

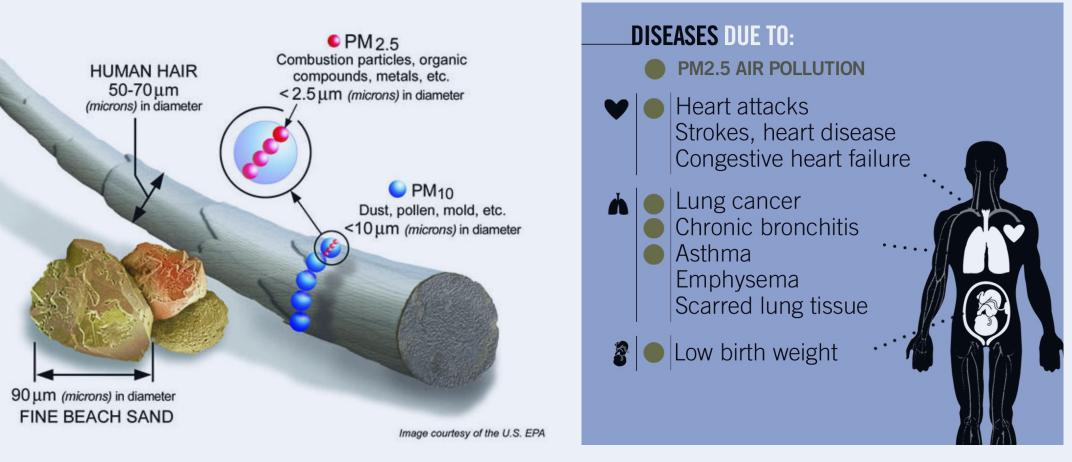
# Global Spatial Variation in the PM<sub>2.5</sub> to Aerosol Optical Depth relationship and its Driving Factors

Haihui Zhu<sup>1\*</sup>, Randall V. Martin<sup>1,2</sup>, Chi Li<sup>1</sup>, Aaron van Donkelaar<sup>1</sup>, Melanie S. Hammer<sup>1</sup>, Jun Meng<sup>1</sup>, Erin McDuffie<sup>1</sup>, Yanshun Li<sup>1</sup>, Dandan Zhang<sup>1</sup> <sup>1</sup> Department of Energy, Environment & Chemical Engineering, Washington University in St. Louis, St. Louis, MO, USA. <sup>2</sup> Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada

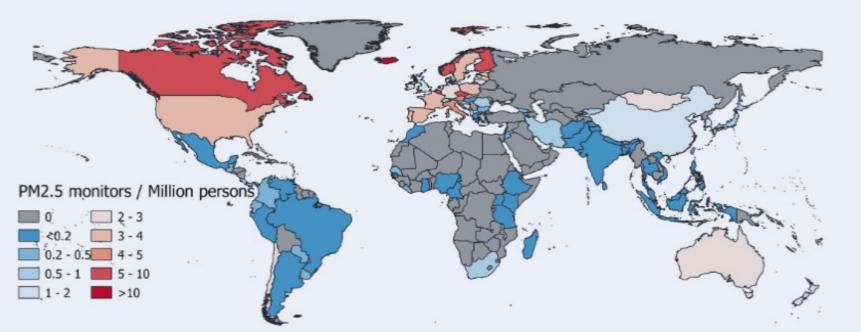
Washington University in St. Louis

# Why Care About the PM<sub>2.5</sub> to AOD Relationship ( $\eta$ )

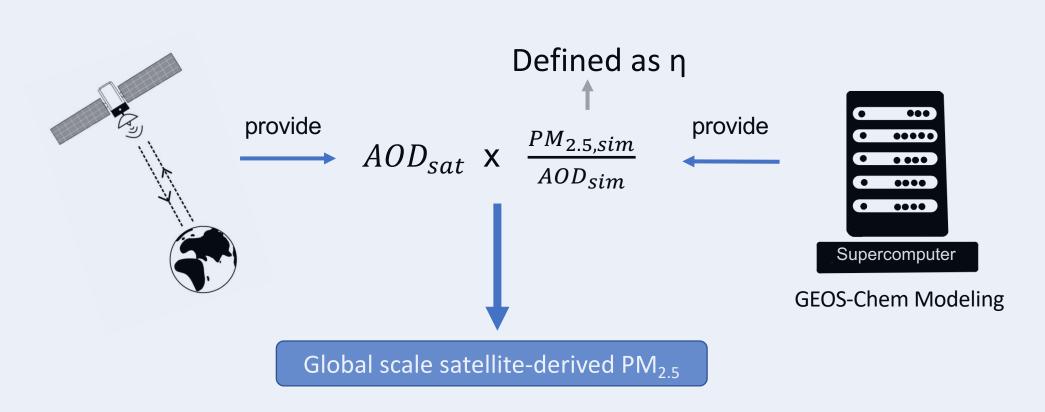
Exposure to fine particulate matter (PM<sub>2.5</sub>) in ambient air is the leading environmental risk factor for the global burden of disease, leading to 4.2 million premature deaths every year



Ground-measured PM<sub>2.5</sub> is sparse, but satellite remote sensing plus a chemical transport model (GEOS-Chem) offer an alternative solution. More specifically, this satellite-derived PM<sub>2.5</sub> is obtained from satellite observation of AOD by applying a modeled PM<sub>2.5</sub> to AOD relationship (n).



Number of PM<sub>2.5</sub> monitors per million inhabitants by country (Martin, R. 2019)



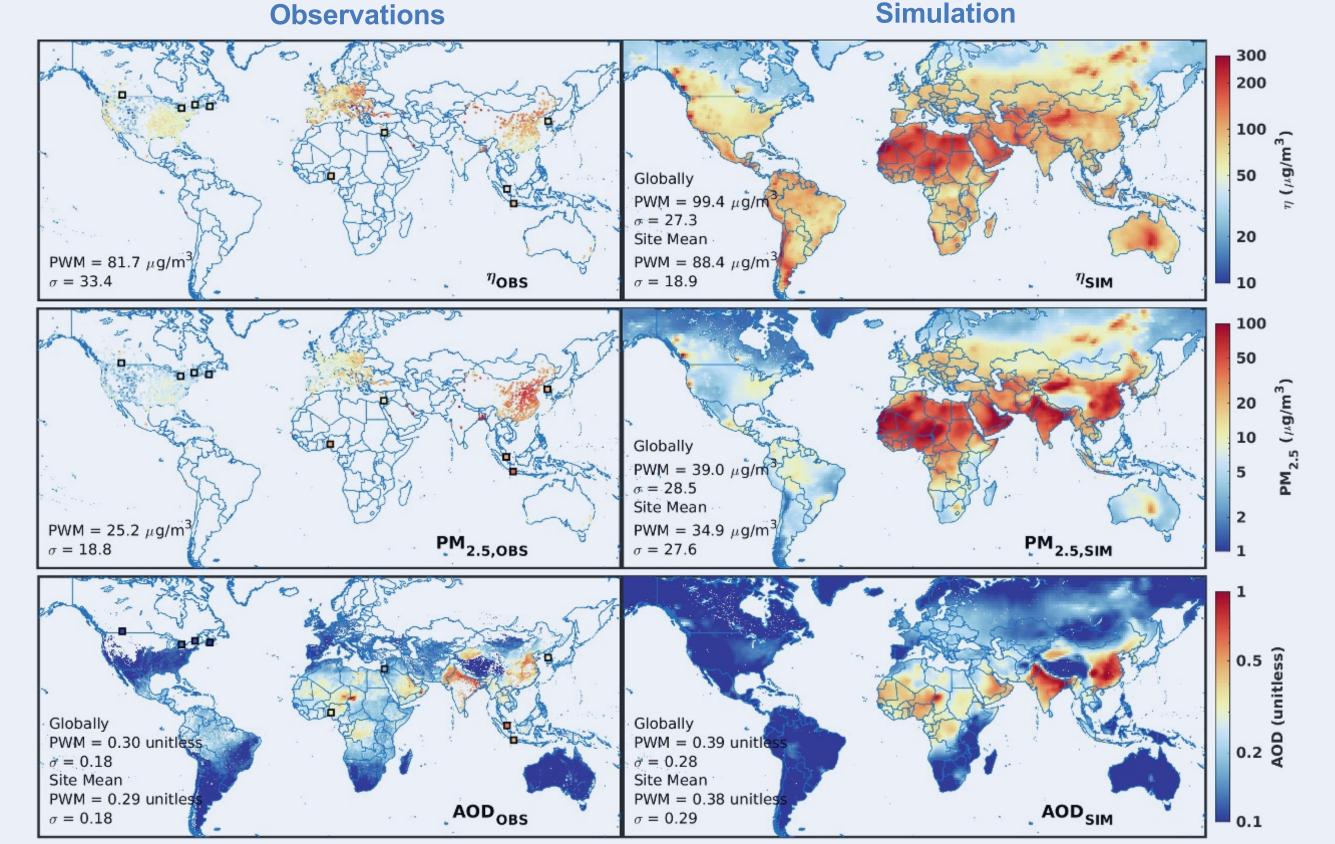
#### Datasets used in this study

- Ground-based PM<sub>2.5</sub> measurement: 6000+ sites from 6 regional networks and 2 global networks. AOD measurements are collected from both Satellite and ground-based sun photometer
- Simulations are conducted using the high-performance implementation of GEOS-Chem (GCHP).

#### measurement China EPA USA EPA FRM **▼** USA EPA nonFRM EU AirBase Australia G M WHO SPARTAN Map of PM<sub>2.5</sub> ground monitoring networks Satellite AOD Simulation **AERONET AOD** • GCHP v 13.4.0 Version 3 Algorithm: the Multi-Angle Implementation of fully automatic cloud • C90 Atmospheric Correction screening and instru-• MERRA-2 (MAIAC) ment anomaly quality CEDS anthropogenic controls Instrument: Moderate emissions Level 2.0 quality Resolution Imaging Spectroradiometer Daily GFED emission (MODIS) With the parameterized • Satellite: Terra and Aqua aerosol size for SNA and • The year 2019 Lyapustin, A. et al. 2018 AMT Giles, D. et al. 2019 AMT

#### The Global Pattern of η

- The annual mean  $\eta$  varies greatly, from less than 10 to more than 200.
- η values are highest over desert regions such as the Middle East, the southern part of Europe, and the western part of China, followed by regions with solid influence from anthropogenic aerosols, such as East Asia, South Asia, and large cities around the world.
- The lowest  $\eta$  is found in humid areas such as coastal areas and areas with high latitudes.



Measured (left) and simulated (right) annual mean  $\eta$  (top), surface PM2.5 (middle), and AOD (bottom) for 2019. PWM = population-weighted mean.

#### What Drives the Spatial Variation of $\eta$

 $\sigma = 30.0$ 

min = -286.65

 $PWM = 3.3 \mu g/m^3$ 

 $\sigma = 18.2$ 

min = -75.51

max = 80.82

max = 83.42

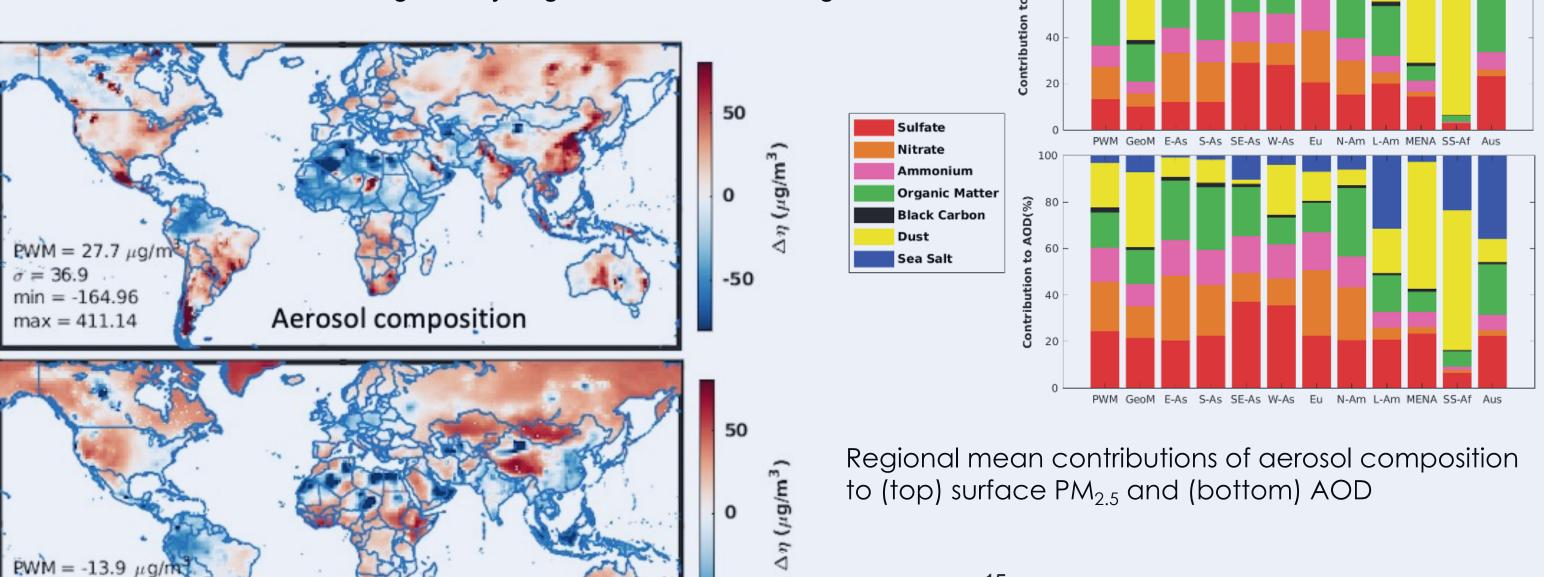
- The PM<sub>2.5</sub> composition, aerosol vertical distribution, and RH are the main drivers for the η spatial variation.
- In populated areas, ambient aerosols contain higher fractions of SNA and OM, which are the main product of anthropogenic emissions. This makes the aerosols more hygroscopic (can grow larger by taking up more water) therefore more efficient in radiation scattering. The higher AOD then results in lower η.
- Industrial areas are the source regions of aerosol, making it accumulate near the surface, resulting in higher  $PM_{2.5}$  near the surface and  $\eta$ .

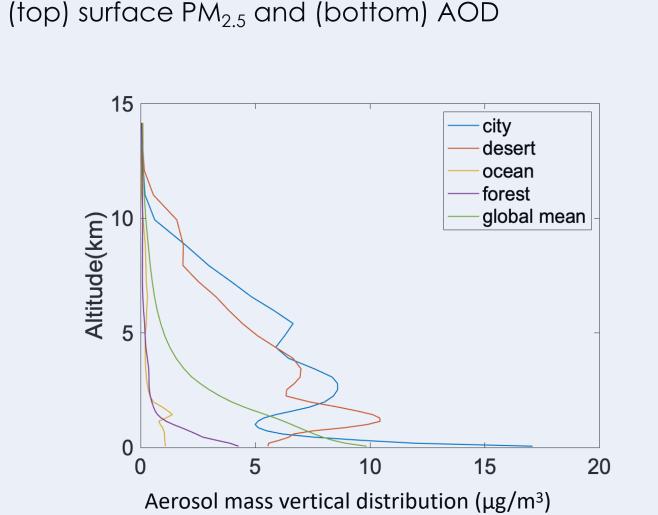
Aerosol vertical distribution

Changes in n when using a continental mean value of (top) fine aerosol

composition, (middle) aerosol vertical profile, and (bottom) RH.

Aerosols in humid areas are generally larger and more scattering efficient.

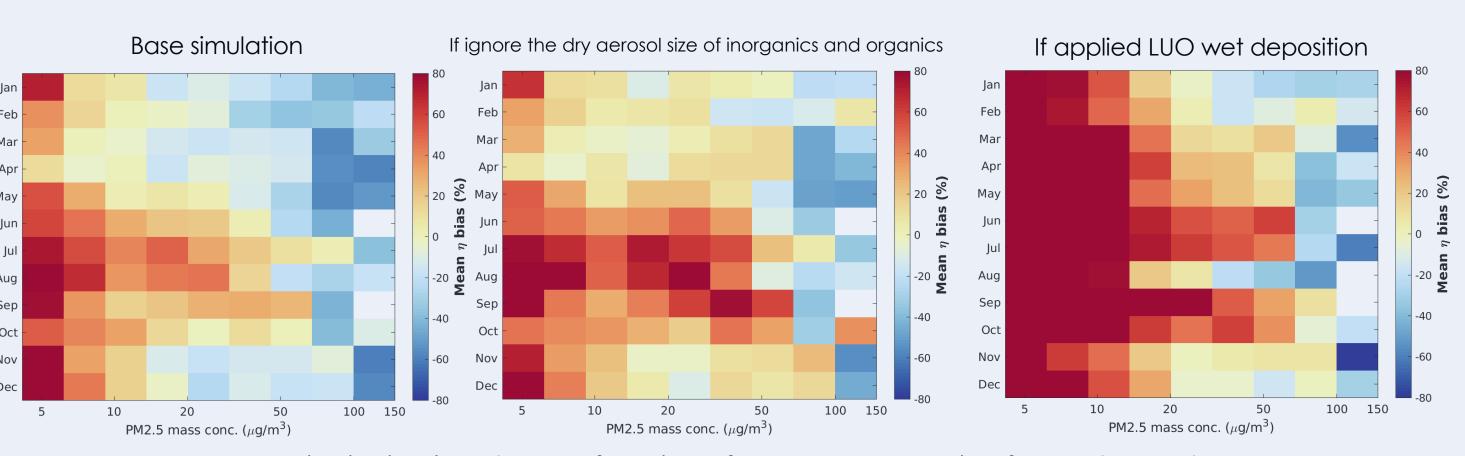




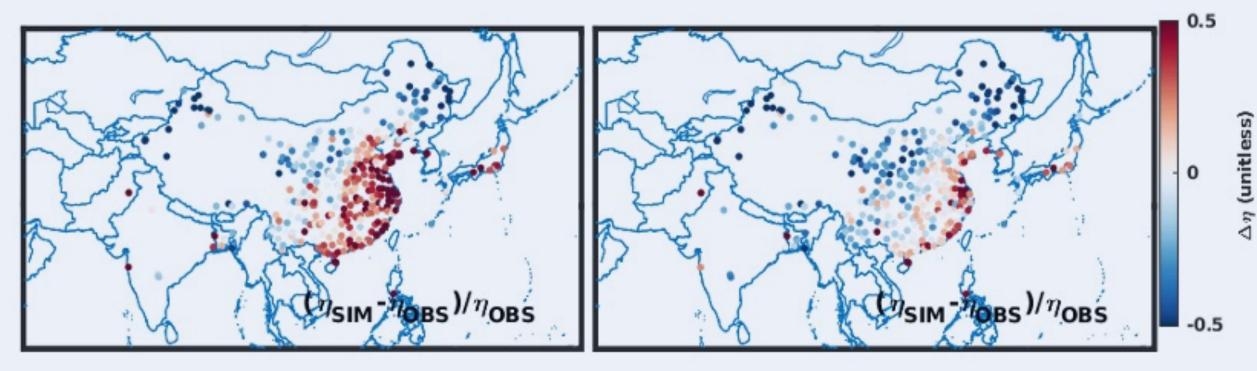
Regional mean aerosol mass concentration profile

#### **Model Uncertainties**

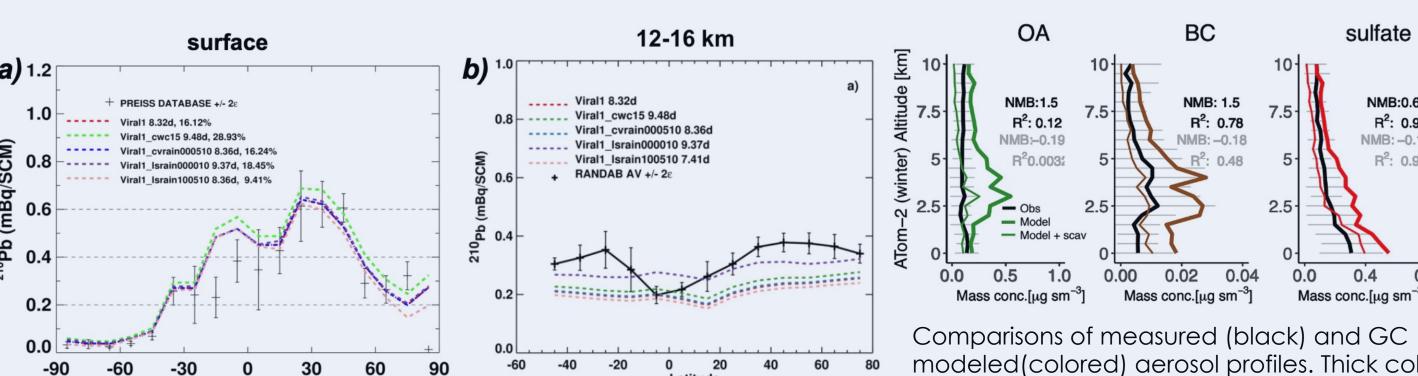
- Simulated  $\eta$  is biased high at low PM<sub>2.5</sub> concentration and biased low at high PM<sub>2.5</sub> concentration.
- Aerosol size plays an important role in AOD estimation and therefore helped mitigate η simulation bias.
- The high bias at low PM<sub>2.5</sub> concentration might reflect the overly strong scavenging aloft, which makes the model underestimate AOD. Some previous studies support this idea while others do not. More investigation is needed.



Bias in simulated  $\eta$  as a function of PM<sub>2.5</sub> concentration for each month.



The relative difference between simulated and measured  $\eta$  (left) before and (right) after applying the parameterized  $R_{\rm eff}$ 



Comparisons of observed and simulated latitudinal distributions of annually averaged <sup>210</sup>Pb concentrations at (a) surface (b) aloft. (Zhang, B. et al)

modeled(colored) aerosol profiles. Thick color lines indicate default simulation, thin color lines indicate that from **updated wet scavenging** (LUO, et al. 2019, Gao, et al. 2022)

### Conclusions

- From global-scale ground-based PM<sub>2.5</sub> measurements, satellite observation, and a 3-D chemical transport model, GEOS-Chem, we found that η values vary largely. They are highest over desert regions, followed by regions with solid influence from anthropogenic aerosols. The lowest  $\eta$  is found in humid areas.
- The spatial variation in  $\eta$  is driven by aerosol composition, aerosol vertical distribution, and RH, which affect PM<sub>2.5</sub> and AOD to different extents.
- Simulated  $\eta$  is biased high in low pollution areas and biased low in strong pollution areas. This indicates the possibility of aerosol scavenging being too strong.
- Including a parameterized dry aerosol size helped reduced model bias.

#### **Future Work**

More investigations are needed for the high  $\eta$  bias at low PM<sub>2.5</sub> concentration and low  $\eta$  bias at high PM<sub>2.5</sub> concentration

## **Key References**

Martin, R. V., Brauer, M., van Donkelaar, A., Shaddick, G., Narain, U., & Dey, S. (2019). No one knows which city has the highest concentration of fine particulate matter. Atmospheric Environment: X, 3, 100040.

Lyapustin, A., Wang, Y., Korkin, S., & Huang, D. (2018). MODIS collection 6 MAIAC algorithm. Atmospheric Measurement Techniques, 11(10), 5741-5765. Giles, D. M., Sinyuk, A., Sorokin, M. G., Schafer, J. S., Smirnov, A., Slutsker, I., ... & Lyapustin, A. I. (2019). Advancements in the Aerosol Robotic Network (AERONET)

Version 3 database—automated near-real-time quality control algorithm with improved cloud screening for Sun photometer aerosol optical depth (AOD) measurements. Atmospheric Measurement Techniques, 12(1), 169-209. Zhang, B., Liu, H., Crawford, J. H., Fairlie, D. T., Chen, G., Dibb, J. E., ... & Yantosca, R. M. (2016, September). Constraints from Airborne (210) Pb Observations on

Aerosol Scavenging and Lifetime in a Global Chemical Transport Model. In AeroCOM/AeroSAT Workshop (No. NF1676L-25449). Luo, G., Yu, F., & Schwab, J. (2019). Revised treatment of wet scavenging processes dramatically improves GEOS-Chem 12.0. 0 simulations of surface nitric acid, nitrate, and ammonium over the United States. Geoscientific Model Development, 12(8), 3439-3447.

Guo, H., Campuzano-Jost, P., Nault, B. A., Day, D. A., Schroder, J. C., Kim, D., ... & Jimenez, J. L. (2021). The importance of size ranges in aerosol instrument intercomparisons: a case study for the Atmospheric Tomography Mission. Atmospheric Measurement Techniques, 14(5), 3631-3655.