

Theoretical Basis for Converting Satellite Observations to Ground-Level $PM_{2.5}$ Concentrations

Pawan Gupta, and Melanie Follette-Cook

Satellite Remote Sensing of Dust, Fires, Smoke, and Air Quality, July 10-12, 2018



Objectives

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

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



Air Quality Monitoring and Reporting

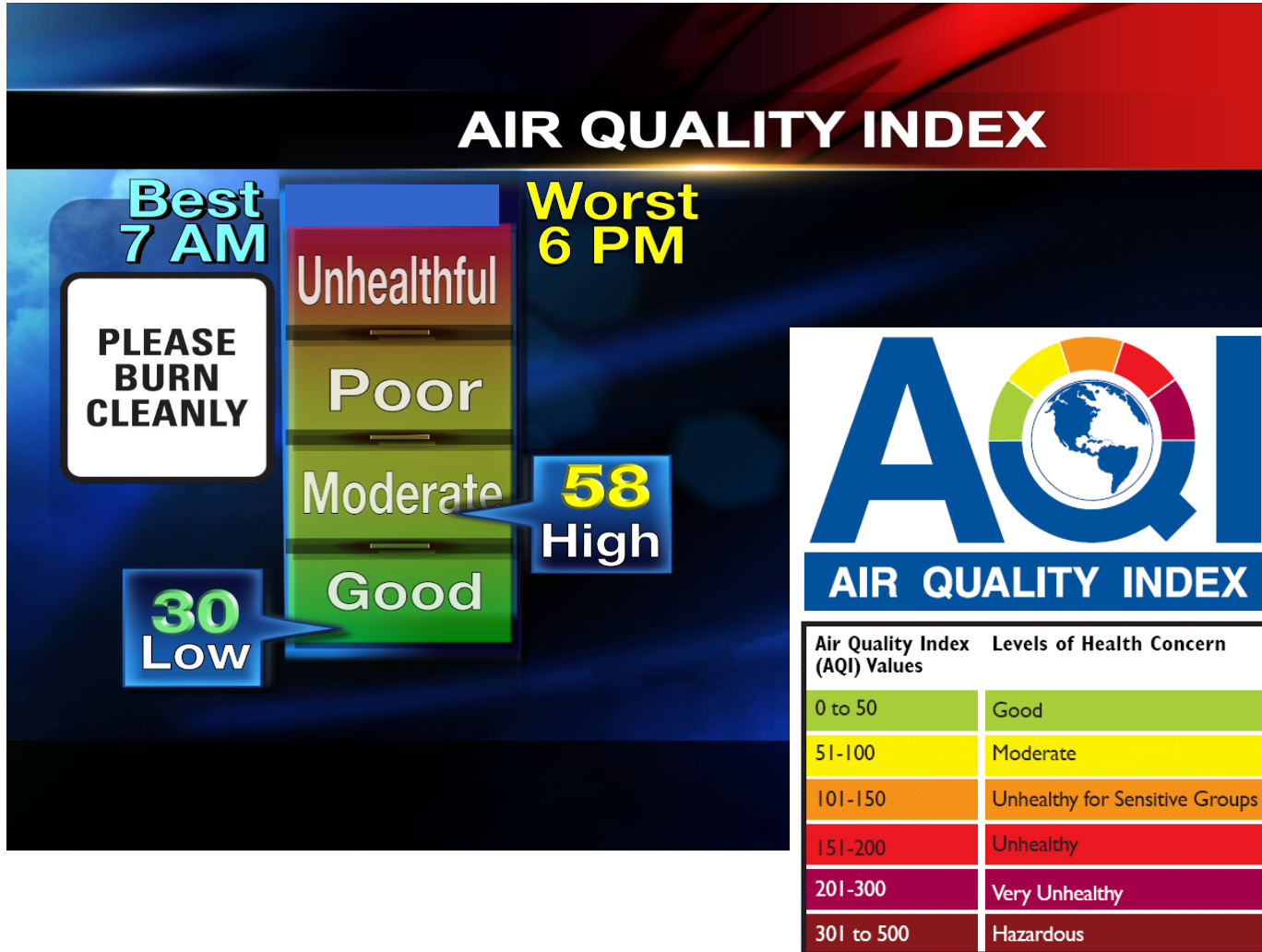
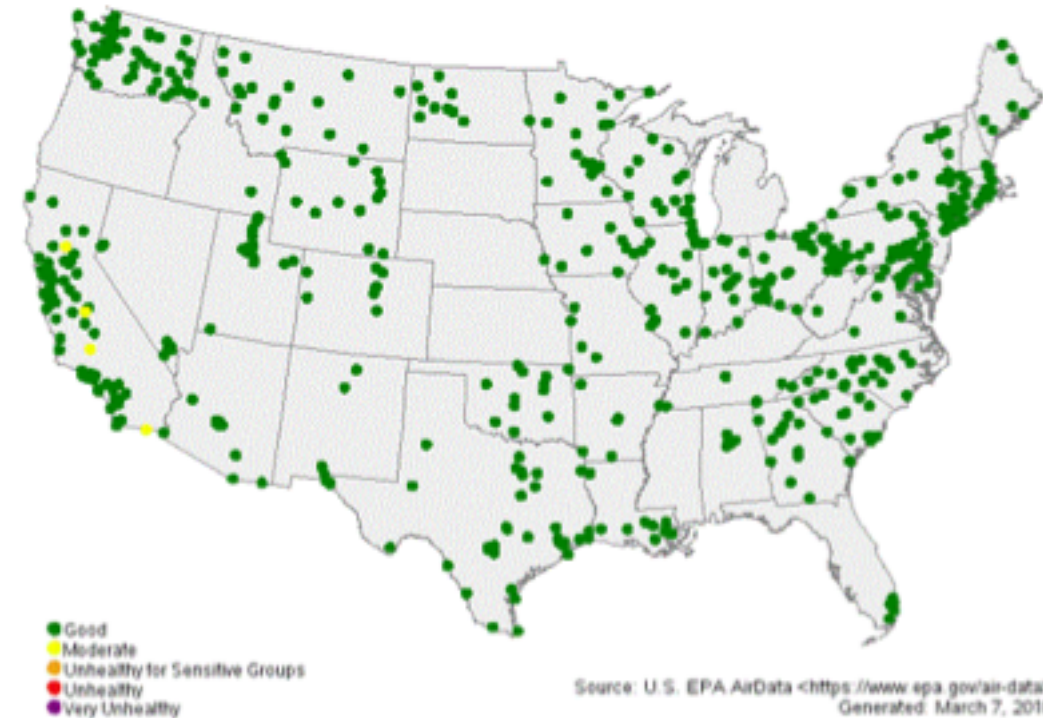


Image Credit: AirNow map, USEPA. <http://www.airnow.gov>

Spatial Gaps

PM_{2.5} AQI Values by site on 10/08/2017



Inferring AOD and PM_{2.5} from Visuals

Pittsburgh

PM_{2.5} = 45 μgm⁻³

PM_{2.5} = 4 μgm⁻³



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 PM_{2.5} from Visuals

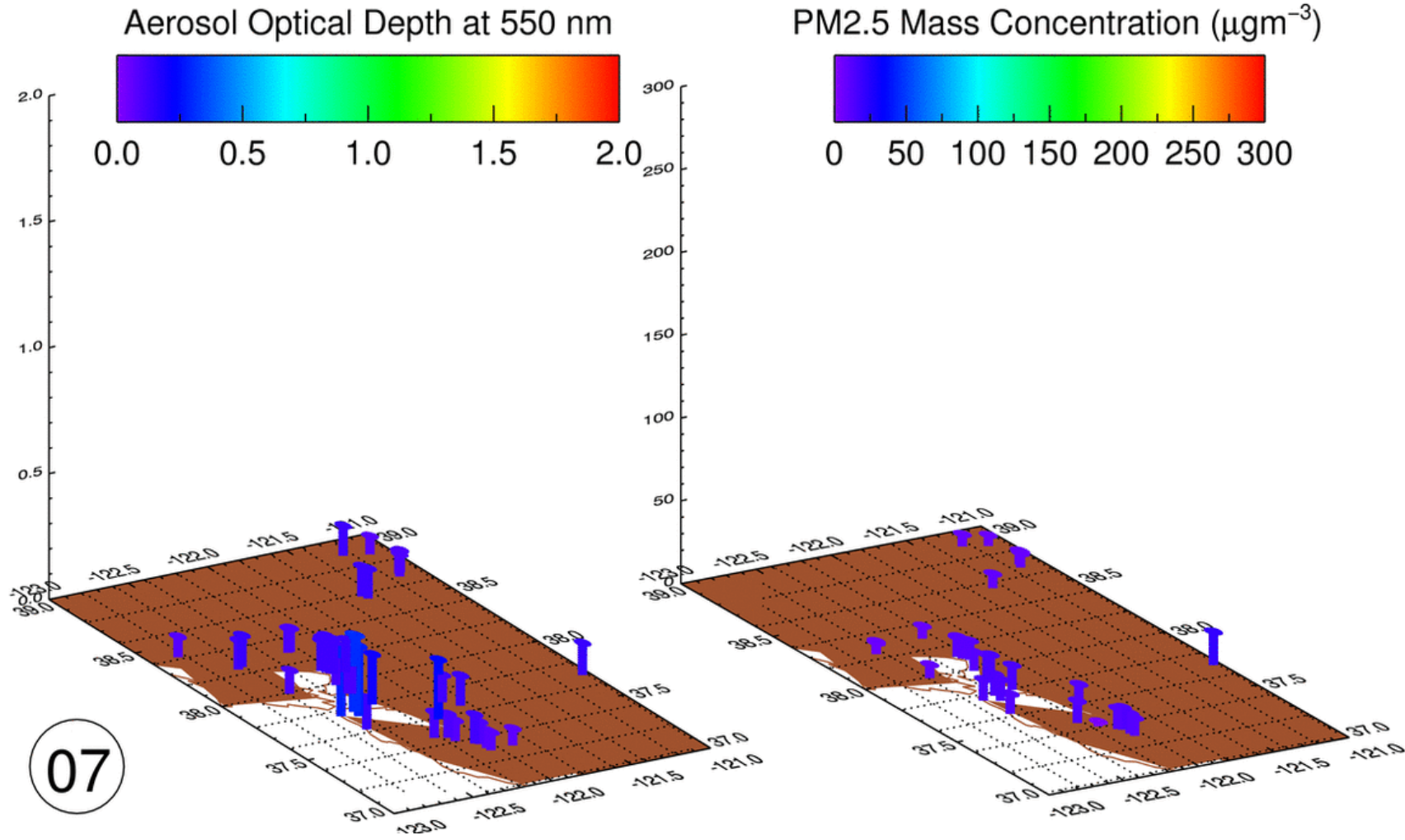
Singapore



Image Credit: Roslan Rahman/AFP/Getty Images



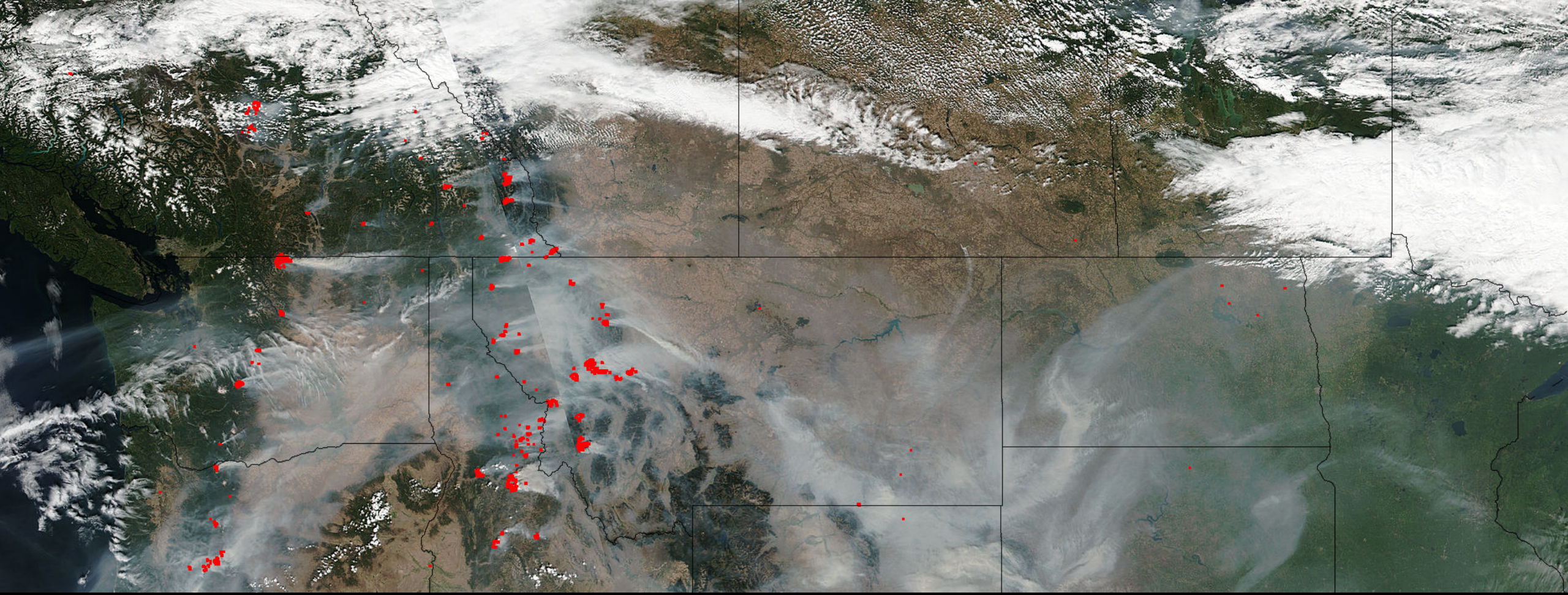
Surface vs. Satellite Measurements



07

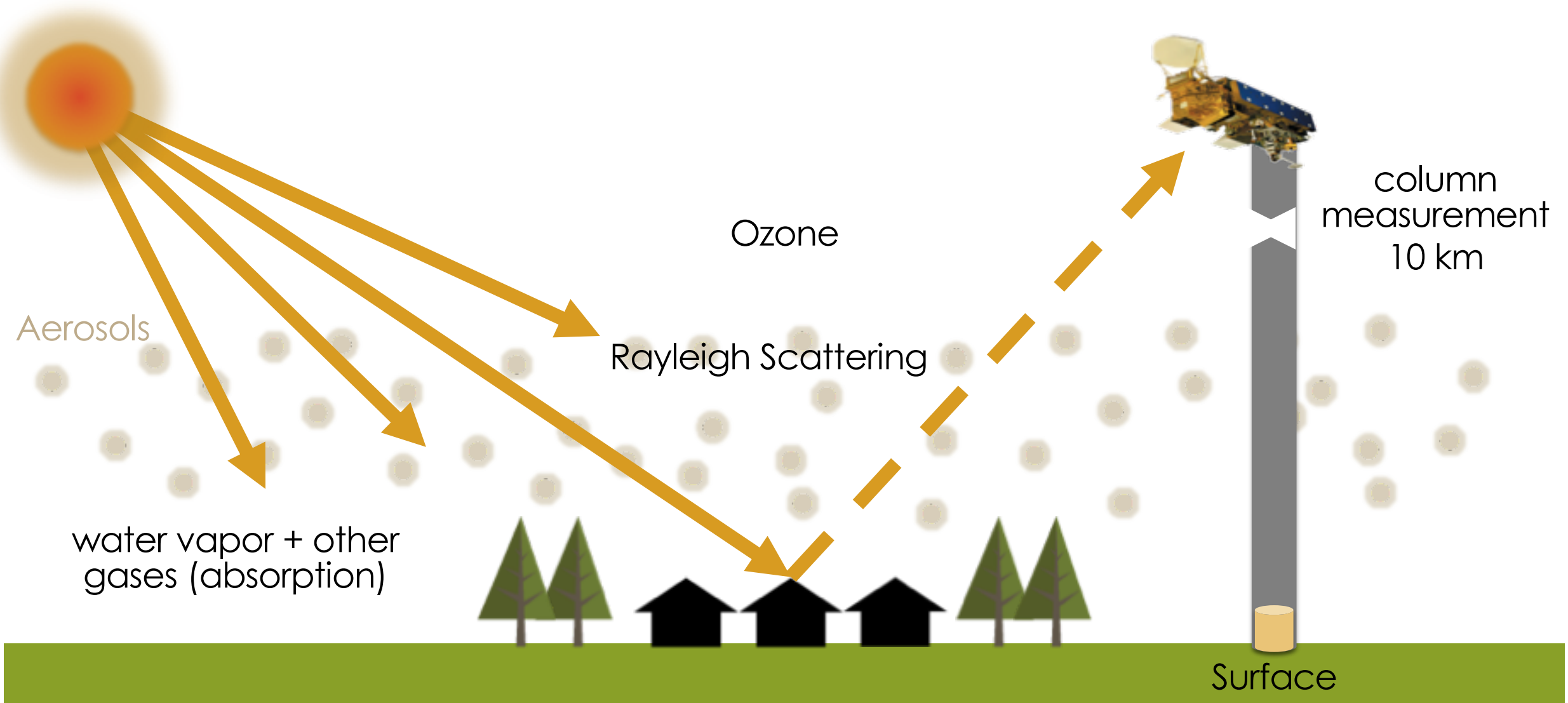
Gupta et al., 2018



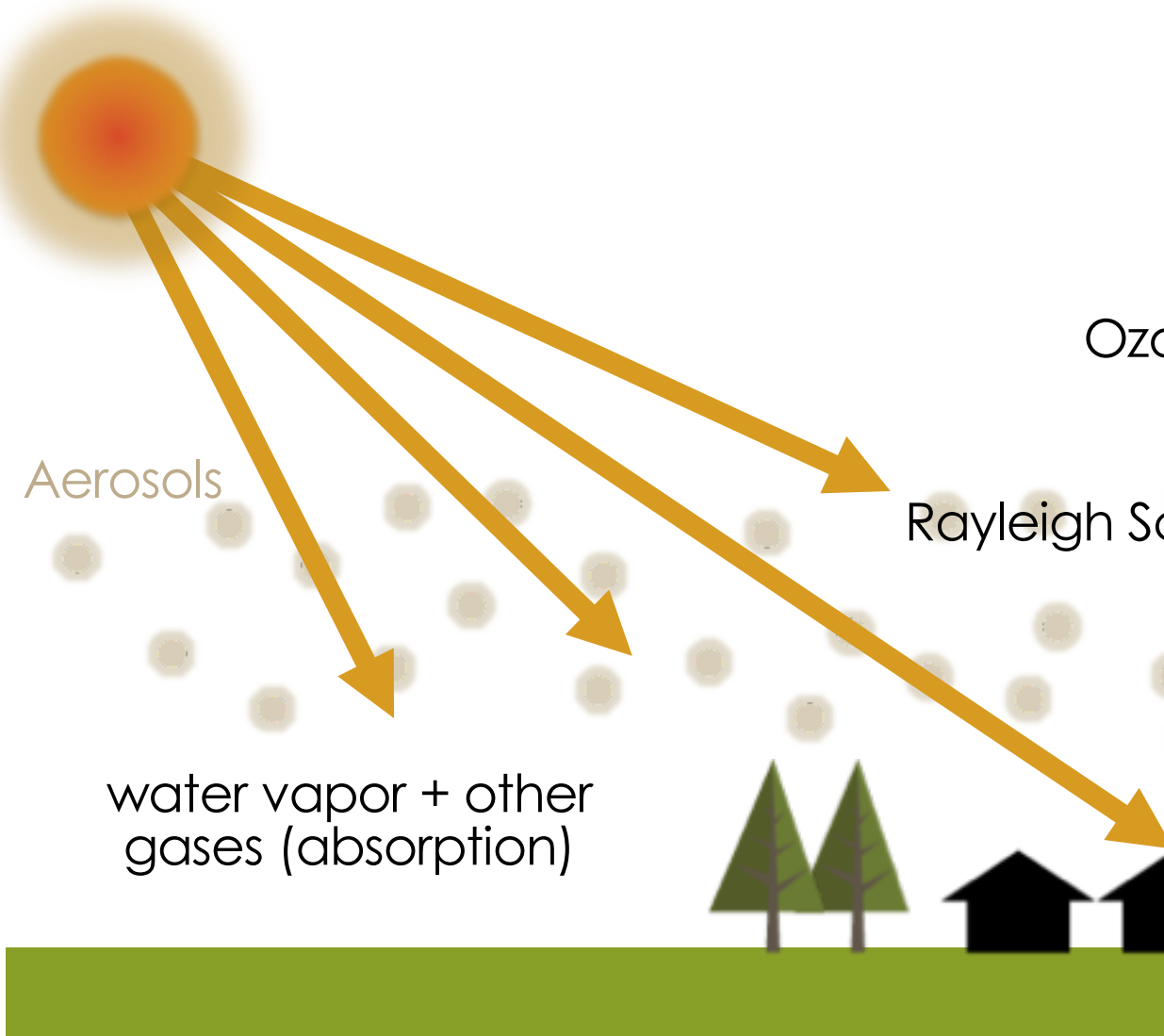


AOD (or AOT) to PM

Aerosol Optical Depth from Satellites



Aerosol Optical Depth from Satellites



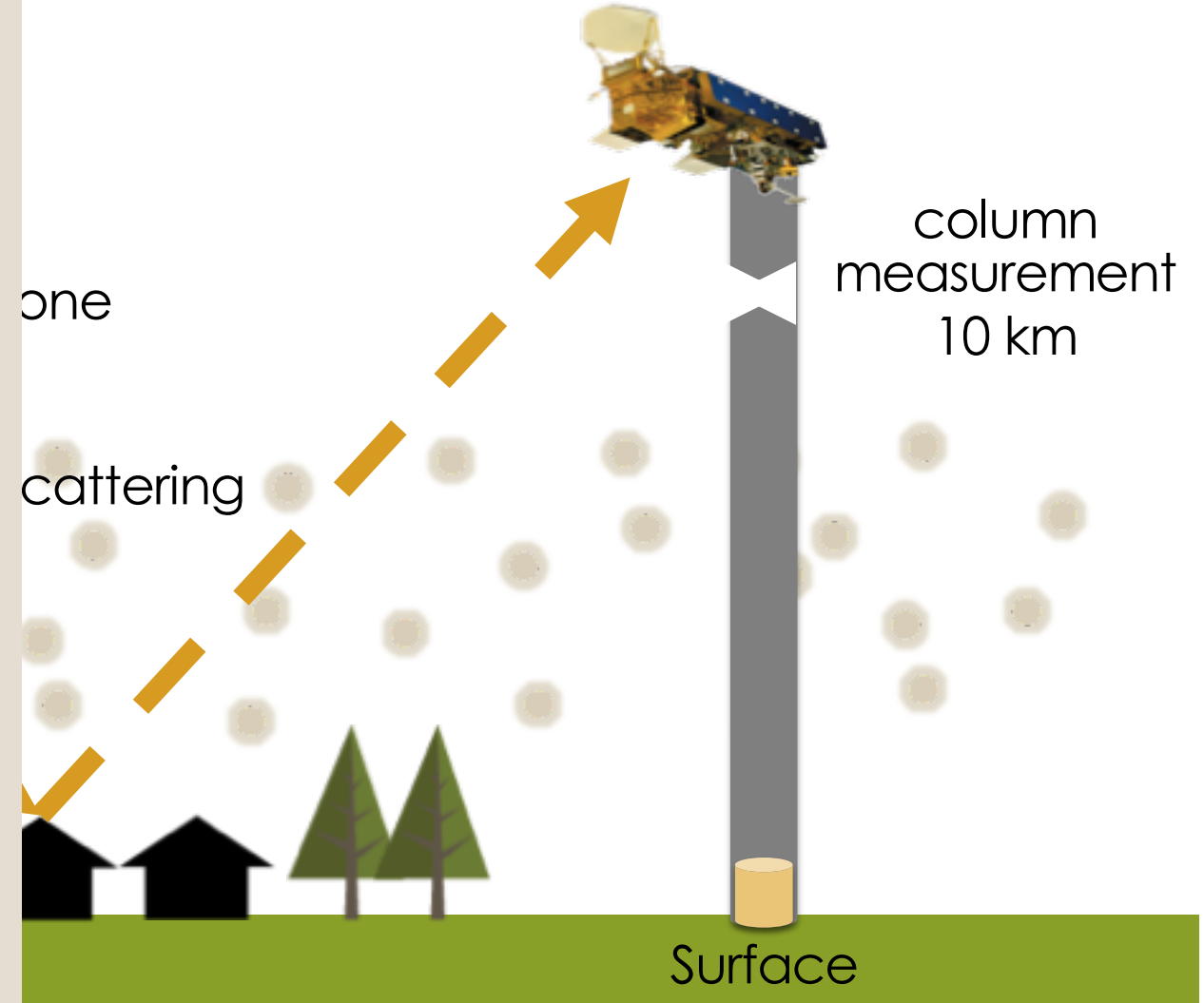
- $AOT(\tau) = \int \beta_{ext} dz$
 - particle size
 - composition
 - water uptake
 - vertical distribution

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

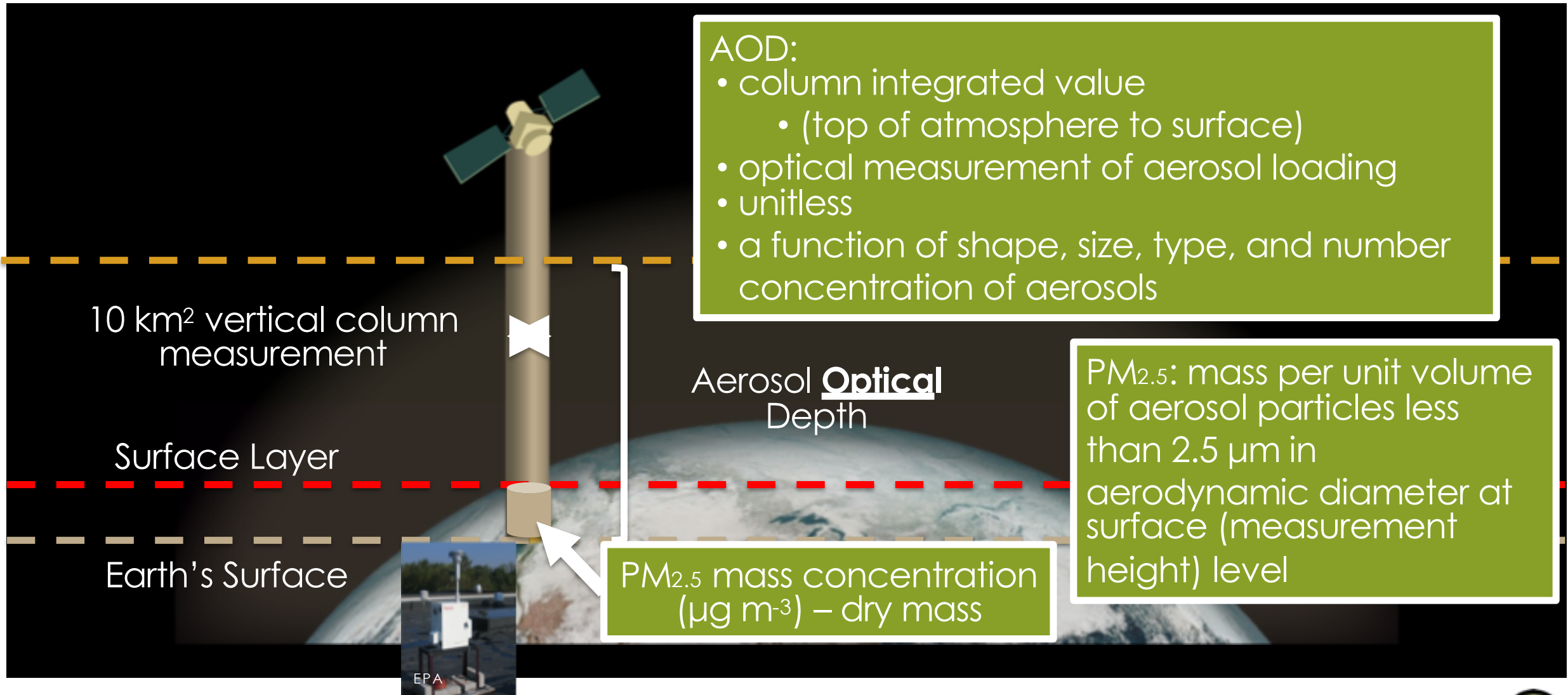


Aerosol Optical Depth from Satellites

- Seven MODIS bands are utilized to derive aerosol properties
 - **0.47 μm**
 - 0.55 μm
 - **0.65 μm**
 - 0.86 μm
 - 1.24 μm
 - 1.64 μm
 - **2.13 μm**
- 10x10 km² resolution
- 3x3 km² resolution

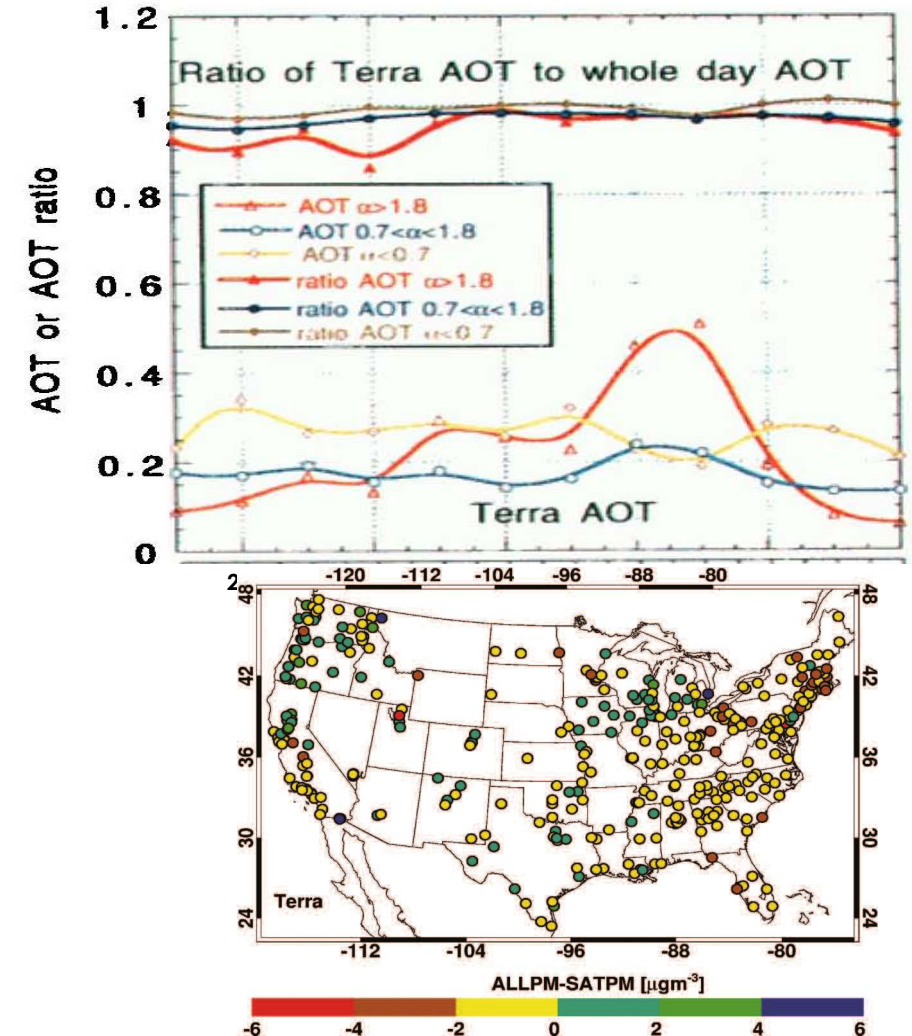


Satellite vs. Ground Observation



Support for AOD-PM_{2.5} Linkage

- Satellite AOD is sensitive to PM_{2.5}
 - 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:

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

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



PM_{2.5} Estimation: Popular Methods

Difficulty Level

Two-Variable Method

$$Y = mX + c$$

Multivariable Method

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

Artificial Intelligence



MSC

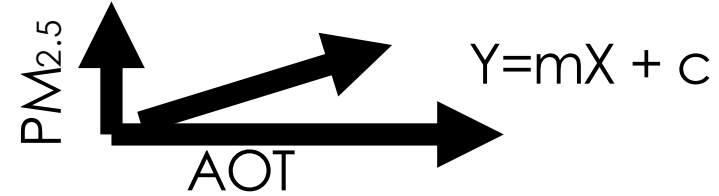
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



PM_{2.5} Estimation: Two Variable Method (TVM)

Difficulty Level

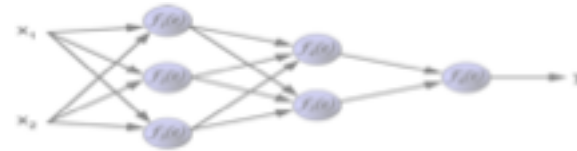
Two-Variable Method


$$Y = mX + c$$

Multivariable Method

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

Artificial Intelligence

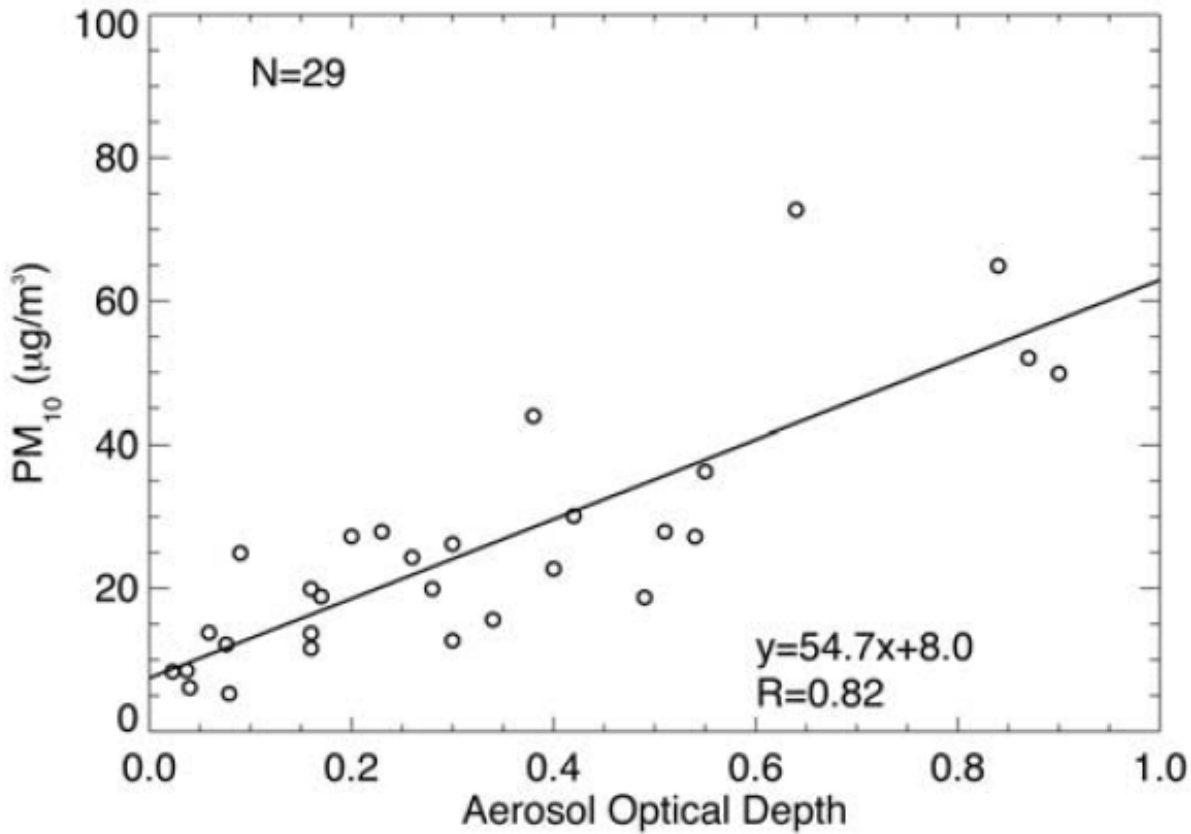


MSC

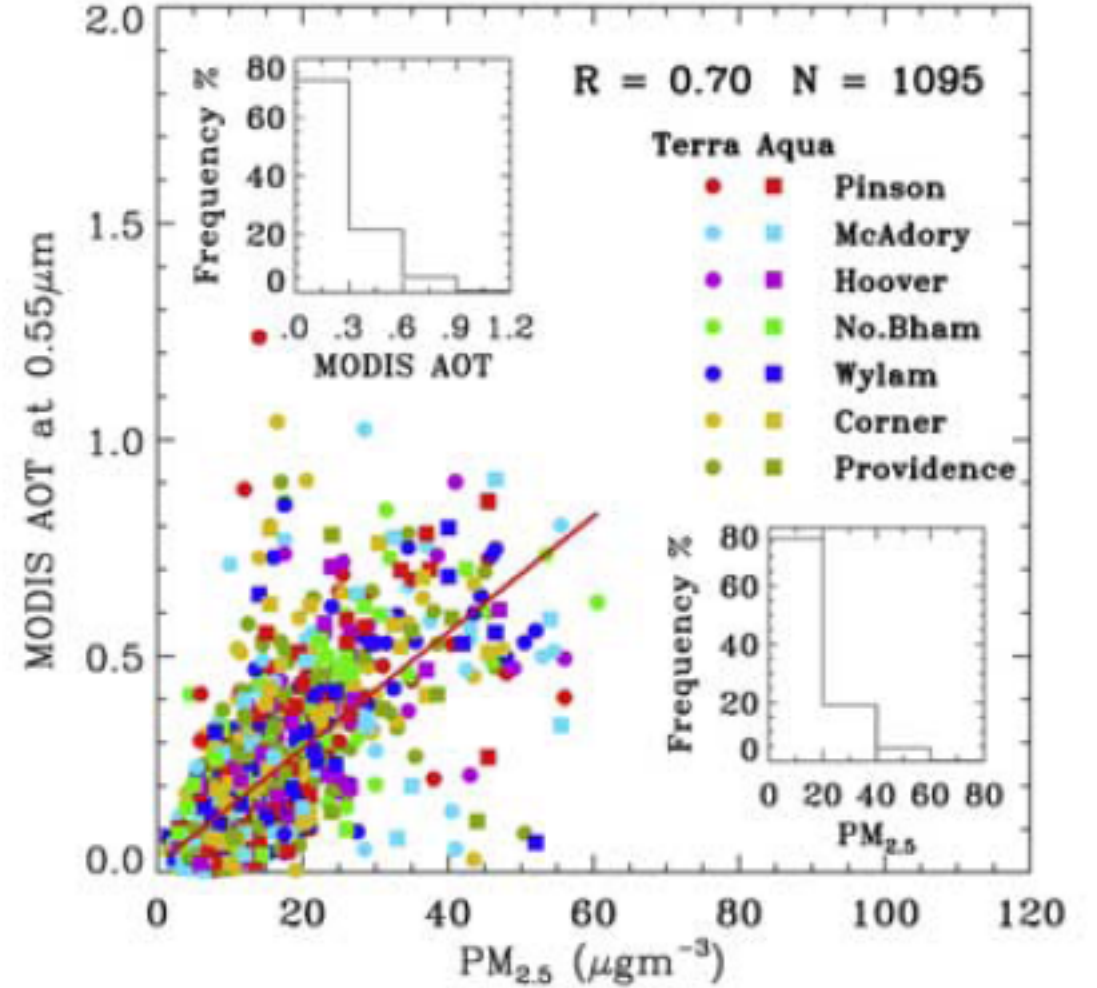
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$



Simple Models from Early Days



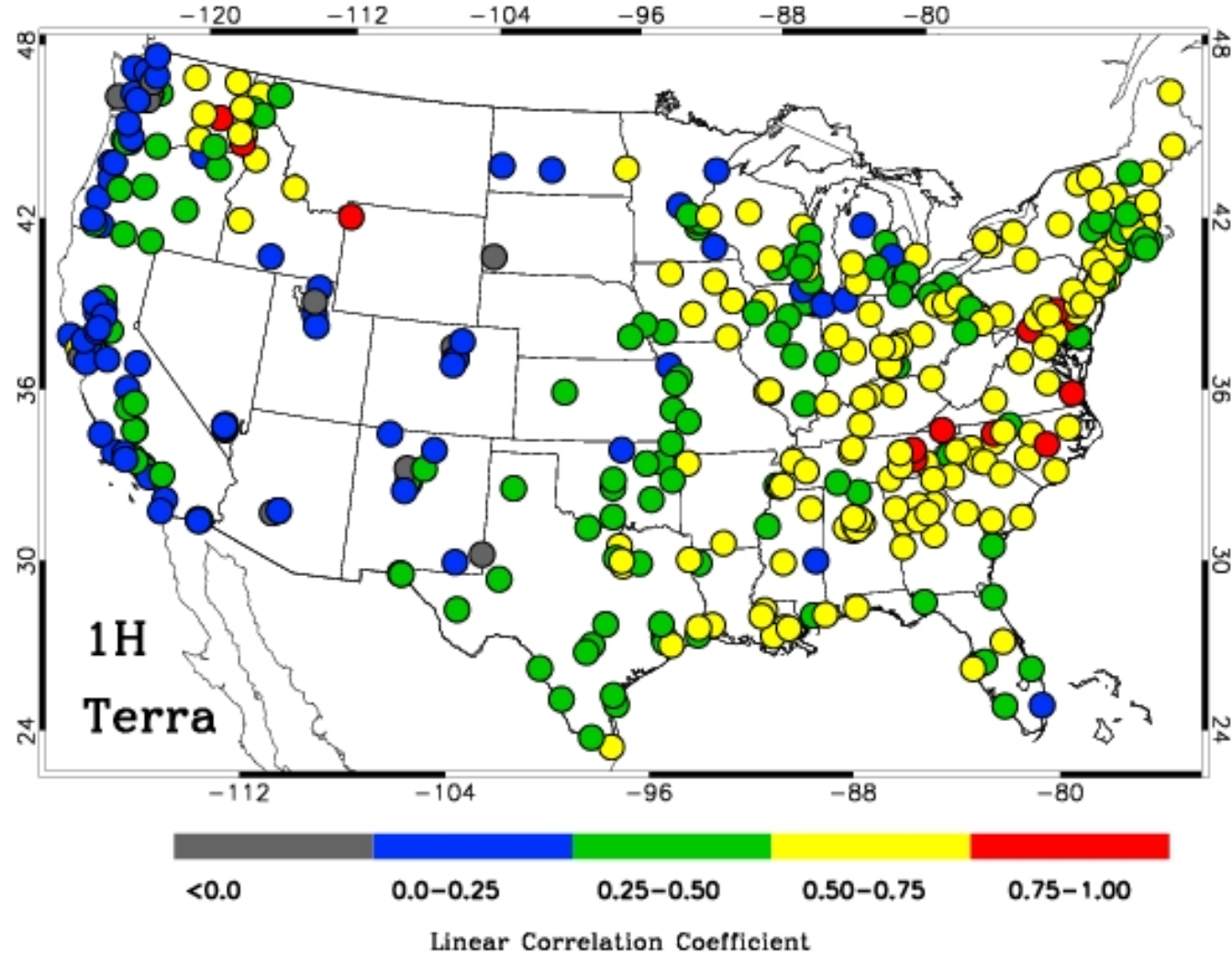
Source: Chu et al., 2003



Source: Wang et al., 2003



AOD-PM_{2.5} Relationship

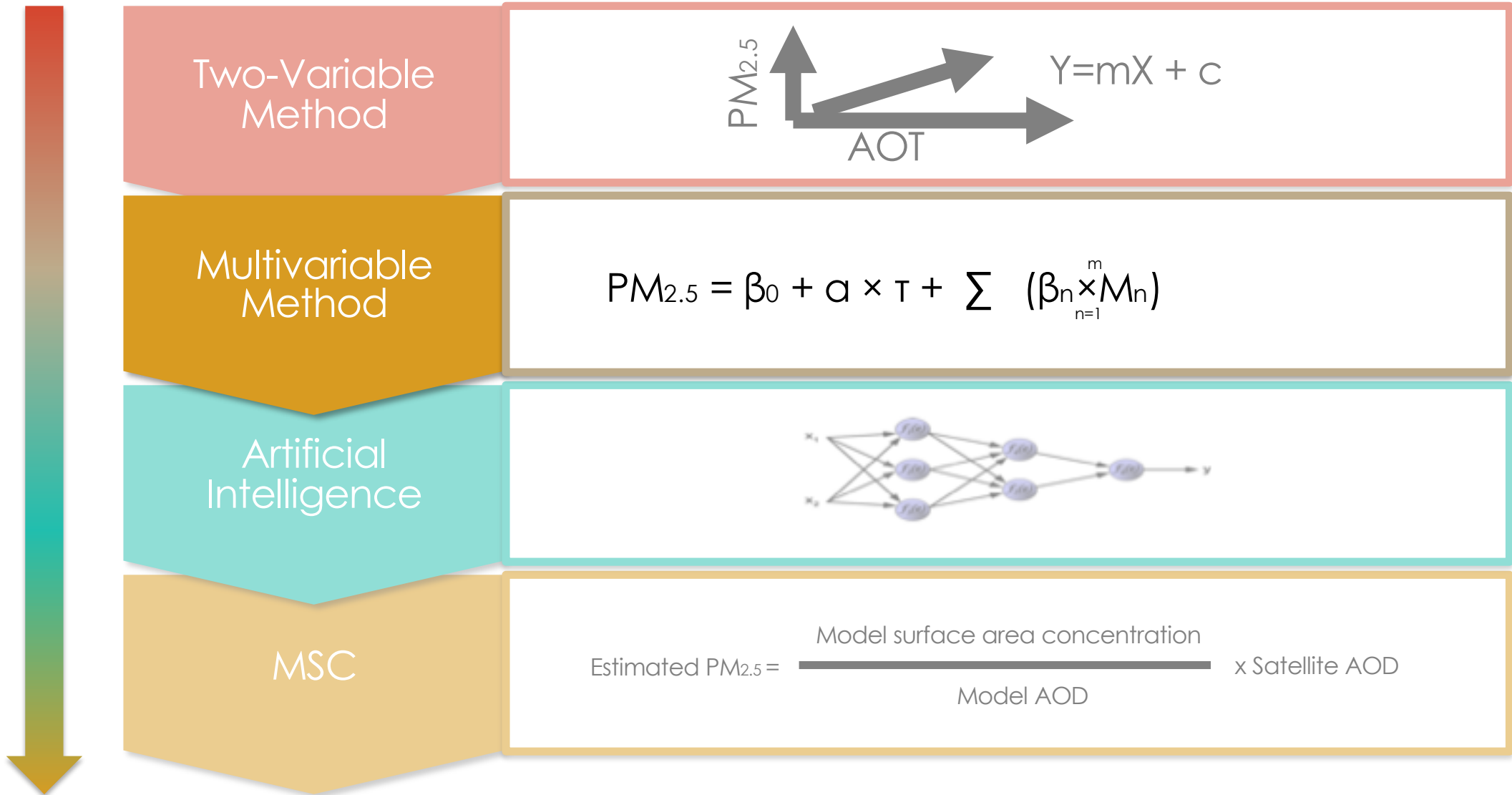


Source: Gupta, 2008



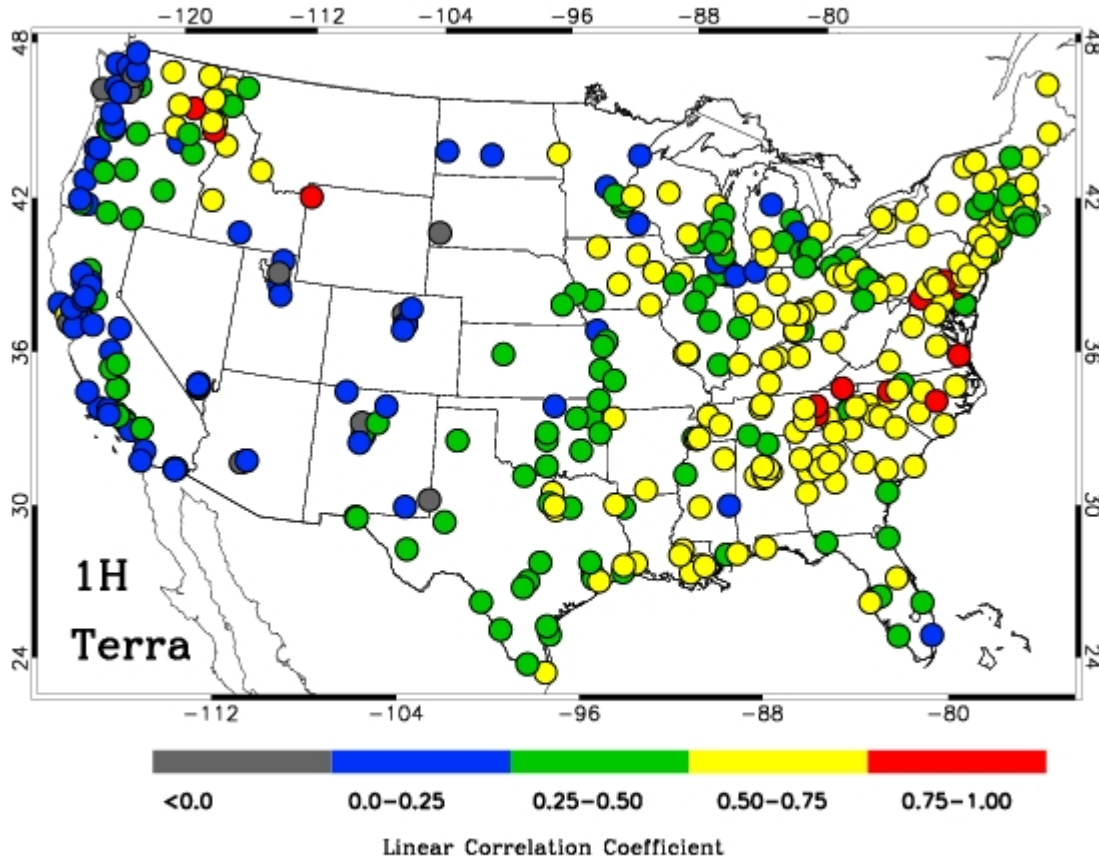
PM_{2.5} Estimation: Multivariable Method (MVM)

Difficulty Level

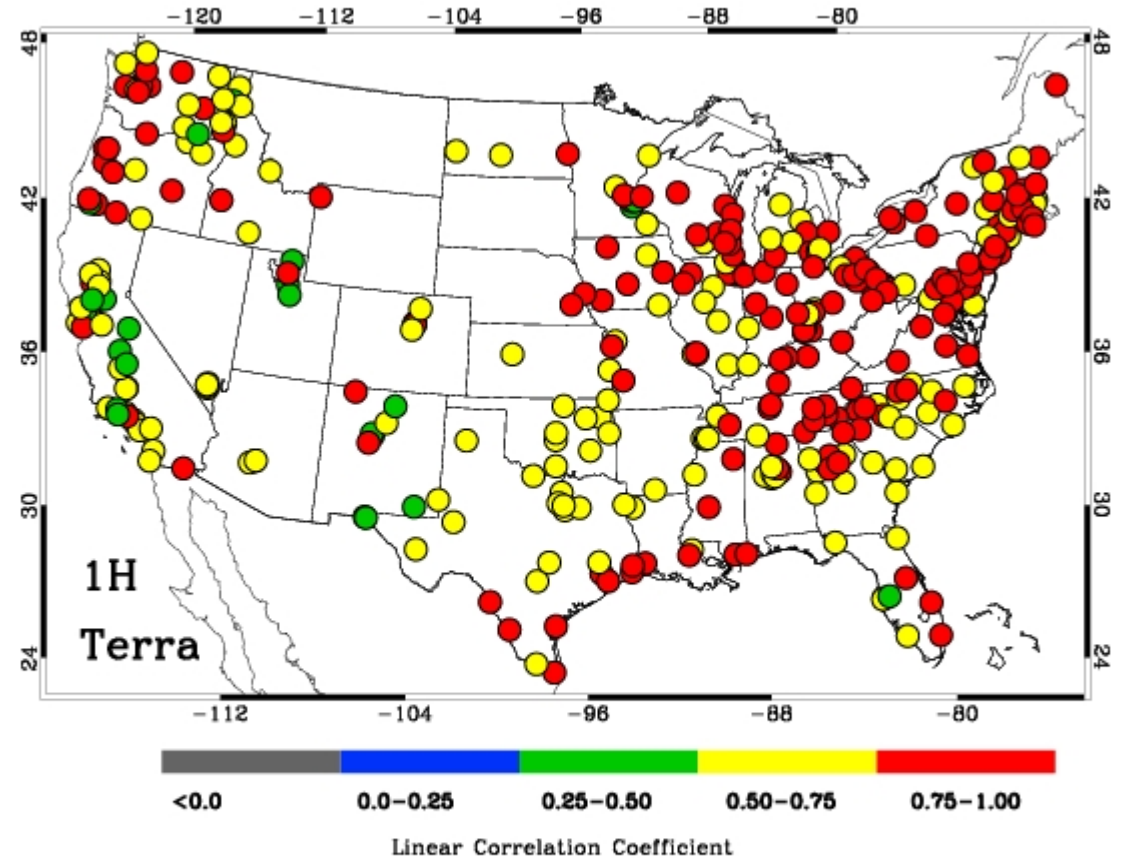


Multivariable Method (MVM)

Predictor: AOD



Predictor: AOD + Meteorology



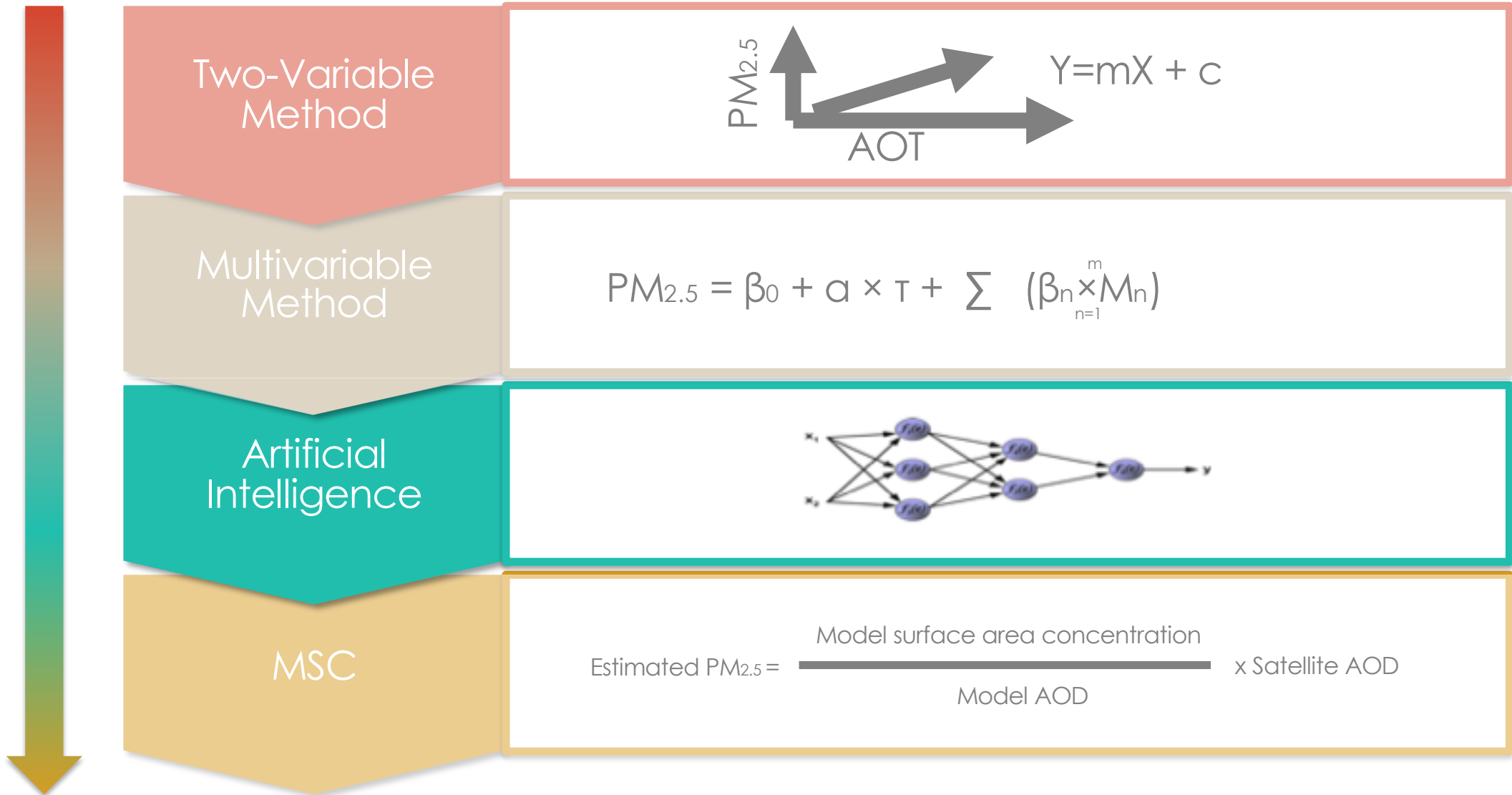
Linear correlation coefficient between observed and estimated PM_{2.5}

Source: Gupta, 2008

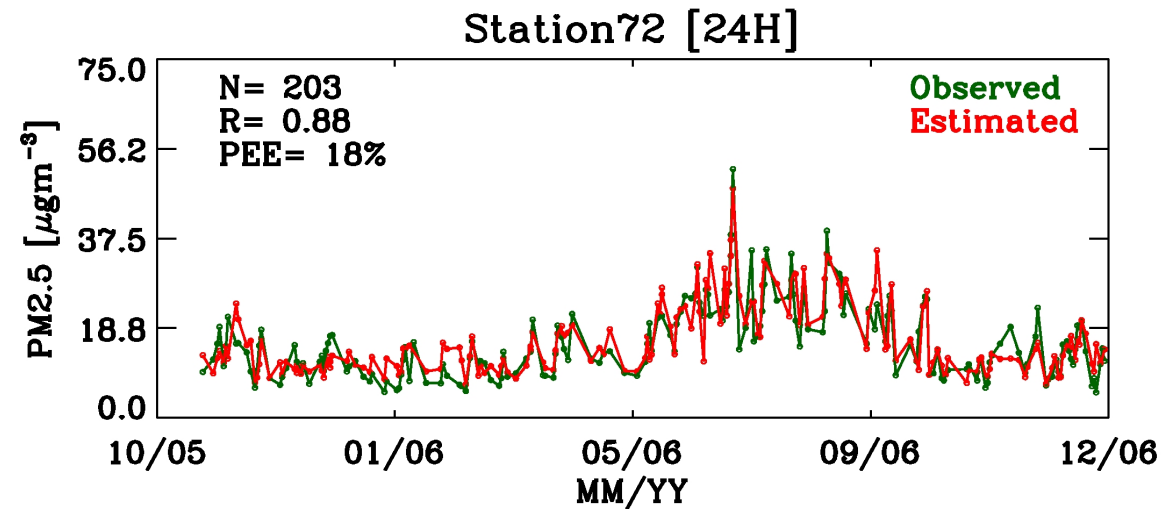
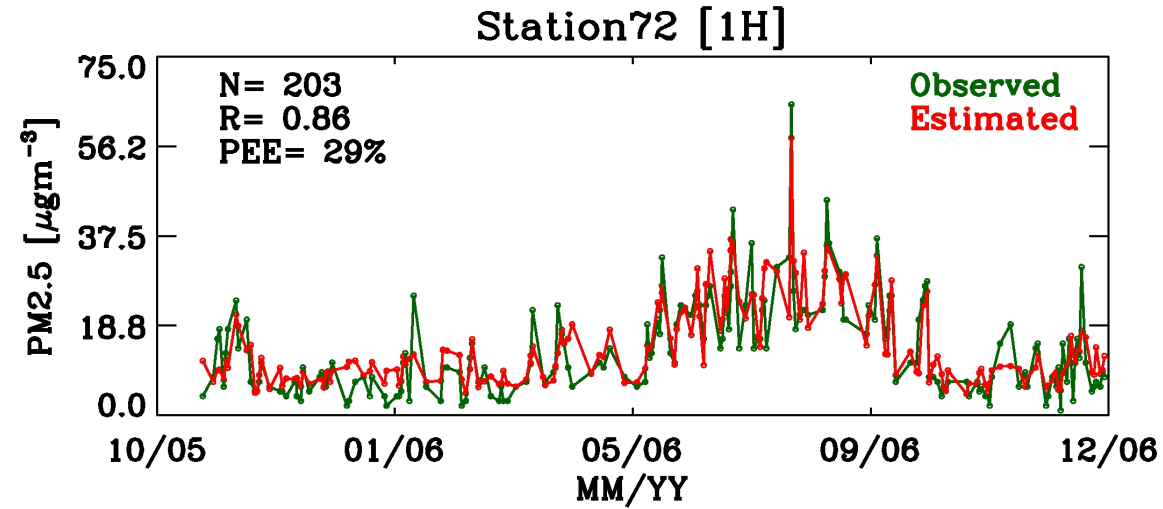


PM_{2.5} Estimation: Artificial Intelligence (or ANN)

Difficulty Level



Time Series Examples of Results from ANN

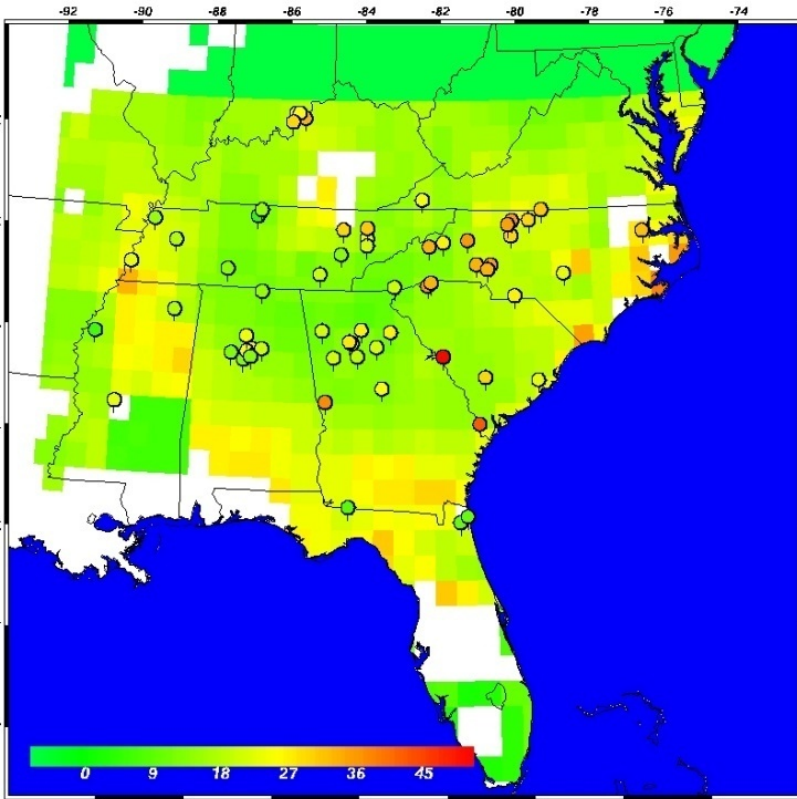


Source: Gupta, 2009

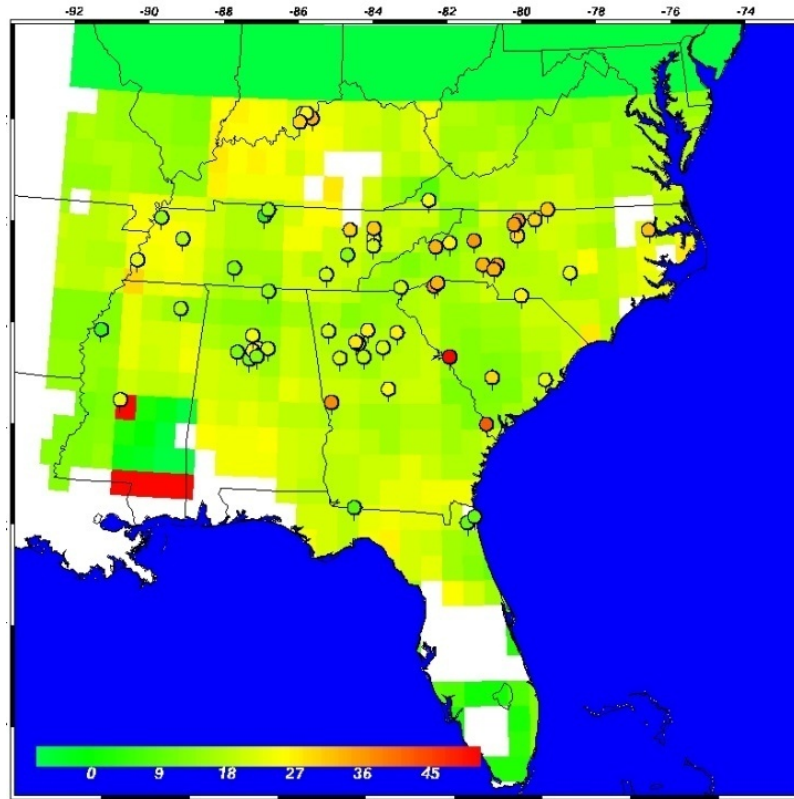


TVM vs. MVM vs. ANN

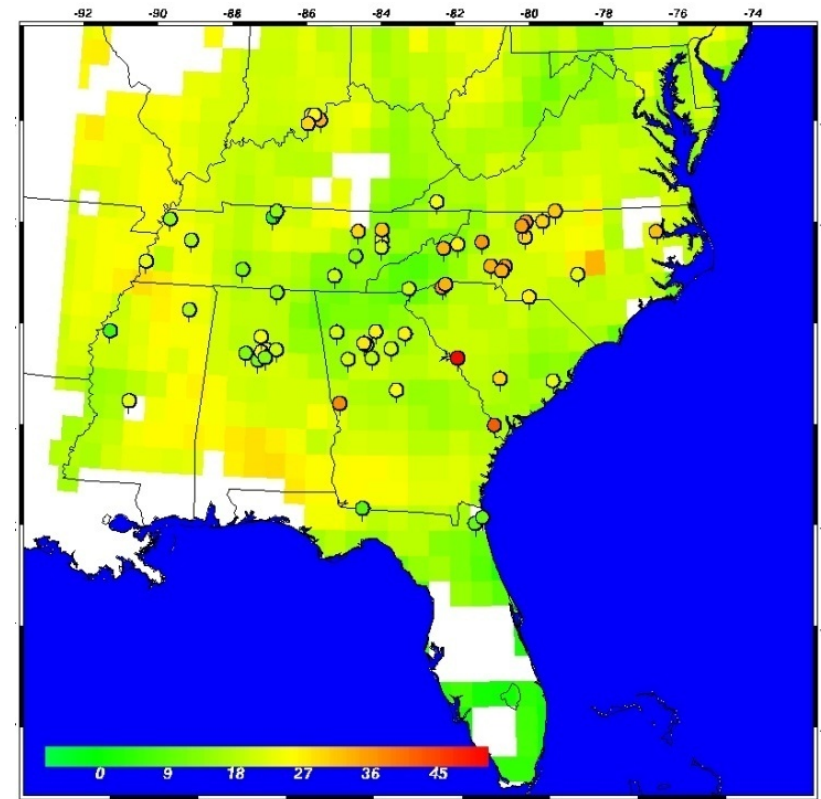
TVM



MVM



ANN



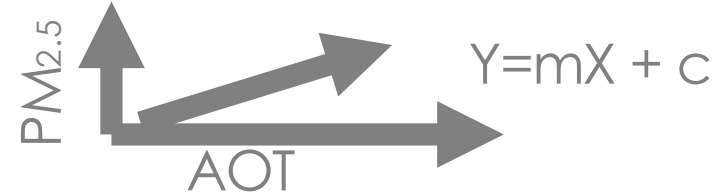
Source: Gupta, 2009



PM_{2.5} Estimation: Model Scaling (MSC)

Difficulty Level

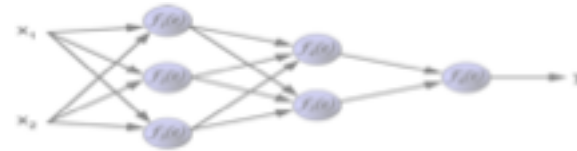
Two-Variable Method



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

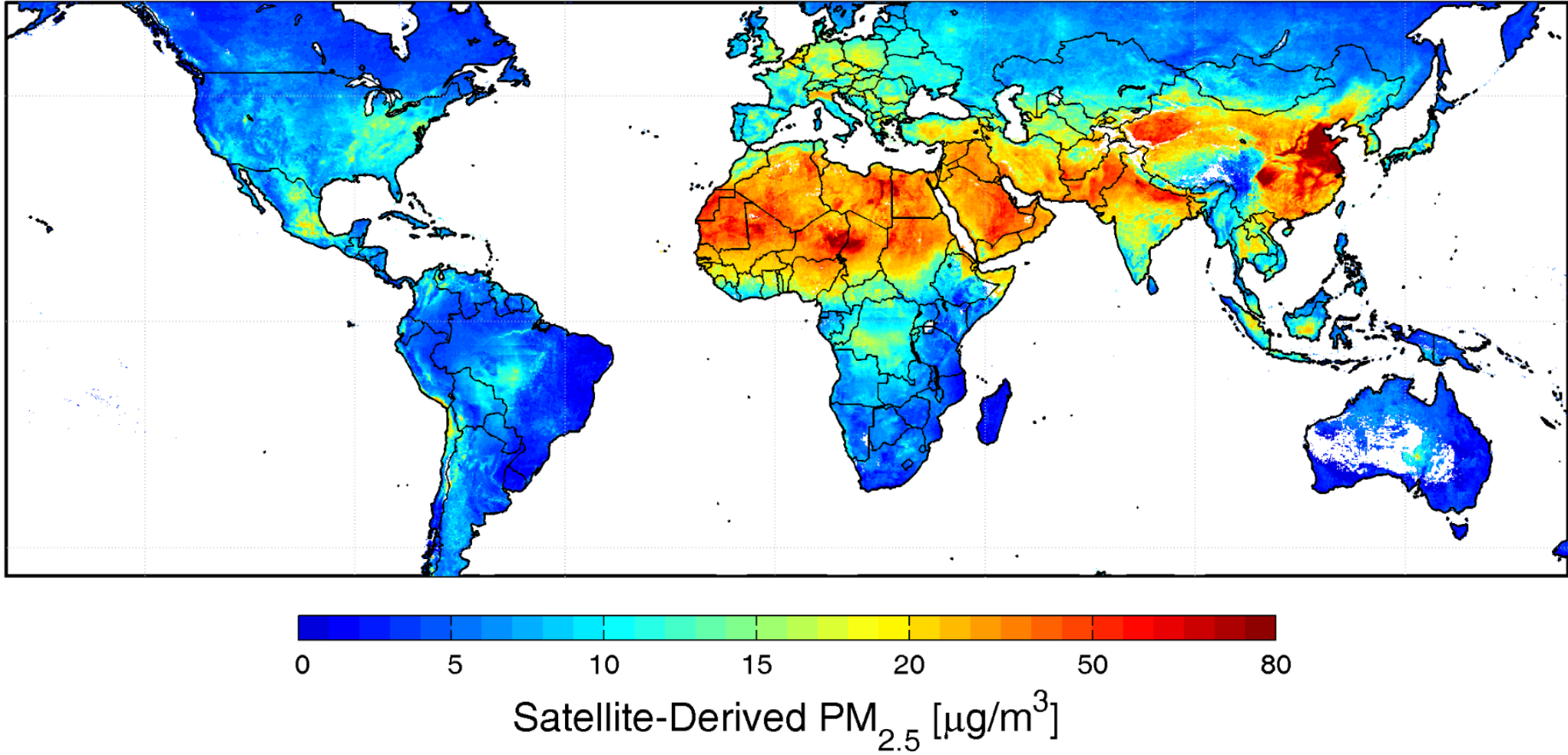
- Basic idea:
 - Let an atmospheric chemistry model decide the conversion from AOD to PM_{2.5}
 - Satellite AOD is used to calibrate the absolute value of the model generated conversion ratio

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

Source: Liu et al., 2006



Annual Mean PM_{2.5} from Satellite Observations



van Donkelaar et al., 2006, 2009

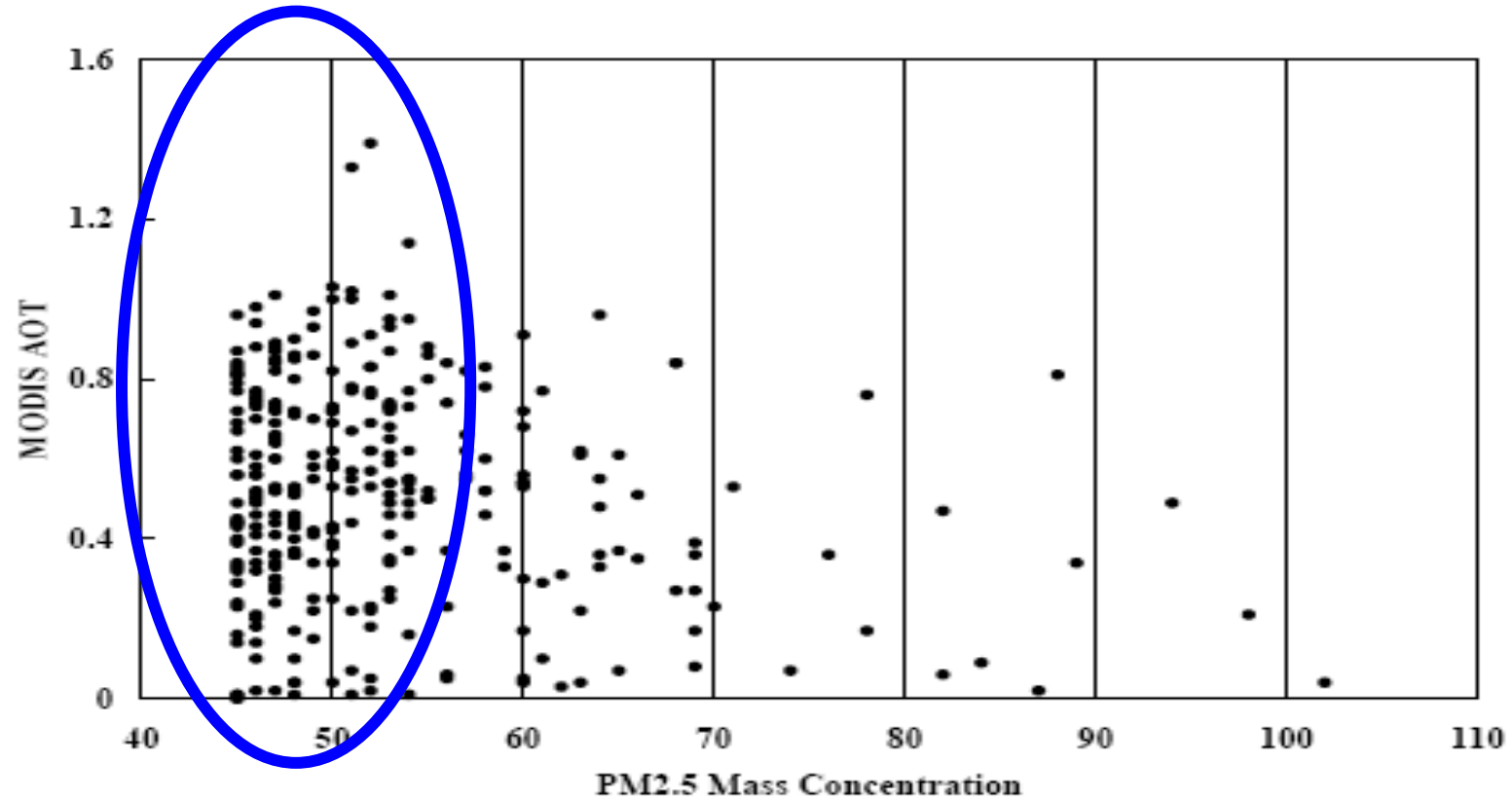


Questions to Ask: Issues

- 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?



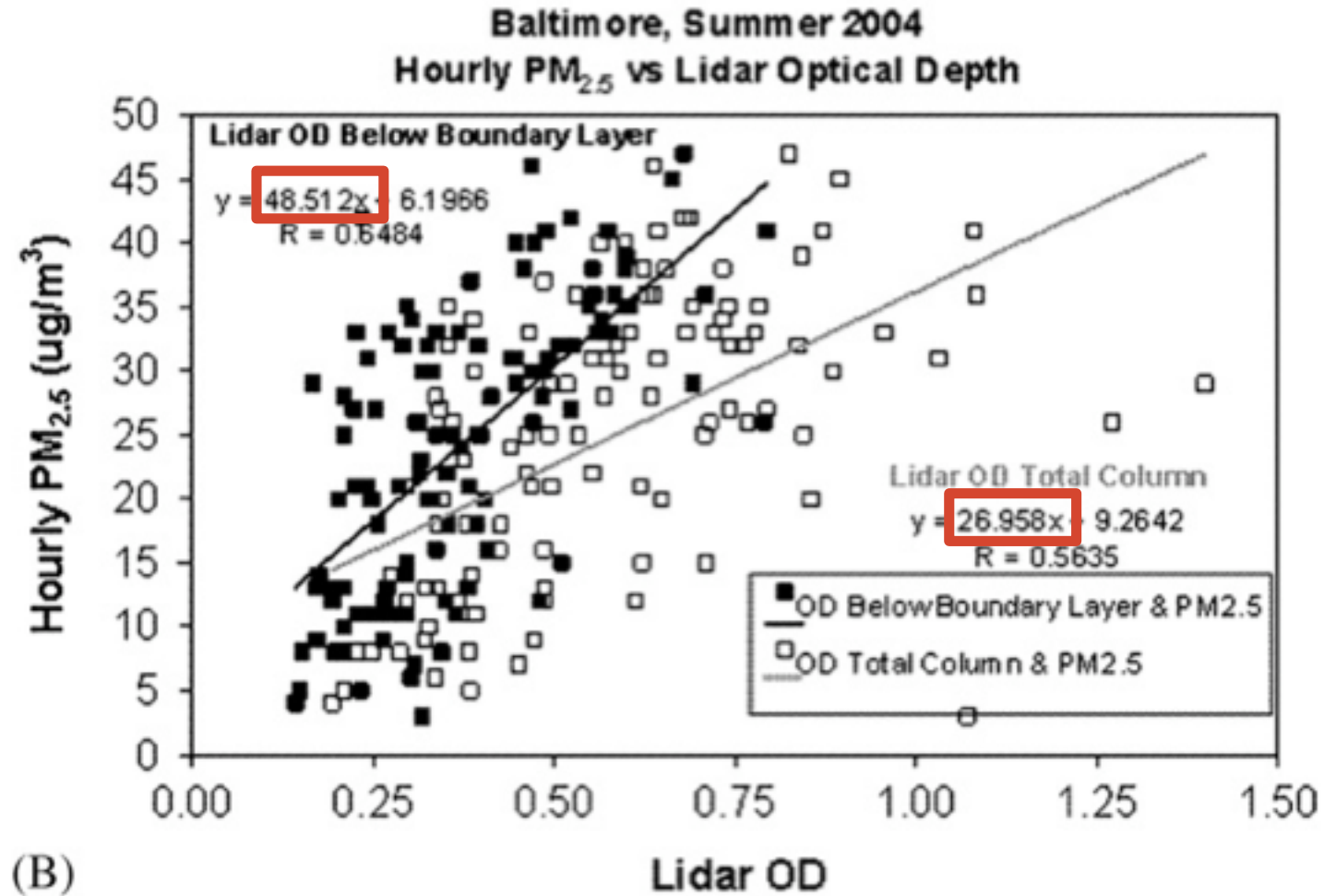
Limitation: Vertical Distribution of Aerosols



Gupta et al., 2009



Vertical Distribution: Impact on AOD-PM_{2.5}

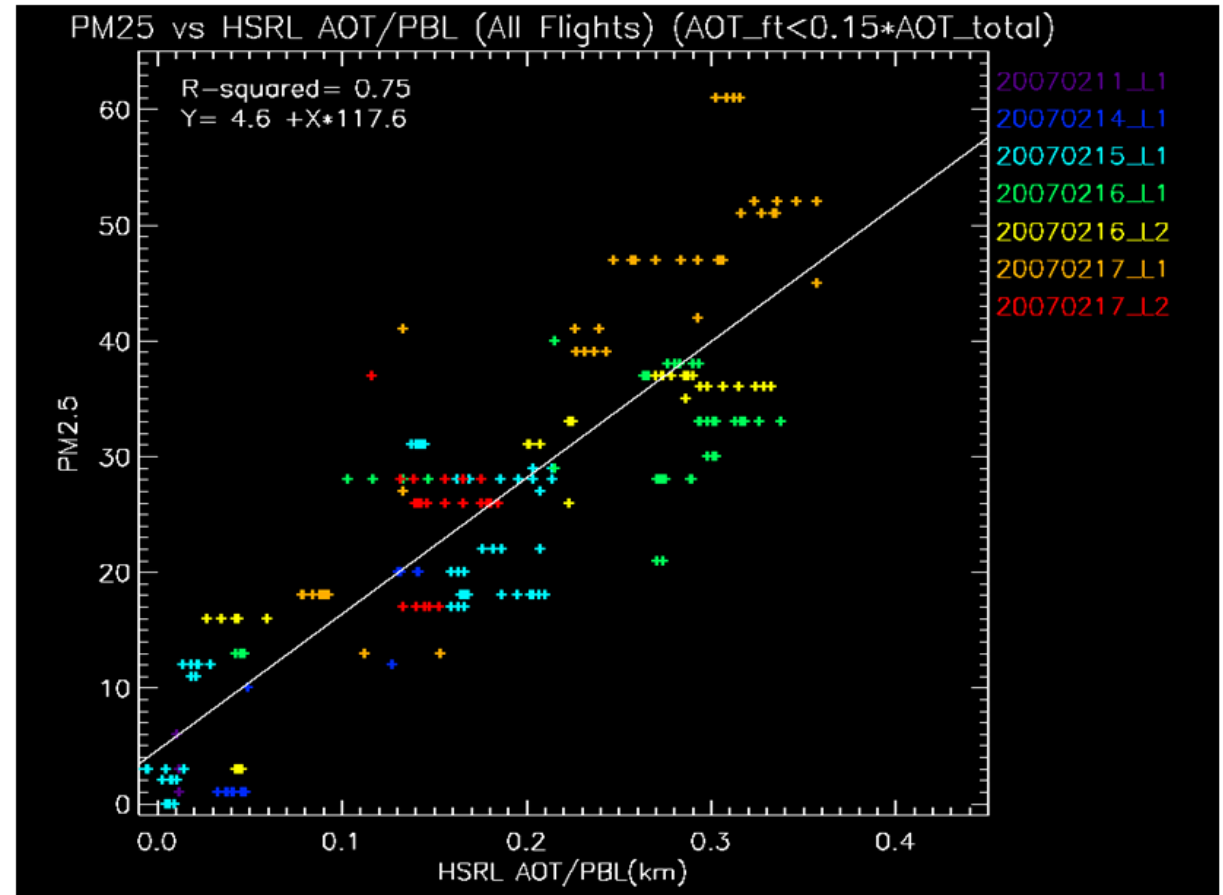


Source: Engel-Cox et al., 2006



Vertical Distribution: Impact on AOD-PM_{2.5}

- Normalizing AOD with boundary layer height significantly improves the correlation with surface PM_{2.5} (R^2 increases from 0.36 to 0.75)
- With accurate estimates of PBL height, AOD can be a good proxy for PM_{2.5}



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 a 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?



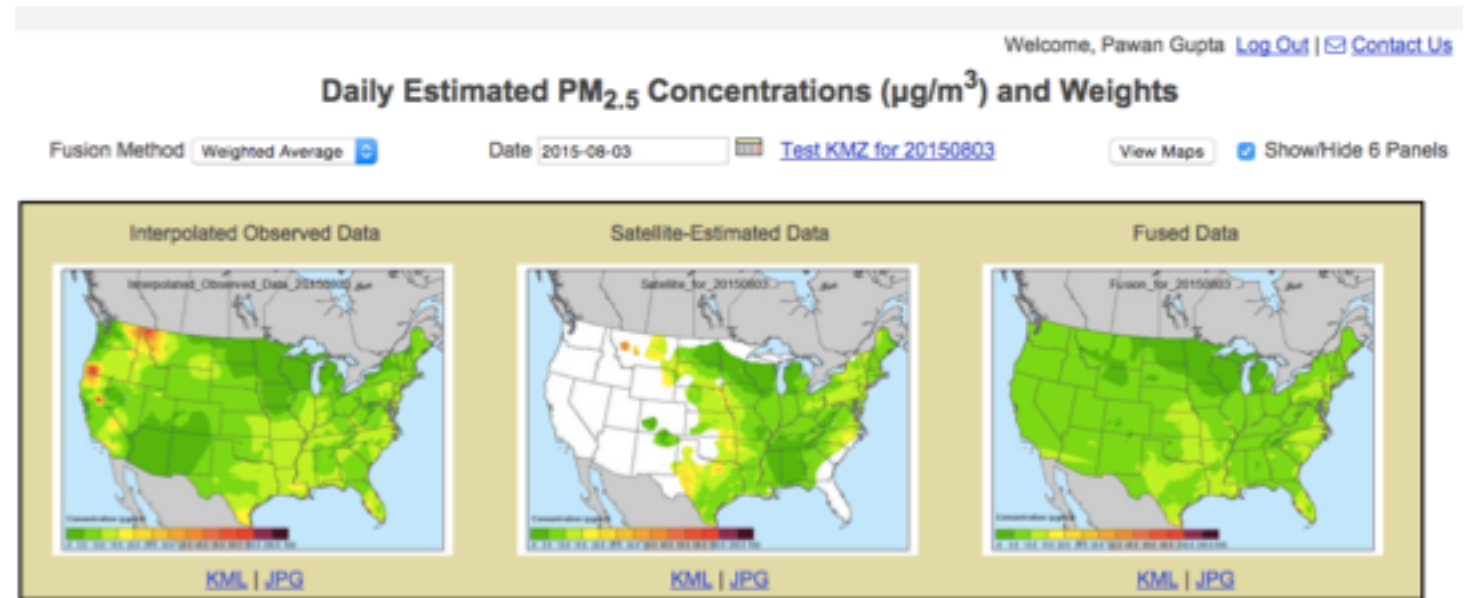
How Satellite Aerosol Data is Used

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_{2.5} 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

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

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).¹⁴² 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 congres-

EPA has taken a satellite observations role for itself in the Exceptional Events Rule.¹⁴⁴ 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_{2.5} Concentration Using Satellite Aerosol Optical Depth

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

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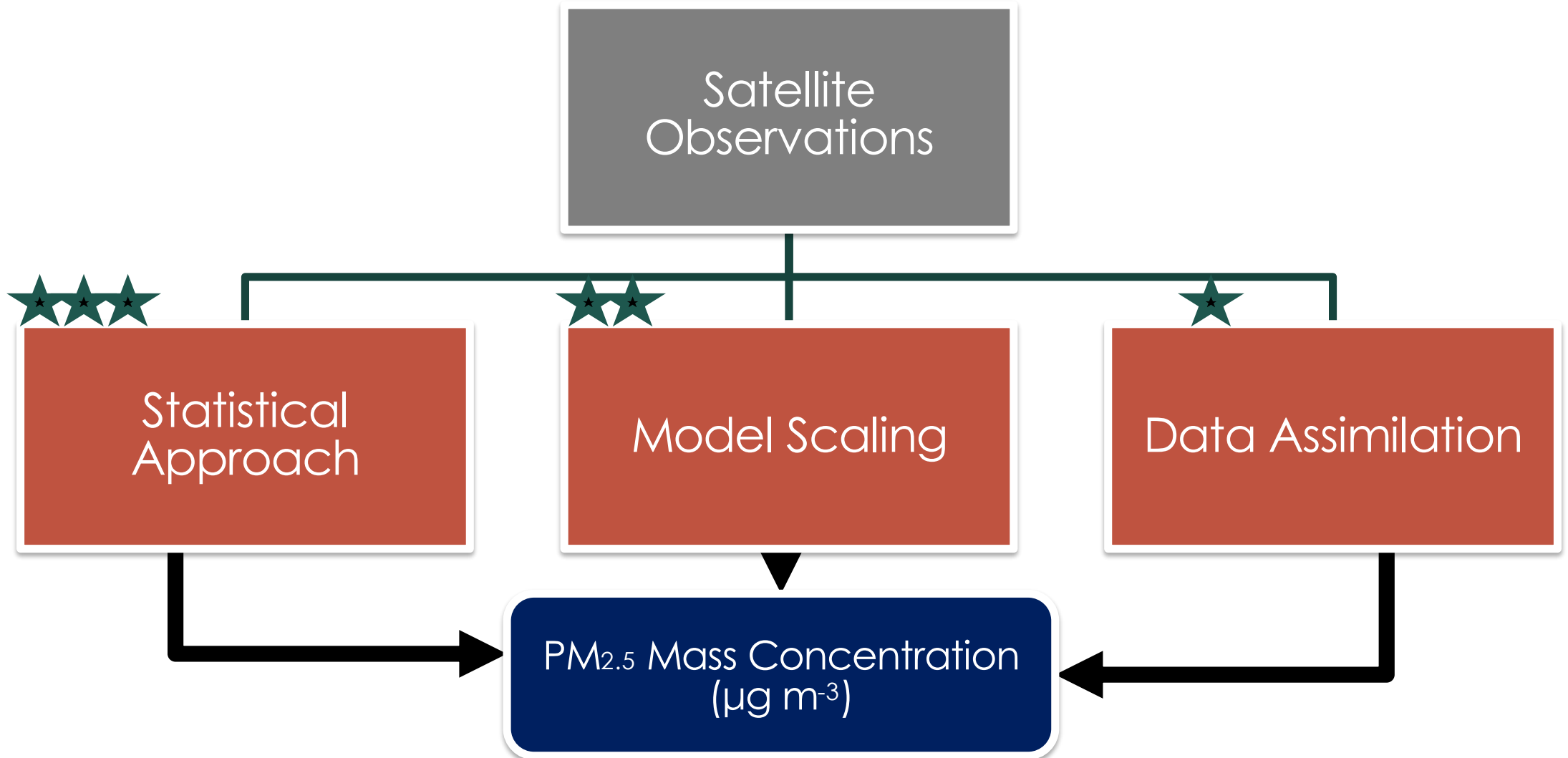


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Satellite Remote Sensing of PM_{2.5}: Summary



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?

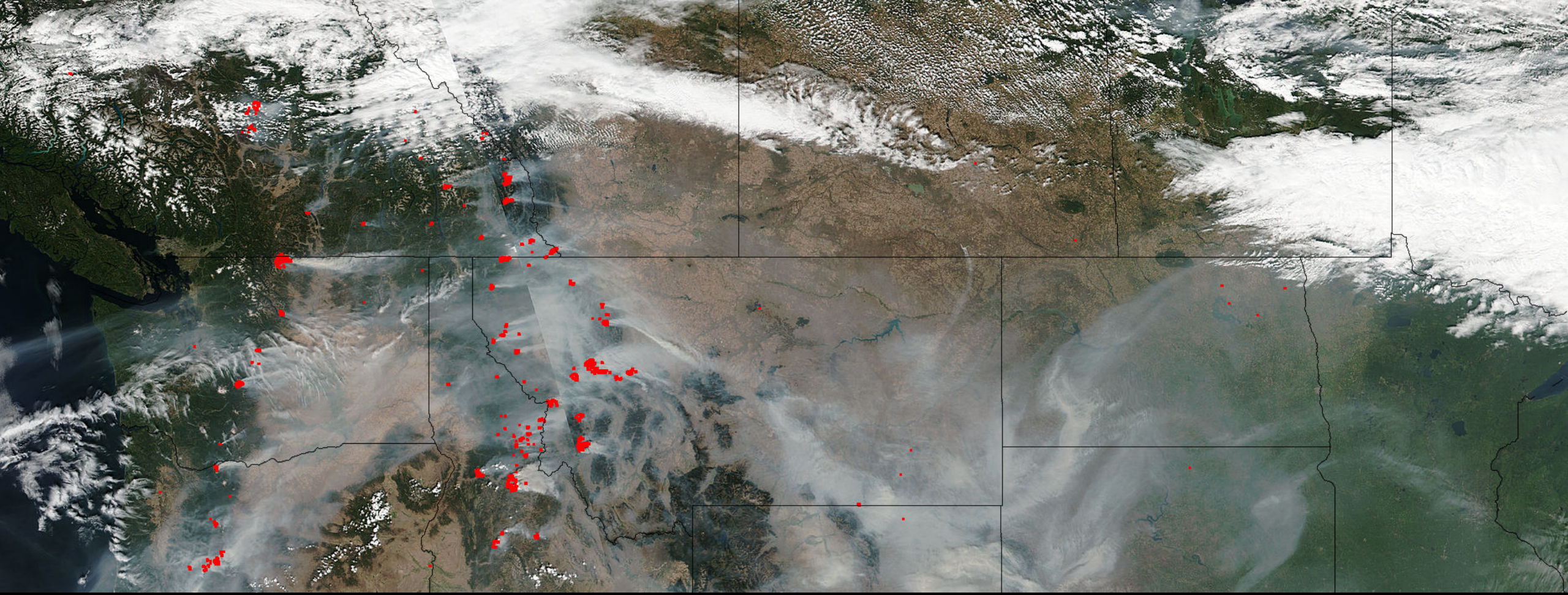


Tour of IDEA

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/aa/>
 - eIDEA: <http://www.star.nesdis.noaa.gov/smcd/spb/aa/eidea/>





Questions