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EPA Tools & Resources Webinar: How to evaluate air sensors for smoke monitoring applications

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Overview of Today's Presentation

- Need for air sensors to monitor smoke
- EPA's initial guidance provided by performance targets for $PM_{2.5}$ sensors
- Recommendations for additional evaluations for sensors used for smoke monitoring
- Considerations associated with reference monitor measurements during smoke
- Review of air sensor related resources

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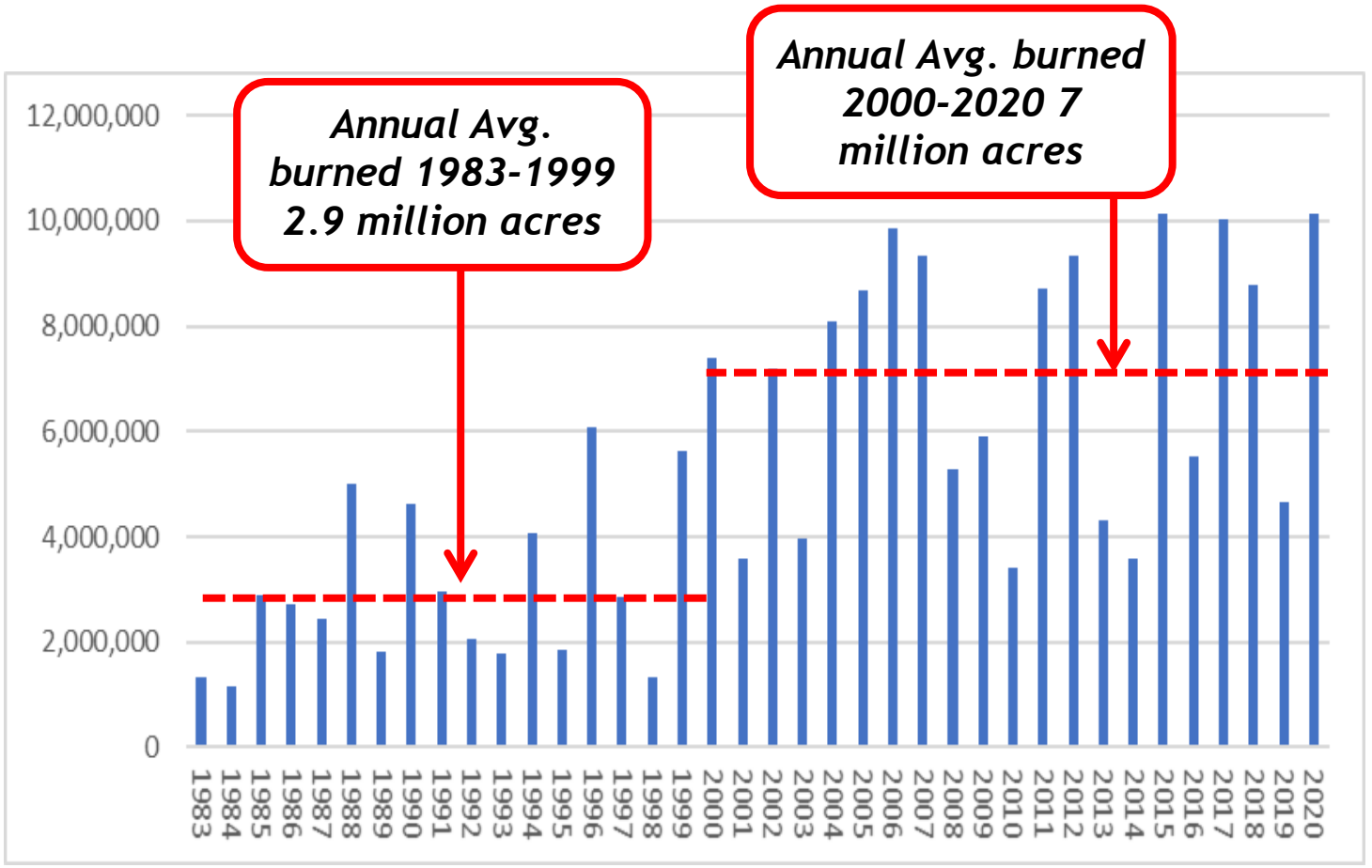
Why do we need sensors for smoke monitoring applications?

Wildfire smoke is increasing

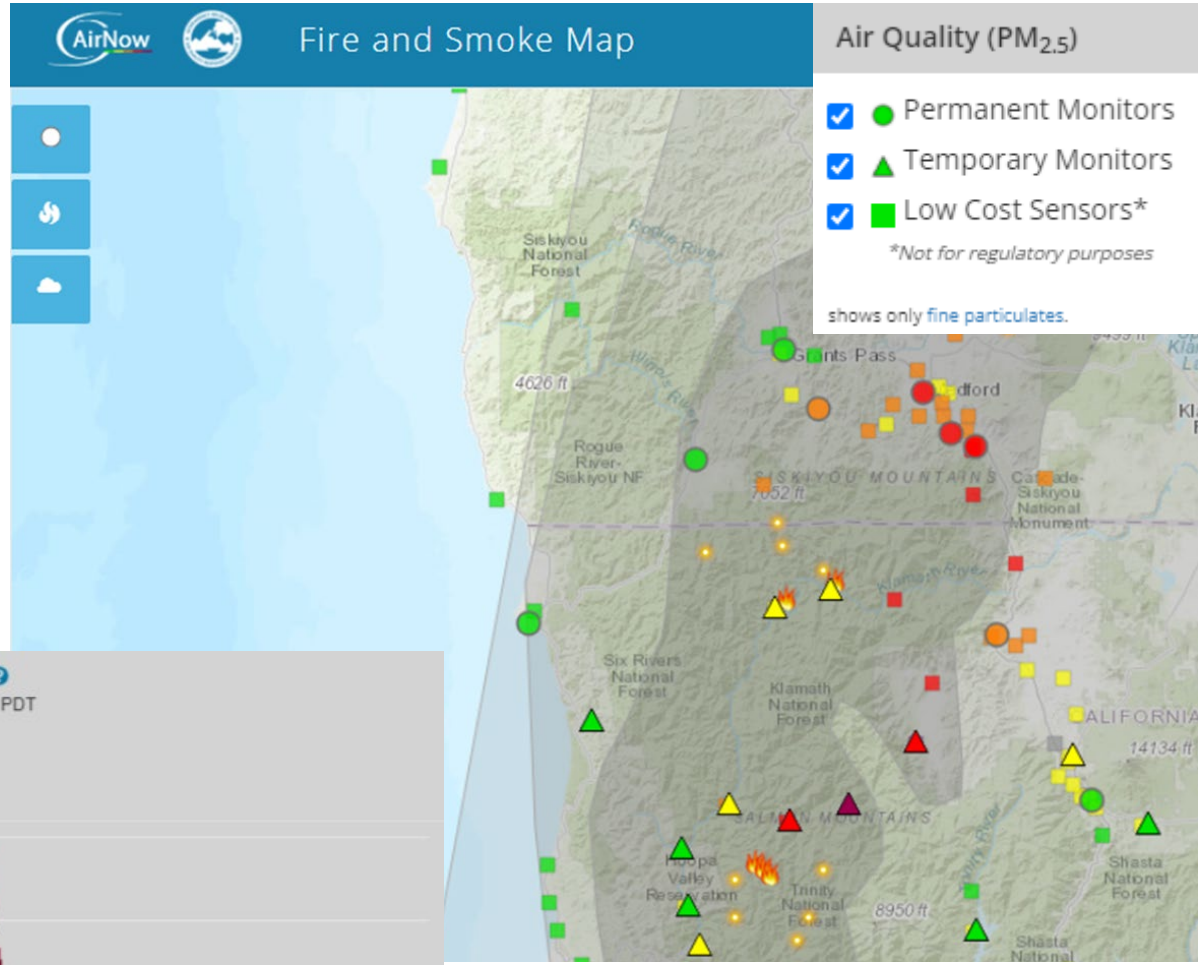
- Wildfires contribute more than 40% of all $PM_{2.5}$ emissions in the US (NEI2017)
- Wildfire smoke has resulted in increasing concentrations in the west, opposite the long-term decreasing anthropogenic $PM_{2.5}$ trends (McClure and Jaffe 2018)
- Estimated economic impact of wildfire attributed $PM_{2.5}$ is immense (Fann et al., 2018)
  - Short-term exposure: $11-20 billion/yr
  - Long-term exposure: $76-130 billion/yr

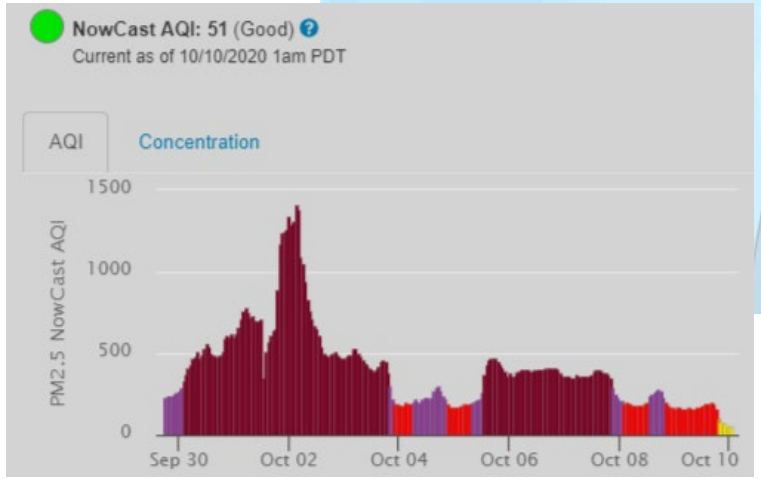


https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html

Smoke concentrations can vary greatly in space and time

- Active fire areas can generate localized high concentration plumes
- Topography can strongly impact spatial variation of smoke concentrations
- Wind shifts and diurnal flows can cause rapid concentration changes

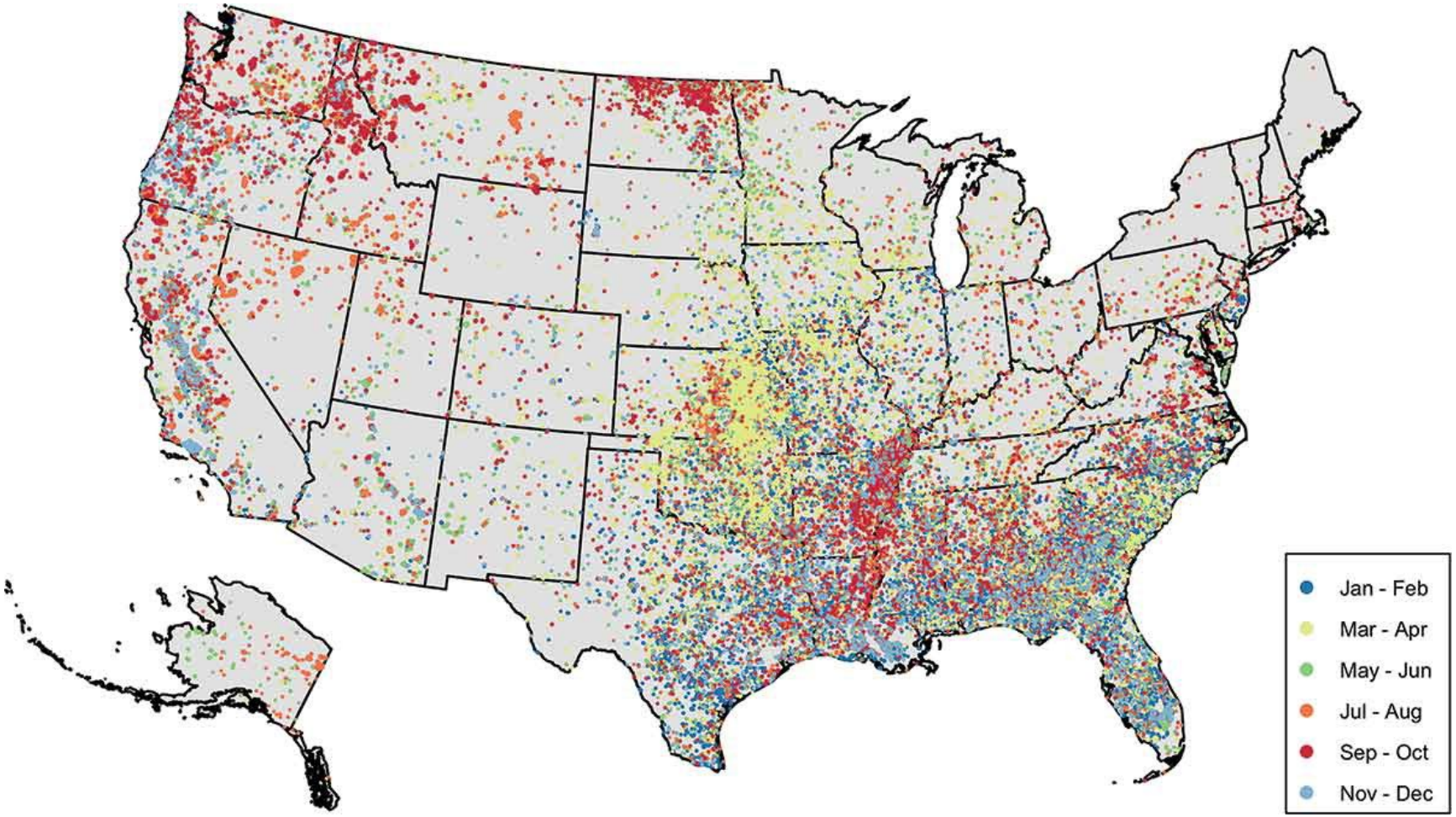




Sensors allow for *more* measurements, often at higher time resolution, than the ambient monitoring network → *more* timely and localized public health information

Smoke impacts vary by region and by season

- Wildland fires occur across the US
- Some regions have seasonal fires that differ from wildfire conditions
  - Spring grassland fires in the midwest
  - Winter pile burns in the west
  - Winter prescribed forest fires in the southeast
  - Fall agricultural residue burns in the south
- Vegetation varies across the country and may impact $PM_{2.5}$ characteristics



Progression of fires throughout the year using 2017 MODIS hotspot fire detections.
Jaffe et al. 2020 https://doi.org/10.1080/10962247.2020.1749731

Other smoke sources also have high spatial and temporal variation

Credit: Brian McCaughey, 2019

- Wood stove use and recreational burning can cause localized high $PM_{2.5}$ concentrations in the wintertime (NEI2017)
- Inversions that frequently setup in mountain valleys can further concentrate emissions and result in stratified layers of $PM_{2.5}$ at different elevations (Chen et al. 2012)

Outdoor worker protection programs need exposure data *where people work*

- Overview of information on health impacts and outdoor worker protection methods
- Links to State Programs

https://www.cdc.gov/niosh/topics/firefighting/wffsmoke.html

Some states enacted outdoor worker wildfire smoke protection programs

California

California Code of Regulations, Title 8, Section 5141.1

https://www.dir.ca.gov/title8/5141_1.html

Oregon

Oregon Temporary Rule (8/19/2021 – 2/4/2022)

https://osha.oregon.gov/OSHARules/adopted/2021/ao9-2021-letter-temp-wildfire-smoke.pdf

Washington

Washington Temporary Rule (7/16/2021 – 11/13/2021)

https://lni.wa.gov/rulemaking-activity/AO21-26/2126CR103EAdoption.pdf

Common features of these programs

1. Threshold Air Quality Index or $PM_{2.5}$ values for exposure reduction actions
2. Some workplaces are exempt (emergency response)
3. Use of direct read $PM_{2.5}$ monitors for ambient measurements
4. Stipulations for instrument accuracy and operation

"…information on the possible error of the monitor from the manufacturer or other published literature…"

Regulatory smoke exposure thresholds

State	Threshold Value (or $PM_{2.5}$ concentration)	Action
CA	AQI ≥ 150 (150.4 µg/m³)	• Implement engineering and administrative controls • Provide respirators for voluntary use
	AQI ≥ 500 (**500.4** µg/m³)	• Require respirator use
OR	AQI ≥ 101 (35.5 µg/m³)	• Develop training and communication program • Provide respirators for voluntary use
	AQI ≥ 201 (150.5 µg/m³)	• Implement engineering and administrative controls • Require respirator use
	AQI ≥ 501 (**500.4** µg/m³)	• Require respirator use • Implement respiratory protection program
WA	20.5 µg/m³	• Develop information and hazard communication plan • Encourage use of exposure controls
	55.5 µg/m³	• Implement engineering and administrative controls • Provide respirators for voluntary use at no cost

Engineering controls
- work in buildings or vehicles with filtered air

Administrative controls
- relocate work
- change schedule or intensity
- increase breaks

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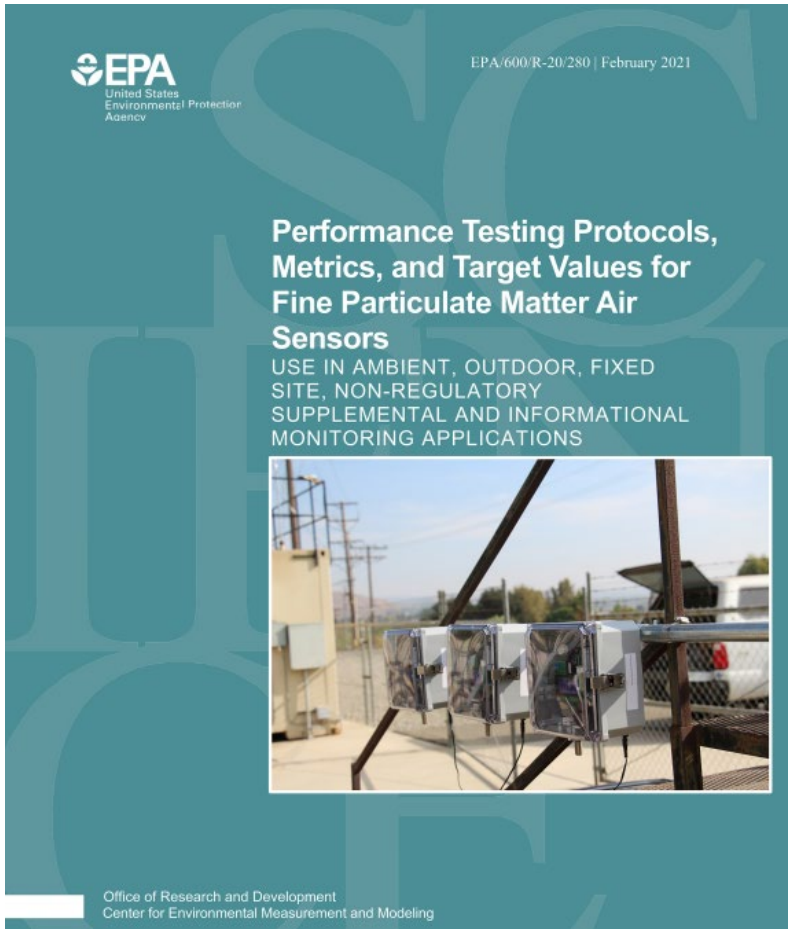
Performance Testing Protocols, Metrics, and Target Values for $PM_{2.5}$ Air Sensors

Intention and Scope of EPA's Performance Testing Protocols, Metrics, and Targets



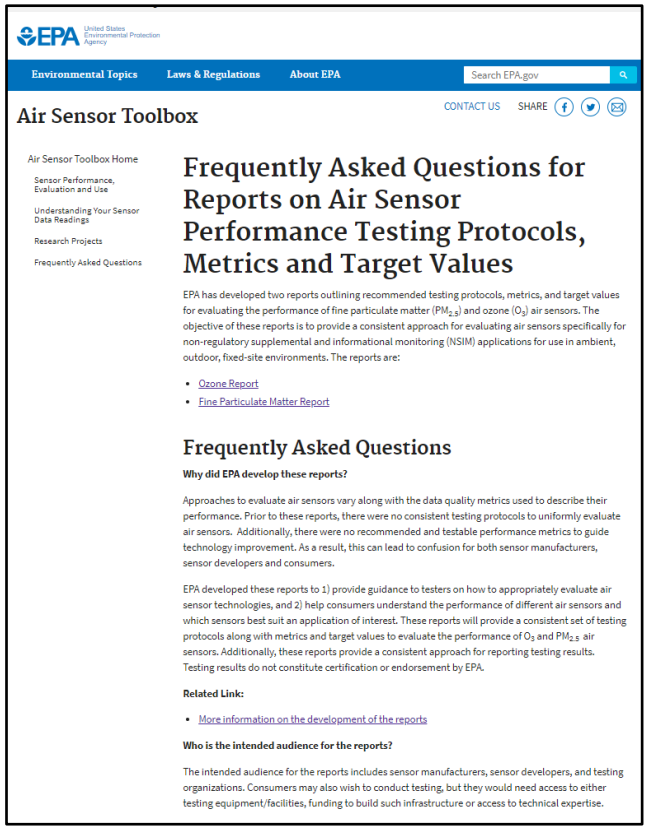
- **Intention:** The goal to provide a consistent approach for performance testing **and** reporting results to help users identify sensors that meet their needs
- **Scope**
  - Focus on non-regulatory, supplemental and informational monitoring applications (NSIM)
  - Ambient, outdoor, fixed site environments

Smoke monitoring fits the NSIM application space. Most monitoring is for outdoor and fixed site environments BUT, **the concentration range is typically wider** than is typically experienced for ambient monitoring.

Available at: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

Important Notes

- Reports provide **recommendations for evaluating sensor performance**
- Conducting the testing protocols is **entirely voluntary**
- Conducting the testing protocols **does not** constitute certification or endorsement by the US EPA
- **EPA does not provide funding** to conduct the testing protocols
- EPA recommends that **testers share results on their respective websites**



For these and other Frequently Asked Questions on the reports visit: https://www.epa.gov/air-sensor-toolbox/frequently-asked-questions-reports-air-sensor-performance-testing-protocols

Overview of Testing Protocols

Base Testing (Field)	Enhanced Testing (Laboratory)

• Evaluate sensors in the field – ambient, outdoor, fixed site environment
• Purpose
  • Obtain information on sensor performance in real-world, ambient, outdoor conditions
  • Provides consumers information on how they might expect a sensor to perform in similar conditions
	• Evaluate sensors in a controlled laboratory exposure chamber
	• Purpose
	  • Evaluate sensors over a wider range of conditions that may be more difficult to capture in the field
	  • Characterize certain performance parameters that are difficult to test in the field

Field measurements are most important for wildfire smoke because it's challenging to generate realistic PM in the laboratory environment.

Controlled lab tests allow for better understanding of the PM characteristics or ambient conditions that may impact sensor performance in the field measurements.

Overview of the Base Testing Protocol

- **Field deployment of 3 or more identical air sensors** with collocated Federal Reference Method or Federal Equivalent Method (FRM/FEM) monitors
- Testers have different **options for field sites**
  - Set up their own FRM/FEM monitors at an outdoor, ambient site
  - Establish collaborations with state/tribal/local agencies who manage existing air quality monitoring sites
- Collect measurements for **at least 30 consecutive days**
- **2 field deployments** recommended to evaluate sensors under different pollutant concentrations, ambient temperatures (T), and relative humidity (RH) levels

Smoke monitoring applications will benefit from additional test site selection guidance

Recommended Test Site Selection Criteria

Base Testing	$PM_{2.5}$
Test Sites	2 deployments at 2 different sites
Season and Pollutant Level	2 different climate regions for each site (goal 1-day, 24-hour average $PM_{2.5}$ level of ≥ 25 $\mu g/m^3$)

Recommended Target Values

- **Target values are based on 24-hour averages and are only recommended for Base Testing**

Performance Metric		O_3 Target Value	$PM_{2.5}$ Target Value
Precision	Standard Deviation (SD) **OR** Coefficient of Variation (CV)	≤ 5 ppbv ≤ 30%	≤ 5 μg/m^3 ≤ 30%
Bias	Slope	1.0 ± 0.2	1.0 ± 0.35
	Intercept (b)	-5 ≤ b ≤ 5 ppbv	-5 ≤ b ≤ 5 μg/m^3
Linearity	Coefficient of Determination (R^2)	≥ 0.80	≥ 0.70
Error	Root Mean Square Error (RMSE)	≤ 5 ppbv	RMSE ≤ 7 μg/m^3 **or** NRMSE ≤ 30%

NRMSE = normalized root mean square error

- Target values considered **reasonably achievable (at this time)** and **adequate for many NSIM applications** (based on literature)
- Exploratory graphs also recommended to understand potential impacts of meteorological parameters (T, RH, dew point)
- **No target values recommended for enhanced testing protocols**

Smoke conditions change rapidly requiring higher time resolution data (e.g., 1-hr avg)

Guidance for Wildfire Smoke Applications

- The Performance Testing Protocols, Metrics, and Target Values Documents **makes provisions for the need for future guidance** for specific applications.

Wildfire smoke monitoring was called out specifically:

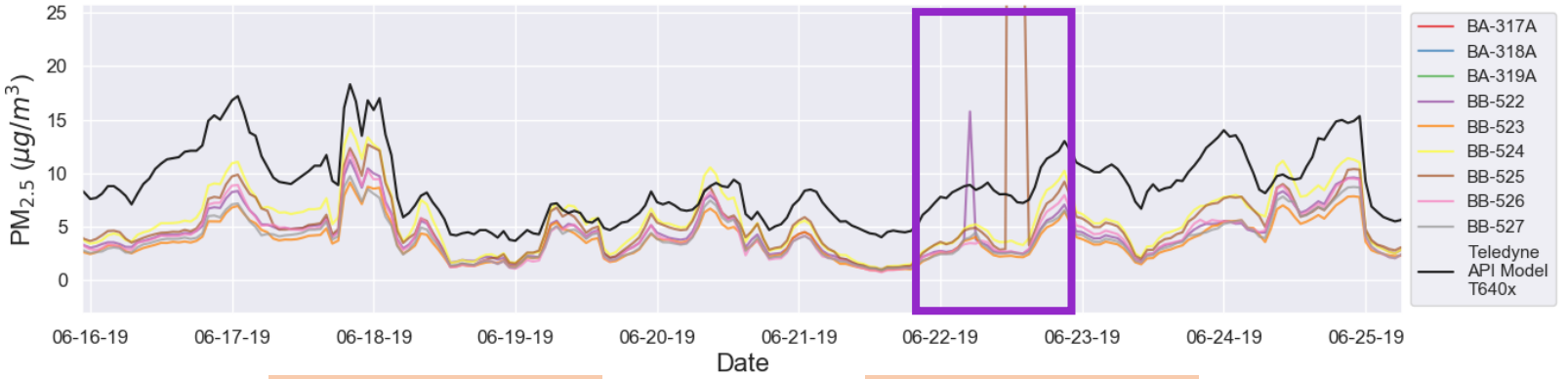
> *"For NSIM applications where high $PM_{2.5}$ concentrations are expected (e.g., wildfire smoke applications), it is recommended that testers conduct base testing in more than two locations and include sites impacted by wildfire smoke and higher $PM_{2.5}$ concentrations."*

Additional evaluations for smoke sensors

Evaluate at hour averages

- Higher time resolution data is needed during smoke events
- Precision at hourly averages is important
  - Enables comparison across the network

Example: 1-hour Averaged Aeroqual AQY $PM_{2.5}$



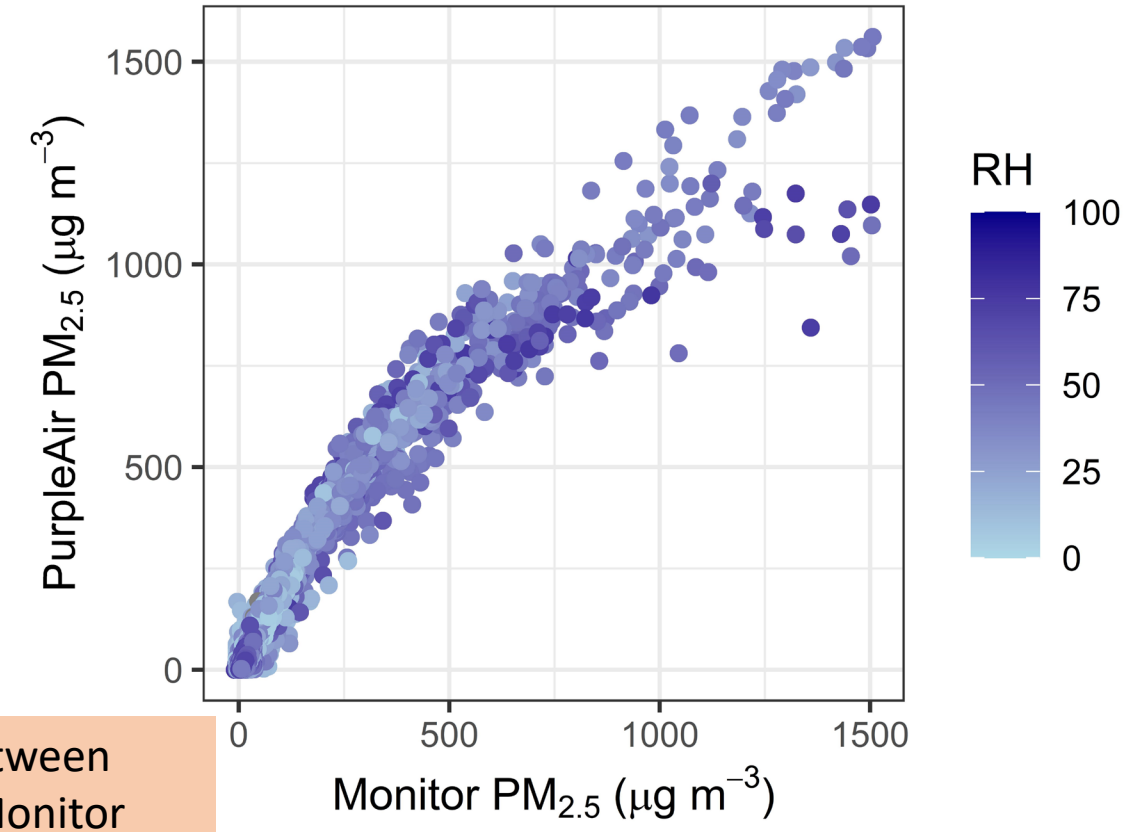
Sensors are typically within a few µg/m³

Occasional issues occur

Corrections may be needed to improve performance

- Sensors may perform differently at different concentration levels

Collocations at multiple sites with multiple FEM and temporary monitor types across the U.S.



Nonlinearity between PurpleAir and Monitor $PM_{2.5}$ ~>250 µg/m^3

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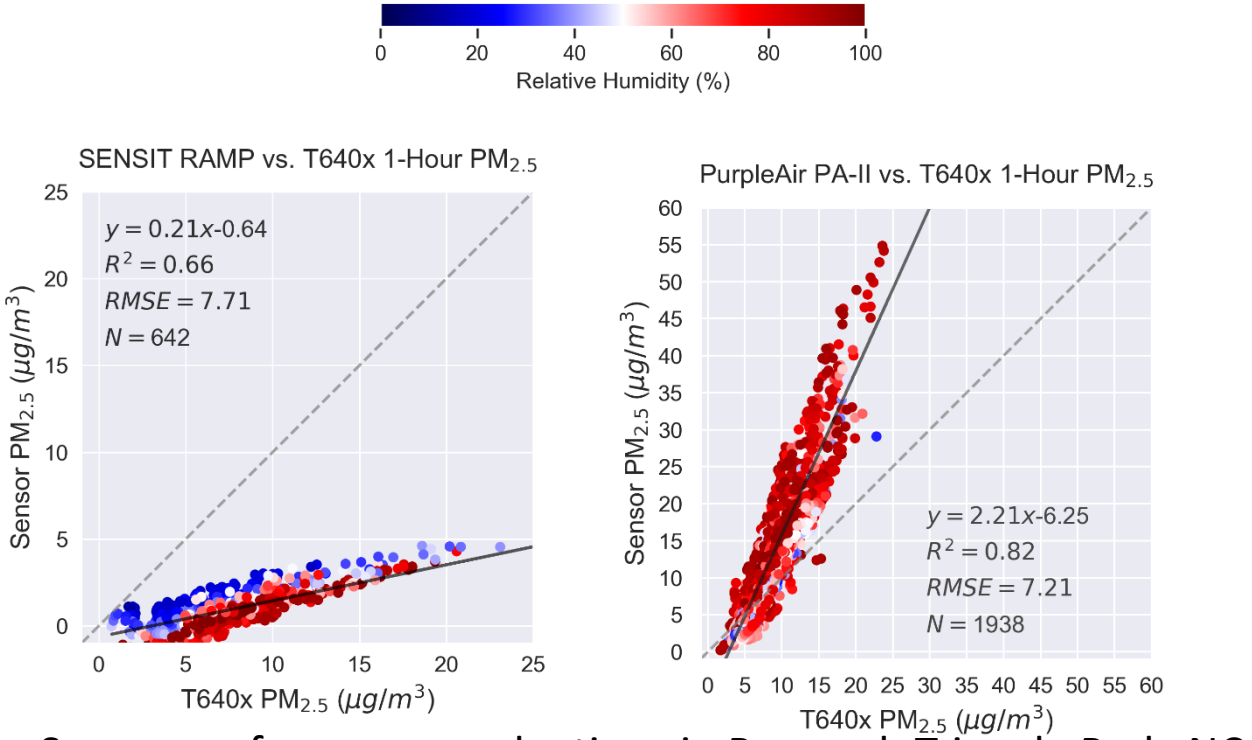
Corrections may be needed to improve performance

- Sensors may perform differently at different concentration levels
- Sensors with the same internal sensor may perform differently



Sensor performance evaluations in Research Triangle Park, NC

RAMP and PurpleAir both contain Plantower PMS5003

- Show different performance
- Likely due to different internal correction algorithms
- May vary with firmware version

Evaluate over expanded concentration range

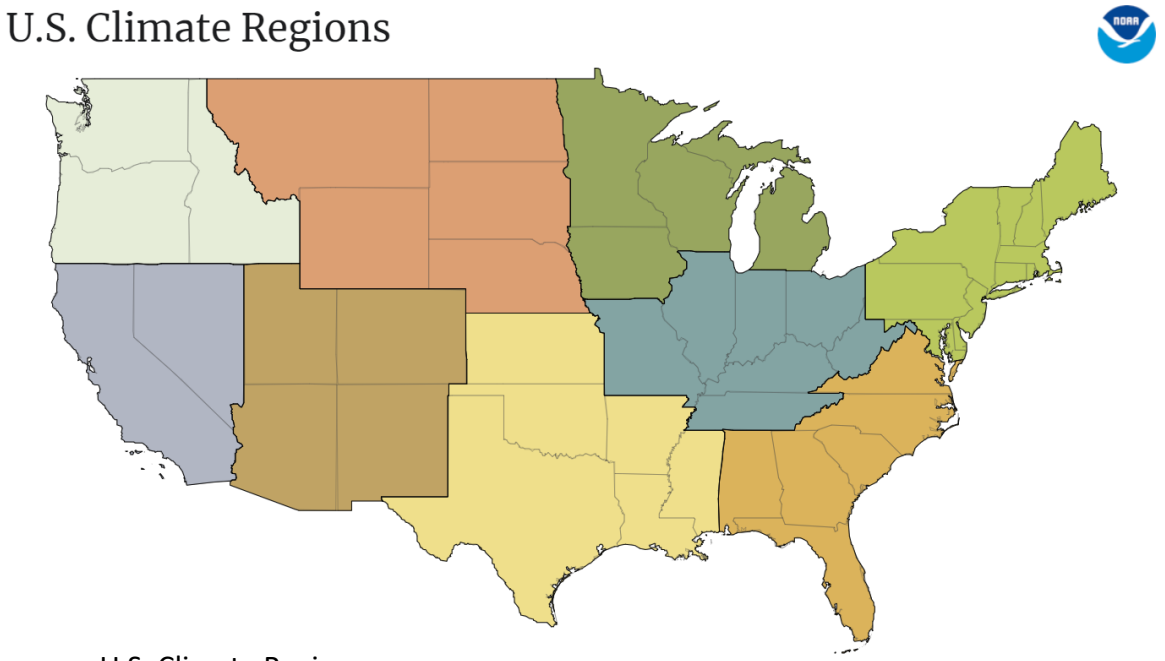
- Consider evaluation at each Air Quality Index (AQI) category or AQI breakpoint
- Evaluate at relevant occupational exposure limits
  - e.g., Cal/OSHA: 500 µg/m^3

Daily AQI Color	Levels of Concern	Values of Index
Green	Good	0 to 50
Yellow	Moderate	51 to 100
Orange	Unhealthy for Sensitive Groups	101 to 150
Red	Unhealthy	151 to 200
Purple	Very Unhealthy	201 to 300
Maroon	Hazardous	301 and higher

(Source: https://www.airnow.gov/aqi/aqi-basics/)

Evaluate in more locations seasonally

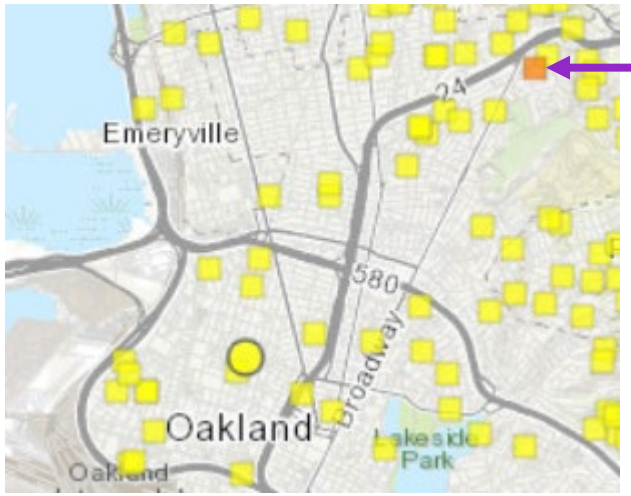
- Temperature, Relative Humidity, and local particle properties may influence sensor performance
- Need collocations in area where the sensors are used
  - Scale with the size of the network
    - Across climate regions for a national network
    - Across a region for a regional network
    - Across a city for a local network
- Collocations seasonal at a minimum
  - Longer collocations (>1 year) may help understand drift and network aging



U.S. Climate Regions
(source: https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions)

Quality control checks are essential

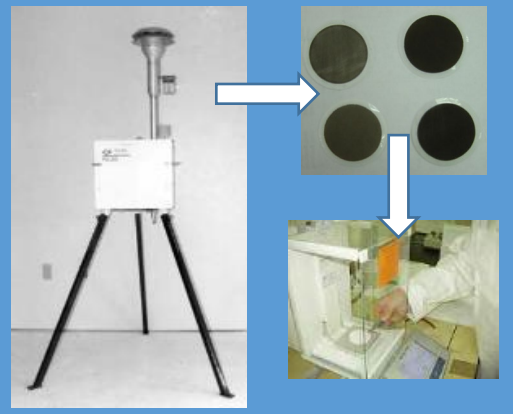
- Sensor failure may not be obvious (e.g., no longer reporting)
- Sensors exposed to high smoke concentrations may fail faster
- Frequently check data for failure modes
  - Repeated concentration values or zeros
  - Baseline shifts
  - Unreasonable values
- Collocate again if possible
- Compare to nearby sensors or monitors if available



Local source?
Sensor issue?

(Source: fire.airnow.gov 1/25/2022)

Consider the monitor type used for comparison



The Federal Reference Method (FRM) is the gold standard for accuracy, but samples are integrated over 24-hours and there is a lag-time due to laboratory analysis.

The Federal Equivalent Methods (FEMs) provide automated data at higher time resolution (generally every hour). They are used across the official air monitoring network and were designated by comparison to FRMs under typical conditions (not smoke).

Temporary monitors also provide hourly data, were tested for performance under high concentrations, and are used extensively by government organizations for supplemental monitoring during wildland fire smoke events.

Higher time resolution comparisons provided by collocation with FEMs or temporary monitors are recommended for smoke evaluations.

Consider all FRM/FEM data available during collocation

- Many continuous Federal Equivalent Methods are not evaluated under extreme smoke conditions
  - Bias or flow rate issues have been observed at high concentrations
- Ensure relative humidity and other quality control parameters are in range
- Collocate with multiple types of monitor so that not overly impacted by a single monitor
- Use comparability assessments with Federal Reference Methods (when available)

Smoke Plumes
Photo credit: Ali Kamal

Quality control for monitors

- Smoke monitoring
  - ± 5% for set flow
  - Ambient temperature < 45 °C
  - Internal relative humidity
    - < 50% for E-BAM
    - < 45% for BAM
  - Concentration < 5 mg/m^3
- Air Quality System (AQS) monitoring
  - FEM and FRM measurements
  - Quality assurance and control are the responsibility of state/local/tribal air monitoring agency
  - Follow specific guidelines: https://www3.epa.gov/ttnamti1/files/ambient/pm25/qa/m212.pdf

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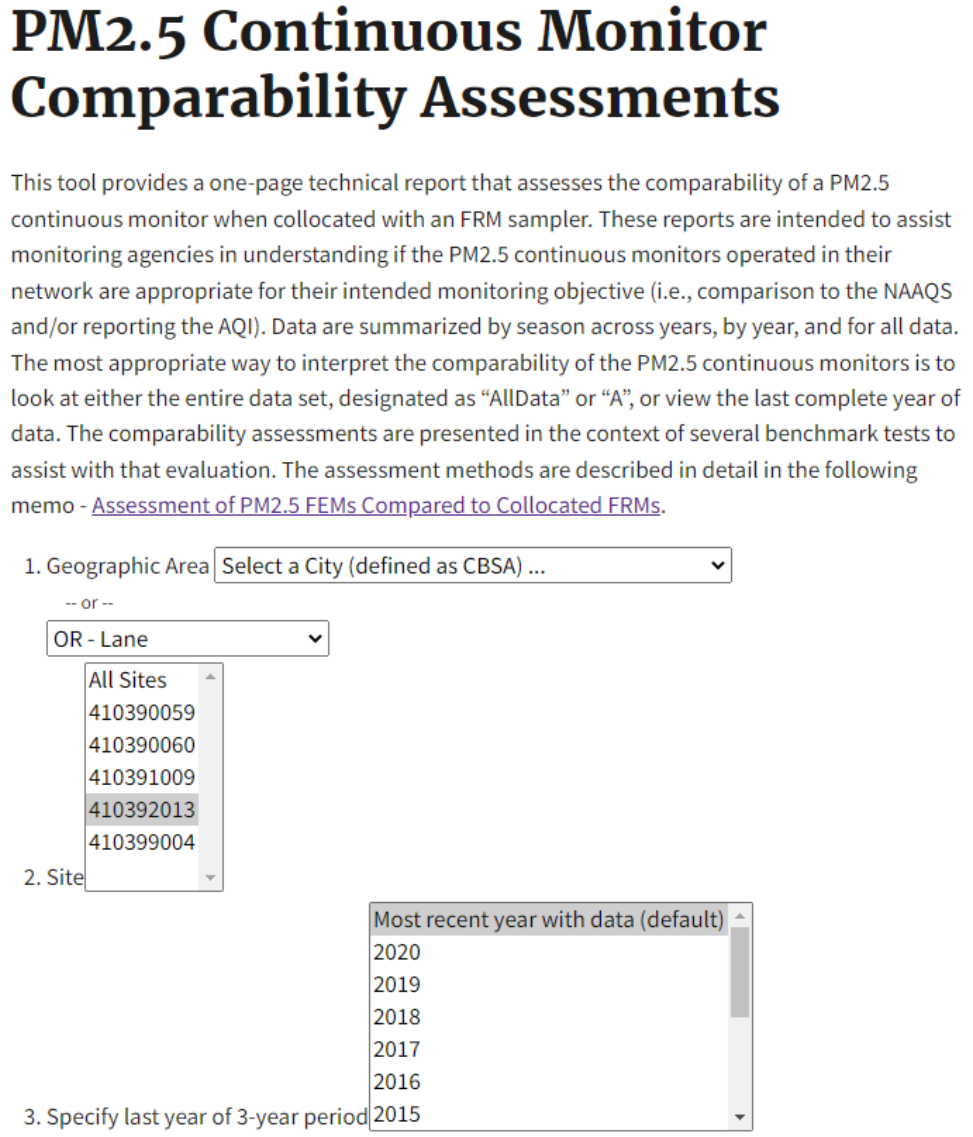
An Example: How to use the comparability assessment tool

Use comparability assessments with Federal Reference Methods

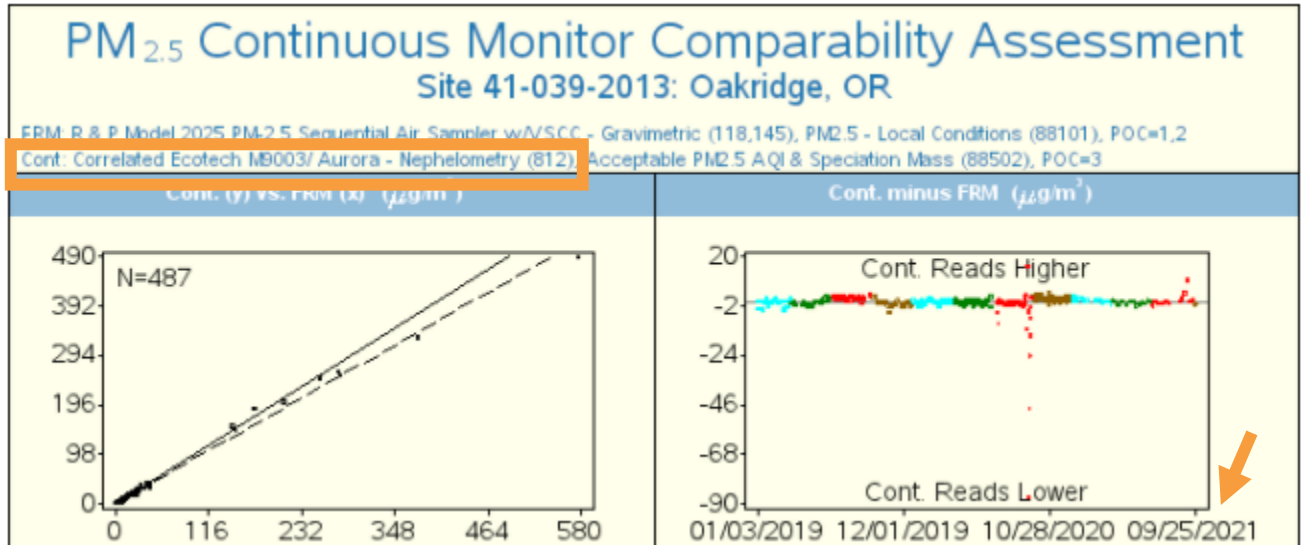
1. Select the site

Link: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments



Use comparability assessments with Federal Reference Methods

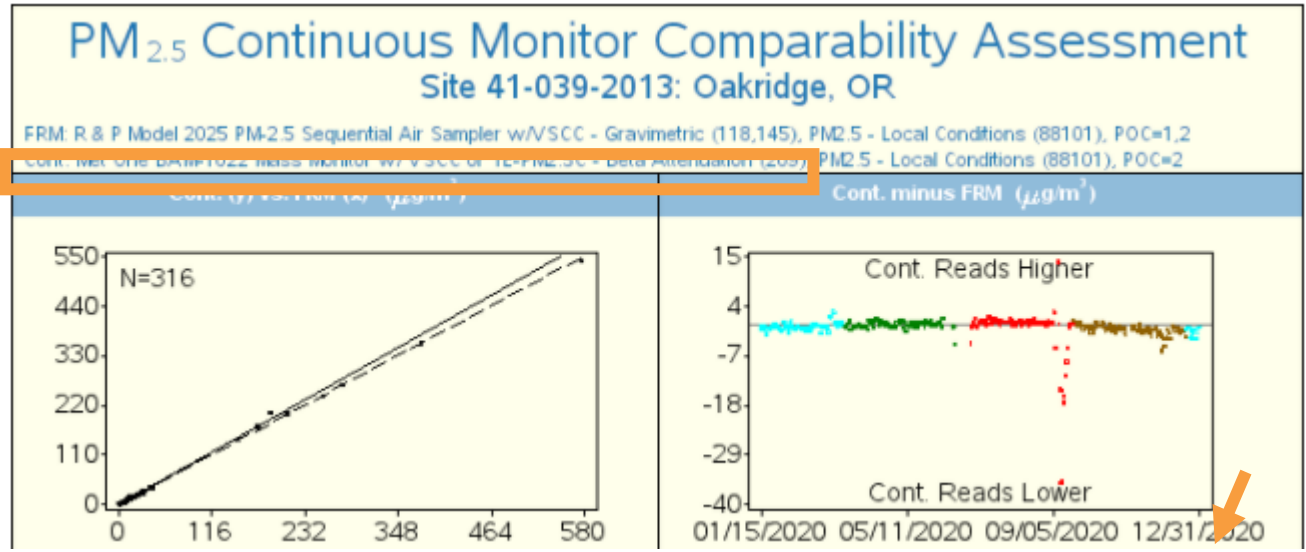
2. Select the monitor of interest
   - Note: Not all monitors or years may be available



We will use the **BAM-1022** as an example on the following slides

Note: the BAM-1022 samples for 60 min/hr while the BAM-1020 samples for 42 min/hr

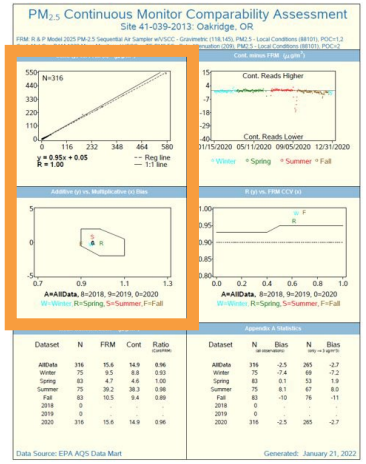
- If concentrations are variable the BAM-1022 provides a better temporal coverage

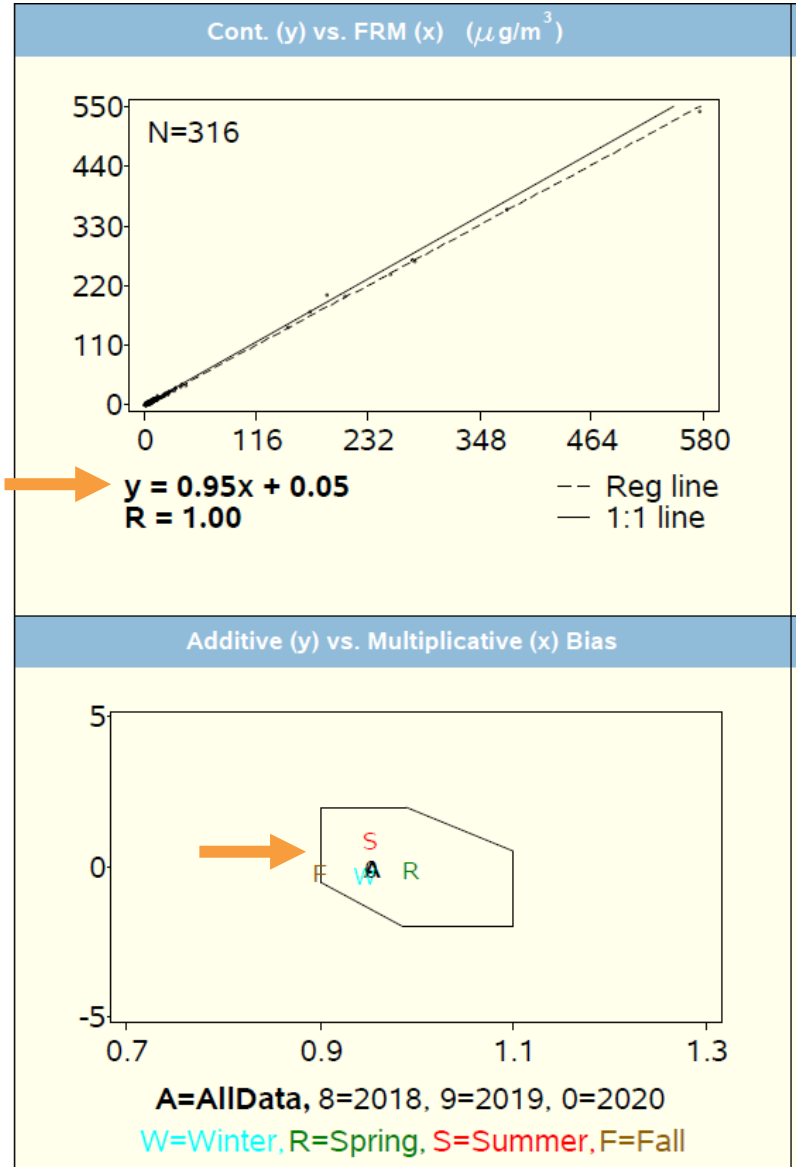


Source: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments site: 41-039-2013

Use comparability assessments with Federal Reference Methods

3. Consider bias
   - Ideally:
     - Within target polygon
     - Multiplicative bias (Slope) = 0.9 to 1.1
     - Additive bias (Intercept)= -2 to 2





Source: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments site: 41-039-2013 BAM-1022

Recommendations Summary

- Evaluate 1-hr averages
- Corrections may be needed to improve performance
- Precision is important
- Evaluate up to 500 µg/m^3 important for respirator use
- Need evaluations/collocations in areas where the sensors are used
- Collocate every season or more frequently if possible
- Federal Equivalent Methods and temporary smoke monitors may be used as “reference monitors” but they may also need additional quality control

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Air Sensor Resources

EPA's Air Sensor Toolbox Webpage

Webpage provides a wealth of resources on air sensors

https://www.epa.gov/air-sensor-toolbox

Select resources available in Spanish: https://espanol.epa.gov/espanol/caja-de-herramientas-de-sensores-de-aire

Sensor Performance, Evaluation and Use

- Sensor Evaluation Results
- Standard Operating Procedures for Sensors
- Sensor Collocation Guide
- Sensor Performance Targets and Test Protocols
- Air Sensor Guidebook
- A Guide to Siting and Installing Air Sensors

Understanding Your Sensor Data Readings

- Technical Approaches for the Sensor Data on the AirNow Fire and Smoke Map
- Videos on Air Sensor Measurement, Data Quality and Interpretation
- RETIGO: Visualize Your Field Data
- Sensor Collocation Macro Analysis Tool
- Air Quality Information Exchange Workgroup Meeting Summaries

AIR SENSOR TOOLBOX

GET AIR SENSOR NEWS BY EMAIL

sign up

Approx. 8-10 emails annually.

Research Projects

- Overview of Current Research
- Collaborative Agreements
- Grants
- Reports and Publications
- Past Projects

Additional Resources

- Frequently Asked Questions
- Air Sensor Loan Programs
- Newsletter Articles, Fact Sheets and Infographics
- Educational Resources
- Conferences, Workshops, and Webinars
- Sensor Evaluations by Other Organizations
- Quality Assurance Handbook and Guidance Documents for Citizen Science Projects

EPA's Performance Targets Reports and Siting/Installation Guidance

EPA Air Sensor Performance Testing Protocols, Metrics, and Targets

- Recommendations on how to evaluate, report, and assess the performance of air sensors for non-regulatory, supplemental and informational monitoring (NSIM) applications
- Available at: https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols

EPA Guide to Siting and Installing Air Sensors

- Recommendations on how to site air sensors outdoors and indoors and how to document the supporting information
- Available at: https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors

Additional Air Sensor Toolbox Links and Publications

- Performance evaluations done by EPA and other organizations
- Technical Details About Air Sensor Data on the Fire & Smoke Map
- Air Sensor Research Overview
- Conferences, Workshops, and Webinars
- Reports and Publications
- Air Sensor Guidebook
- Collocation Guide
- Educational resources

Related Research Publications

Holder, A., A. Mebust, L. Maghran, M. McGown, K. Steward, D. Vallano, R. Elleman, and K. Baker, 2020. 'Field Evaluation of Low-Cost Particulate Matter Sensors for Measuring Wildfire Smoke', Sensors. https://doi.org/10.3390/s20174796

Barkjohn, K, B. Gantt, A. Clements, 2021 'Development of a United States Wide Correction for $PM_{2.5}$ Data Collected with the PurpleAir Sensor', Atmospheric Measurement Techniques. https://doi.org/10.5194/amt-2020-413

Barkjohn, K, A. Holder, S. Frederick, A. Clements, (in preparation) 'PurpleAir $PM_{2.5}$ US Correction and Performance During Smoke Events'. In preparation.

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Questions?

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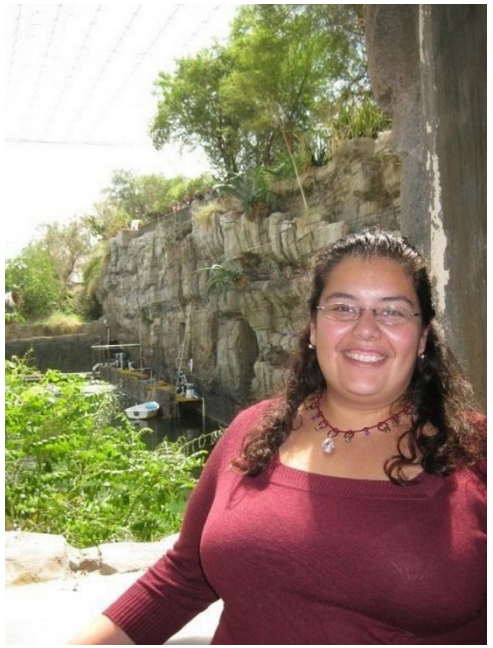

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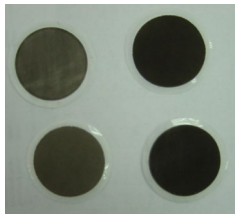
Additional Slides

Federal Reference Method



The Federal Reference Method (FRM) for $PM_{2.5}$, to which other instruments are compared, measures in this way:

Particles are precisely size-selected based on their inertial properties (how they move in an air flow)

Particles deposit to a filter at a known and controlled air flow rate (e.g., 16.7 lpm)

Filters are conditioned and weighed at a laboratory facility

This approach is the gold standard for accuracy, but slow in the data duration **(24 hr samples),** sometimes discontinuous (e.g., 1 in 3 days), and has a lag-time due to laboratory analysis.

Higher time resolution comparisons are recommended for smoke evaluations

Federal Equivalent Methods

To provide timely and automated $PM_{2.5}$ data, Federal Equivalent Methods (FEMs) are used across the official U.S. air monitoring network.

The most common method:

1. Particles are size-selected with a cyclone on the inlet
2. Particles deposit to a filter tape inside the instrument
3. Particle mass is measured by beta-attenuation
4. Outputs hourly data

MetOne BAM-1020

The second most common method:

1. Particles are size-selected with a cyclone on the inlet
2. Particles pass through a polychromatic light – the scattered light from the particles is converted to a particle mass concentration through a proprietary algorithm
3. Outputs hourly data (faster time resolution possible)

Teledyne API T640 / T640x

The FEM designation process requires field tests comparing to FRMs under typical USA concentrations (not wildfire smoke events)

Reference for FEM designation process: 40 CFR Part 53

Comparison Measurements: Temporary Smoke Monitors

Two monitor types – E-BAMS and E-Samplers – are used extensively by government organizations for supplemental monitoring during wildland fire smoke events.

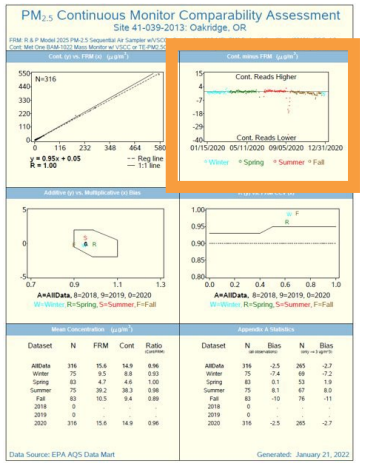
Measurement principle:
E-BAM: beta-attenuation by particles deposited to a filter
E-Sampler: optical measurement of particles in an air stream

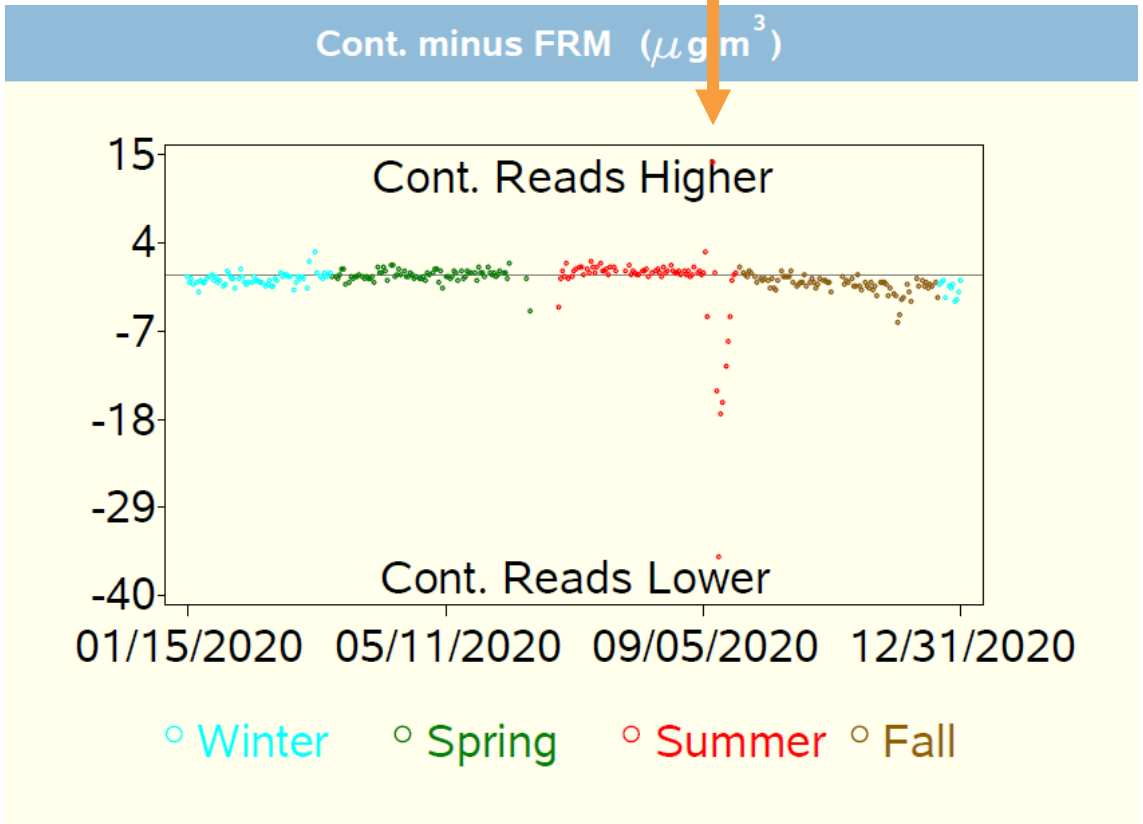
General traits:
- Size selection inlet
- Long history of use worldwide
- Rugged design to support outdoor sampling in all weather conditions
- Well-controlled flow rate
- Self-diagnostic capability

Use comparability assessments with Federal Reference Methods

4. Consider any time periods where errors may have occurred

- Due to high concentration?
  - Low % error?
- Due to error?
  - Exclude time period from collocation





This monitor experienced high concentration smoke in September

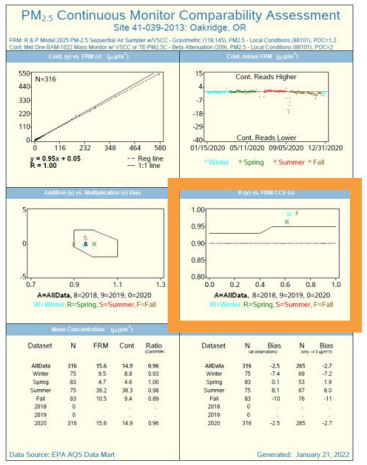
Source: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments site: 41-039-2013 BAM-1022

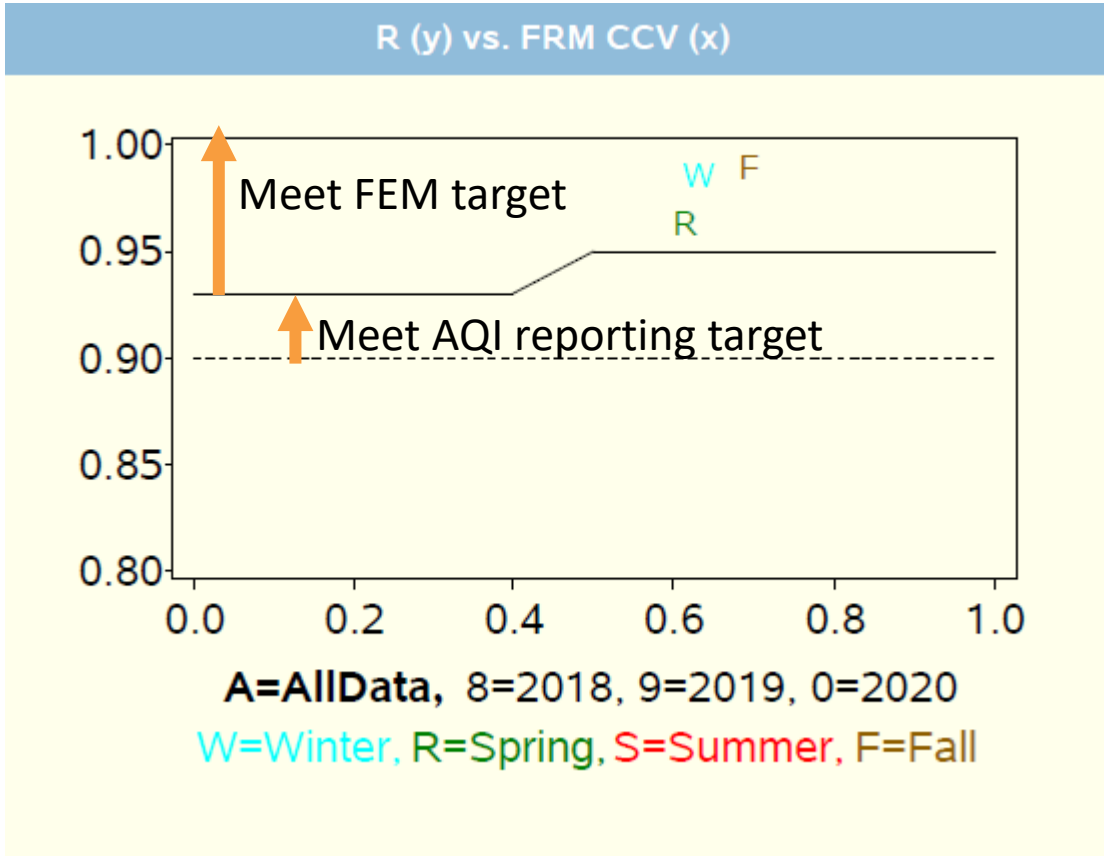
Use comparability assessments with Federal Reference Methods

5. Consider correlation –R

Consider concentration coefficient of variation (CCV)

- Describes spread of sample population



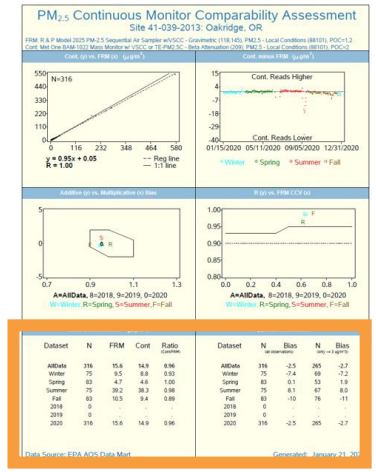


Source: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments site: 41-039-2013 BAM-1022

Use comparability assessments with Federal Reference Methods

6. Consider tabular statistics as needed

Mean Concentration ($\mu g/m^3$)					Appendix A Statistics				
Dataset	N	FRM	Cont	Ratio (Cont/FRM)	Dataset	N (all observations)	Bias	N (only >= 3 ug/m^3)	Bias
AllData	**316**	**15.6**	**14.9**	**0.96**	**AllData**	**316**	**-2.5**	**265**	**-2.7**
Winter	75	9.5	8.8	0.93	Winter	75	-7.4	69	-7.2
Spring	83	4.7	4.6	1.00	Spring	83	0.1	53	1.9
Summer	75	39.2	38.3	0.98	Summer	75	8.1	67	8.0
Fall	83	10.5	9.4	0.89	Fall	83	-10	76	-11
2018	0	.	.	.	2018	0	.	.	.
2019	0	.	.	.	2019	0	.	.	.
2020	316	15.6	14.9	0.96	2020	316	-2.5	265	-2.7



Source: https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments site: 41-039-2013 BAM-1022