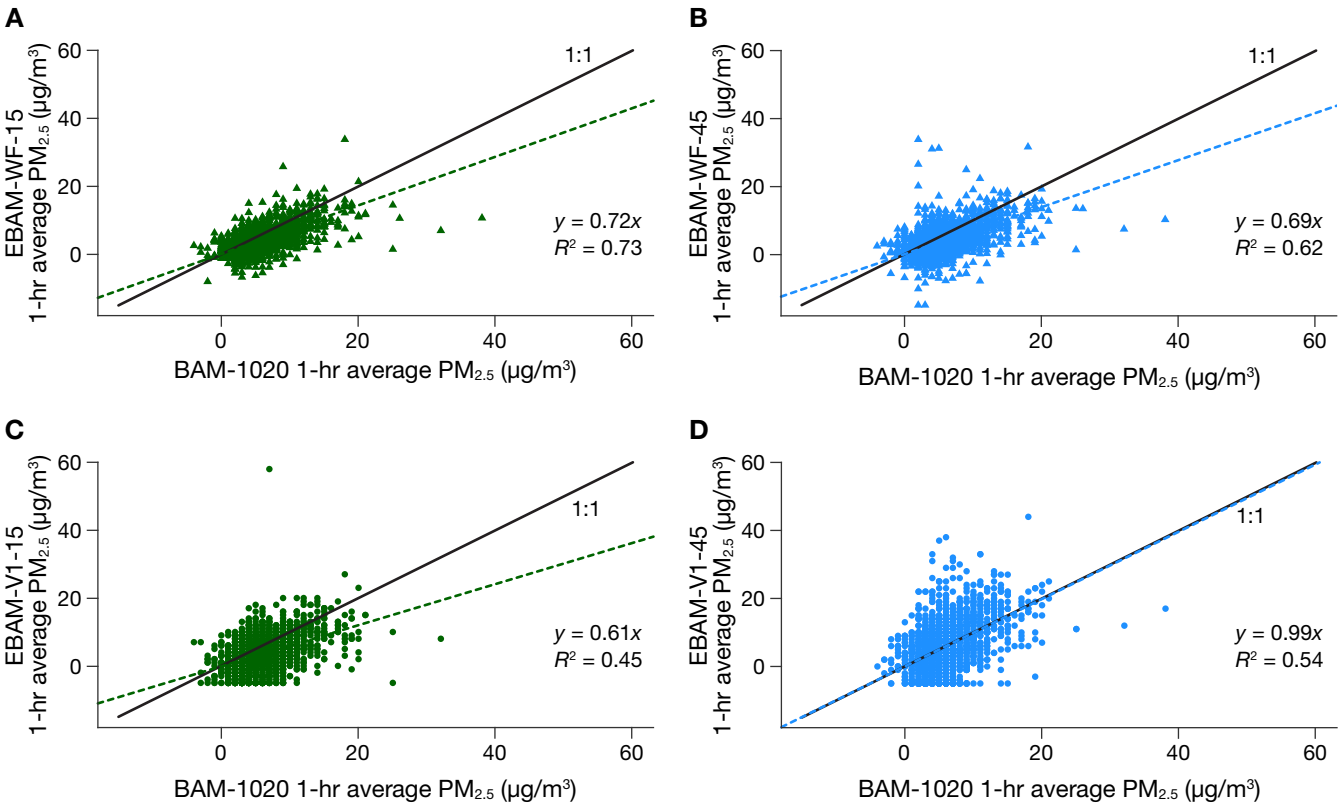


Figure 5—Scatterplots of the BAM-1020 (a federal equivalent method monitor) 1-hour average fine particulate matter ($PM_{2.5}$) concentration data versus (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint data. The solid line is the reference line, and the dashed line is the line of best fit with the equation. Triangles indicate EBAM-WF, and circles indicate EBAM-V1. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

The nephelometer, while highly sensitive to RH, is calibrated to the BAM-1020 and E-SEQ-FRM sampler based on the location and site conditions for converting the instrument's measure of light scattering to $PM_{2.5}$ concentrations. Its data exhibited less noise/variability and made another useful comparison. The nephelometer data included the lowest maximum 1-hour average $PM_{2.5}$ concentration (25.1 µg/m^3) and standard deviation (2.3 µg/m^3). Appendix figures A1 and A2 show time series and scatterplots, respectively, of the EBAM data with the nephelometer data. Figure 4 also includes the nephelometer data (red). R^2 values range from $R^2 = 0.43$ (EBAM-V1 at the 15-percent RH setpoint) to $R^2 = 0.75$ (EBAM-

WF at the 15-percent RH setpoint). The degree of variability in the EBAM data compared to the nephelometer data (figs. 4 and A1) is rather large, with the EBAM data exhibiting more hour-to-hour scatter compared to the nephelometer curve, which is smoother and has a narrower range. The standard deviation and RMSE data reflect this, but again, the qualitative evaluation of a times series is useful given that is what a data reviewer primarily uses when investigating local air quality conditions.

Evaluation of 24-Hour Average $PM_{2.5}$ Concentration Measurements

The BAM-1020 measured a maximum 24-hour average $PM_{2.5}$ concentration of 12.3 µg/m^3, and the E-SEQ-FRM measured a maximum 24-hour average $PM_{2.5}$ concentration of 11.3 µg/m^3. EBAM maximums ranged from 9.8 to 12.2 µg/m^3 (table 7).

EBAM performance for 24-hour average $PM_{2.5}$ concentrations was superior to that of the 1-hour averaging period, with R^2 values ranging from 0.95 to 0.99 when comparing data with the BAM-1020 (fig. 6) and E-SEQ-FRM (fig. 7). Note that there are more data points for the BAM-1020 comparison than the E-SEQ-FRM comparison because the E-SEQ-FRM only took measurements every three days. The E-SEQ-FRM, as a federal reference method sampler, provides the highest standard. When comparing to the E-SEQ-FRM, the EBAM-WF at the 15-percent RH setpoint and the EBAM-V1 at the 45-percent RH setpoint performed best, having an of R^2 of 0.99 and lines of best fit slopes close to 1.00 (0.91 and 1.08, respectively), and similar mean bias (−0.6 and 0.6 µg/m^3, respectively), fractional bias (−0.1 and 0.1 µg/m^3, respectively), RMSE (0.8 µg/m^3), and maximum absolute error (1.6 and 1.7 µg/m^3, respectively). Table 8 summarizes these performance metrics; data in bold indicate the best-performing EBAM(s). Results are similar to those comparing EBAM and BAM-1020 data, with a slight reduction in the lines of best fit slopes, slightly higher RMSE, and higher maximum absolute error. The EBAM-V1 at the 15-percent RH setpoint performed least optimally, with the largest underestimation and relatively low R^2 values of 0.95 and 0.96 compared to the BAM-1020 and E-SEQ-FRM, respectively, although these R^2 values are excellent.

Table 7—Instrument 24-hour average $PM_{2.5}$ concentration mean, median, maximum, minimum, and standard deviation, February 15–May 1, 2024

Instrument	Relative humidity setpoint	Mean $PM_{2.5}$	Median $PM_{2.5}$	Maximum $PM_{2.5}$	Minimum $PM_{2.5}$	$PM_{2.5}$ standard deviation	Data points
	Percent	*µg/m³*	*µg/m³*	*µg/m³*	*µg/m³*	*µg/m³*	*Number*
BAM-1020	35	6.0	5.9	12.3	2.3 (2.5)	2.0	76
E-SEQ-FRM	NA	6.0	5.6	11.3	2.6	2.4	13
Nephelometer	40	5.6	5.3	10.7	3.5	1.4	74
EBAM-WF	15	4.7 (4.8)	4.2 (4.3)	11.0	1.6 (1.8)	2.0	68
EBAM-WF	45	4.6 (4.8)	4.2 (4.3)	10.1	1.8 (2.2)	1.8	75
EBAM-V1	15	3.6 (4.3)	3.5 (4.3)	9.8 (10.0)	0.4 (1.8)	2.0 (1.7)	73
EBAM-V1	45	6.4 (7.0)	6.1 (6.7)	12.2 (12.5)	2.8 (3.6)	2.0 (1.8)	74

Data in parentheses are changes from setting negative concentrations to zero.

NA = not applicable.

Table 8—Evaluation metrics comparing the environmental beta attenuation monitors (EBAMs) to the BAM-1020, E-SEQ-FRM, and nephelometer for 24-hour average $PM_{2.5}$ concentrations

Experimental measurement monitor	Actual observation monitor	Mean bias	Fractional bias	Root mean square error	Maximum absolute error	Data points
		µg/m³	*µg/m³*	*µg/m³*	*µg/m³*	*Number*
EBAM-WF-15	BAM-1020	−1.3 (−1.2)	−0.3	1.5 (1.4)	3.1 (2.9)	68
EBAM-WF-45	BAM-1020	−1.4 (−1.2)	−0.3 (−0.2)	1.6 (1.5)	3.7	75
EBAM-V1-15	BAM-1020	−2.4 (−1.7)	−0.6 (−0.4)	2.5 (1.9)	4.4 (3.7)	73
EBAM-V1-45	BAM-1020	**0.4** (1.0)	**0.1** (0.2)	**1.0** (1.4)	**3.0** (3.6)	74
EBAM-WF-15	E-SEQ-FRM	**−0.6**	**−0.1**	**0.8** (0.7)	**1.6** (1.5)	13
EBAM-WF-45	E-SEQ-FRM	−1.0 (−0.8)	−0.2	1.3 (1.1)	2.3 (2.0)	13
EBAM-V1-15	E-SEQ-FRM	−2.2 (−1.5)	−0.5 (−0.3)	2.3 (1.7)	3.0 (2.7)	13
EBAM-V1-45	E-SEQ-FRM	**0.6** (1.0)	**0.1** (0.2)	**0.8** (1.1)	1.7	13
EBAM-WF-15	Nephelometer	−1.0 (−0.9)	−0.3 (−0.2)	1.3 (1.2)	**2.5**	66
EBAM-WF-45	Nephelometer	−1.1 (−0.9)	−0.3 (−0.2)	1.3 (1.2)	3.0 (2.8)	73
EBAM-V1-15	Nephelometer	−2.0 (−1.3)	−0.5 (−0.3)	2.2 (1.6)	3.9 (3.4)	71
EBAM-V1-45	Nephelometer	**0.7** (1.3)	**0.1** (0.2)	**1.2** (1.6)	3.3 (4.2)	72

The EBAM relative humidity (RH) setpoint is appended to the EBAM name (e.g., The EBAM-WF at the 15 percent RH setpoint is EBAM-WF-15). Data in parentheses are changes from setting negative concentrations to zero. Data in bold indicate the optimal performing EBAM.

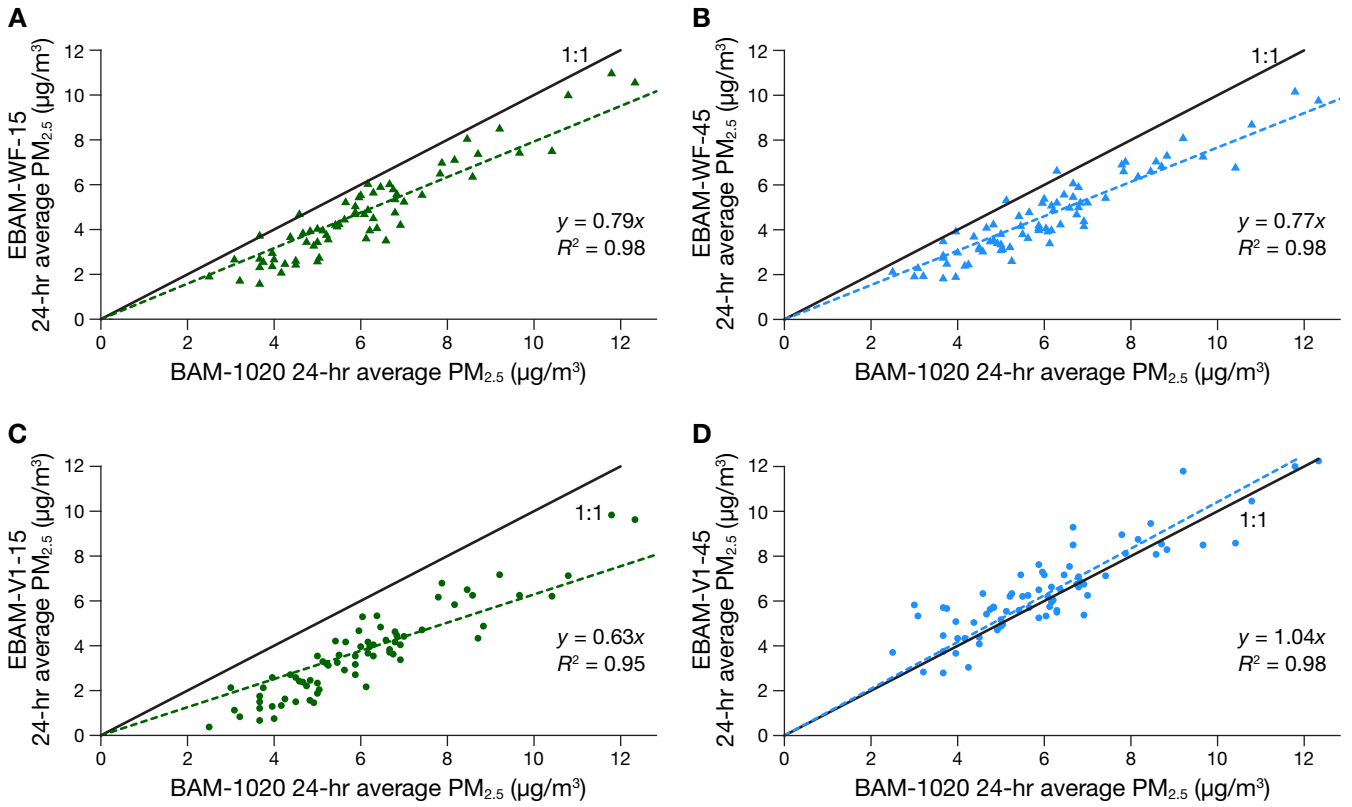


Figure 6—Scatterplots of the BAM-1020 24-hour average fine particulate matter ($PM_{2.5}$) concentration data versus (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint data. The solid line is the reference line, and the dashed line is the line of best fit with the equation. Triangles indicate EBAM-WF, and circles indicate EBAM-V1. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

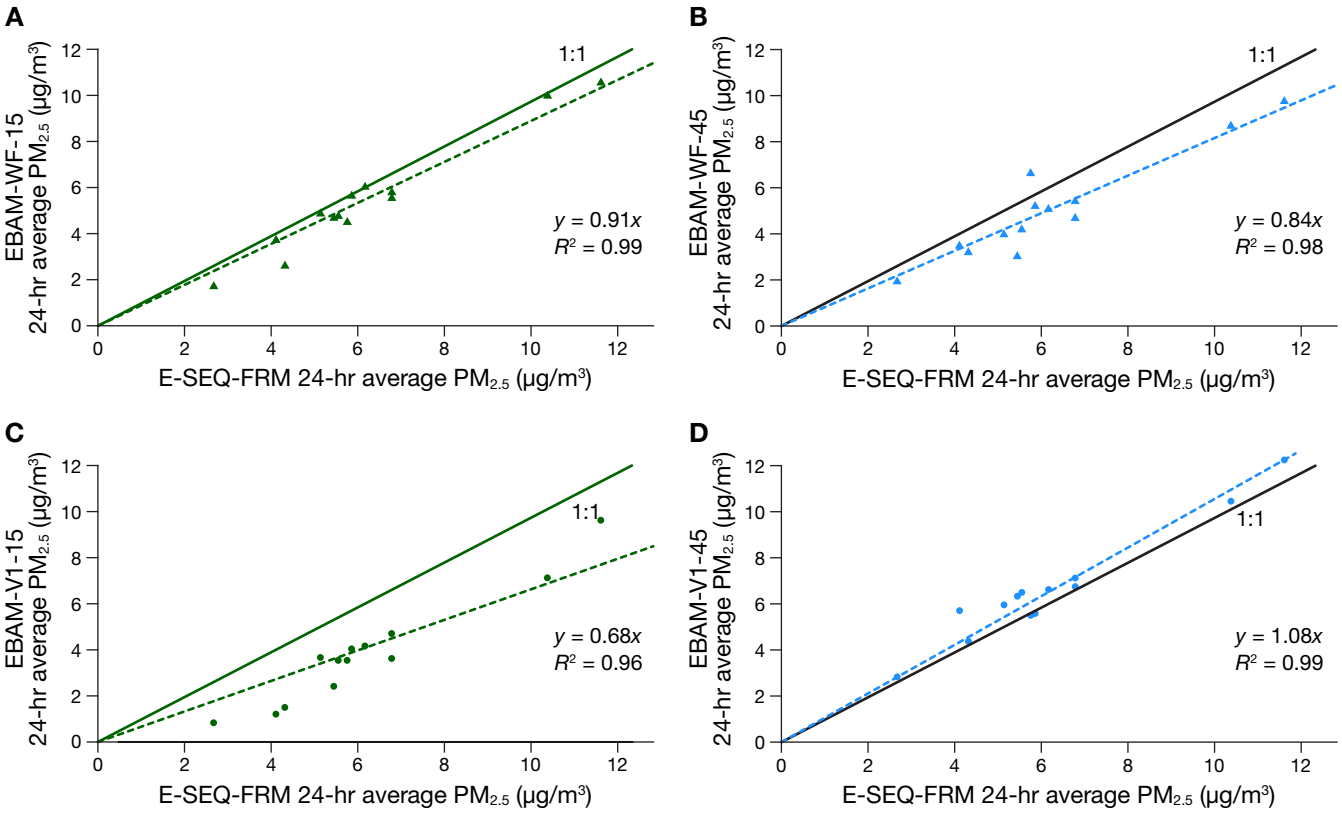


Figure 7—Scatterplots of E-SEQ-FRM 24-hour average fine particulate matter ($PM_{2.5}$) concentration data versus (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V, 45-percent RH setpoint data. The solid line is the reference line, and the dashed line is the line of best fit with the equation. Triangles indicate EBAM-WF data, and circles indicate EBAM-V1 data. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

Our results are similar to other studies (Mehadi et al. 2020; Schweizer et al. 2016; Trent 2003, 2006), which were based on the older model EBAM-V1. The EBAM-V1 optimal performance at the 45-percent RH setpoint supports using the manufacturer recommended 45-percent RH setpoint for the EBAM-V1 model. However, this is the first evaluation of the new EBAM-WFs, and they performed differently than the EBAM-V1s. The EBAM-WF at the 15-percent RH setpoint performed equally as well as the EBAM-V1 at the 45-percent RH setpoint for the 24-hour average $PM_{2.5}$ concentration evaluation and much better for 1-hour average $PM_{2.5}$ concentrations, which are the data most often used in the field. The comparisons within EBAM models also illustrate differences. Unlike the EBAM-V1s, the EBAM-WFs at the two RH setpoints were similar in performance, with $R^2 = 0.98$ and lines of best fit slopes close to 1.00. Although this indicates that the EBAM-WF is less sensitive to the RH setpoint, the more stringent setpoint of 15 percent is more successful at controlling noise in the results, as indicated by lower RMSE and standard deviation, and qualitatively by the time series inspection/results.

Because the E-SEQ-FRM provides the highest standard, we also compared the BAM-1020 and nephelometer data to the E-SEQ-FRM data. Both instruments performed well. The BAM-1020 achieved an $R^2 = 1.00$, while the nephelometer achieved an $R^2 = 0.99$. The line of best fit slopes are close to 1.00 (1.07 for the BAM-1020 and 0.95 for the nephelometer). There is a slight tendency of the BAM-1020 to overestimate 24-hour average $PM_{2.5}$ concentrations.

Effects of Setting Measured Negative $PM_{2.5}$ Concentrations to Zero

Negative 1-hour average $PM_{2.5}$ concentrations can occur in clean atmospheric conditions (such as below 3 $\mu g/m^3$) when the hourly change in concentration is within the noise band of the instrument (Met One Instruments, Inc. 2021). The underlying technology of the BAM-1020 and EBAMs is similar; the BAM-1020 is the nonmobile, EPA-certified FEM version, and EBAMs are more rugged and designed for mobile deployments. The EBAM-V1s have a floor value of -5 $\mu g/m^3$, while the EBAM-WFs have a floor of -15 $\mu g/m^3$. Across the study period, few (about 1.3 percent) BAM-1020 1-hour average $PM_{2.5}$ concentration measurements were less than zero, with a minimum value of -4 $\mu g/m^3$. However, the percentage of 1-hour average $PM_{2.5}$ concentration measurements that were less than zero for the EBAMs ranged from 7.1 to 22.2 percent. The EBAM-V1s had more (one-and-a-half to three times) negative values than the EBAM-WFs. The 15-percent RH setpoint tended to decrease the occurrence of negative $PM_{2.5}$ concentrations for the EBAM-WFs but conversely tended to increase the occurrence of negative

$PM_{2.5}$ concentrations for the EBAM-V1s. Negative $PM_{2.5}$ concentrations occurred more often when the ambient RH was <65 percent.

We calculated evaluation metrics after setting negative $PM_{2.5}$ concentrations to zero (tables 4–8: data in parentheses). If a number in parentheses is not provided in the table, then there is no change in the data. After setting negative $PM_{2.5}$ concentrations to zero, mean 1-hour average $PM_{2.5}$ concentrations generally increase; EBAM-V1 data have higher increases than EBAM-WF data. Setting negative $PM_{2.5}$ concentrations to zero decreases 1-hour average $PM_{2.5}$ concentration standard deviations and RMSEs, with greater decreases in scatter in EBAM-V1 data than EBAM-WF data. The R^2 values for the 1-hour average $PM_{2.5}$ concentrations increased noticeably for all the EBAMs. The EBAM-V1 at the 15-percent RH setpoint has the largest improvement from $R^2 = 0.45$ to $R^2 = 0.58$. The EBAM-WF at the 15-percent RH setpoint is the least sensitive to this, improving from $R^2 = 0.73$ to $R^2 = 0.75$. It is already the EBAM with the best performance.

When comparing EBAM data with BAM-1020 and E-SEQ-FRM data, setting the negative 1-hour average $PM_{2.5}$ concentrations to zero before averaging to 24 hours generally improves R^2 values for the EBAM-V1s, while R^2 values remain unchanged for the EBAM-WFs (table 6). Setting the negative 1-hour average $PM_{2.5}$ concentrations to zero does not affect 24-hour $PM_{2.5}$ concentrations for the BAM-1020 and EBAM-WFs, but 24-hour $PM_{2.5}$ concentrations are slightly higher (a 0.2 to 0.3 $\mu g/m^3$ increase) for the EBAM-V1s. Setting negative $PM_{2.5}$ concentrations to zero minimally affects BAM-1020 data because there are few occurrences of negative $PM_{2.5}$ concentrations.

Studies differ in their treatment of negative 1-hour average $PM_{2.5}$ concentrations. Some evaluate EBAM performance with and without the negative $PM_{2.5}$ concentrations (Schweizer et al. 2016), set them to zero (Mehadi et al. 2020), or invalidate the data (Cisneros et al. 2014). Jiang et al. (2023) provide an indepth analysis of the occurrence and treatment of negative $PM_{2.5}$ concentration values, discussing how they can occur when ambient concentrations are below the detection limit of the instrument, or when volatile species partition between the gas and aerosol phases within the sampling system. Overall, removal of otherwise valid negative values in data averaging and analysis creates a positive bias (Hart 2013) and is not recommended (Jiang et al. 2023). The EPA also provides training at their National Ambient Air Monitoring Conference, which includes addressing negative data (US EPA 2014, 2016). They recommend that valid negative numbers should be reported to the EPA Air Quality System (US EPA 2026a) and AirNow (US EPA 2026b) but that public reports of the data should not include the negative numbers.

Effects of Relative Humidity

Like Schweizer et al. (2016) and Mehadi et al. (2020), we found that ambient RH conditions affected EBAM performance, especially at ≥65 percent RH. During this study, RH was ≥65 percent for about two-thirds of the study period and was <65 percent for about one-third of the study period. Schweizer et al. (2016) had a much more even distribution of RH (from low to high RH conditions) compared to this study, which by design was conducted in a higher humidity environment.

Across all instruments (BAM-1020, nephelometer, and EBAMs), average $PM_{2.5}$ concentrations were higher when RH was ≥65 percent. This was especially pronounced in the data for the EBAM-V1 at the 45-percent RH setpoint. Maximum $PM_{2.5}$ concentrations and standard deviations also followed this trend, except for the EBAM-V1 at the 15-percent RH setpoint, which had a single $PM_{2.5}$ measurement of 58 µg/m^3 that biased the results. While it was an outlier, we did not remove the data point from the analysis because the purpose here is to illustrate all measured data. As noted earlier, negative $PM_{2.5}$ concentrations occurred more often in the BAM-1020 data and in three of the four EBAMs when the ambient RH was <65 percent. Interestingly, the EBAM-WF at the 15-percent RH setpoint had higher average mean and median $PM_{2.5}$ concentrations when ambient RH was ≥65 percent than the EBAM-WF at the 45-percent RH setpoint, although it had a reduced standard deviation (as expected). This may indicate an issue with continuous running of the internal heater, which is what essentially occurred because ambient RH was >15 percent for the entire study.

Next, we investigated how ambient RH affects EBAM measurements that have large departures from the BAM-1020 measurements (i.e., error = EBAM value minus BAM-1020 value). To do this, we calculated paired differences between the $PM_{2.5}$ concentration measurements from the EBAMs and the BAM-1020 as well as the nephelometer and applied the evaluation metrics of table 3. Results are in table 5. On an hour-to-hour basis, the absolute error between the EBAM and BAM-1020 $PM_{2.5}$ concentration measurements was >10 µg/m^3 for 1.2 percent (EBAM-WF, 15-percent RH setpoint) to 8.6 percent (EBAM-V1, 45-percent RH setpoint) of the measurements. The largest maximum absolute error (51.0 µg/m^3) occurred with the EBAM-V1 model at the 15-percent RH setpoint, while the lowest maximum absolute error (27.3 µg/m^3) occurred with the EBAM-WF model at the 15-percent RH setpoint. This is further quantification of the variability we see in the time series plots of figures 3 and 4.

Figure 8 shows boxplots of the paired differences (EBAM value minus BAM-1020 value) plotted versus bins of ambient RH for each of the EBAMs. Figure 8, panel A, shows data for the EBAM-WF at the

15-percent RH setpoint. At ≤65 percent RH, almost all the data has a difference within ±10 µg/m^3 (except three datapoints extending down to −12.7 µg/m^3). Differences get larger as the RH setpoint is relaxed to 45 percent, and the ambient RH increases (fig. 8: panel B), especially in EBAM-V1 data with this combination of settings/conditions (fig. 8: panel D). At <65 percent ambient RH, all EBAMs have a low occurrence (<4 percent) of differences >10 µg/m^3. At ≥65 percent ambient RH, the occurrence of differences >10 µg/m^3 increases, especially with the EBAM-V1s. The EBAM-WF at the 15-percent RH setpoint performed best for these criteria. Setting negative $PM_{2.5}$ concentrations to zero generally slightly decreases the paired differences in various evaluation metrics (mean, median, etc.), except for the mean difference between BAM-1020 and EBAM-V1 at the 45-percent RH setpoint, which increases from 0.4 to 1.0 µg/m^3 (table 5).

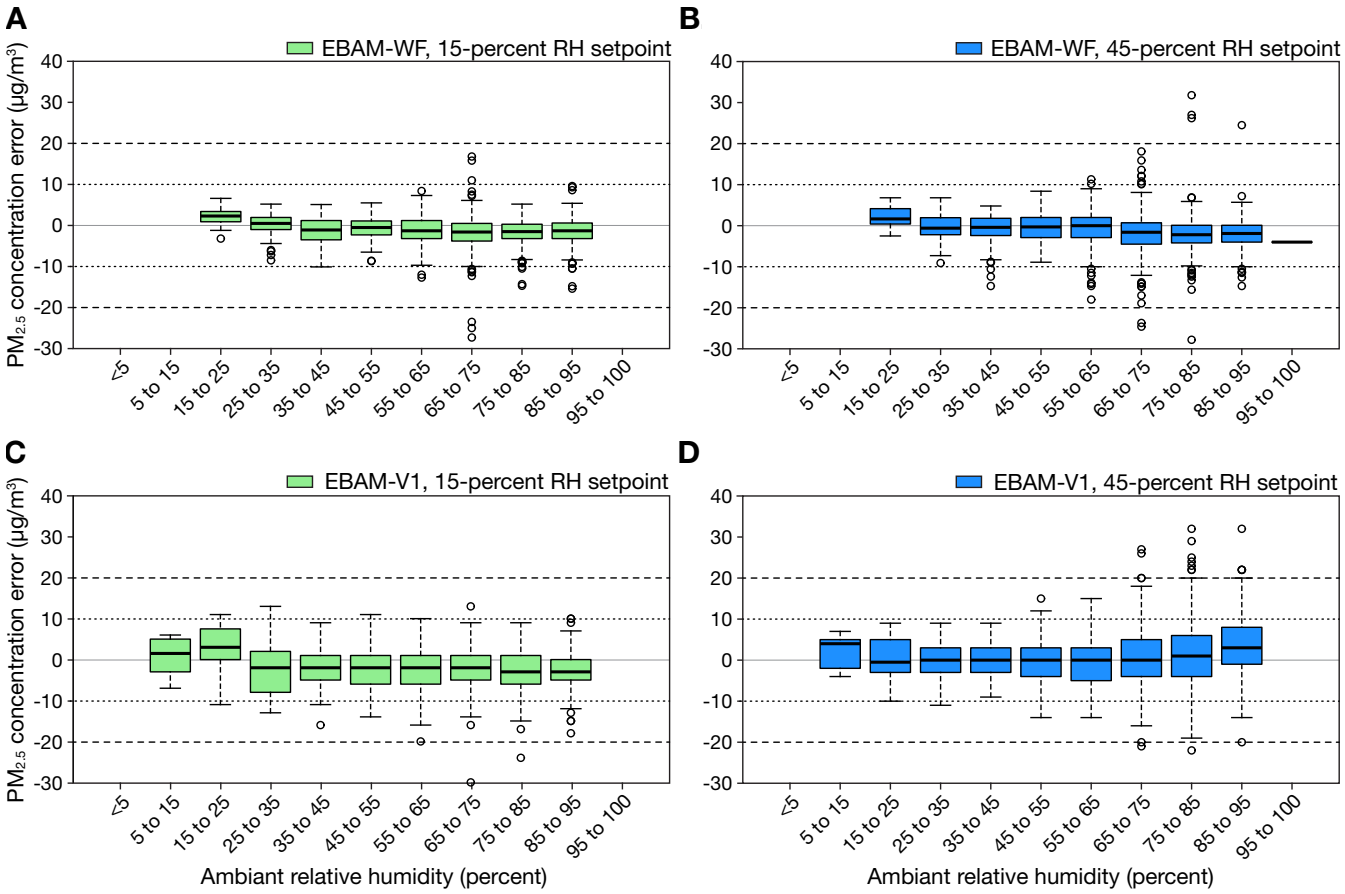


Figure 8—Boxplots of paired differences (error = EBAM value minus BAM-1020 value) in 1-hour average fine particulate matter ($PM_{2.5}$) concentrations by ambient relative humidity (RH) for (A) EBAM-WF, 15-percent RH setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint. Whiskers represent maximum and minimum values excluding the outliers (which are shown as circles). Horizontal, dashed lines indicate ±20 µg/m^3 error, and horizontal, dotted lines indicate ±10 µg/m^3 error.

The minimum and maximum values for the EBAM-WF at the 15-percent RH setpoint are mostly in the ±10 µg/m^3 range (one value extends to −11 µg/m^3). The occurrence of outliers > ±20 µg/m^3 starts at 65 percent ambient RH. The EBAM-WF at the 45-percent RH setpoint has whiskers that extend to about −12 µg/m^3 across all ambient RH bins. The EBAM-V1s have whiskers extending closer to ±20 µg/m^3.

Sensitivity to the Internal Heater

The RH setpoint parameter turns on the internal heater to control (reduce) aerosol water content when ambient RH exceeds the setpoint value. To understand EBAM sensitivity to the RH setpoint, we compared the two EBAM-WFs to each other (fig. 9: panels A and C, 1-hour and 24-hour average $PM_{2.5}$ concentrations, respectively) and the two EBAM-V1s to each other (fig. 9: panels B and D, 1-hour and 24-hour average $PM_{2.5}$ concentrations, respectively). The 1-hour average $PM_{2.5}$ concentrations

measured by the two EBAM-WFs were quite similar, with an R^2 = 0.77 and a line of best fit slope near 1.00 (0.91), which indicates a low sensitivity to the RH setpoint. However, the EBAM-WF at the 45-percent RH setpoint had several high and low outliers compared to the EBAM-WF at the 15-percent RH setpoint. Conversely, the 1-hour average $PM_{2.5}$ concentrations measured by the two EBAM-V1s were quite different, with an R^2 = 0.37, although the line of best fit slope is near 1.00 (0.91). These results may indicate that the EBAM-V1s are more sensitive to the RH setpoint than the EBAM-WFs. The 24-hour average $PM_{2.5}$ concentration scatterplots and R^2 values also indicate this. The colocated EBAM-WF units exhibited a highly predictable linear relationship (R^2 = 0.98), and the line of best fit slope is near 1.00 (0.95). For the EBAM-V1s, although the R^2 value is much improved at R^2 = 0.93, the line of best fit slope is 1.58, indicating that the $PM_{2.5}$ concentrations at the 45-percent RH setpoint were much higher than at the 15-percent RH setpoint (as expected).

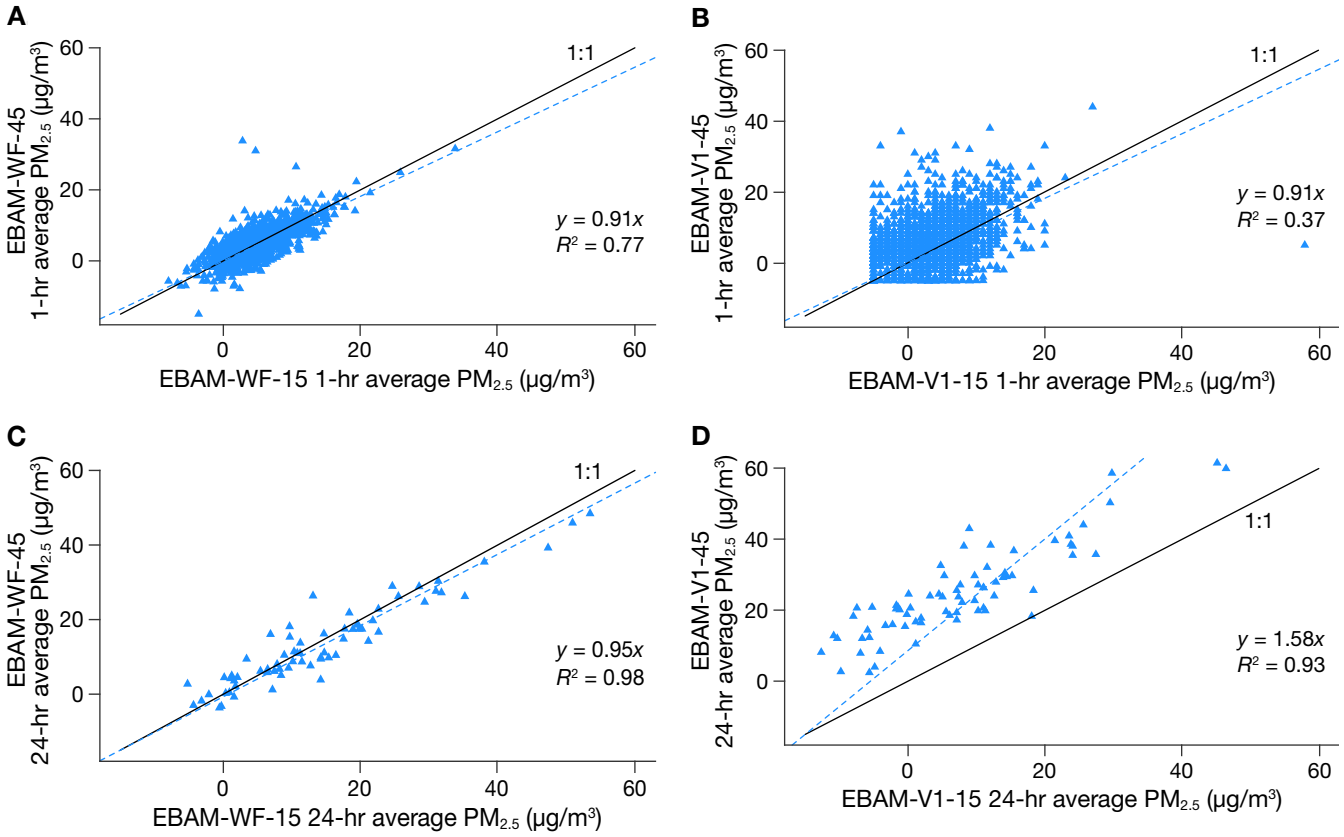


Figure 9—Scatterplots comparing 1-hour average fine particulate matter ($PM_{2.5}$) concentration data for (A) EBAM-WF, 15-percent relative humidity (RH) setpoint and EBAM-WF, 45-percent RH setpoint and (B) EBAM-V1, 15-percent RH setpoint and EBAM-V1, 45-percent RH setpoint. Scatterplots comparing 24-hour average $PM_{2.5}$ concentration data for (C) EBAM-WF, 15-percent RH setpoint and EBAM-WF, 45-percent RH setpoint and (D) EBAM-V1, 15-percent RH setpoint and EBAM-V1, 45-percent RH setpoint. The solid line is the reference line, and the dashed line is the line of best fit with the equation.

EBAMs record and output the internal RH, which is used as a quality assurance/quality control parameter. Data are flagged when the internal RH is above a certain specification, the thought being that the heater is not performing well enough to provide acceptable $PM_{2.5}$ concentration measurements. Figure 10 compares the internal RH data for all four EBAMs and the ambient RH. All EBAM internal RH trends are similar to the ambient RH trend. The RH setpoint turns on the internal heater to control for aerosol water content, so one would expect the measured internal RH would be similar between the two EBAM-WFs because the $PM_{2.5}$ concentration measurements tended to be similar. This was not the case, as shown in figure 10, where there is an appreciable difference between the measured internal RH for the two EBAM-WFs, especially at lower ambient RHs (e.g., fig. 10: April 19–21, 2022). Conversely, the measured internal RHs for the two EBAM-V1s were quite similar even though the 1-hour average concentrations were much more different. EBAM-V1s had an internal RH difference (45-percent RH setpoint minus 15-percent RH setpoint) ranging from −5 to 7, while EBAM-WFs had an internal RH difference ranging from −10 to 18.

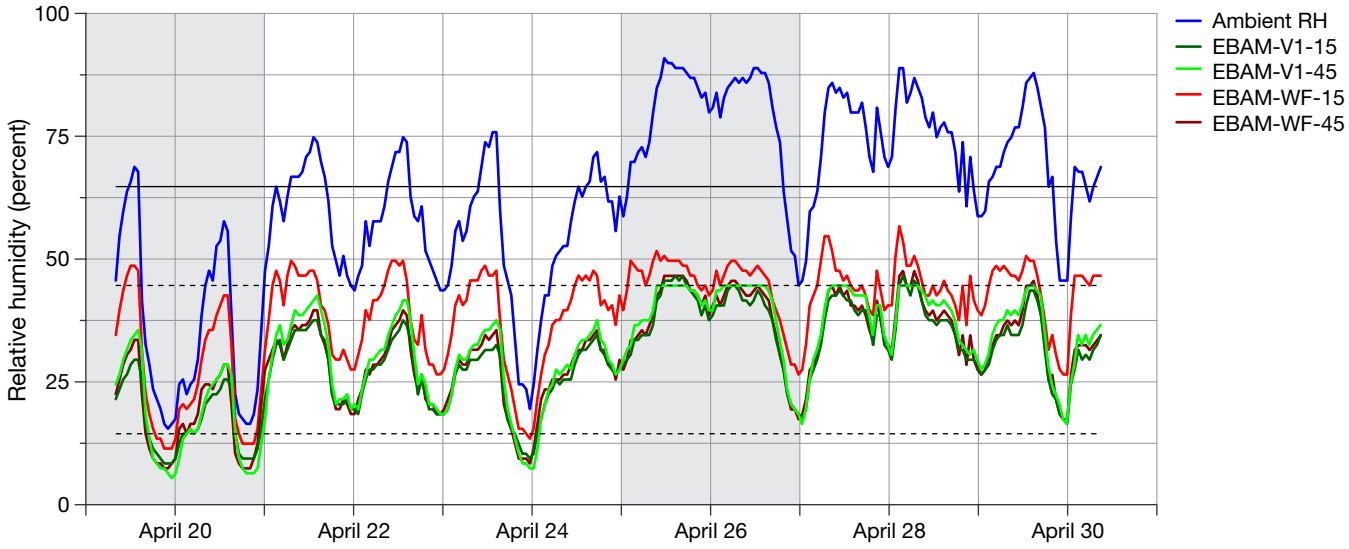


Figure 10—Ambient relative humidity (RH) and internal RH for EBAM-V1, 15-percent RH setpoint; EBAM-V1, 45-percent RH setpoint; EBAM-WF, 15-percent RH setpoint; and EBAM-WF, 45-percent RH setpoint, April 19–30, 2024. Ambient RH was consistently <65 percent from April 19–21, 2024 and ≥65 percent from April 25–27, 2024. Horizontal, solid lines indicate 65 percent RH, and horizontal dashed lines indicate the 15-percent RH setpoint and 45-percent RH setpoint.

To investigate how the EBAM RH setpoint and resulting effects on internal humidity could affect EBAM $PM_{2.5}$ concentration measurements, we plotted the error (EBAM value minus BAM value) versus the internal RH. Only the EBAM-V1 at the 45-percent RH setpoint was successful at controlling the EBAM internal RH to the setpoint value; all the others simply had reduced RH (as compared to ambient) indicating that the internal heater was functional but not able to meet specifications (fig. 11).

This is not entirely unexpected at the more stringent 15-percent RH setpoint, but it was surprising to observe this in the new EBAM-WF at the 45-percent RH setpoint, which had the maximum internal RH (57 percent) of the four monitors.

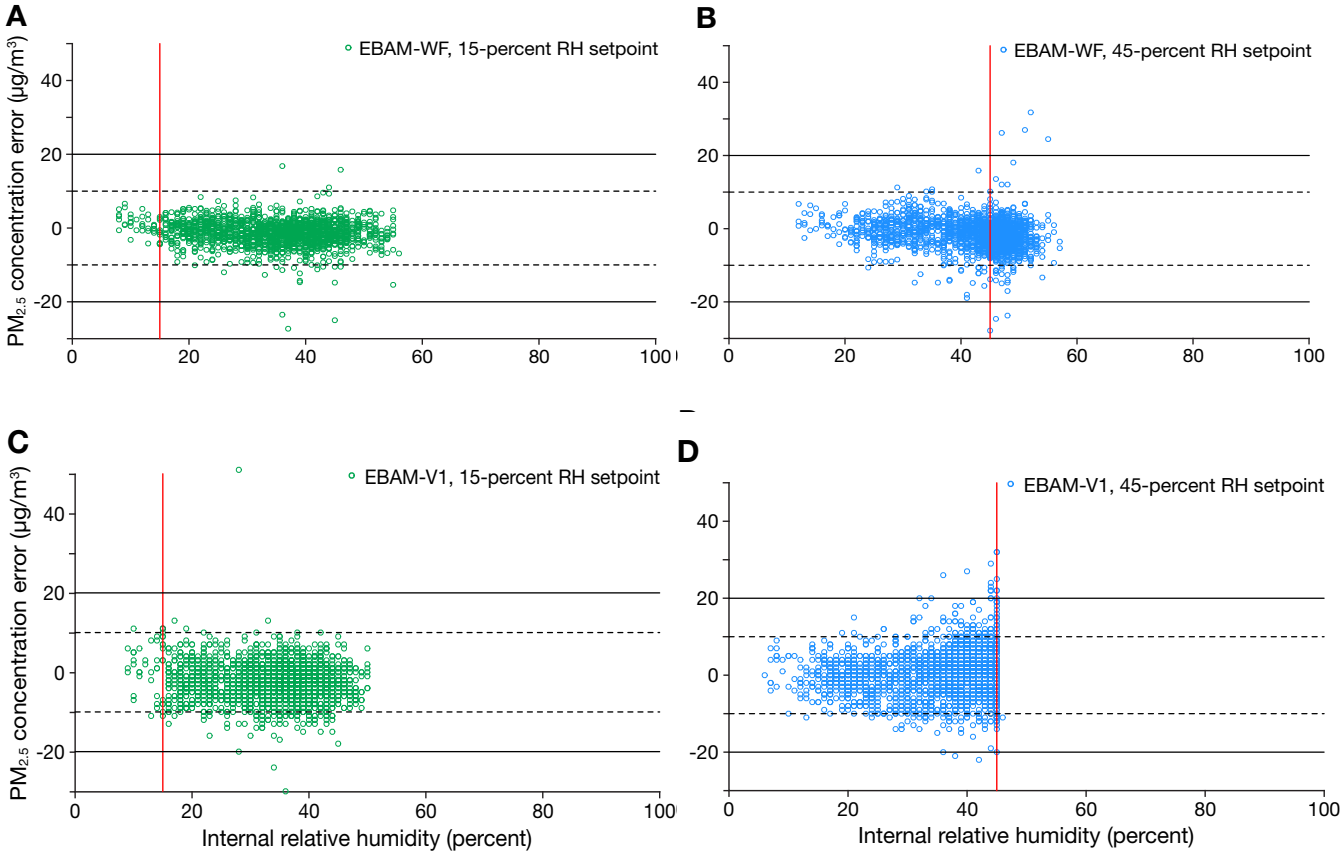


Figure 11—Scatterplots of EBAM internal relative humidity (RH) versus the error (EBAM value minus BAM-1020 value) in 1-hour average $PM_{2.5}$ concentration data for (A) EBAM-WF, 15-percent RH setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint. Red vertical lines indicate the EBAM RH setpoint. Horizontal, solid black lines indicate ±20 µg/m^3 error, and horizontal, dashed lines indicate ±10 µg/m^3 error. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

Invalidating data where the internal RH is >40 percent as recommended by Schweizer et al. (2016) would result in a substantial loss of data. Instead, EBAM users may consider using 65 percent as the cutoff to invalidate or flag data, given that this was the threshold at which this study and Schweizer et al. (2016) document reduced EBAM performance. At the 45-percent RH setpoint, both the EBAM-WF and EBAM-V1 had higher differences between their 1-hour average $PM_{2.5}$ concentration data and the BAM-1020 data (error) as internal RH increased. This was not the case for the two EBAMs at the 15-percent RH setpoint, which tended to have few 1-hour average $PM_{2.5}$ concentration measurements that differed from the BAM-1020 data by more than ±20 µg/m^3.

Summary and Considerations

EBAMs are commonly used to measure $PM_{2.5}$ concentrations in smoke from prescribed fires and wildfires. Compared to wildfires, prescribed fires are typically smaller, emit lower quantities of $PM_{2.5}$ per hectare (US EPA 2023), are of shorter duration (several hours to days if smoldering), and may occur when the atmosphere is cleaner and perhaps more humid. Particulate matter concentration increases can be more subtle from prescribed fires than from wildfires and may be subject to scrutiny (Oregon Secretary of State 2023, Schweizer et al. 2016). These conditions highlight the need to better understand the capabilities and limitations of instruments deployed to measure $PM_{2.5}$ concentrations during prescribed fire operations, especially in a more humid and cleaner environment at the shorter, 1-hour period.

To address this need, we colocated four mobile EBAMs—two older model EBAM-V1s and two new EBAM-WFs—with an EPA-certified E-SEQ-FRM sampler (federal reference method) and a BAM-1020 (a federal equivalent method, or FEM) monitor at the Duwamish Valley air quality site (operated by the Puget Sound Clean Air Agency) in Seattle, Washington. We investigated two internal heater settings, 15 and 45 percent RH setpoints. This is the first evaluation of the new EBAM-WF model and is one of few studies that examines the variability of the hourly measurements in low ambient $PM_{2.5}$ concentrations (<40 $\mu g/m^3$) and elevated RH (>65 percent for about two-thirds of the study period) conditions. Key findings include the following:

- For 1-hour average $PM_{2.5}$ concentrations, R^2 values between the EBAM $PM_{2.5}$ concentration data and FEM/FRM data ranged from $R^2 = 0.45$ (EBAM-V1, 15-percent RH setpoint) to $R^2 = 0.73$ (EBAM-WF, 15-percent RH setpoint). Other studies (Mehadi et al. 2020) in high ambient $PM_{2.5}$ conditions (about 200–1000 $\mu g/m^3$) measured much improved R^2 of 0.95 for 1-hour average $PM_{2.5}$ concentrations, and the EBAM outperformed six other models of monitors in those smoky conditions.

- For 24-hour average $PM_{2.5}$ concentrations, R^2 values were much improved, ranging from $R^2 = 0.95$ (EBAM-V1, 15-percent RH setpoint) to $R^2 = 0.99$ (EBAM-V1, 45-percent RH setpoint and EBAM-WF, 15-percent RH setpoint). These results, when combined with others, such as Mehadi et al. (2020), Schweizer et al. (2016), and Trent (2003, 2006), show that the EBAM performs well at the 24-hour averaging period across all ambient $PM_{2.5}$ conditions.

- Hourly EBAM measurements exhibited substantial variability. The more stringent 15-percent RH setpoint

tended to dampen that effect in both EBAM models, but this also resulted in negative mean biases of −1.3 and −2.4 $\mu g/m^3$ (EBAM-WF and EBAM-V1, respectively), likely because of evaporation of volatile aerosol species.

- On an hour-to-hour basis, the error (the difference between the EBAM and FEM measurements) was as high as 51 $\mu g/m^3$, although 91.4 to 98.8 percent of the differences were less than ±10 $\mu g/m^3$ across all four EBAMs. These spikes in the data, however, can make it difficult for a data reviewer to discern if wildland fire smoke is affecting the monitor or if it is instrument noise at low/clean atmospheric concentrations. Data from the EBAM-WF at the 15-percent RH setpoint exhibited the lowest occurrence and lowest magnitude of fluctuations from the FEM data.

- Above an ambient RH of 65 percent, hourly differences between EBAM and FEM measurements became greater than ±20 $\mu g/m^3$ for both EBAM models and occurred more often at the 45-percent RH setpoint. The EBAM-WF at the 15-percent RH setpoint performed the best at staying within ±10 $\mu g/m^3$ of the FEM measurement, with only statistical outliers being greater (fig. 8), even in the higher RH conditions.

- Only the EBAM-V1 at the 45-percent RH setpoint was successful at controlling the internal RH to the setpoint value. All other monitors simply had reduced RH (compared to ambient), indicating that the internal heater was functional but not able to keep up with specifications. This is not entirely unexpected at the more stringent 15-percent RH setpoint, but it was surprising to observe this in the new EBAM-WF at the 45-percent RH setpoint. Schweizer et al. (2016) recommend invalidating data when the internal RH exceeds 40 percent (their RH setpoint). Given that the internal heater in three of the four monitors could not maintain this specification, EBAM users may consider accounting for this in quality assurance/quality control parameters and using a somewhat higher value than the setpoint, such as 65 percent, the point at which studies note that aerosol water content is likely inflating $PM_{2.5}$ concentration values (e.g., this study, Schweizer et al. 2016), as the cutoff to invalidate or flag data.

- Negative $PM_{2.5}$ concentrations occur in a clean atmosphere when the hourly change in concentration is within the noise band of the instrument (Met One Instruments, Inc. 2021). Across the study period, negative hourly $PM_{2.5}$ concentrations occurred 7.1 to 22.2 percent of the time, with the EBAM-V1 producing about one-and-a-half to three times as many negative 1-hour average $PM_{2.5}$ concentrations as the EBAM-WF. Replacing those low-level

concentrations with zero enhanced the linear agreement between the 1-hour EBAM and FEM measurements, yielding higher R^2 values across the dataset. These negative concentrations tended to occur more often when ambient RH was <65 percent, possibly because of evaporation of volatile aerosol species reducing particle concentration. Studies vary in the treatment of negative concentrations, but removing or invalidating the data creates a positive bias (Jiang et al. 2023). The EPA Air Quality System and AirNow support reporting of valid negative concentration data.

- Across most evaluation metrics, the EBAM-WF at the 15-percent RH setpoint was the best performer, although it tended to underestimate $PM_{2.5}$ concentrations.
- A study to investigate settings between 20 and 35 percent could further refine an optimal RH setpoint.

Finally, these are significant and practical lessons learned about EBAM operation and data. We illustrate what to expect with the data, such as variability at low concentrations, occurrence (and treatment) of negative concentrations, performance at 1-hour and 24-hour time averaging scales, and the criticality of reducing the water content in the sample. Although several of these issues have been noted previously, this study demonstrates how they directly influence data quality and usability in operational smoke monitoring. These findings may help land managers and smoke specialists better interpret EBAM measurements to gain the most from their data.

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U.S. Standard Equivalents

When you know:	Multiply by:	To find:
Nanometer (nm)	3.937e−8	Inches
Micrometer (µm)	3.937e−5	Inches
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.47	Acres
Cubic meters (m^3)	35.3	Cubic feet
Liters (L)	0.0353	Cubic feet
Micrograms (µg)	3.5274e−8	Ounces

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Appendix

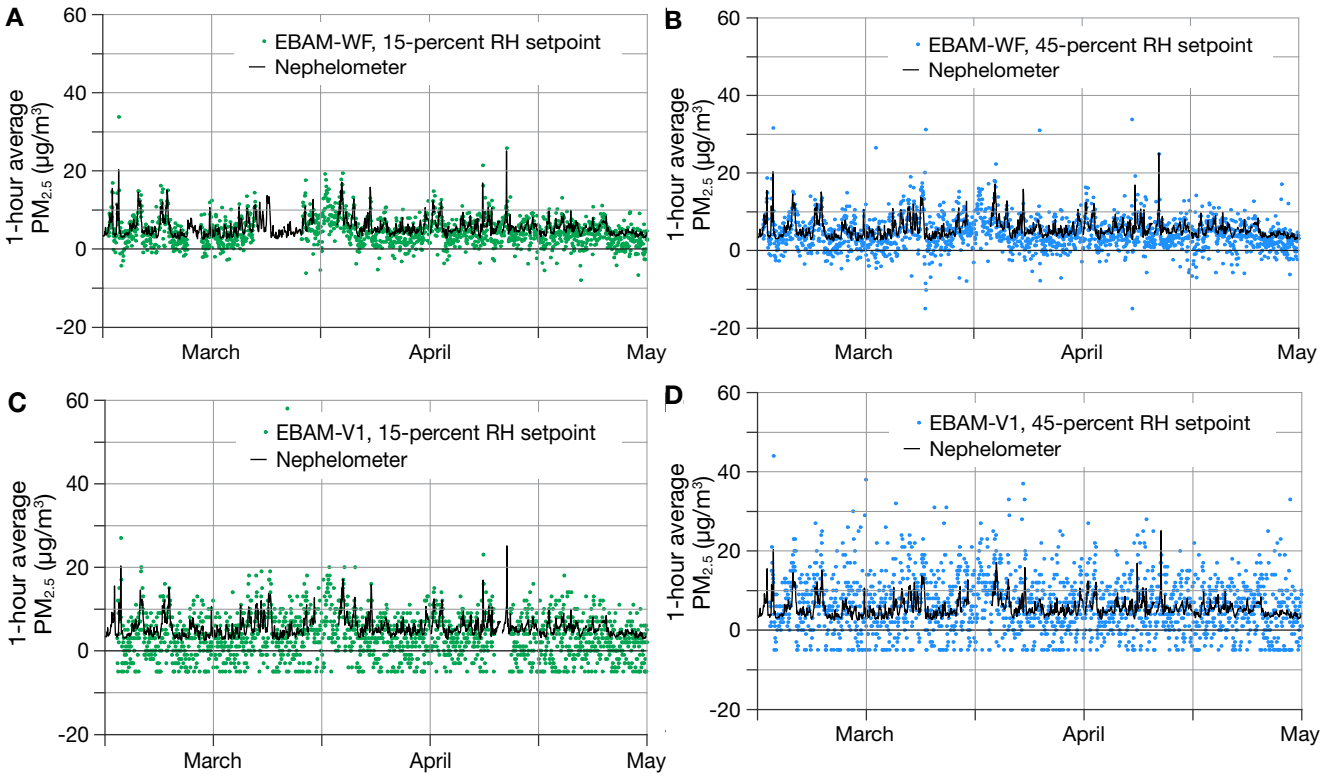


Figure A1—Time series comparing the nephelometer (black) 1-hour average fine particulate matter ($PM_{2.5}$) concentration data with (A) the EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) the EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) the EBAM-V1, 45-percent RH setpoint. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

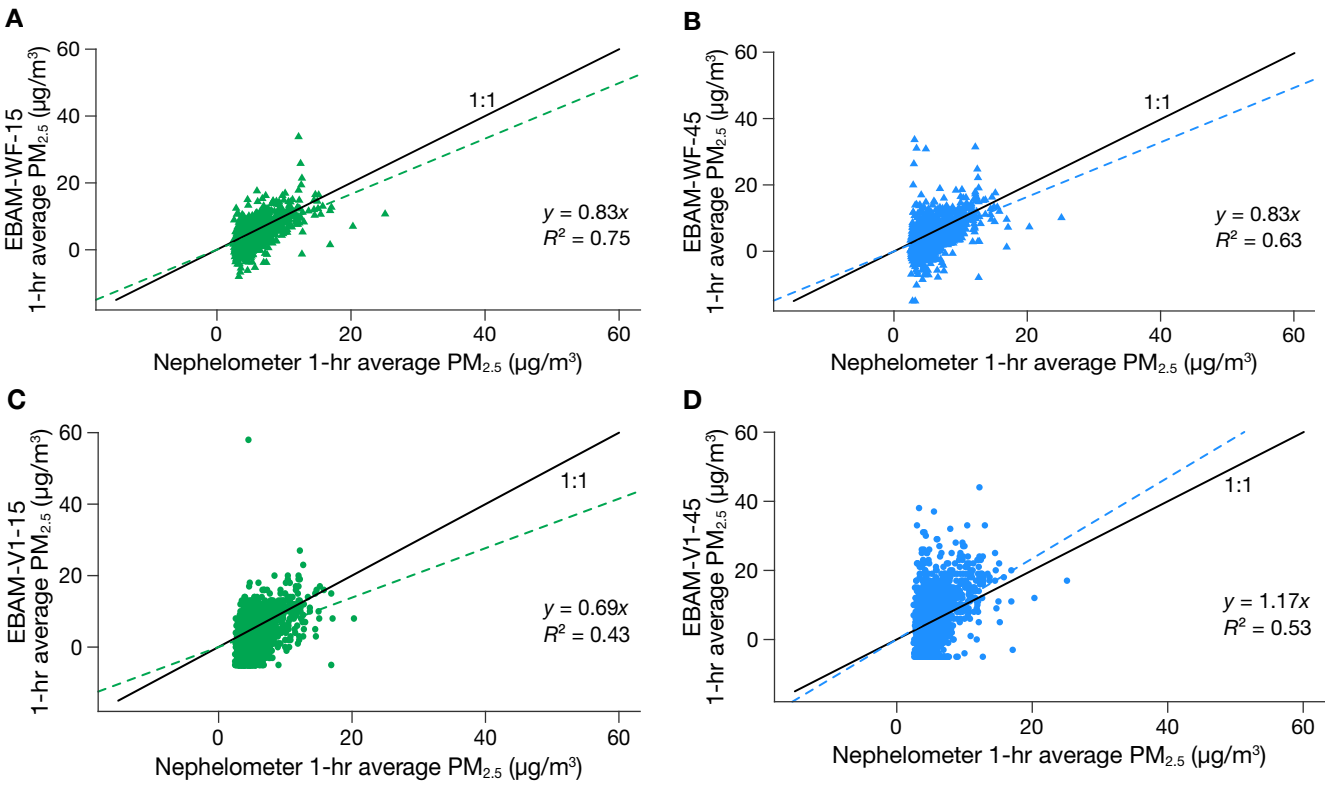


Figure A2—Scatterplots of the nephelometer 1-hour average fine particulate matter ($PM_{2.5}$) concentration data versus (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint data. The solid line is the reference line, and the dashed line is the line of best fit with the equation. Triangles indicate EBAM-WF data, and circles indicate EBAM-V1 data. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

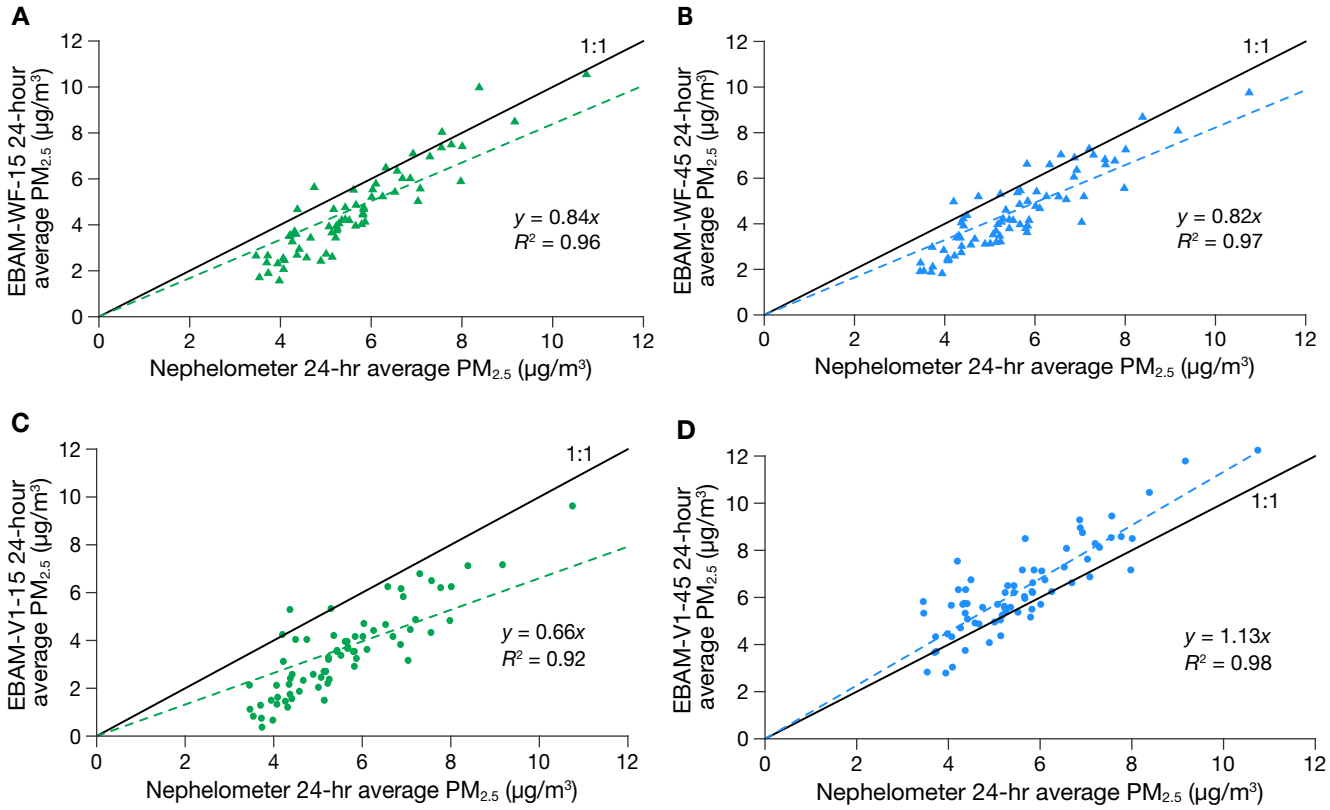


Figure A3—Scatterplots of nephelometer 24-hour average fine particulate matter ($PM_{2.5}$) concentration data versus (A) EBAM-WF, 15-percent relative humidity (RH) setpoint; (B) EBAM-WF, 45-percent RH setpoint; (C) EBAM-V1, 15-percent RH setpoint; and (D) EBAM-V1, 45-percent RH setpoint data. The solid line is the reference line, and the dashed line is the line of best fit with the equation. Triangles indicate EBAM-WF, and circles indicate EBAM-V1. Green represents the 15-percent RH setpoint, and blue represents the 45-percent RH setpoint.

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