

# Theoretical Basis for Converting Satellite Observations to Ground-Level PM<sub>2.5</sub> Concentrations

Pawan Gupta, Melanie Follette-Cook, and Bryan Duncan

NASA Remote Sensing for Air Quality Applications, March 20-23, 2018, Jakarta, Indonesia



# Objectives

By the end of this presentation, you will learn to:

- Estimate  $PM_{2.5}$  mass concentration at the surface level ( $\mu\text{g m}^{-3}$ ) while using satellite derived Aerosol Optical Depth (AOD) at visible wavelengths



# Air Quality Monitoring and Reporting

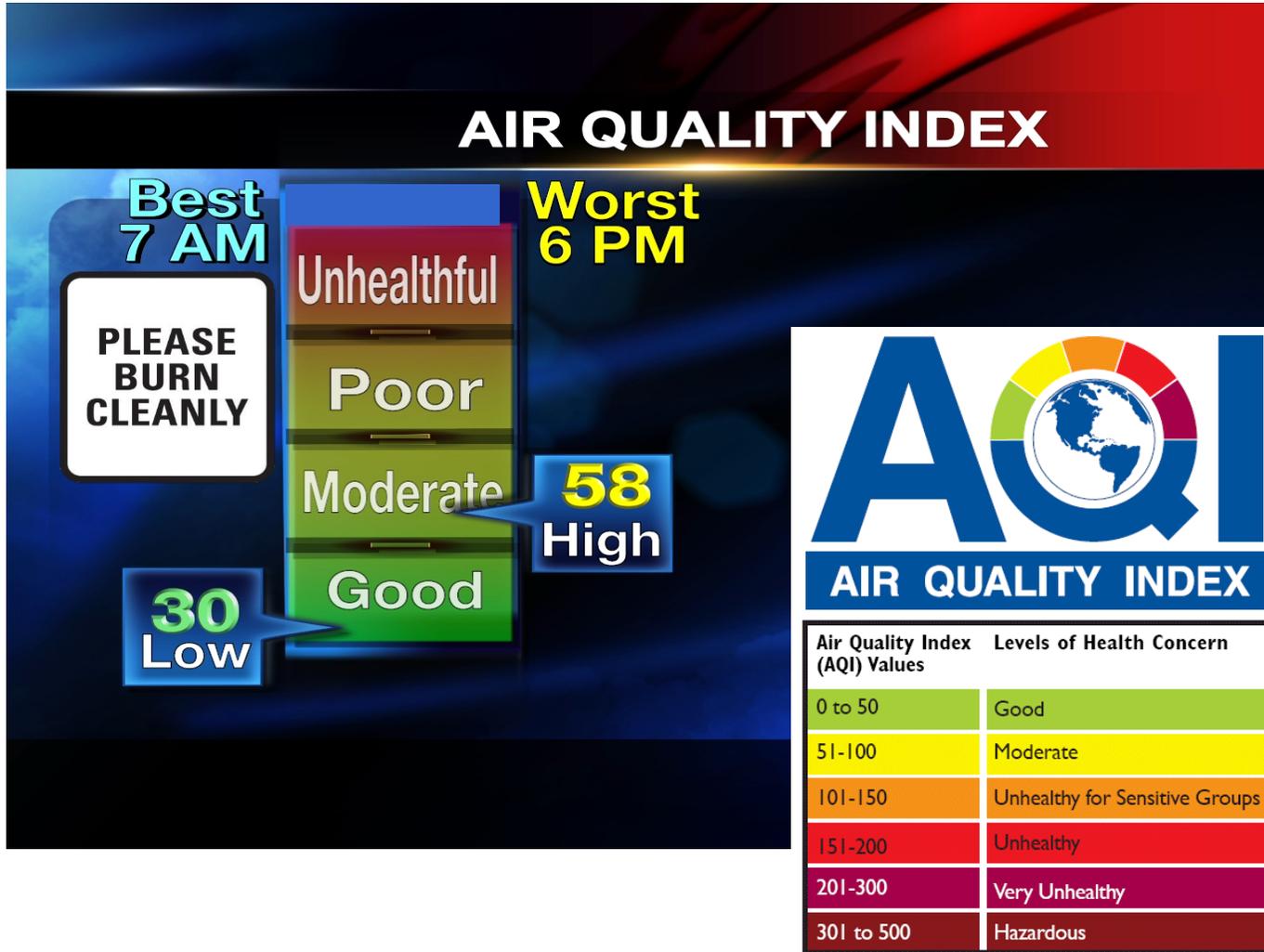
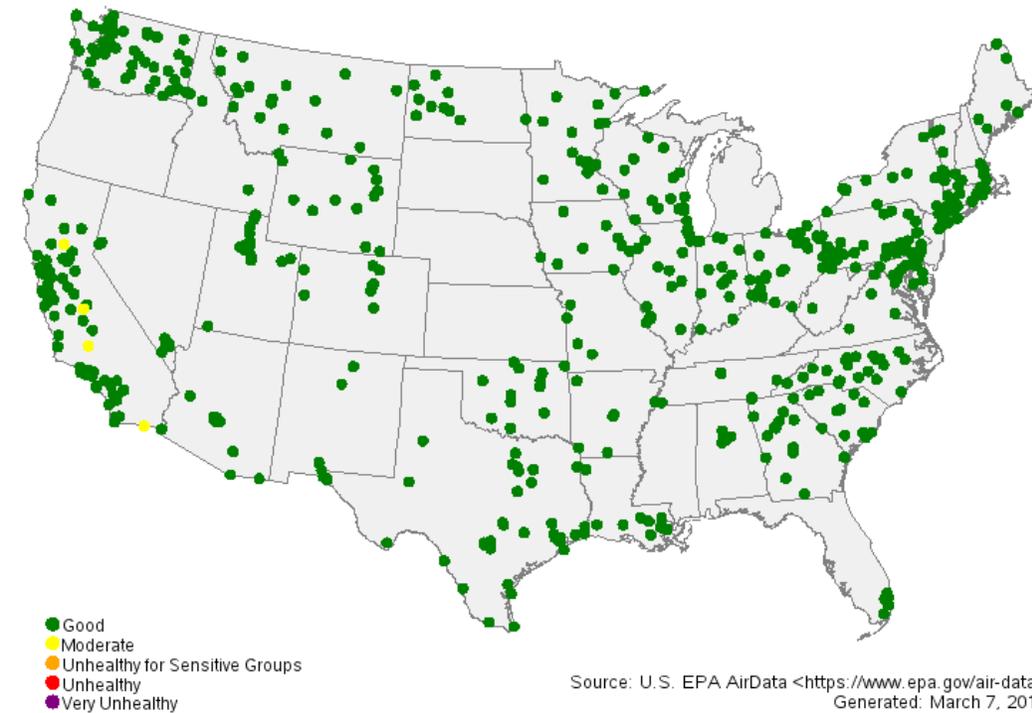


Image Credit: AirNow map, USEPA. <http://www.airnow.gov>

## Spatial Gaps

PM2.5 AQI Values by site on 10/08/2017



# Inferring AOD and PM<sub>2.5</sub> from Visuals

## Pittsburgh

PM<sub>2.5</sub> = 45 μgm<sup>-3</sup>

PM<sub>2.5</sub> = 4 μgm<sup>-3</sup>



Pictures are taken from the same location, at the same time of day, on two different days

**AOD = ~0.8**

**AOD = ~0.1**

Image Credit: Learning with CLEAR: Introduction to Aerosols - What Are Aerosols? <http://caice.ucsd.edu/index.php/education/clear/learning-with-clear/introduction-to-aerosols/>

# Inferring AOD and PM2.5 from Visuals

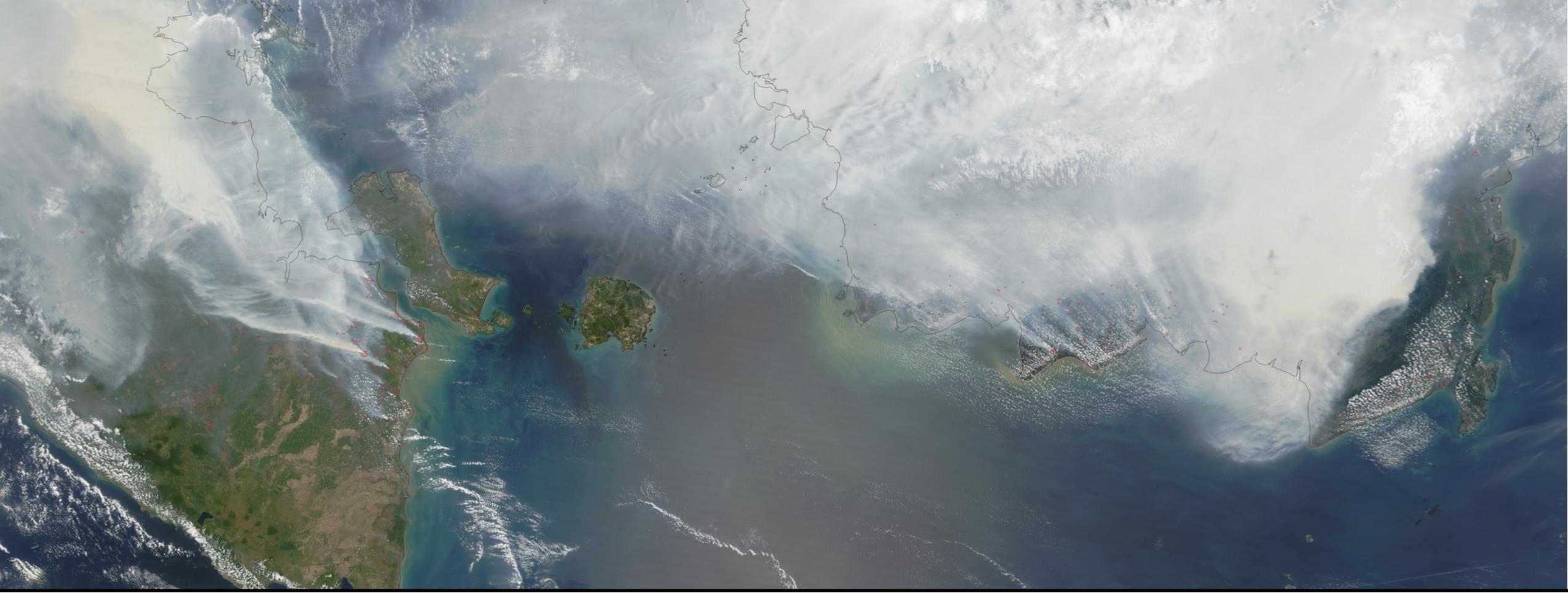
## Singapore



Image Credit: Roslan Rahman/AFP/Getty Images

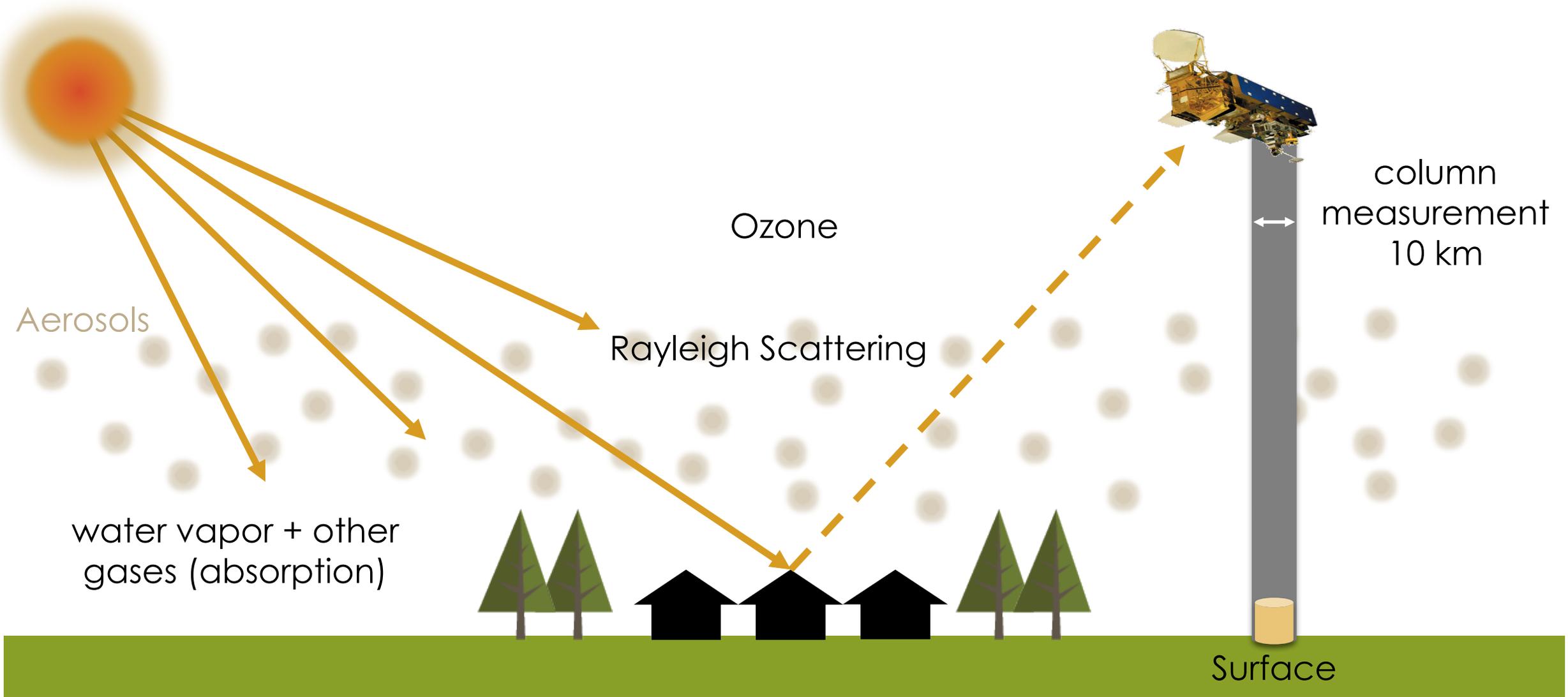
# Surface vs. Satellite Measurements



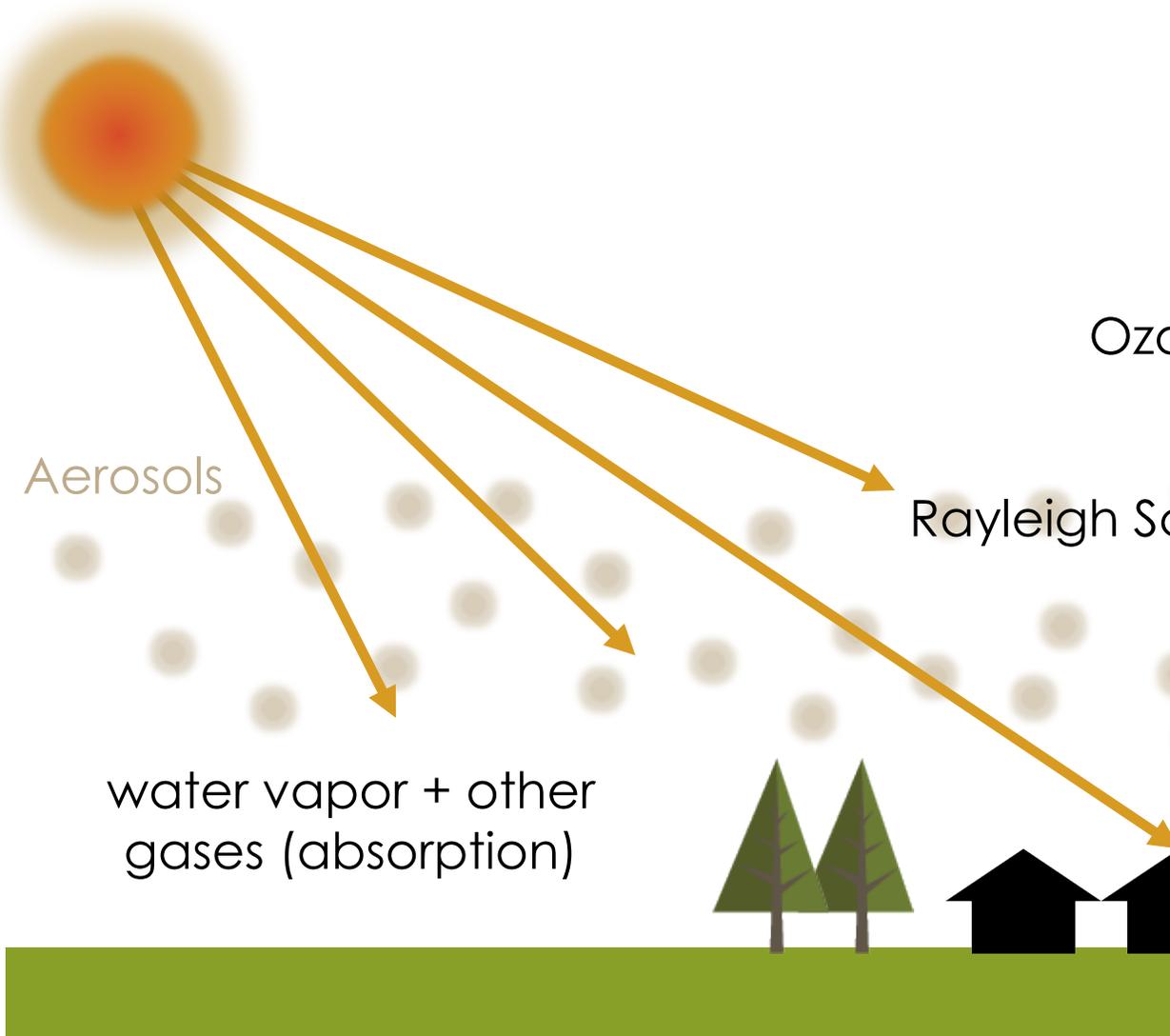


AOD (or AOT) to PM

# Aerosol Optical Depth from Satellites



# Aerosol Optical Depth from Satellites



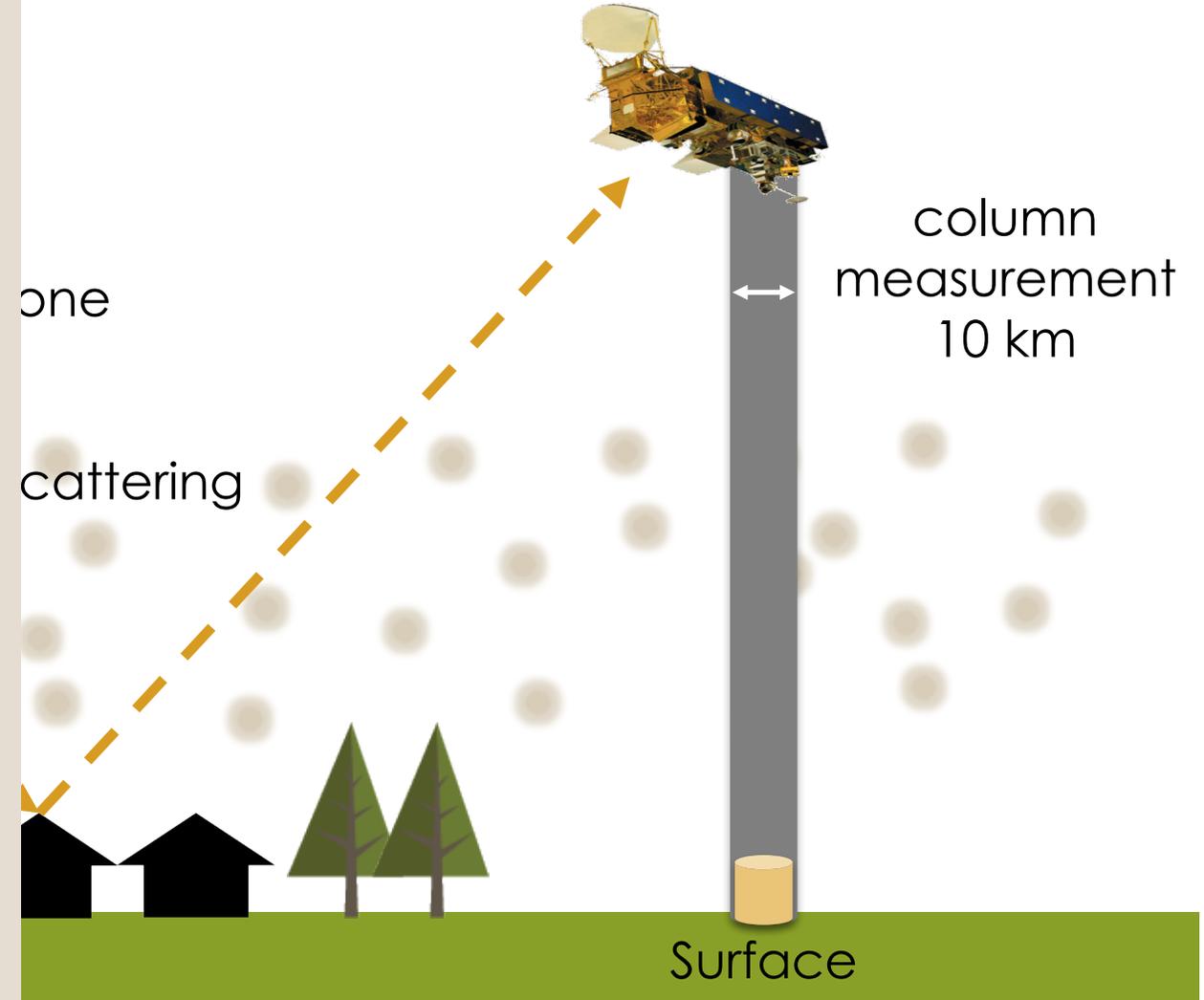
- $AOT(\tau) = \int \beta_{ext} dz$ 
  - particle size
  - composition
  - water uptake
  - vertical distribution

- There are satellite retrieval issues: inversion (e.g. aerosol model, background)

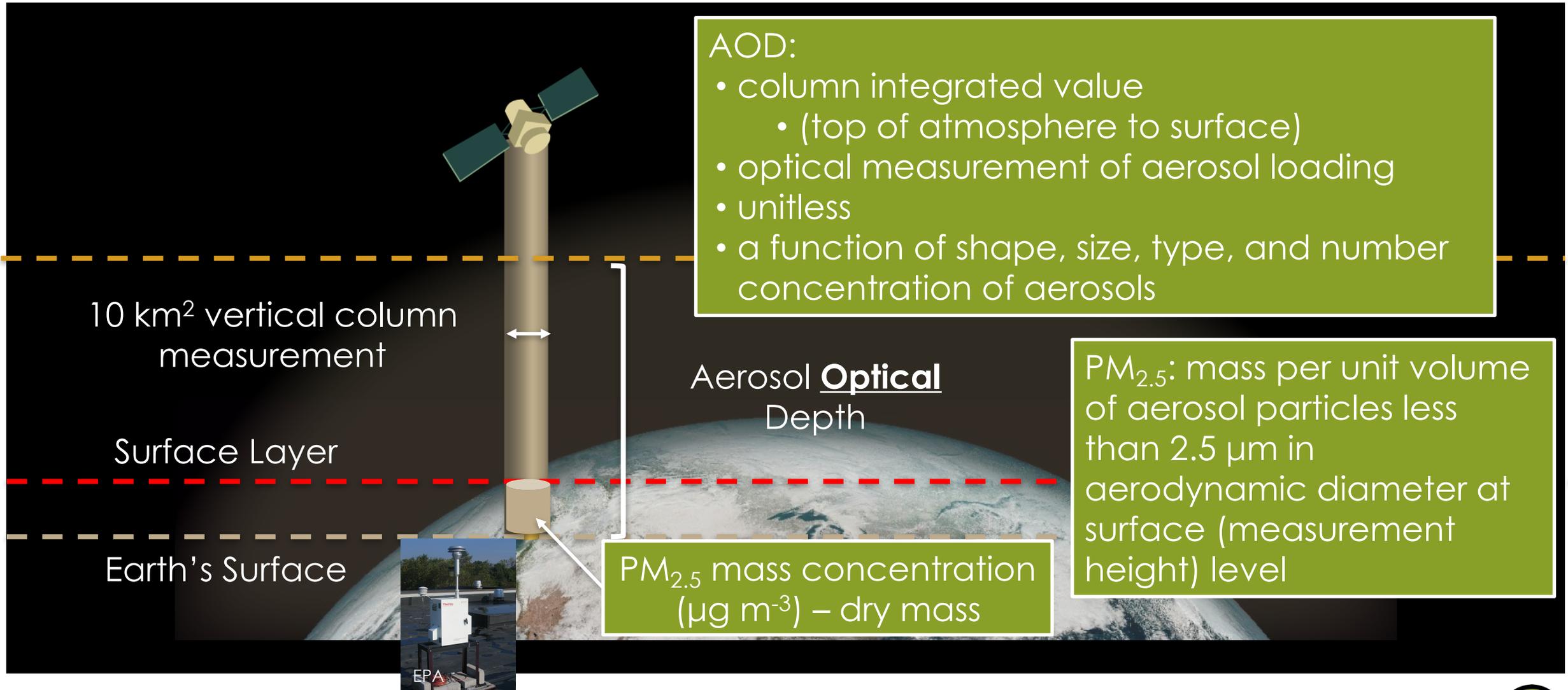


# Aerosol Optical Depth from Satellites

- Seven MODIS bands are utilized to derive aerosol properties
  - **0.47  $\mu\text{m}$**
  - 0.55  $\mu\text{m}$
  - **0.65  $\mu\text{m}$**
  - 0.86  $\mu\text{m}$
  - 1.24  $\mu\text{m}$
  - 1.64  $\mu\text{m}$
  - **2.13  $\mu\text{m}$**
- 10x10 km<sup>2</sup> resolution
- 3x3 km<sup>2</sup> resolution

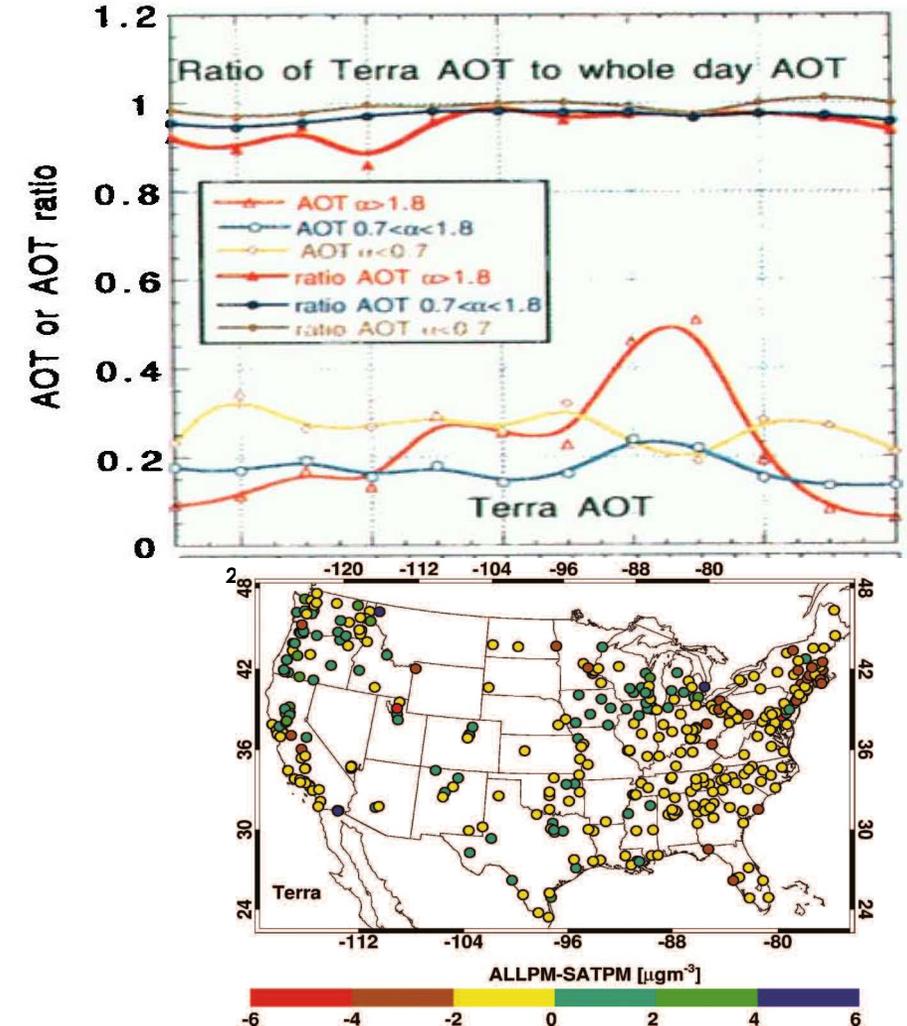


# Satellite vs. Ground Observation



# Support for AOD-PM<sub>2.5</sub> Linkage

- Satellite AOD is sensitive to PM<sub>2.5</sub>
  - Kahn et al. 1998
- Polar-orbiting satellites can represent at least daytime average aerosol loadings
  - Kaufman et al. 2000
- Missing data due to cloud cover appear random in general
  - Christopher and Gupta 2010



# AOD-PM Relationship

Assuming cloud-free skies, a well mixed boundary layer with no overhead aerosols, and aerosols that have similar optical properties\*, AOD and  $PM_{2.5}$  can be related by this equation:

$$\tau = PM_{2.5} H f(RH) \frac{3Q_{ext,dry}}{4 \rho r_{eff}}$$

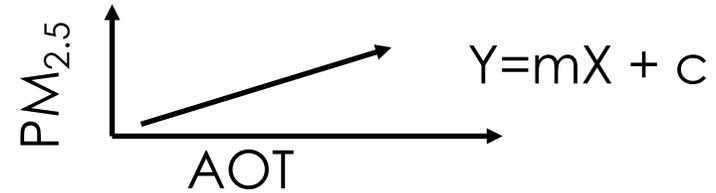
- $\tau$ : AOD at 550 nm
- $\rho$ : aerosol mass density
- $r_{eff}$ : particle effective radius
- $Q$ : extinction coefficient
- $H$ : mixing height
- $f(RH)$ : how aerosol scattering changes with changing relative humidity



# PM<sub>2.5</sub> Estimation: Popular Methods

Difficulty Level

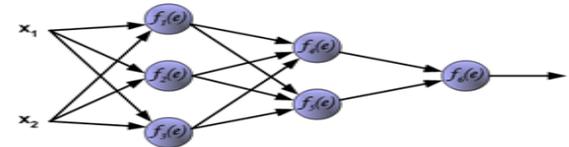
Two Variable Method



Multivariable Method

$$PM_{2.5} = \beta_0 + a \times T + \sum_{n=1}^m (\beta_n \times M_n)$$

Artificial Intelligence



MSC

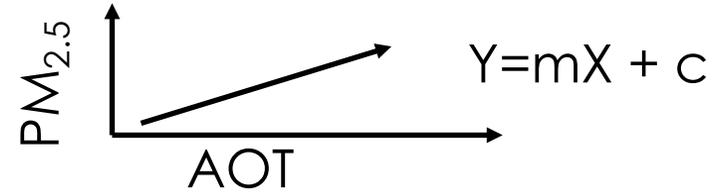
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



# PM<sub>2.5</sub> Estimation: Two Variable Method (TVM)

Difficulty Level

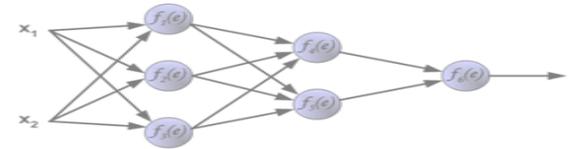
Two Variable Method



Multivariable Method

$$PM_{2.5} = \beta_0 + a \times T + \sum_{n=1}^m (\beta_n \times M_n)$$

Artificial Intelligence

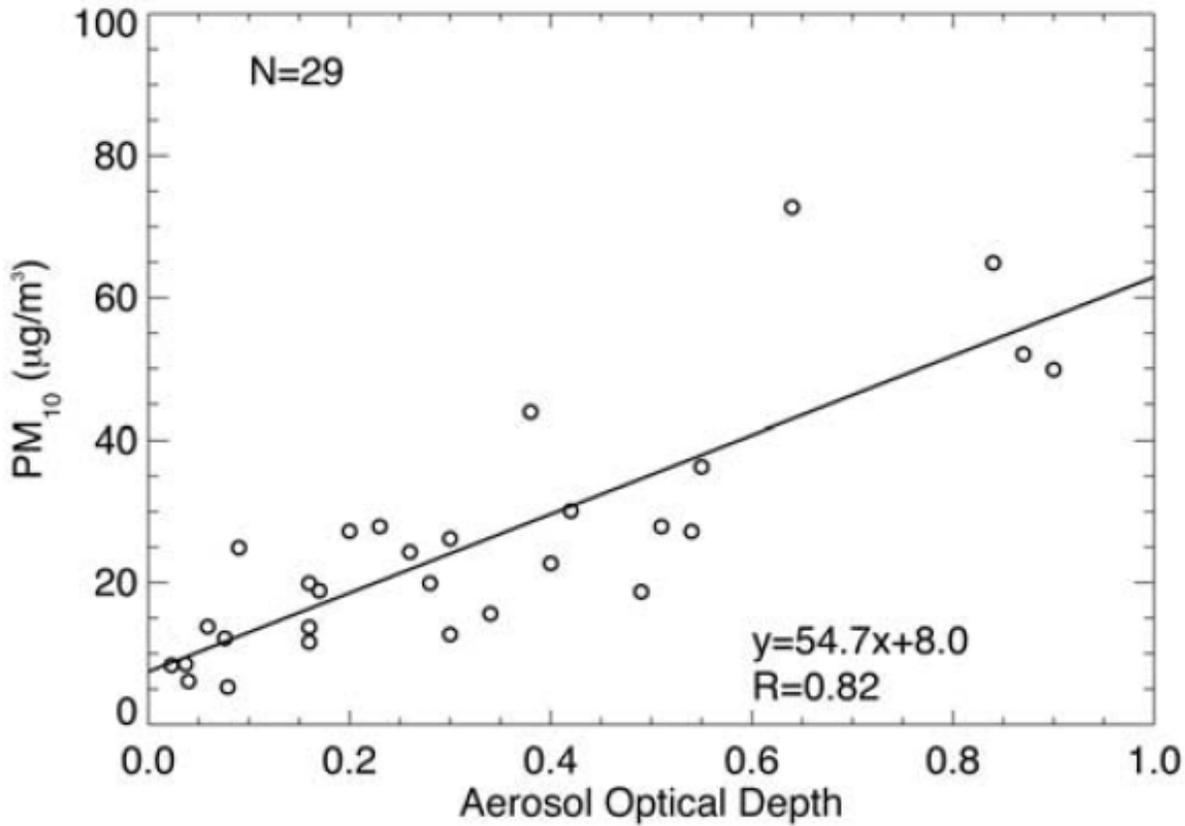


MSC

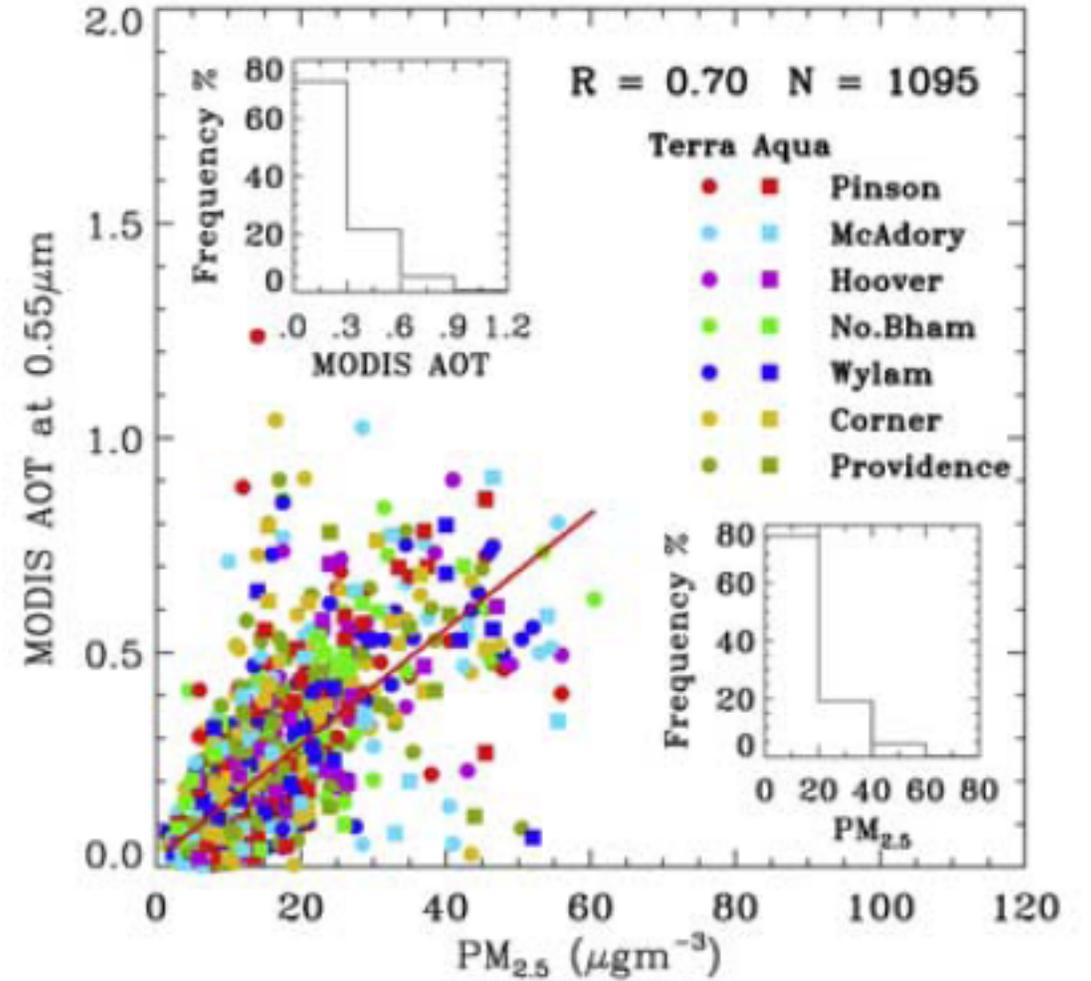
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



# Simple Models from Early Days



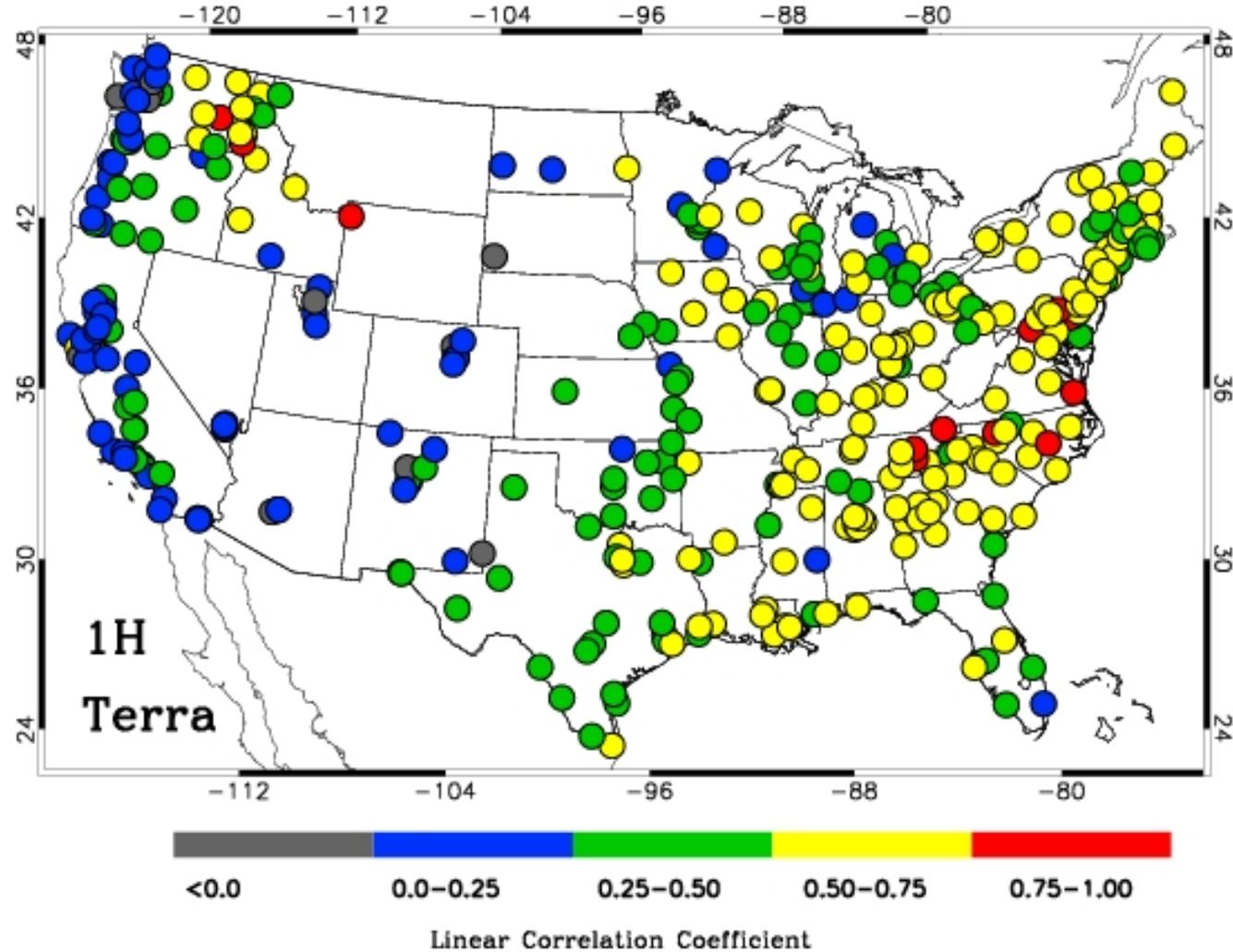
Source: Chu et al., 2003



Source: Wang et al., 2003



# AOD-PM<sub>2.5</sub> Relationship

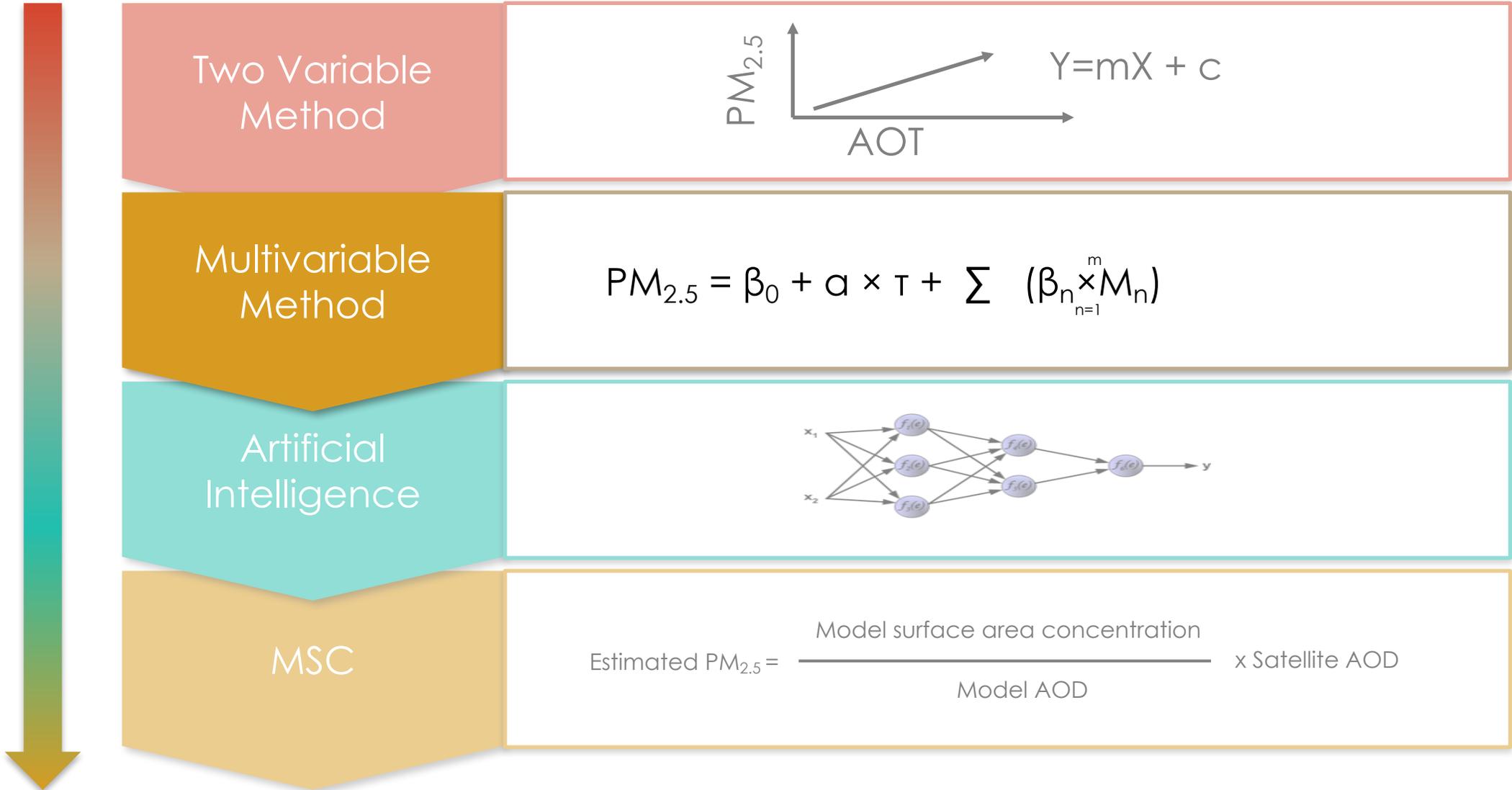


Source: Gupta, 2008



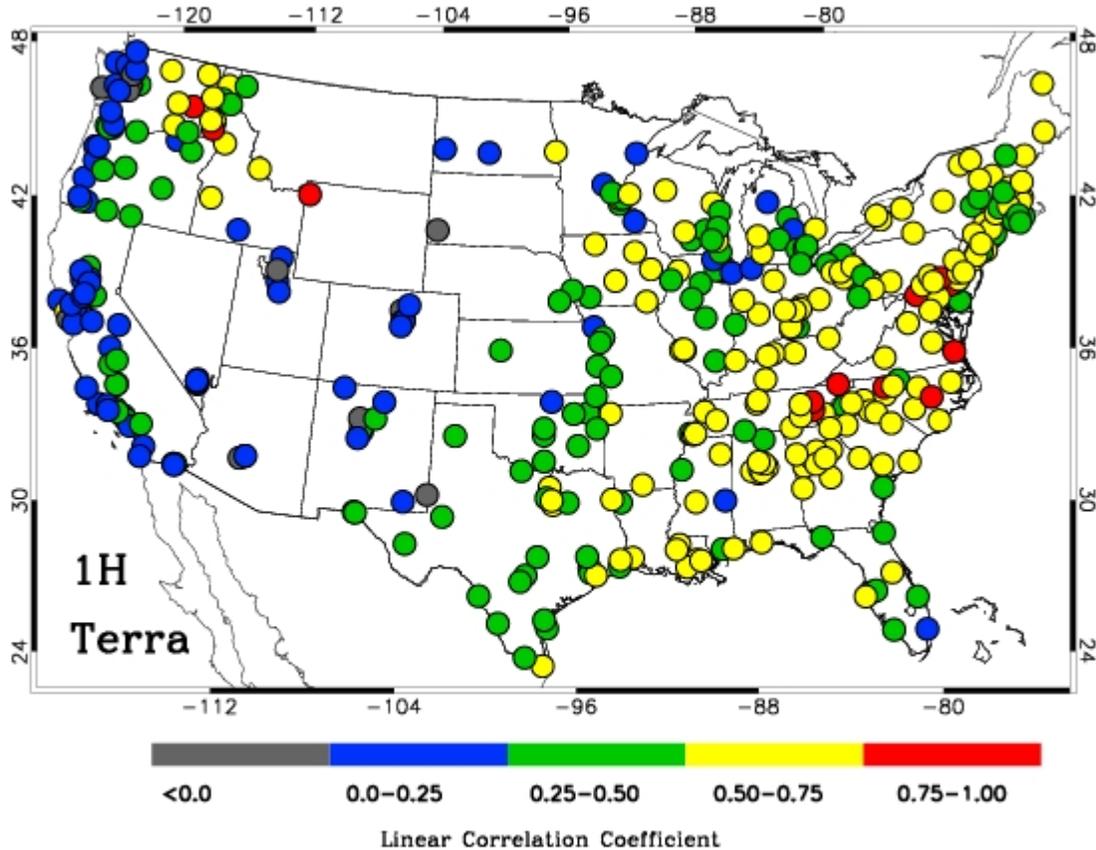
# PM<sub>2.5</sub> Estimation: Multivariable Method (MVM)

Difficulty Level

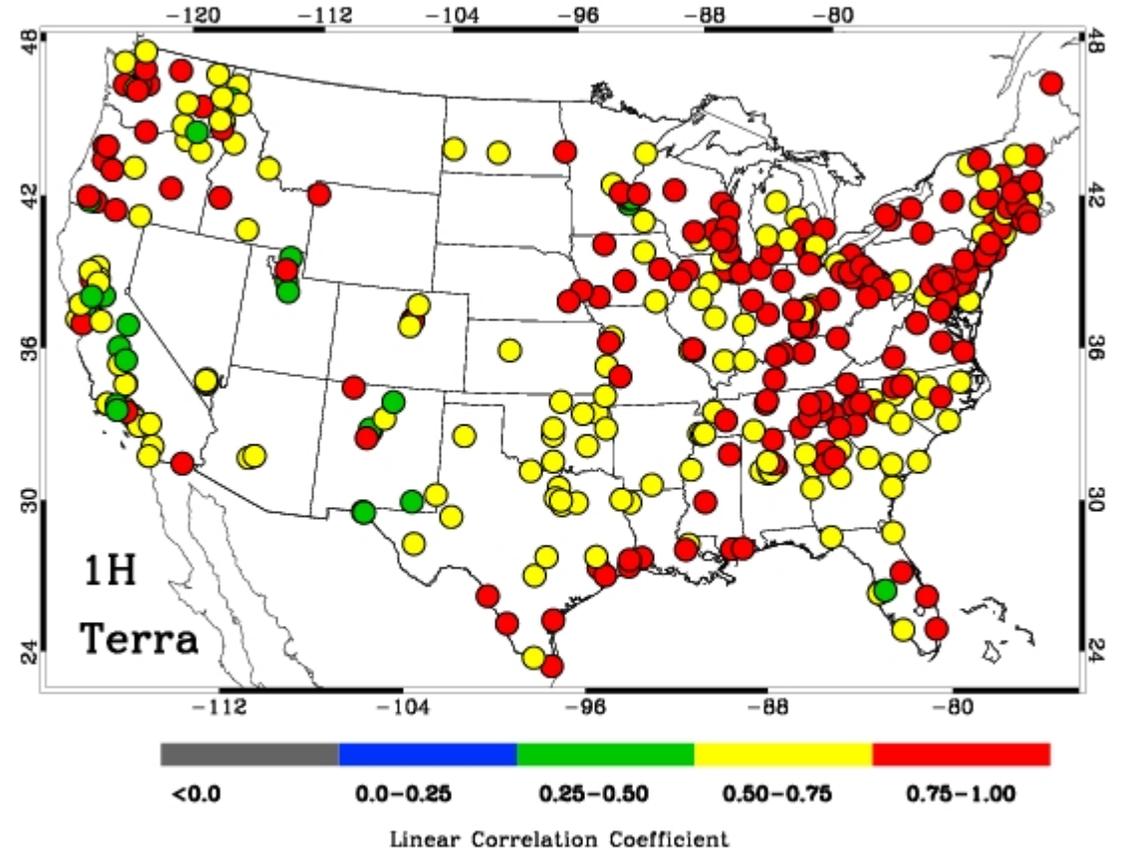


# Multivariable Method (MVM)

Predictor: AOD



Predictor: AOD + Meteorology



Linear correlation coefficient between observed and estimated  $PM_{2.5}$

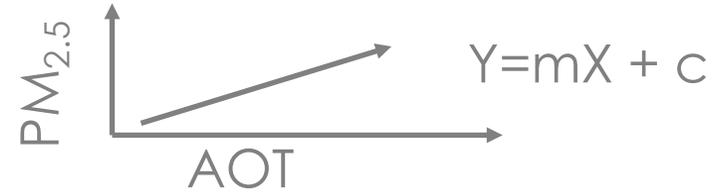
Source: Gupta, 2008



# PM<sub>2.5</sub> Estimation: Artificial Intelligence (or ANN)

Difficulty Level

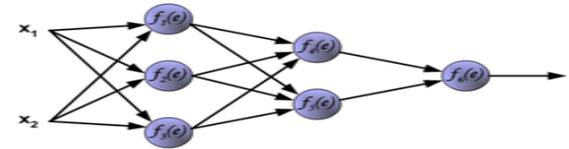
Two Variable Method



Multivariable Method

$$PM_{2.5} = \beta_0 + a \times T + \sum_{n=1}^m (\beta_n \times M_n)$$

Artificial Intelligence

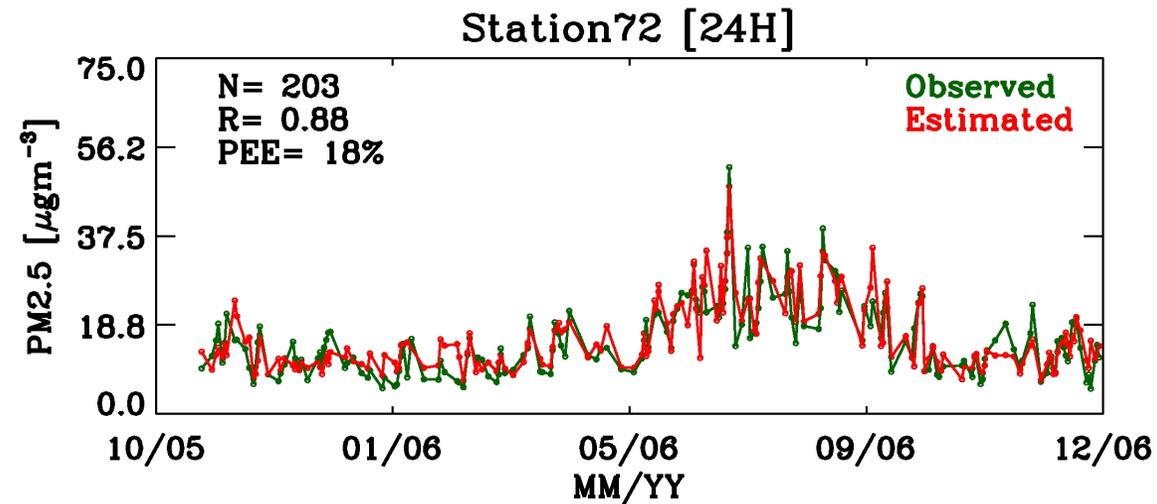
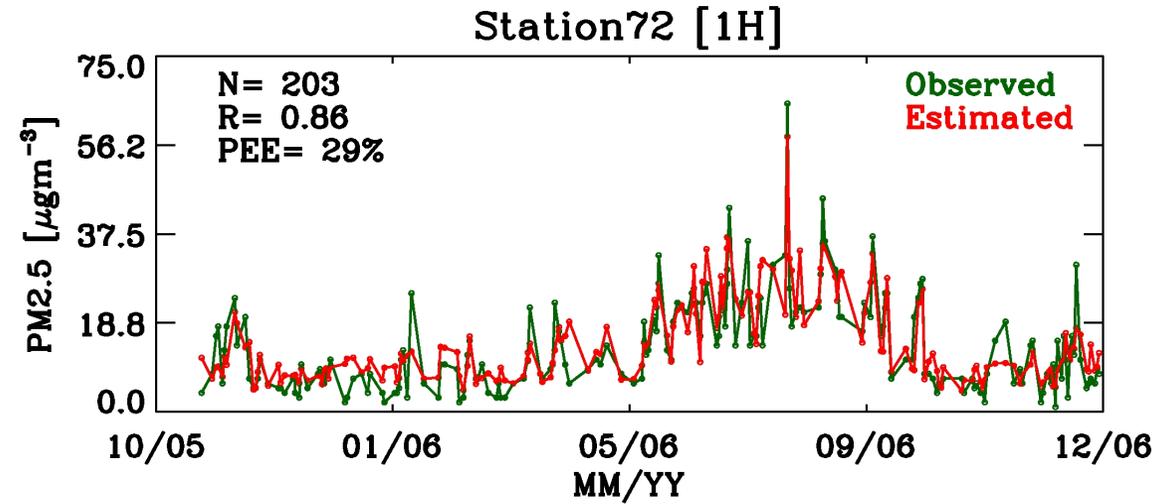


MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



# Time Series Examples of Results from ANN

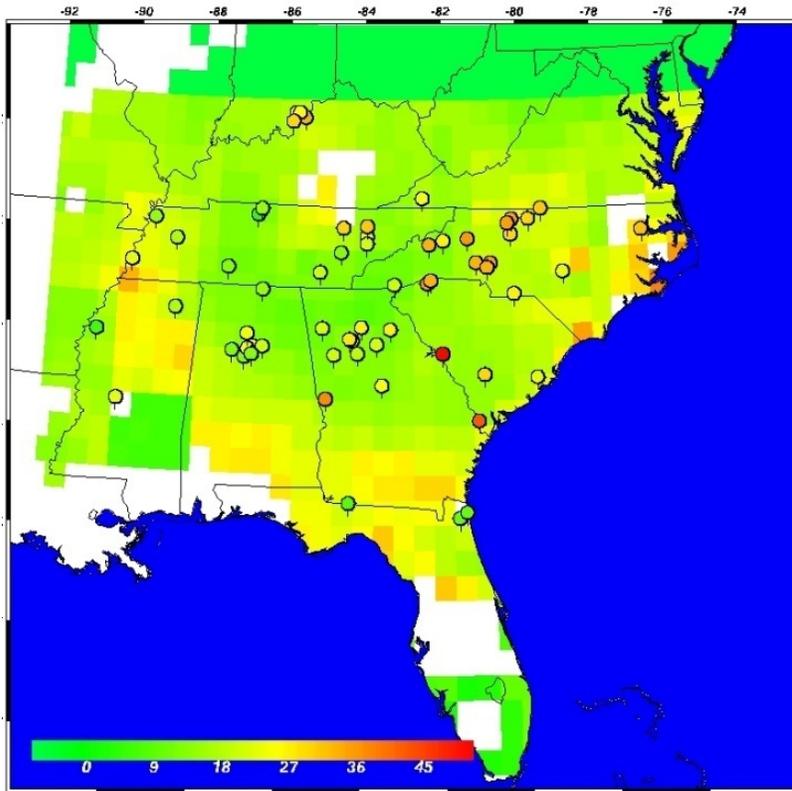


Source: Gupta, 2009

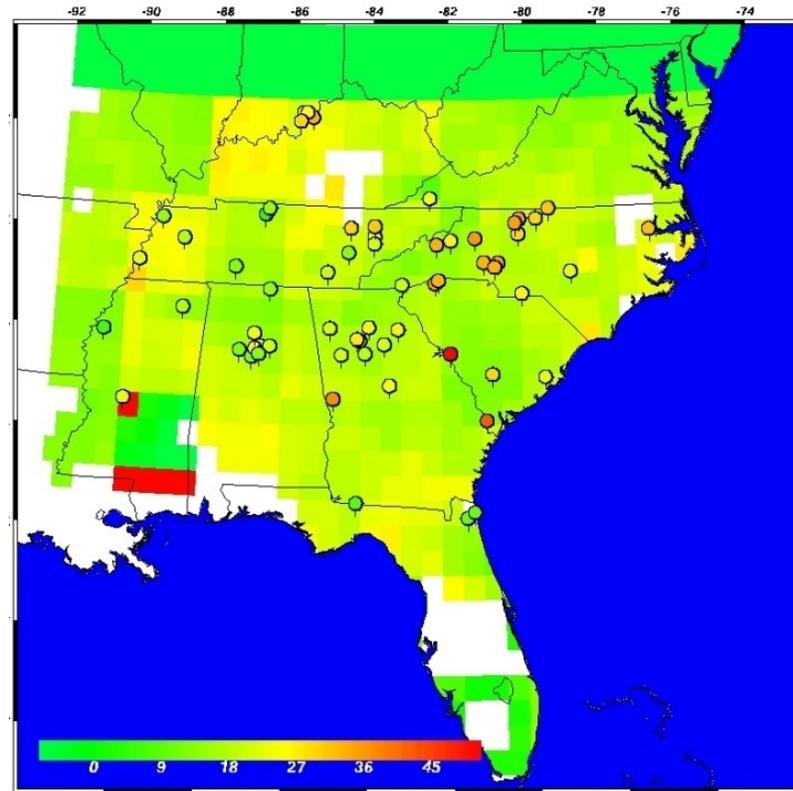


# TVM vs. MVM vs. ANN

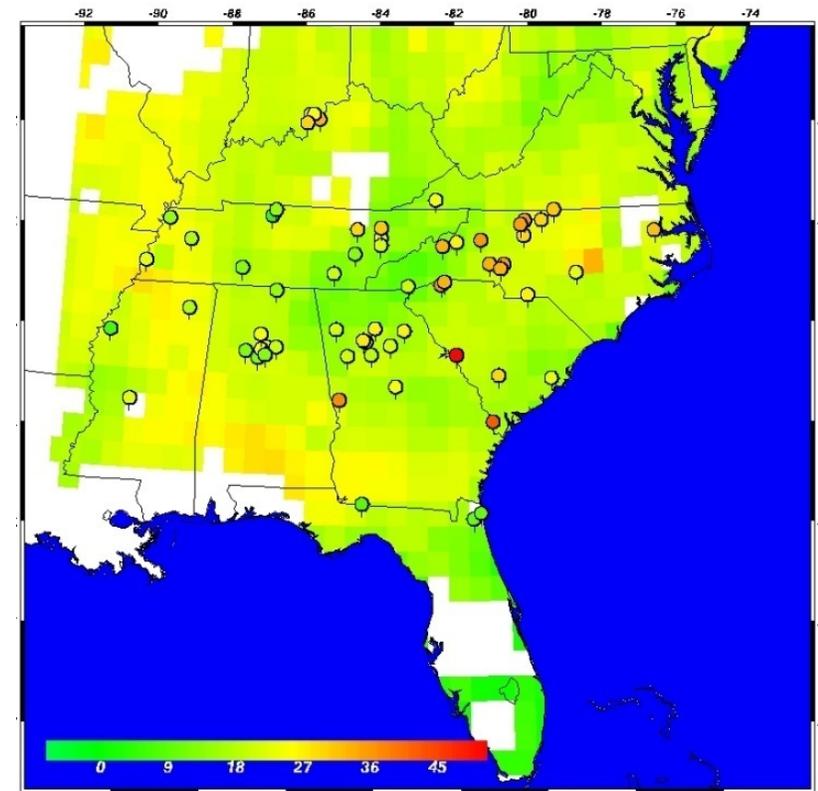
## TVM



## MVM



## ANN



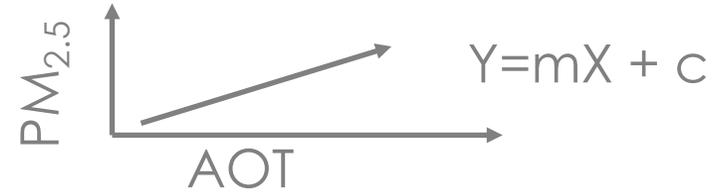
Source: Gupta, 2009



# PM<sub>2.5</sub> Estimation: Model Scaling (MSC)

Difficulty Level

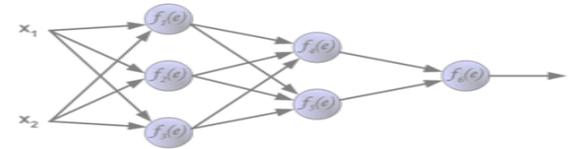
Two Variable Method



Multivariable Method

$$PM_{2.5} = \beta_0 + a \times T + \sum_{n=1}^m (\beta_n \times M_n)$$

Artificial Intelligence



MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



# Scaling Approach

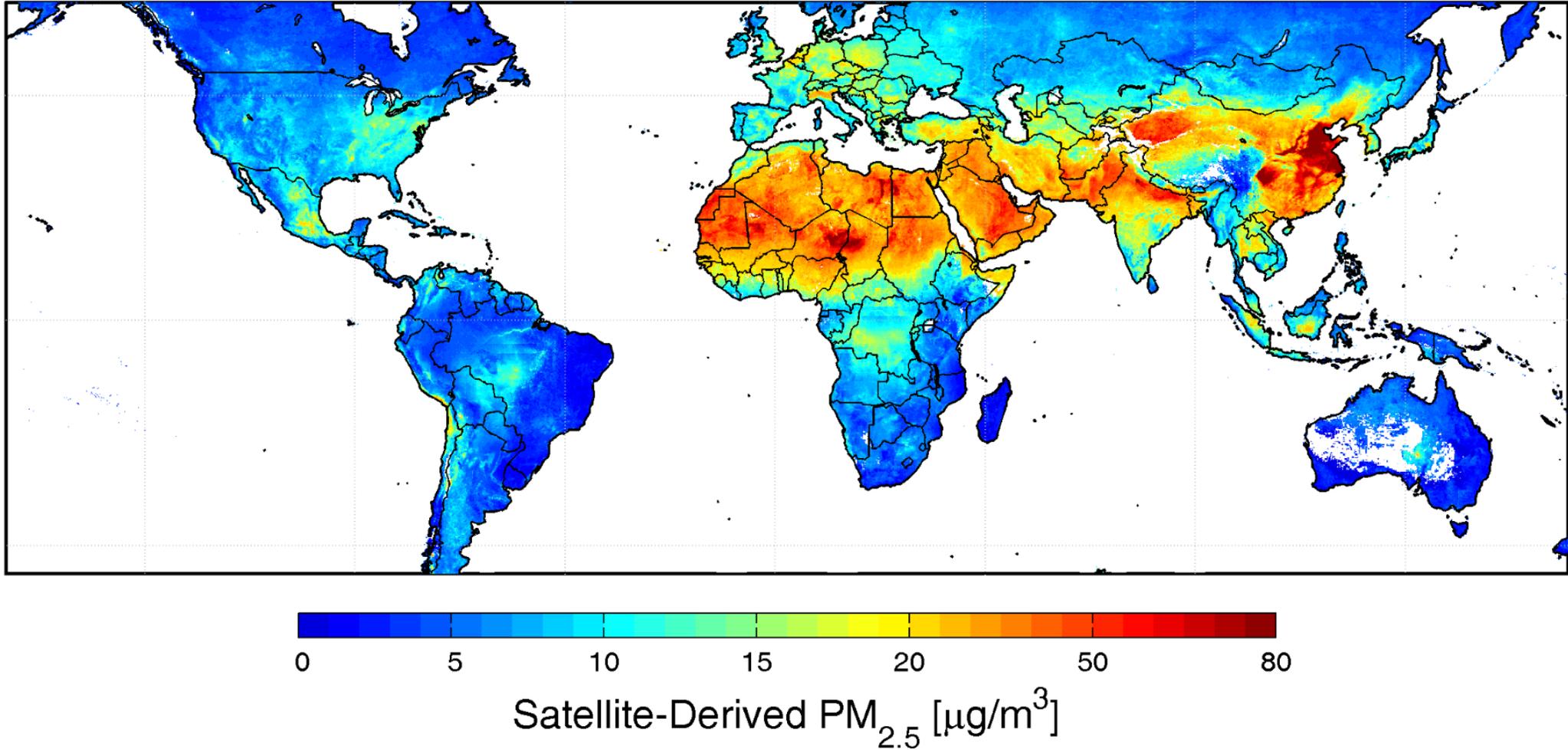
- Basic idea:
  - Let an atmospheric chemistry model decide the conversion from AOD to  $PM_{2.5}$
  - Satellite AOD is used to calibrate the absolute value of the model generated conversion ratio

- Satellite-Derived  $PM_{2.5}$  =  $\left( \frac{PM_{2.5}}{AOD} \right)_{\text{Model}} \times \text{satellite AOD}$

Source: Liu et al., 2006



# Annual Mean PM<sub>2.5</sub> from Satellite Observations



van Donkelaar et al., 2006, 2009

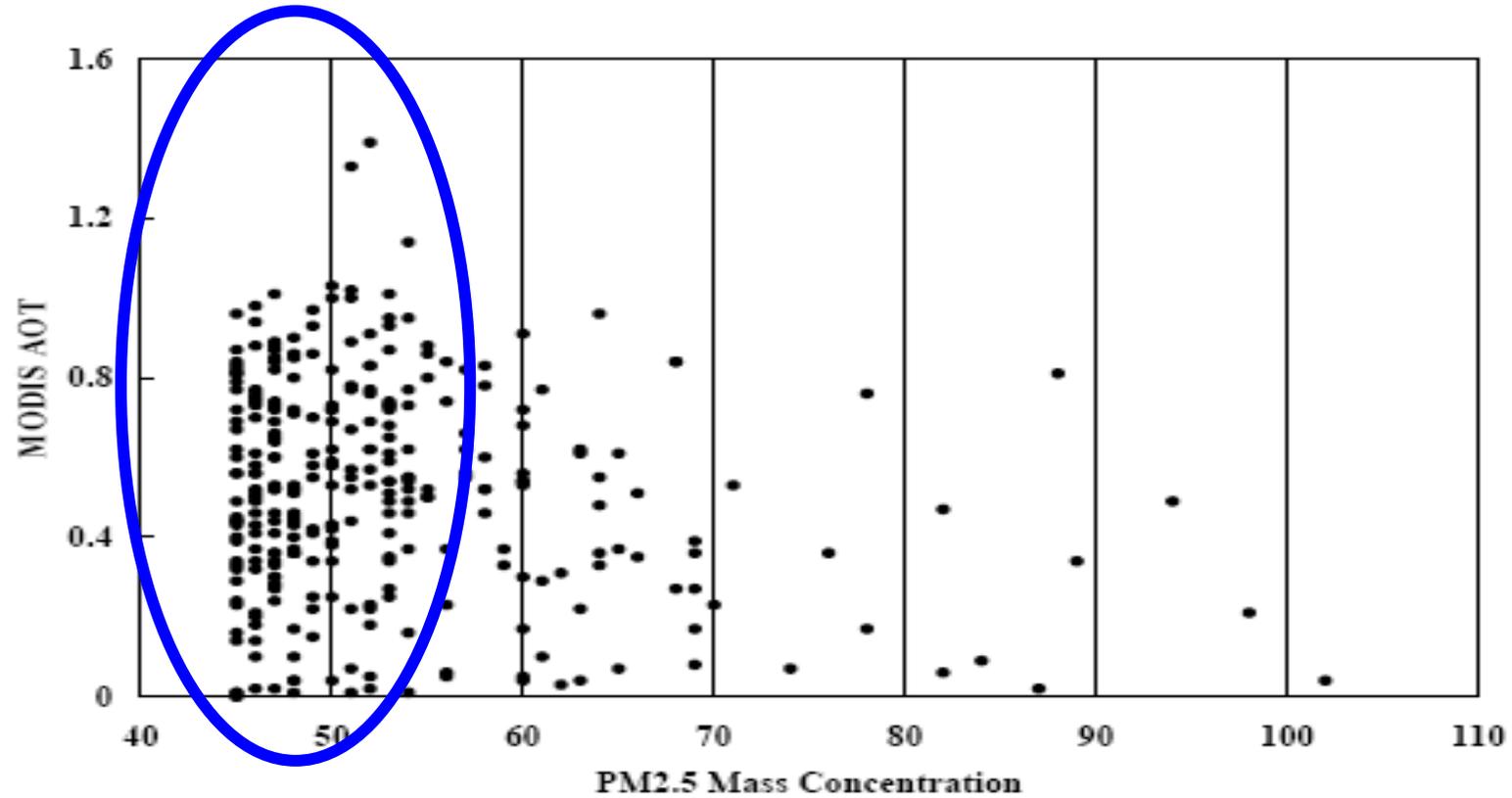


# Questions to Ask: Issues

- How accurate are these estimates?
- Is the  $PM_{2.5}$  – AOD relationship always linear?
- How does AOD retrieval uncertainty impact estimation of air quality?
- Does this relationship change in space and time?
- Does this relationship change with aerosol type?
- How does meteorology drive this relationship?
- How does the vertical distribution of aerosols in the atmosphere impact these estimates?



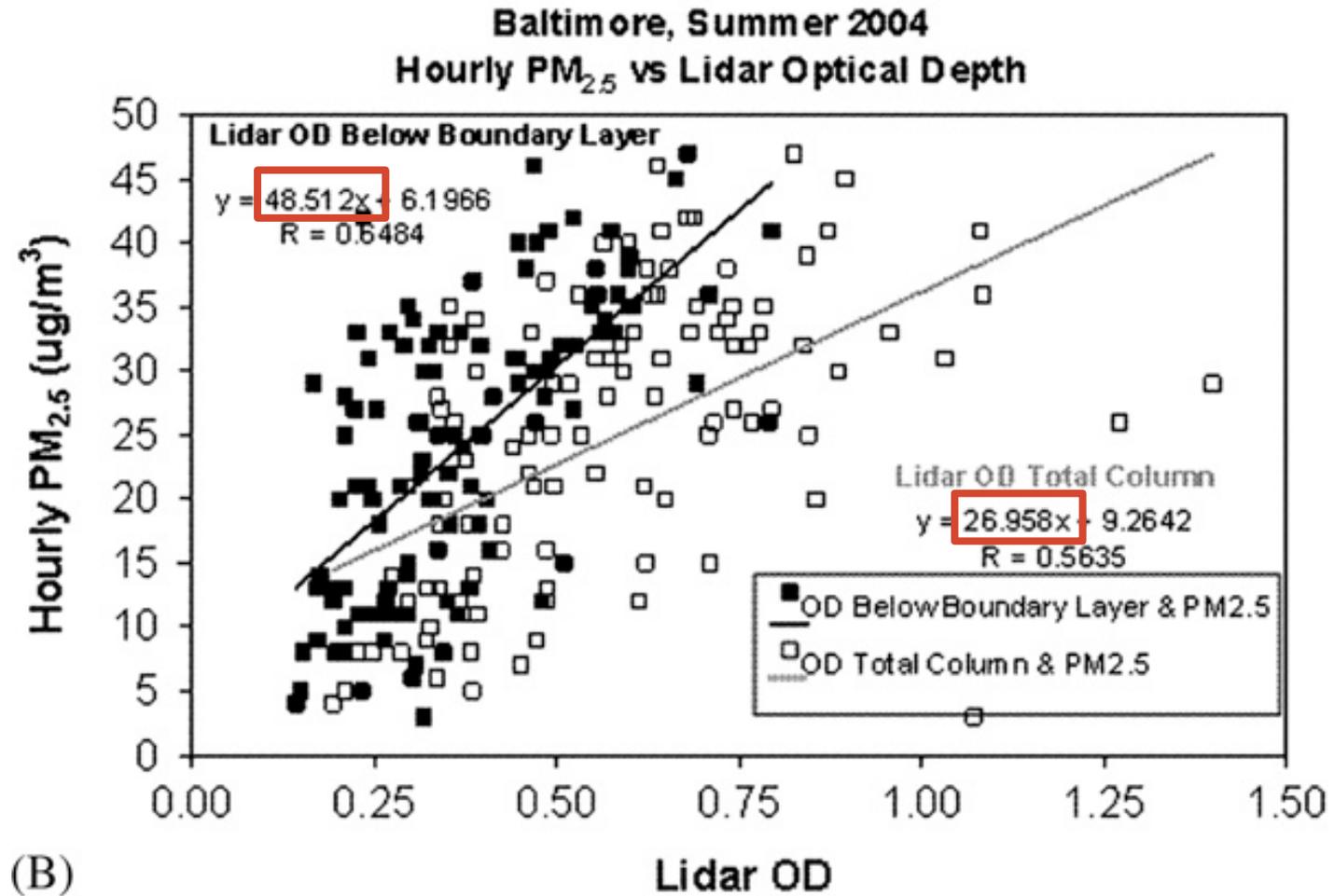
# Limitation: Vertical Distribution of Aerosols



Gupta et al., 2009



# Vertical Distribution: Impact on AOD-PM<sub>2.5</sub>

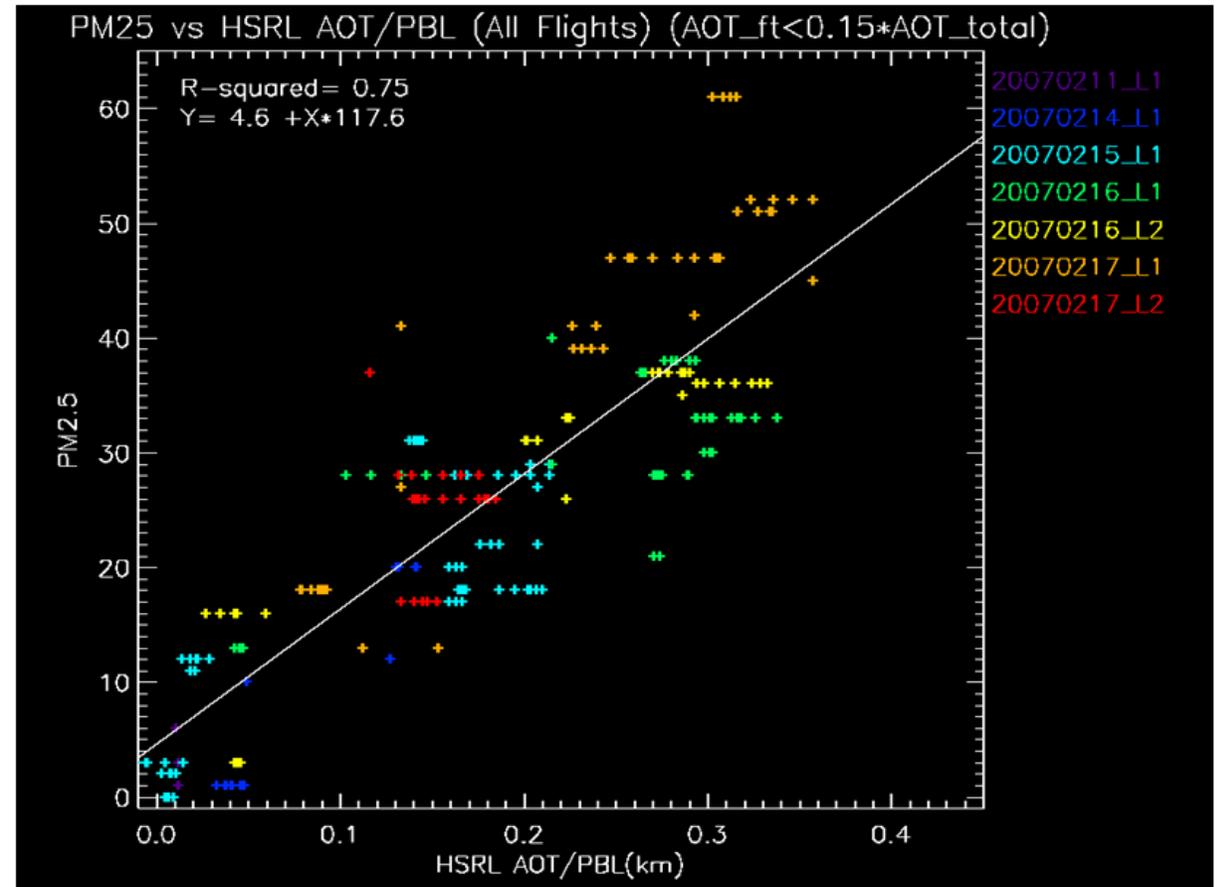


Source: Engel-Cox et al., 2006



# Vertical Distribution: Impact on AOD-PM<sub>2.5</sub>

- Normalizing AOD with boundary layer height significantly improves the correlation with surface PM<sub>2.5</sub> ( $R^2$  increases from 0.36 to 0.75)
- With accurate estimates of PBL height, AOD can be a good proxy for PM<sub>2.5</sub>



Source: Al-Saadi et al., 2006



# Assumption for Quantitative Analysis

When most particles are concentrated and well mixed in the boundary layer, satellite AOD contains a strong signal of ground-level particle concentrations

**No textbook solution**



# Use of Satellite Data

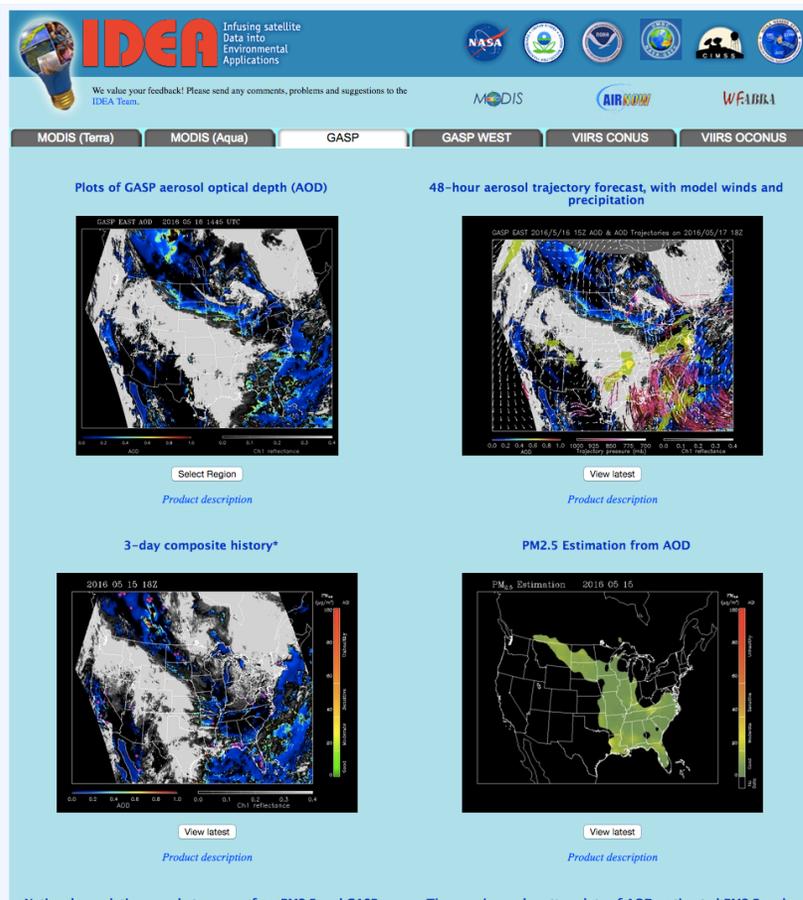
- Currently for Research
  - Spatial distribution of  $PM_{2.5}$  on regional to national level
  - Long term trends of  $PM_{2.5}$
  - Model calibration, data assimilation, and validation
  - Exposure assessments for health effect studies
- Near Future Research
  - Spatial trends at urban scales
  - Improved coverage and accuracy
  - Fused statistical-deterministic models
- For Regulation?



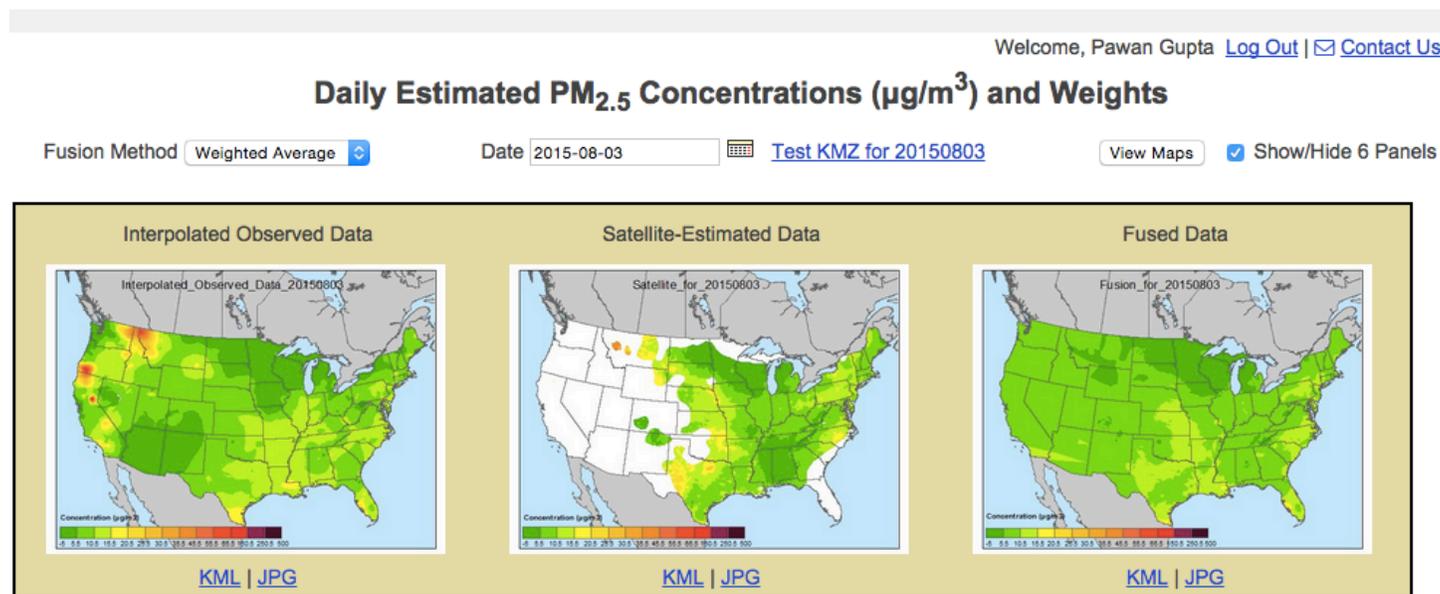
# How Satellite Aerosol Data is Used

## Infusing Satellite Data Into Environmental Applications

- Objective: near real-time product for state and local air quality forecasters
- Goal: improve accuracy of next day PM<sub>2.5</sub> AQI forecasts during large aerosol events



## AirNow Satellite Data Processor (ASDP)



# Suggested Reading

<http://www.nsstc.uah.edu/sundar/papers/2009/AWMA-proof.pdf>

## 2009 CRITICAL REVIEW



R.M. Hoff



S.A. Christopher

## Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land?

### Raymond M. Hoff

Department of Physics and the Joint Center for Earth System Science and Technology Center, University of Maryland, Baltimore

### Sundar A. Christopher

Department of Atmospheric Sciences and Earth System Science, Alabama-Huntsville, Huntsville, AL

ISSN:1047-3289 J. Air & Waste Manage. Assoc. 59:645-675  
DOI:10.3155/1047-3289.59.6.645  
Copyright 2009 Air & Waste Management Association

### IMPLICATIONS

Satellite measurements are going to be an integral part of the Global Earth Observing System of Systems. Satellite measurements by themselves have a role in air quality studies but cannot stand alone as an observing system. Data assimilation of satellite and ground-based measurements into forecast models has synergy that aids all of these air quality tools.

the “but for” provision in the rule makes the use of satellite data possible in significant exceedances only. Applications such as event identification, transport, and atmospheric composition determination are strengths of satellite measurements. Where high precision is required (compliance monitoring, the “but for” test, and quantitative measurement of visibility effects on Class I areas), satellite data are presently of limited utility.

The use of the AOD as a measure for mass concentration has skill in some regions but less in others and does not provide a uniform way to measure aerosols across the United States. We discussed in Table 4 the range of mea-

In 2007, the A&WMA Critical Review by Bachmann discussed the history of the National Ambient Air Quality Standards (NAAQS).<sup>142</sup> The 39-yr history of those standards parallels the time period that satellite meteorology and observations have developed and yet, to date, no satellite measurements have been used to quantitatively address the NAAQS. From the review conducted here, only one congress-

EPA has taken a satellite observations role for itself in the Exceptional Events Rule.<sup>144</sup> If a region can show conclusively that they are being impacted by an event (a fire, a dust storm, etc.) that is outside of their jurisdiction to regulate, the event can be flagged as a nonexceedance event. This provides a significant motivation for regional

Although the desire for the use of satellite data for air quality purposes is widely stated, the reality is that many of the measurements have not yet met the promise that they can be operationally used for today’s air quality monitoring requirements. Precision in measuring AOD is



# Another Review Article

<http://www.mdpi.com/2073-4433/7/10/129/pdf>



*Review*

## A Review on Predicting Ground PM<sub>2.5</sub> Concentration Using Satellite Aerosol Optical Depth

Yuanyuan Chu <sup>1,2,†</sup>, Yisi Liu <sup>1,†</sup>, Xiangyu Li <sup>1,2</sup>, Zhiyong Liu <sup>3</sup>, Hanson Lu <sup>4</sup>, Yuanan Lu <sup>2,5</sup>, Zongfu Mao <sup>1,2</sup>, Xi Chen <sup>1</sup>, Na Li <sup>1</sup>, Meng Ren <sup>1</sup>, Feifei Liu <sup>1</sup>, Liqiao Tian <sup>6</sup>, Zhongmin Zhu <sup>6,7</sup> and Hao Xiang <sup>1,2,\*</sup>

<sup>1</sup> Department of Epidemiology and Biostatistics, School of Public Health, Wuhan University, 115# Donghu Road, Wuhan 430071, China; 2014203050033@whu.edu.cn (Y.C.); roselewis@sina.com (Y.L.); 2015203050022@whu.edu.cn (X.L.); zfmiao@126.com (Z.M.); aries\_c\_7@163.com (X.C.); 2012302170047@whu.edu.cn (N.L.); melodyren@163.com (M.R.); 2015203050008@whu.edu.cn (F.L.)

<sup>2</sup> Global Health Institute, Wuhan University, 115# Donghu Road, Wuhan 430071, China; yuanan@hawaii.edu

<sup>3</sup> The National Environmental Satellite, Data, and Information Service (NESDIS), National Oceanic and Atmospheric Administration (NOAA), 5830 University Research Court, College Park, MD 20740, USA; Zhiyonglu@gmail.com

<sup>4</sup> International Baccalaureate Diploma Program, Wuhan Foreign Languages School, Wan Song Yuan Road, Wuhan 430022, China; hansonlu\_hl@hotmail.com

<sup>5</sup> Environmental Health Laboratory, Department of Public Health Sciences, University of Hawaii at Manoa, 1960 East-West Road, Honolulu, HI 96822, USA

<sup>6</sup> State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, 129# Luoyu Road, Wuhan 430079, China; tianliqiao@whu.edu.cn (L.T.); zhongmin.zhu@whu.edu.cn (Z.Z.)

<sup>7</sup> College of Information Science and Engineering, Wuchang Shouyi University, Wuhan 430064, China

\* Correspondence: xianghao@whu.edu.cn; Tel.: +86-27-6875-9118

† These authors contributed equally to this work

Academic Editor: Robert W. Talbot

Received: 25 July 2016; Accepted: 5 October 2016; Published: 14 October 2016

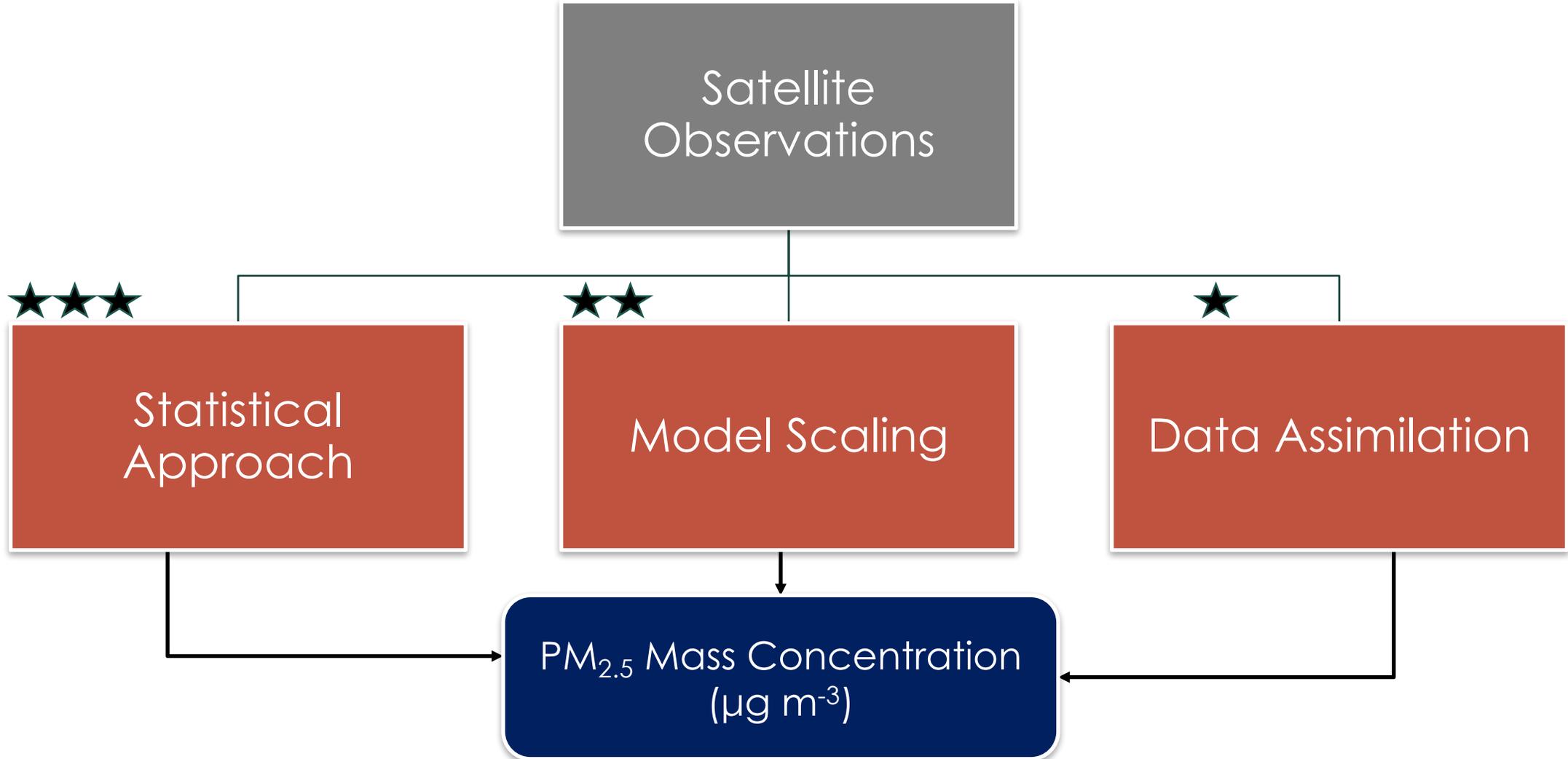


# Suggested References

- Al-Saadi, J., Szykman, J., Pierce, R. B., Kittaka, C., Neil, D., Chu, D. A., Remer, L., Gumley, L., Prins, E., Weinstock, L., Macdonald, C., Wayland, R., Dimmick, F., Fishman, J., Improving national air quality forecasts with satellite aerosol observations, *Bull. Am. Meteorol. Soc.*, 86(9), 1249–1264, 2005.
- Gupta, P., Christopher, S. A., Wang, J., Gehrig, R., Lee, Y.C., Kumar, N., Satellite remote sensing of particulate matter and air quality over global cities, *Atmos. Environ.*, 40 (30), 5880-5892, 2006.
- Gupta, P., and S. A. Christopher, An evaluation of Terra-MODIS sampling for monthly and annual particulate matter air quality assessment over the southeastern United States, *Atmospheric Environment* 42, 6465-6471, 2008b.
- Liu, Y., J. A. Sarnat, V. Kilaru, D. J. Jacob, and P. Koutrakis, Estimating ground level pm2.5 in the eastern united states using satellite remote sensing, *Environmental Science & Technology*, 39(9), 3269-3278, 2005.
- Wang, J., and S. A. Christopher, Intercomparison between satellite-derived aerosol optical thickness and PM<sub>2.5</sub> mass: Implications for air quality studies, *Geophys. Res. Lett.*, 30(21), 2095, doi:10.1029/2003GL018174, 2003.
- van Donkelaar, A., R. Martin V., Park R. J., Estimating ground-level PM<sub>2.5</sub> using aerosol optical depth determined from satellite remote sensing. *J. Geophys. Res.*, 111, D21201, doi:10.1029/2005JD006996, 2006.
- **Hoff, R., S.A. Christopher, Remote Sensing of Particulate Matter Air Pollution from Space : Have we reached the promised land, J. Air&Waste Manage. Assoc., 59:642-675 - (pdf file) , May, 2009.**
- van Donkelaar, A., R. V. Martin, M. Brauer and B. L. Boys, Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter, *Environmental Health Perspectives*, 123, 135-143, do:10.1289/ehp.1408646, 2015.



# Satellite Remote Sensing of PM<sub>2.5</sub>: Summary



# Questions and Discussion

- What are three differences between AOD and  $PM_{2.5}$  mass concentrations?
- What are three advantages of using satellite observations for  $PM_{2.5}$  air quality monitoring?
- What are the pros and cons of using a scaling approach over the regression method?

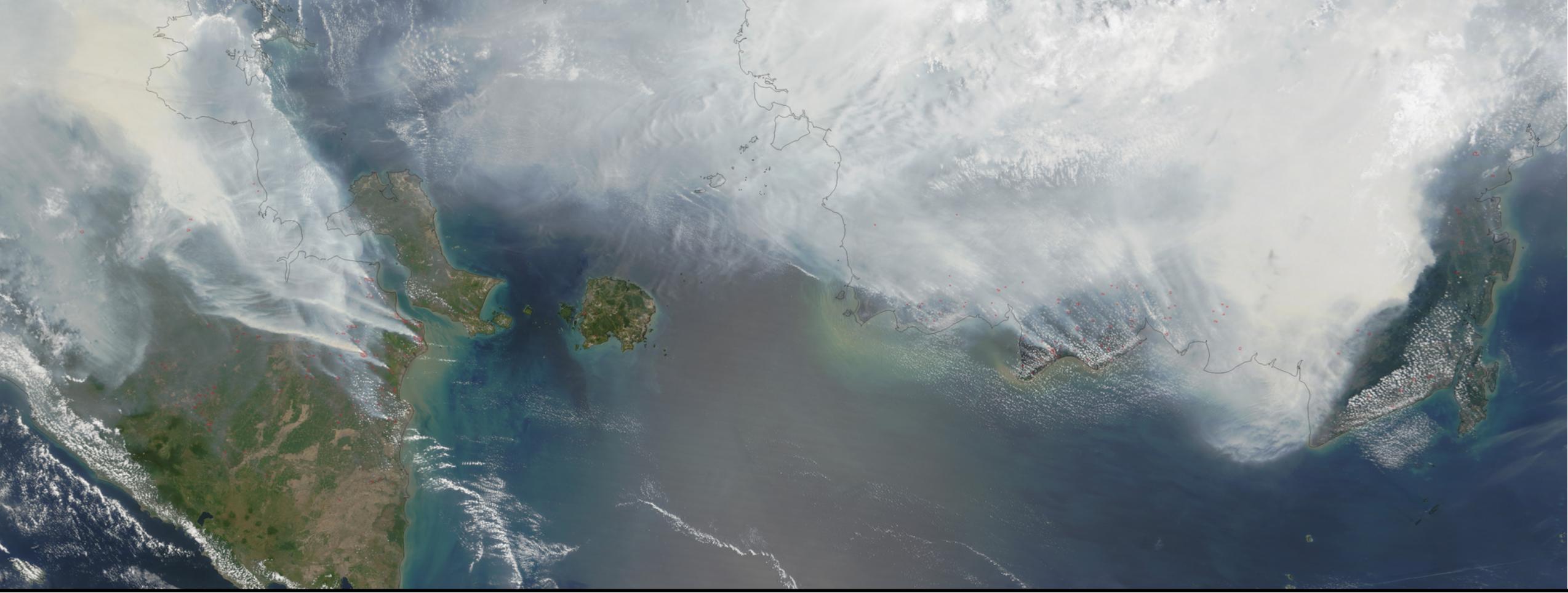


# Tour of IDEA

## Accessing Near Real-Time Satellite Data for U.S. Air Quality

- Air Quality Case Study
  - Fires in Canada and Smoke Transport over U.S.
    - June 09, 2015
  - Buffalo Fires, Wyoming
    - August 13, 2016
- Tools
  - IDEA: <http://www.star.nesdis.noaa.gov/smcd/spb/aq/>
  - eIDEA: <http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/>





Questions