Comparison of multiple $PM_{2.5}$ exposure products for estimating health benefits of emission controls

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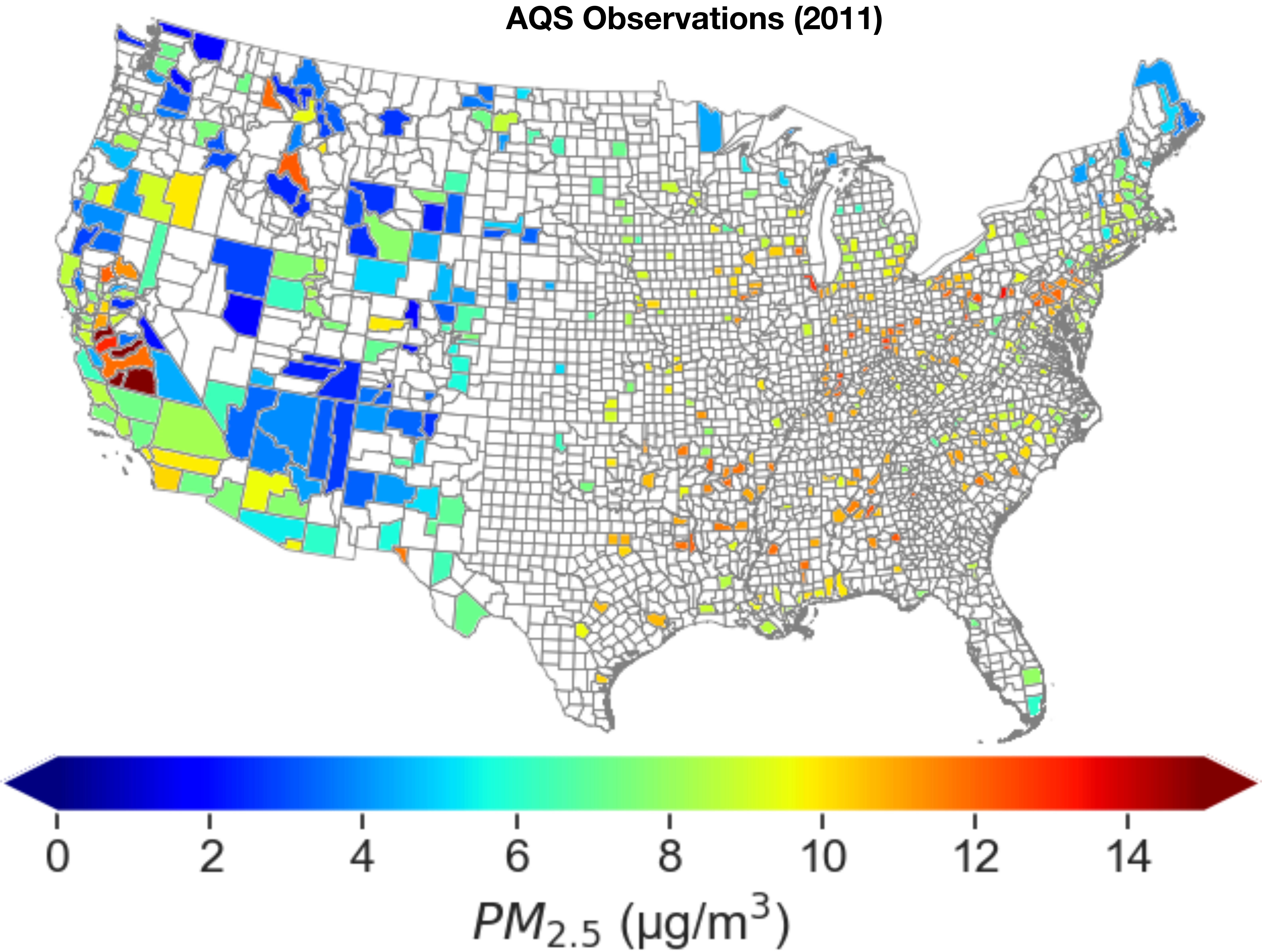
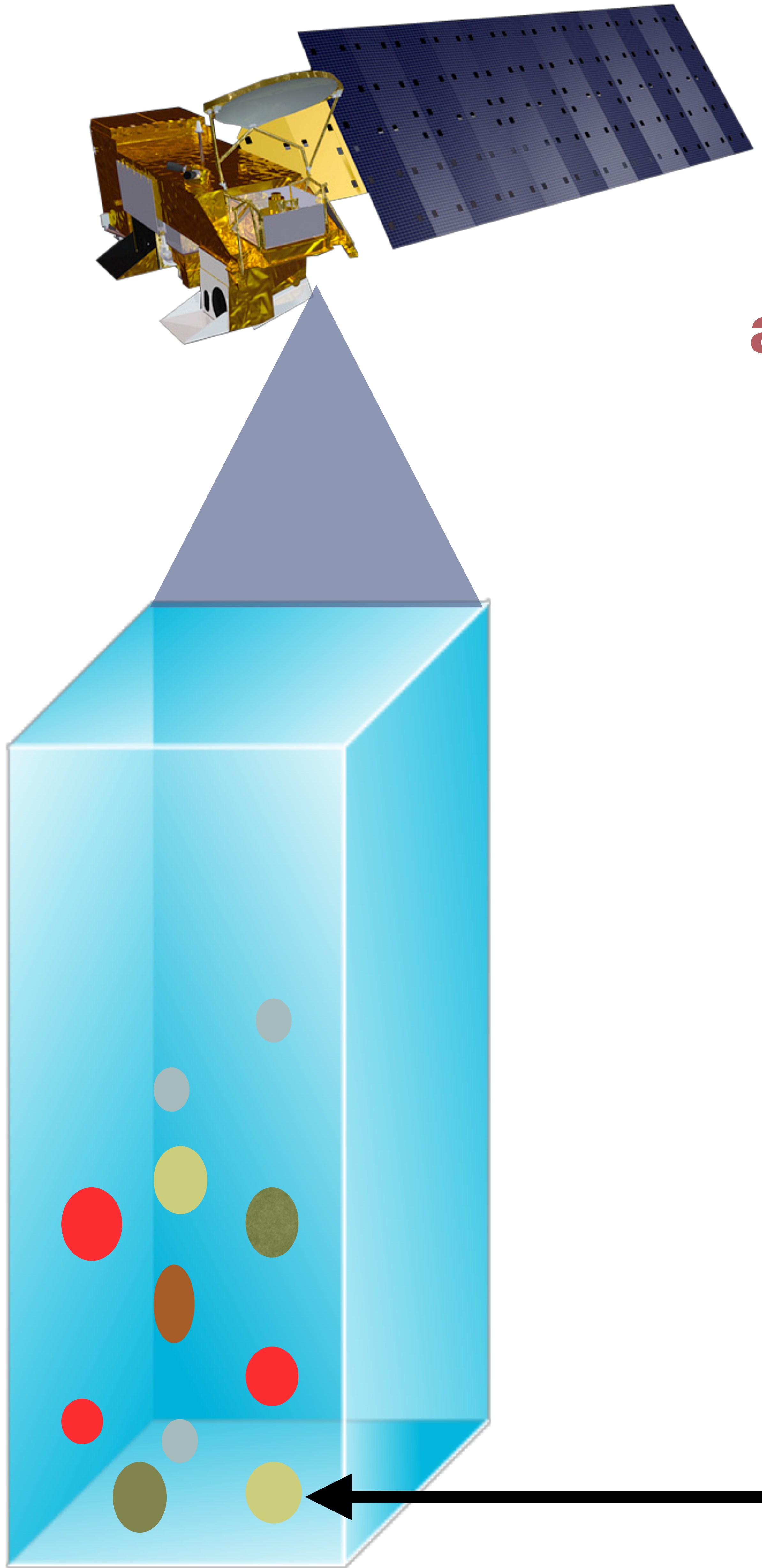
Limited $PM_{2.5}$ ground-based measurements for exposure assessment



Diao et al. (2019)

Linking satellite observations of AOD with ground-Level $PM_{2.5}$ pollution



Satellite-observed AOD: Sum of light extinction by all aerosols from bottom to top

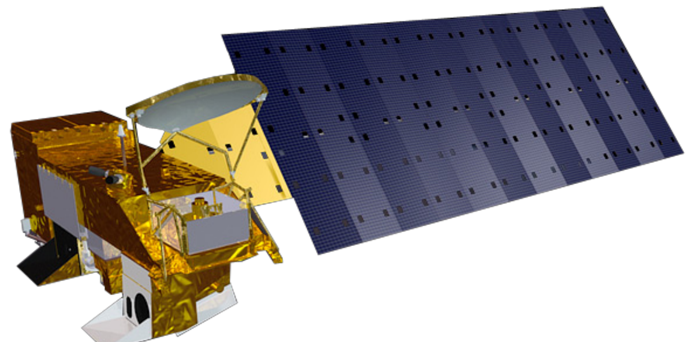
?

The relationship between AOD and $PM_{2.5}$ depends on aerosol mass, species, vertical distribution, size, hygroscopicity and ambient environment.

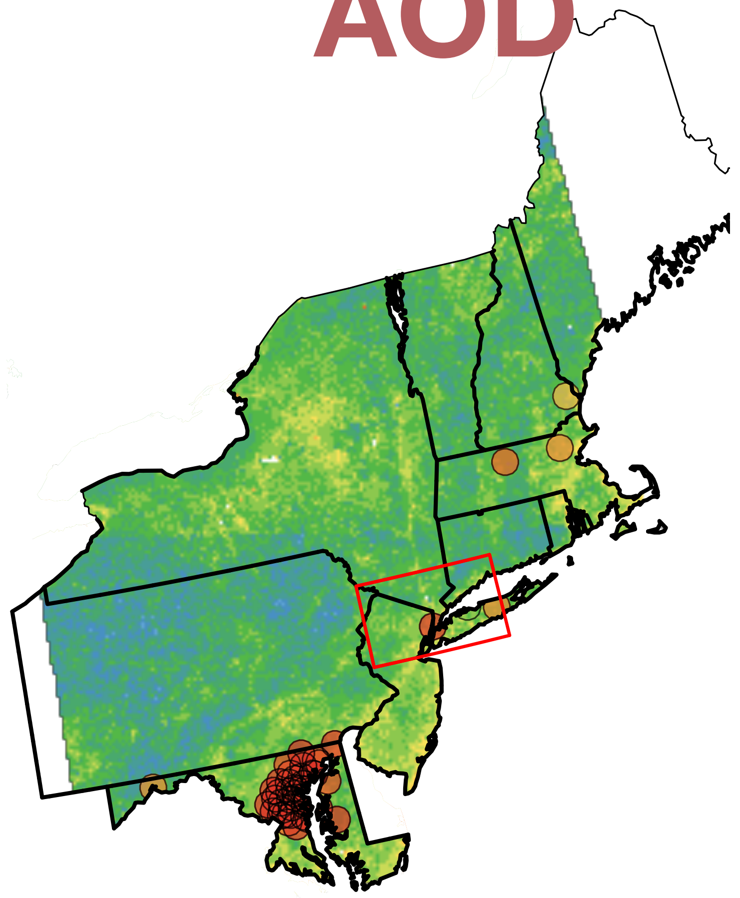
$PM_{2.5}$: Mass of small particles (diameter < 2.5 μm) near the surface

Ground-based observations

Linking satellite observations of AOD with $PM_{2.5}$: Geophysical Approach



Satellite-observed AOD



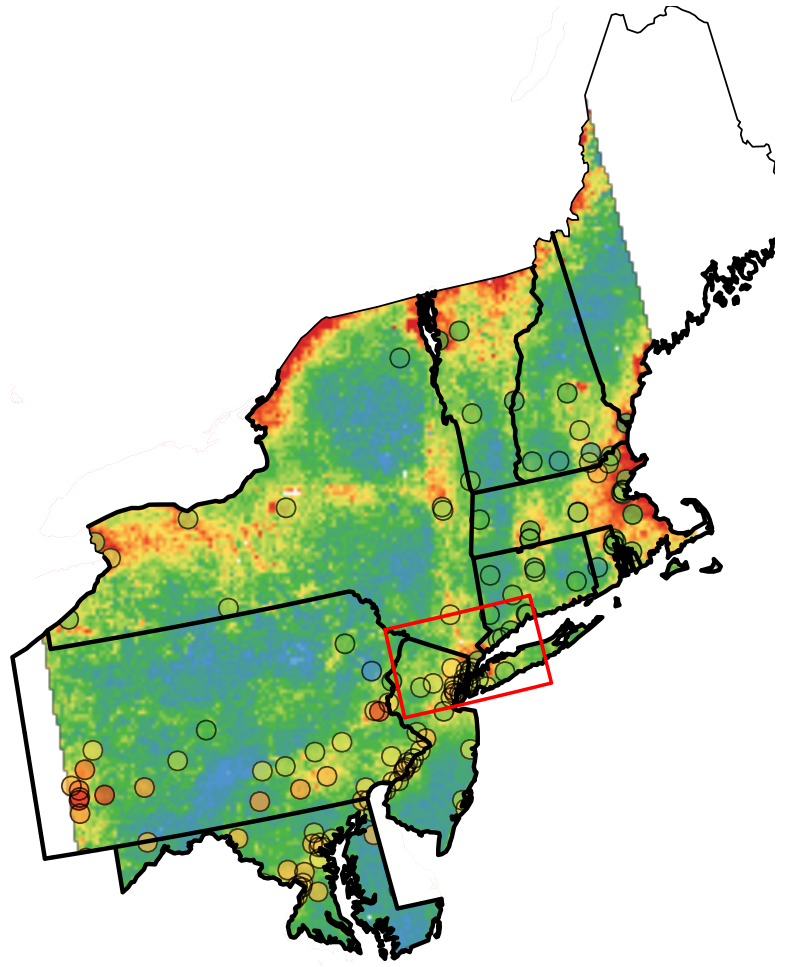
CMAQ

GEOS-Chem

Chemical Transport Model

$$AOD_{satellite} \times \frac{PM_{2.5\_Model}}{AOD_{Model}} = PM_{2.5\_satellite}$$

Satellite-derived $PM_{2.5}$

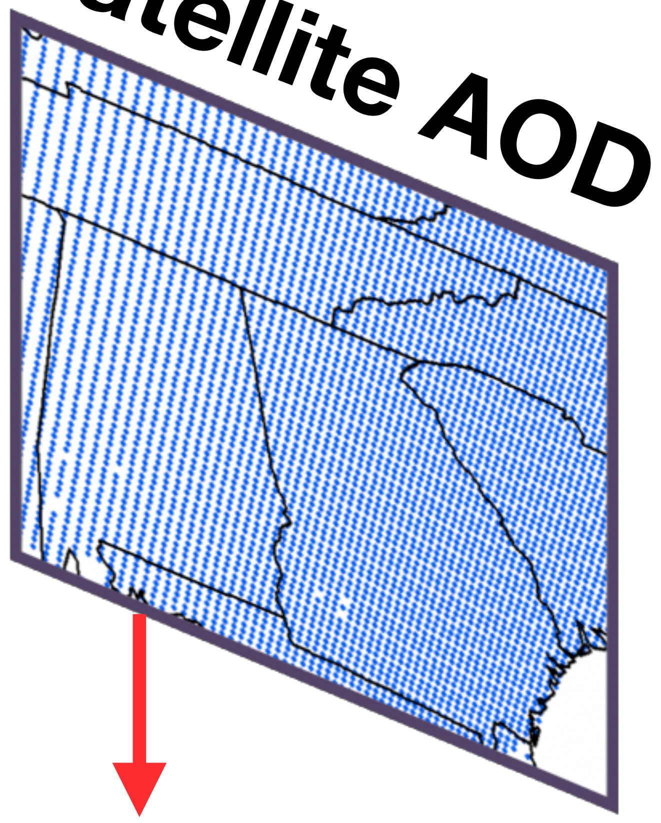


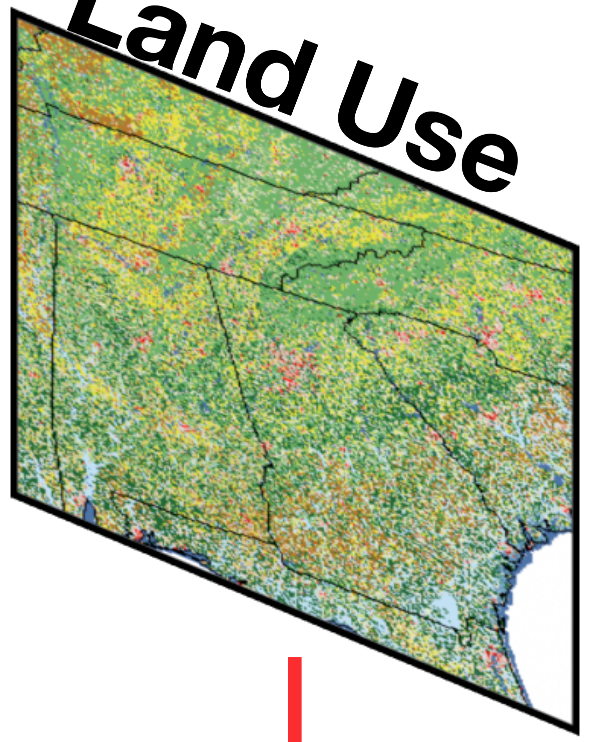
- Size Distribution
- Water Uptake
- Refractive Indices
- Aerosol Density

Radiative Transfer Theory

- Aerosol Vertical Profile
- Aerosol Column Mass
- Aerosol Speciation
- Modeled Meteorology

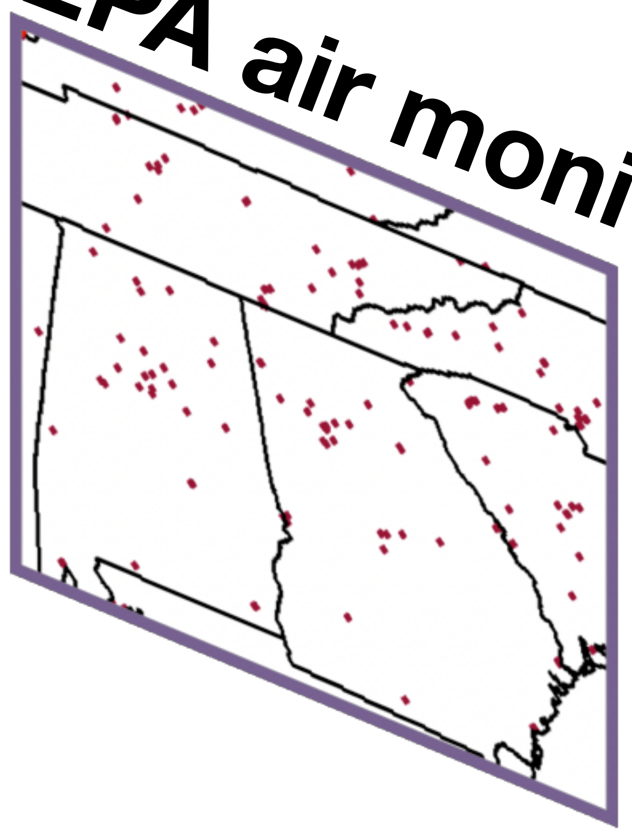
Linking satellite observations of AOD with $PM_{2.5}$: Statistical Approach



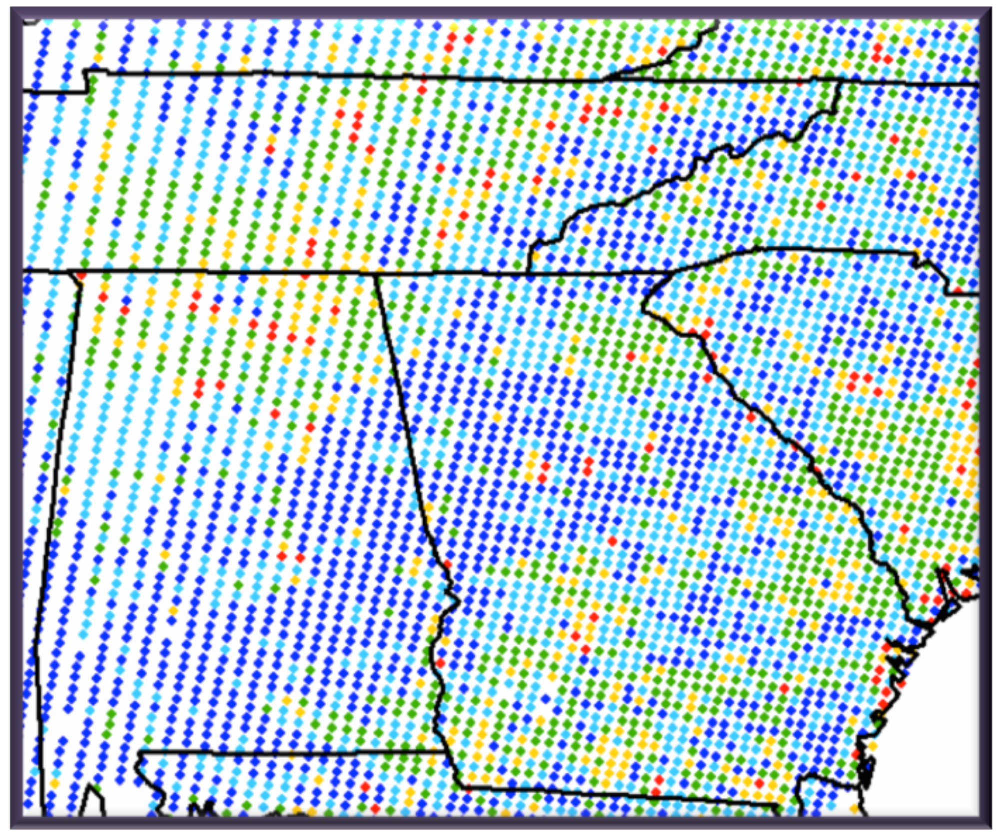


Statistical Model

$$
\begin{aligned}
\mathrm{PM}_{2.5,st} &= (b_0 + b_{0,t}) + (b_1 + b_{1,t})\mathrm{AOD}_{st} + (b_2 + b_{2,t}) \\
&\quad \mathrm{Meteorological\,Fields}_{st} + b_3\mathrm{Elevation}_s + b_4\mathrm{MajorRoads}_s \\
&\quad + b_5\mathrm{Forest\,Cover}_s + b_6\mathrm{Point\,Emissions}_s \\
&\quad + \varepsilon_{st}\,(b_{0,t} b_{1,t} b_{2,t}) \sim N\left[(0,0,0)\,,\,\Psi\right],
\end{aligned}
$$



Predicted $PM_{2.5}$

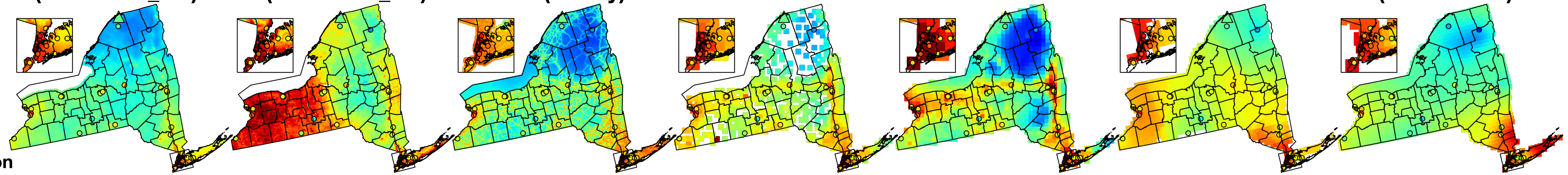


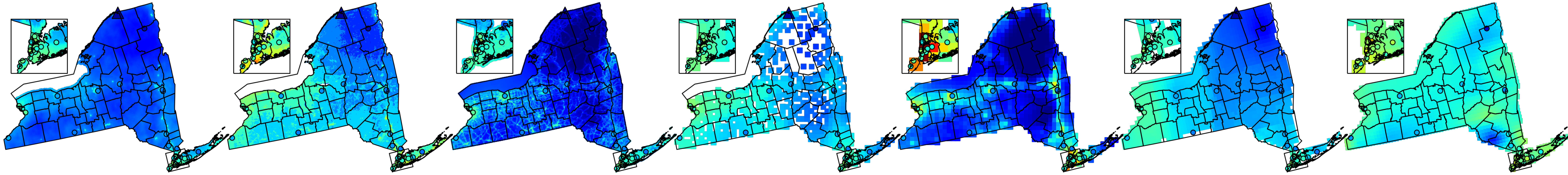
Yang Liu (Emory University)

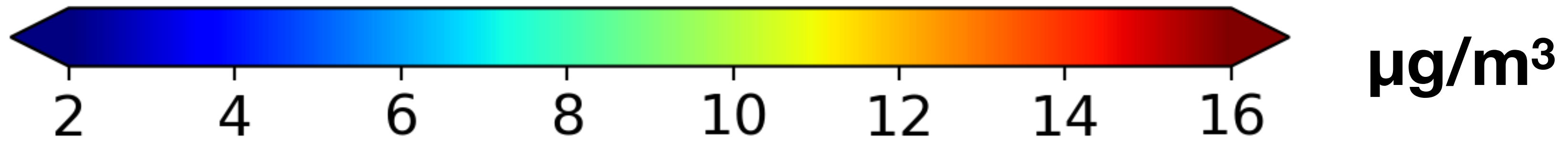
Which long-term $PM_{2.5}$ products are available for health studies over NYS ?

	Dataset	Spatial Resolution	Spatial Coverage	Temporal Resolution	In-situ	Remote Sensing	Atmospheric Model (CTM)	Ancillary Data	Reference
1	**Global Geophysical Satellite-Based $PM_{2.5}$ (Dalhousie_GL)**	0.01 ° x 0.01 ° (~ 1 km x 1 km)	Global	Annual	GBD annual ground-based PM2.5	MODIS, MISR and SeaWIFS AOD	GEOS-Chem (v9-01-03)	x	Van Donkelaar *et al* 2016
2	**North America Geophysical Satellite-Based $PM_{2.5}$ (Dalhousie_NA)**	0.01 ° x 0.01 ° (~ 1 km x 1 km)	North America	Monthly	US EPA AQS	MODIS, MISR and SeaWIFS AOD	GEOS-Chem (v9-01-03)	x	Van Donkelaar *et al* 2019
3	**Machine Learning Satellite-Based $PM_{2.5}$ (Emory)**	1 km x 1 km	New York State	Daily	US EPA AQS	MAIAC AOD	x	Meteorology, land use	Bi *et al.* 2019
4	**AQS and remote sensing merged $PM_{2.5}$ (CDC WONDER)**	10 km x 10 km	USA	Daily	US EPA AQS	MODIS AOD	x	x	Al-Hamdan *et al* 2012
5	**Fused Air Quality Surface using Downscaling (FAQSD)**	12 km x 12 km	USA	Daily	US EPA AQS	x	CMAQ (v4.7)	x	Berrocal *et al* 2010, 2011
6	**CMAQ Simulation**	12 km x 12 km	USA	Daily	x	x	CMAQ (v4.7)	x	Byun *et al* 2006
7	**Inverse Distance Weighed $PM_{2.5}$ (IDW)**	12 km x 12 km	New York State	Daily	US EPA AQS	x	x	x	US EPA 2018

How do these $PM_{2.5}$ products differ?







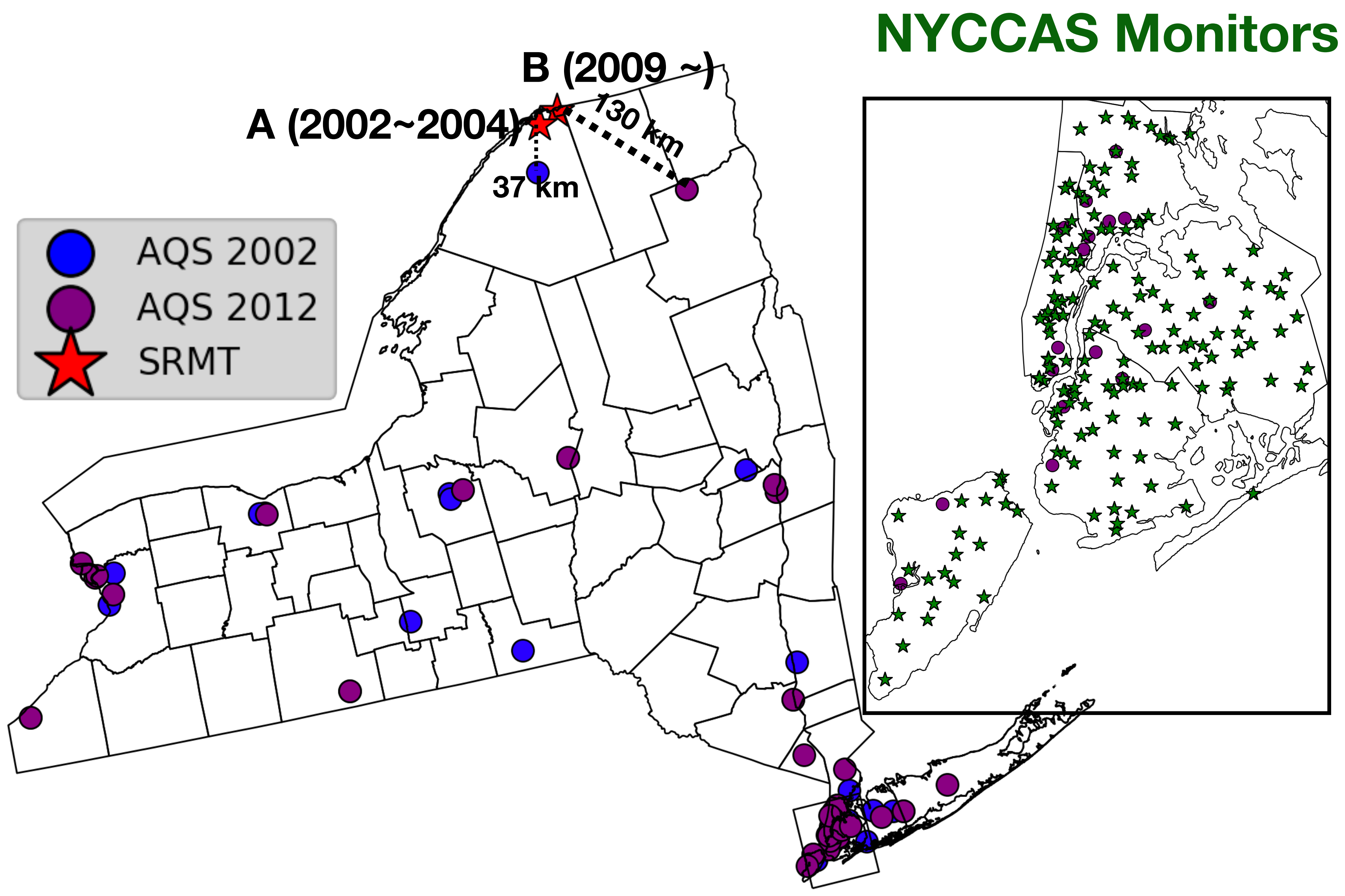
	NA Geophysical (Dalhousie_NA)	Global Geophysical (Dalhousie_GL)	Machine Learning (Emory)	FAQSD	CMAQ	AQS IDW	CDC WONDER (2003 - 2011)
2002 Population Weighted average (µg/m³)	14.0	13.2	12.7	13.3	17.4	10.9	13.0
2012 Population Weighted average (µg/m³)	9.8	9.0	8.5	8.7	12.9	6.9	9.8
Difference (µg/m³)	-4.2	-4.2	-4.2	-4.6	-4.5	-4.0	
Relative Change	-30%	-32 %	-33%	-34 %	-25 %	-36%	

- The annual population weighed average $PM_{2.5}$ over NYS vary by **6 µg/m³ (44%)**, but the decreasing trends are consistent across all products.

Jin et al., 2019a, ERL

Evaluation of $PM_{2.5}$ products using independent ground-based observations

- Urban Area: NYC Community Air Quality Survey (NYCCAS) Program.
- Remote Area: St. Regis Mohawk Tribe (SRMT) Air Quality Program



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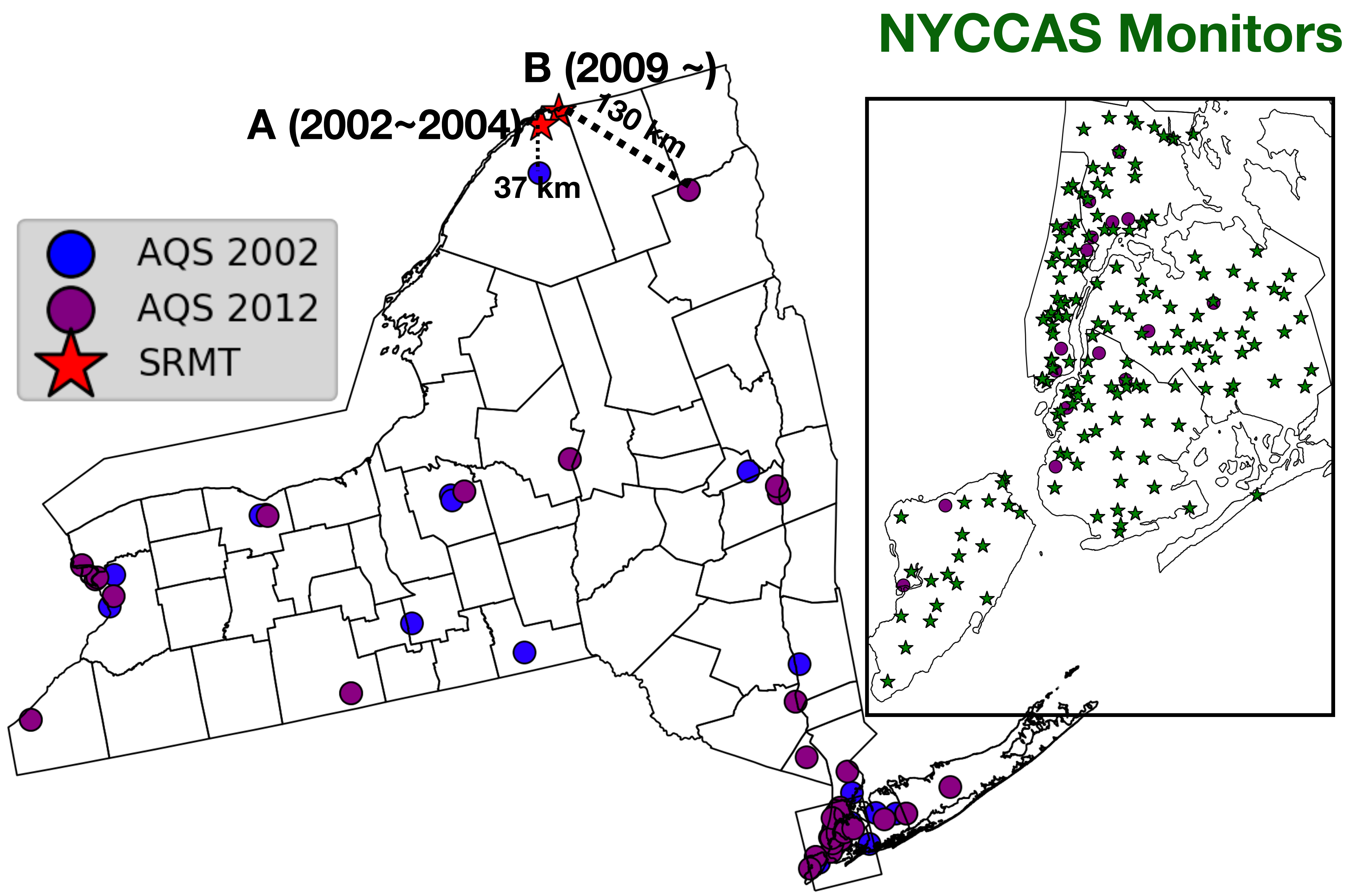

Pearson Correlation Coefficient (R)

	Dataset	NYC CAS Spatial	NYC CAS Temporal	SRMT A (37 km) Temporal	SRMT B (130 km) Temporal
With Remote Sensing	Geophysical (1km)	0.33	0.83	0.81	**0.79**
	Machine learning (1km)	**0.62**	**0.94**	**0.89**	0.77
	CDC WONDER (10 km)	0.31	0.82	0.86	0.75
Without Remote Sensing	FAQSD (12 km)	0.53	0.93	0.74	0.58
	CMAQ (12 km)	0.41	0.42	0.22	0.04
	AQS IDW (12 km)	0.58	0.92	0.87	0.60

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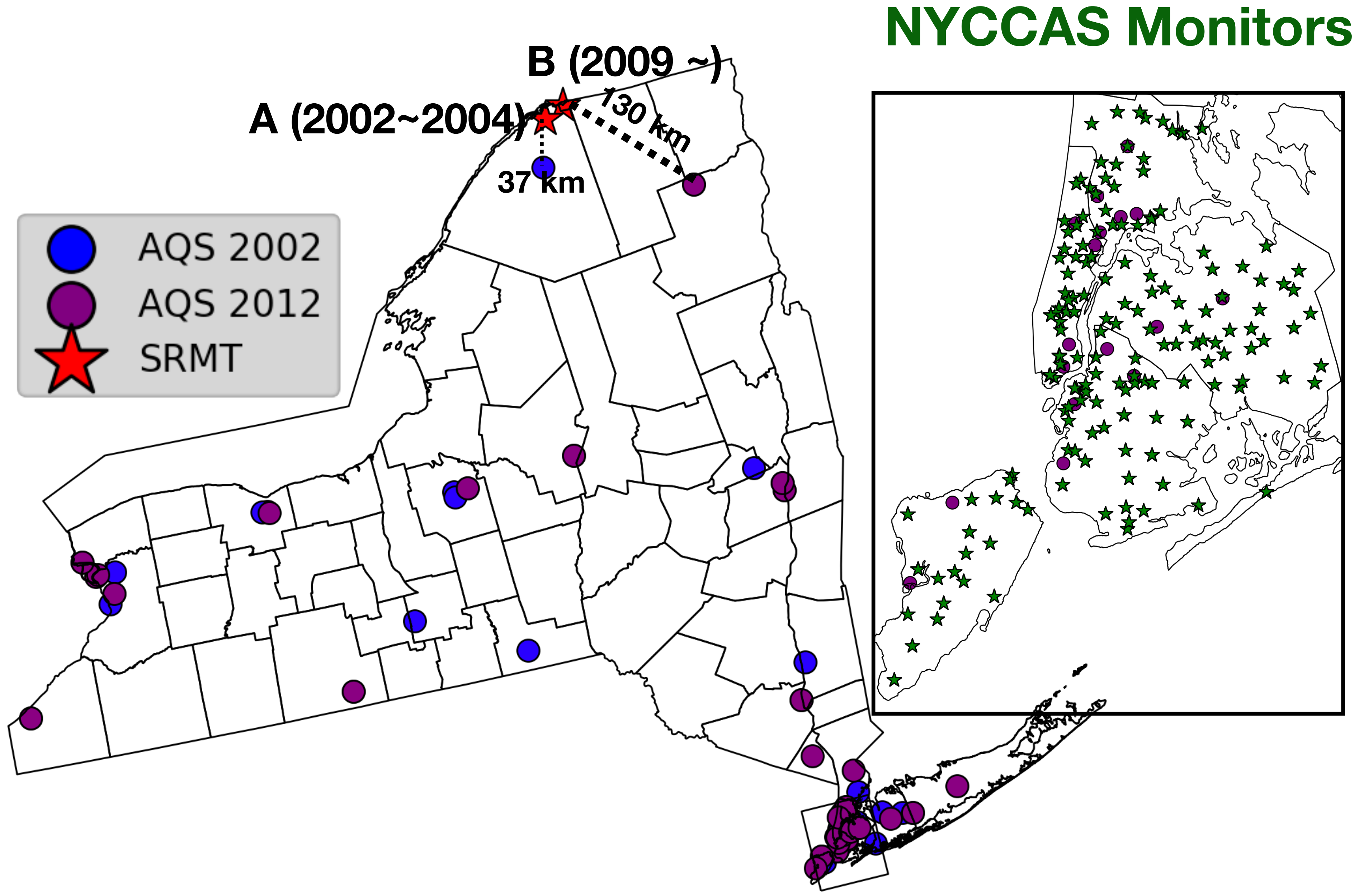

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- Inclusion of satellite remote sensing improves the estimate of $PM_{2.5}$ over remote area.
- **Machine learning-based (Emory)** product best captures the spatial and temporal variability of ground-level $PM_{2.5}$ at the site **closer to** AQS monitors (< 40 km), but **geophysical (Dalhousie_NA)** product performs best at the site **far** from AQS monitors (> 100 km).

Jin et al., 2019a, ERL

Quantifying the $PM_{2.5}$-related health benefits of emission reduction over NYS

Excess mortality burden attributed to $PM_{2.5}$ exposure =
Baseline Mortality $\times$ Attributable Fraction ($PM_{2.5}$) $\times$ Population

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- Attributable fraction (1 - 1/RR):
  - Relative risk (RR) factors from the Global Burden of Disease Collaborative Network.
  - Based on an integrated exposure-response model (Burnett et al., 2014).
  - Cause-specific RR factors for four causes of diseases: chronic obstructive pulmonary diseases (COPD), ischemic heart disease (IHD), lung cancer (LC), and cerebrovascular and ischemic stroke (STROKE).

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- Population: County-level population from CDC WONDER, spatially distributed with Gridded Population of the World (GPW, v4) data from SEDAC.

$PM_{2.5}$-related mortality burden over NYS decreased by 67% from 2002 to 2012

Jin et al., 2019a, ERL

Comparison of the geophysical vs. machine learning approaches to estimating $PM_{2.5}$ from satellite AOD

		Geophysical Satellite-Based $PM_{2.5}$ (Dalhousie)	Machine Learning Satellite-Based $PM_{2.5}$ (Emory)
Accuracy	Urban		👍
	Remote	👍	
Availability	Spatial	👍	
	Temporal	👍	👍
Resolution	Spatial		👍
	Temporal		👍

Key uncertainties of the geophysical approach at daily scale

$$AOD_{satellite} \times \frac{PM_{2.5\_CMAQ}}{AOD_{CMAQ}} = PM_{2.5\_satellite}$$

- Measurements uncertainty
- Invalid obs (clouds/snow)

$PM_{2.5}$-AOD Relationship

- Aerosol mass
- Aerosol vertical distribution
- Aerosol speciation
- Modeled meteorology
- Refractive index
- Aerosol density
- Size distribution
- Hygroscopic growth factor

Jin et al., 2019b, ACP

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Co-located AERONET + AQS Sites

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Jin et al., 2019b, ACP

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EPA CSN + IMPROVE

Jin et al., 2019b, ACP

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EPA CSN + IMPROVE

Atmospheric Soundings Network

Jin et al., 2019b, ACP

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Co-located AERONET + AQS Sites

EPA CSN + IMPROVE

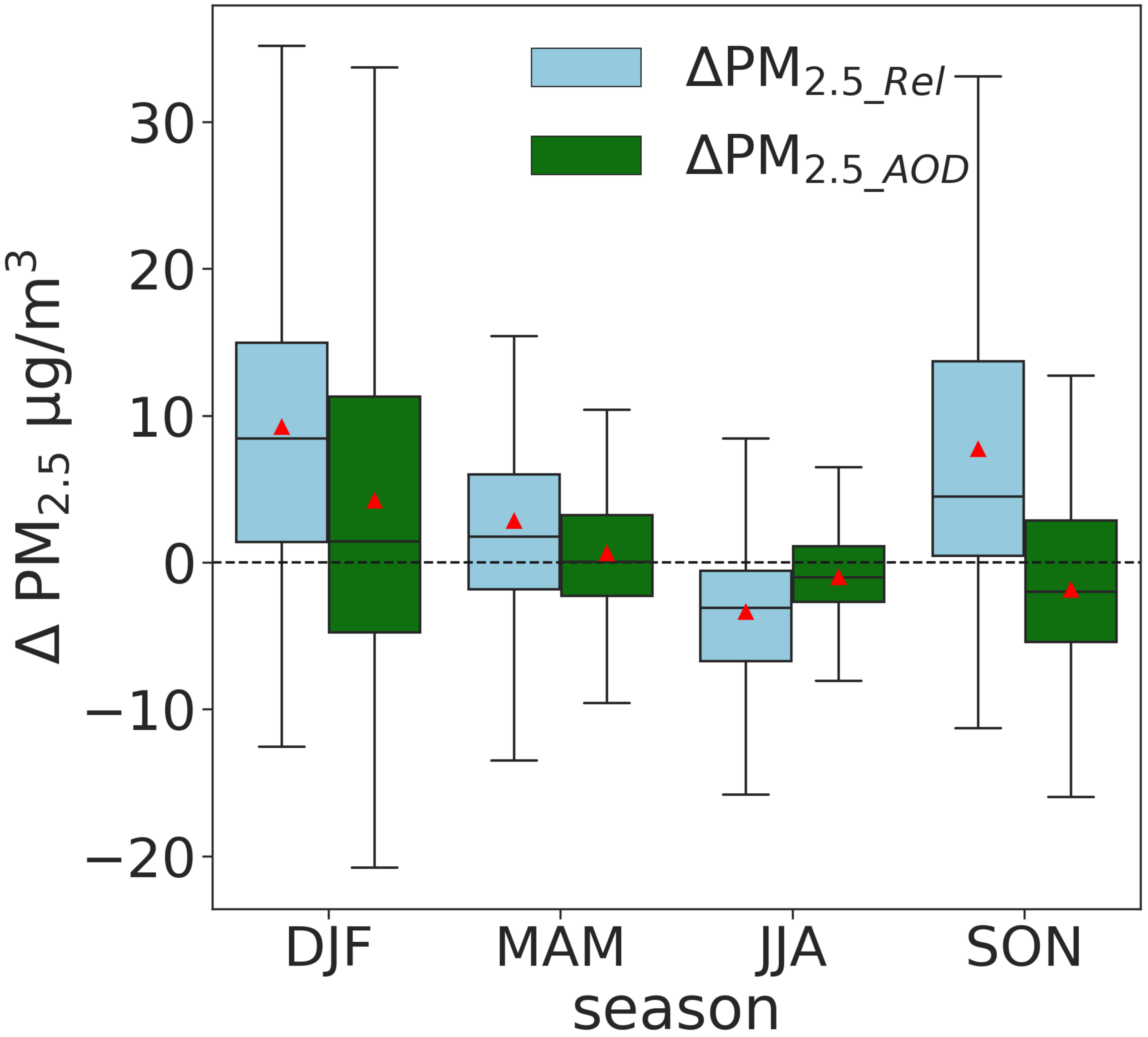
Atmospheric Soundings Network

Meta-analysis & Sensitivity Simulations in Model

Jin et al., 2019b, ACP

Model $PM_{2.5}$/AOD contributes more uncertainty to satellite derived daily $PM_{2.5}$ than satellite AOD

Errors attributed to satellite AOD vs. modeled $PM_{2.5}$/AOD



$$\Delta PM_{2.5\_AOD} = (AOD_{Sat} - AOD_{AERONET}) \times \frac{PM_{2.5\_Model}}{AOD_{Model}}$$

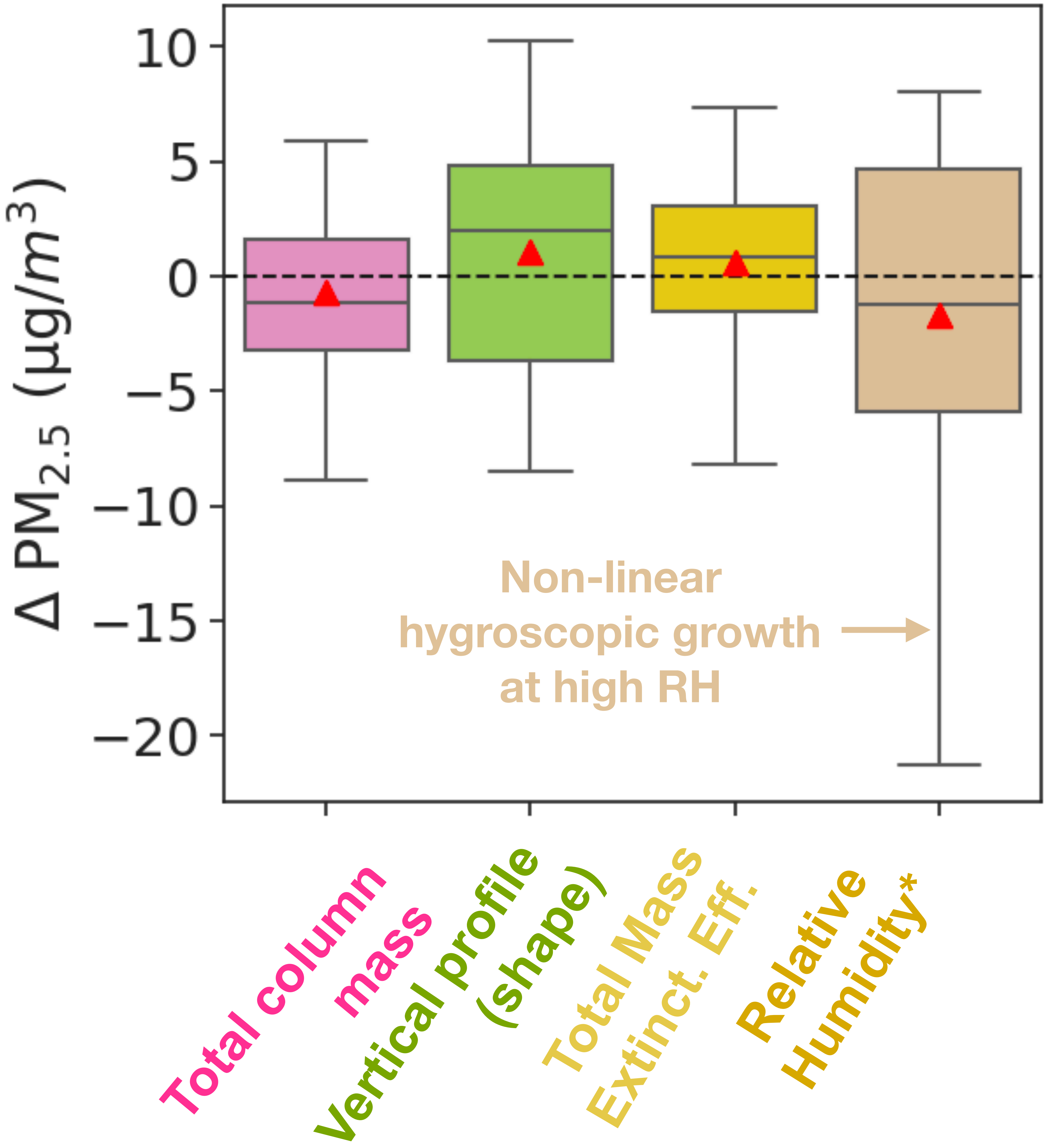
Co-located AERONET + AQS Sites
(within 10 km difference, 11 sites)

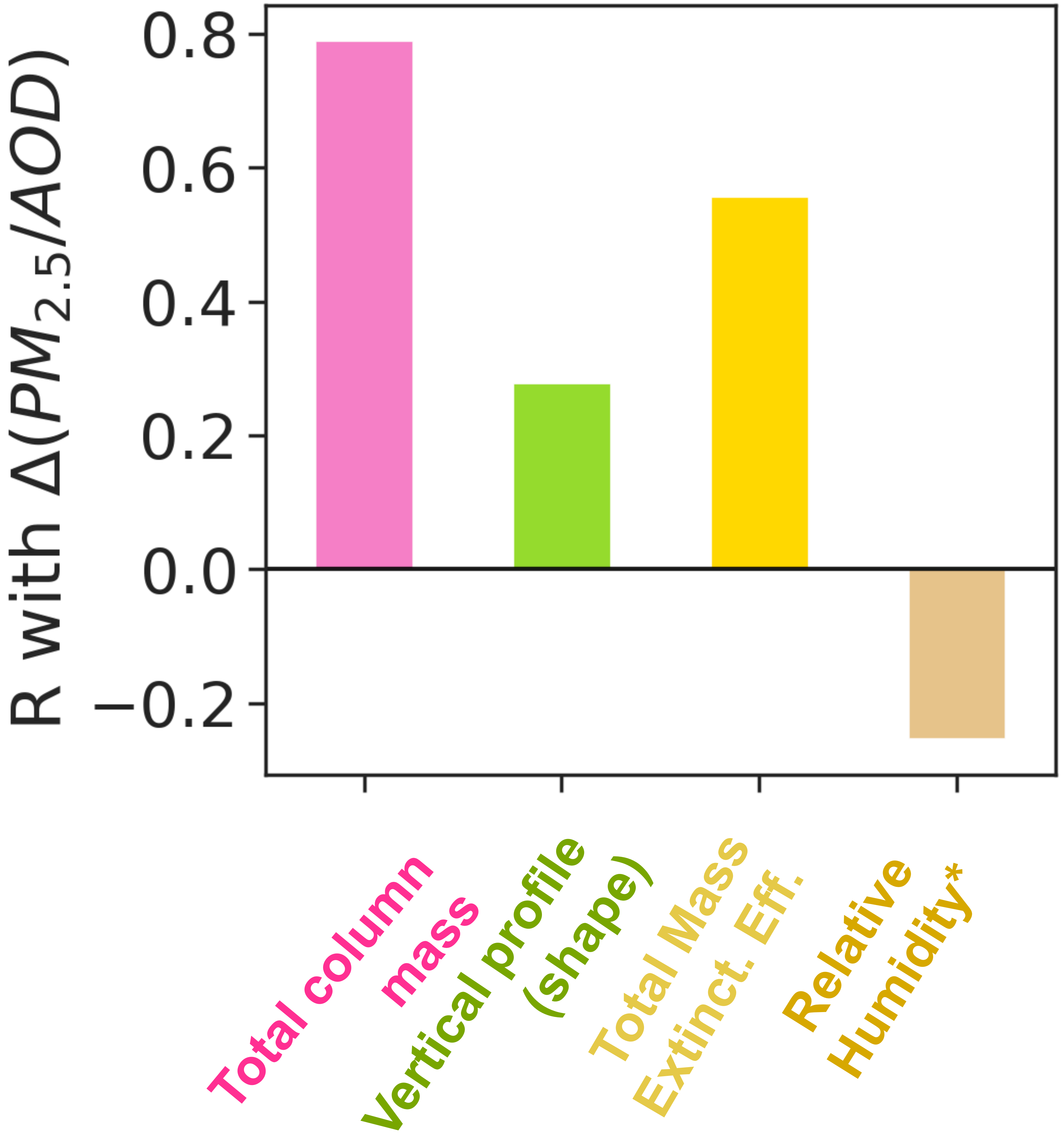
$$\Delta PM_{2.5\_Rel} = \left(\frac{PM_{2.5\_Model}}{AOD_{Model}} - \frac{PM_{2.5\_AQS}}{AOD_{AERONET}}\right) \times AOD_{Sat}$$

Jin et al., 2019b, ACP

Evaluating uncertainty in model $PM_{2.5}$/AOD using aircraft data

(July 2011 over Baltimore-Washington, D.C.)





- **Swap in DISCOVER-AQ observed quantities into calculation of AOD**
- **Replace modeled AOD with the new AOD and derive a new $PM_{2.5}$**
- **$\Delta PM_{2.5}$ = original $PM_{2.5}$ - new $PM_{2.5}$**

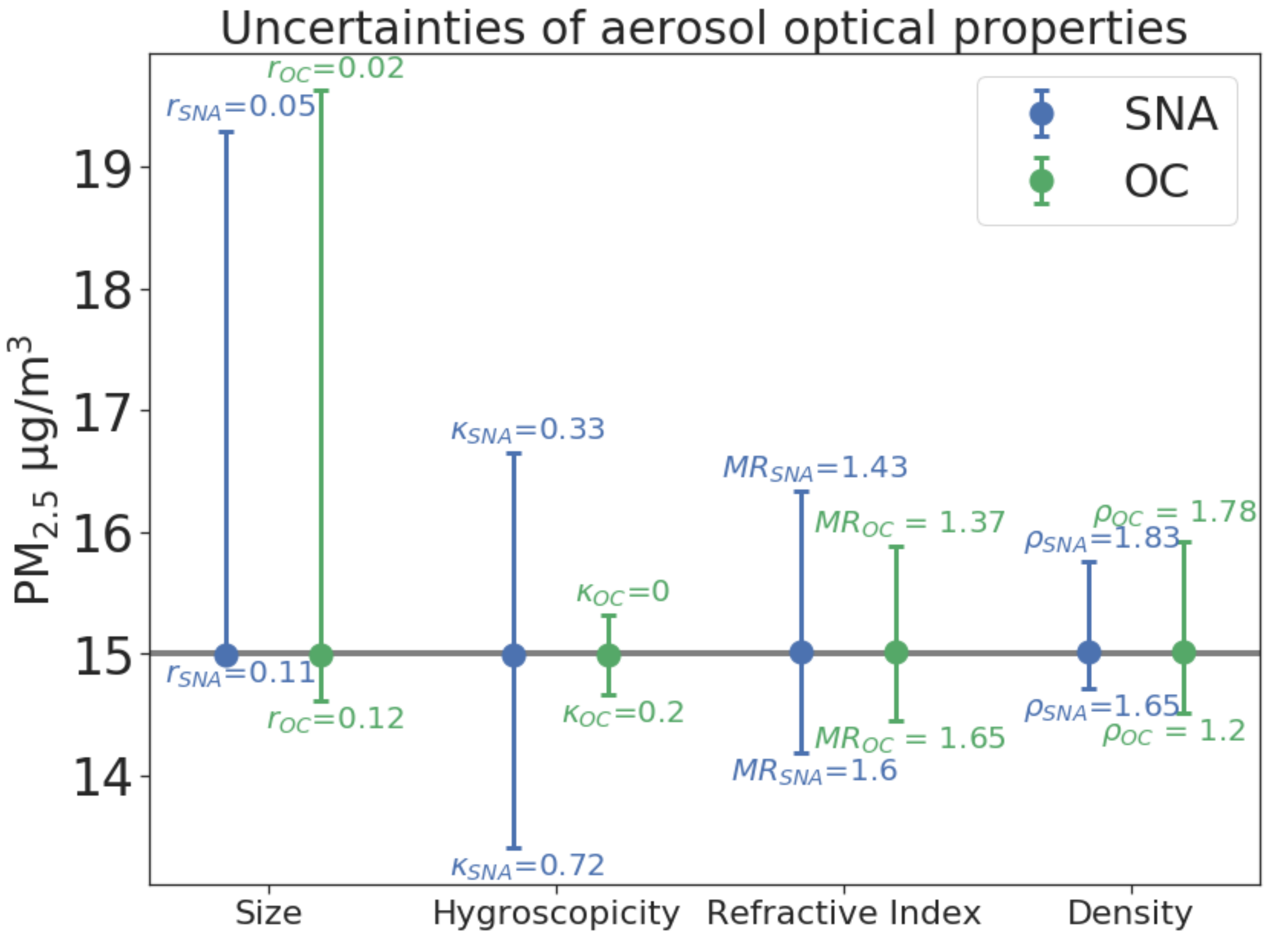
Jin et al., 2019b, ACP

Satellite-derived $PM_{2.5}$ is sensitive to the parameterization of aerosol properties

$$PM_{2.5\_satellite} = AOD_{satellite} \times \frac{PM_{2.5\_CMAQ}}{AOD_{CMAQ}}$$

Calculate model AOD offline using FlexAOD in which individual optical properties vary over ranges reported in the literature.

FlexAOD



Jin et al., 2019b, ACP

Take-aways

- We estimate **28%** uncertainty in mortality burden due to choice of $PM_{2.5}$ products, but such uncertainty is **much smaller** than the uncertainty of exposure-response functions (**130%**).

- Inclusion of satellite remote sensing improves the representativeness of $PM_{2.5}$ in remote area.

- Multi-platform *in situ* measurements are valuable for quantifying the uncertainties of satellite-derived $PM_{2.5}$.

Jin, X. et al. (2019a), Comparison of multiple $PM_{2.5}$ exposure products for estimating health benefits of emission controls over New York State, USA, *Environ. Res. Lett.*, *14*(8), 084023–14.

Jin, X., et al. (2019b), Assessing uncertainties of a geophysical approach to estimate surface fine particulate matter distributions from satellite-observed aerosol optical depth, *Atmos. Chem. Phys.*, *19*(1), 295–313.

Aerosol Optical Depth

Mie extinction efficiency (m²/m²)
Ratio of effective to geometrical cross-section

Hygroscopic scaling factor

Column mass (g/m²)

$$AOD = \frac{3}{4}\frac{Q_{ext}\, f_{RH}}{r_{eff}\,\rho} M = \alpha M$$

Mass extinction coefficient (m²/g)

Effective radius (µm)
"Optically" weighted mean radius

Species density (g/cm³)

[C. Heald and R. Martin, GC wiki]