



# AirFuse

## EPA's multi-pollutant fusion system

Barron H. Henderson and Phil Dickerson

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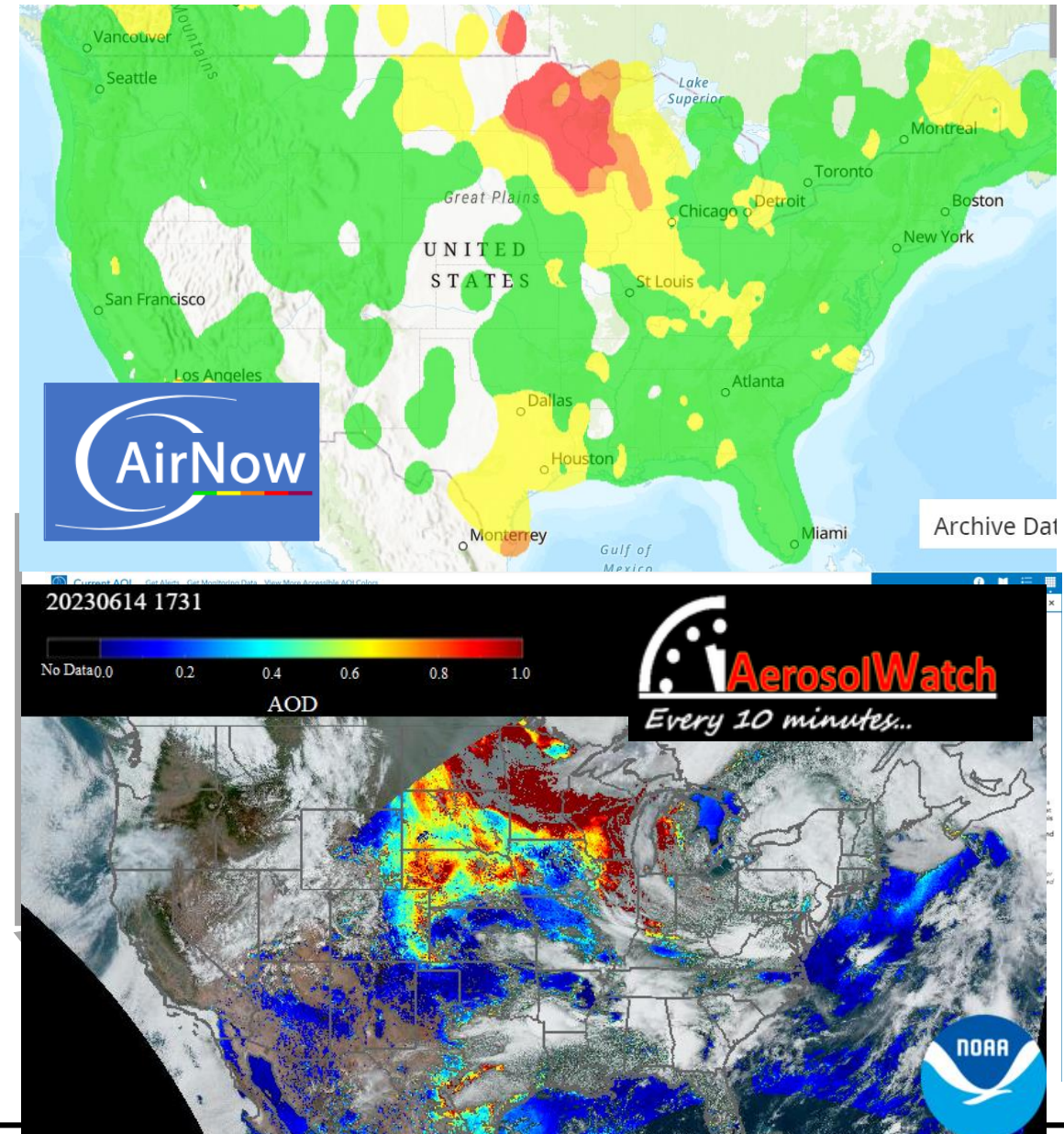
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# Motivation

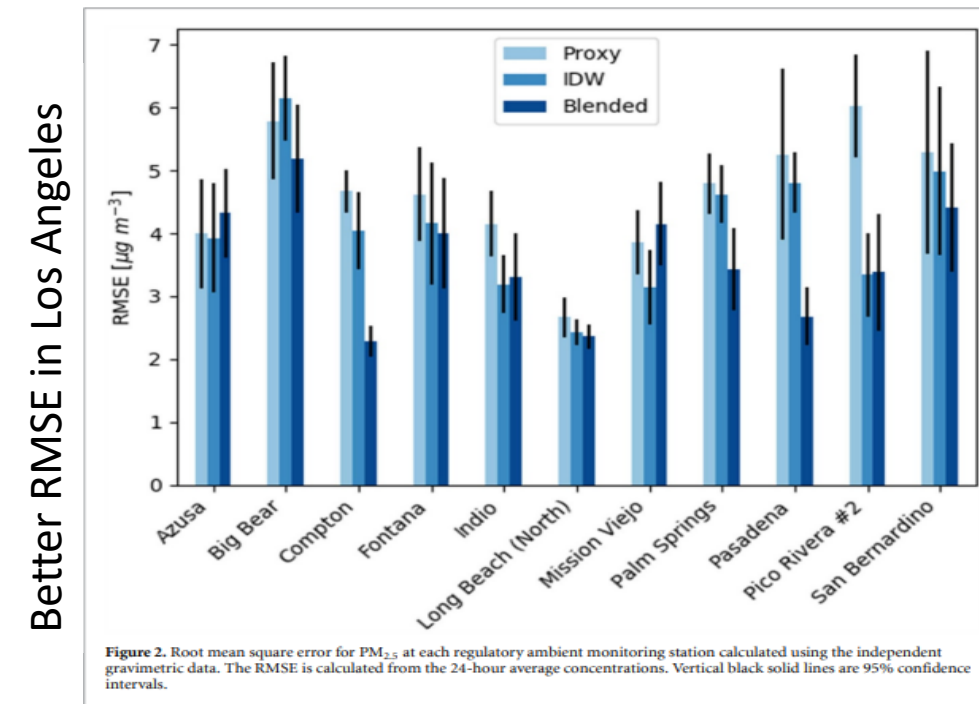
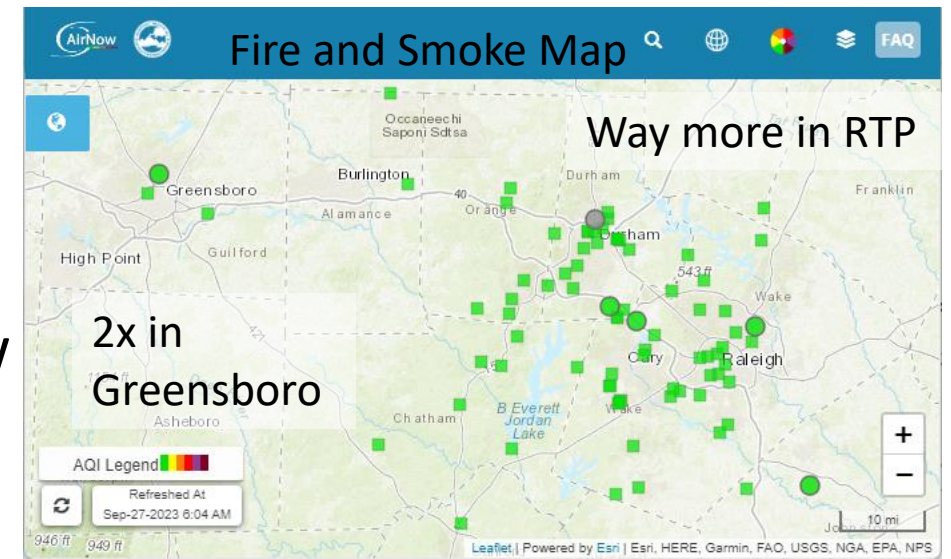
- AirNow communicates air quality in real time
  - Millions of visitors per day during fire seasons
  - Simple weighted ( $d^{-5}$ ) contours monitors only
- 4x more PurpleAir sensors than monitors
  - Increased the spatial coverage of monitored particulate matter.
  - Spoiler alert: sensor data improves predictions.
- Near-real-time satellite observations
  - Recent development by NOAA/NESDIS/STAR
  - NASA HAQAST project connecting AirNow to NOAA geostationary satellite data
- What about fusing AirNow, PurpleAir and satellites?

Example Day in AirNow and Aerosol Watch



# Monitors and PurpleAir sensors

- Many agencies report monitor data to AirNow
  - ~1000 reporting monitors per hour
  - Publicly available thru AirNowAPI
- Schulte et al (2020) using PurpleAir
  - Residual Kriging with both AirNow and PurpleAir
    - NOAA Forecast model
    - Model Correction :  $Y = M_n - \text{Krig}(M_n - O_n)$
  - Improved performance of PM<sub>2.5</sub> in leave-one-out validation and compared to Federal Reference Monitors
- We use corrected PurpleAir low-cost sensors
  - Barkjohn et al. 2021 developed a national correction
  - Extended correction via RSIG





#### 4. Enabling USEPA to ingest high-frequency satellite air quality data into the AirNow system

**Team Lead:** HAQAST investigator Pawan Gupta

**Partners:** Phil Dickerson and Barron Henderson with the US Environmental Protection Agency (EPA), and Shobha Kondragunta with the National Oceanic and Atmospheric Administration (NOAA)

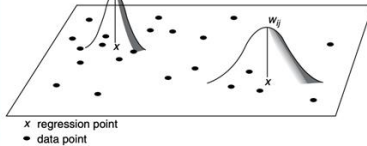
**HAQAST Members and Collaborators:** Jianqiu Mao, Yang Liu, Kel Markert, Robert Levy, Randall Martin, Amber J. Soja, Martin Stuefer, Jenny Bratburd, Emily Gargulinski, Yanshun Li, and Daniel Tong also contribute to this team.

<https://haqast.org/tiger-teams/#2021-tiger-teams>

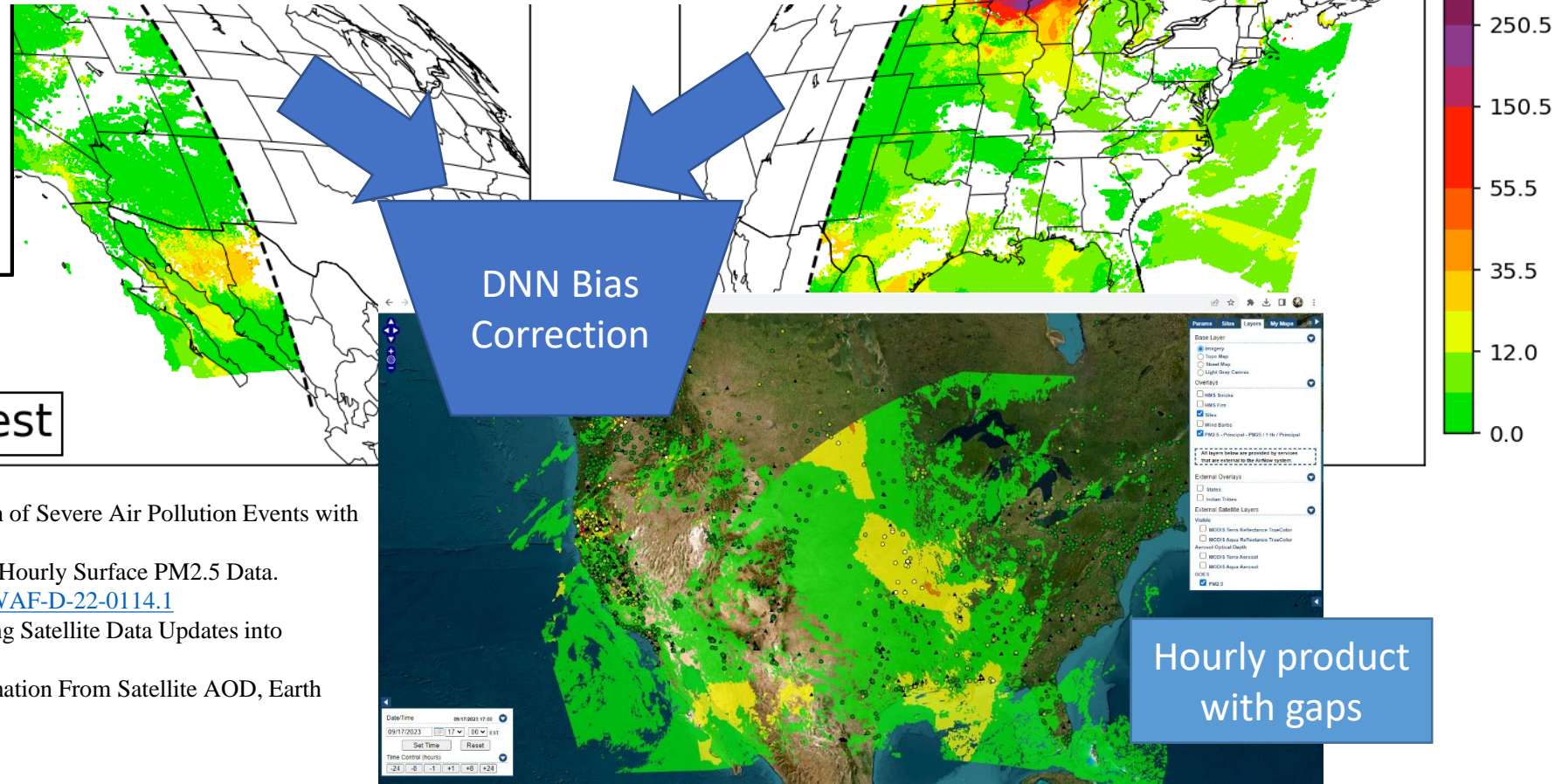


Satellite AOD + Geographic Weighted Regression

$$PM2.5_{ij} = a_{0ij} + a_{1ij} AOD$$



GOES-West



DNN Bias Correction

Hourly product with gaps

1. Sayeed et al.: Deep Neural Network bias corrections.
2. O'Dell et al.: Public Health Benefits from Improved Identification of Severe Air Pollution Events with Geostationary Satellite Data, *submitted to GeoHealth*, 2023.
3. Zhang et al.: Nowcasting Applications of Geostationary Satellite Hourly Surface PM2.5 Data. *Weather and Forecasting*, 37(12), 2313-2329, 2022. doi: [10.1175/WAF-D-22-0114.1](https://doi.org/10.1175/WAF-D-22-0114.1)
4. Bratburd et al.: Air Quality Data When You Need It: Incorporating Satellite Data Updates into AirNow, [EM Plus](#), 2022.
5. Zhang and Kondragunta.: Daily and Hourly Surface PM2.5 Estimation From Satellite AOD, *Earth Space Sci*, 8, doi: [10.1029/2020EA001599](https://doi.org/10.1029/2020EA001599), 2021.

# Hourly National-scale Fusion Ensemble

- Interpolating bias to “correct” the forecast model\*
  - NOAA’s Forecast Model (NAQFC) as mediating layer
  - $VNA\ Bias = \sum(d_n^{-2} (m_n - o_n)) / \sum(d_n^{-2})$  •  $n$  = Voronoi Neighbor
  - $Y_i = NAQFC - VNA\ Bias_i$
- One layer from AirNow ( $Y_{AN}$ ) **observations**:
  - mostly regulatory grade hourly observations
  - paired with collocated grid cell.

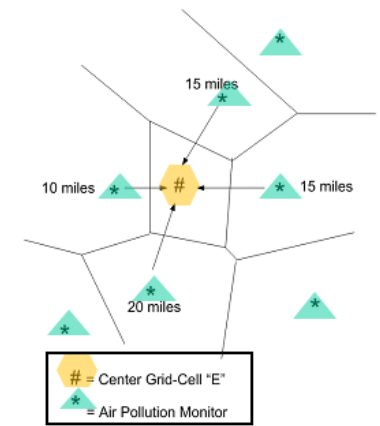
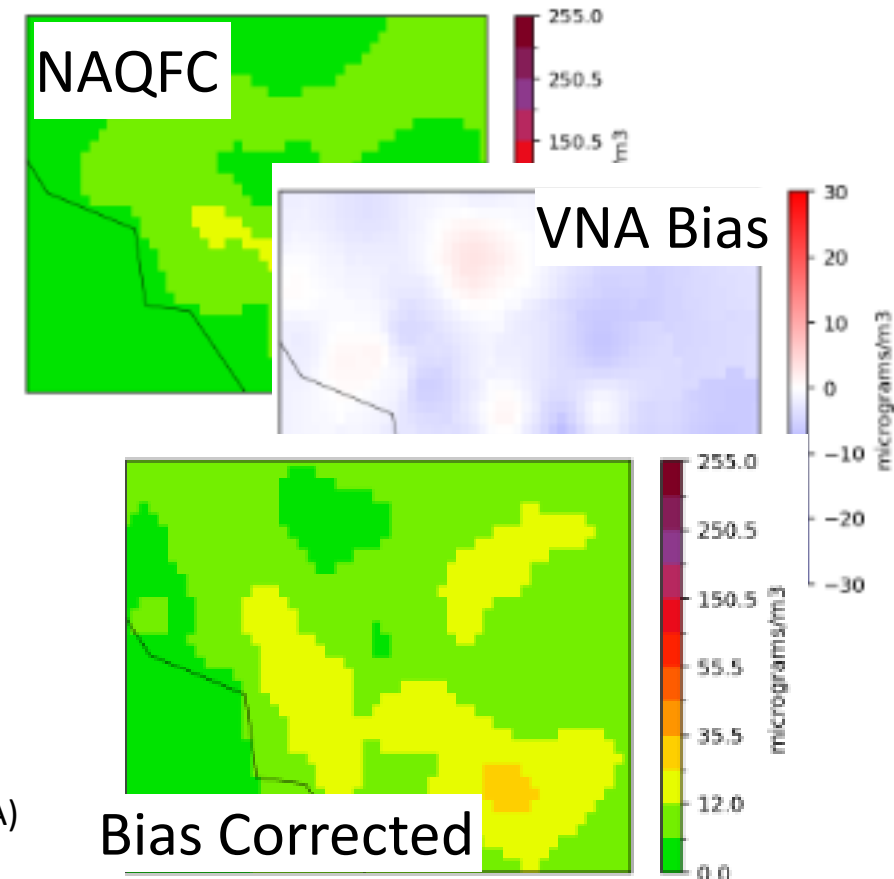


Figure courtesy of: Brian Timin



\*A multiplicative corrector of this type is called extended VNA (eVNA)

\*\*Piece-wise regression as in Fire and Smoke Map

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  - Aggregated within grid cells to create a pseudo-observation

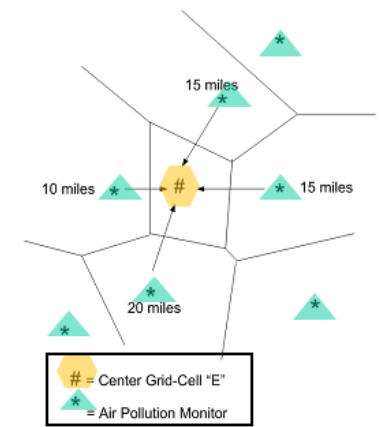
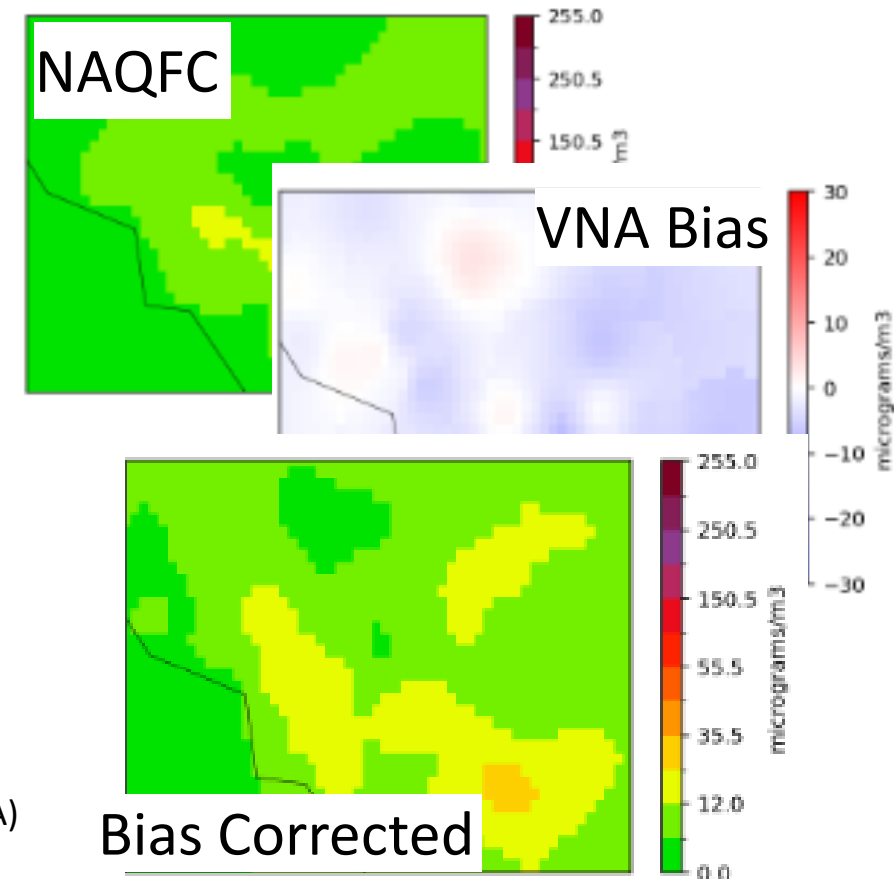


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- One layer from GOES-PM25 ( $Y_{GOES}$ ) **“observations”**
  - Geostationary Operational Environmental Satellite (GOES)
  - Aerosol Optical Depth from the GOES Advanced Baseline Imager
  - Geographic Weighted Regression (GWR) against AirNow
  - Deep Neural Network Corrected (Sayeed et al *in prep*)

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\*\*Piece-wise regression as in Fire and Smoke Map

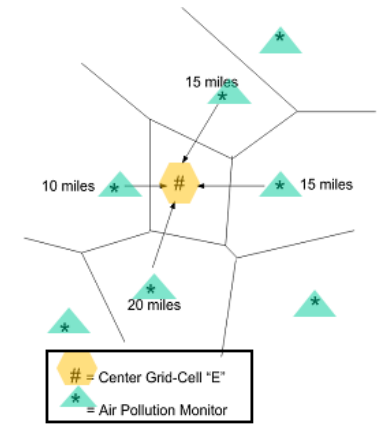
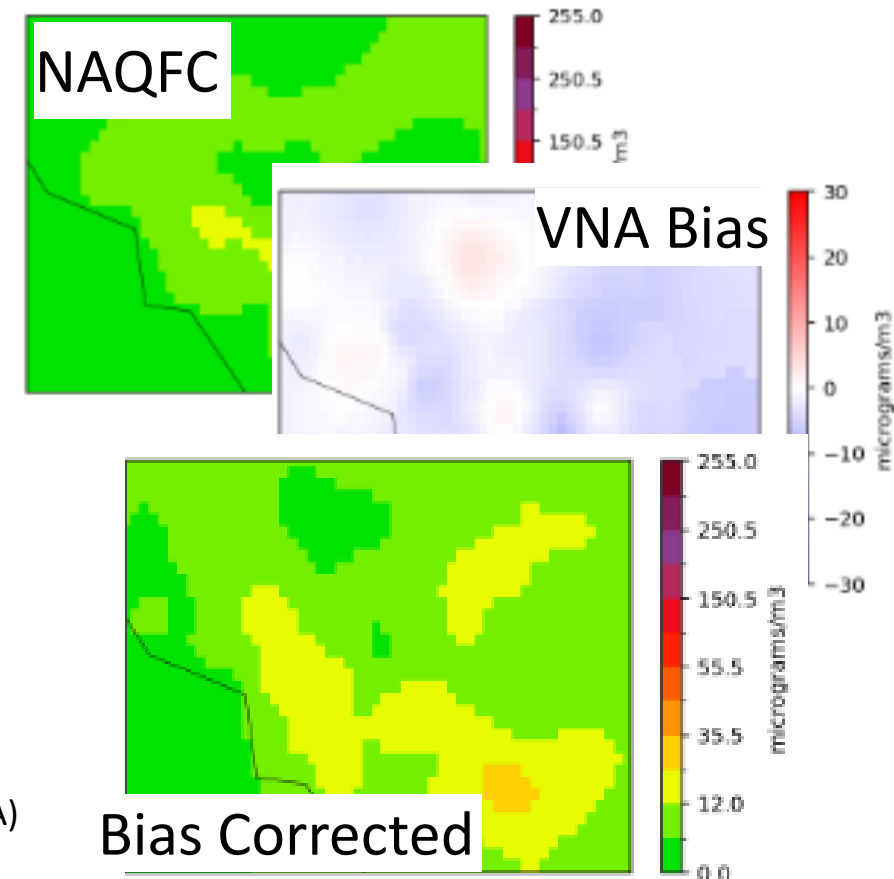
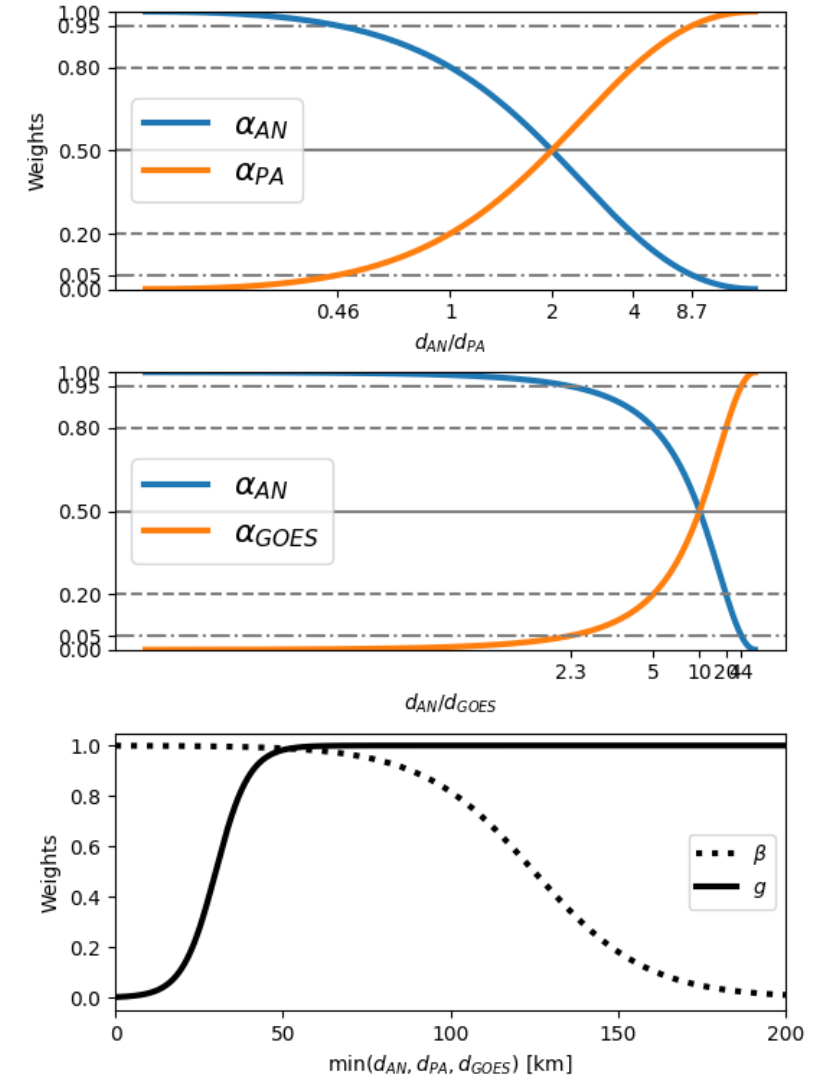


Figure courtesy of: Brian Timin



# Ensemble Averaging Method

- Simple fusion of bias corrected surfaces
  - NAQFC, AirNow, PurpleAir, GOES-PM25
  - Fuse the surfaces based on distance
  - Apply different weights to ensembles
- $Y_{AN,PA,GOES} = \alpha_{AN} Y_{AN} + \alpha_{PA} Y_{PA} + \alpha_{GOES} Y_{GOES}$ 
  - $\alpha'_{AN} = (1 \times d_{AN})^{-2}$
  - $\alpha'_{PA} = (2 \times d_{PA})^{-2}$
  - $\alpha'_{GOES} = (10 \times d_{GOES})^{-2}$
  - $\alpha'_{tot} = \alpha'_{AN} + \alpha'_{PA} + \alpha'_{GOES}$
  - Normalize them all:  $\alpha_i = \alpha'_i / \alpha'_{tot}$
- $Y_{AN,PA,GOES} = \beta \times Y_{AN,PA,GOES} + (1 - \beta) \times Y_{NAQFC}$

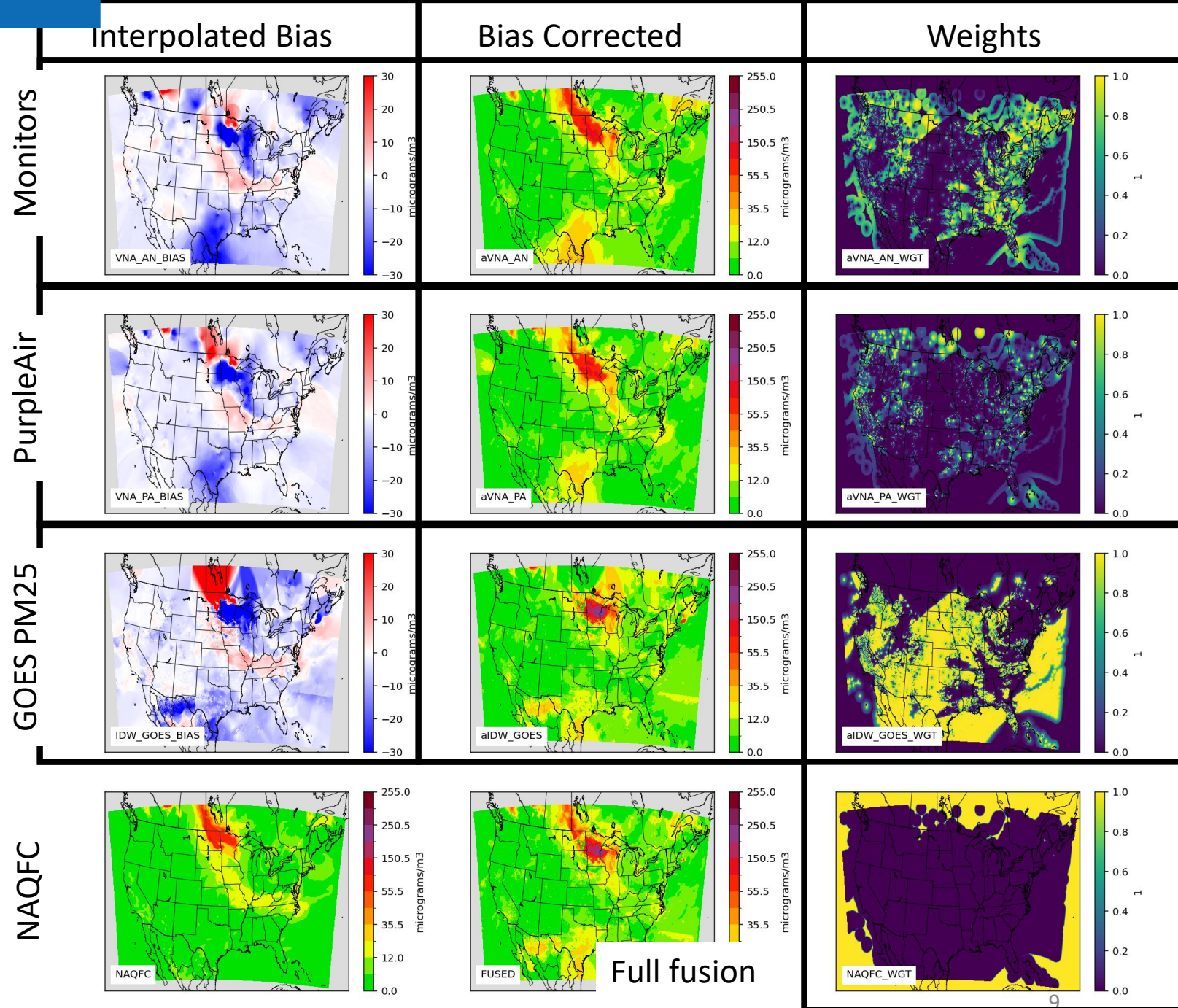




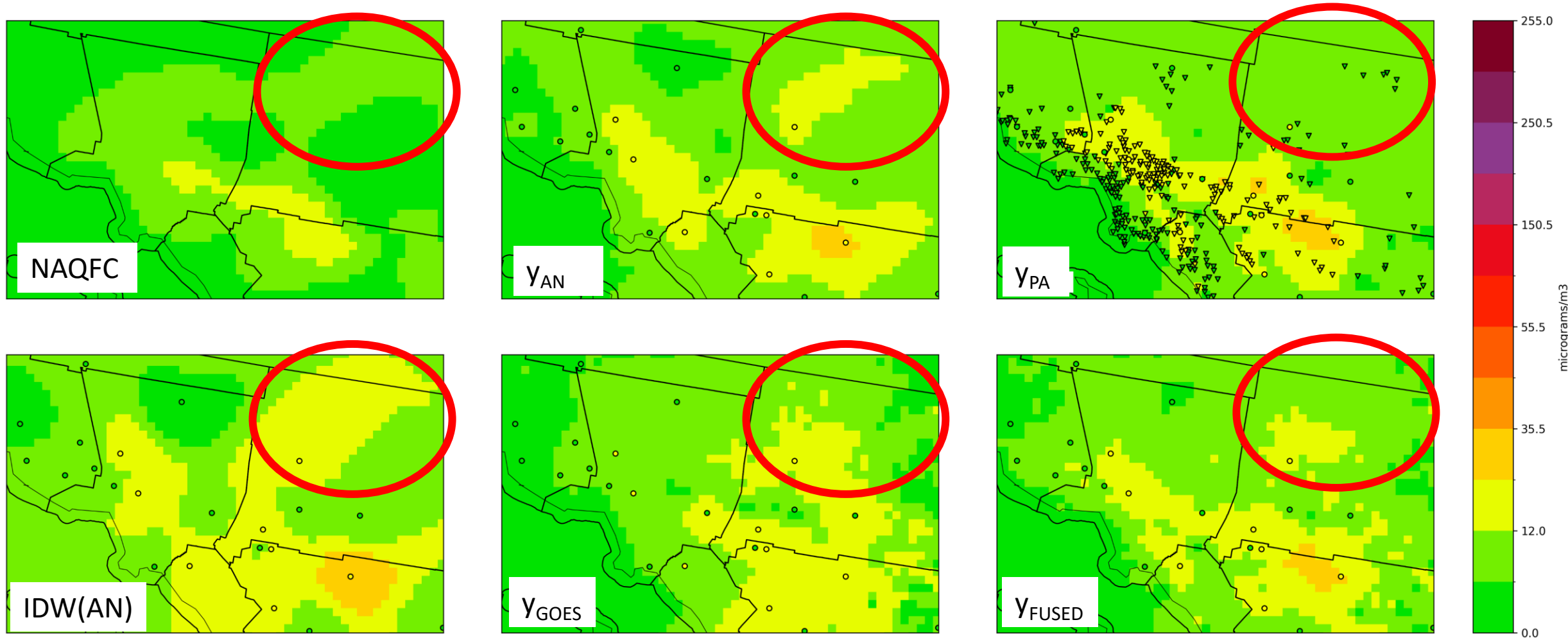
# Case Study

## 2023-06-14T17Z

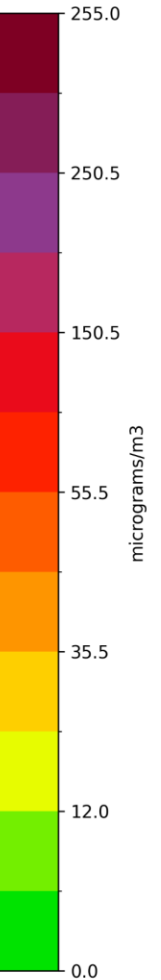
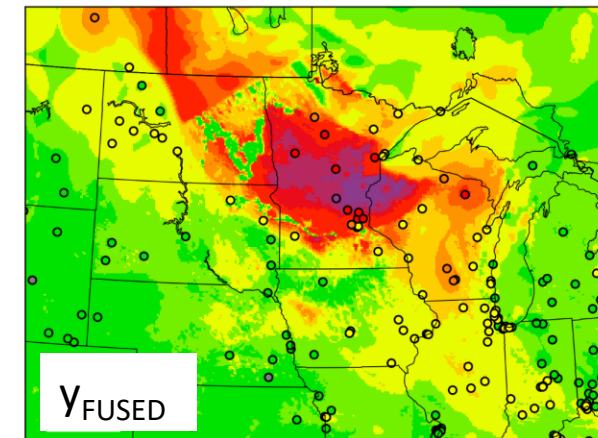
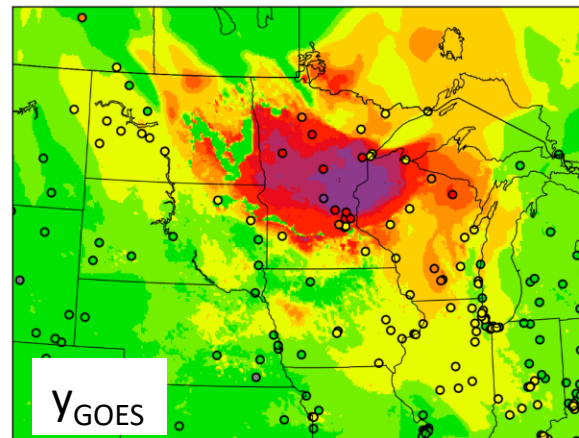
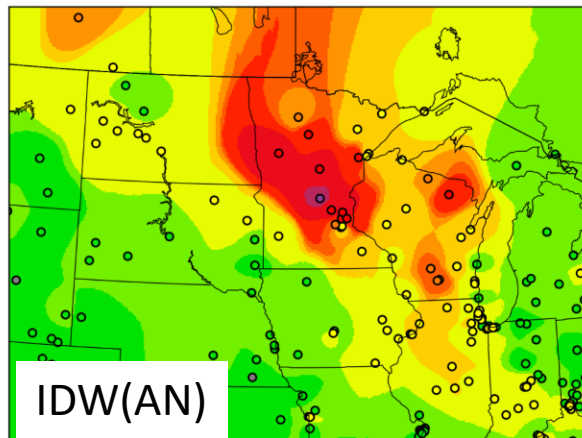
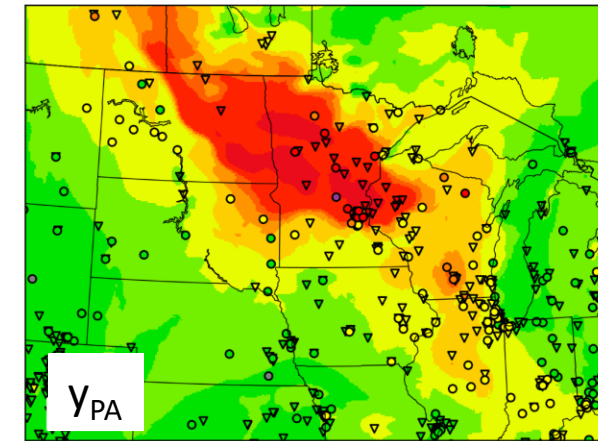
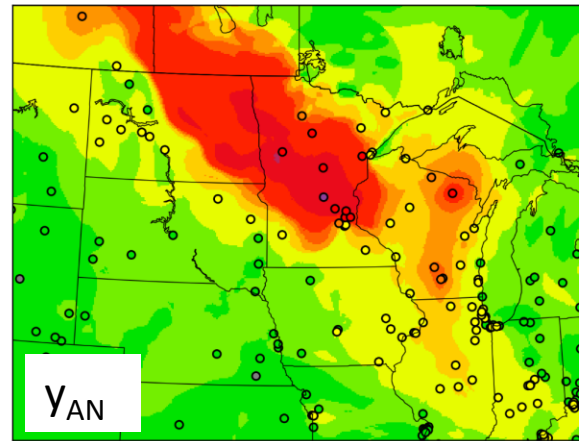
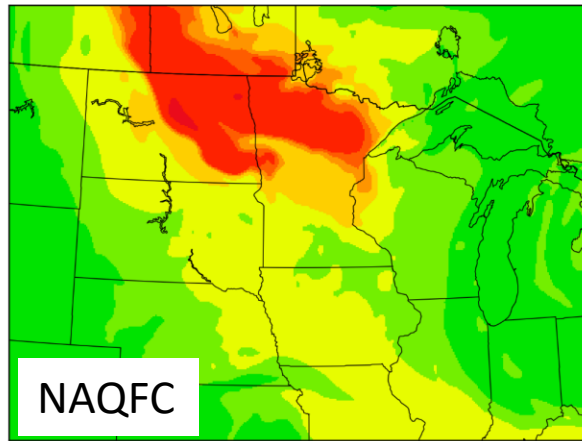
- Fairly typical day June day in the south western domain.
- Large fire contributions in Canada and sweeping down through Minnesota, Wisconsin and further
- 4 data sources
  - AirNow Monitors (top)
  - PurpleAir sensors
  - GOES PM25
  - NAQFC (bottom)
- Estimates
- Bias Corrections
- Full fusion



# Los Angeles: 2023-06-14T17Z

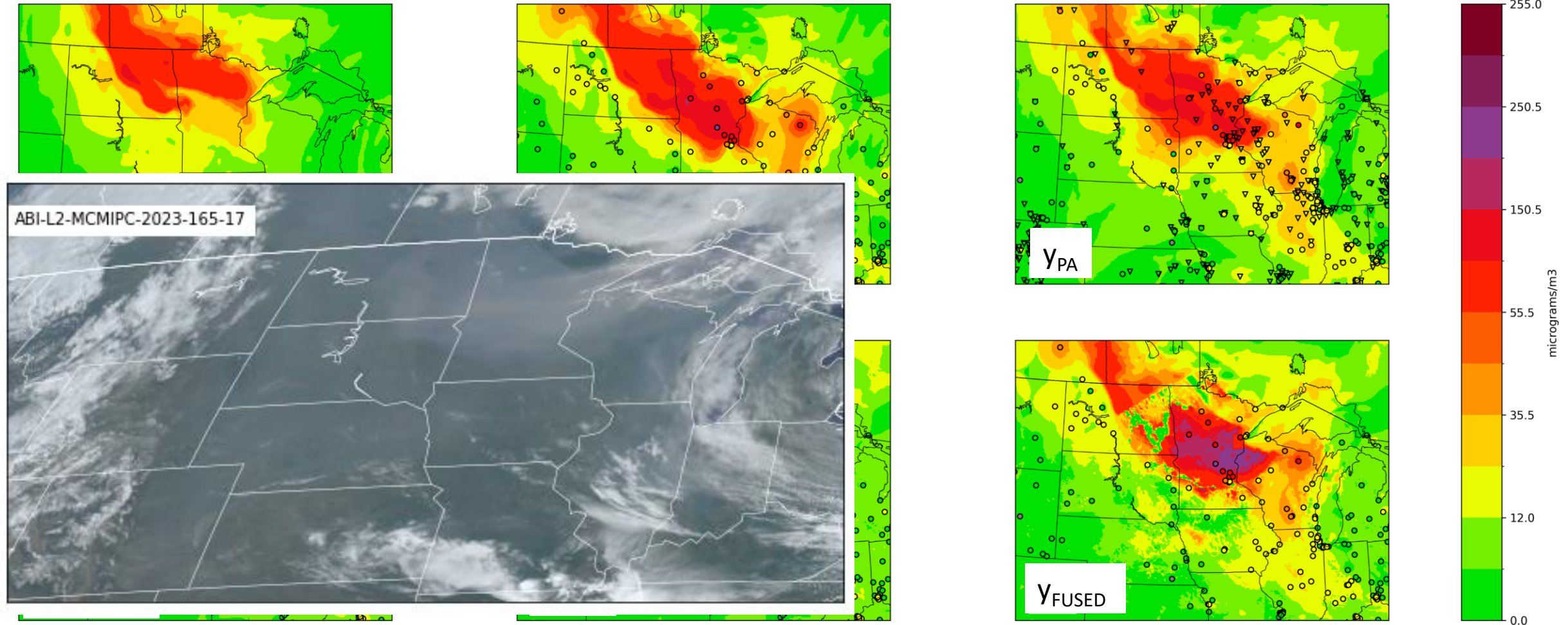


# Canadian Wildfires: 2023-06-14T17Z



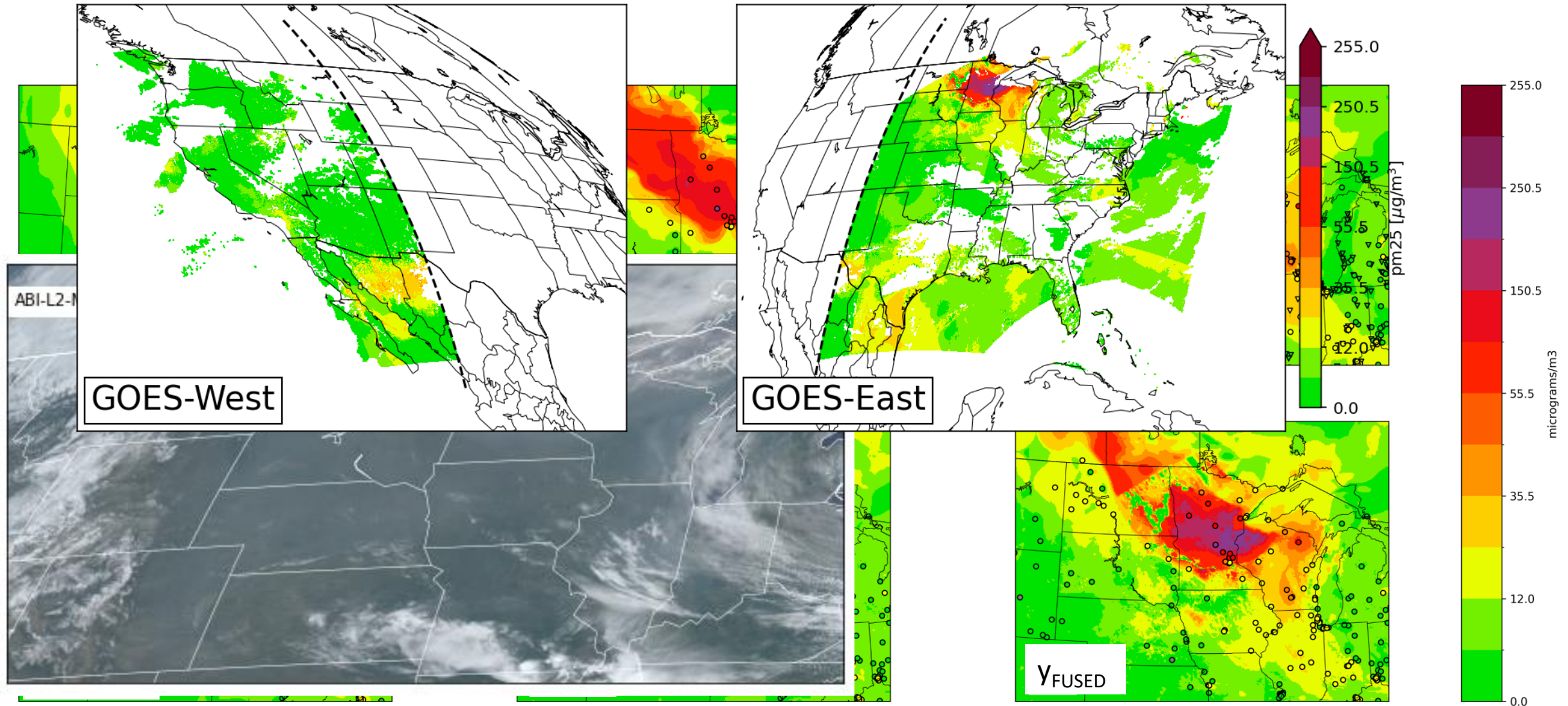


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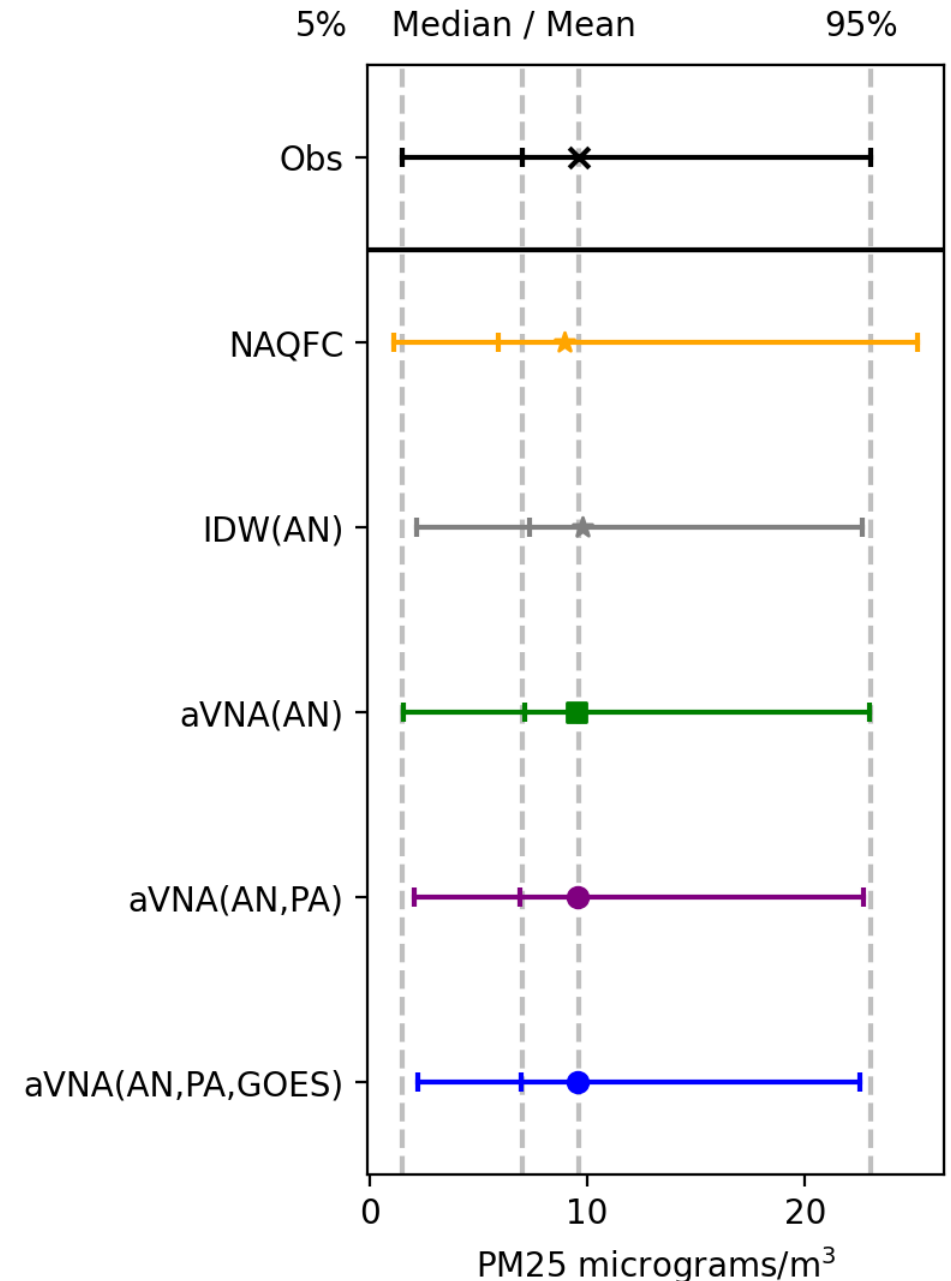


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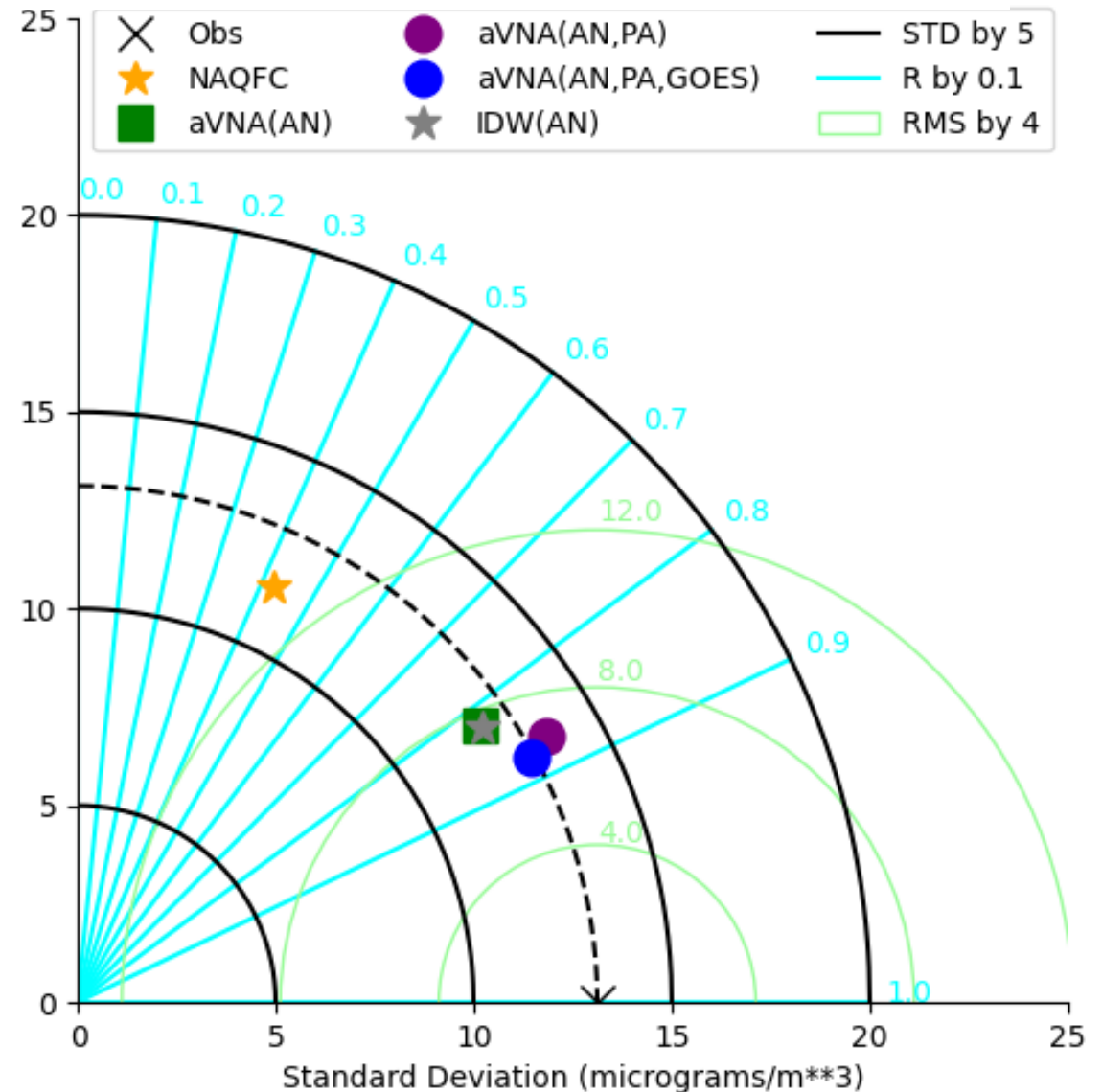
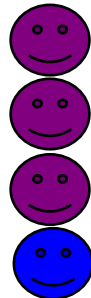
# Evaluating the approach

- That was just one hour...
- Applied daylight from Jun 2023 to Sept 2023
  - IDW as in AirNow (\*)
  - NAQFC from NOAA (\*)
  - Corrected w/ AirNow: AN
  - Correction w/ AN and PurpleAir: AN+PA
  - Correction w/ AN, PA and GOES: AN+PA+GOES
- Predicted each AirNow monitor without that monitor in the fusion
  - $n=1.3M = 12 \text{ h/d} * 30 \text{ d/m} * 3.75m * 1000 / h$
- Statistics: Normalized Mean Bias, Normalized Mean Error, RMSE, Correlation.



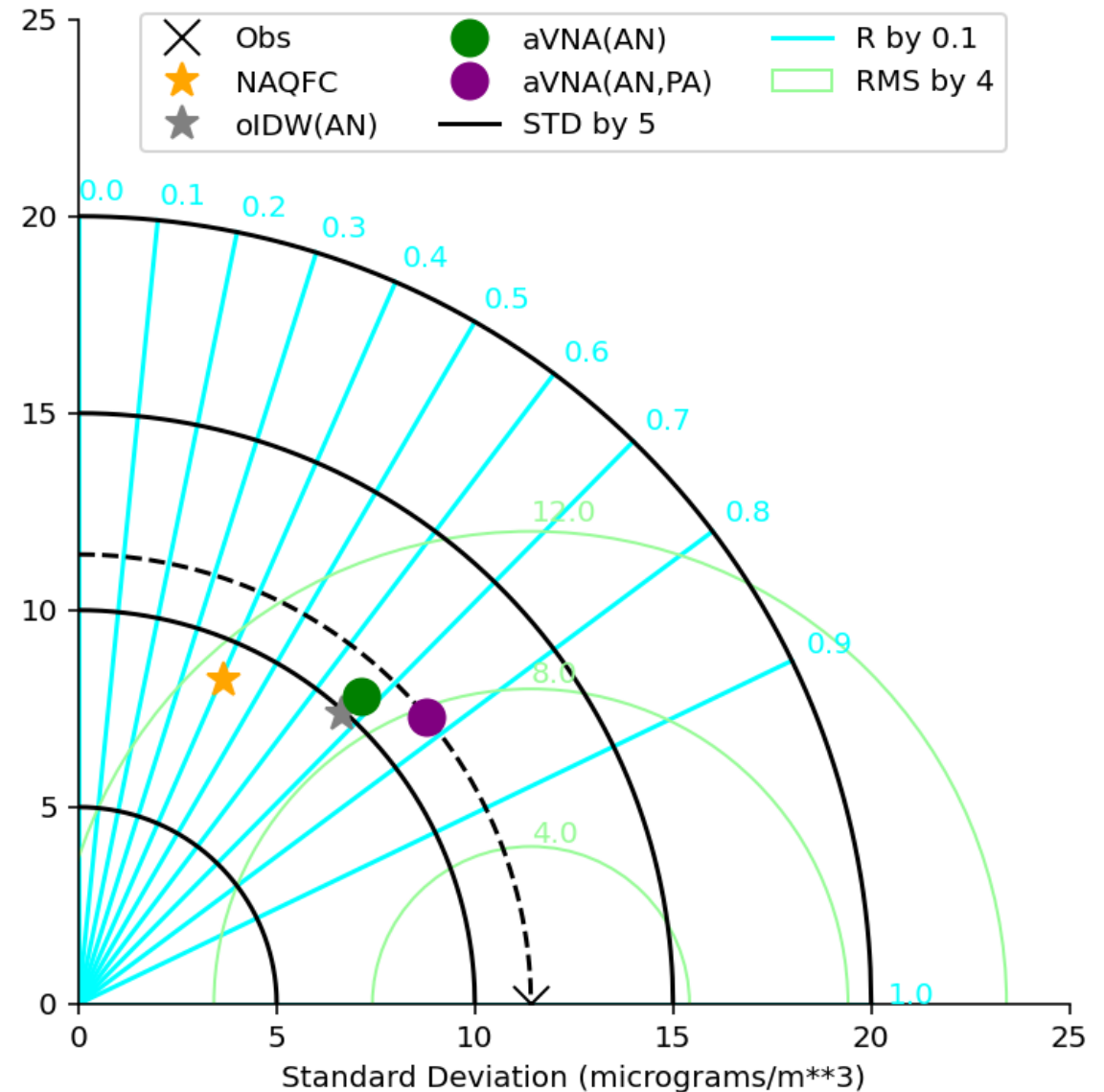
# Performance Summary: June-Sept 2023 (daylight hours; n=1.3M)

- Multiple statistics matter
  - Pearson correlation (y-axis)
  - centered Root Mean Squared Error (x-axis)
  - Reproduction of standard deviation
- The **NAQFC** has the lowest correlation, the highest RMSE, and the worst standard deviation.
- The **AirNow** and IDW have similar correlation, **AirNow** has better standard deviation.
- The fusion with **PurpleAir** improves standard deviation, correlation, and root mean squared error.
- The fusion with **GOES** is even better.



# Performance Summary: June 2021-June 2022 (All hours; n=8M)

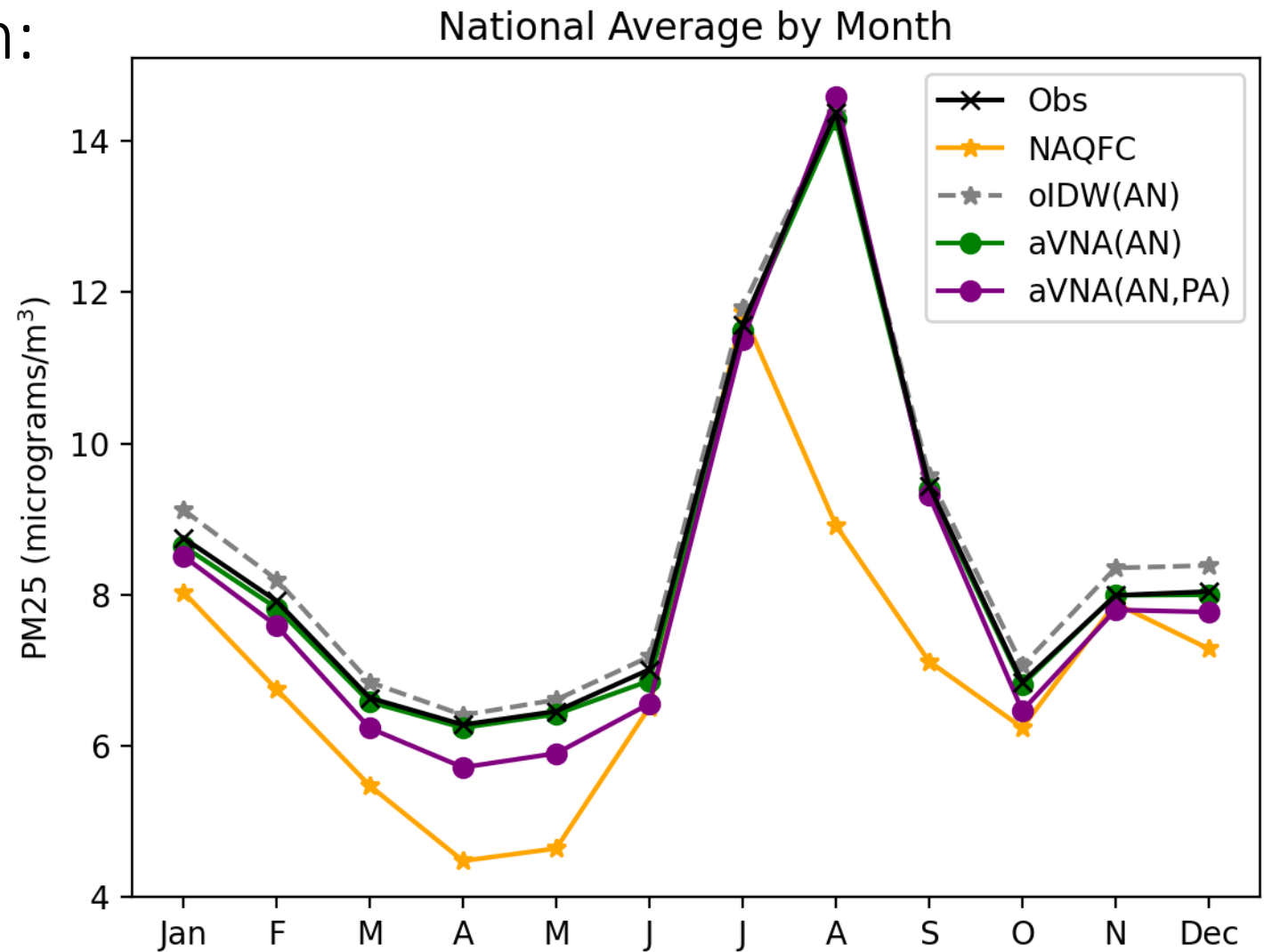
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- Is the story more complex? When does one fail and the other succeeds?





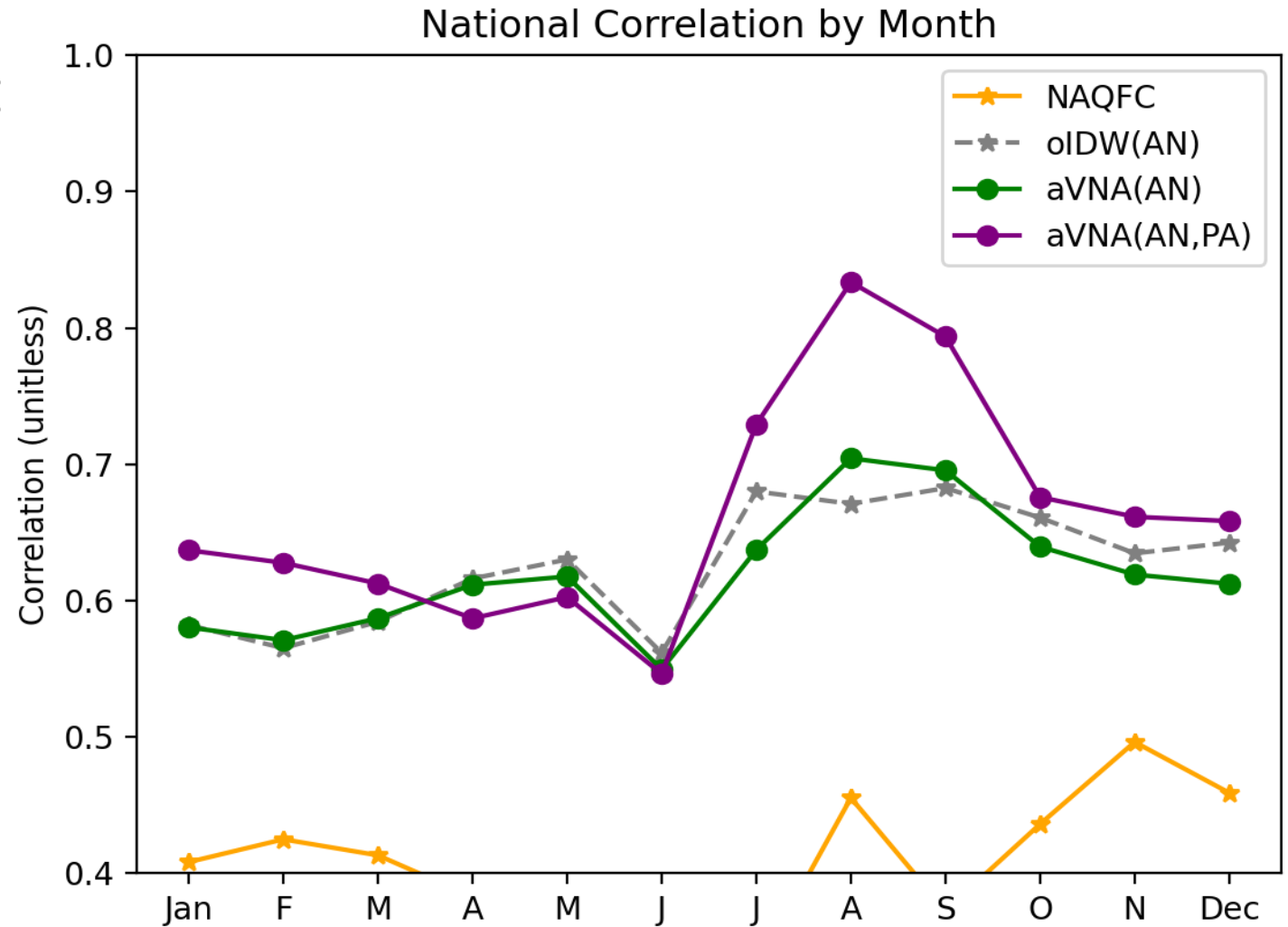
# Leave-1-out Validation: National Average of Predictions

- This figure summarizes the concentration of PM<sub>2.5</sub> over the months of the year by method.
- All methods peak during the fire season with the NAQFC peaking during July.
- Whereas the observations and other methods all peak during August.
- Remember, this is validation. In application, the prediction at the monitor is equal to the monitor.



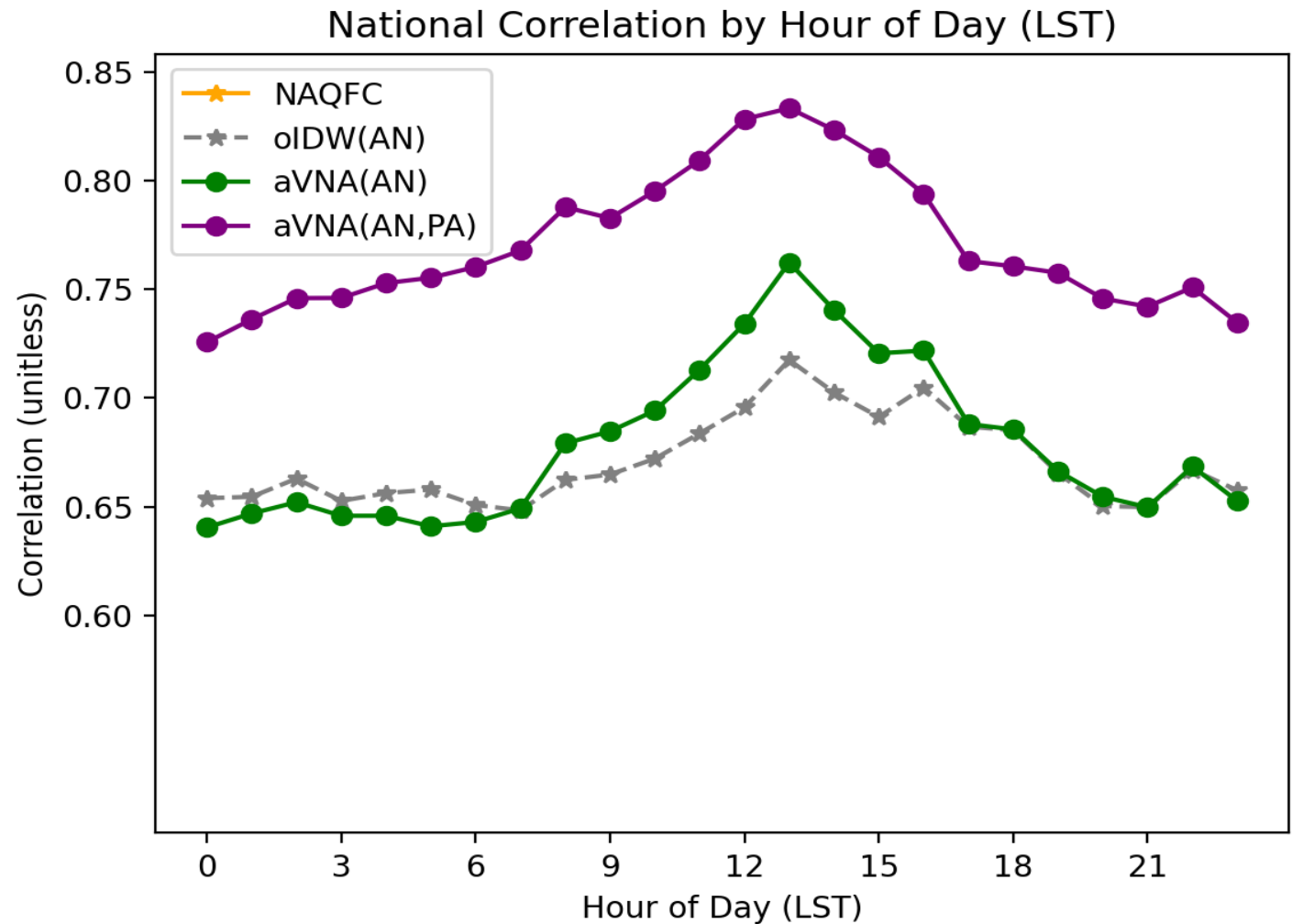
## Leave-1-out Validation: National Correlation

- Incorporating PA improves the correlation especially during the fire season.
- aVNA(AN) has lowest correlation overall.
- aVNA(AN,PA) improves the correlation over the time of day.
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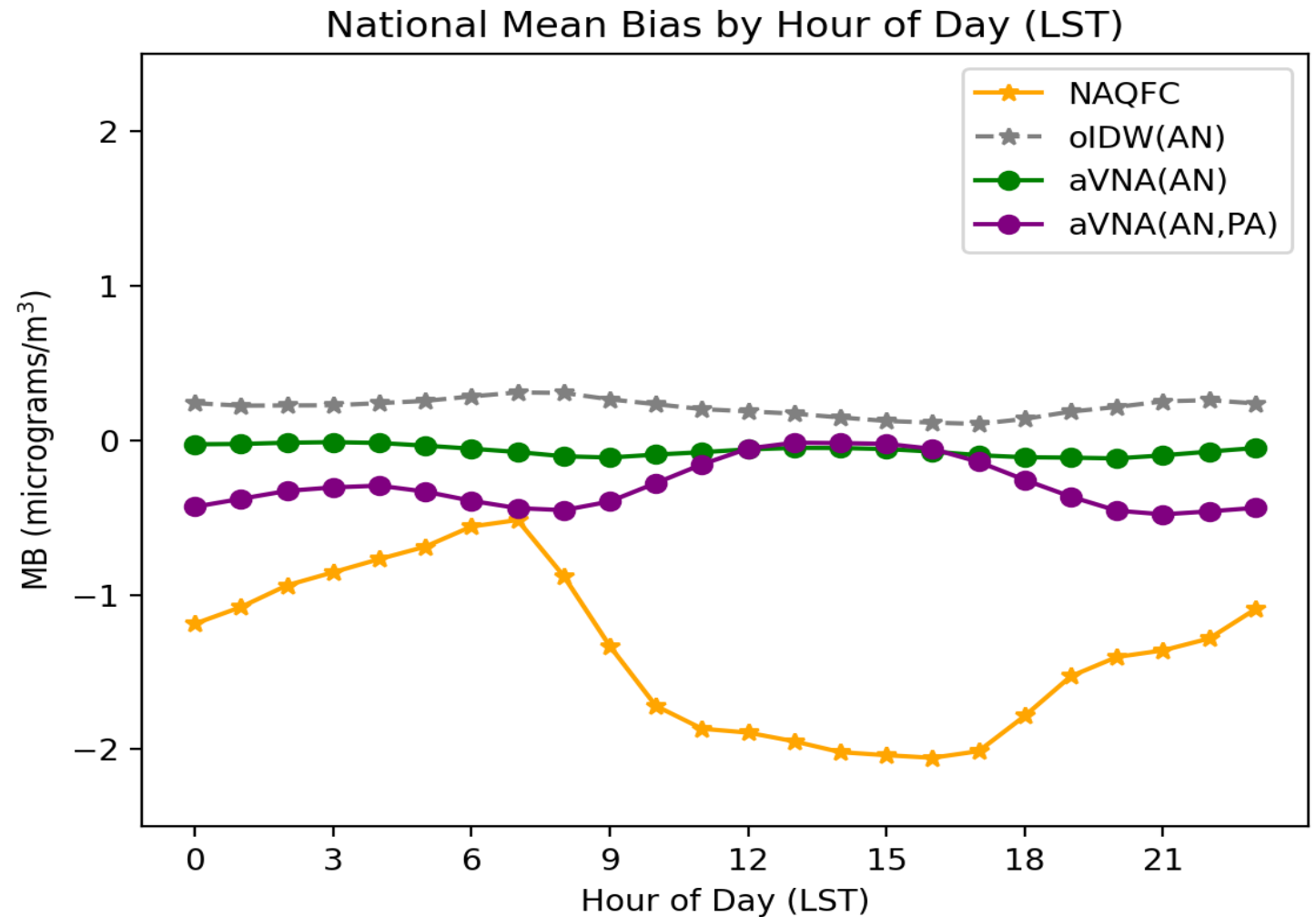
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# Leave-1-out Validation: National Mean Bias

- oIDW and aVNA(AN) have the most consistent bias.
- aVNA(AN,PA) has highest bias at night but is still quite good.
  - Currently, we use a single bias correction for PurpleAir.
  - Humidity varies with time of day and may need more complex correction.
  - Also, FEM technologies are evaluated most strictly for daily average concentration.
- Remember, this is validation. In application, the prediction at the monitor is equal to the monitor.





# Summary

- AirNow needs an updated interpolation method.
  - EPA has long used models and statistical fusion to fill gaps with regulatory but has not incorporated these methods into AirNow.
  - Schulte et al. demonstrated including models and PurpleAir improved on simple interpolations and applied it in an AirNow-like system.
  - HAQAST Tiger Team evaluated GOES PM25 for real-time-applications.
- Fusion with PurpleAir is ready.
  - Discontinuities are less stark than GOES because datasets are more spatially consistent (ie sparse in the same places).
  - Value of PurpleAir is obvious because they are dense near monitors.
- Fusion with GOES PM25 ongoing work
  - HAQAST Tiger Team 2021 (Gupta) – now 2023 (Yang Liu)
  - Conceptually, the satellite value is highest away from monitors and sensors... making it hard to evaluate
  - ~5% of monitors are further than 30km from their nearest withheld monitor...



# Questions?

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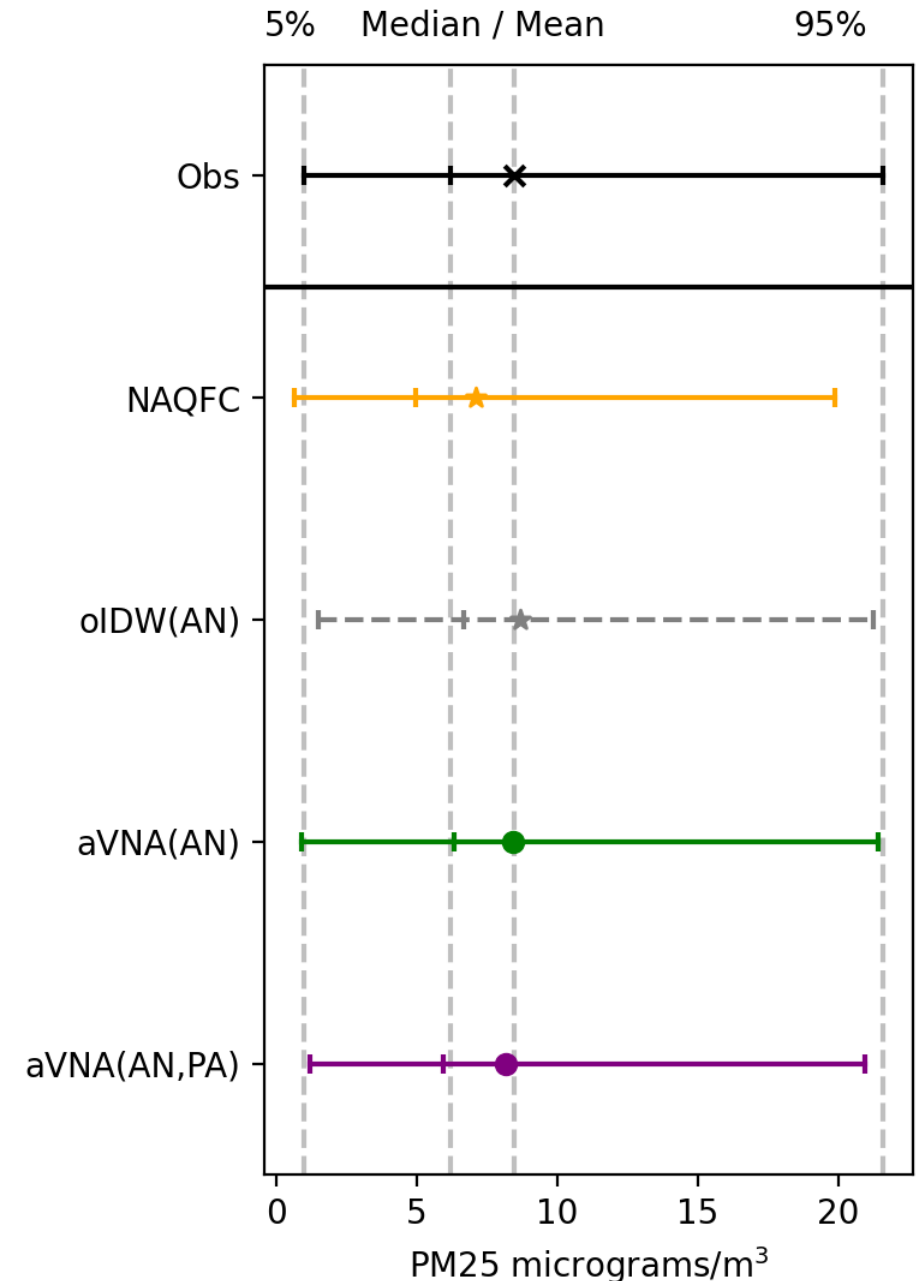
# Extra Slides

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  - ~~Correction w/ AN, PA and GOES: AN+PA+GOES~~
- Predicted each AirNow monitor without that monitor in the fusion
  - $n=8M = 8760 \text{ h/y} * 1000 \text{ /h}$
- Statistics: Normalized Mean Bias, Normalized Mean Error, RMSE, Correlation.





# Alternative Ensemble Weighting Approaches

- We need a method to synthesize the products:
  - At this point, we have a potential of 4 fusion products
  - 2 bias correction methods (aVNA, eVNA), 2 data sources (AirNow, PurpleAir)
- Geographically Varying Weights (GVW)
  - Similar to Requia[1], but implemented like Skipper[2]
  - $Y_{\text{fused}} = \sum_i \alpha_i Y_i$       •  $\alpha_i = c_i + \beta_{i,0}x + \beta_{i,1}y + \beta_{i,2}d_{\text{PA}} + \beta_{i,2}d_{\text{AN}}$
  - $c_i$  and all  $\beta$  are fit using least squares regression
- Random Forest Regression (RF)
  - Features:  $x, y, d_{\text{PA}}, d_{\text{AN}}, Y_i$  estimates from leave-one-out cross-validation
  - Configuration: Minimum 20 features for a split; 100 trees.
- **Not Shown:** Few day tests show
  - Both GVW and RF have better correlation than current approach; RF best.
  - But.... Current approach has better standard deviation than either
- This will likely need to be revisited when bringing in the GOES-PM25.

[1] Requia et al. <https://pubs.acs.org/doi/10.1021/acs.est.0c01791>

[2] Skipper et al. <https://doi.org/10.1021/acs.est.0c08625>

# Leave-1-out Validation: National Mean Bias

- GOES shows structure in the bias that is associated with long-distance extrapolation...
- The fusion actually doesn't use those cells (too far away)
- Remember, this is validation. In application, the prediction at the monitor is equal to the monitor.

