Development and Performance Validation of U.S.-Wide Correction Equation for PurpleAir Sensor Data

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AirNow Sensor Data Pilot – Technical Webinar

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Introductions

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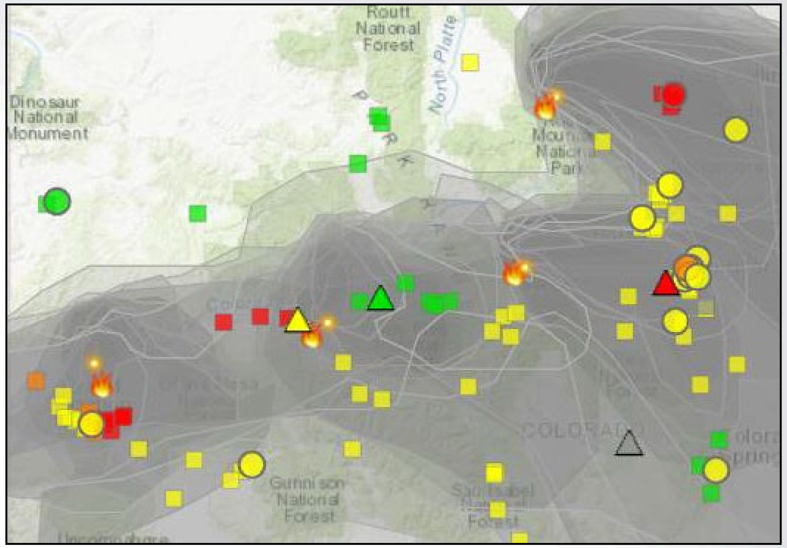
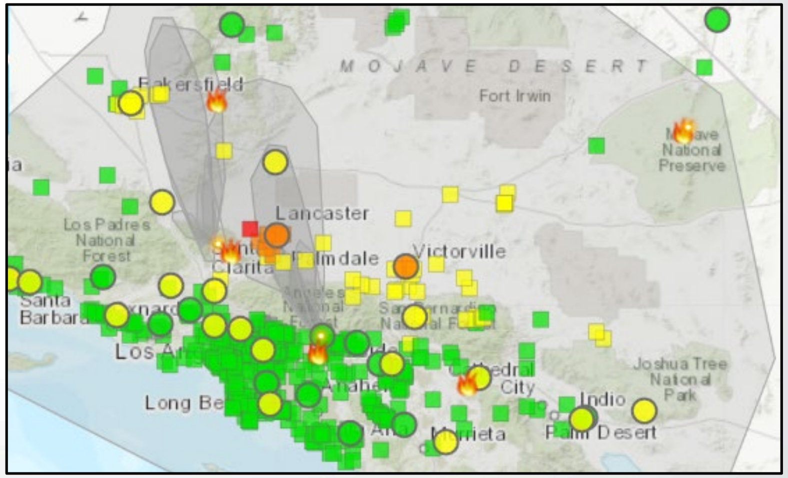
Overview of Today's Presentation



- Motivation and goals
- Primer on PurpleAir sensors
- Review of the data used in this analysis
- Development of the U.S.-wide correction equation for PurpleAir sensors
- Validation of the U.S.-wide correction in determining the Nowcast Air Quality Index (AQI) for 1-hr ambient and smoke-impacted data sets
- Known/suspected performance issues
- Crowdsourced sensor quality assurance/control concerns



AirNow Fire and Smoke Map

Motivation and Goals Guiding the Development of a U.S.-Wide Correction

Motivation for EPA ORD's work with PurpleAir

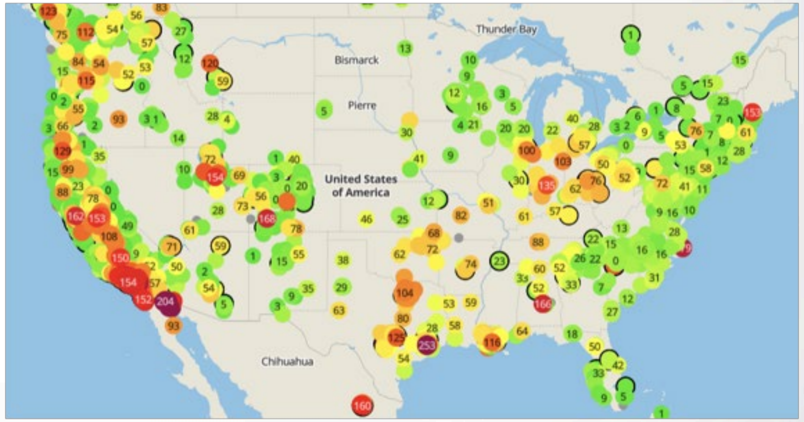
Rapid expansion in the use of sensors creates a growing need to understand the data being produced.

- PurpleAir is one of the largest sensor networks providing publicly available, crowdsourced Particulate Matter (PM) data.
- Some academic researchers, testing agencies, and state, local, and tribal (STL) air quality agencies have conducted collocations to better understand the data produced.
- Several local corrections exist, but they sometimes conflict and it is unknown whether the corrections will be effective for other locations.

AirNow dataset *Image source:* gispub.epa.gov/airnow/

Air sensor networks are increasingly being used by the media for reporting on wildfire smoke impacts.

- Example: "To check air quality, visit PurpleAir or AirNow" *Sonoma West Times & News* (Oct 2019)
- Confusion due to conflicting air quality information
- Little discussion of the difference in data quality



PurpleAir dataset *Image source:* PurpleAir.com

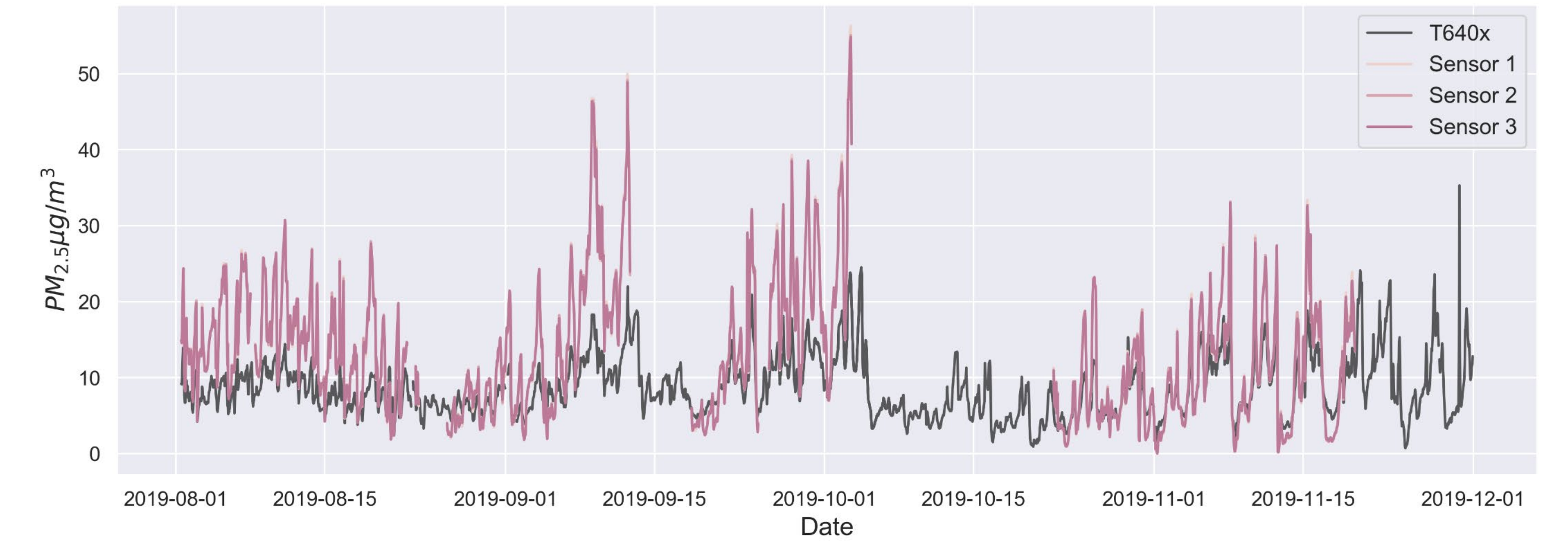
Source: http://www.sonomawest.com/cloverdale_reveille/news/county-issues-smoke-related-health-advisory/article_6e492418-f6e3-11e9-a992-ab6d643d2663.html

Motivation for EPA ORD's work with PurpleAir

EPA's Office of Research and Development has conducted application focused research using the PurpleAir sensor and has found its $PM_{2.5}$ data to be of value:

- Show **similar trends** when compared to Federal Reference Method and Federal Equivalent Method (FRM/FEM) instruments.
- Have **tight precision** = report similar concentrations when collocated
  - Fleet-wide data corrections possible - particularly helpful for large network applications
  - Two channels allow for some sensor health checks
- Tend to overestimate $PM_{2.5}$ concentrations, but **correction equations make data comparable** to reference instruments.

PurpleAir 1-Hour Averaged $PM_{2.5}$



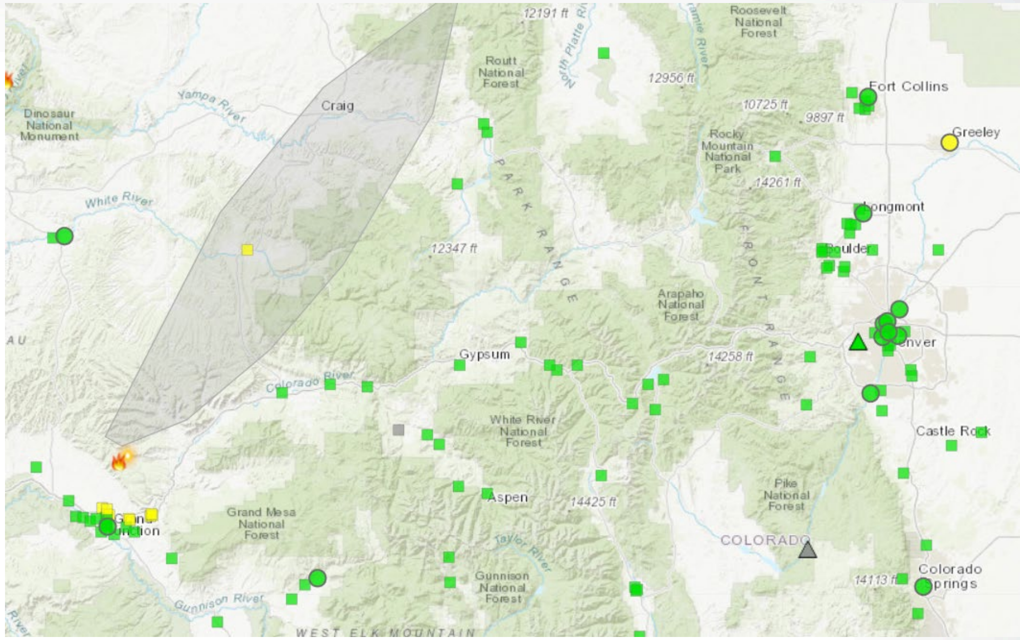
Motivation for EPA ORD's work with PurpleAir

Air sensors can provide more spatially resolved air quality information

- Provides enhanced information at neighborhood scales
- Especially important in rural areas where distance and terrain reduce the applicability of data from the nearest regulatory monitor or interpolated air quality surfaces

Additional data is especially helpful in understanding the impact of wildland fire smoke

- Smoke impacts can vary significantly in both time and space
- Terrain impacts smoke drainage
- Meteorology impacts the height and dispersion of smoke plumes



Additional Information in Remote Mountainous Areas

Image source: https://maps.airfire.org/ara/

Image source: http://nwcg.gov

Motivation for EPA ORD's work with PurpleAir

- Much work exists in the literature about the performance of PurpleAir sensors
- However, studies are typically limited to a few PurpleAir sensors in a single site or region and sometimes sensors are not collocated

Feenstra, et al. 2019. 'Performance evaluation of twelve low-cost $PM_{2.5}$ sensors at an ambient air monitoring site', *Atmospheric Environment*, 216: 116946.

Gupta, et al. 2018. 'Impact of California Fires on Local and Regional Air Quality: The Role of a Low-Cost Sensor Network and Satellite Observations', *GeoHealth*, 2: 172-81.

Kim et al. 2019. 'Evaluation of Performance of Inexpensive Laser Based $PM_{2.5}$ Sensor Monitors for Typical Indoor and Outdoor Hotspots of South Korea', *Applied Sciences*, 9: 1947.

Magi et al. 2019. 'Evaluation of $PM_{2.5}$ measured in an urban setting using a low-cost optical particle counter and a Federal Equivalent Method Beta Attenuation Monitor', *Aerosol Science and Technology*: 1-13.

Malings et al. 2019. 'Fine particle mass monitoring with low-cost sensors: Corrections and long-term performance evaluation', *Aerosol Science and Technology*: 1-15

Sayahi et al. 2019. 'Long-term field evaluation of the Plantower PMS low-cost particulate matter sensors', *Environmental Pollution*, 245: 932-40.

Tryner et al. 2020. 'Laboratory evaluation of low-cost PurpleAir PM monitors and in-field correction using co-located portable filter samplers', *Atmospheric Environment*, 220: 117067.

Zou et al. 2019. 'Examining the functional range of commercially available low-cost airborne particle sensors and consequences for monitoring of indoor air quality in residences', Indoor Air: 30(2).

Motivation for EPA ORD's work with PurpleAir

- Some work exists in the literature about the performance of PurpleAir sensors during smoke impacts
- However, these studies are typically limited investigating only smoke
- Most of this literature emerged in late 2019 - 2020
    - **Holder, et al. 2020.** 'Field Evaluation of Low-Cost Particulate Matter Sensors for Measuring Wildfire Smoke', Sensors.
    - **Robinson 2020.** 'Accurate, Low Cost $PM_{2.5}$ Measurements Demonstrate the Large Spatial Variation in Wood Smoke Pollution in Regional Australia and Improve Modeling and Estimates of Health Costs', Atmosphere: 11(8), 856.
    - **Delp and Singer 2020.** 'Wildfire Smoke Adjustment Factors for Low-Cost and Professional $PM_{2.5}$ Monitors with Optical Sensors', Sensors: 20(13) 3683.
    - **Mehadi, et al. 2019.** 'Laboratory and field evaluation of real-time and near real-time $PM_{2.5}$ smoke monitors', *Journal of the Air & Waste Management Association*: 1-22.

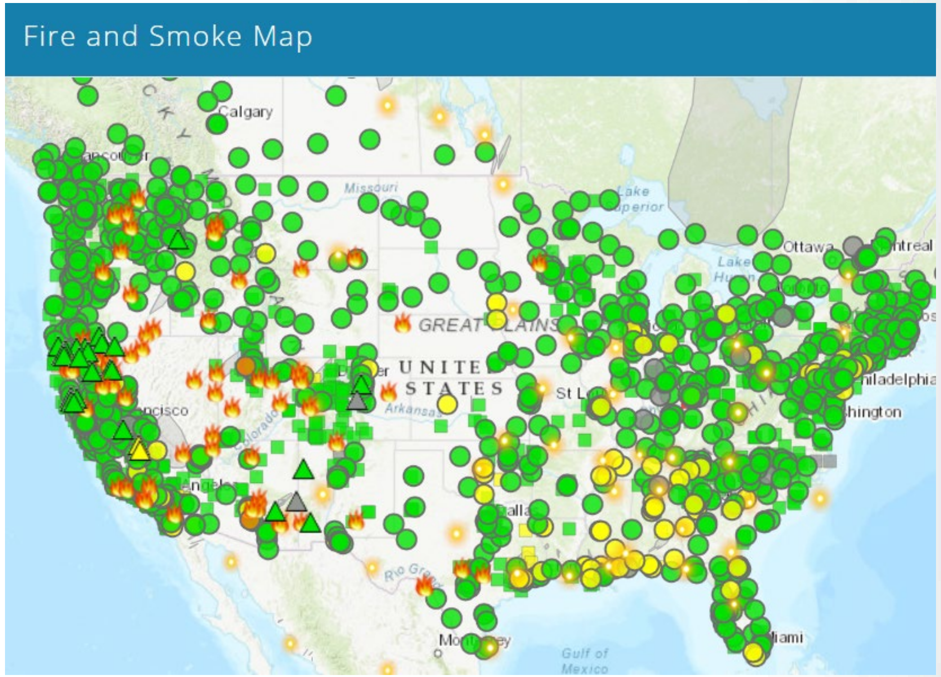
Goals for U.S.-Wide Correction Work and AirNow Pilot

Guiding Question

- Using collocations across the country, is it feasible to use a single correction to improve performance across the U.S.?

Goals

- Balance the improved performance across all collocation sites/states with model complexity to avoid overfitting.
- Evaluate the performance of the correction for ambient applications and at smoke impacted sites to validate the use of PurpleAir for wildland fire smoke monitoring.
- Determine how well the correction equations is at accurately determining the NowCast AQI to assist with health messaging.
- Use the volume of crowdsourced sensors to provide additional data on the AirNow fire map, especially during smoke impacted periods and where none exists.



AirNow Fire and Smoke Map

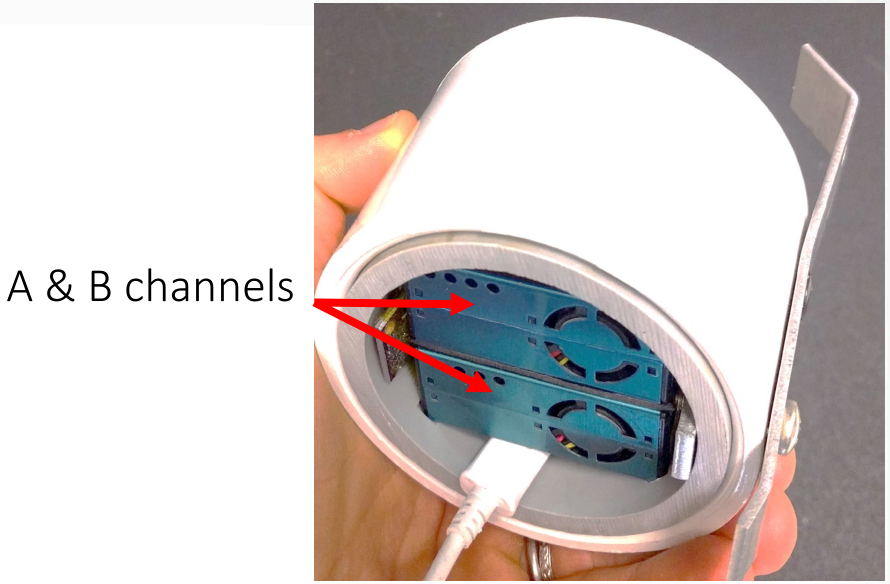
Image source: https://maps.airfire.org/ara/

Primer on PurpleAir Sensors

Primer on PurpleAir Sensors: Hardware and Outputs

PurpleAir Data Hardware

- 2 Plantower PMS5003 PM sensor (channels A & B)
- BME280 pressure, temperature, humidity sensor
- Sample for alternating 10-second intervals
- Generate 2-minute averages
  - Previously 80-second averages



PurpleAir underside view

PurpleAir Data Outputs

- Reports PM_1, $PM_{2.5}$, PM_{10}, particle count
- Reports ***internal*** temperature

  and relative humidity (RH)

PurpleAir Data Storage

- Stored locally on a microSD card (PA-II-SD model)
- Streamed to the PurpleAir cloud via wifi
  - Public – displays on the PurpleAir map
  - Private - data download/view with permission of owner

Primer on PurpleAir Sensors: Correction Factors

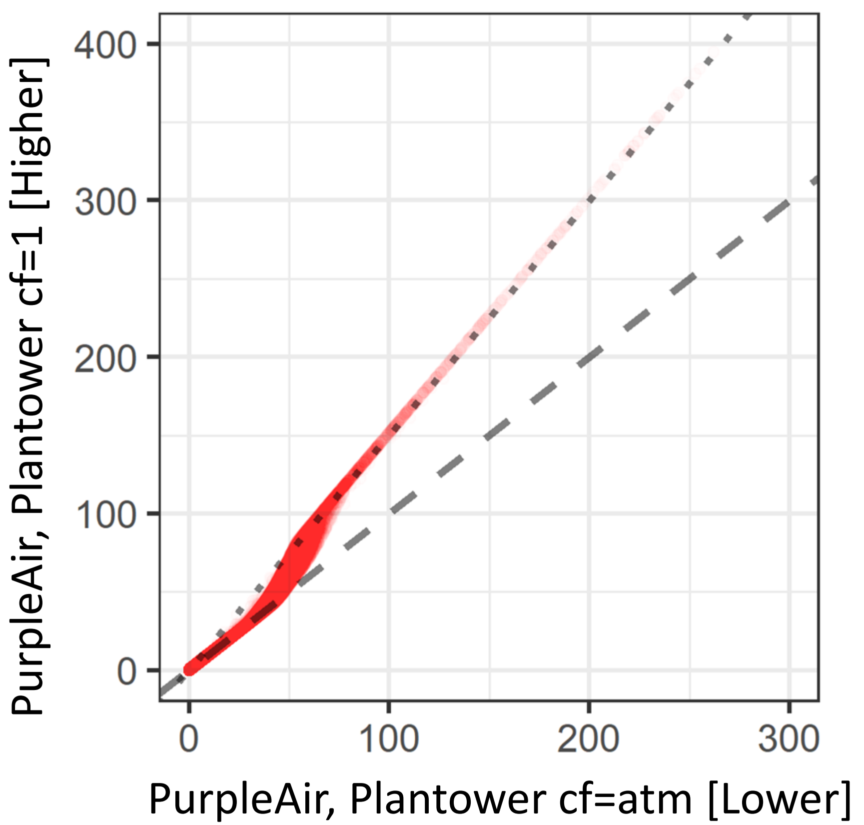
PurpleAir provides PM data directly from the Plantower sensors with two correction factors (CFs)

- **CF=atm described on the PurpleAir website as “outdoor”**
  - lower concentrations
  - Currently displayed on PurpleAir map for **outdoor** sensors
- **CF=1 described on the PurpleAir website as “indoor”**
  - higher concentrations
  - Currently displayed on PurpleAir map for **indoor** sensors

Both CFs typically report concentrations that are higher than collocated regulatory monitors

Previously, PurpleAir had these labels switched

- Easy check: cf=1 is higher
- Helps create confusion in the literature about which cf was used

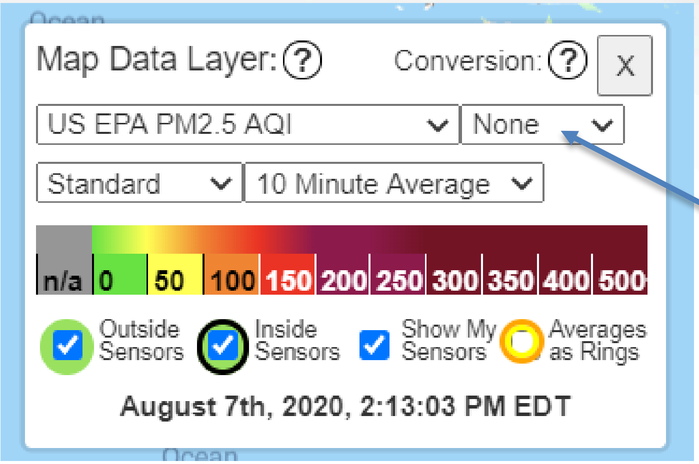


Primer on PurpleAir Sensors: Online Conversions

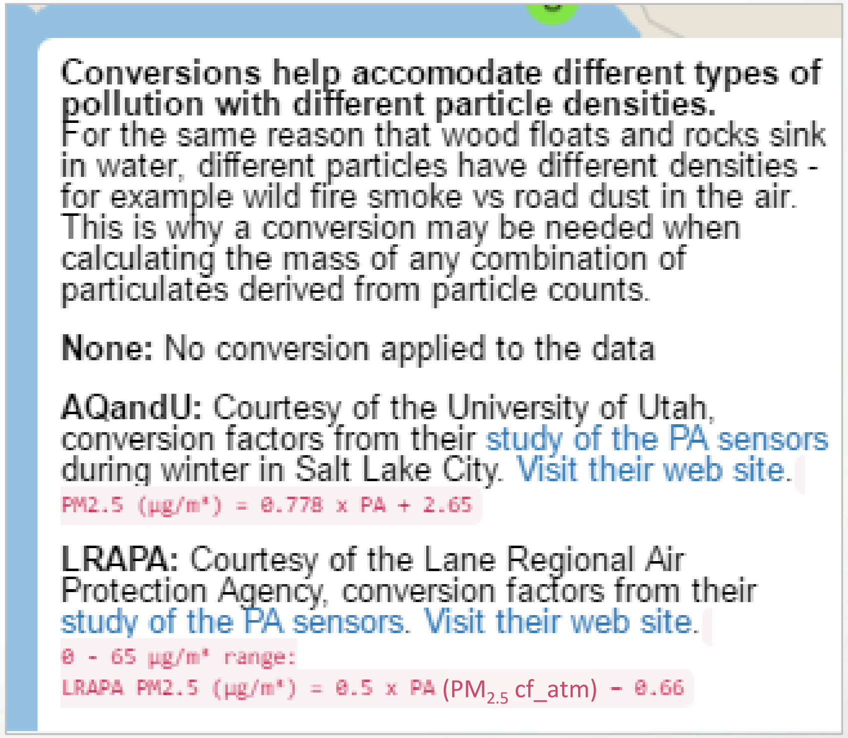
PurpleAir's Map allows users to view data sensor data in multiple ways:

- The first drop-down menu can be used to select what data is displayed.
  - The default is the "US EPA PM2.5 AQI" which directly relates the sensor data to the AQI.
  - Data can be viewed with different time averages.
  - "Raw PM2.5 in µg/m^3" displays the CF=atm data.

- Two conversion factors can be applied to data on the map (not downloaded) and the conversion information page gives more information about the options
  - **"AQ and U"** was developed by U. Utah during wintertime in Salt Lake City
  - **"LRAPA"** was developed by Lane Regional Air Protection Agency for woodsmoke dominated times



Conversions can be applied with this drop-down.



Conversions help accomodate different types of pollution with different particle densities.
For the same reason that wood floats and rocks sink in water, different particles have different densities - for example wild fire smoke vs road dust in the air. This is why a conversion may be needed when calculating the mass of any combination of particulates derived from particle counts.

None: No conversion applied to the data

AQandU: Courtesy of the University of Utah, conversion factors from their study of the PA sensors during winter in Salt Lake City. Visit their web site.
PM2.5 (µg/m³) = 0.778 x PA + 2.65

LRAPA: Courtesy of the Lane Regional Air Protection Agency, conversion factors from their study of the PA sensors. Visit their web site.
0 - 65 µg/m³ range:
LRAPA PM2.5 (µg/m³) = 0.5 x PA ($PM_{2.5}$ cf_atm) – 0.66

Image source: PurpleAir.com/map

Data Sources

Data Sources for this work

Secondary data collected independently by air monitoring agencies and provided to EPA

PurpleAir sensors sent out by EPA

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Secondary data collected independently by air monitoring agencies and provided to EPA

PurpleAir sensors sent out by EPA

→

Long Term Performance Project (and LTPP+)

Team: EPA ORD, partner local air agencies
Objective: Evaluate multiple sensors across the U.S. (LTPP+ PurpleAir only)

Data Sources for this work

Secondary data collected independently by air monitoring agencies and provided to EPA

PurpleAir sensors sent out by EPA

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→ Smoke impacted projects

Team: EPA ORD, Regions 9 & 10, USFS
Objective: Evaluate multiple sensors in smoke

Data Sources for this work

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24-hr U.S.-Wide Correction Development

Method: collocations with FEM and FRM measurements
Objective: Build a correction model that improves performance across the U.S.

Data Sources for this work

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24-hr U.S.-Wide Correction Development

Method: collocations with FEM and FRM measurements
Objective: Build a correction model that improves performance across the U.S.

1-hr Ambient and Smoke impacted validation

Method: collocations with FEM and near FEM measurements
Objective: Test the correction model on ambient and smoke impacted datasets

Development of the U.S.-Wide Correction Equation for PurpleAir Sensor Data

Correction Development Steps

1. Identify collocated PurpleAir monitors
2. Develop data cleaning methods
3. Identify potential correction equations and variables
4. Use data withholding to validate whether correction is likely to provide reasonable accuracy during times or locations not represented in the dataset

Description of Collocation Sites

Collocation sites across the U.S.

Collocation Dataset:

- 50 sensors at 39 sites across 16 states
- Range of meteorological conditions
- Aerosols include a variety of particle types and sizes

Reference monitors operated by STLs:

- Permanent regulatory monitors operated and maintained by state, local, and tribal agencies (SLT) with approved monitoring plans, followed their QA/QC protocols, and maintained by their personnel.

Site characteristics:

- Regulatory monitoring sites characterized as urban and neighborhood sites with no clear hyperlocal sources

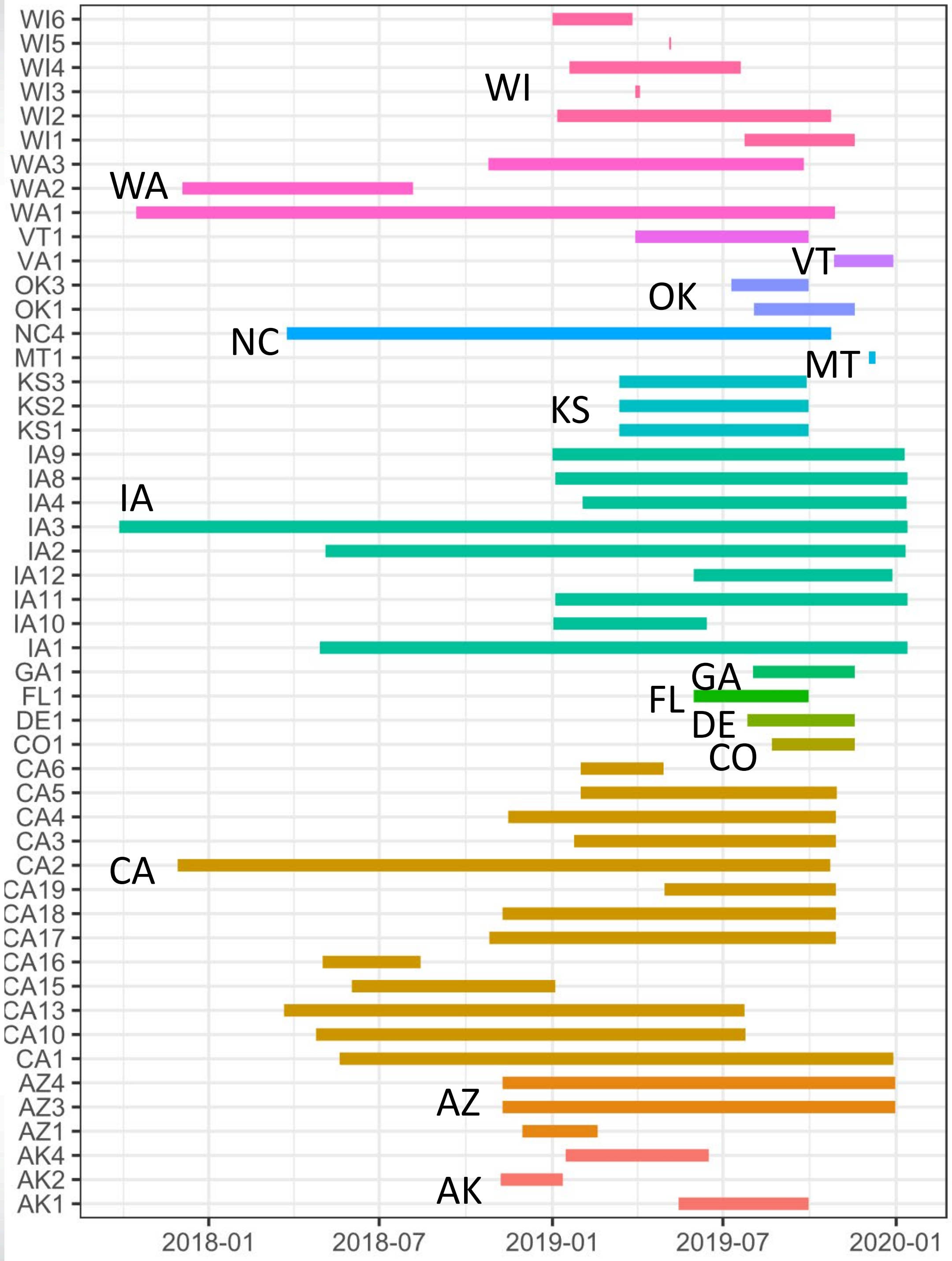
Collocation characteristics:

- PurpleAir sensors were sited at regulatory sites
  - PurpleAir typically within 10m horizontal distance and 1m vertical distance of the regulatory monitor, no flow obstructions, not near trees
- Sites identified
  - Through analysis of publicly available sensors within 50m of a reference monitor. Then agencies were contacted to determine if true collocations.
  - Other sensors sent by EPA or identified by ORD contacts

PurpleAir U.S.-Wide Correction: Sites

Oldest sensors began operating at the end of 2017

Sensors ran from 1 week to >2 years

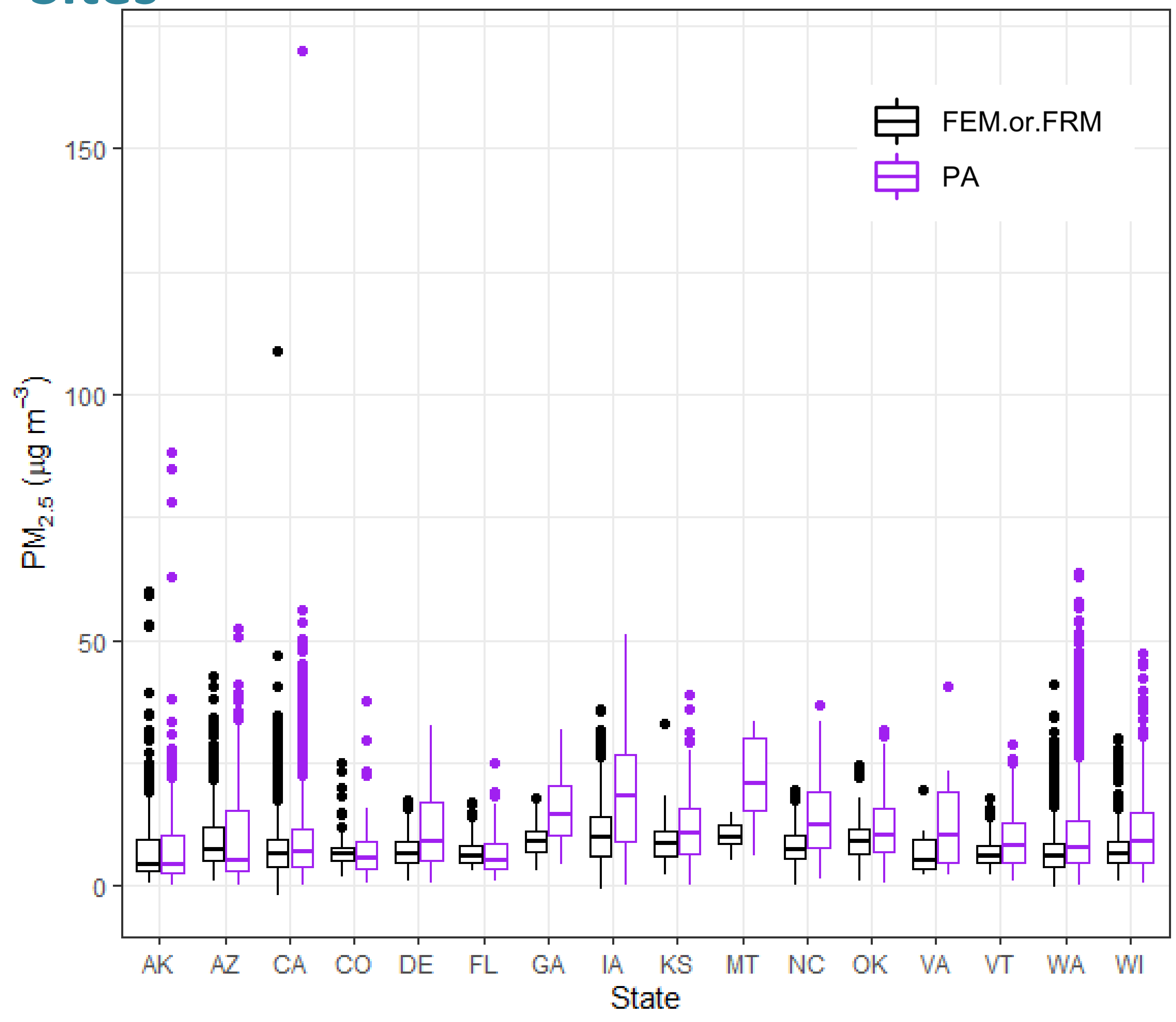


PurpleAir U.S.-Wide Correction: Sites

Wide range of 24-hr concentrations experienced

Exceptional events included in the dataset

Max 24-hr $PM_{2.5}$ 109 µg m^{-3}

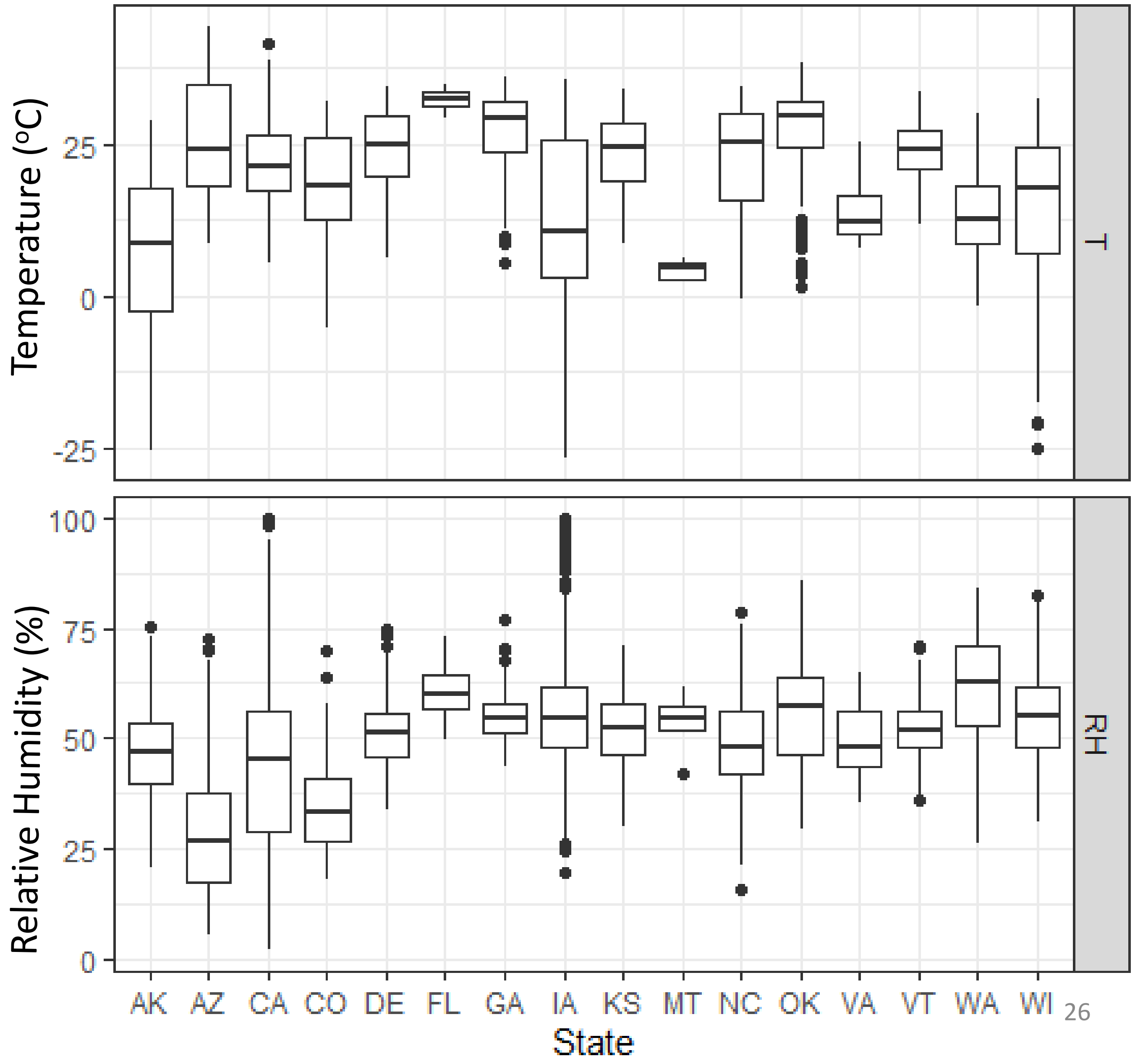


PurpleAir U.S.-Wide Correction: Sites

Wide range 24-hr temperature and RH

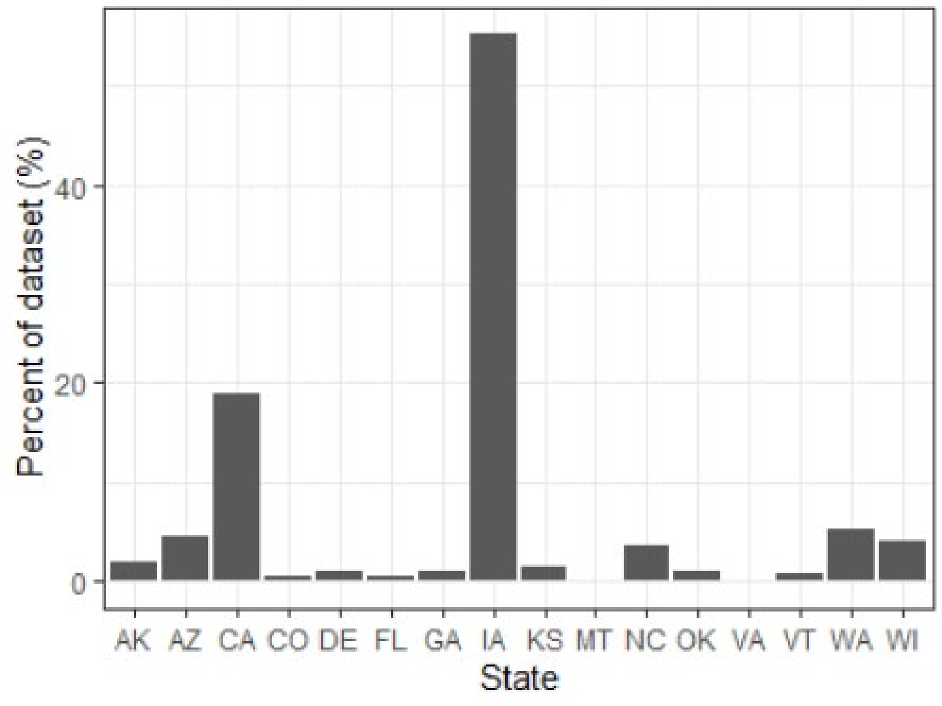
Coldest in AK, IA, WI

Driest in AZ and CO



PurpleAir U.S.-Wide Correction: Dataset Balancing by State

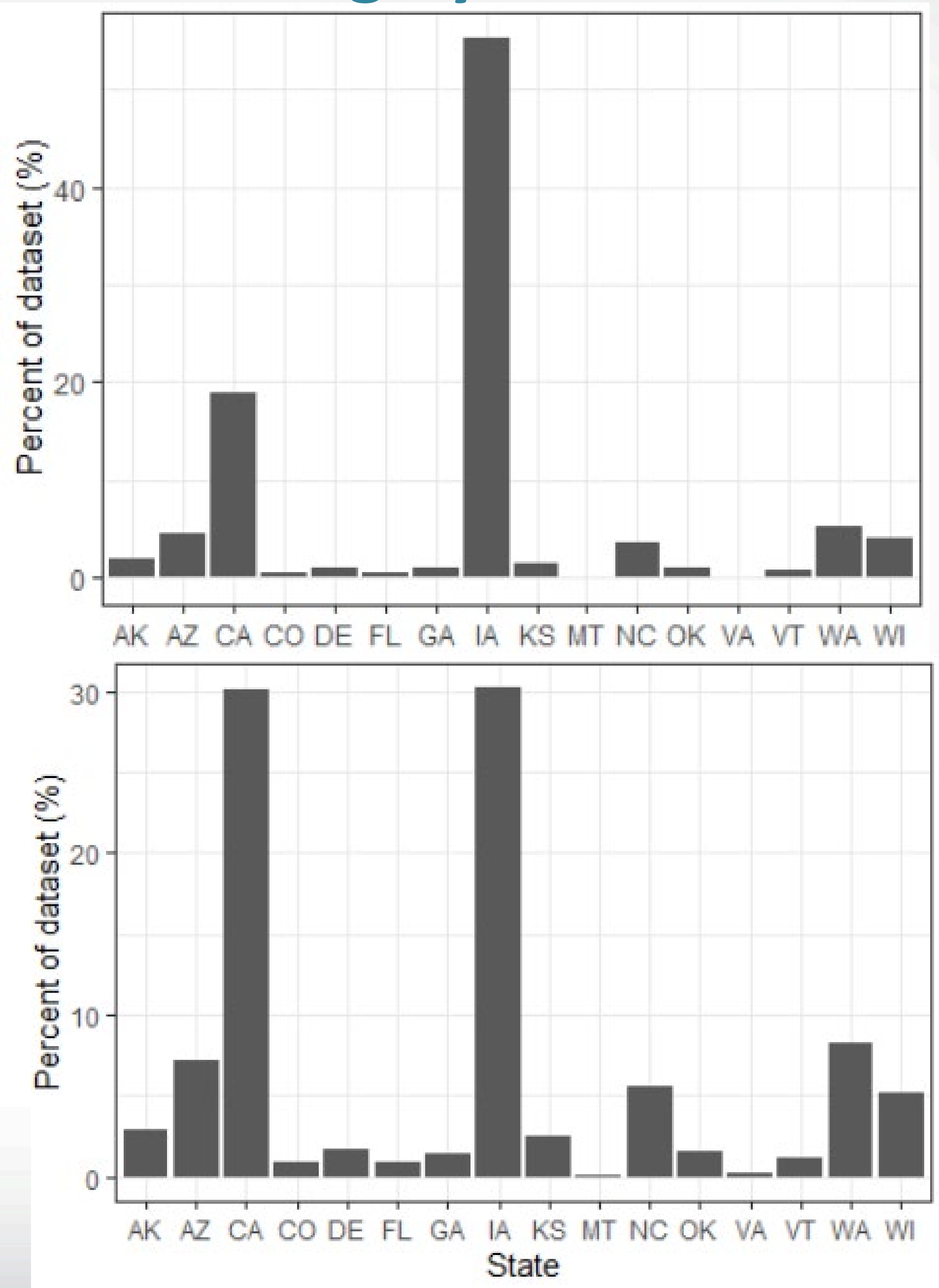
Initially >50% of data from Iowa



PurpleAir U.S.-Wide Correction: Dataset Balancing by State

Initially >50% of data from Iowa

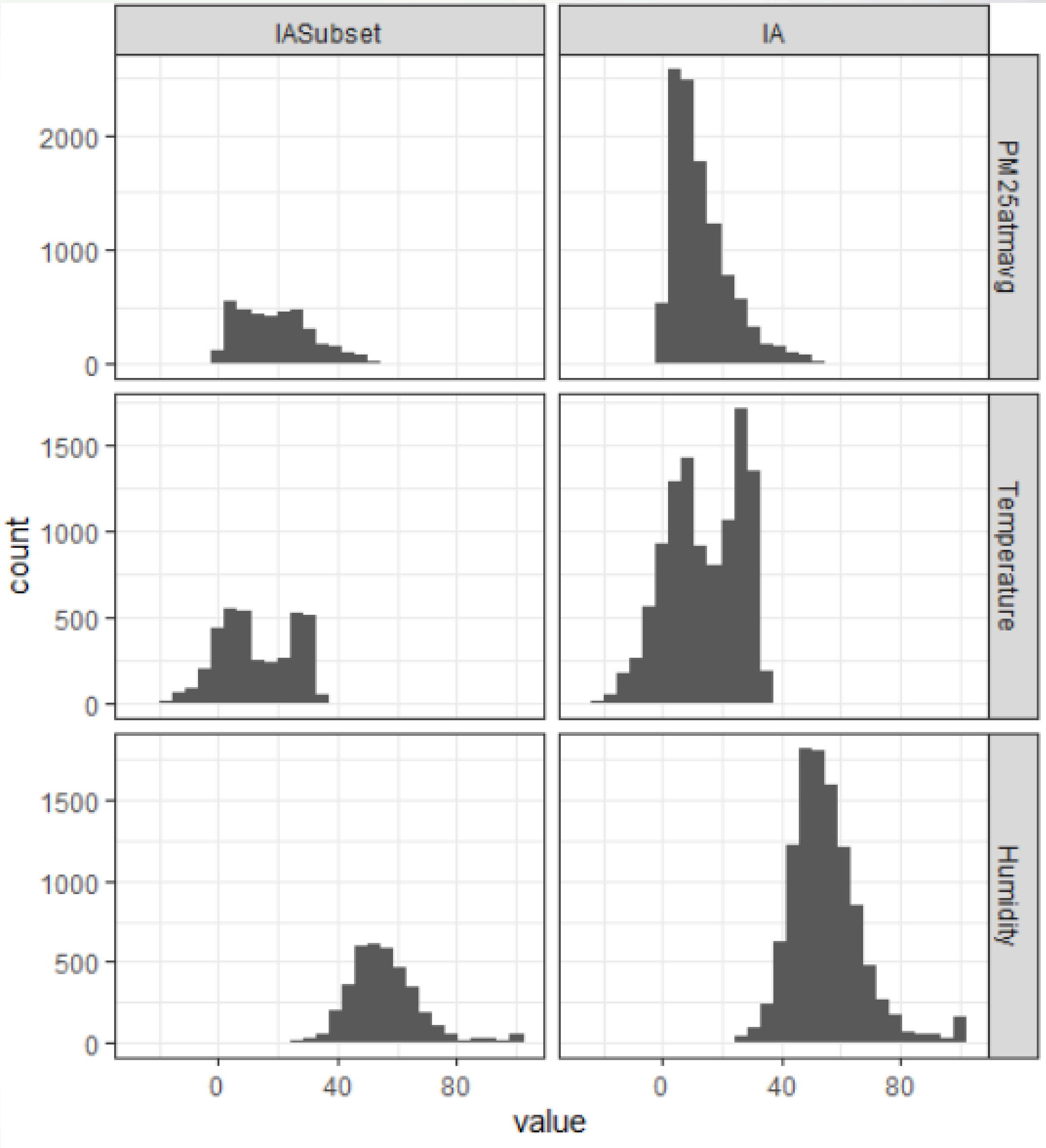
Subset included in model building equivalent to next largest contributor (CA)



PurpleAir U.S.-Wide Correction: Dataset Balancing by State

High concentration Iowa data conserved

- Split into 10 concentration bins
- All data ≥25 µg m^{-3} conserved since limited data
- Equivalent amount of data in bins <25 µg m^{-3} included



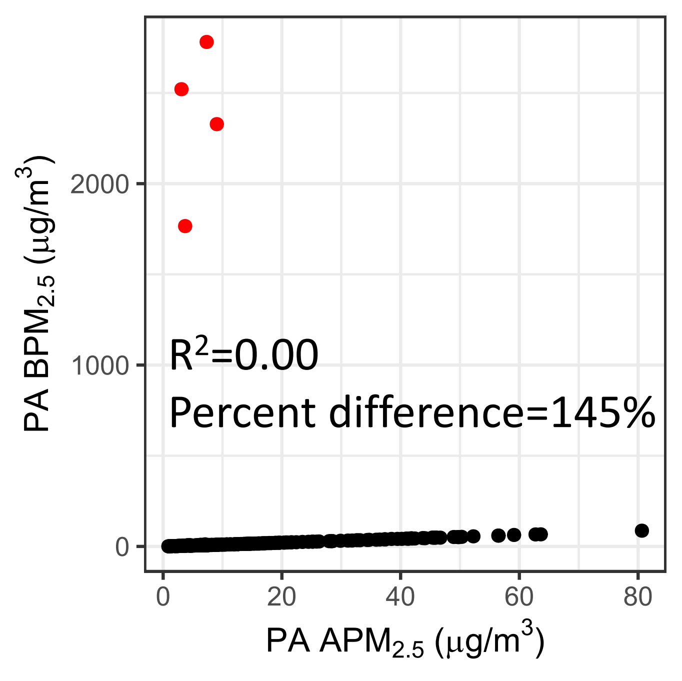
PurpleAir U.S.-Wide Correction: Data Cleaning

Agreement between A and B channels provides confidence in measurements

Out of the box AB channel differences are sometimes high due to outlier points

- Out of the box 24-hr AB agreement
  - r=-0.06 to 1.00
  - Percent difference=-181% to 150%

Example: WA3 sensor



PurpleAir U.S.-Wide Correction: Data Cleaning

Agreement between A and B channels provides confidence in measurements

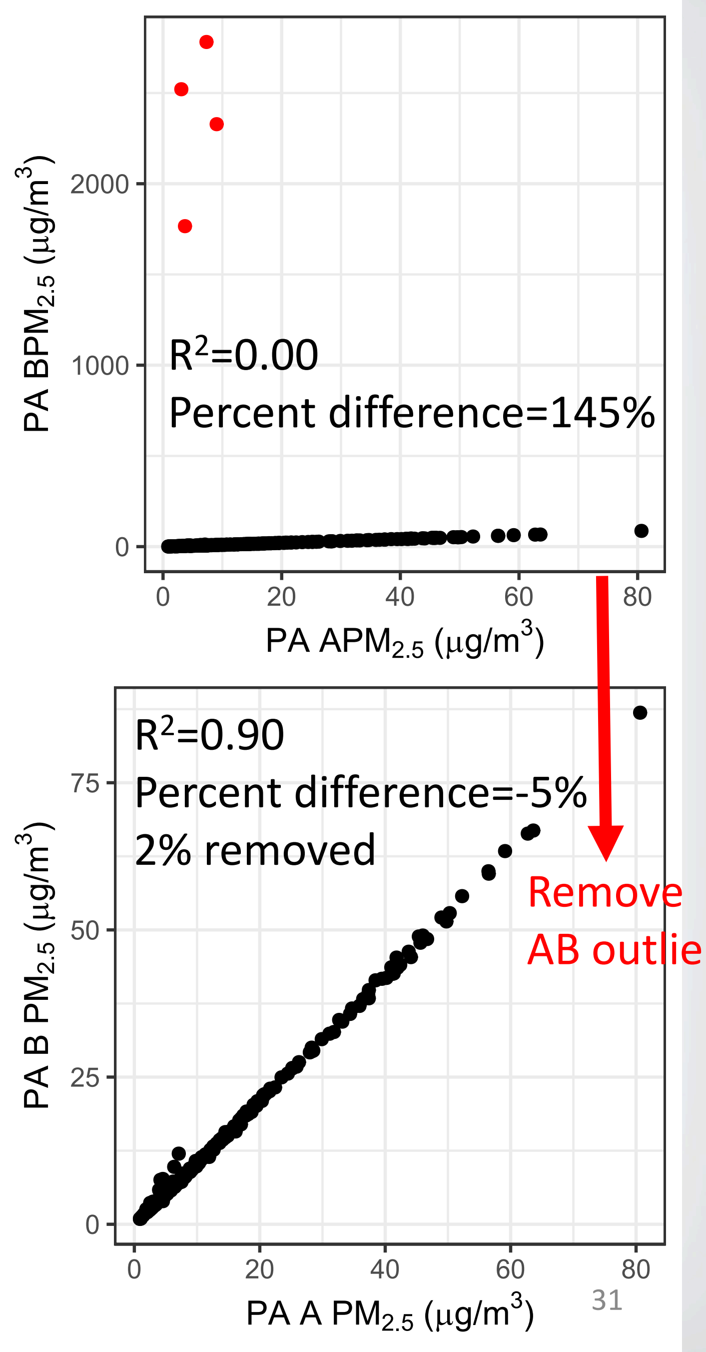
Out of the box AB channel differences are sometimes high due to outlier points

- Out of the box 24-hr AB agreement
    - R^2=0.00 to 1.00
    - Percent difference=-181% to 150%

Need to first remove outliers and then evaluate performance

- 24-hr AB agreement after AB outlier removal
    - R^2=0.55 to 1.00
    - Percent difference=-49% to 45%

Example: WA3 sensor



PurpleAir U.S.-Wide Correction: Data Cleaning

Points removed if 24-hr averaged A & B $PM_{2.5}$ differ by

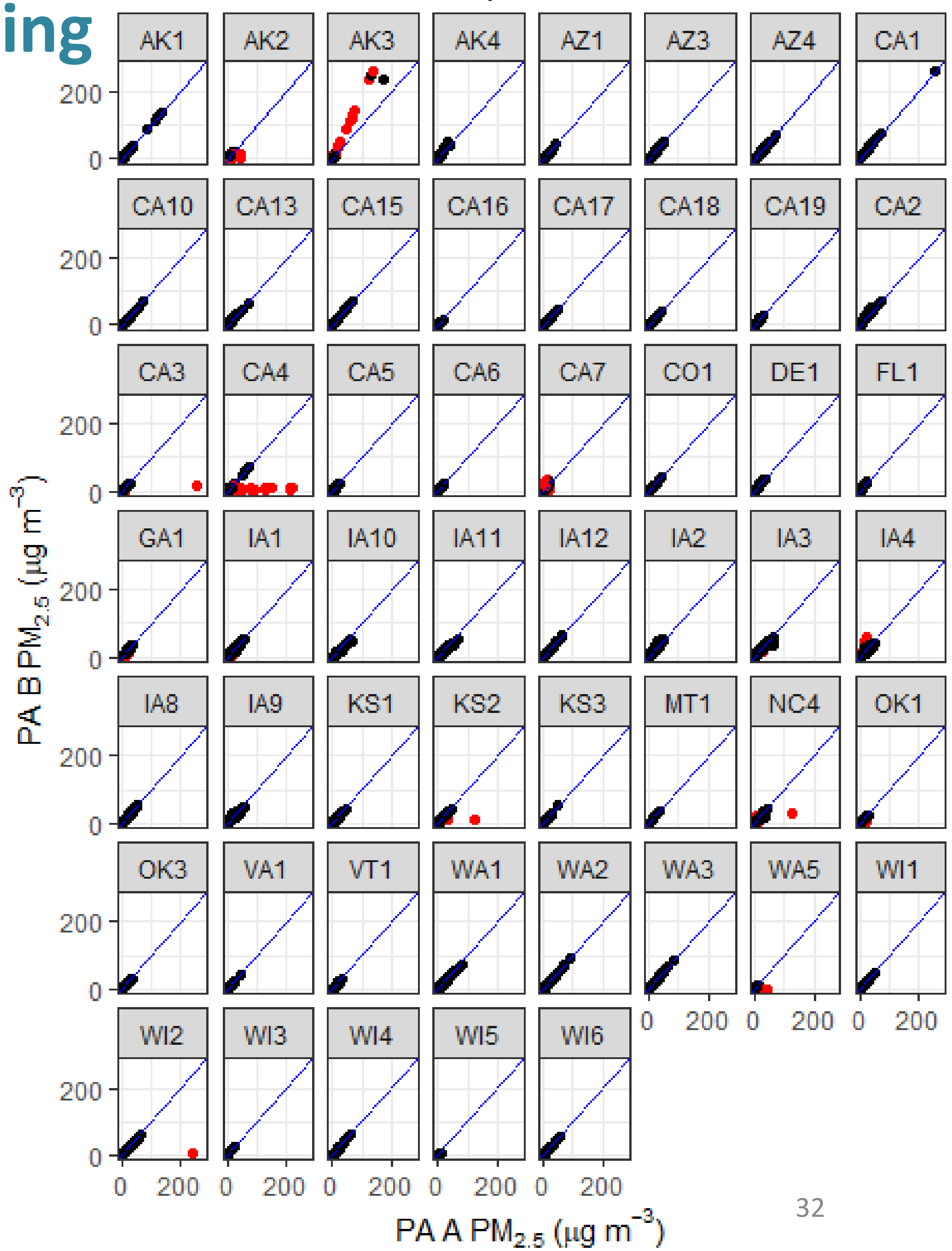
- ≥ ± 5 µg m^{-3} AND
- ≥ ± 62%
  - (95% Confidence interval on % error [2*sd(% error)])

2% of points of full dataset excluded

19/53 sensors had at least 1 point removed (36%)

A & B channels averaged moving forward to increase certainty

Red points removed



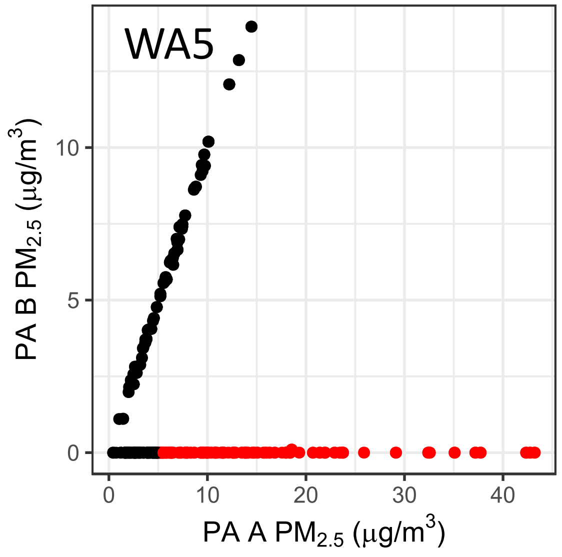
PurpleAir U.S.-Wide Correction: Data Cleaning

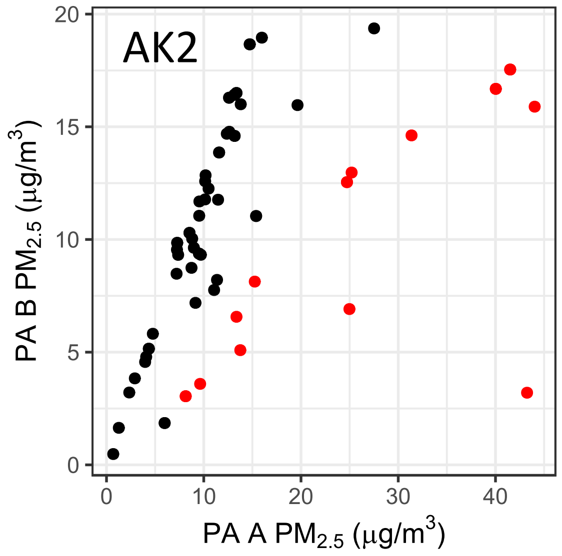
3 sensors identified with large bias (>25%) remaining after outlier removal

- Excluded from further analysis

This is important to make sure we are building the model based on a reliable dataset

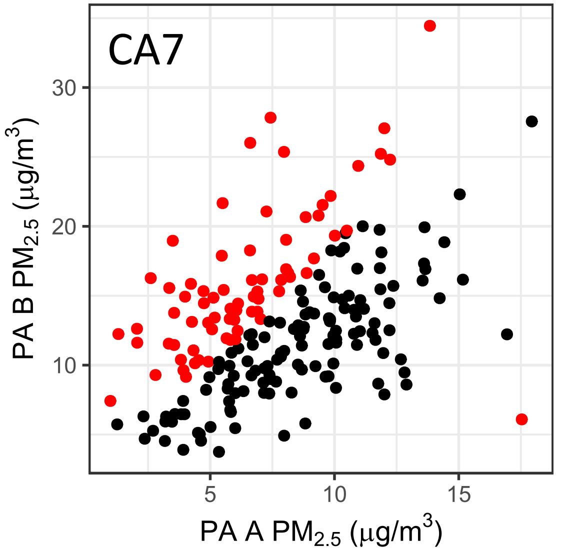
- **Not needed for other PurpleAir data applications since A B comparison removes most of the error**





Sensors with poor agreement between A and B after outliers removed

Red points removed



PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination

Considered parameters on board the PurpleAir (or calculated from these) at 24-hr averages

$PM_{2.5}$

- $PM_{2.5}$ cf_1
- $PM_{2.5}$ cf_atm
- binned counts (algorithm computed not true counts)
  - $B_{>0.3}$, $B_{>0.5}$, $B_{>1.0}$, $B_{>2.5}$, $B_{>5.0}$, $B_{>10.0}$

Environmental parameters

- Temperature (T), Relative Humidity (RH), Dewpoint (D)
  - Dewpoint calculated based on T and RH as measured by the PurpleAir

Statistical method for comparison: Adjusted R^2 (R^2_{adj})

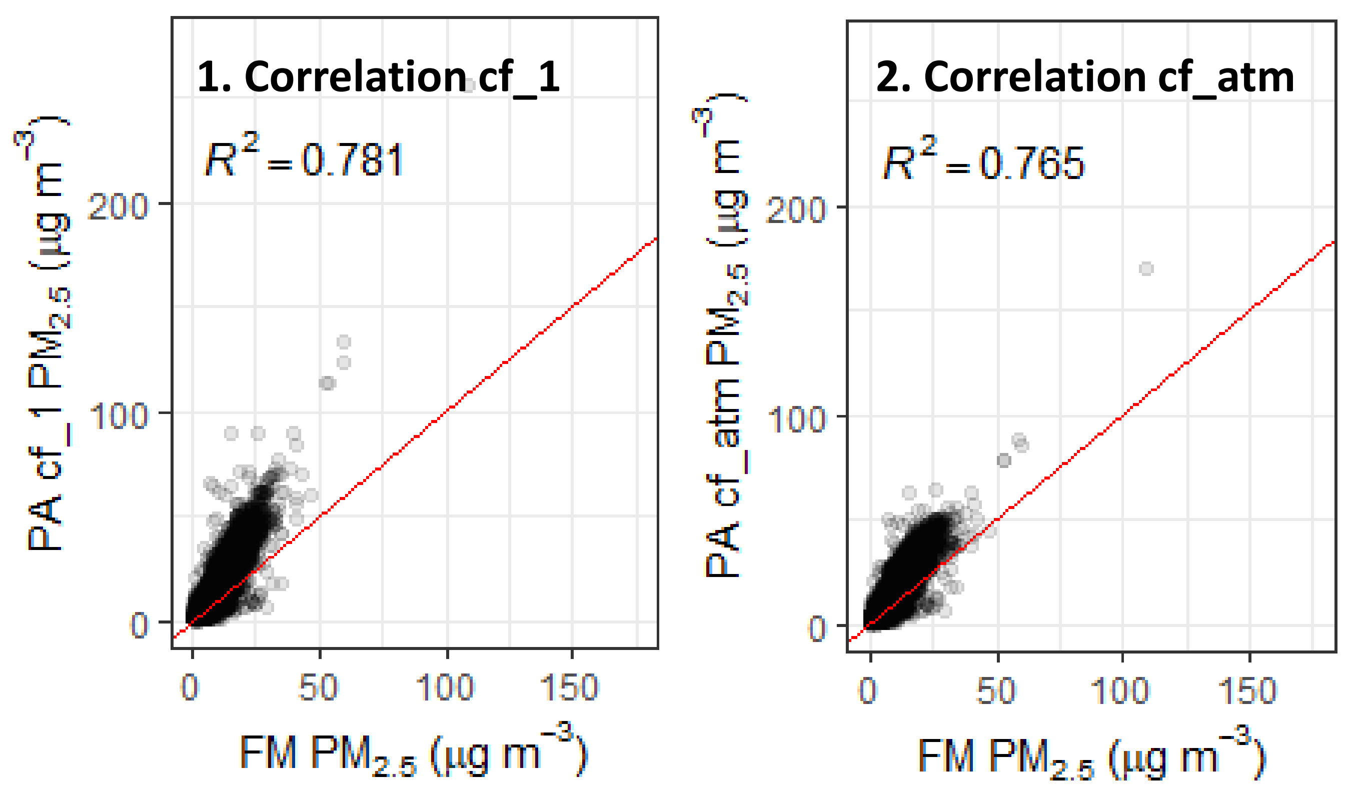
- $R^2_{adj} \leq R^2$
- Penalizes adding extra variables that do not improve the model
- Prevents overfitting since R^2 always increases when additional variables are added

PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination – $PM_{2.5}$

Cf_1 data most strongly correlated

Cf_atm data would require piecewise regression with break around 15-20 µg m^{-3}

- determined using segmented regression package in R



#	Name	Eqn	R^2_{adj}
1	Cf_1	$PA[cf\_1]=PM_{2.5}*s_1+b$	0.78
2	Cf_atm	$PA[cf\_atm]=PM_{2.5}*s_1+b$	0.76
3	Bins	$PM_{2.5} = (s_1*B>0.3) + (s_2*B>0.5) + (s_3*B>1.0) + (s_4*B>2.5) + (s_5*B>5.0) + (s_6*B>10.0) + i$	0.77

PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination - Met

Adding RH improves R^2adj more than any other single environmental parameter

#	Name	Eqn	R^2_{adj}
1	Cf_1	PA[cf_1]=$PM_{2.5}$*s_1+b	0.780
4	PM2.5+RH	PA[cf_1] = s_1*$PM_{2.5}$ + s_2*RH + i	0.831
5	Nonlinear RH*	PA = s_1*$PM_{2.5}$ + $s_2 \frac{RH^2}{(1-RH)}$*$PM_{2.5}$ + s_3* $\frac{RH^2}{(1-RH)}$ + i	0.782
6	+T	PA[cf_1] = s_1*$PM_{2.5}$ + s_2*T + i	0.792
7	+D	PA[cf_1] = s_1*$PM_{2.5}$ + s_2*D + i	0.788

PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination - Met

Adding RH and T improves R^2_{adj} more than RH alone

- Adding dewpoint increases the R^2_{adj} an equivalent parameter but is not used moving forward since it is a calculated variable

#	Name	Eqn	R^2_{adj}
4	PM2.5+RH	PA[cf_1] = s_1*$PM_{2.5}$ + s_2*RH + i	0.831
8	+RH+T	PA = s_1*$PM_{2.5}$ + s_2*RH + s_3*T + i	0.832
9	+RH+D	PA = s_1*$PM_{2.5}$ + s_2*RH + s_3*D + i	0.832
10	+D+T	PA = s_1*$PM_{2.5}$ + s_2*T + s_3*D + i	0.827

PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination - Met

Adding all 3 environmental parameters does not improve the R^2_{adj}

#	Name	Eqn	R^2_{adj}
8	+RH+T	$PA = s_1*PM_{2.5} + s_2*RH + s_3*T + i$	0.832
9	+RH+D	$PA = s_1*PM_{2.5} + s_2*RH + s_3*D + i$	0.832
10	+D+T	$PA = s_1*PM_{2.5} + s_2*T + s_3*D + i$	0.827
11	+RH+T+D	$PA = s_1*PM_{2.5} + s_2*RH + s_3*T + s_4*D + i$	0.832

PurpleAir U.S.-Wide Correction: Duplicate Parameter Elimination - Met

Since T, RH, and $PM_{2.5}$ are significantly correlated with each other we consider interactions by multiplying parameters

- R^2_{adj} improves PM*RH
- R^2_{adj} improves PM*RH*T

#	Name	Eqn	R^2_{adj}
8	+RH+T	$PA = s_1 * PM_{2.5} + s_2 * RH + s_3 * T + i$	0.832
12	PM*RH	$PA = s_1 * PM_{2.5} + s_2 * RH + s_3 * RH * PM_{2.5} + i$	0.836
13	PM*RH*T	$PA = s_1 * PM_{2.5} + s_2 * RH + s_3 * T + s_4 * PM_{2.5} * RH + s_5 * PM_{2.5} * T + s_6 * RH * T + s_7 * PM_{2.5} * RH * T + i$	0.838

PurpleAir U.S.-Wide Correction: Equations Considered

Selected best model of each complexity moving forward

#	Name	Eqn	R^2_{adj}
1	Cf_1	$PA[cf\_1]=PM_{2.5}*s_1+b$	0.780
4	PM2.5+RH	$PA[cf\_1] = s_1*PM_{2.5} + s_2*RH + i$	0.831
8	+RH+T	$PA = s_1*PM_{2.5} + s_2*RH + s_3*T + i$	0.832
12	PM*RH	$PA = s_1*PM_{2.5} + s_2*RH + s_3*RH*PM_{2.5} + i$	0.836
13	PM*RH*T	$PA = s_1*PM_{2.5} + s_2*RH + s_3*T + s_4*PM_{2.5}*RH + s_5*PM_{2.5}*T + s_6*RH*T + s_7*PM_{2.5}*RH*T + i$	0.838

PurpleAir U.S.-Wide Correction: Model Validation – Withholding Methods

Leave out by date (LOBD)

- Separate dataset into 4-week periods
- 30 periods total
- 27 periods used to build model
- 3 periods used to test model
- Iterate through all possible combinations (27,000)

Leave one state out (LOSO)

- Build on 15 states
- Test on the excluded state

PurpleAir U.S.-Wide Correction: Model Validation – Statistics Considered

0:raw
1:linear
2:+RH
3:+RH+T
4:*RH
5:*RH*T

Statistics:

- Mean Bias error (MBE)
  - Overall bias on the test dataset
- Mean Absolute error (MAE)
  - 24-hr error on the test dataset

PurpleAir U.S.-Wide Correction: Results – Raw to Linear

Linear correction

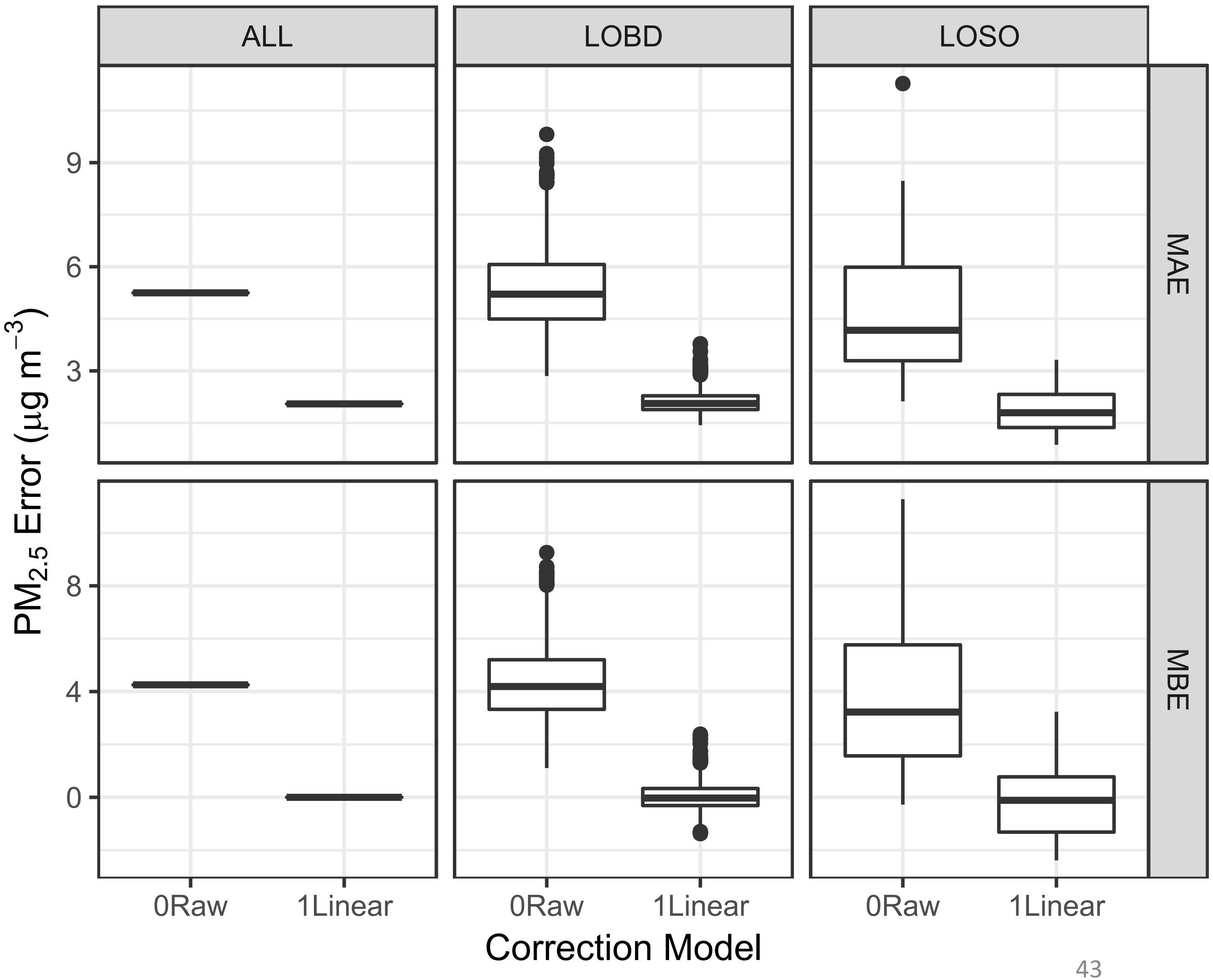
Mean Absolute Error (MAE)

- Leave One State Out (LOSO) median MAE improves
  - 4.2 to 1.8 µg m^{-3}
- Leave Out By Date (LOBD) same improvement

Mean Bias Error (MBE)

- LOSO median MBE improves
  - 3.3 to 0 µg m^{-3}
- LOBD improves 4.2 to 0 µg m^{-3}

A linear regression reduces error as measured by MBE and 24-hr MAE



PurpleAir U.S.-Wide Correction: Results – Linear to +RH

+RH correction improvement from Linear

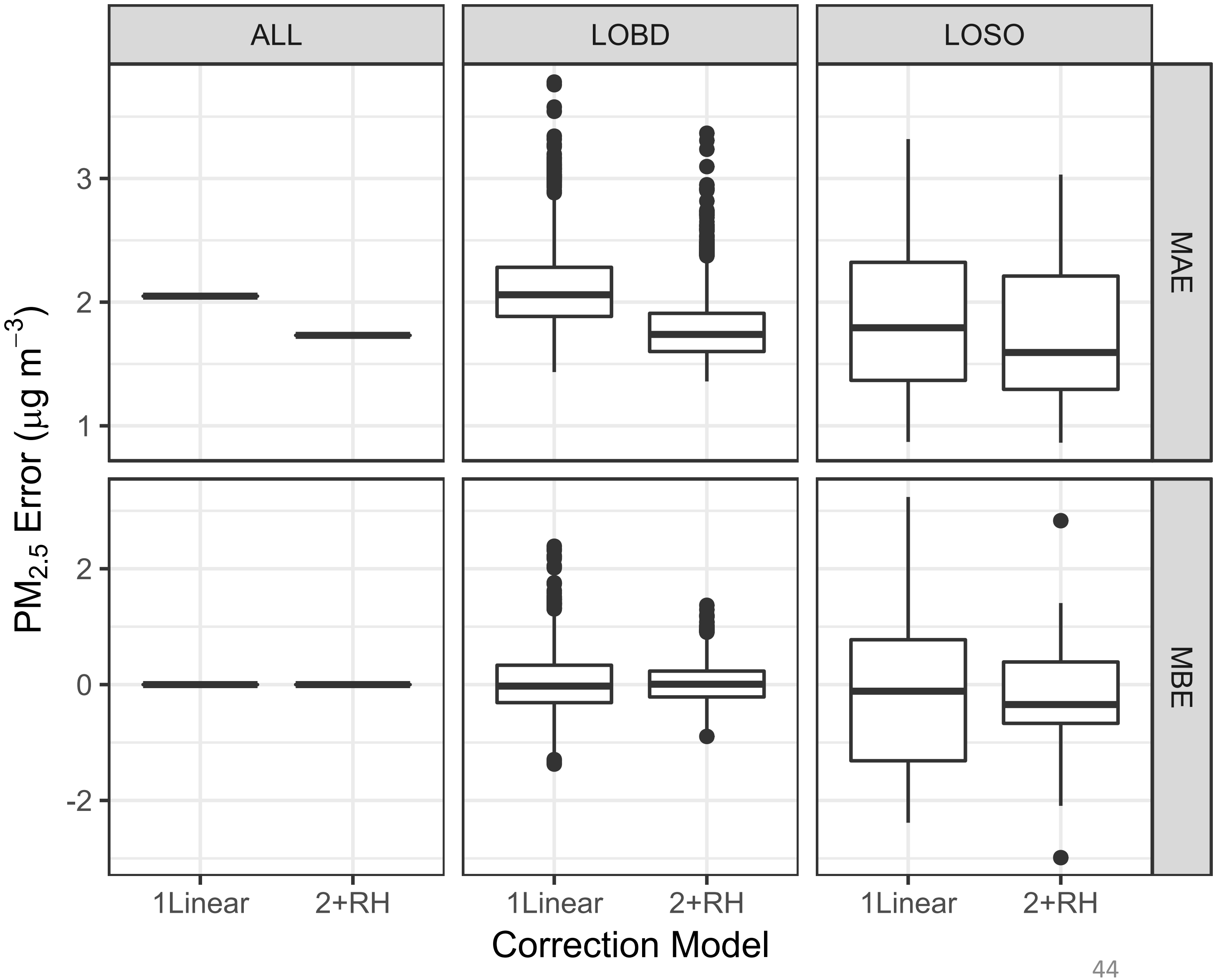
Mean Absolute Error (MAE)

- Leave One State Out (LOSO) median MAE drops from 1.8 to 1.6 µg m^{-3}
- Leave Out By Date (LOBD) same improvement

Mean Bias Error (MBE)

- LOSO median error increases
  - 0 to -0.2 µg m^{-3}
  - Increased bias in FL
  - Decrease bias in CA and AZ (dryer)
  - Tightening of interquartile range (IQR box)
- LOBD same 0 to 0 µg m^{-3}

+RH equation is typically able to further improve performance in withheld datasets



PurpleAir U.S.-Wide Correction: Results - +RH to +RH+T

+RH+T improvement over +RH

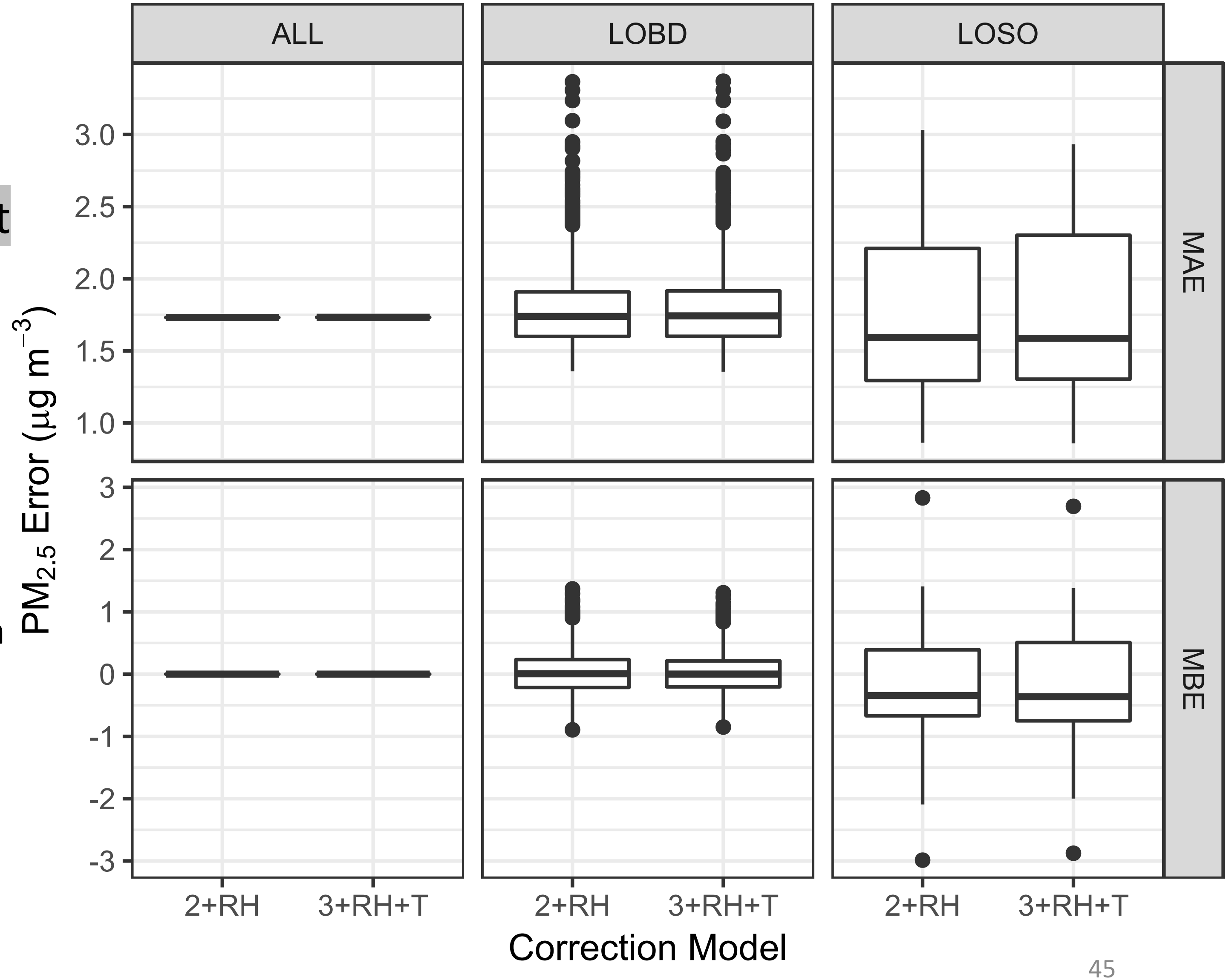
Mean Absolute Error (MAE)

- Leave One State Out (LOSO) median MAE no improvement
- Leave Out By Date (LOBD) no improvement

Mean Bias Error (MBE)

- LOSO median error increases
  - -0.2 to -0.3 µg m^{-3}
  - Increased bias in FL
  - Wider IQR
  - States are driving the temperature coefficient in different directions
- LOBD no change
  - Tighter IQR

+RH+T does not systematically improve performance



PurpleAir U.S.-Wide Correction: Results - +RH to *RH

***RH improvement over +RH**

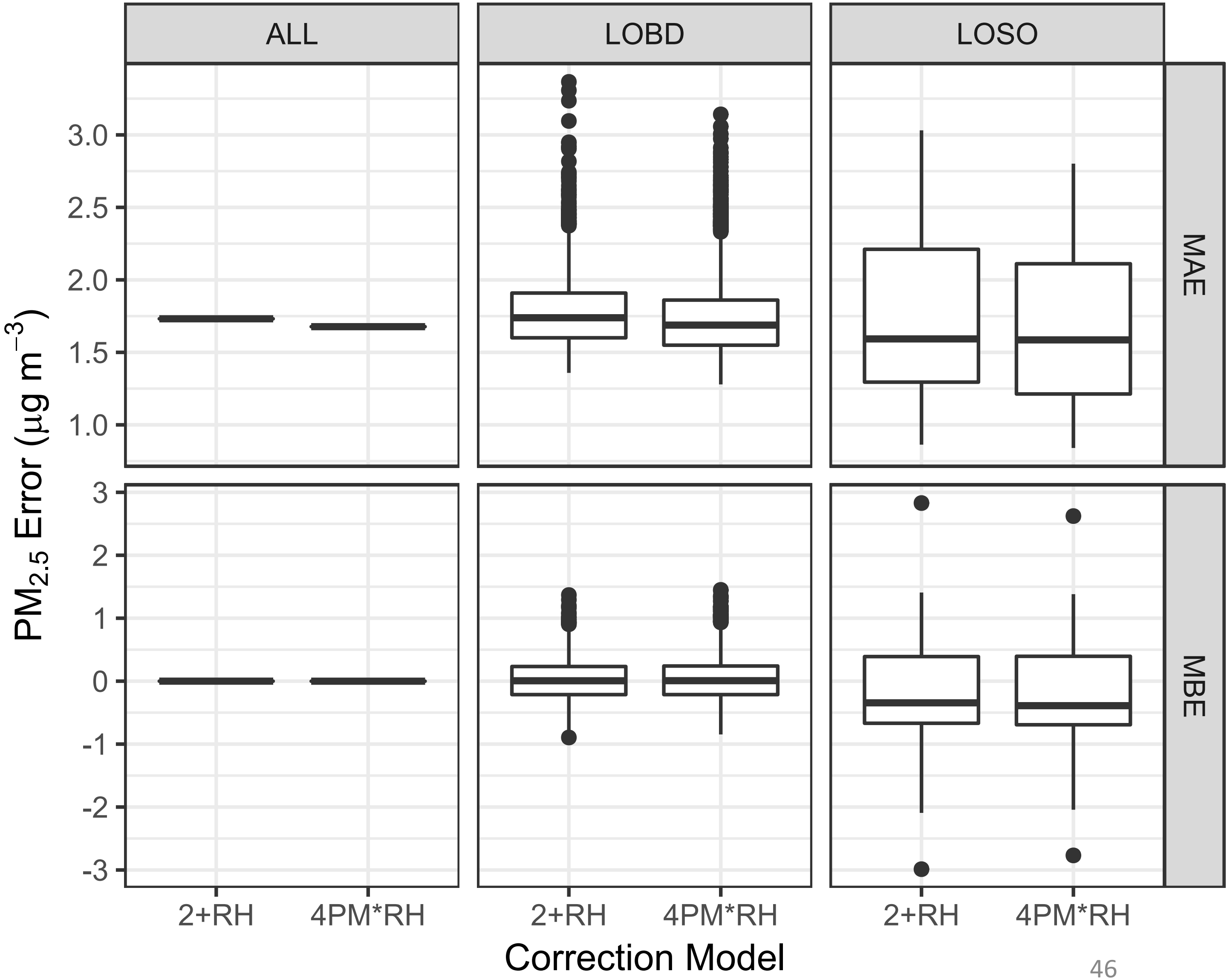
Mean Absolute Error (MAE)

- Leave One State Out (LOSO) median MAE no improvement
- Leave Out By Date (LOBD) slight improvement

Mean Bias Error (MBE)

- LOSO median slight error increases
  - -0.2 to -0.3 µg m^{-3}
- LOBD no change

*RH does not improve performance



PurpleAir U.S.-Wide Correction: Results - +RH to *RH*T

***RH*T improvement over +RH**

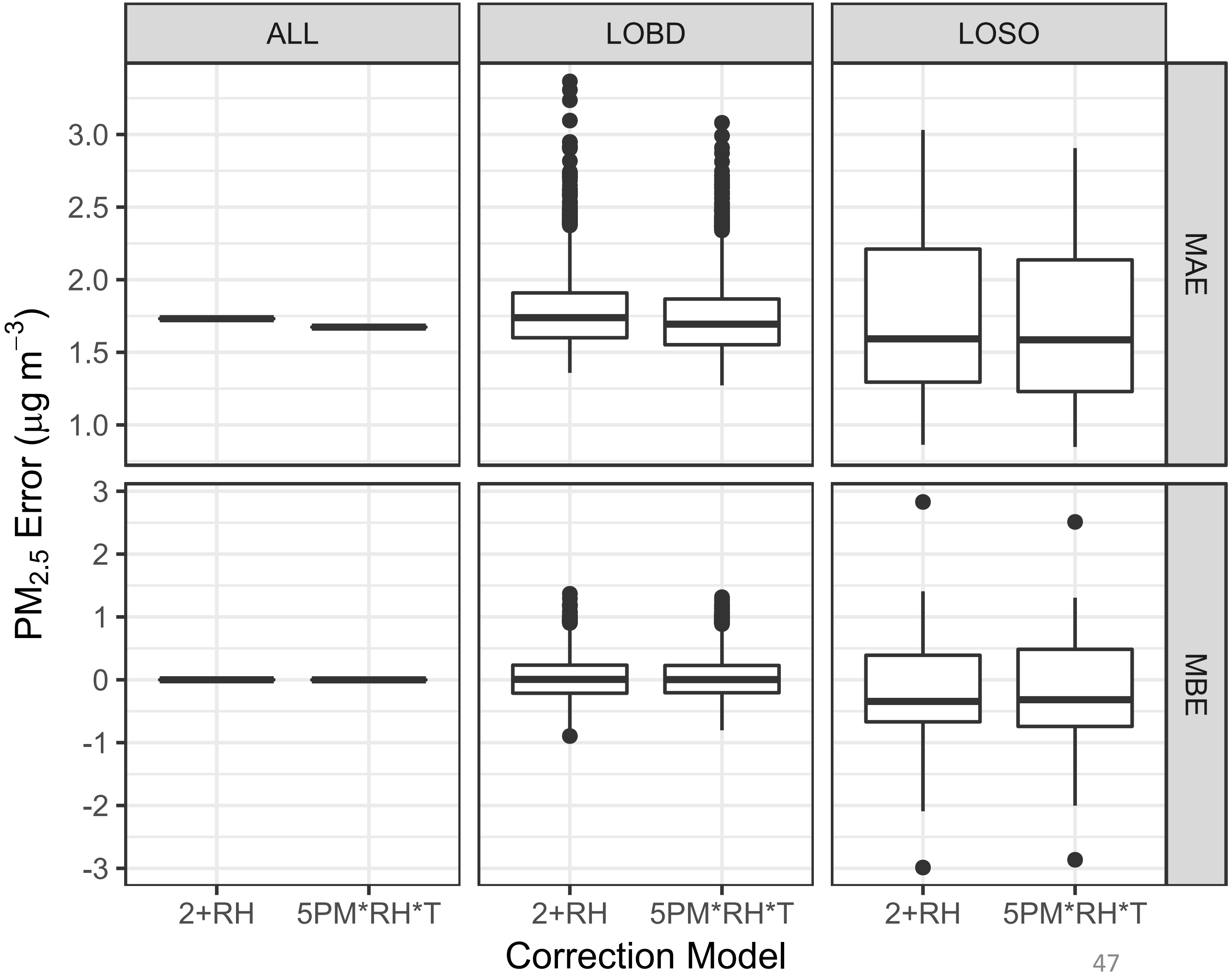
Mean Absolute Error (MAE)

- Leave One State Out (LOSO) median MAE no improvement
- Leave Out By Date (LOBD) slight improvement

Mean Bias Error (MBE)

- LOSO median error increases
  - -0.2 to -0.3 $\mu g\ m^{-3}$
- LOBD no change

*RH*T does not improve performance



PurpleAir U.S.-Wide Correction: Selected Model

Resulting Correction Equation

$PM_{2.5}$ corrected= $0.52*[PurpleAir_{CF=1;\ avgAB}] - 0.085*RH + 5.71$

- $PM_{2.5}$ = (µg m^{-3})
- RH = Relative Humidity (%)
- $PA_{cf=1;\ avgAB}$ = PurpleAir higher correction factor data averaged from the A and B channels

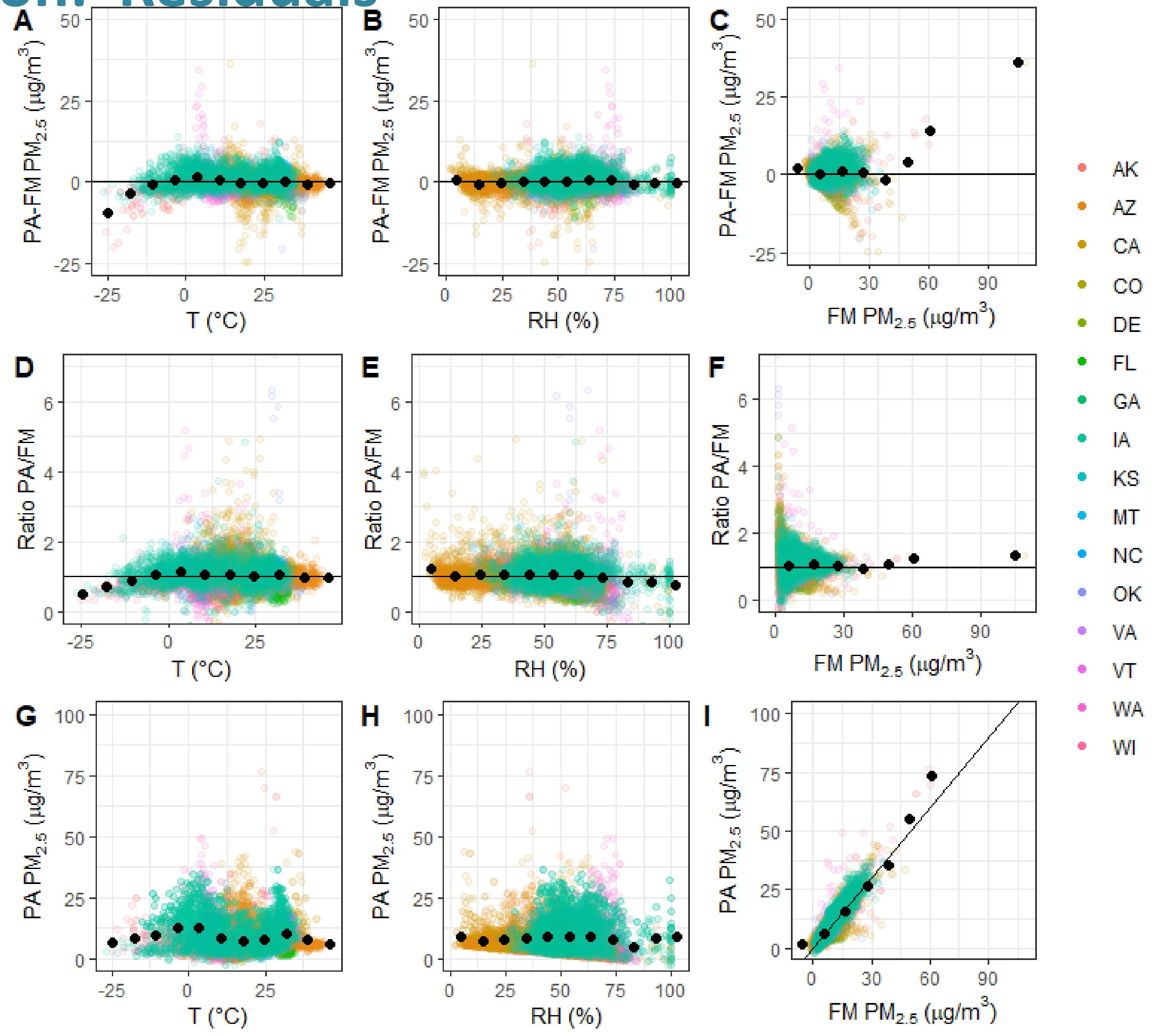
Reasoning:

- A less complex model is less likely to over fit the data
- Although MAE and MBE have been discussed thus far, RMSE and spearman correlation showed similar trends and support the conclusions

PurpleAir U.S.-Wide Correction: Residuals

Some uncertainty in very low temperatures (< -12°C) but limited data (<1%)

Otherwise error does not appear related to variables



PurpleAir U.S.-Wide Correction: Performance by State

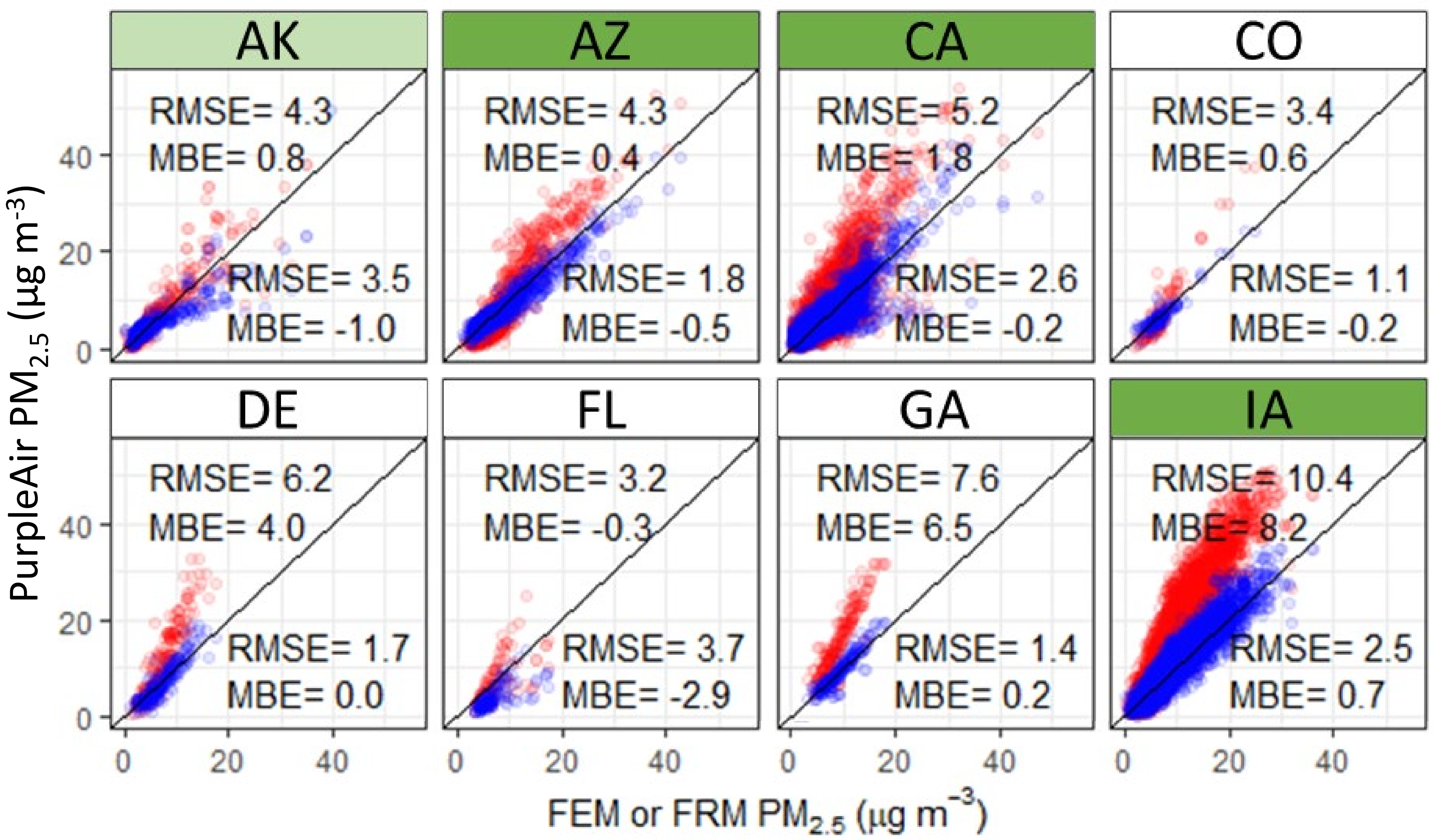
State bias typically within 2 µg m^{-3}

RMSE typically reduced to within 3 µg m^{-3}

Low bias in FL

- <1 year of data, so may be some seasonal bias
- More data needed in this region

Data before correction and after correction
With >1 year of data in green (10+months in light green)

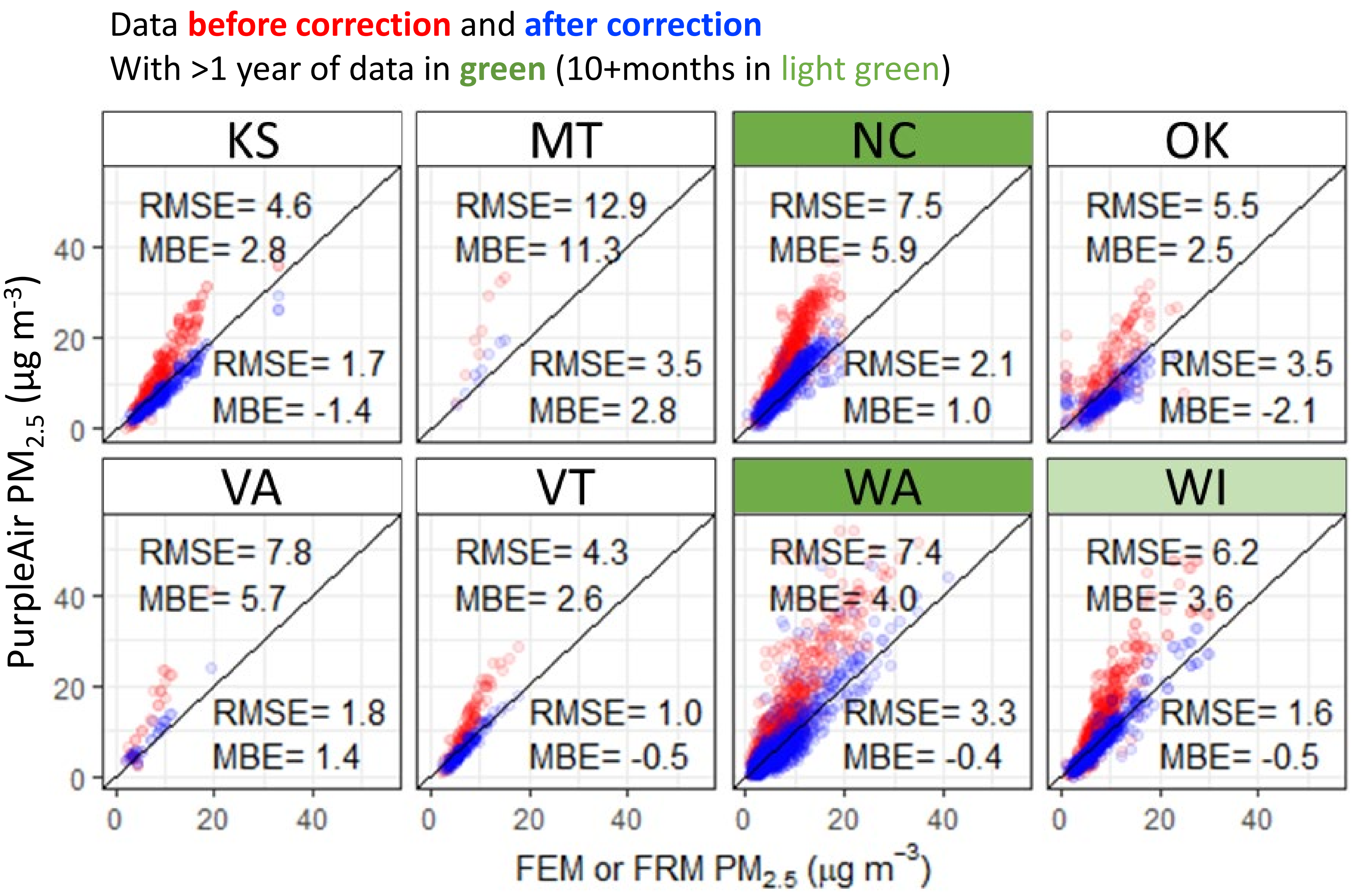


PurpleAir U.S.-Wide Correction: Performance by State

State bias typically within 2 µg m^{-3}

RMSE typically reduced to within 3 µg m^{-3}

High bias in MT, but only ~1 week of data



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PurpleAir U.S.-Wide Correction: Importance of QA Steps

- Averaging A and B channels can reduce error
- The AB criteria is more important than completeness
- Other corrections do not reduce error as much

QA steps

Completeness: 24-hr averages excluded if <90% of expected PurpleAir data points available
AB: 24-hr averages excluded if A and B differ by 5 µg m^{-3} and 62%
Problem sensors: Exclude sensors with >25% difference after 24-hr point removal

Performance with correction applied

QA steps	Channels	RMSE (µg m^{-3})	MAE (µg m^{-3})	R^2
None	A	87	7	0
None	B	161	12	0
None	AB	92	9	0
Completeness	AB	38	3	0.02
AB	AB	4	2	0.73
AB, completeness	AB	3	2	0.74
AB, completeness, problem sensors	AB	3	2	0.77

PurpleAir U.S.-Wide Correction: Summary

- A correction was developed that improves performance across the U.S.
- Its limited complexity helps ensure it will work more broadly across U.S. conditions
- Excluding times with large differences between the A and B channel improves accuracy

Remaining questions:

- This was all 24-hr averaged data
  - Will the correction work at <24-hr averages?
- This data was primarily urban ambient $PM_{2.5}$
  - What about $PM_{2.5}$ from smoke where additional real-time data is even more valuable?

Application of Correction to Ambient AND Smoke Impacted Datasets

Application/Validation Steps

1. Compile 1-hr averaged collocation datasets from typical ambient and smoke impacted sites across the U.S.
2. Evaluate the data quality assurance methods and U.S.-wide correction equation's performance for the hourly datasets (after developing based on 24-hr).
3. Compare the U.S.-wide correction equation to other published corrections.
4. Apply the Nowcast (weighted 12-hr rolling average) and gauge the performance of the correction.

EPA ORD's Long Term Performance Project – Ambient Dataset

Ambient collocation dataset:

- Sensors collocated at 7 sites across the U.S.
- Range of meteorological conditions and particle types and sizes
- All sites operating a T640/T640x
- Collocations started Aug 2019

Reference monitors operated by STLs:

- Permanent regulatory monitors operated and maintained by STLs with approved monitoring plans, followed their QA/QC protocols, and maintained by their personnel

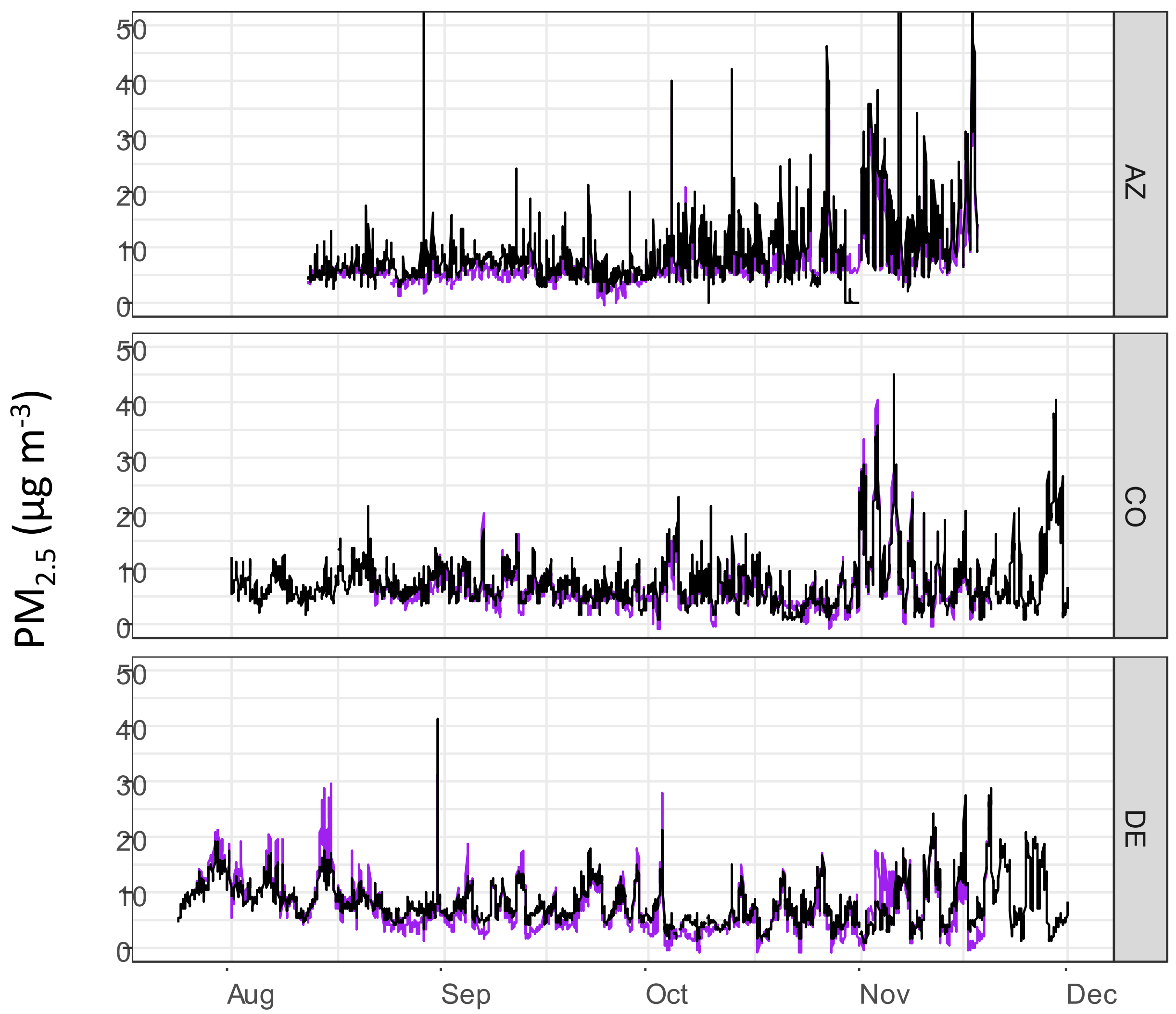
Site characteristics:

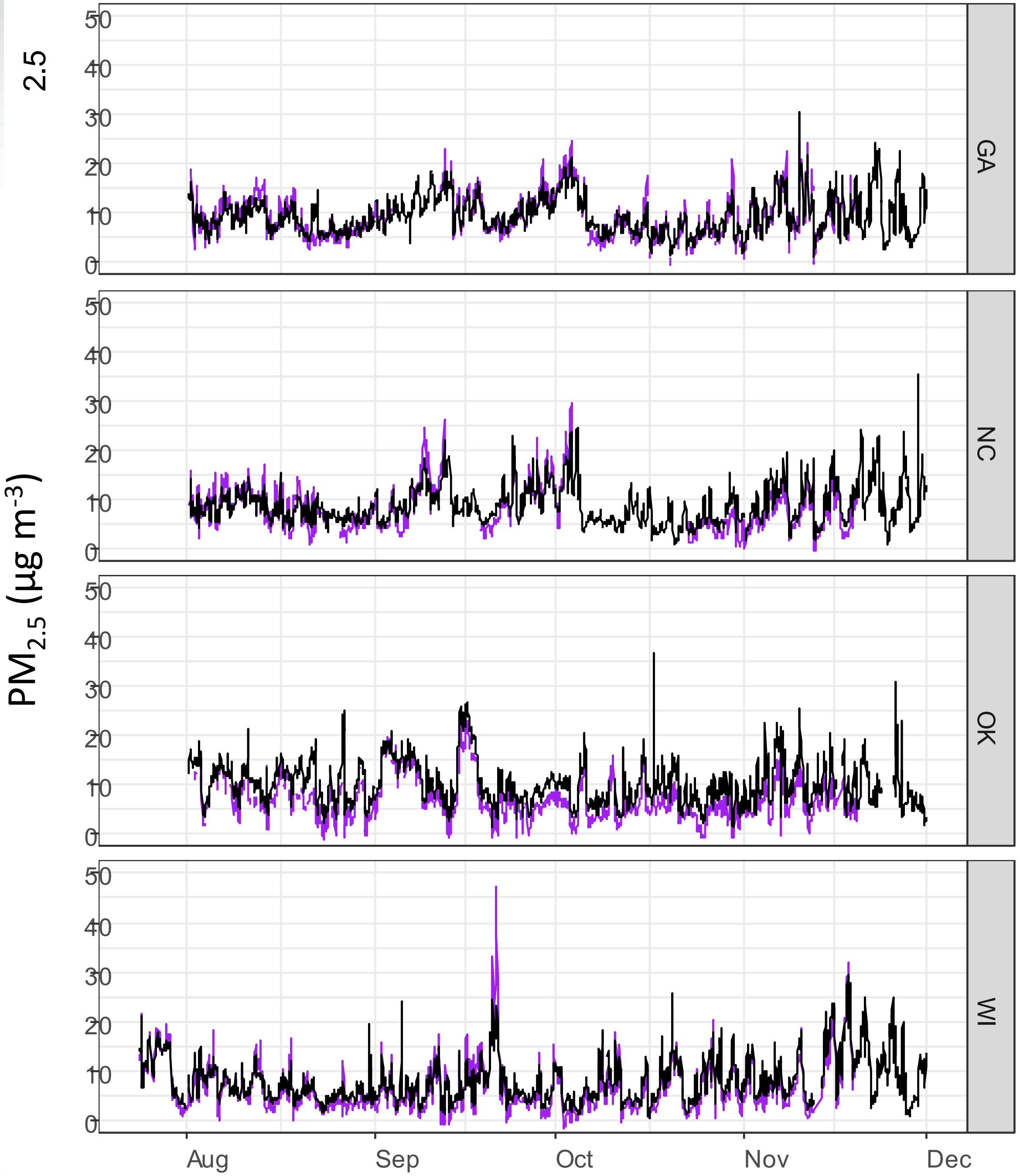
- Regulatory monitoring sites characterized as urban and neighborhood sites with no clear hyperlocal sources

Collocation characteristics:

- PurpleAir sensors sited at regulatory monitoring sites nominally following FRM/FEM siting criteria (e.g., within 10 m horizontal distance and 1 m vertical distance of the regulatory monitor, no flow obstructions, not near trees)

1-hr Typical Ambient:
FEM and Corrected PurpleAir





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Description of Smoke Measurements

Approach:

- Collocate sensors with FEM/temporary smoke monitors
- Operate where $PM_{2.5}$ concentrations were highest
- Capture a range of smoke characteristics, concentrations, and environmental conditions

Reference monitors provided by external agencies:

- Operated by multiple agencies followed their QA/QC protocols, maintained by their personnel

Site types: Fire stations/USFS facilities, monitoring shelters, other

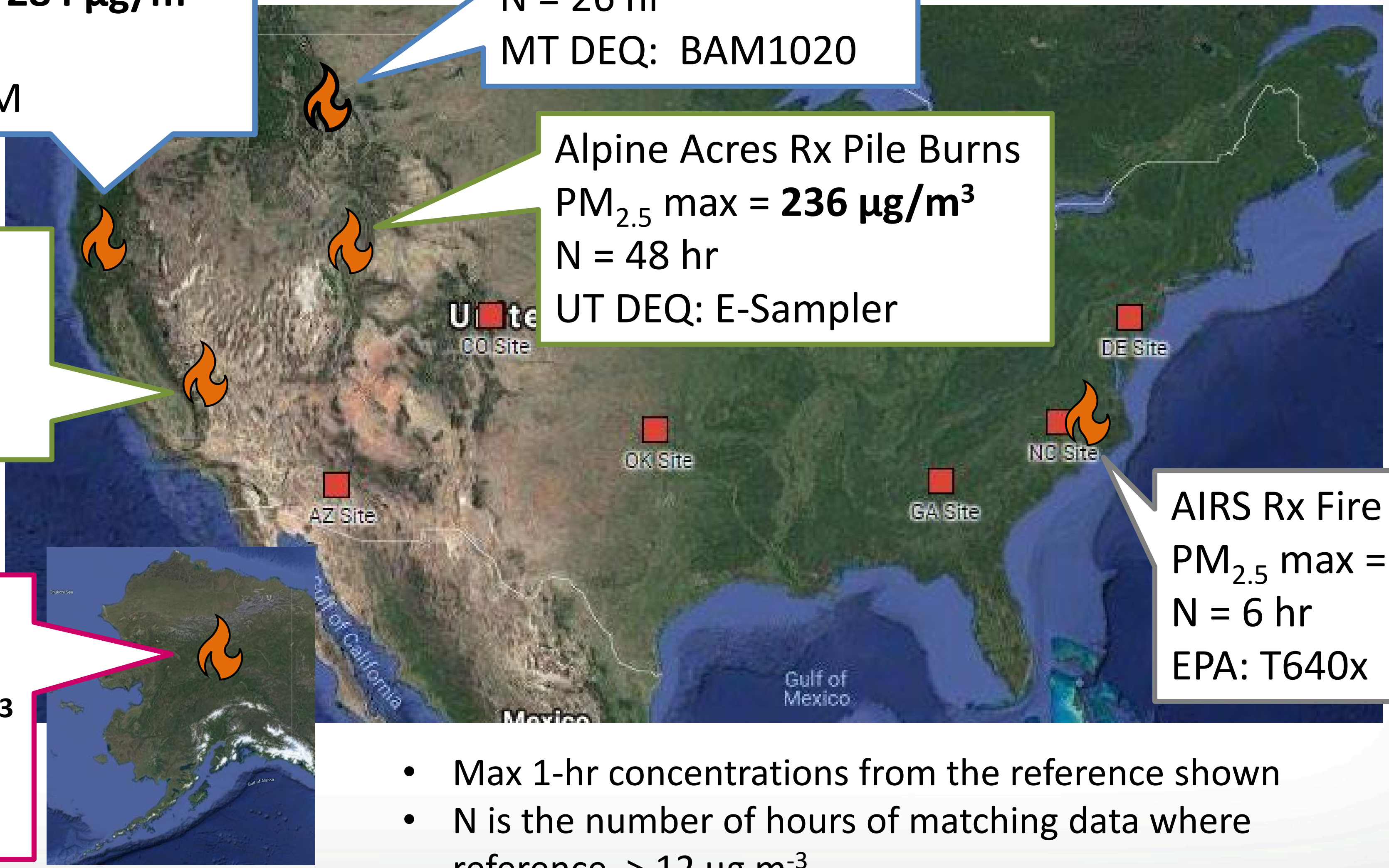
Collocation characteristics:

- Sensors within 10 m of reference instrument
- In open area without flow obstructions
- Not near trees
- Installed 1.0 – 3 m above ground

Site characteristics:

- Most were near a roadway, some unpaved
- No hyperlocal sources (e.g. barbecue grills, generators)
- Possible diesel exhaust sources
- Possible smokers

Smoke Impacted Datasets



Natchez Wildfire
$PM_{2.5}$ max = **284 µg/m³**
N = 290 hr
CARB: E-BAM

Missoula Rx Fires
$PM_{2.5}$ max = **75 µg/m³**
N = 26 hr
MT DEQ: BAM1020

Alpine Acres Rx Pile Burns
$PM_{2.5}$ max = **236 µg/m³**
N = 48 hr
UT DEQ: E-Sampler

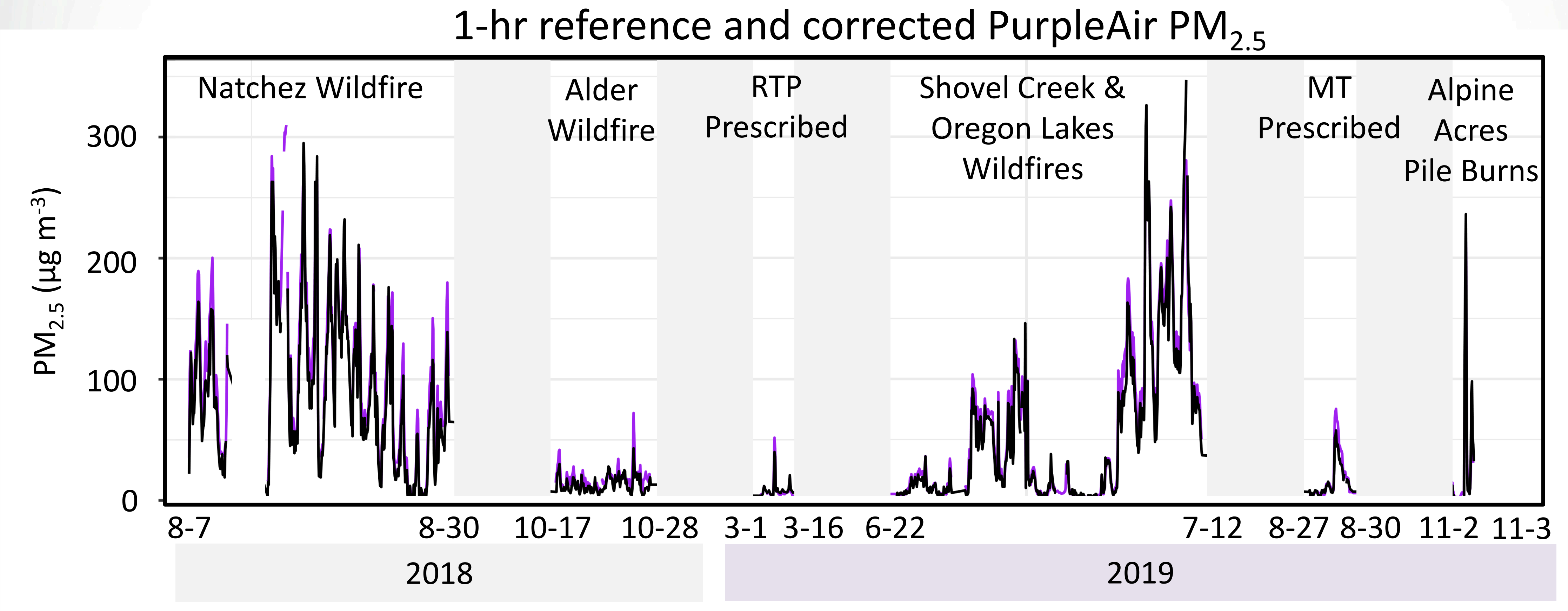
Alder Wildfire
$PM_{2.5}$ max = **32 µg/m³**
N = 64 hr
USFS: BAM 1020

AIRS Rx Fire
$PM_{2.5}$ max = **40 µg/m³**
N = 6 hr
EPA: T640x

Shovel Creek/Oregon Lakes Wildfires
$PM_{2.5}$ max = **200 µg/m³**
N = 290 hr
ADEC: BAM 1020

- Max 1-hr concentrations from the reference shown
- N is the number of hours of matching data where reference > 12 µg m^{-3}

Smoke Impacted Time Series



Applying the Correction to 1-hr Data

1. Average PurpleAir data to 1-hour
2. Clean the data; channels differ by ≥ ± 5 μg m^{-3} and ≥ ± 70%
3. Average A & B channels
4. Apply U.S.-wide correction equation to **1-hr data**
5. Apply the Nowcast (weighted 12-hr rolling average)
   – NowCast is used to make 1-hr measurements more similar to the 24-hr measurements that health effects research is based on

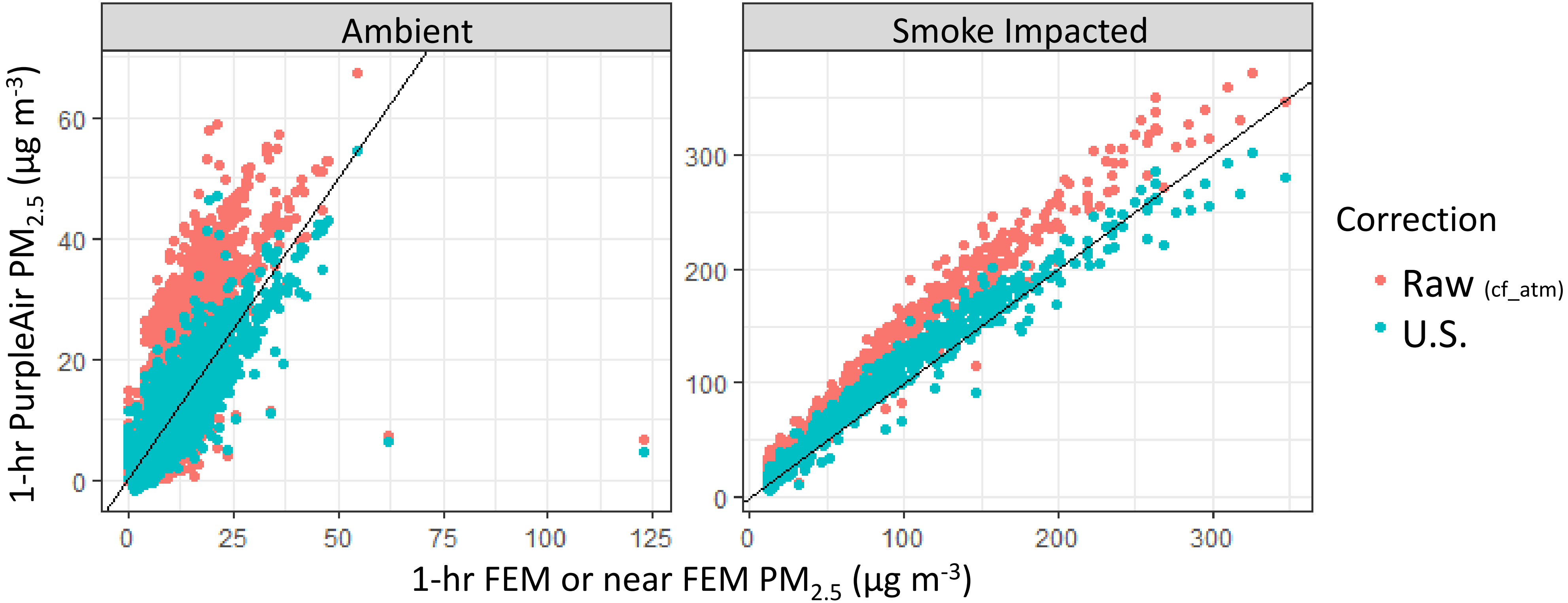
Verify performance

- Gauge ambient performance using 1-hr data from the 7 long-term performance site (NC, DE, GA, WI, OK, CO, AZ)
- Examine smoke-impacted performance (6 sites)

1-hr U.S.-Wide Correction Equation Performance

				Ambient	Smoke
Correction	type	cf	Equation	MBE µg m^{-3} (%)	MBE µg m^{-3} (%)
U.S.	U.S. ambient	1	PAx0.52 - 0.085xRH + 5.71	-1.0 (12%)	6.4 (12%)
None		atm		2.7 (32%)	30.2 (38%)

U.S.-wide correction reduces error from raw cf_atm data



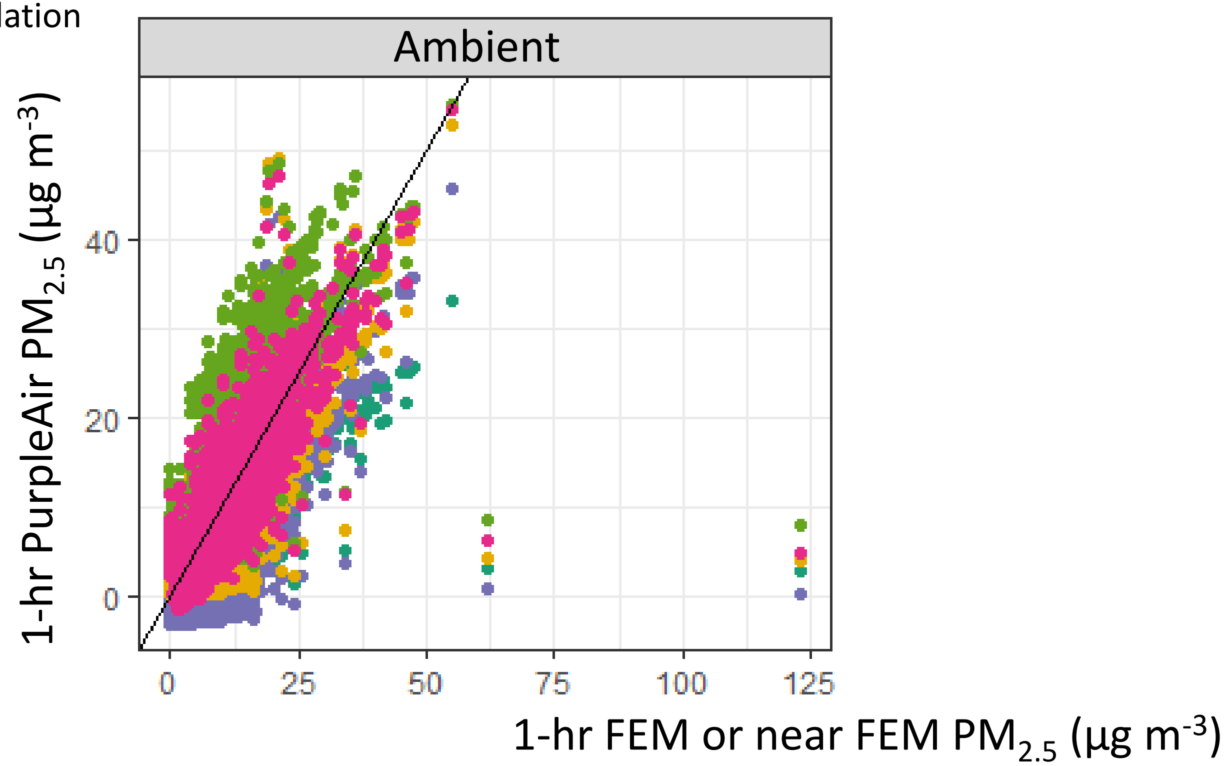
Comparison of PurpleAir Corrections

Correction	Type	cf	Equation	Ambient MBE μg m^{-3} (%)
U.S.	U.S. ambient	1	PAx0.52 - 0.085xRH + 5.71	-1 (11%)
Holder	Wildfire	1	PAx0.51 - 3.21	-6 (70%)
LRAPA	Woodsmoke	atm	PAx0.5 - 0.66	-4 (42%)
Robinson	Woodsmoke	1	PAx0.55	-2 (27%)
AQ&U	UT ambient	atm	PAx0.778 + 2.65	3 (34%)
Mehadi	Woodsmoke	?*		--

*Not included since uncertain on calculation

For typical ambient data:

- **U.S.-wide correction** reduces bias more than other corrections



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Correction	Type	cf	Equation	MBE μg m^{-3} (%)	MBE μg m^{-3} (%)
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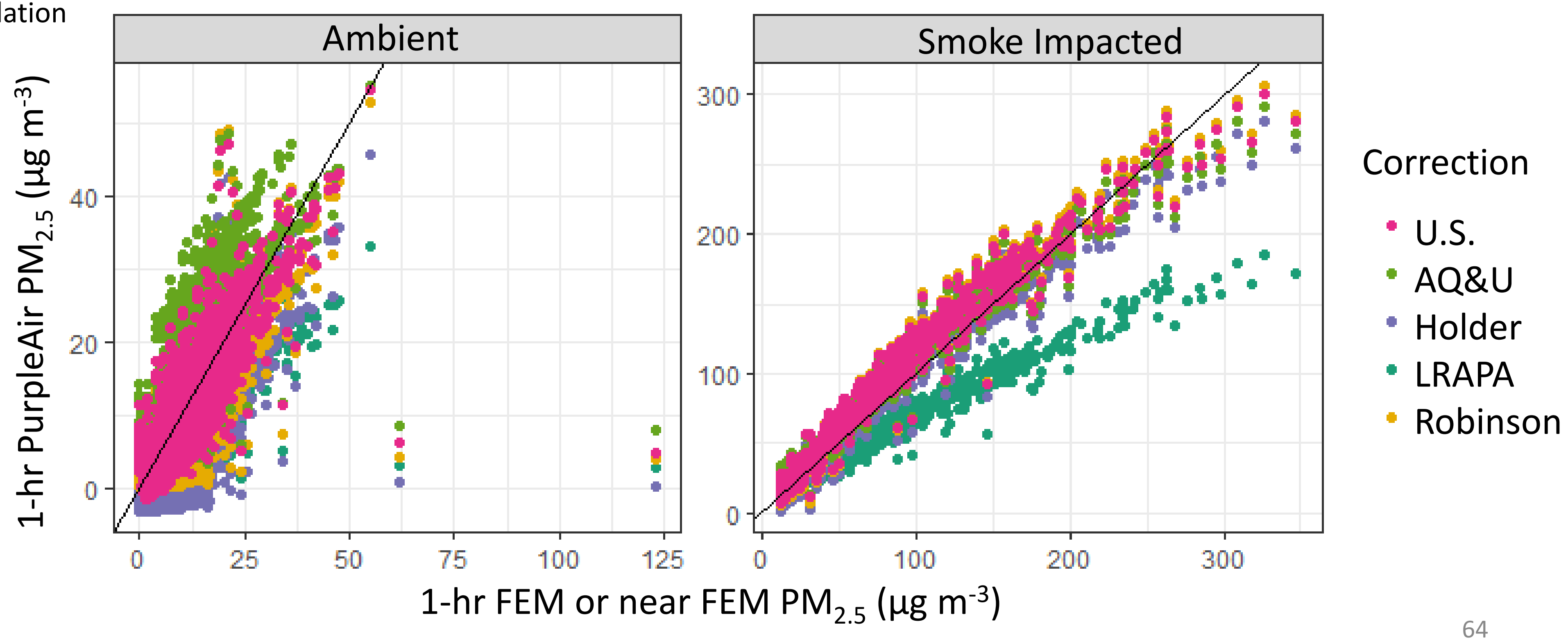
Holder	Wildfire	1	PAx0.51 - 3.21	-6 (70%)	0 (1%)
LRAPA	Woodsmoke	atm	PAx0.5 - 0.66	-4 (42%)	-25 (32%)
Robinson	Woodsmoke	1	PAx0.55	-2 (27%)	9 (12%)
AQ&U	UT ambient	atm	PAx0.778 + 2.65	3 (34%)	9 (11%)
Mehadi	Woodsmoke	?*		--	--

*Not included since uncertain on calculation

Under smoke conditions:

- **Holder** correction reduces most bias



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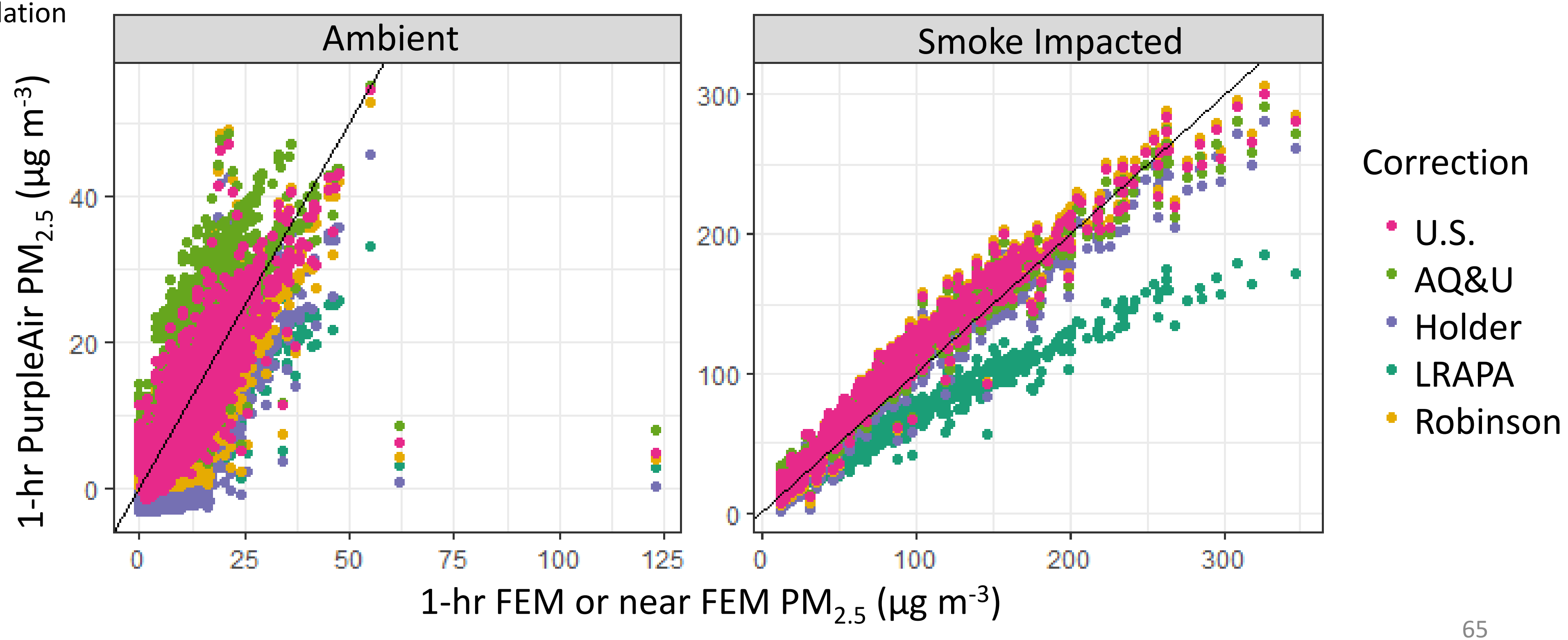
*Not included since uncertain on calculation

Under smoke conditions

- **Holder** correction reduces most bias
- **U.S., Robinson, & AQ&U** work similarly



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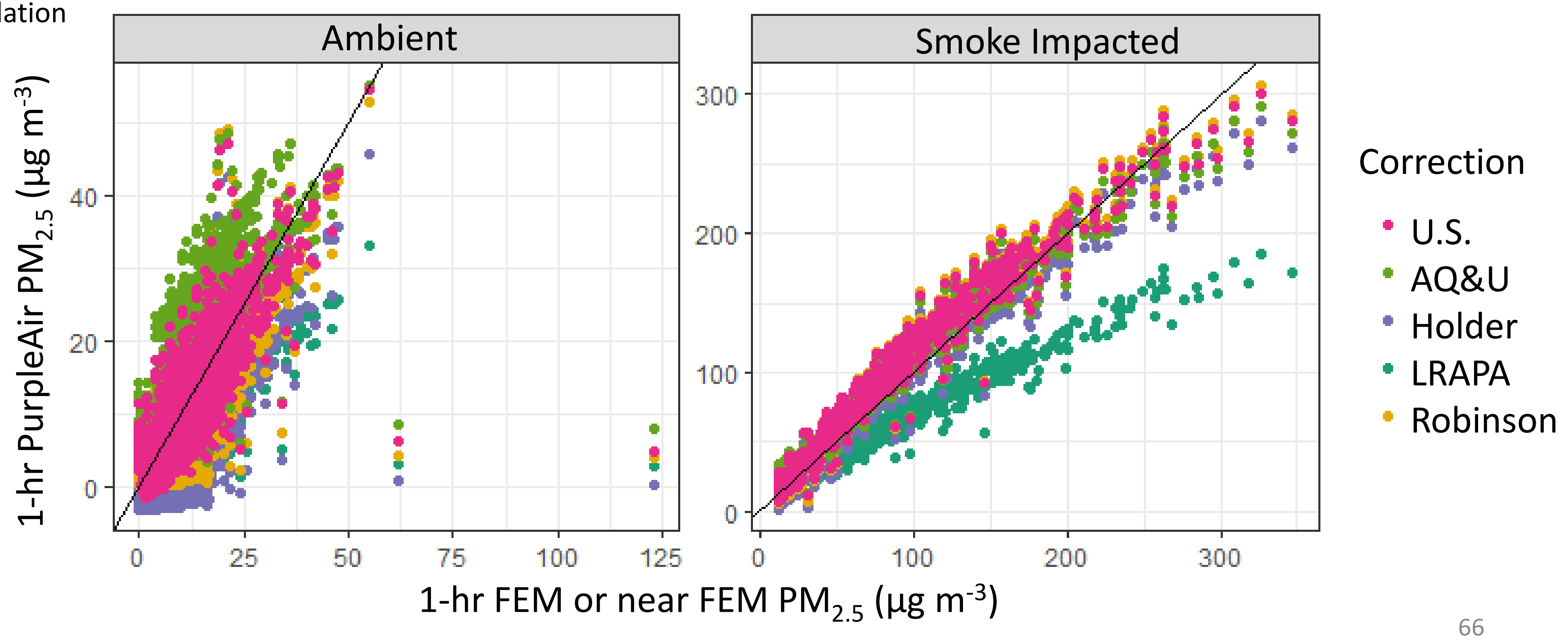
Mehadi	Woodsmoke	?*		--	--

*Not included since uncertain on calculation

Under smoke conditions

- **Holder** correction reduces most bias
- **U.S., Robinson, & AQ&U** work similarly
- **LRAPA** shows strong underestimation
  - Likely because it was developed on data 0-65 µg m^{-3}



Comparison of PurpleAir Corrections

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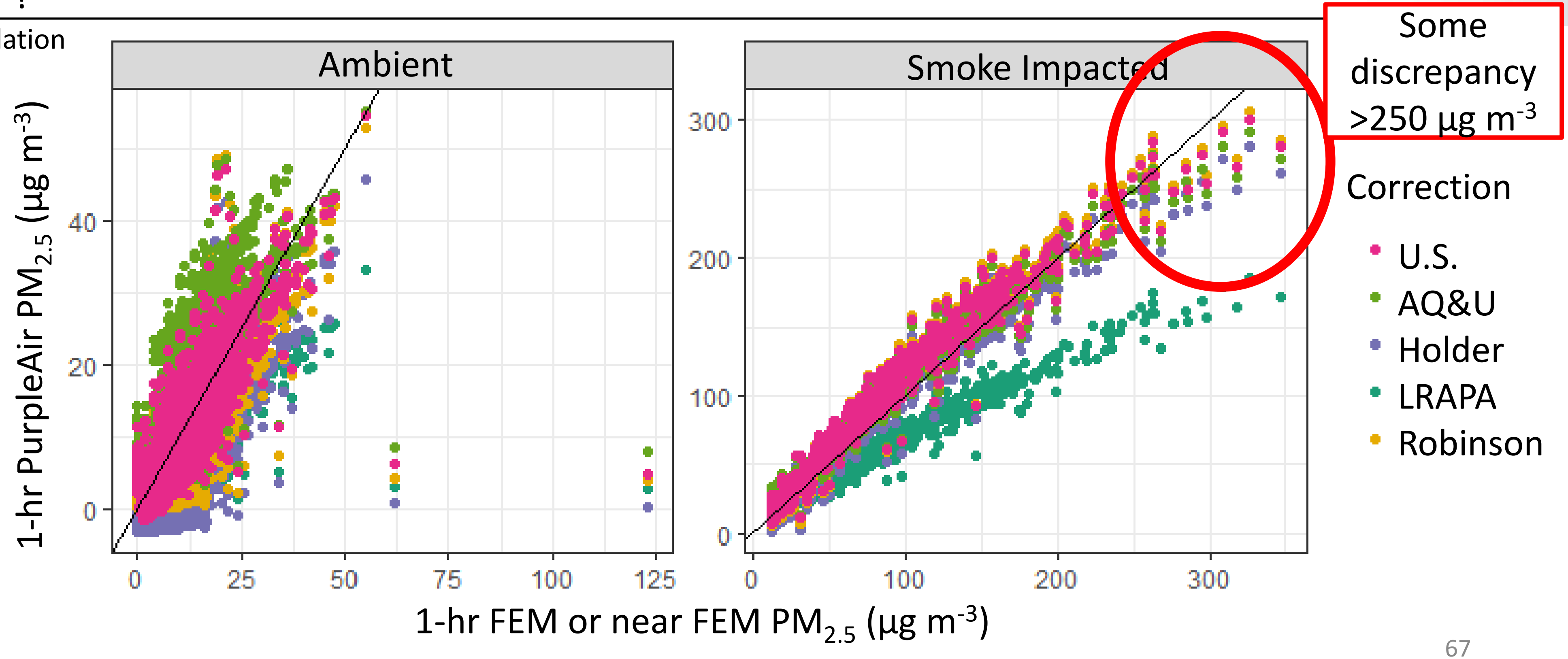
Under smoke conditions

- **Holder correction** reduces most bias
- **U.S., Robinson, & AQ&U** work similarly
- **LRAPA** shows strong underestimation
    - Likely because it was developed on data 0-65 µg m^{-3}



Comparison of PurpleAir Corrections

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Correction	Type	cf	Equation	MBE µg m-3 (%)	MBE µg m-3 (%)
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AQ&U	UT ambient	atm	PAx0.778 + 2.65	3 (34%)	9 (11%)
Mehadi	Woodsmoke	?*		--	--

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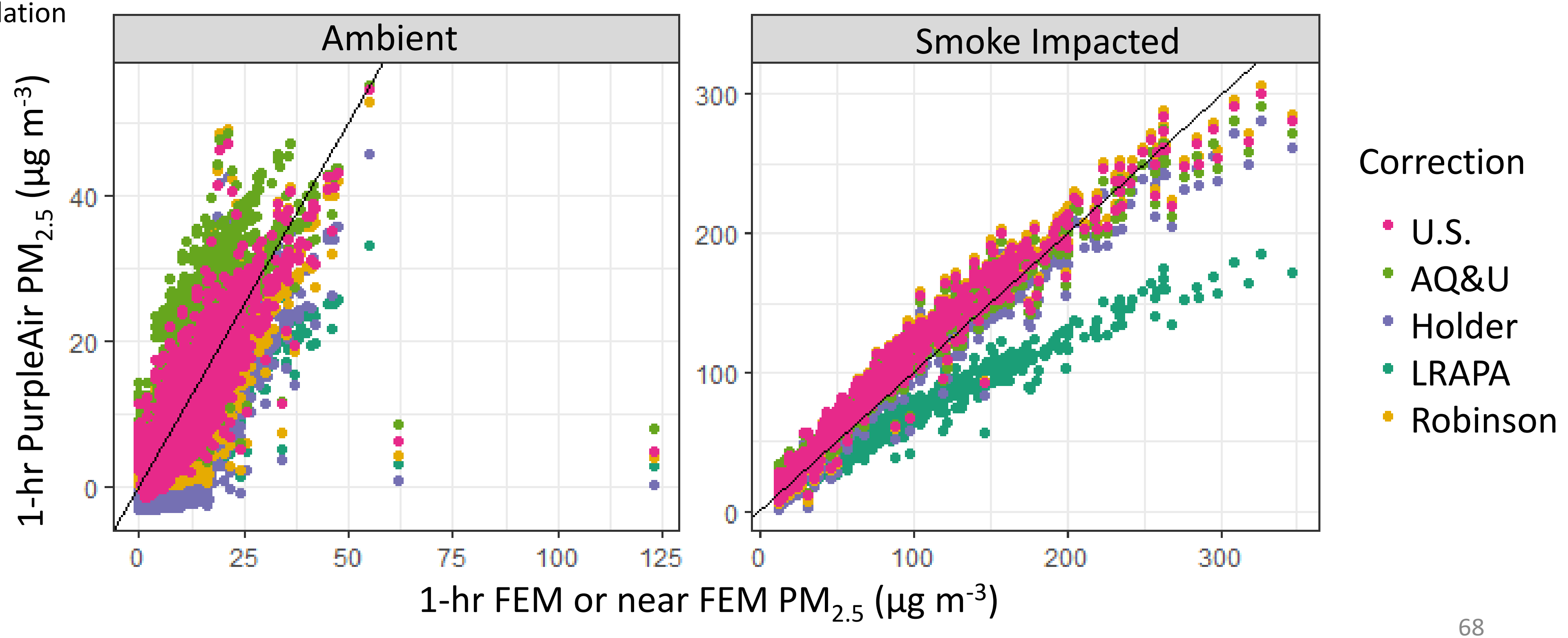
U.S. correction used on the AIRNow map

- Reduces bias under typical ambient conditions
- Some high bias 50-200 µg m^{-3}
- Less underestimate at high concentration



Evaluating Correction with NowCasted Datasets

Comparing the NowCasted PurpleAir and reference measurements

- Both “Raw” as displayed on PurpleAir.com/map
- And “Corrected” with U.S.-wide correction
- Includes both the smoke and ambient datasets

Evaluating Correction with NowCasted Datasets

Comparing the NowCasted PurpleAir and reference measurements

- Both "Raw" as displayed on the PurpleAir.com/map
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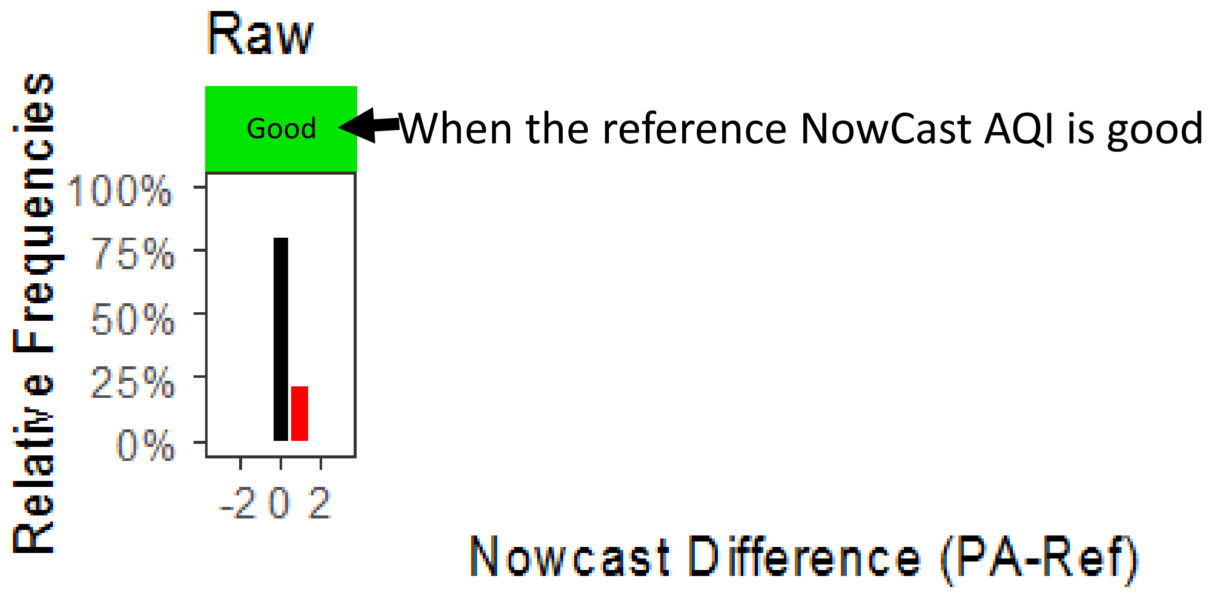

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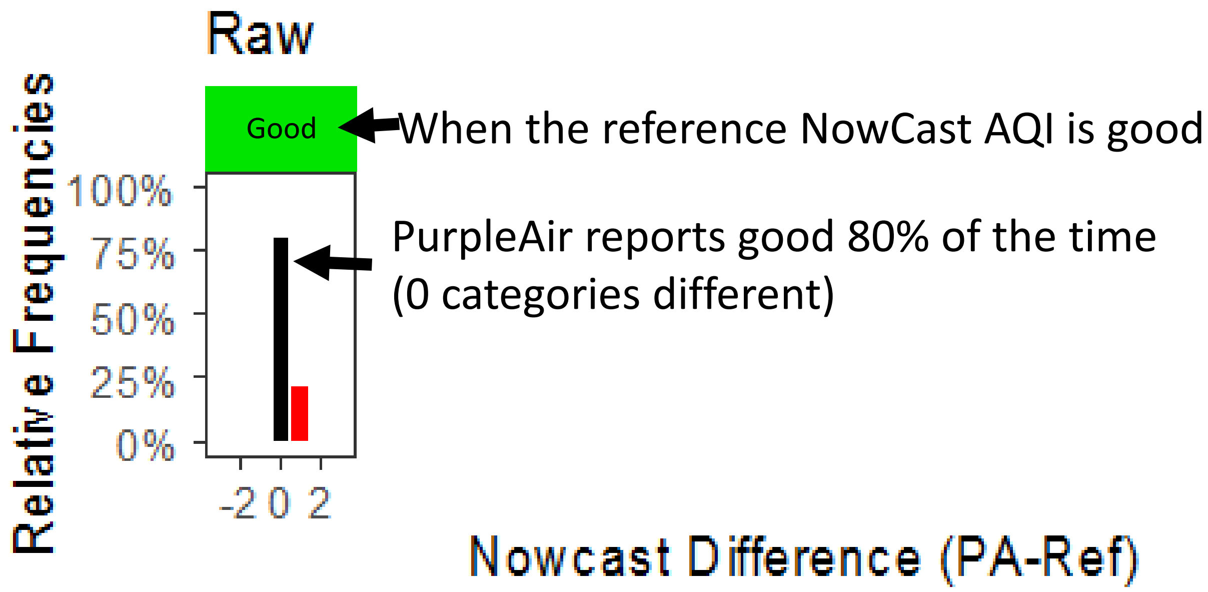
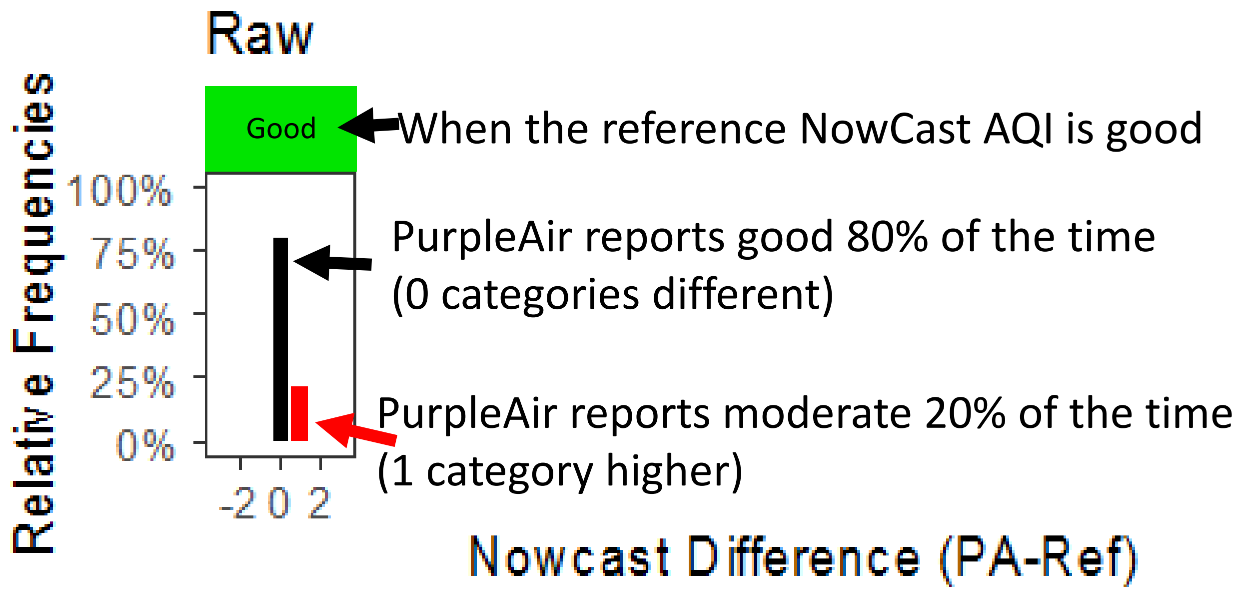


Evaluating Correction with NowCasted Datasets

Comparing the NowCasted PurpleAir and reference measurements

- Both “Raw” as displayed on the PurpleAir.com/map
- And “Corrected” with U.S.-wide correction



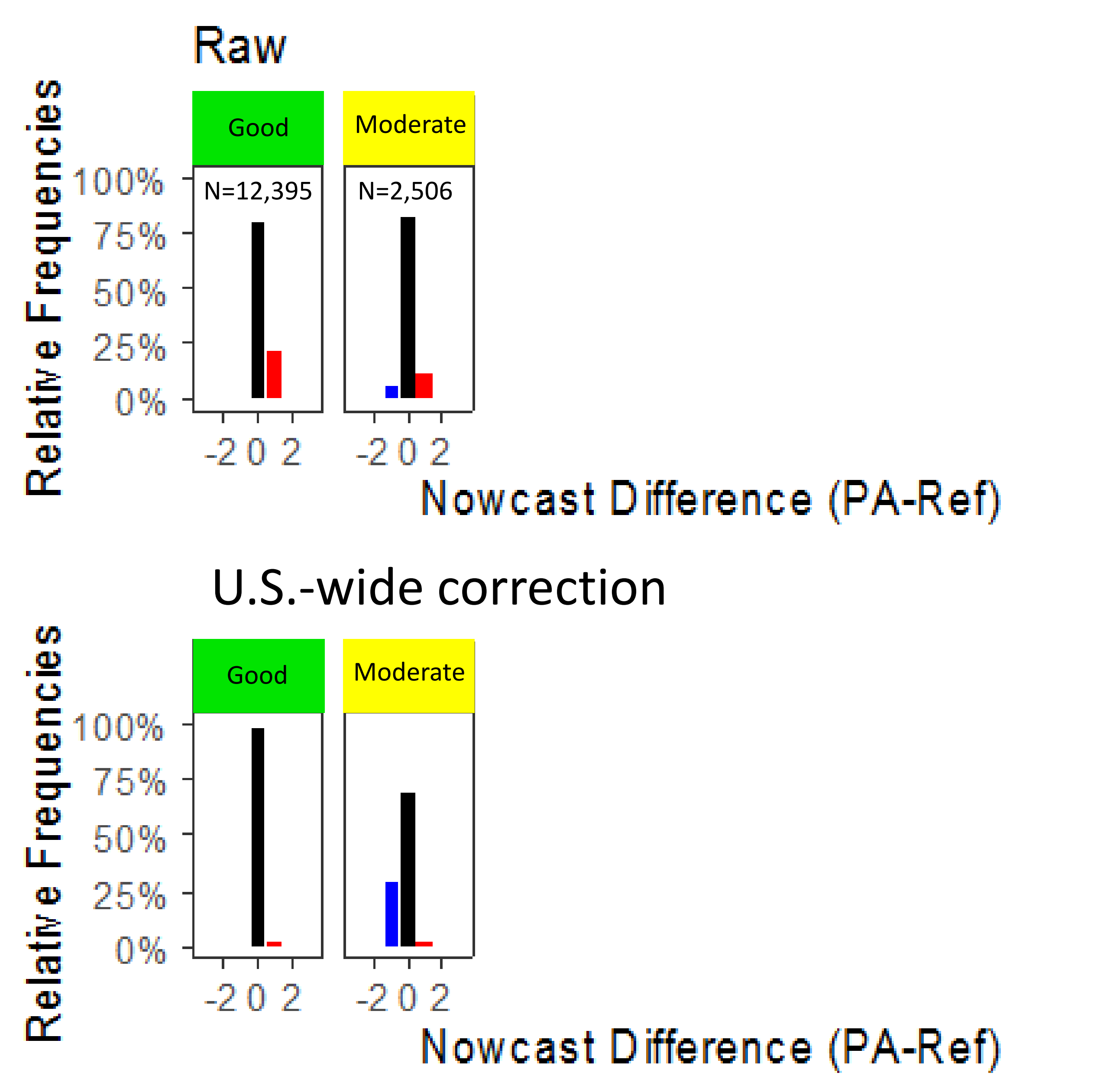
Evaluating Correction with NowCasted Datasets: Low-Moderate

PurpleAir map data:

- Overestimates NowCast AQI ~20% of the time
- Some underestimation at moderate AQI

U.S.-wide correction:

- Less over estimation at Good AQI
- More under estimation at Moderate AQI



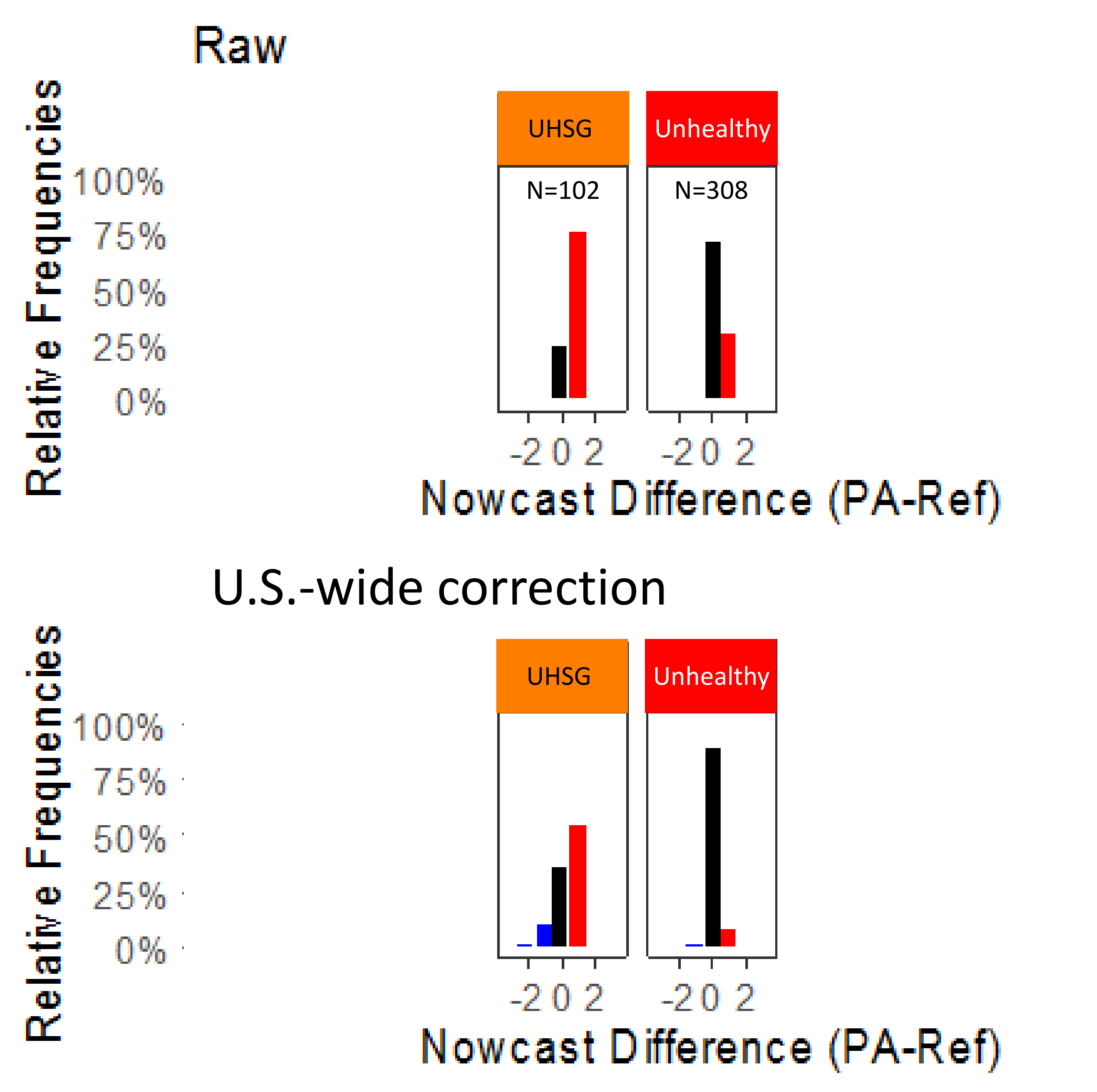
Evaluating Correction with NowCasted Datasets: UHSG-Unhealthy

PurpleAir map data:

- Overestimates NowCast AQI most (75%) of the time in the Unhealthy for Sensitive Groups (UHSG) category
- 30% overestimate during Unhealthy AQI

U.S.-wide correction:

- More balanced estimate of UHSG
- More often predicts correct Unhealthy AQI



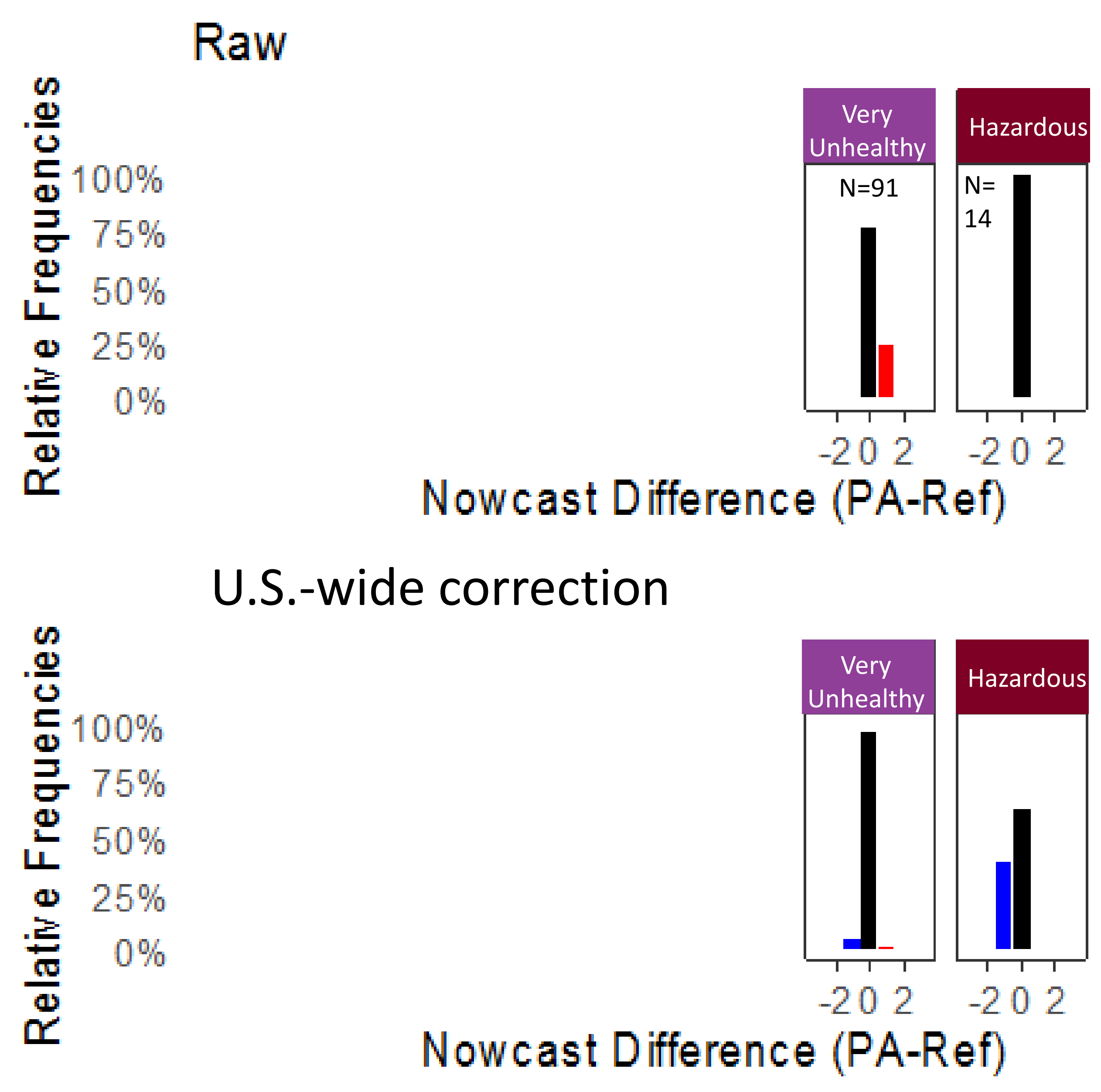
Evaluating Correction with NowCasted Datasets: Very Unhealthy-Hazardous

PurpleAir map data:

- Overestimates 20% of the time during Very Unhealthy AQI

U.S.-wide correction:

- 40% underprediction at Hazardous AQI
- Only 14 hours in the Hazardous category
- More data needed to constrain potential quadradic relationship above ~300 μg m^{-3}
- Actions taken at Very Unhealthy and Hazardous levels may be similar



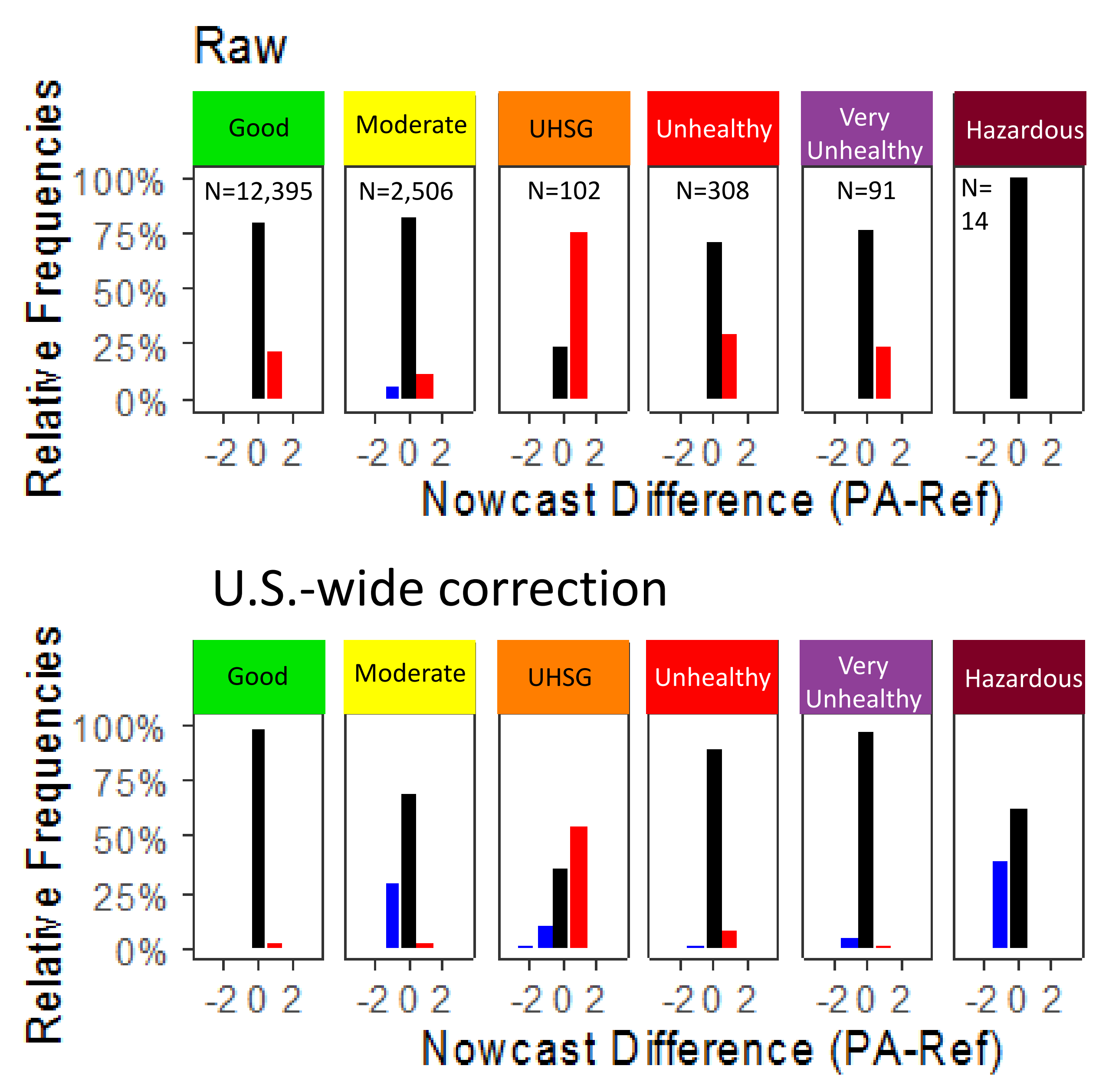
Evaluating Correction with NowCasted Datasets: Overall

PurpleAir map data systematically over predicts AQI category:

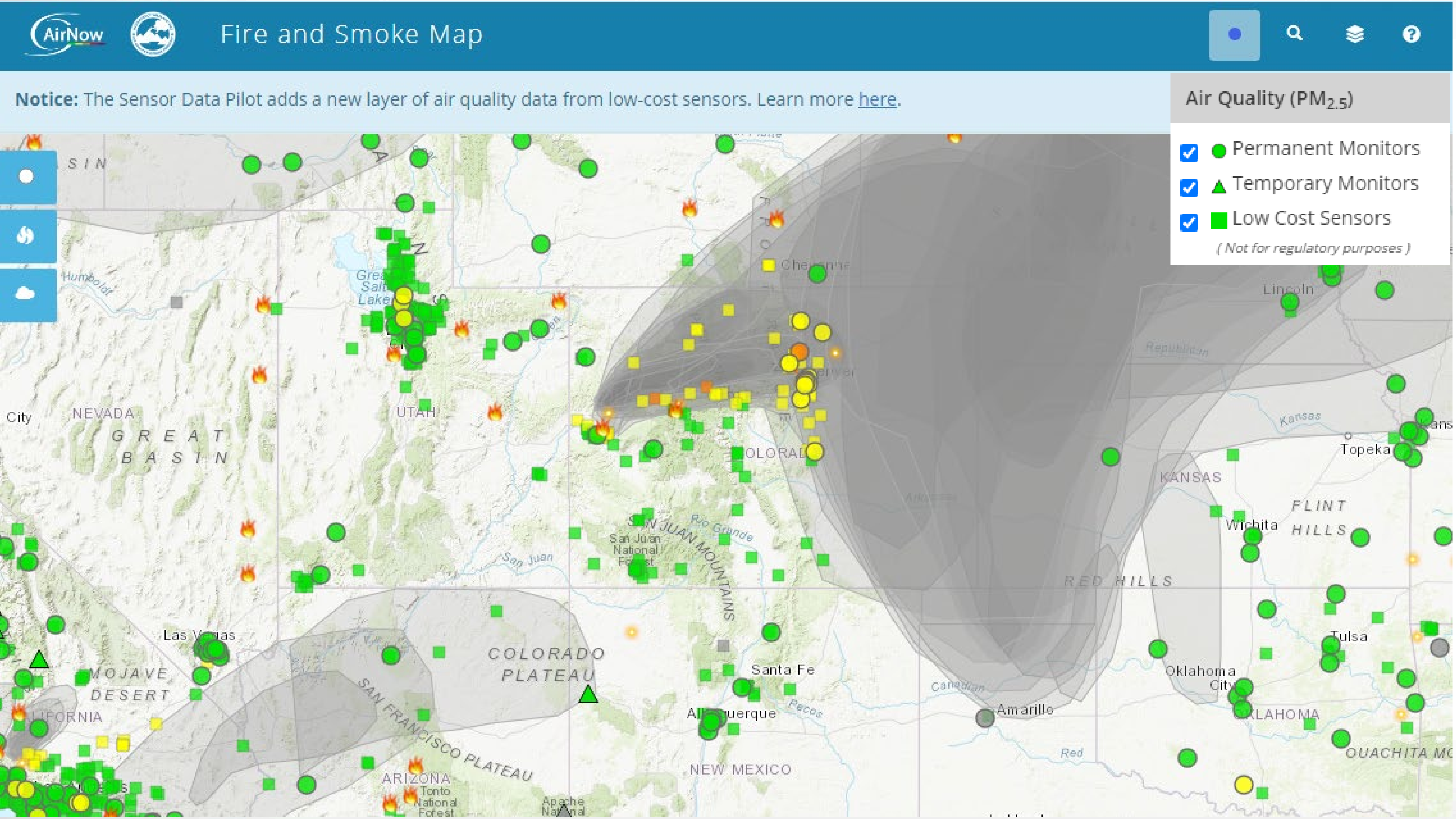
- Overestimates more often in most categories
- Typically within 1 AQI category

U.S.-wide correction typically improves $PM_{2.5}$ accuracy

- Reports correct category more often than "Raw" except in the Moderate and Hazardous categories
- Typically within 1 AQI category
- More high concentration data needed



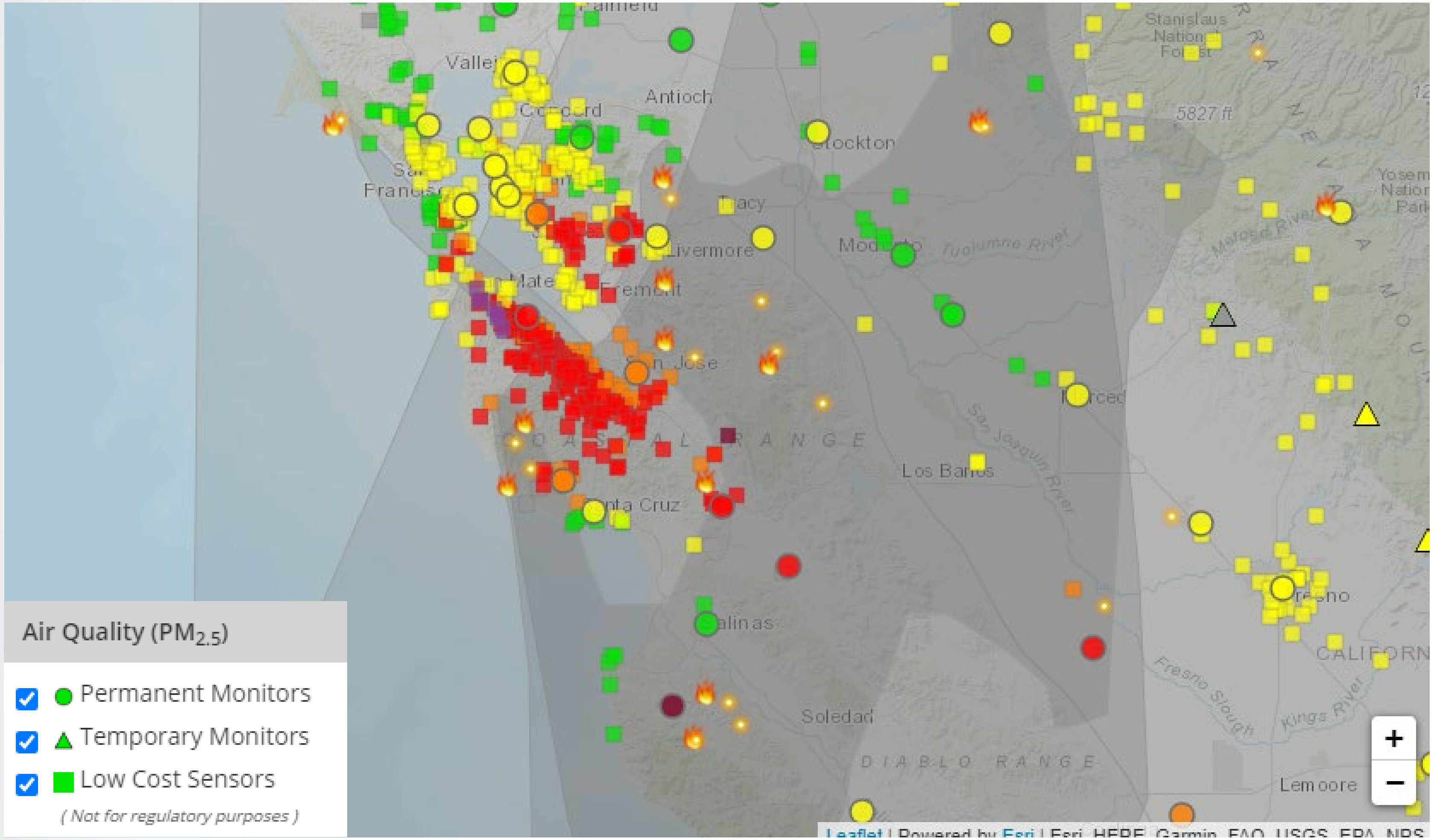
PurpleAir Performance on the AirNow Map



PurpleAirs add spatial variation

https://fire.airnow.gov/ (8/11/2020)

PurpleAir Performance on the AirNow Map



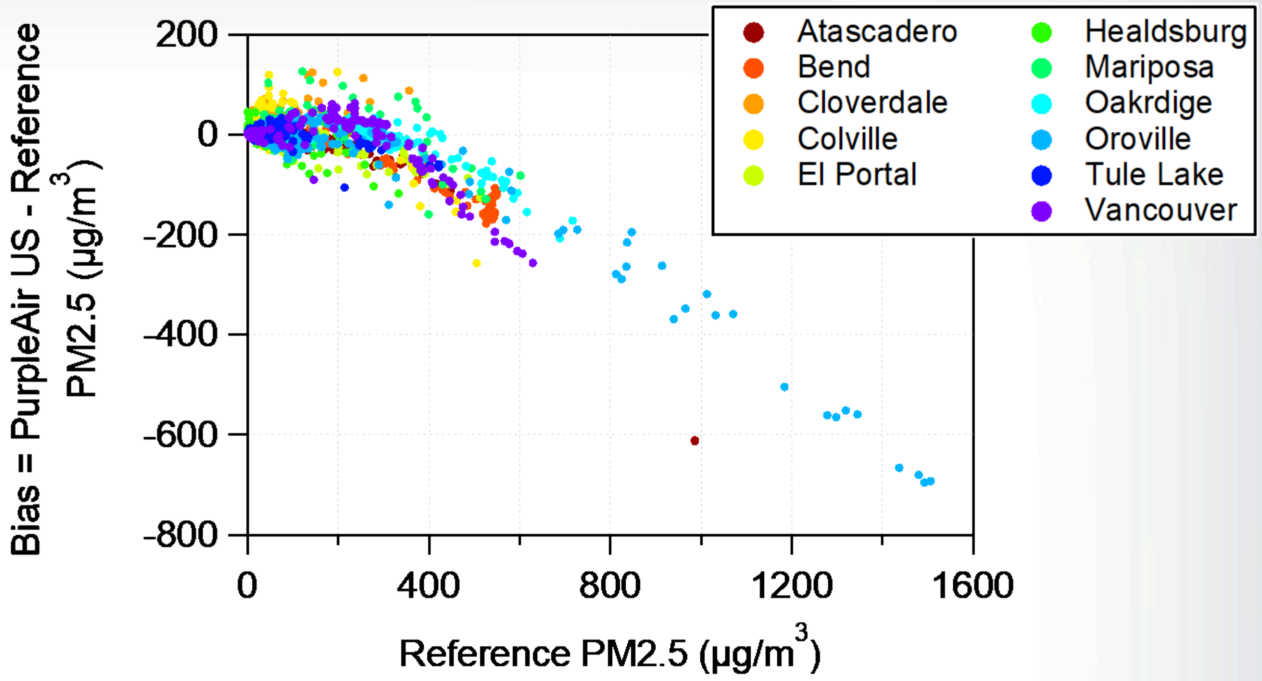
PurpleAirs show similar trends to AirNow monitors

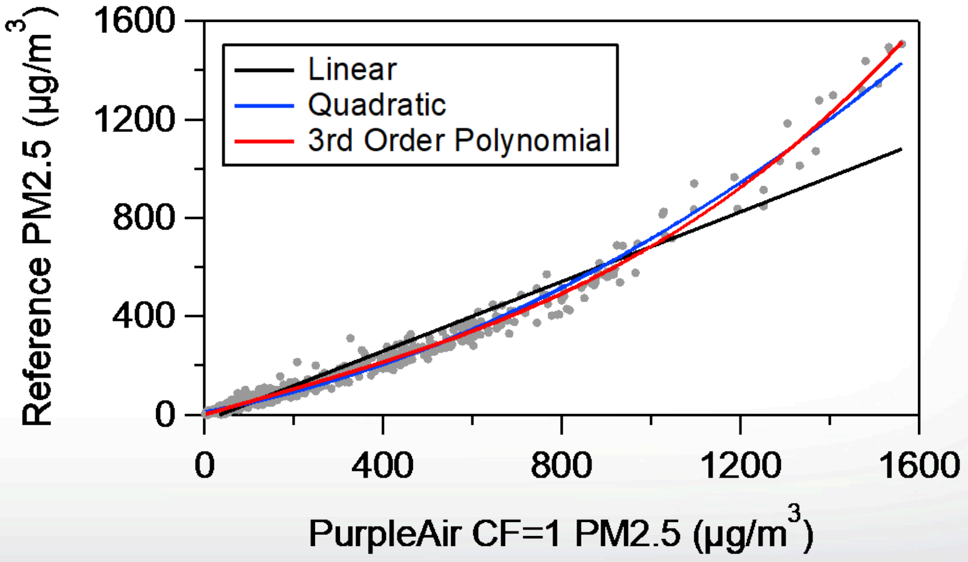
https://fire.airnow.gov/ (8/19/2020)

Suspected/Known Issues Requiring Further Investigation

Evidence of Saturation at High Concentrations

- PurpleAir has a linear response to about 200 μg m^{-3}
- Lab studies have shown:
  - Polynomial fit may be better at higher concentrations (Sayahi et al. 2019)
  - PurpleAir stops responding at about 11,000 – 13,000 μg m^{-3}, depends upon PM composition and size (Zou et al. 2019)
- In the past month used crowdsourced collocated data at ***very high*** concentrations investigate new correction at high concentration





Linear
Corrected = 0.71*PurpleAir(CF=1) - 23.5
Quadratic
Corrected = $0.000363 \cdot \text{PurpleAir(CF=1)}^2 + 0.342 \cdot \text{PurpleAir(CF=1)} + 10.81$
3rd Order Polynomial
Corrected = $2.26\times10^{-7} \cdot \text{PurpleAir(CF=1)}^3 - 6.86\times10^{-5} \cdot \text{PurpleAir(CF=1)}^2 + 0.525 \cdot \text{PurpleAir(CF=1)} + 0.97$

Sensor Response is Sensitive to Size and Optical Properties

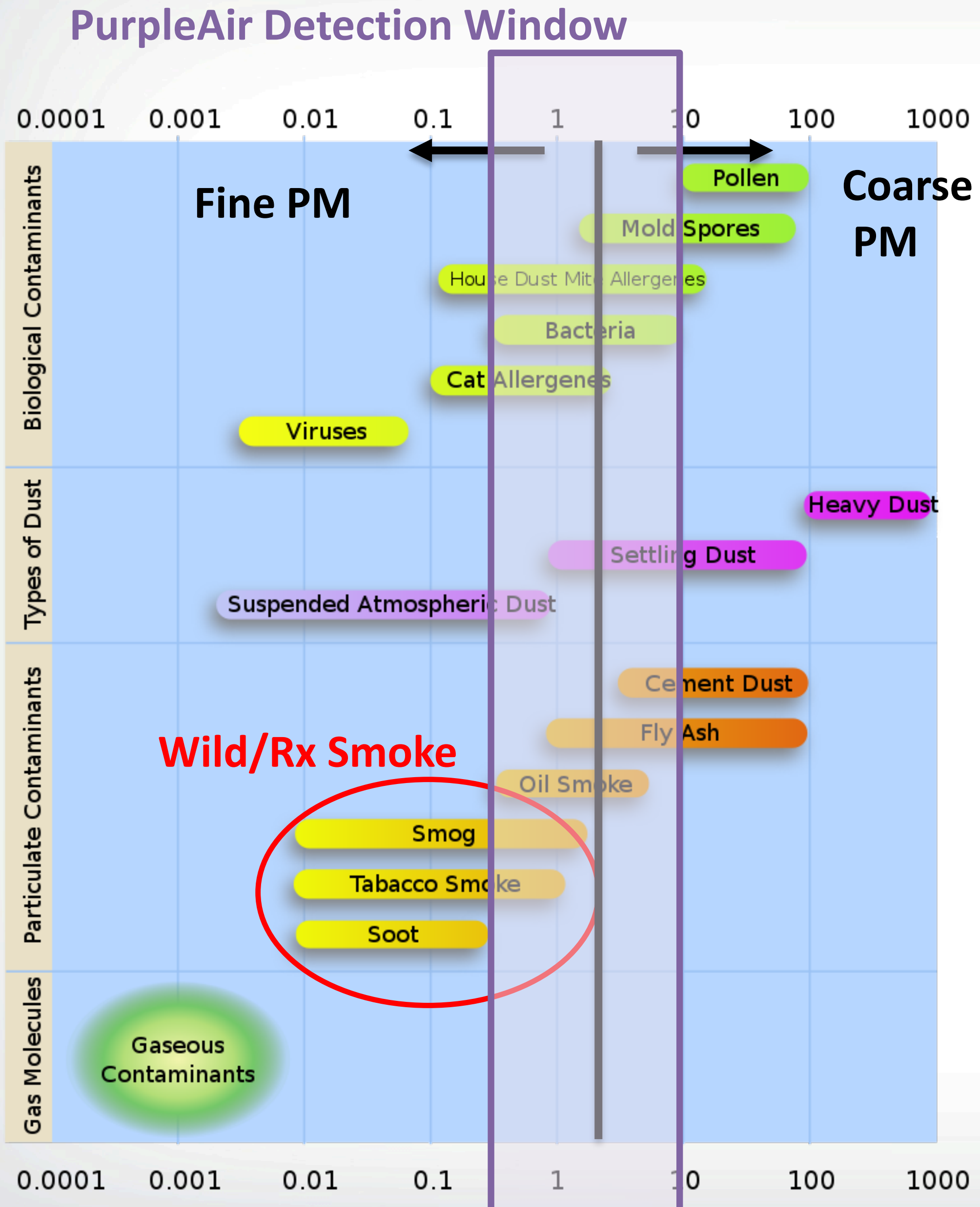
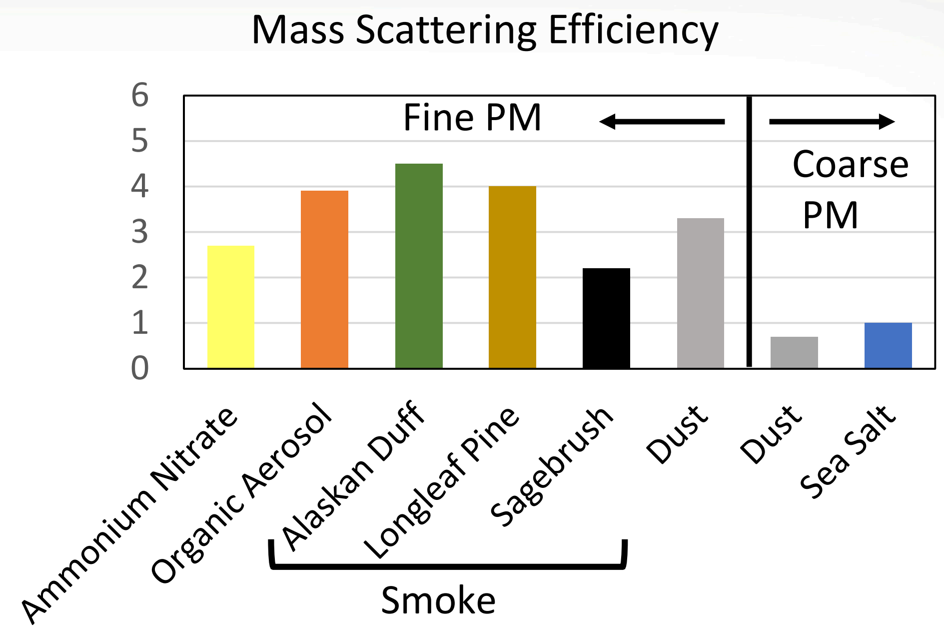


Image source: Wikipedia



- Most ambient PM and smoke is in the fine size range ($PM_{2.5}$)
- Coarse PM e.g. dust and sea salt have **very different** response
- Mass scattering efficiency approximates PurpleAir response and can vary by size and by composition
- Response may vary by fuel type and smoke source
- Correction will not always apply (e.g., sea salt, dust, other types of pollution)

Impact of Other Source Types on Sensor $PM_{2.5}$ Concentrations

- Sensors respond to PM light scattering
- Large dust particles scatter much less light than small particles per unit mass
- Sensor low bias compared to reference monitors
- Example shows Saharan dust episode in southeastern U.S.
- **U.S.-wide correction is not applicable to some PM sources**

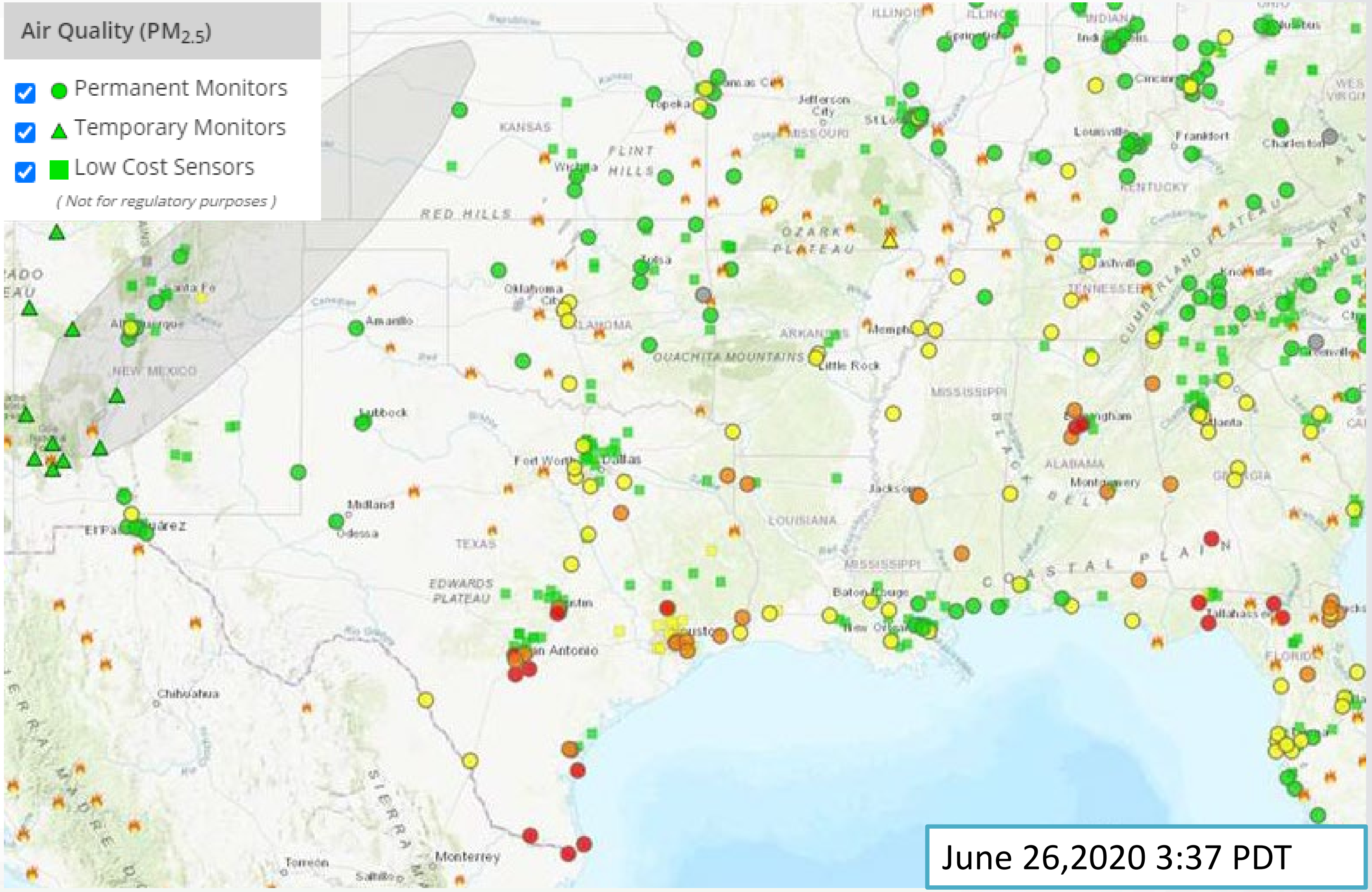


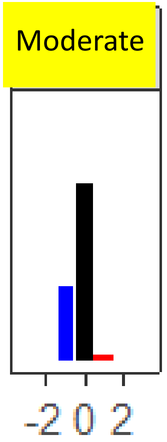
Image source: Duc Nguyen BAAQMD

Unknown Source of Disagreement

Example shows sensors with Good AQI levels while regulatory monitors show Moderate

Potential reasons:

- Refresh rate difference between sensors and monitors
- $PM_{2.5}$ concentrations are right at borderline of the AQI
- Unique aerosol source
- Other problem??



Nowcast Difference (PA-Ref)

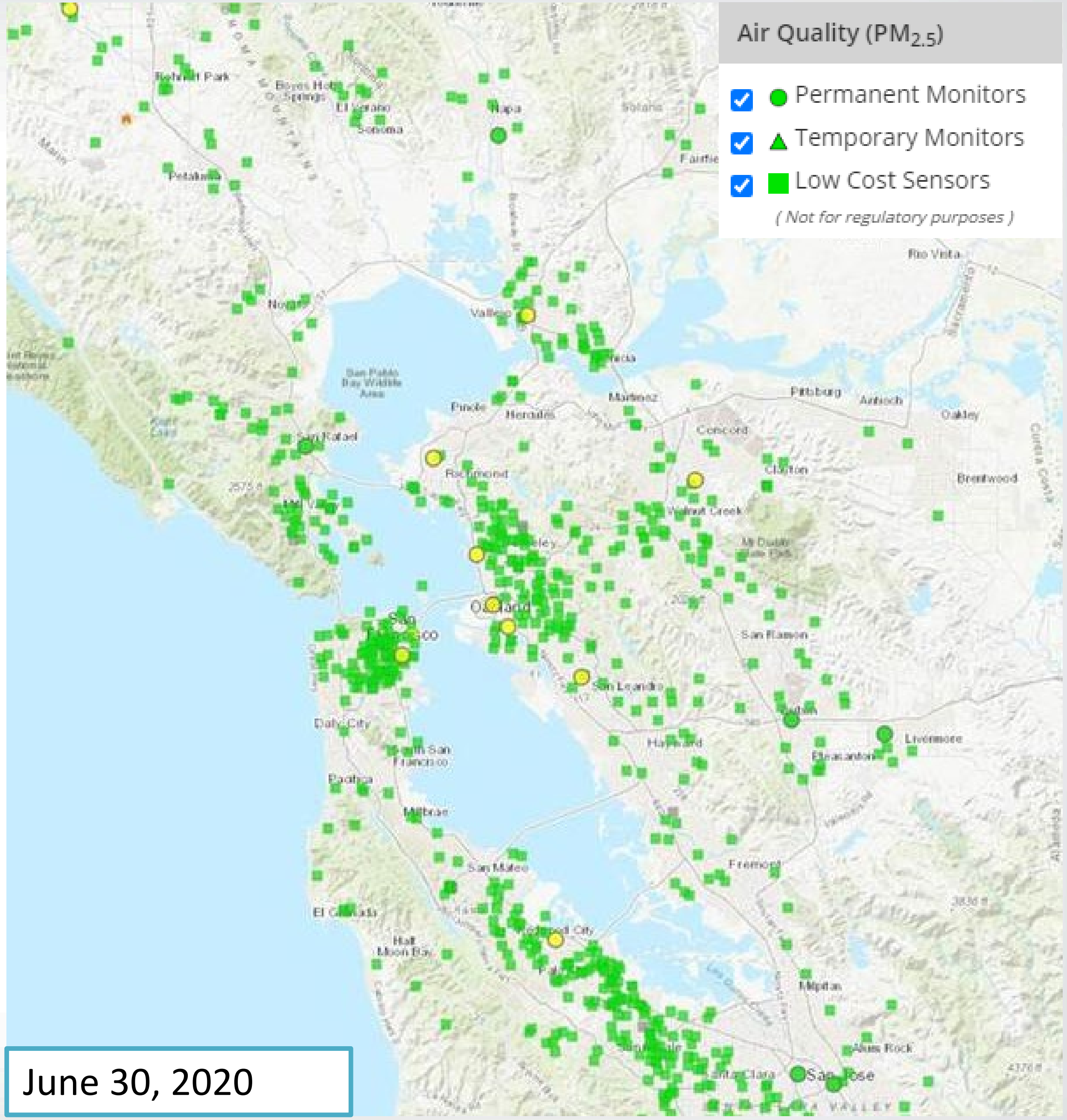


Image source: Duc Nguyen BAAQMD

Crowdsourced Data QA/QC Concerns

PurpleAir Sensor Issues

- **Most PurpleAir failures are captured by A – B channel cleaning steps.**

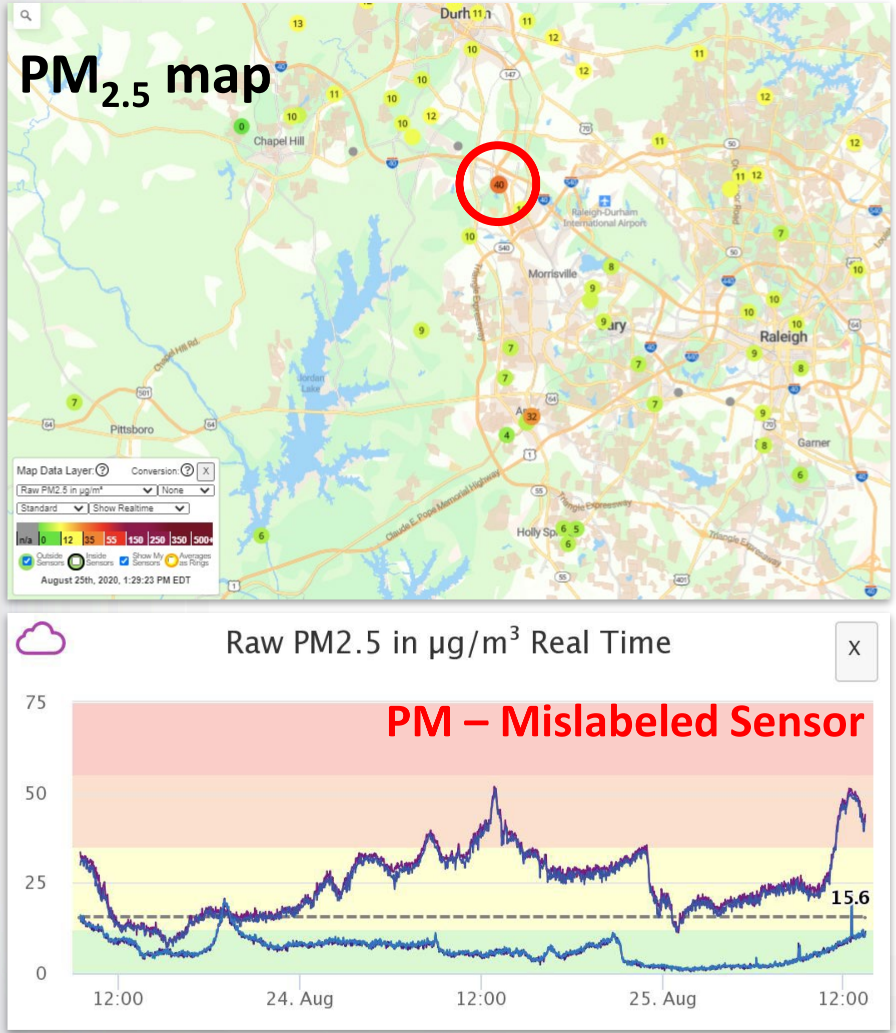
  Mazama Science developed a list of example failure modes that can be found here:
  https://mazamascience.github.io/AirSensor/articles/articles/purpleair_failure_modes.html

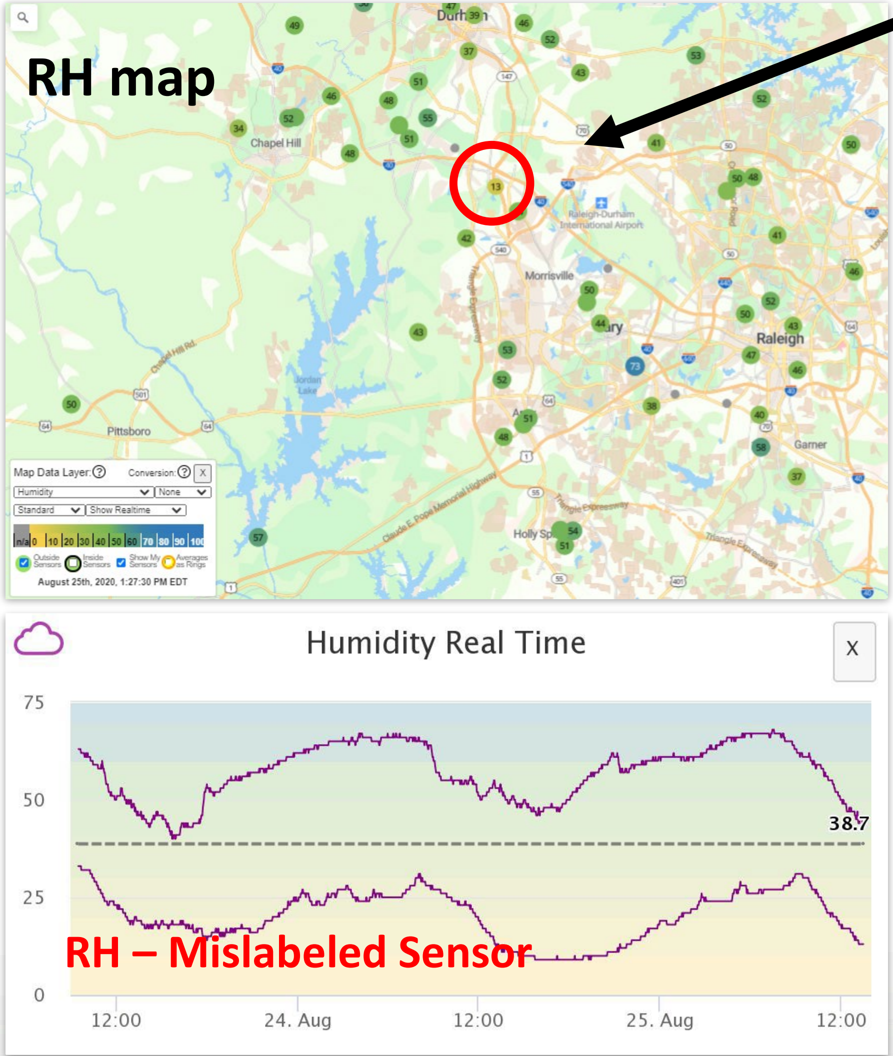
  Briefly:
  - Single channel noise
  - Large jump in single channel data
  - Single channel tracks RH or T
  - Single channel stuck at a number or zero

- **Sensor drift with age is not easy to identify.**

- **Sensor lifespan under different $PM_{2.5}$ concentrations or ambient conditions is still unknown.**

Crowd Sourced Data Issue: Mislabeled GPS Coordinates

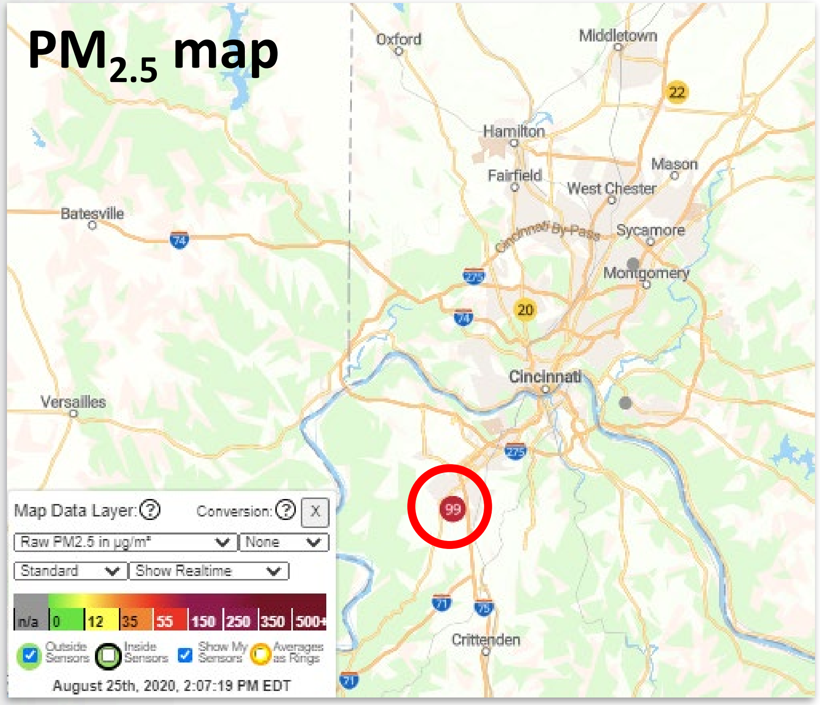


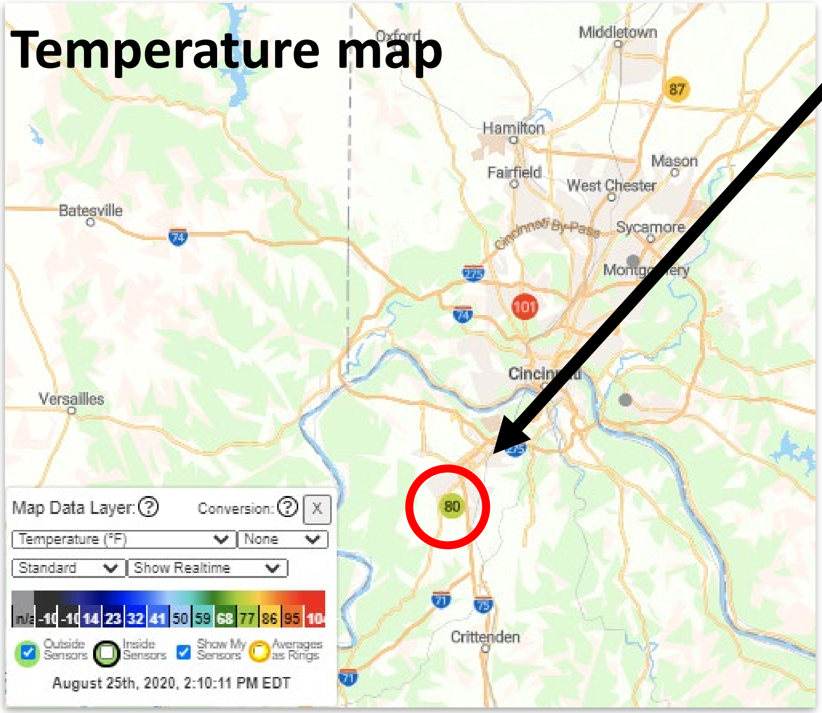


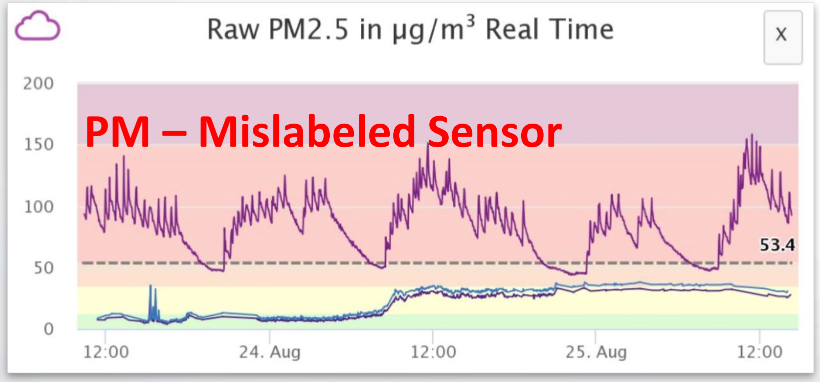
Example of outdoor sensor that disagrees with neighbors

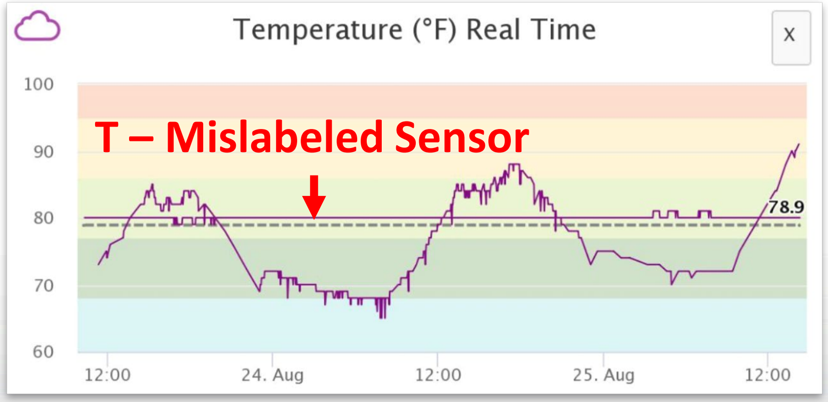
Use RH, T, and PM from nearest neighbors to identify sensors with a 'bad' location

Crowd Sourced Data Issue: Mislabeled Indoor Sensor







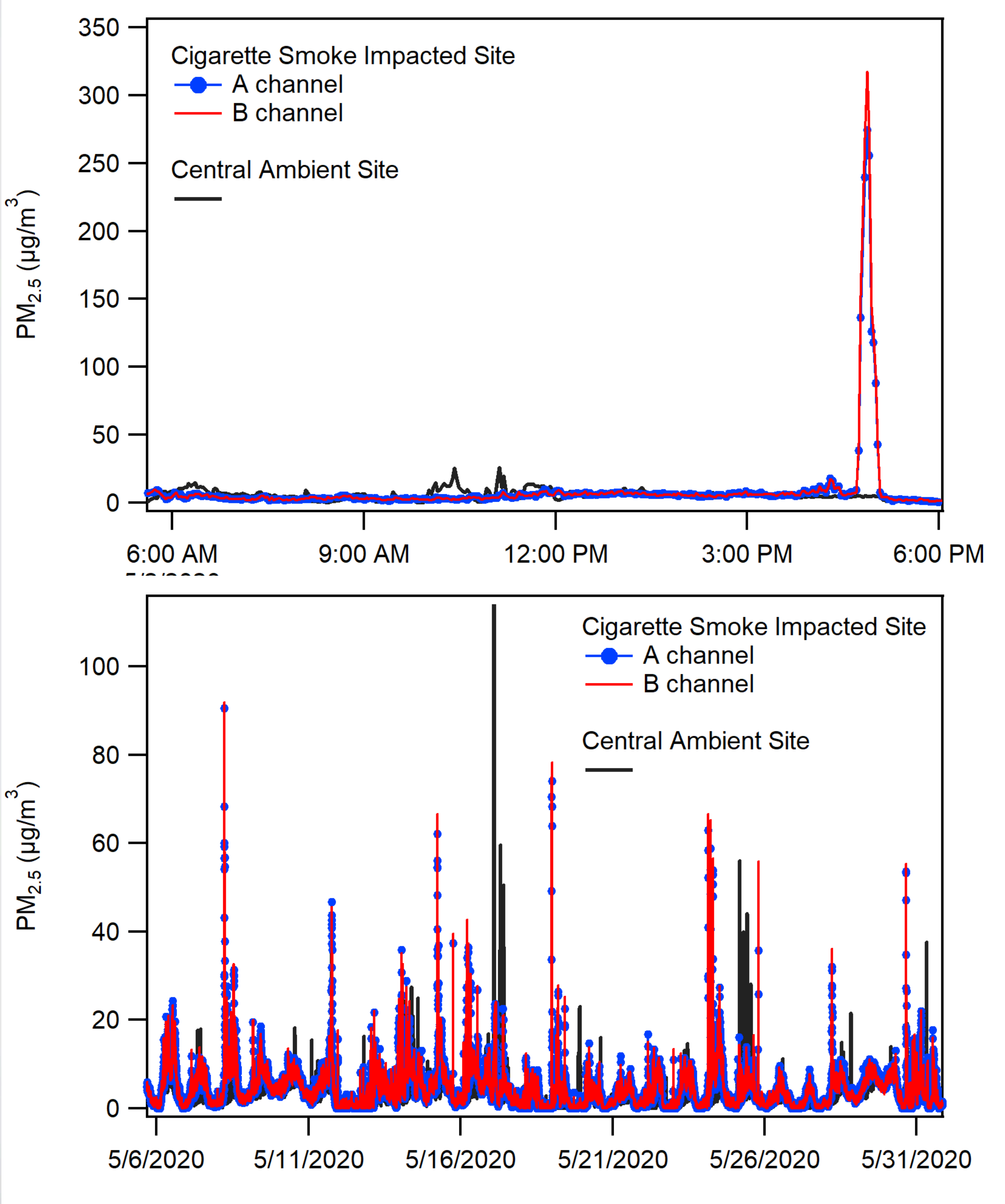


Example of outdoor sensor that disagrees with neighbors

Compare T and PM from surrounding sensors to identify sensors indoor

Diurnal trends can also be used to identify

Crowd Sourced Data Issue: Hyperlocal Source



Hyperlocal sources may complicate map displays of regional air quality, but are reflective of local $PM_{2.5}$ concentrations and of public exposure at that site

Potential characteristics of data impacted by a hyperlocal source:

- Short duration (~22 minutes)
- High concentration (270 $\mu g\ m^{-3}$)
- A and B channels agree
- Not seen at nearby sensor
- Repeated spikes over time

Due to local knowledge, suspect sensor is impacted by a nearby informal smoking area

Crowd Sourced Data Issue: Poorly Sited Sensor

Sensors operated by the public may be poorly sited. We investigated a few suboptimal siting scenarios to identify the impact.

Next to strong air flow

Close to the ground

Obstructed air flow

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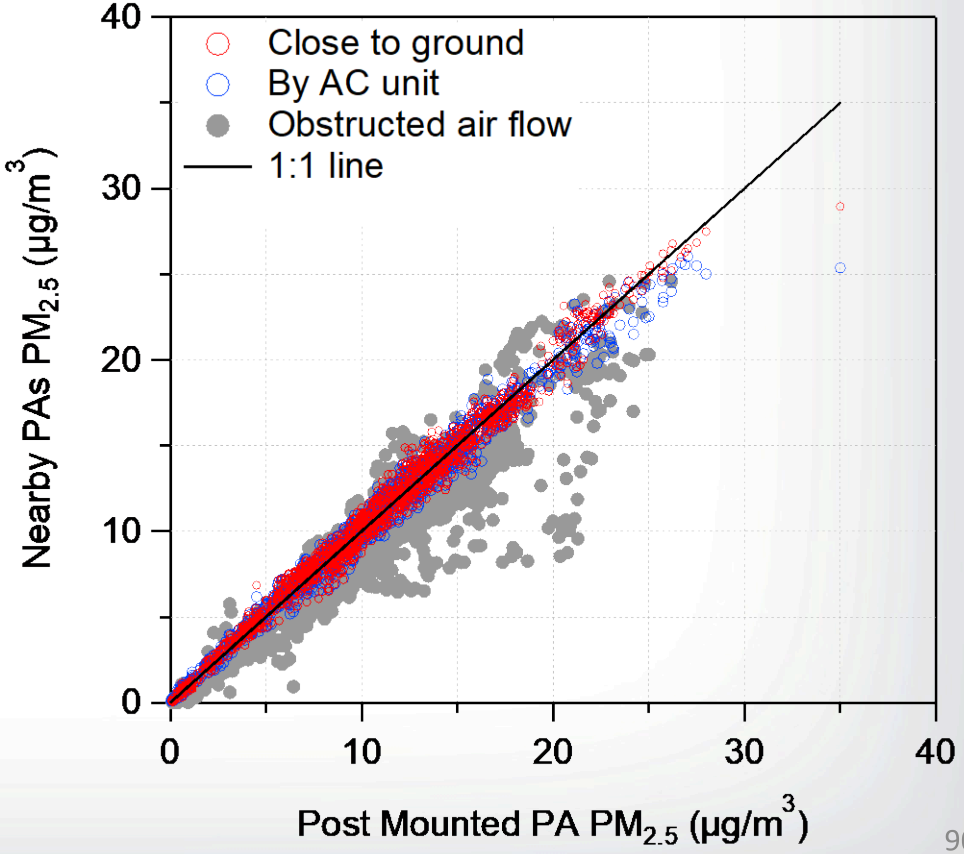


Crowd Sourced Data Issue: Poorly Sited Sensor

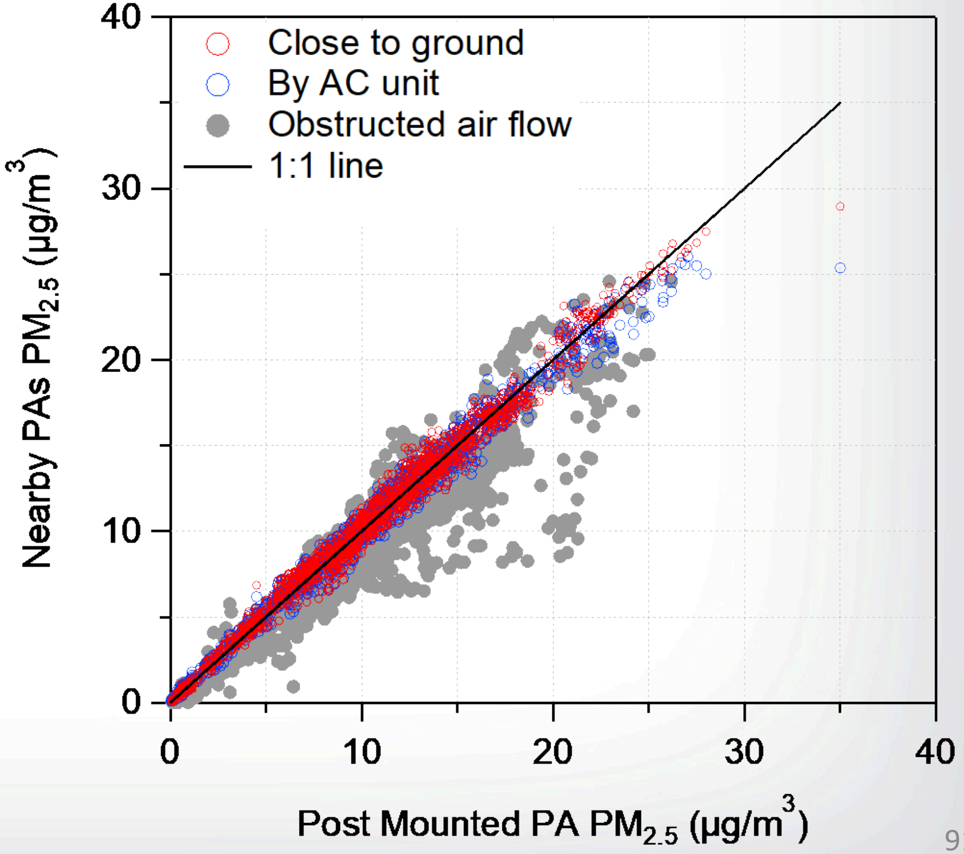
Sensors operated by the public may be poorly sited. We investigated a few suboptimal siting scenarios to identify the impact

Next to strong air flow

Close to the ground

Obstructed air flow

Siting	Regression	R^2	RMSE (µg m^{-3})	MAE (µg m^{-3})
Ground	Y = 0.98x +0.31	0.98	0.69	0.53
AC Unit	Y = 0.96x + 0.51	0.98	0.71	0.51
Obstructed	Y = 0.86x + 0.14	0.88	2.30	1.66



Most siting scenarios provide acceptable data

Approaches to QA/QC of Crowdsourced Data

- **Crowdsourced data presents some unique challenges. Like any sensor, there are no status codes that can indicate when the data should be invalidated.**
- **Frequent review will be necessary until algorithms are developed to detect malfunctioning, improperly sited or mislabeled sensors.**

Potential QA/QC approaches:

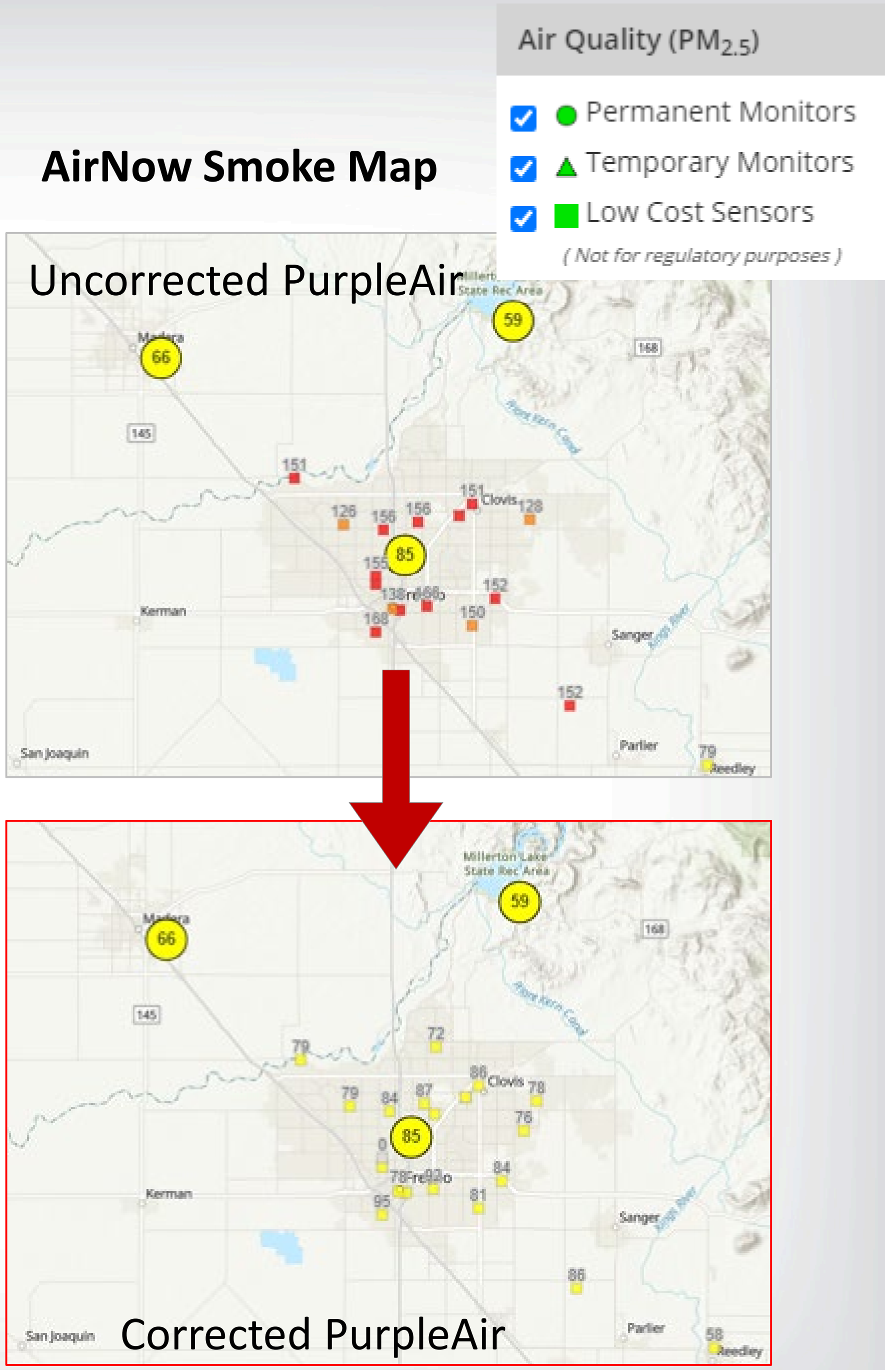
- Use daily T and RH ranges to identify indoor (some misplaced) sensors
- Use nearest neighbor comparisons
  - Compare T and RH to further identify mislabeled, questionably cited, and misplaced sensors
  - Compare $PM_{2.5}$ to identify sensor failure or drift
- Use coefficient of variation on high time resolution data to identify poor siting
- Use collocated sensors for identification of times/conditions when the correction does not work and develop messaging and potential flagging

Research needs:

- What is the effectiveness of these approaches for removing problematic sensors?
- How can these methods be operationalized for real-time, large scale sensor QA/QC?

Take Home Summary

- **A significant amount of research** has been done by EPA, local agencies, and academia to better understand PurpleAir performance giving us more confidence in reported measurements
- EPA's PurpleAir **correction equation** improves the accuracy of $PM_{2.5}$ measurements for many different cases including during smoke conditions
- PurpleAir sensors provide **additional spatial variation** of $PM_{2.5}$ on the AirNow Smoke map
- Additional QA/QC steps may be added to automatically remove problematic sensors
- Other $PM_{2.5}$ sensor networks may exist, but will require collocation, correction, and an understanding of their performance during smoke impacts before being added to the map.



Resources & Project Publications

Additional resources and details about EPA's work with air sensors

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

AirNow fire and smoke map

https://fire.airnow.gov/

Project 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.

Barkjohn (Johnson), K, B. Gantt, A. Clements, (under management review) ‘Development of a United States Wide Correction for $PM_{2.5}$ Data Collected with the PurpleAir Sensor’.

Barkjohn (Johnson), K, A. Holder, S. Frederick, A. Clements, (in preparation) ‘PurpleAir $PM_{2.5}$ U.S. Correction and Performance During Smoke Events’.

Acknowledgements

AK: State of Alaska, Citizens for Clean Air

AZ: Maricopa County Air Quality Department

CA: San Luis Obispo County Air Pollution Control District, Mojave Desert Air Quality Management District, Antelope Valley Air Quality Managment District, California Air Resources Board, Santa Barbara County Air Pollution Control District, Air Quality Sensor Performance Evaluation Center, Ventura County Air Pollution Control District, Bay Area Air Quality Management District

CO: Colorado Department of Public Health and Environment

DE: Delaware Division of Air Quality

FL: Sarasota County Government

GA: EPA Region 4, Georgia Environmental Protection Division

IA: Iowa Department of Natural Resources, Polk and Linn County Local Programs, and the State Hygienic Laboratory at the University of Iowa

MT: Missoula County, Montana Department of Environmental Quality

NC: Forsyth County Office of Environmental Assistance & Protection, Clean Air Carolina, UNC Charlotte, North Carolina Department of Environmental Quality

OH: Akron Regional Air Quality Management District

OK: Quapaw Nation, Oklahoma Department of Environmental Quality

UT: University of Utah, Utah Department of Environmental Quality

VA: Virginia Department of Environmental Quality

VT: State of Vermont

WA: Washington Department of Ecology, Puget Sound Clean Air Agency

WI: Wisconsin Department of Natural Resources

Federal: Forest Service, Wildland Fire Air Quality Response Program, National Park Service, EPA Region 9, EPA Region 10, Lauren Maghran, Ed Brunson, Mike McGown, Sam Frederick, Brett Gantt, Ian Vonwald, Heidi Vreeland, Gayle Hagler

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Supplemental Slides

EPA ORD's PurpleAir Secondary Data Study

Study Objective:

- Evaluate the performance of PurpleAir sensors at numerous locations throughout the U.S. to determine what variables (environmental conditions) affect performance.
- Develop a U.S.-Wide Correction Equation to help STLs better interpret and use this data.

Approach:

- Collect data from multiple locations throughout the U.S. to capture a wide range of ambient particle characteristics, $PM_{2.5}$ mass concentrations, and environmental conditions.
- Compare sensors to Federal Reference Method (FRM - filter based) and Federal Equivalent Method (FEM – a variety of continuous instruments) being used for regulatory air quality monitoring.
- Compare 24-hour averaged data to minimize variation in the FRM/FEM measurements.
- Institute a 90% data completeness threshold to ensure only the highest quality data was used to generate the correction equation.

Project Team:

- EPA ORD – Karoline (Johnson) Barkjohn, Samuel Frederick, Andrea Clements
- Partnerships with 30 state, local, and tribal (STLs) air agencies sharing data from PurpleAir sensors collocated at regulatory monitoring sites across the U.S.

Sensor QA/QC:

- PurpleAir sensors were sited at regulatory monitoring sites nominally following FRM/FEM siting criteria.
- PurpleAir sensors streamed data to the PurpleAir cloud in either public or private modes thereby minimizing clock drift.

EPA ORD's Long Term Performance Project – Ambient Dataset

Study Objective:

- Evaluate the performance of a number of air sensors at numerous locations throughout the U.S. to determine what variables (environmental conditions) affect performance.
- Investigate how performance changes over time.

Approach:

- Collect data from multiple locations throughout the U.S. to capture a wide range of ambient particle characteristics, $PM_{2.5}$ mass concentrations, and environmental conditions.
- Compare sensors to equivalent Federal Equivalent Method instruments (FEM – T640/T640x) to minimize variation in reference measurements.
- Compare a sensor and reference data on a variety of time scales and during different seasons incorporating meteorological data, etc. as available to better interpret the results.

Project Team:

- EPA ORD – Karoline (Johnson) Barkjohn, Samuel Frederick, Andrea Clements,
- Jacobs – Cortina Johnson, Brittany Thomas, Robert Yaga, local technicians
- Partnerships with 6 state or local air agencies sharing regulatory data

Sensor QA/QC:

- PurpleAir sensors initially collocated in RTP to check the precision between identical sensors.
- PurpleAir sensors were sited at regulatory monitoring sites nominally following FRM/FEM siting criteria.
- PurpleAir sensors streamed data to the PurpleAir cloud in private mode thereby minimizing clock drift.

EPA ORD's Sensor Smoke Performance Study

Study Objective:

- Evaluate low-cost PM sensors at wildland fires to evaluate their accuracy at high smoke concentrations
- Develop regional guidelines for communities and agencies on the effective use of sensors during wildfire smoke events

Project Team:

- EPA ORD - Amara Holder
- EPA Region 9 – Anna Mebust, Dena Vallano, Katie Stewart, Lauren Maghran
- EPA Region 10 – Mike McGown, Rob Elleman

Approach:

- Compare sensors to Federal Equivalent Method (FEM) and near FEM grade instruments routinely used for smoke monitoring
- Build portable, solar-powered sensor packages for easy deployment with minimal infrastructure requirements
- Operate sensors near wildfires or prescribed fires where smoke concentrations are highest
- Target multiple fires and locations to capture a range of smoke characteristics, concentrations, and environmental conditions
- Compare sensor 1-hour averages to reference instruments

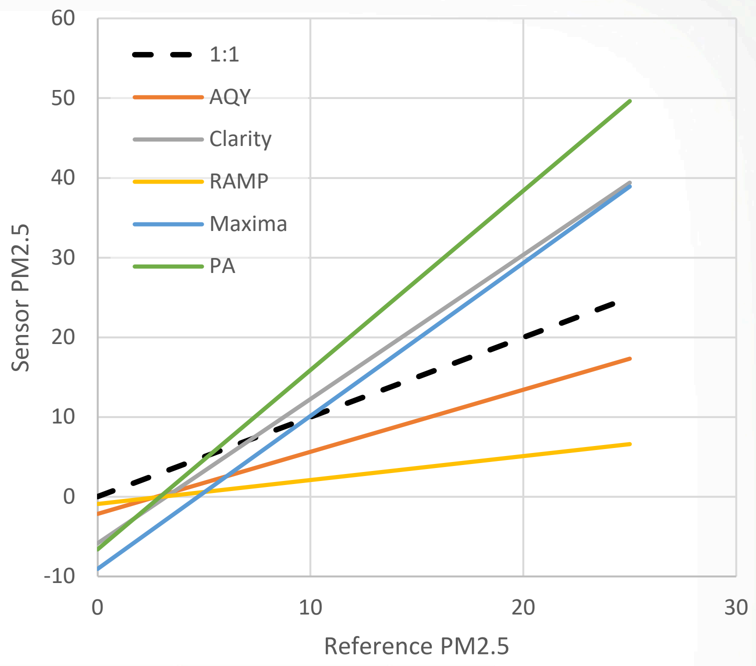
Sensor QA/QC:

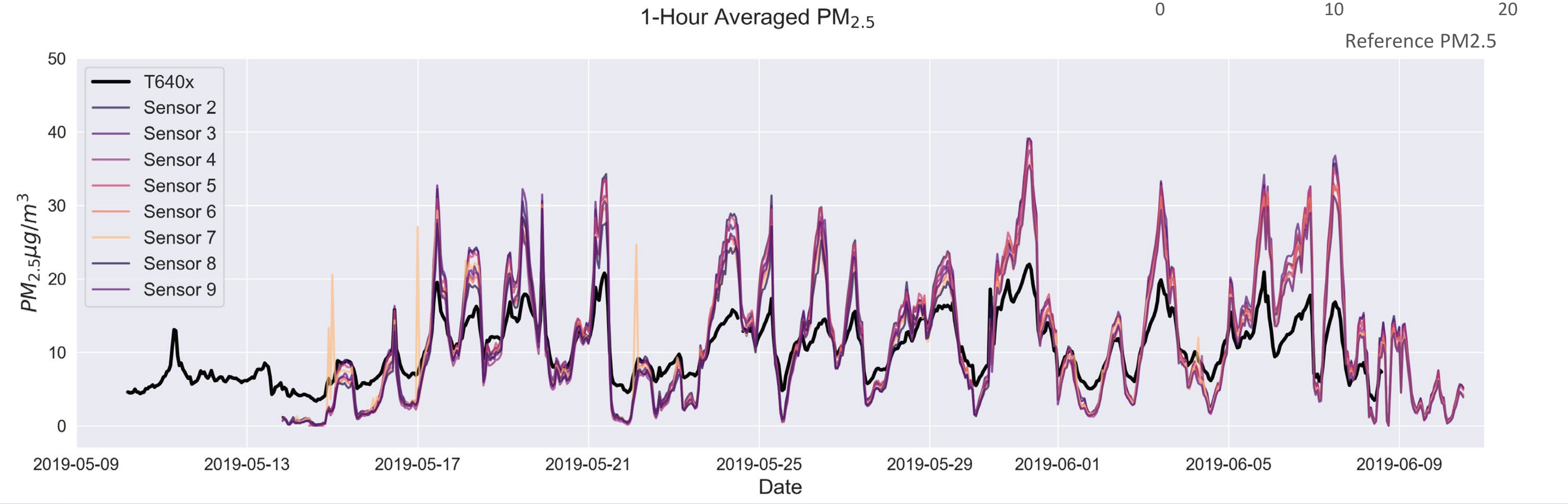
- Initial health/precision check is done at EPA-RTP ambient monitoring site
- Field evaluation of sensor health is through comparison to reference measurements

Performance Of All $PM_{2.5}$ Sensors Is Not The Same

- Many PM **sensors show similar trends** when compared to regulatory-grade reference instruments
- **Sensor data must be corrected** to be more comparable
- Cleaning/correction methodology is dependent on make/model
- Sensors with identical sensing units can have different performance
- The degree to which sensors of the same make/model agree with one another (precision) is also variable
- Tight precision is necessary for fleet-wide corrections necessary for large network applications

Corrections for different sensors





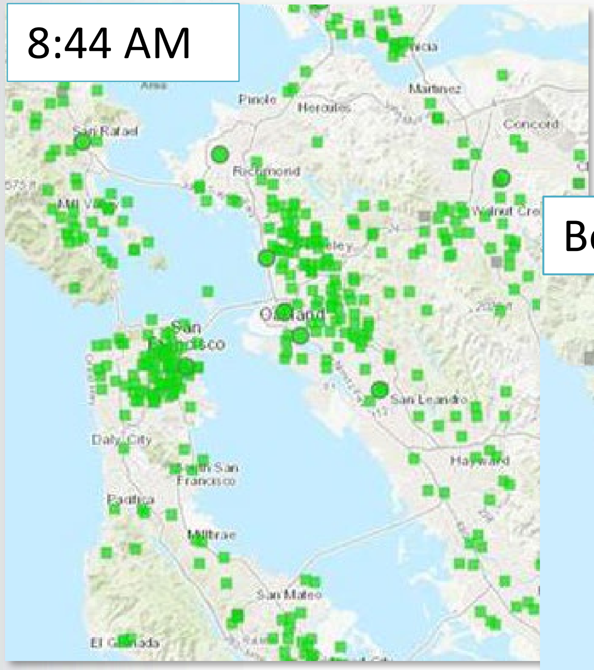
PurpleAir U.S.-Wide Correction: Sites

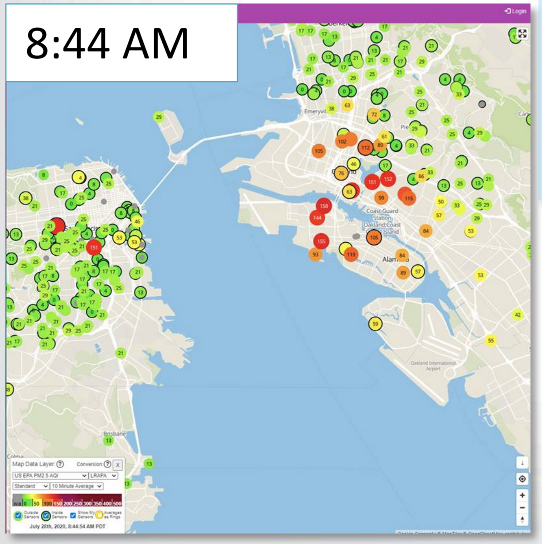
For your reference

Summary of the dataset used to generate the U.S.-wide PurpleAir correction equation. Summarized as median (min, max).

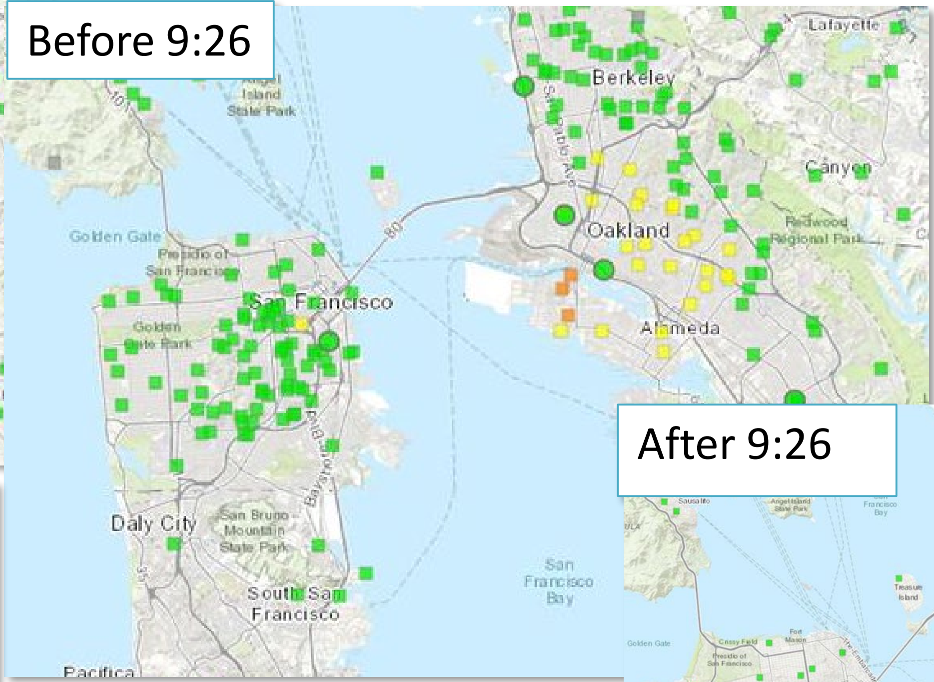
State	Start Date	End Date	# of PA	# of Sites	# of Days	FEM or FRM	FEM or FRM $PM_{2.5}$ (µg m^{-3})	PA $PM_{2.5}$ (µg m^{-3})	T (°C)	RH (%)
CA	11/29/2017	12/29/2019	13	12	3762	Both	6 (-2,109)	7 (0,250)	22 (6,42)	45 (2,100)
IA	9/29/2017	1/13/2020	9	5	3762	Both	10 (0,36)	19 (0,69)	11 (-27,35)	55 (21,100)
WA	10/16/2017	10/28/2019	3	3	1035	FEM	6 (0,41)	8 (0,89)	13 (-2,30)	63 (26,84)
AZ	11/9/2018	12/31/2019	3	3	895	Both	7 (1,43)	6 (0,74)	24 (9,44)	26 (5,73)
WI	1/1/2019	11/18/2019	6	4	811	Both	6 (1,32)	9 (1,64)	18 (-25,33)	53 (31,82)
NC	3/25/2018	10/24/2019	1	1	700	Both	7 (0,20)	13 (1,43)	25 (-1,35)	48 (16,79)
AK	11/7/2018	9/30/2019	3	1	369	FRM	4 (0,60)	4 (0,131)	8 (-25,29)	47 (21,76)
KS	3/13/2019	9/30/2019	3	1	306	FEM	9 (2,33)	11 (0,50)	24 (9,34)	52 (30,71)
DE	7/27/2019	11/18/2019	1	1	205	Both	7 (1,17)	9 (1,35)	25 (6,35)	51 (34,75)
OK	7/10/2019	11/18/2019	2	2	190	Both	9 (1,25)	11 (1,35)	30 (1,38)	57 (29,86)
GA	8/2/2019	11/18/2019	1	1	184	Both	9 (3,18)	15 (5,34)	29 (5,36)	55 (44,77)
VT	3/30/2019	9/30/2019	1	1	146	Both	6 (2,18)	8 (1,31)	24 (12,34)	52 (36,71)
FL	5/31/2019	9/30/2019	1	1	119	FEM	6 (3,17)	5 (1,25)	32 (29,35)	60 (49,73)
CO	8/22/2019	11/18/2019	1	1	113	both	7 (2,25)	6 (1,45)	18 (-5,32)	33 (18,70)
VA	10/27/2019	12/29/2019	1	1	30	FRM	5 (2,20)	10 (2,41)	12 (8,25)	48 (35,65)
MT	12/3/2019	12/10/2019	1	1	8	FEM	10 (5,15)	22 (6,36)	4 (2,6)	54 (42,62)
All	9/29/2017	1/13/2020	50	39	12635	both	7 (-2,109)	10 (0,250)	19 (-27,44)	51 (2,100)

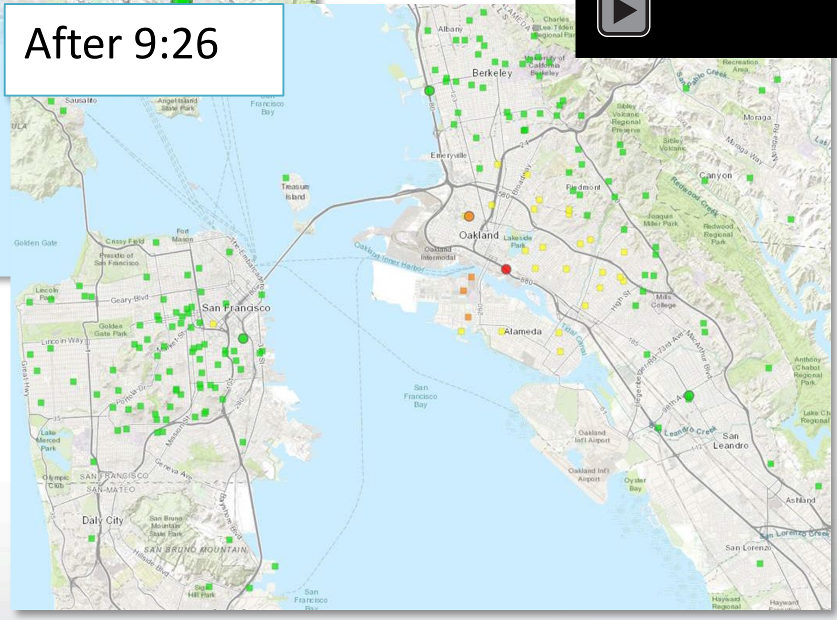
Example of Rapidly Changing $PM_{2.5}$

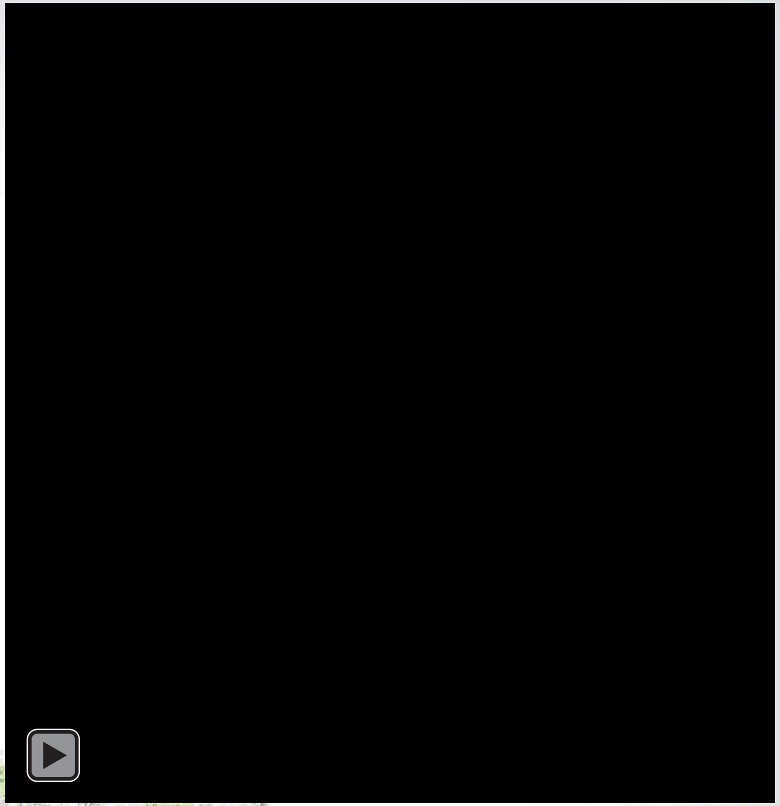




5 alarm fire in SF quickly spreads smoke across the bay area







PurpleAir map reflects smoke plume moving across the area in real-time

Hourly NowCast data does not reflect rapidly changing air quality resulting in disagreement between AirNow Fire and Smoke map and PurpleAir map

Source: Duc Nguyen BAAQMD