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

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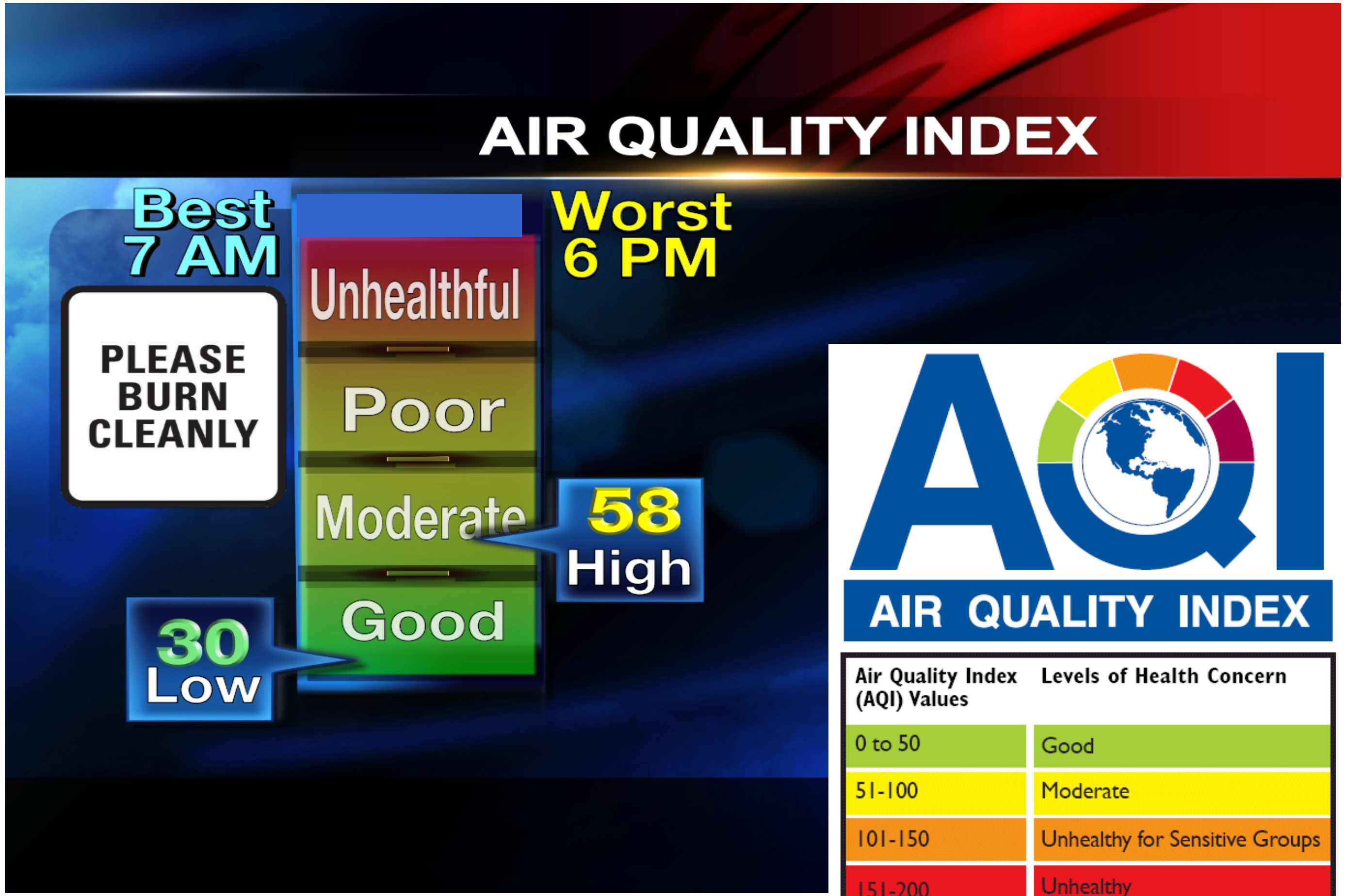
Satellite Remote Sensing of Air Quality, 18-19 November 2018

Objectives

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

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

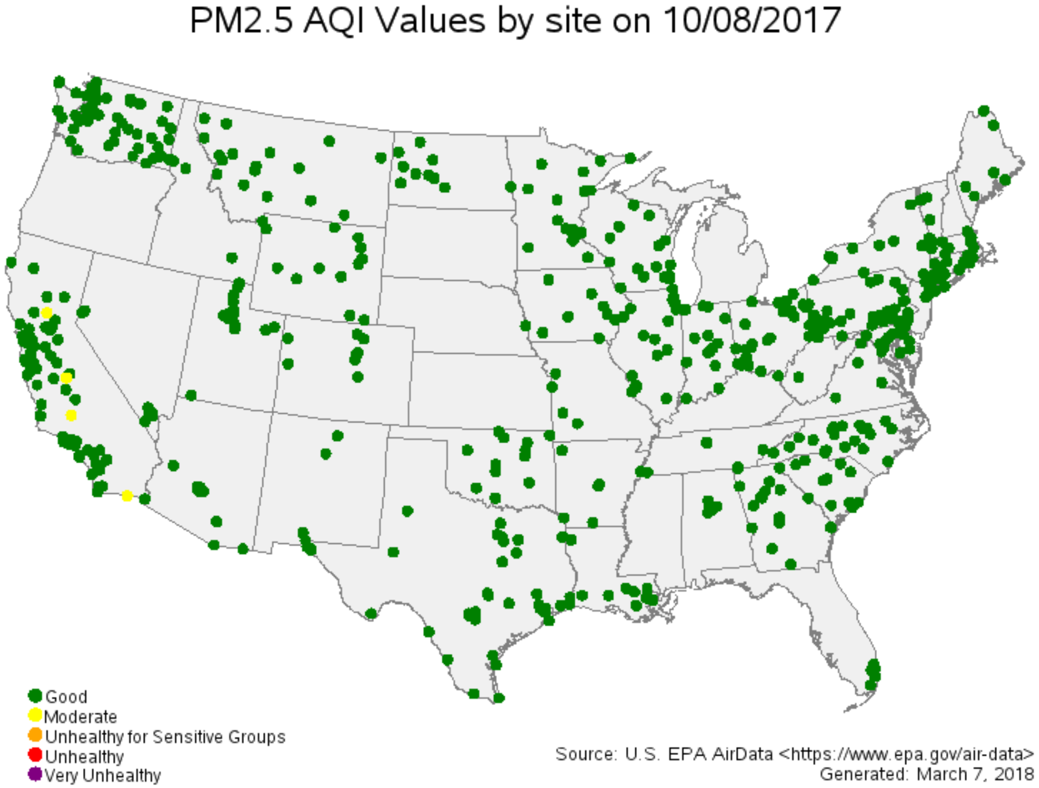
Air Quality Monitoring and Reporting



Air Quality Index (AQI) Values	Levels of Health Concern
0 to 50	Good
51-100	Moderate
101-150	Unhealthy for Sensitive Groups
151-200	Unhealthy
201-300	Very Unhealthy
301 to 500	Hazardous

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

Spatial Gaps



Inferring AOD and PM2.5 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 PM2.5 from Visuals

Singapore

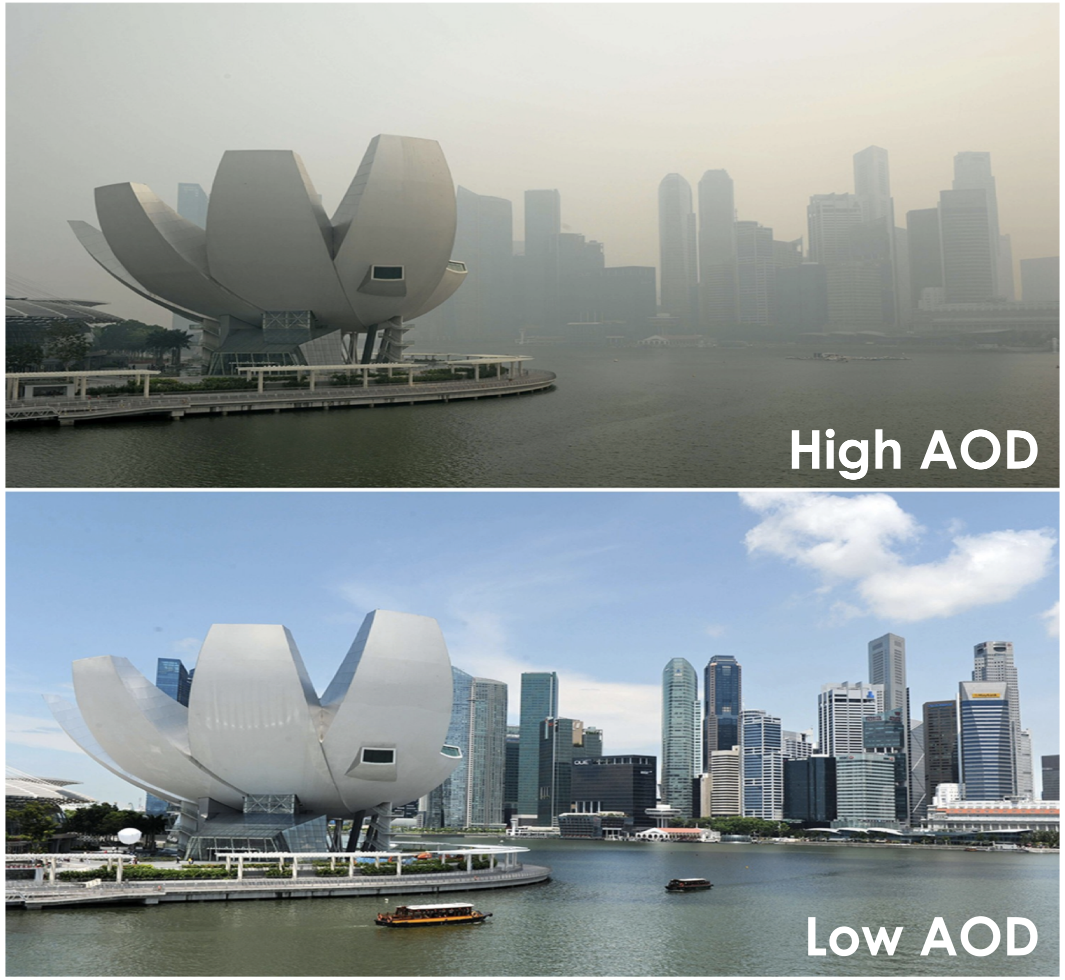
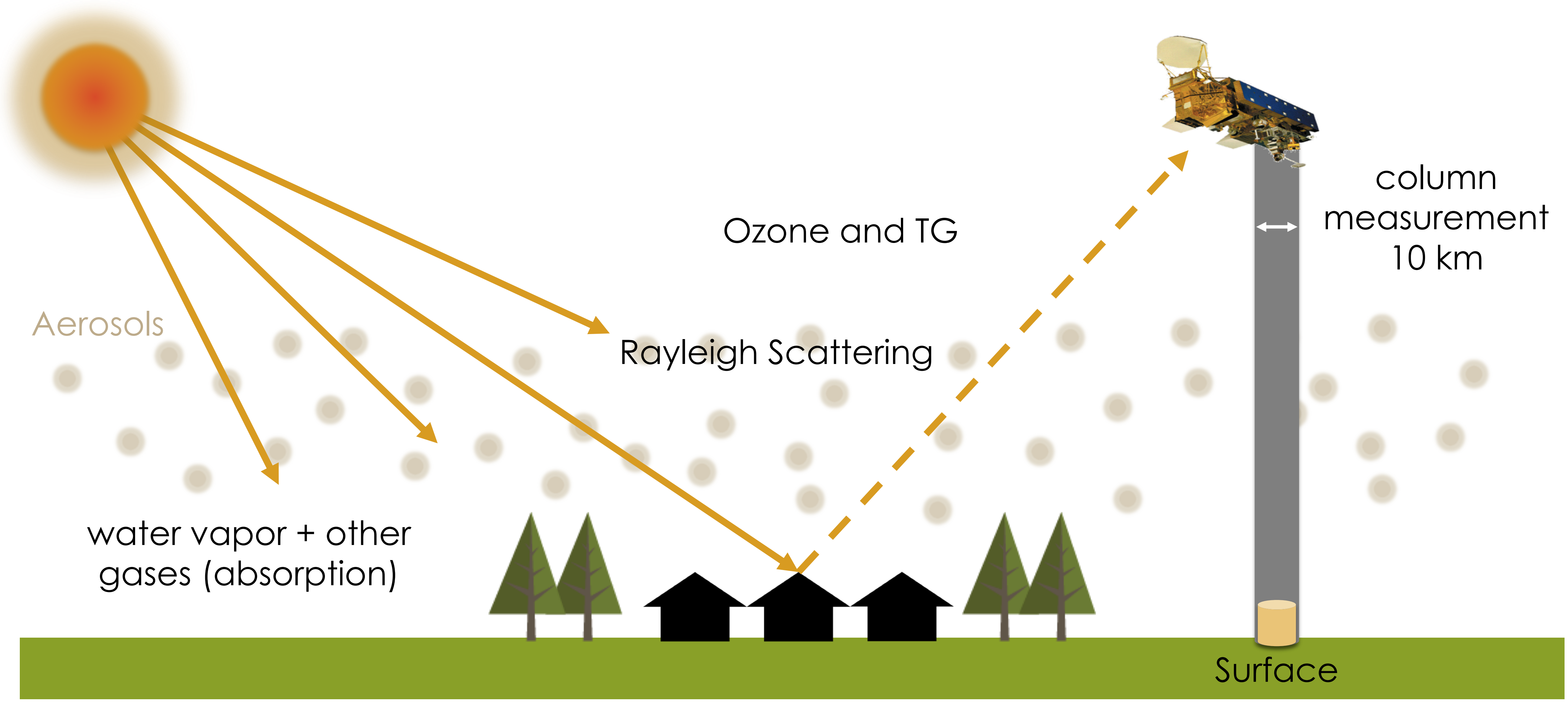


Image Credit: Roslan Rahman/AFP/Getty Images

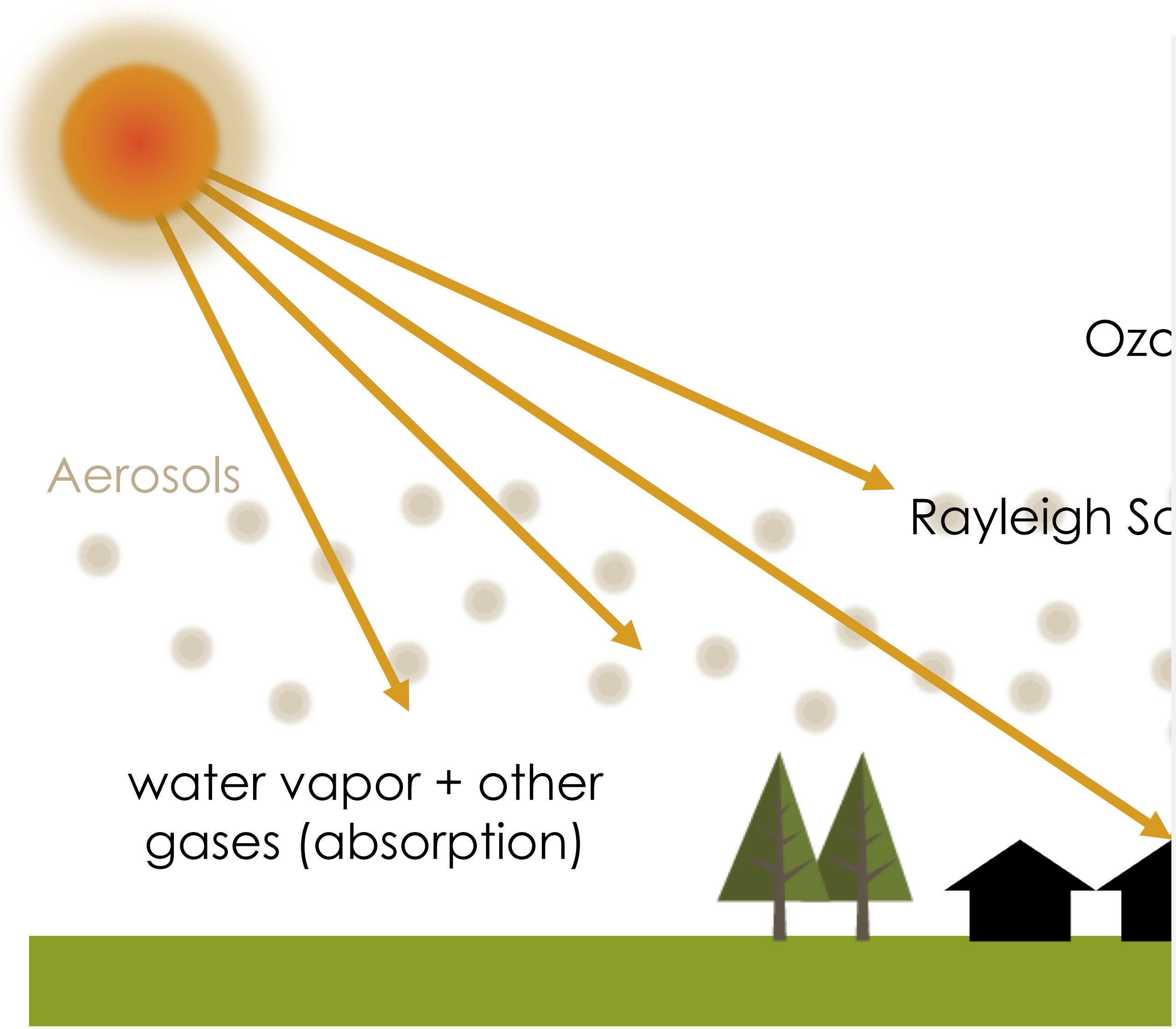
Surface vs. Satellite Measurements

AOD (or AOT) to PM

Aerosol Optical Depth from Satellites



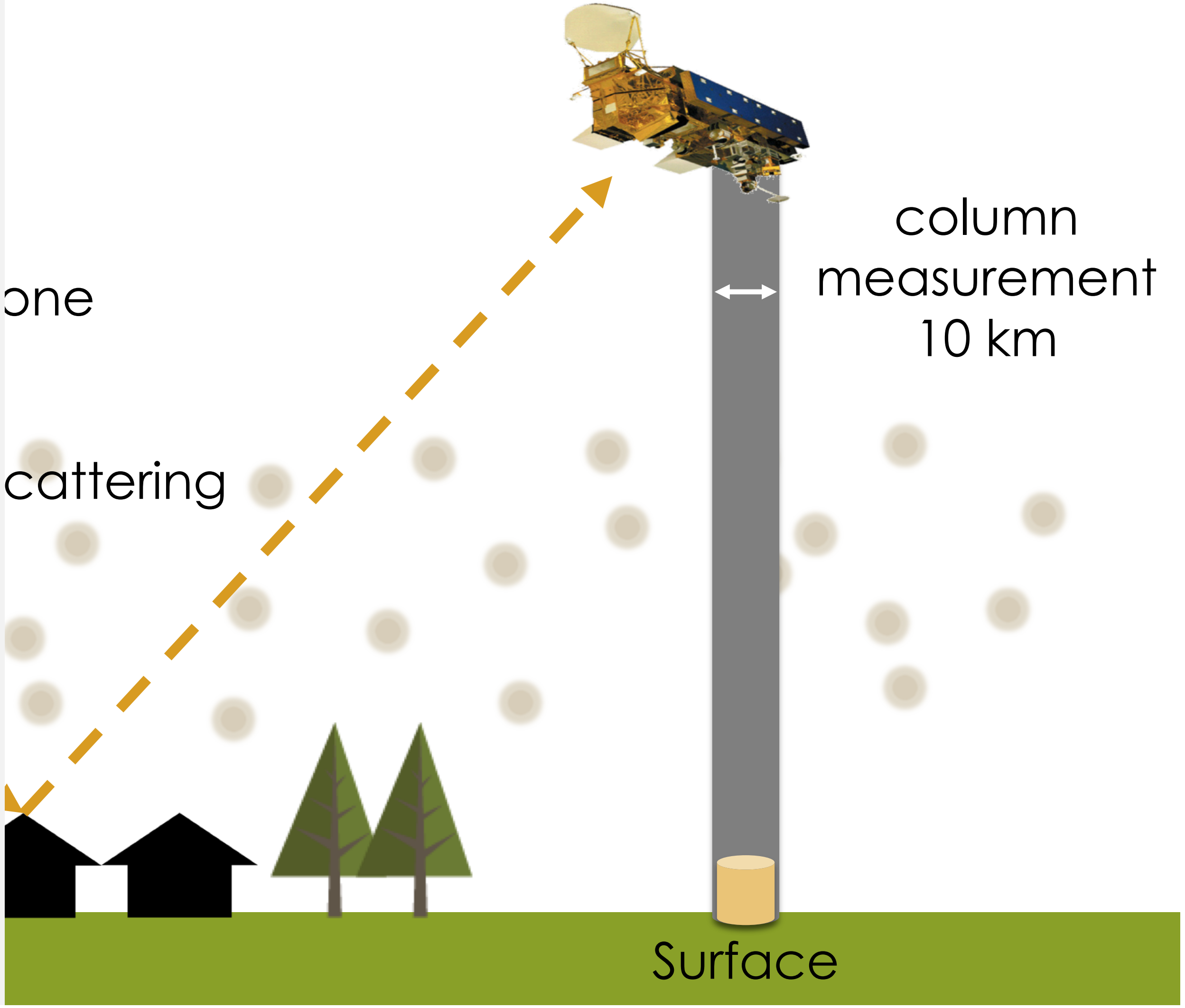
Aerosol Optical Depth from Satellites



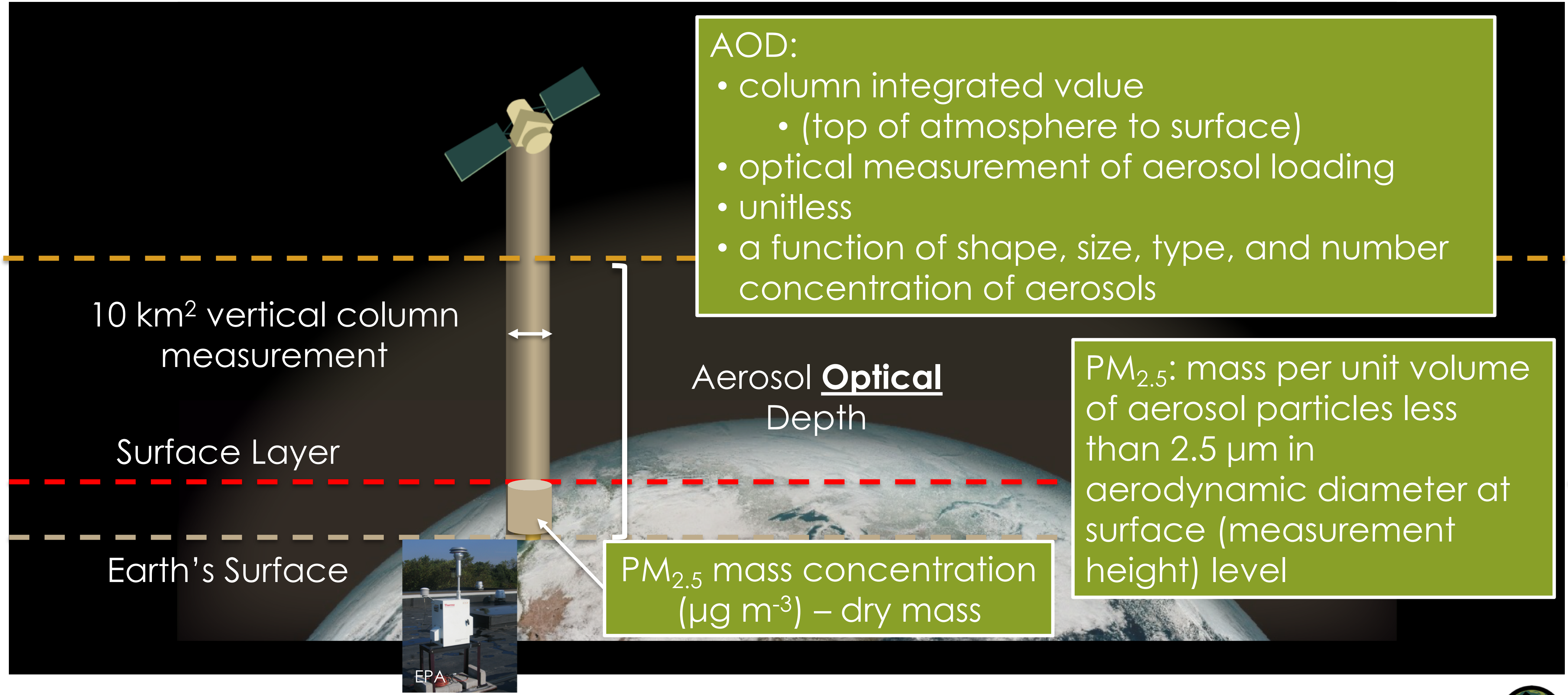
- AOT(τ)= $\int \beta_{ext}\, dz$
  - particle size
  - composition
  - water update
  - vertical distribution
- There are satellite retrieval issues: inversion (e.g. aerosol model, background)

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 km^2 resolution
- 3x3 km^2 resolution
- 1x1 km^2 resolution



Satellite vs. Ground Observation



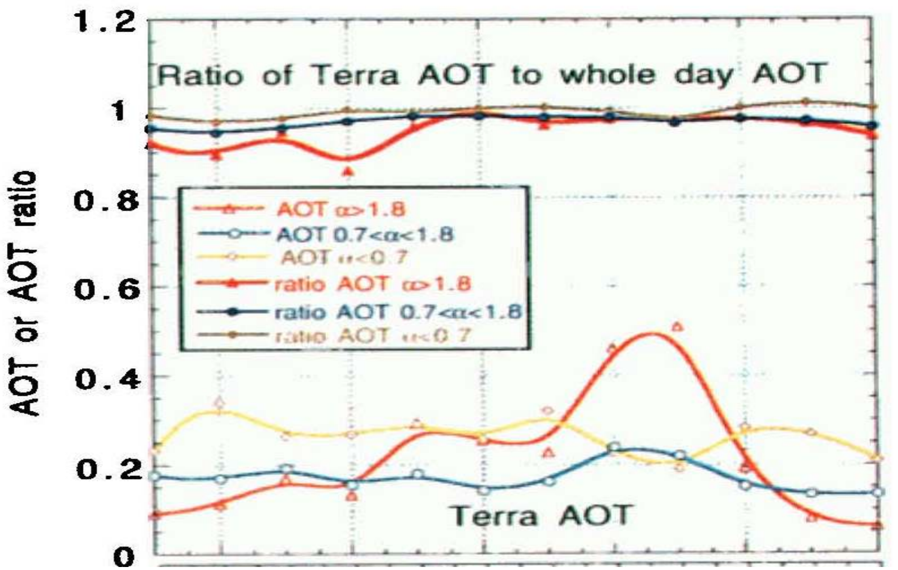
AOD:
- column integrated value
  - (top of atmosphere to surface)
- optical measurement of aerosol loading
- unitless
- a function of shape, size, type, and number concentration of aerosols

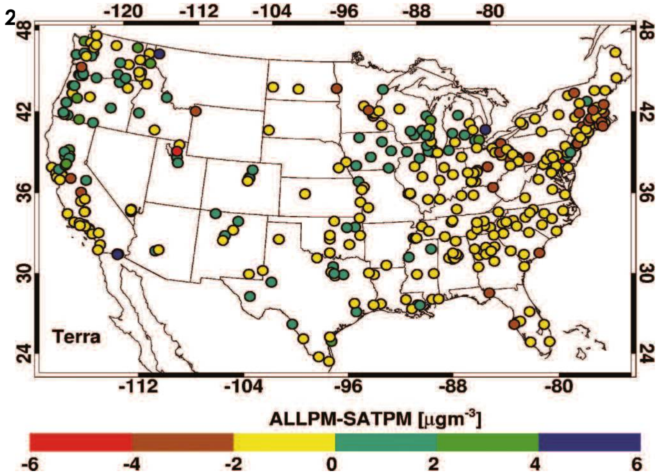
$PM_{2.5}$ mass concentration ($\mu g\ m^{-3}$) – dry mass

$PM_{2.5}$: mass per unit volume of aerosol particles less than 2.5 μm in aerodynamic diameter at surface (measurement height) level

Support for AOD-$PM_{2.5}$ Linkage

- Satellite AOD is sensitive to $PM_{2.5}$
  - Kahn et al. 1998
- Polar-orbing 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:

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

- τ: AOD at 550 nm
- ρ: aerosol mass density
- r_e: particle effective radius
- Q: extinction coefficient
- H: mixing height
- *ƒ(RH)*: how aerosol scattering changes with changing relative humidity

Hoff, R. & Christopher, S., 2009

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

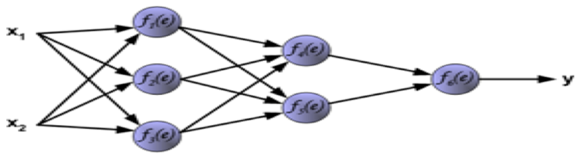
Two Variable Method

$Y = mX + c$

Multivariable Method

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

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

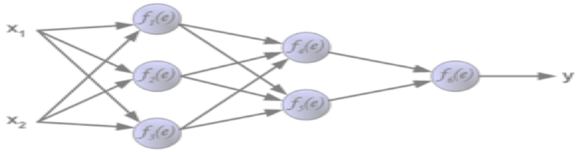
Two Variable Method

$$Y = mX + c$$

Multivariable Method

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

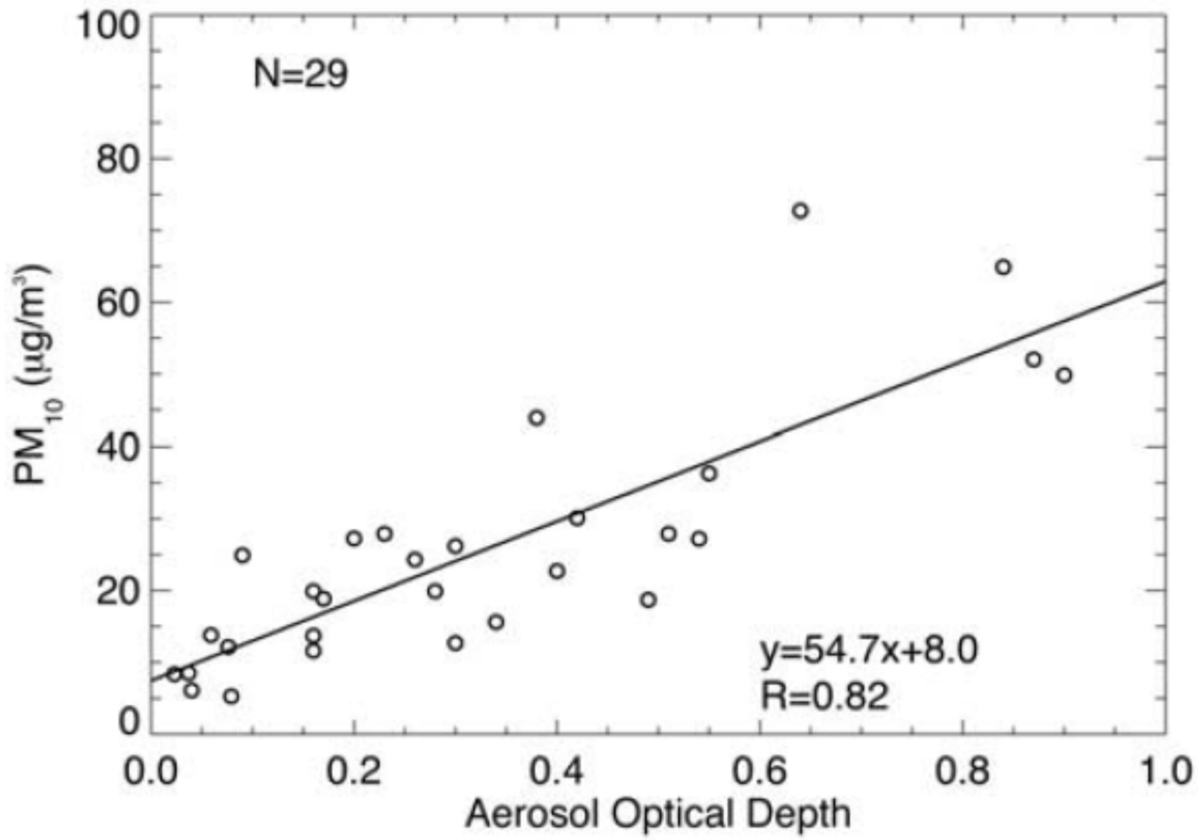
Artificial Intelligence

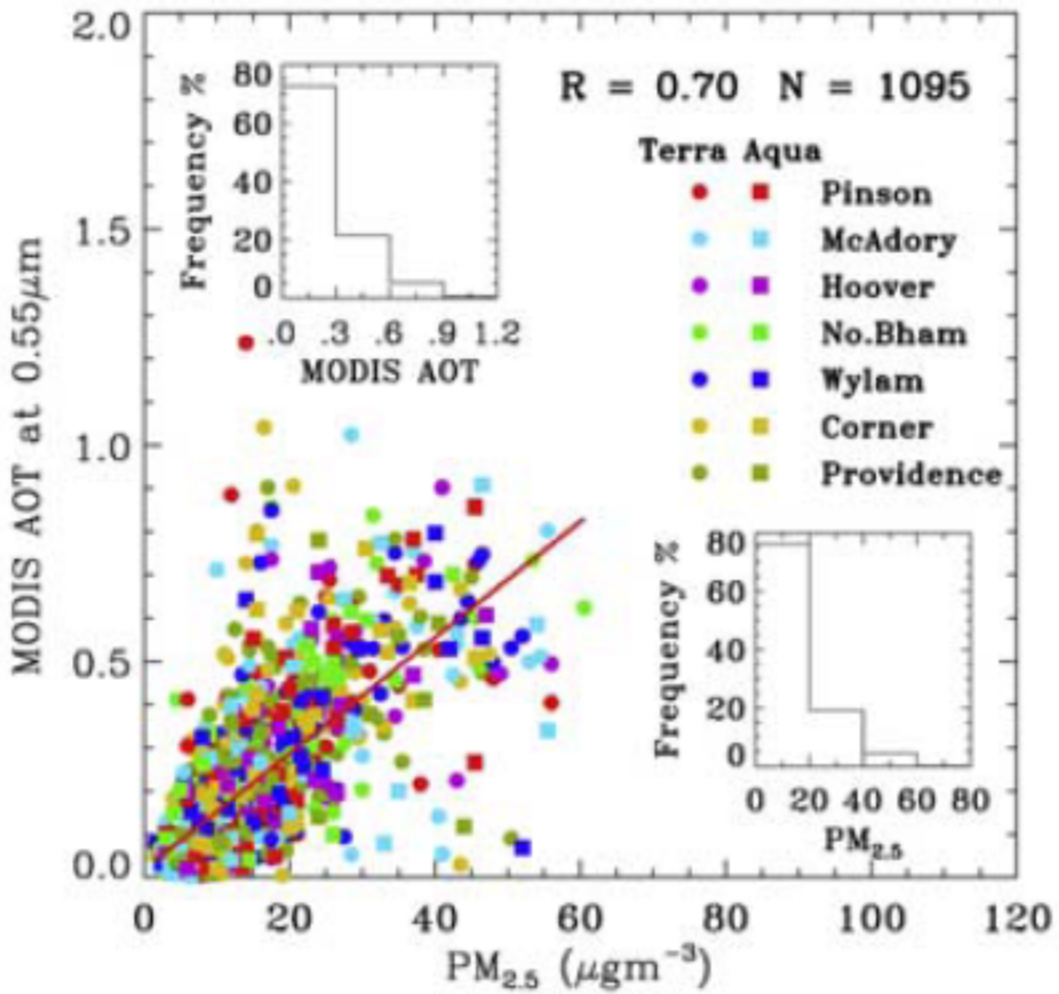


MSC

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

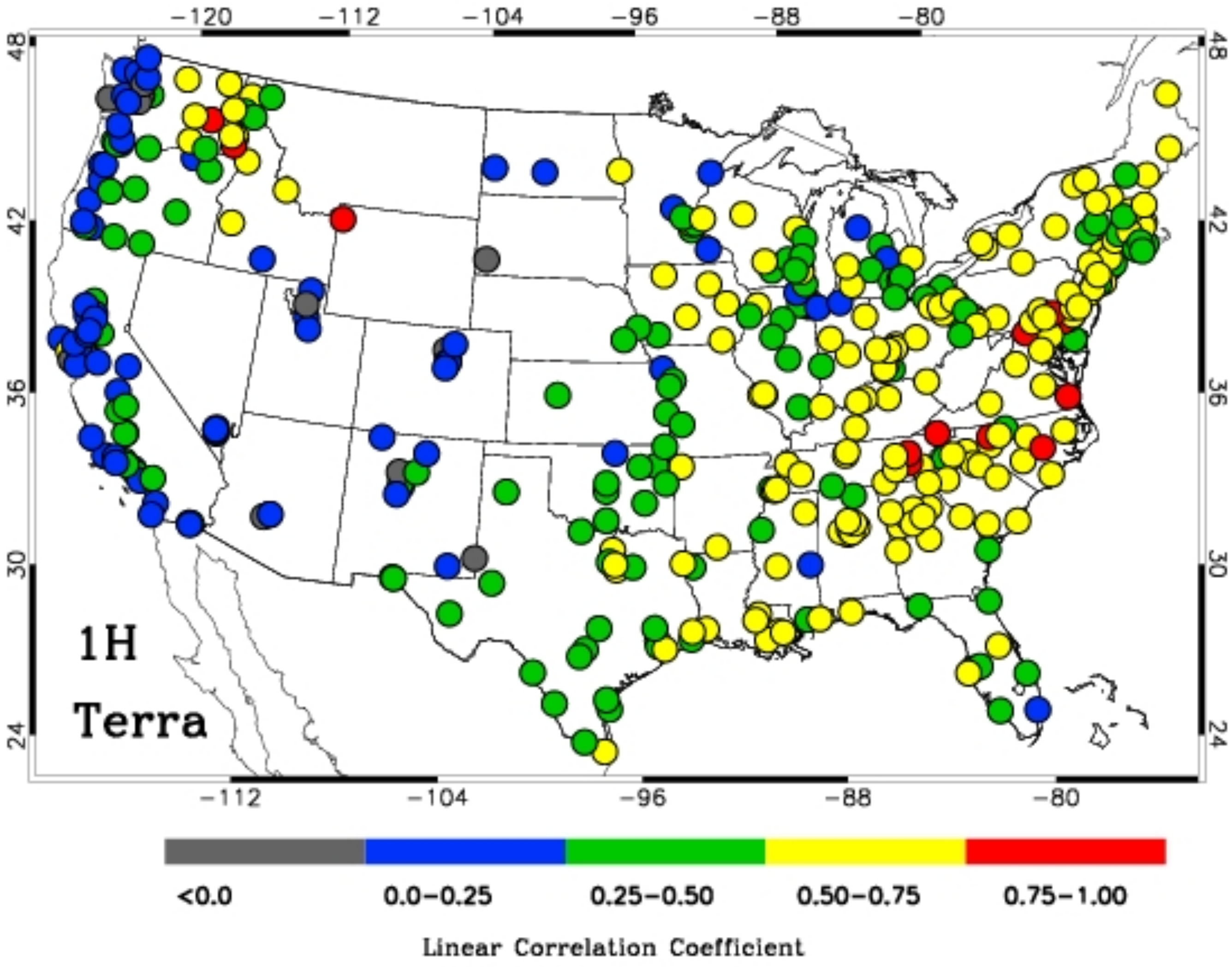
Simple Models from Early Days





Source (left): Chu et al., 2003; (right) Wang et al., 2003

AOD-$PM_{2.5}$ Relationship



Source: Gupta, 2008

$PM_{2.5}$ Estimation: Multivariable Method (MVM)

Difficulty Level

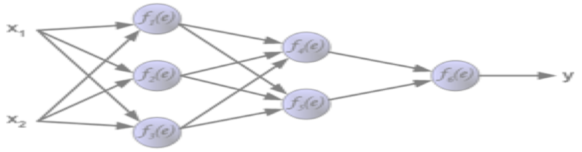
Two Variable Method

$Y = mX + c$

Multivariable Method

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

Artificial Intelligence

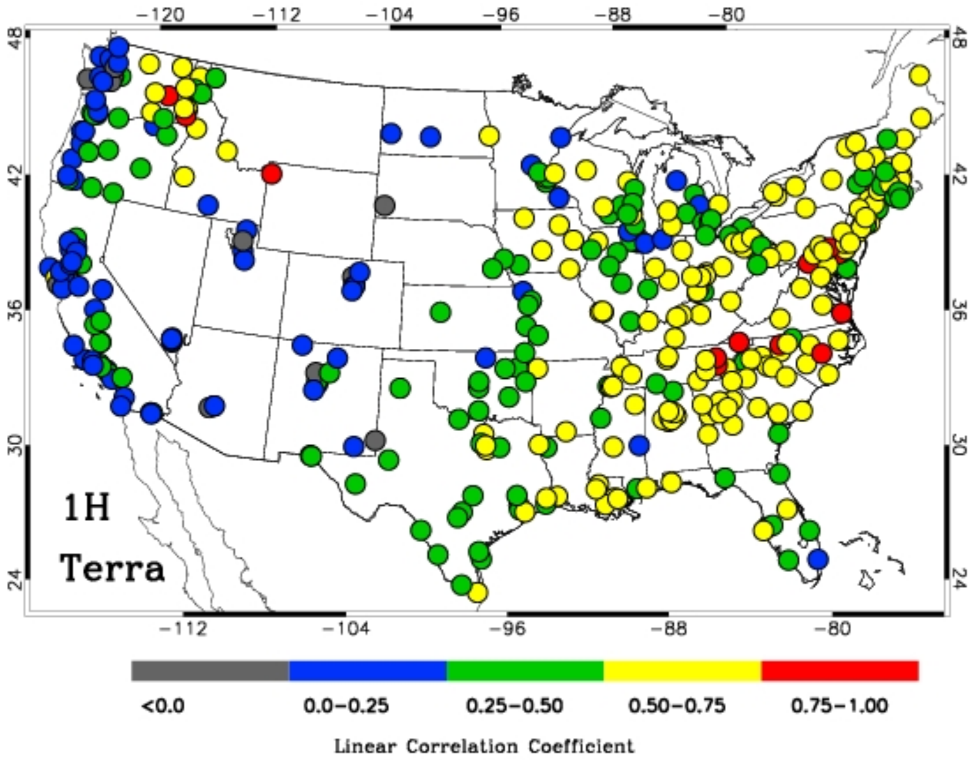


MSC

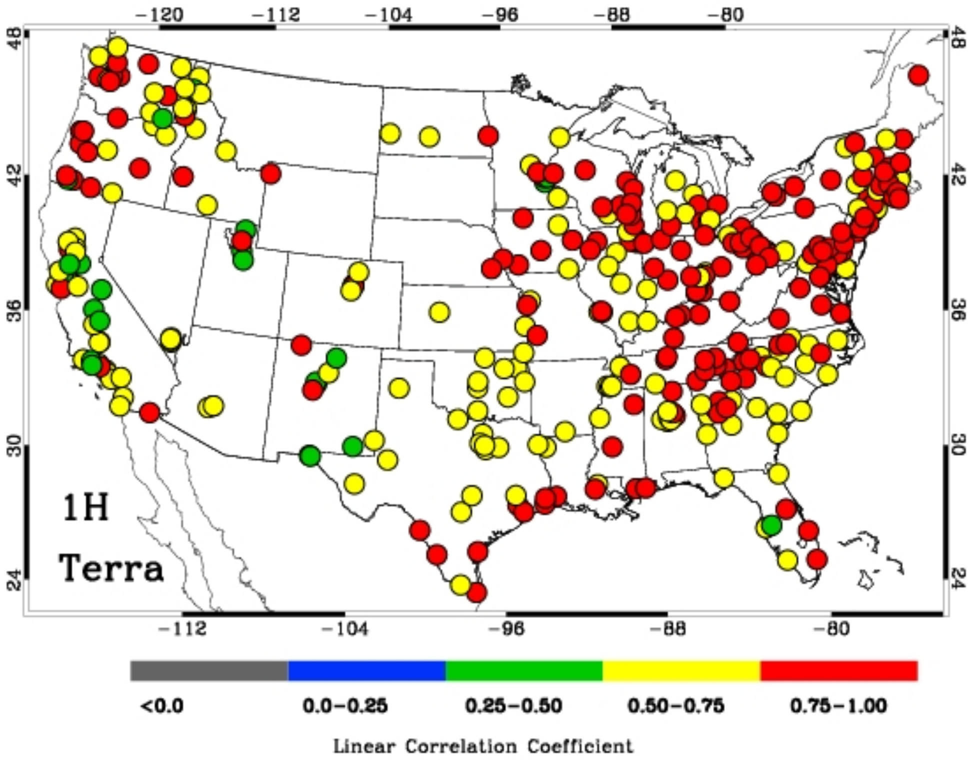
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$

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

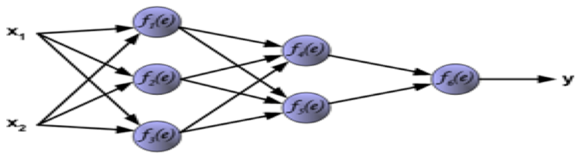
Two Variable Method

$Y = mX + c$

Multivariable Method

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

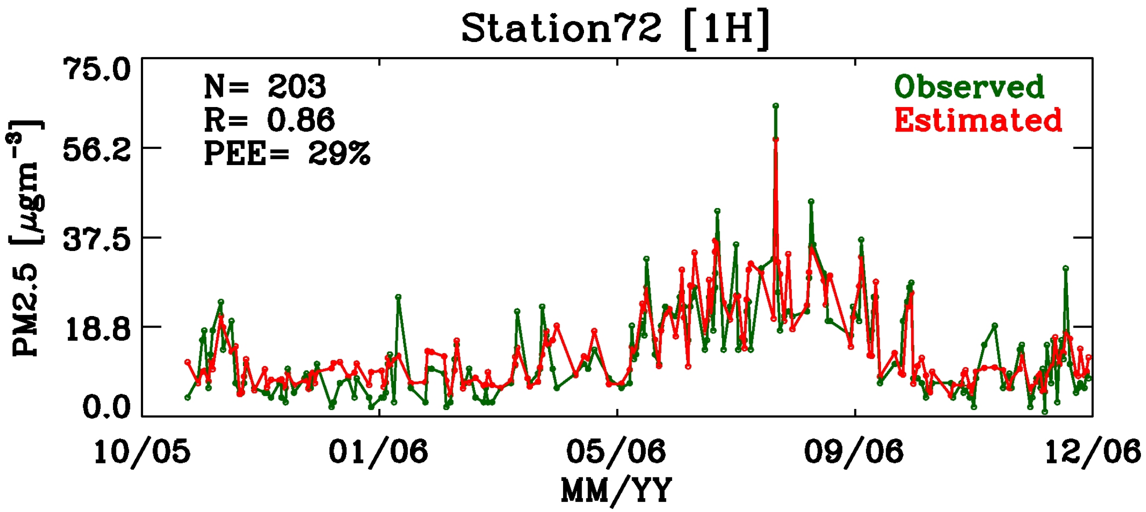
Artificial Intelligence

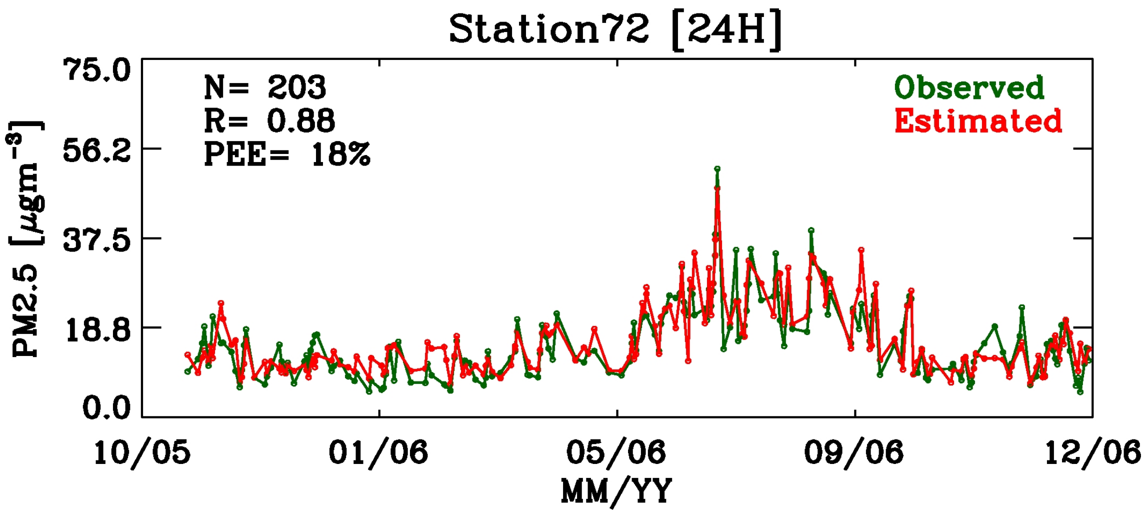


MSC

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

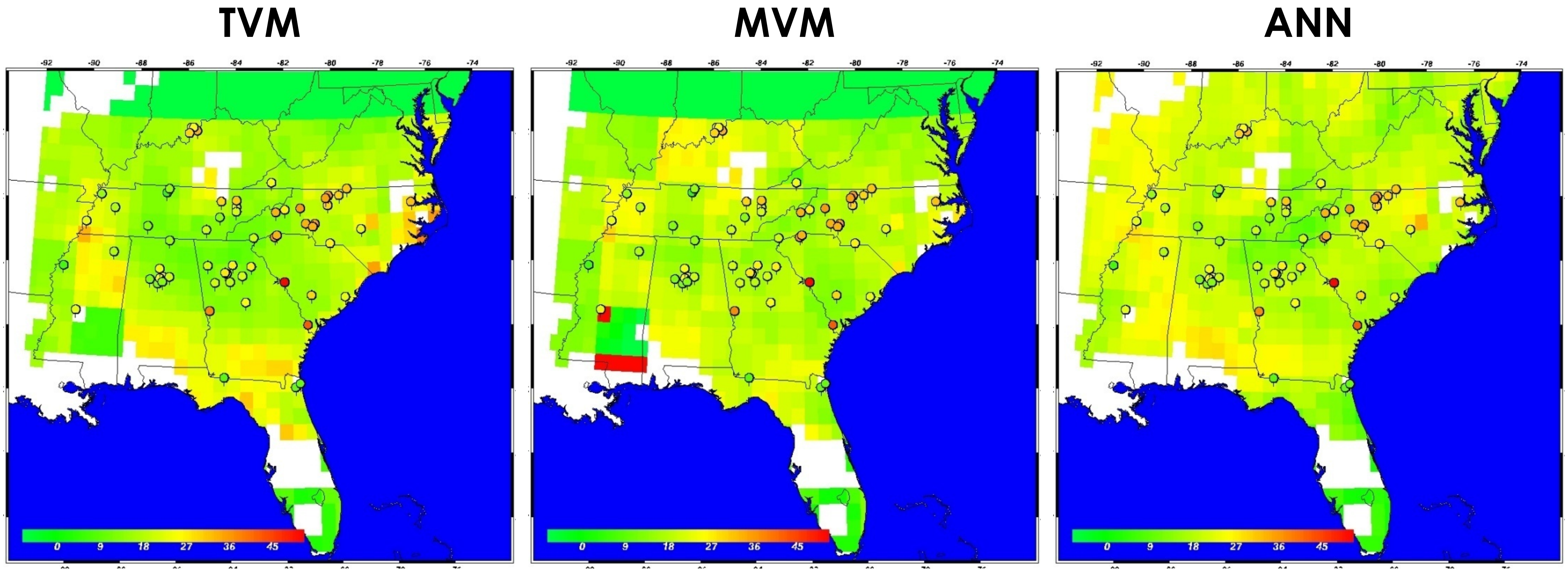
Time Series Examples of Results from ANN





Source: Gupta, 2009

TVM vs. MVM vs. ANN



Source: Gupta, 2009

$PM_{2.5}$ Estimation: Model Scaling (MSC)

Difficulty Level

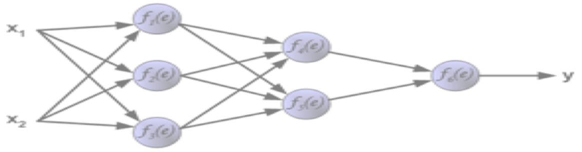
Two Variable Method

$$Y = mX + c$$

Multivariable Method

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

Artificial Intelligence



MSC

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

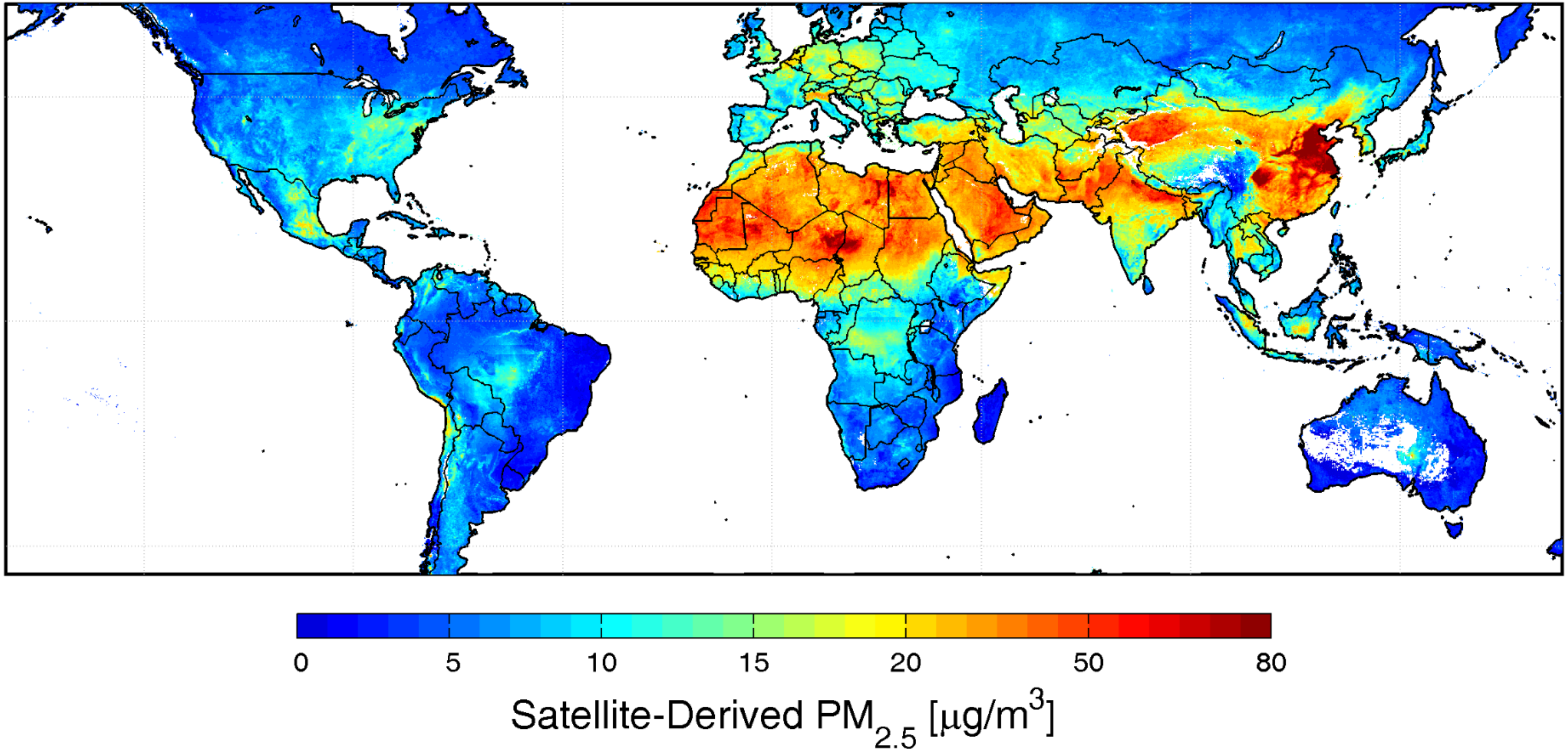
Scaling Approach

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

Source: Liu et al., 2006

Annual Mean $PM_{2.5}$ from Satellite Observations

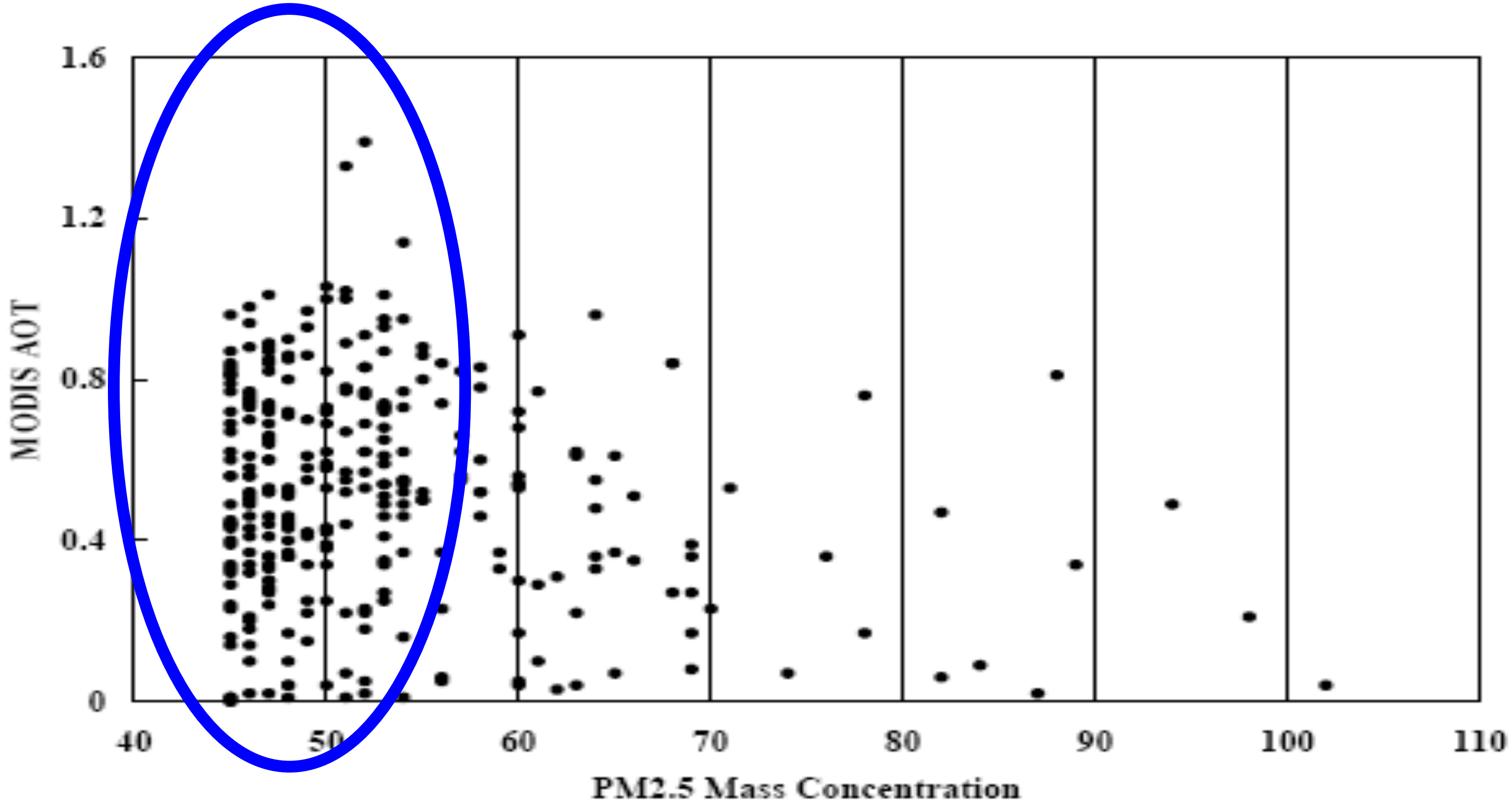


van Donkelaar et al., 2006, 2009

Questions to Ask: Issues

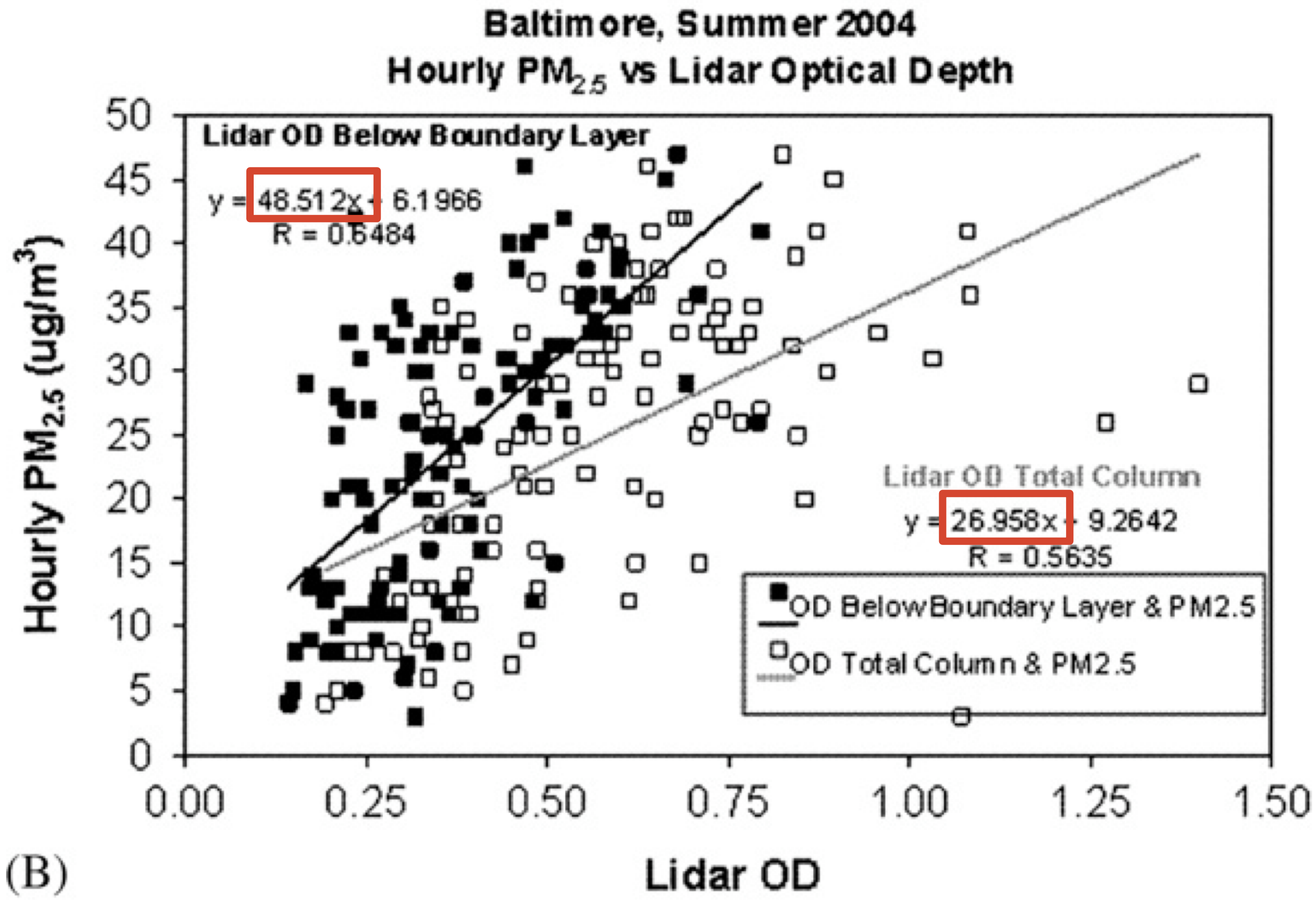
- How accurate are these estimates?
- Is the $PM_{2.5}$ – AOD relationship always linear?
- How does AOD retrieval uncertainty impact estimation of air quality?
- Does this relationship change in space and time?
- Does this relationship change with aerosol type?
- How does meteorology drive this relationship?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

Limitation: Vertical Distribution of Aerosols



Gupta et al., 2009

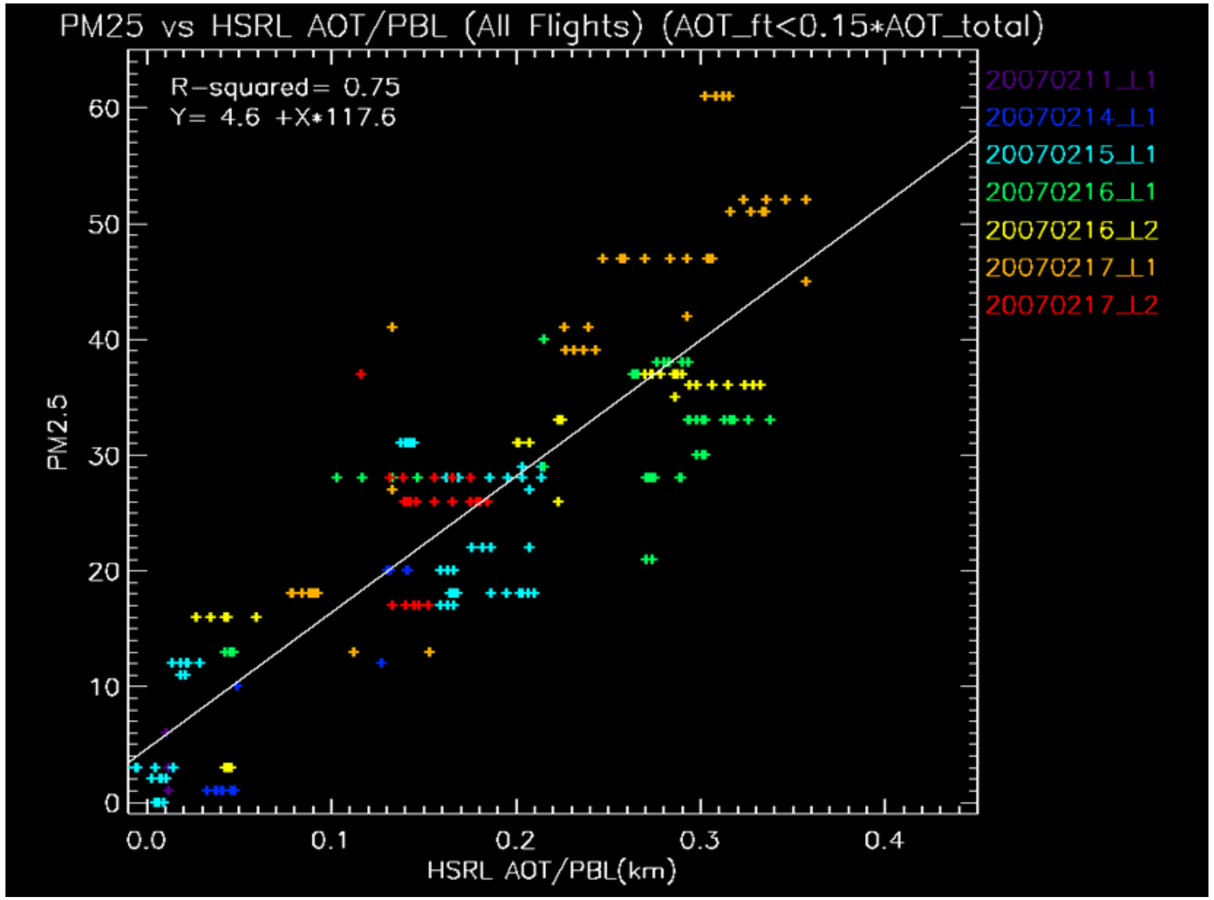
Vertical Distribution: Impact on AOD-$PM_{2.5}$



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 $PM_{2.5}$



Source: Al-Saadi et al., 2008

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

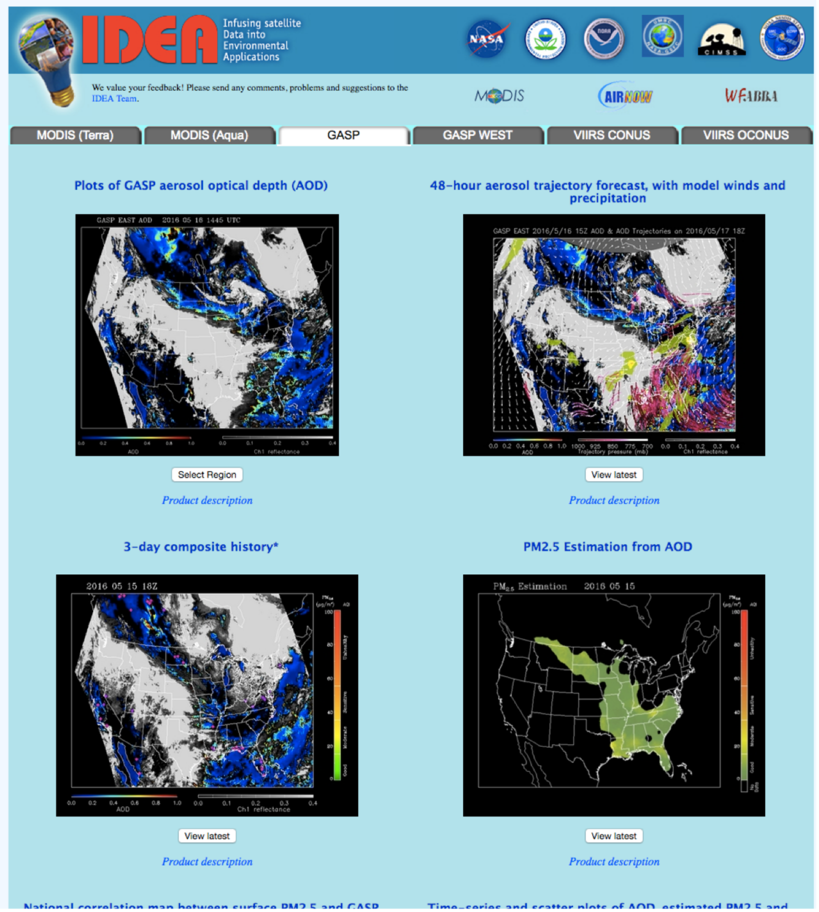
No textbook solution

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?

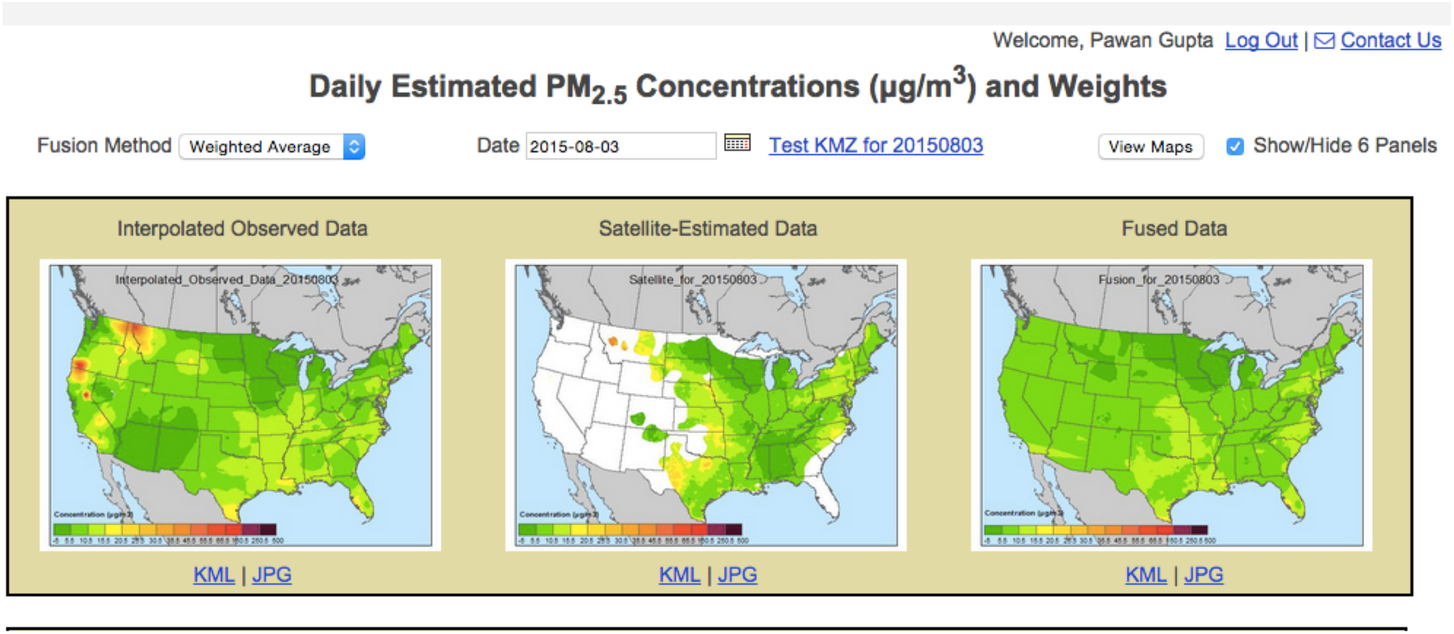
How Satellite Aerosol Data is Used

Infusing Satellite Data Into Environmental Applications



- Objective: near real-time product for state and local air quality forecasters
- Goal: improve accuracy of next day $PM_{2.5}$ 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

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* 59:645–675
DOI:10.3155/1047-3289.59.6.645

R.M. Hoff

S.A. Christopher

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

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Department of Atmospheric Sciences and Earth System Sc... Alabama–Huntsville, Huntsville, AL

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

atmosphere

MDPI

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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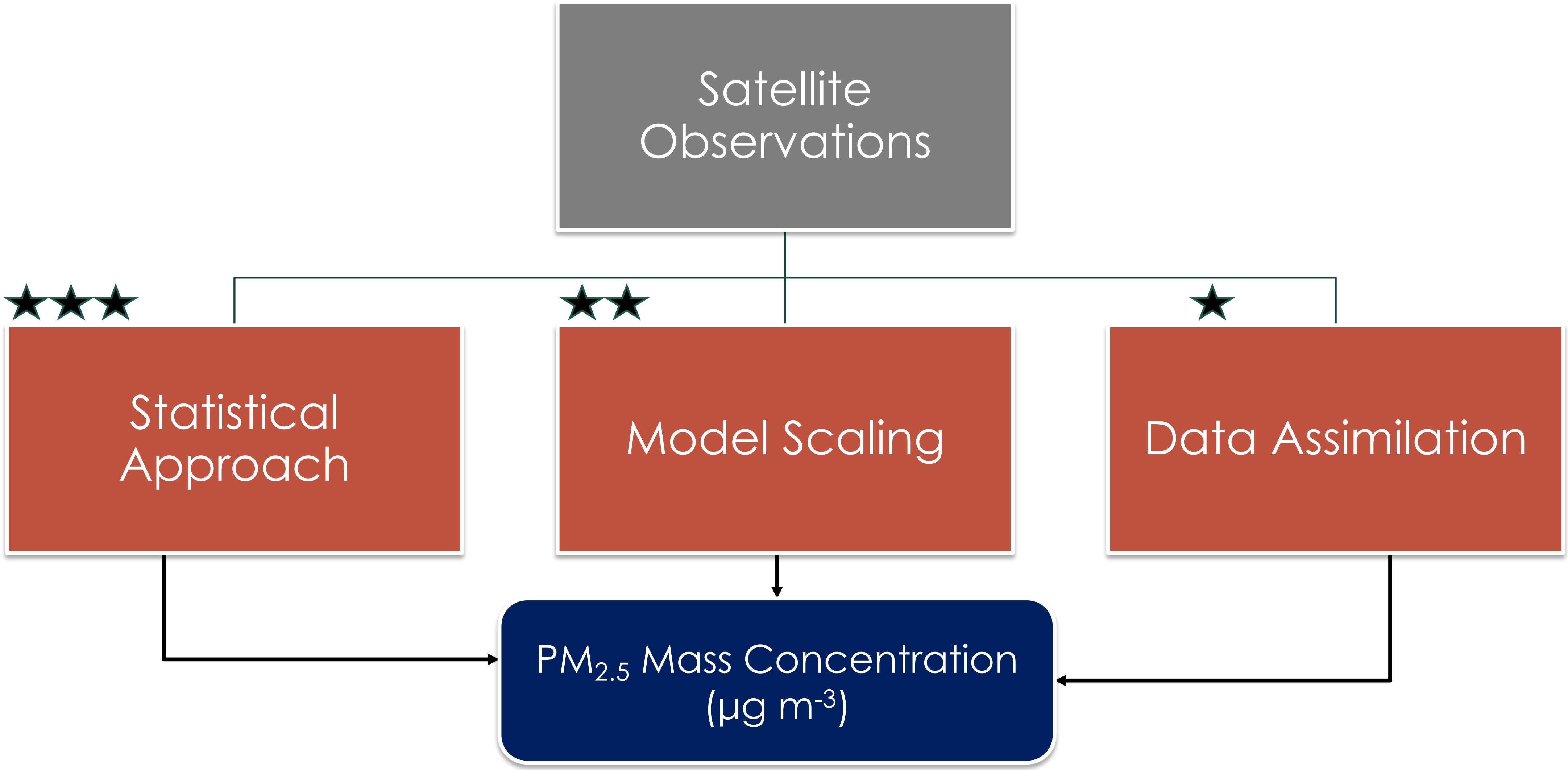
Academic Editor: Robert W. Talbot
Received: 25 July 2016; Accepted: 5 October 2016; Published: 14 October 2016

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 $PM_{2.5}$ 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 $PM_{2.5}$ 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 Particualte 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 $PM_{2.5}$: 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/aq/
  - eIDEA: http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/

Questions