



ARSET

Applied Remote Sensing Training

<http://arset.gsfc.nasa.gov>

 @NASAARSET

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

**NASA ARSET Workshop: NASA Earth Observations, Data and
Tools for Air Quality Applications**

Sunday, August 28, 2016 to Monday, August 29, 2016

17th IUAPPA World Clean Air Congress and 9th CAA Better Air Quality
(BAQ) Conference

Pusan National University, Busan, South Korea

Objective

- 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

What are we looking for? Why?



AIR QUALITY INDEX

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

AIR QUALITY INDEX

**Best
7 AM**

**Worst
6 PM**

**PLEASE
BURN
CLEANLY**

Unhealthful

Poor

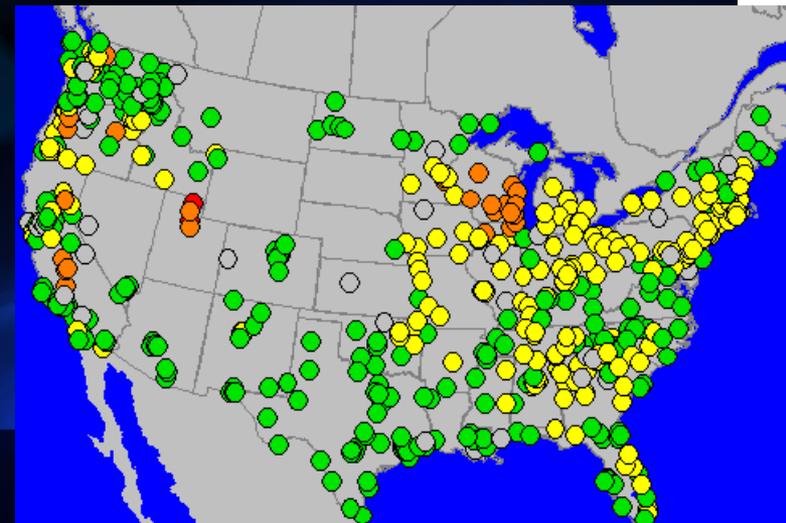
Moderate

Good

**58
High**

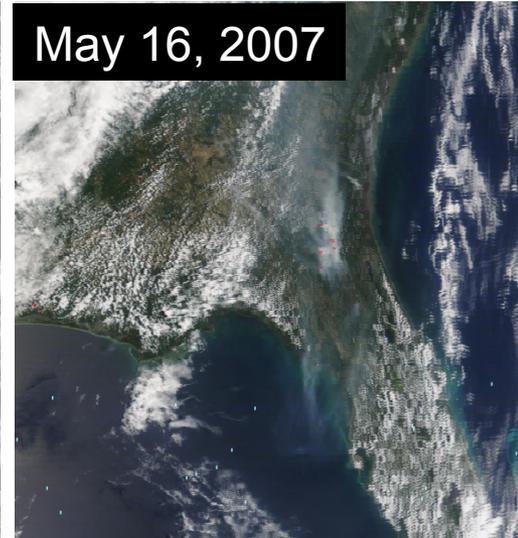
**30
Low**

Spatial Gaps



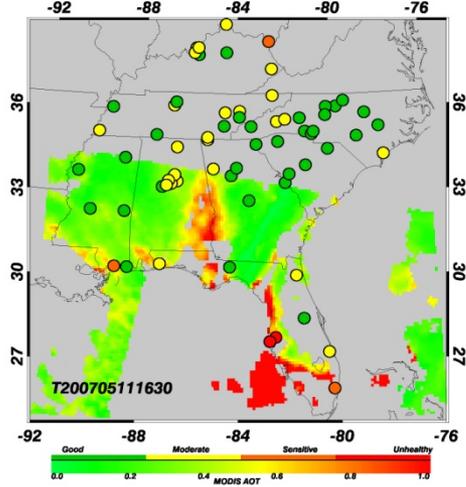
January 23, 2009 12:00 am EST

MODIS-Terra True Color Images

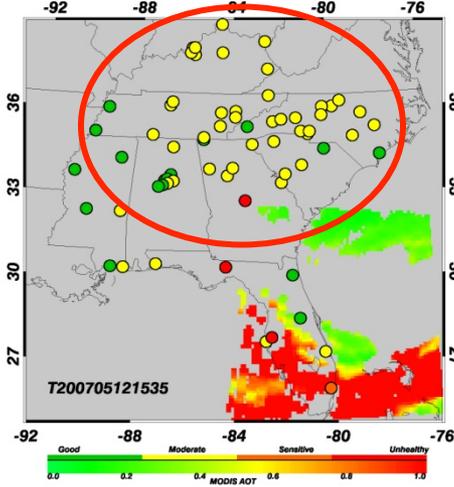


MODIS-Terra Aerosol Optical Thickness

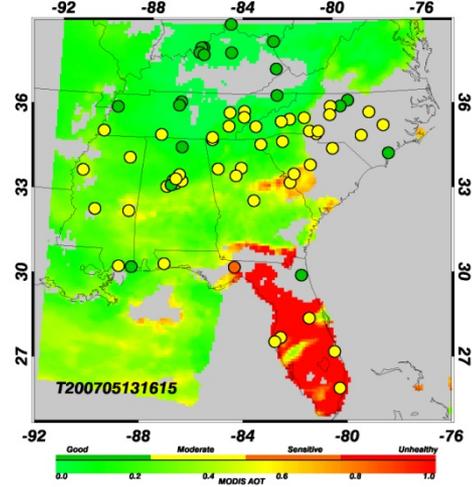
May 11, 2007



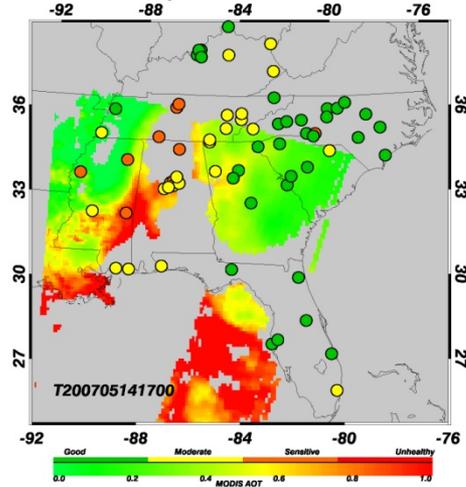
May 12, 2007



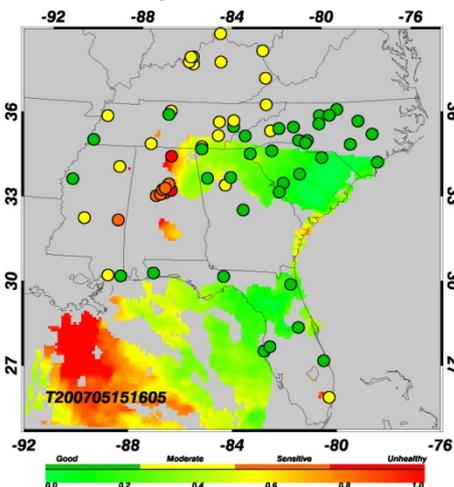
May 13, 2007



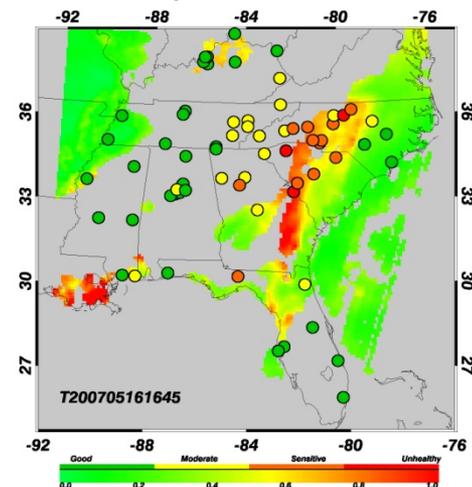
May 14, 2007



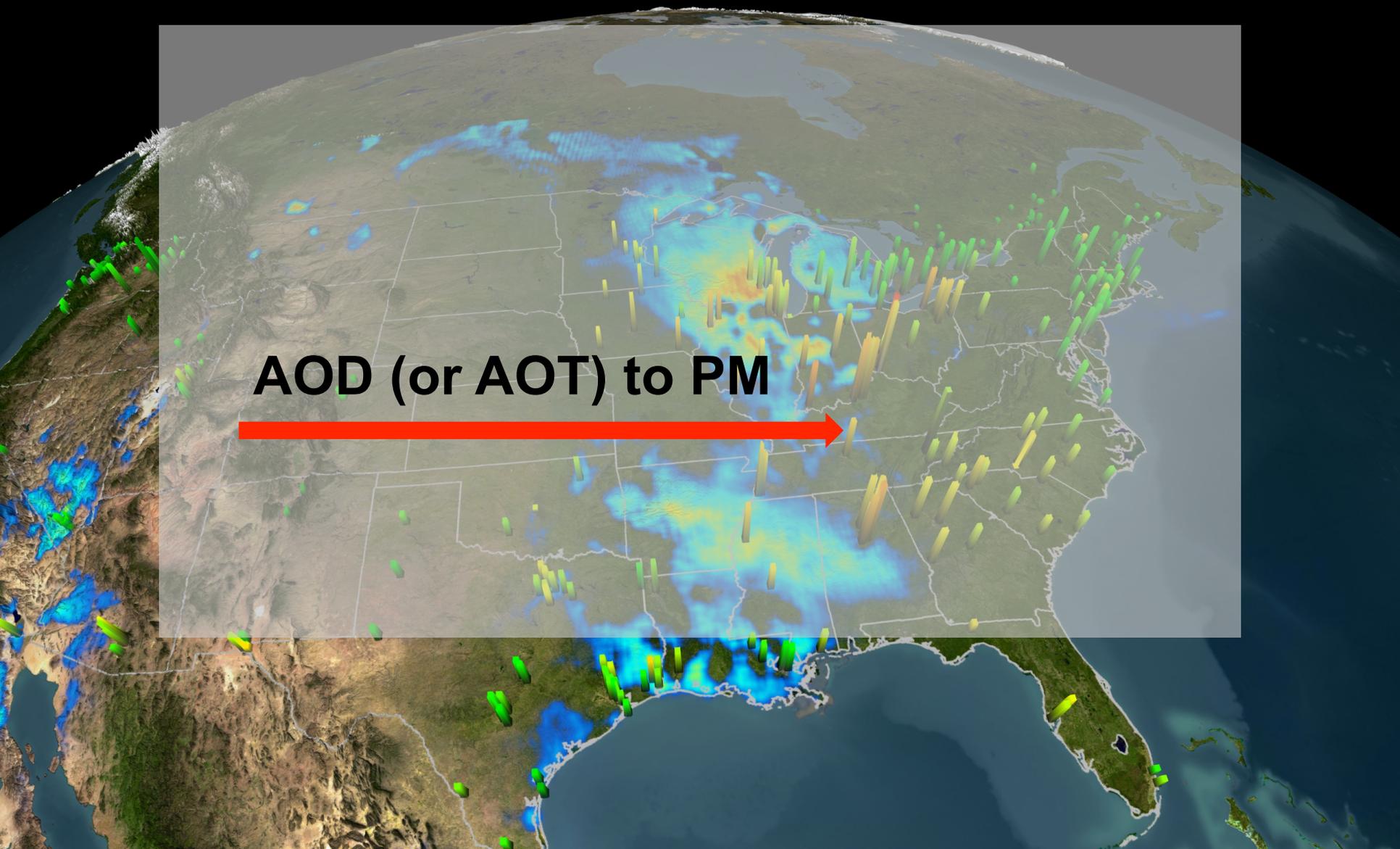
May 15, 2007



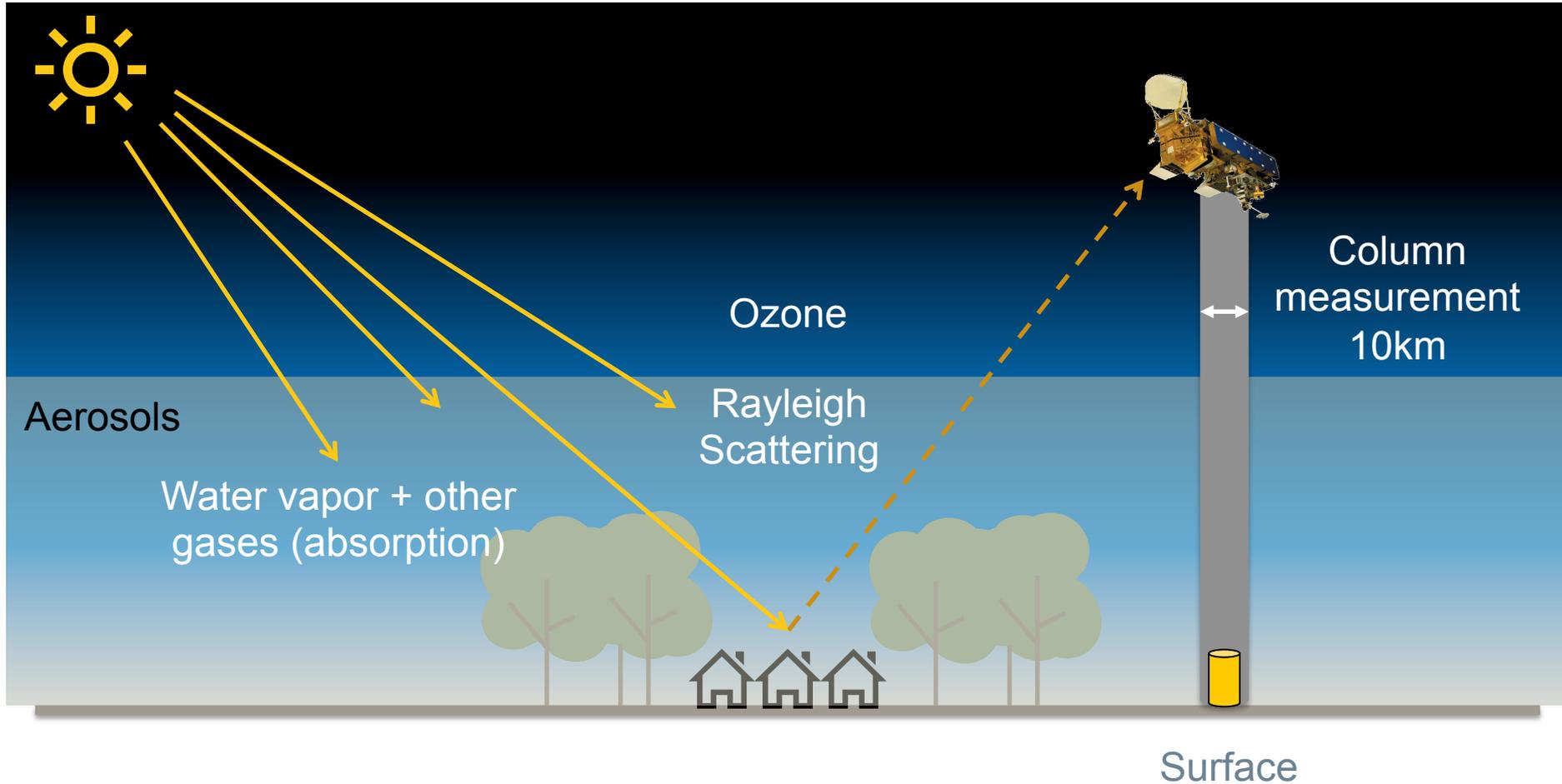
May 16, 2007



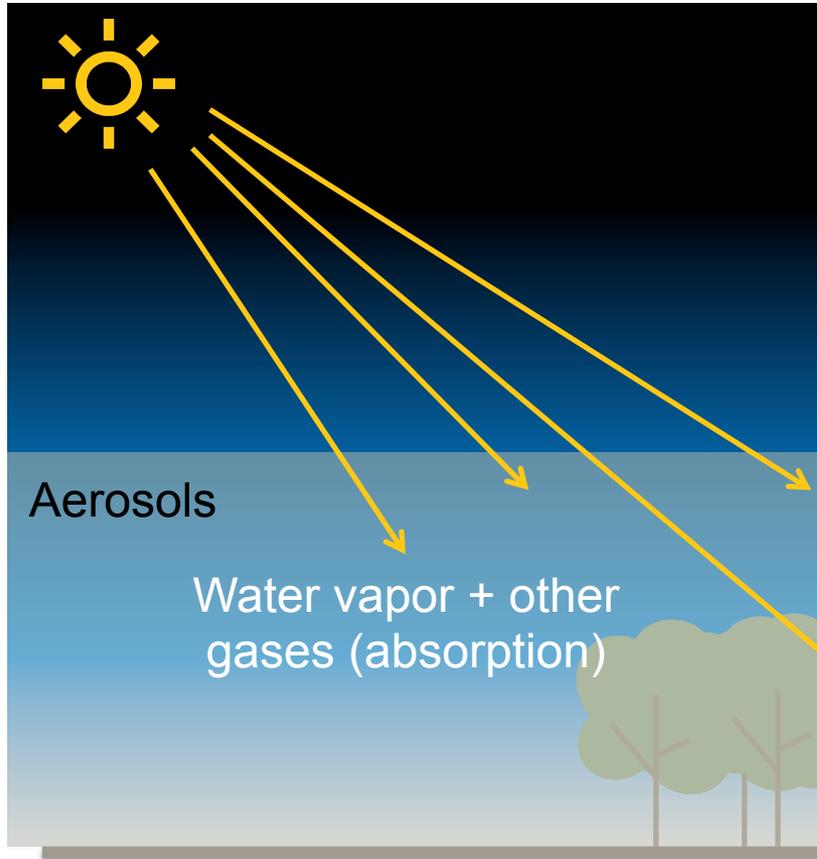
AOD (or AOT) to PM



What do satellites provide?



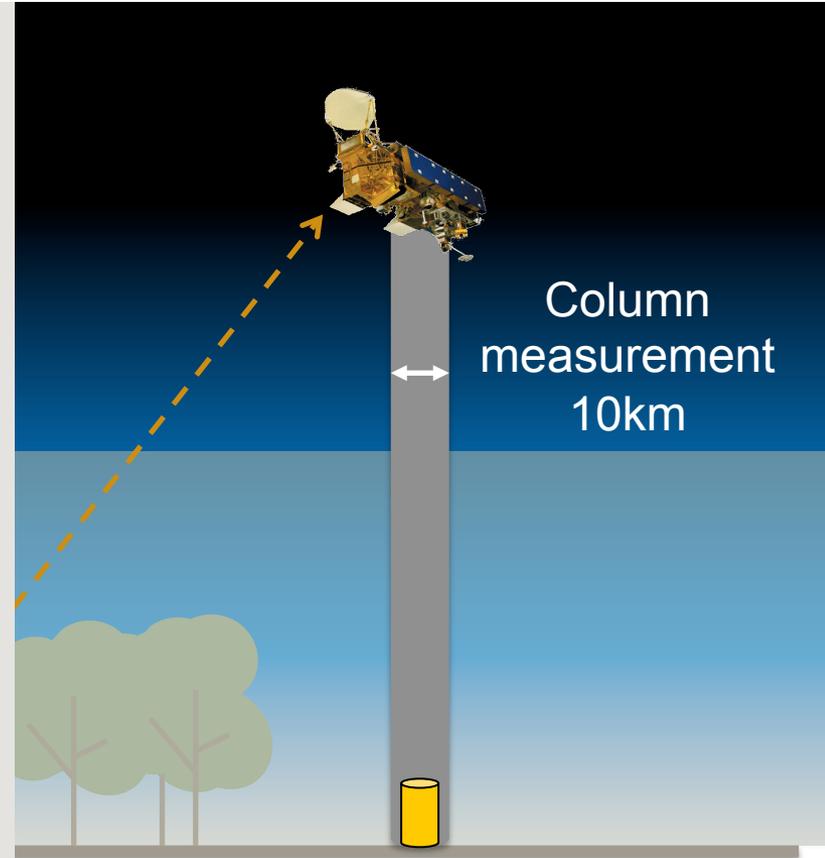
What do satellites provide?



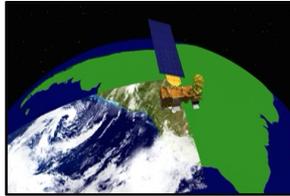
- $AOT(\tau) = \int \beta_{ext} dz$
 - particle size
 - composition
 - water uptake
 - vertical distribution
- There are satellite retrieval issues: inversion (e.g. aerosol model, background)

What do satellites provide?

- 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



Satellite vs Ground Observation



AOD – Column integrated value (top of the atmosphere to surface) - Optical measurement of aerosol loading – unitless. AOD is function of shape, size, type and number concentration of aerosols

Top of the Atmosphere

10 km² Vertical Column

Aerosol Optical Depth

Surface Layer

Earth Surface

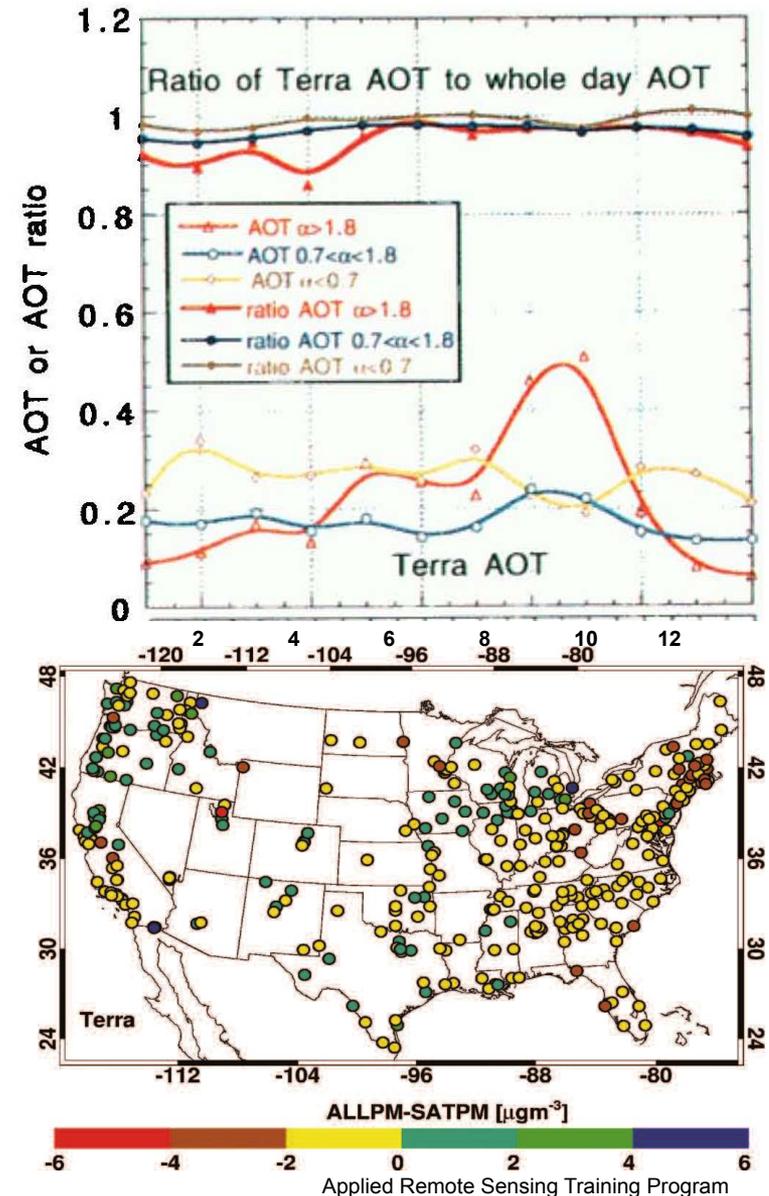
PM2.5 mass concentration
($\mu\text{g m}^{-3}$) -- Dr

PM2.5 – Mass per unit volume of aerosol particles less than 2.5 μm in aerodynamic diameter at surface (measurement height) level



Support for AOD-PM2.5 Linkage

- Current satellite AOD is sensitive to PM2.5
 - 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

$$\text{AOD}(\lambda) = \int_{\text{surface}}^{\text{top-of-atmosphere}} \beta_{\text{ext}, \rho}(\lambda, z) dz$$

$$C = \frac{4\rho r_e}{3Q} \times \frac{f_{\text{PBL}}}{H_{\text{PBL}}} \times \text{AOD}$$

- ρ : particle density
- Q : extinction coefficient
- r_e : effective radius

Composition

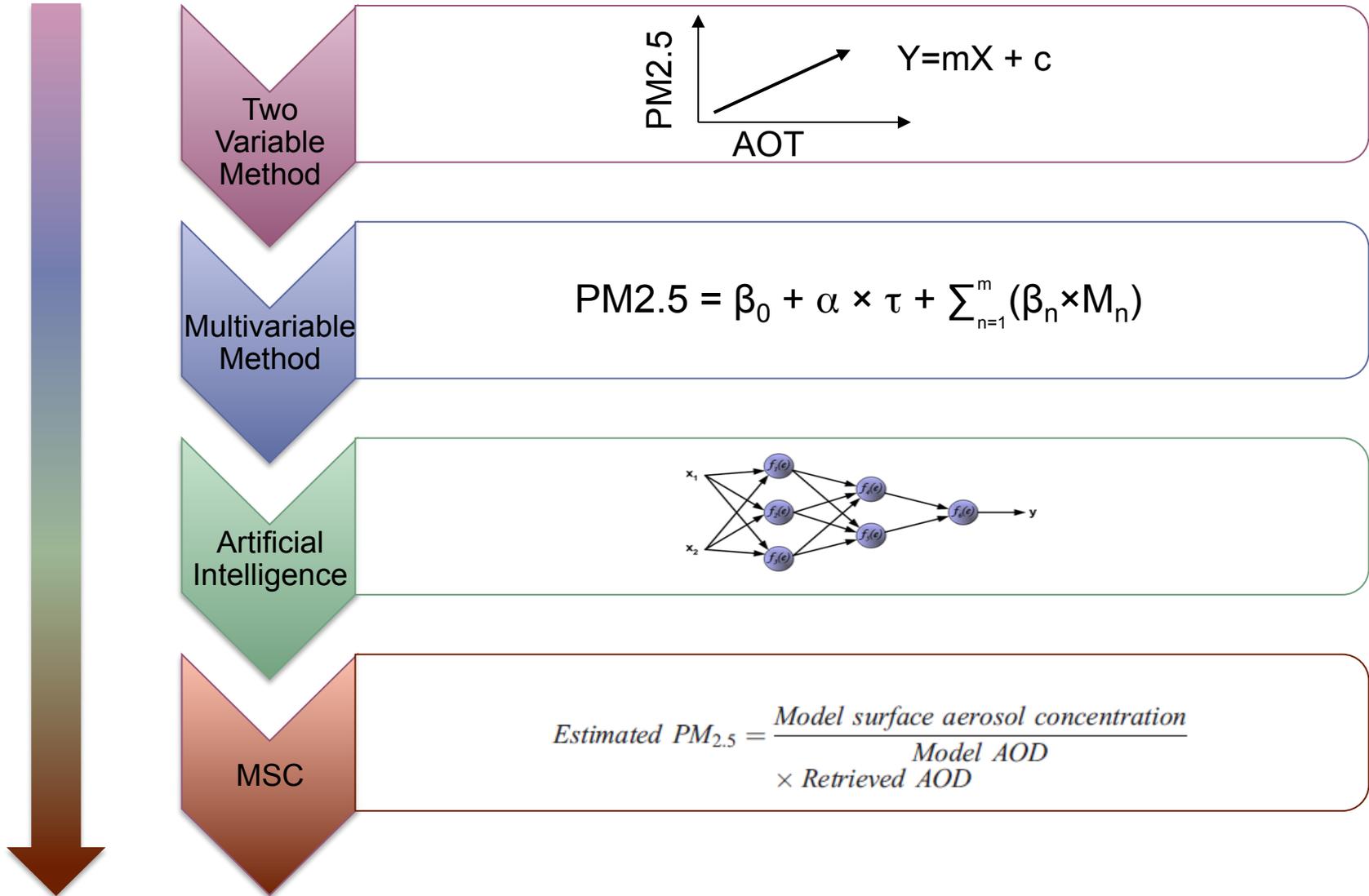
• f_{PBL} : % AOD in PBL

→ Size distribution

• H_{PBL} : mixing height → Vertical Profile

PM2.5 Estimation: Popular Methods

Difficulty Level

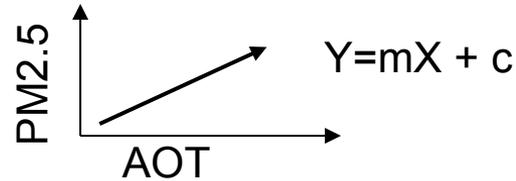


PM2.5 Estimation: Popular Methods

Difficulty Level



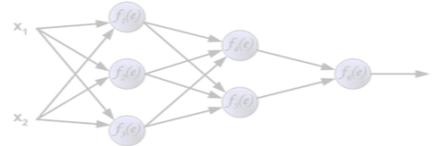
Two Variable Method



Multivariable Method

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

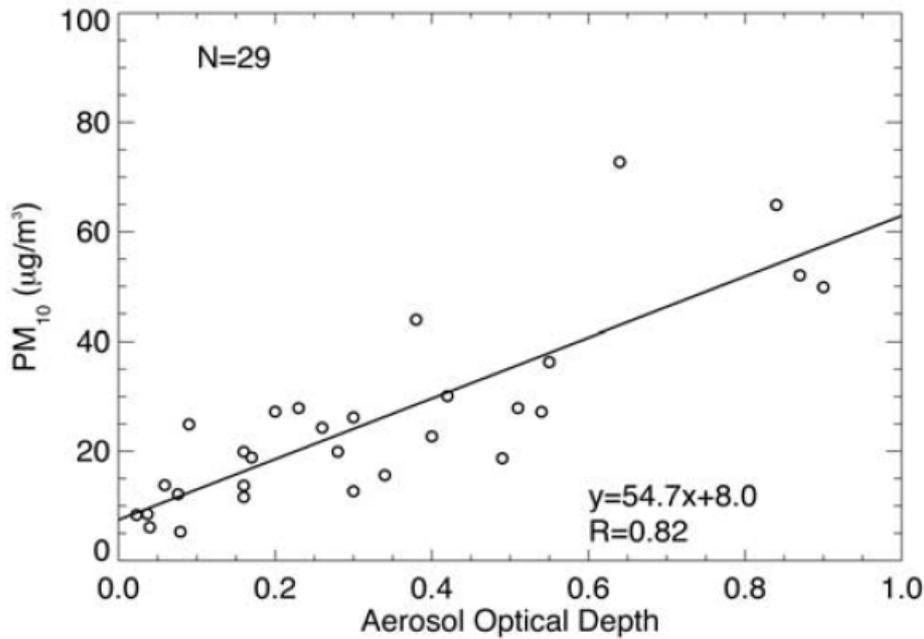
Artificial Intelligence



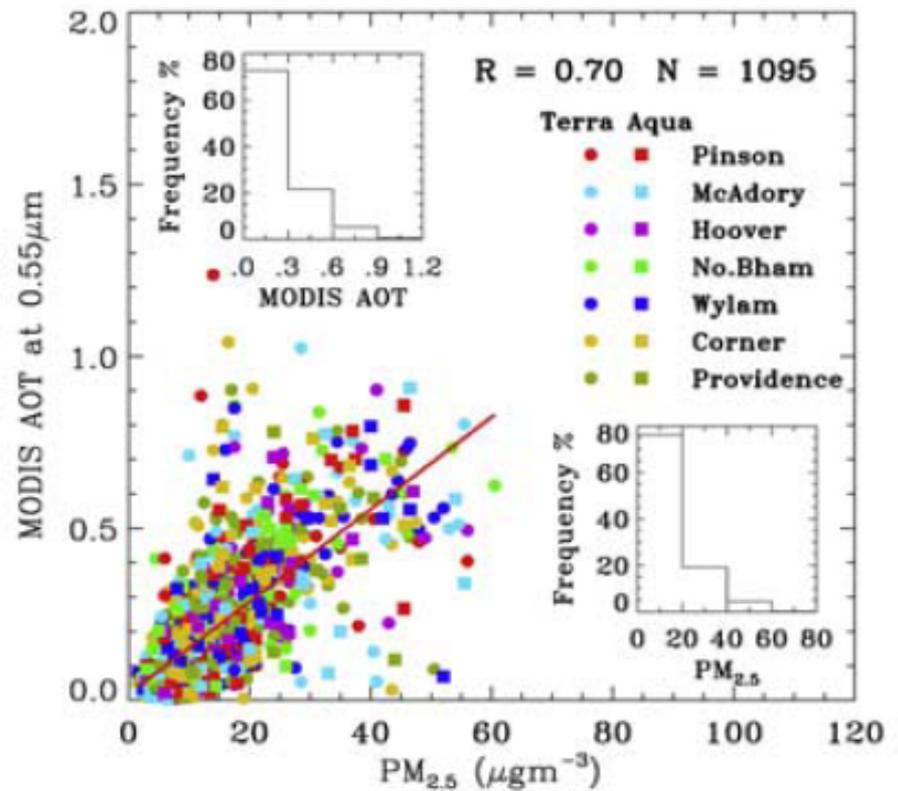
MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface aerosol concentration}}{\text{Model AOD} \times \text{Retrieved AOD}}$$

Simple Models from Early Days

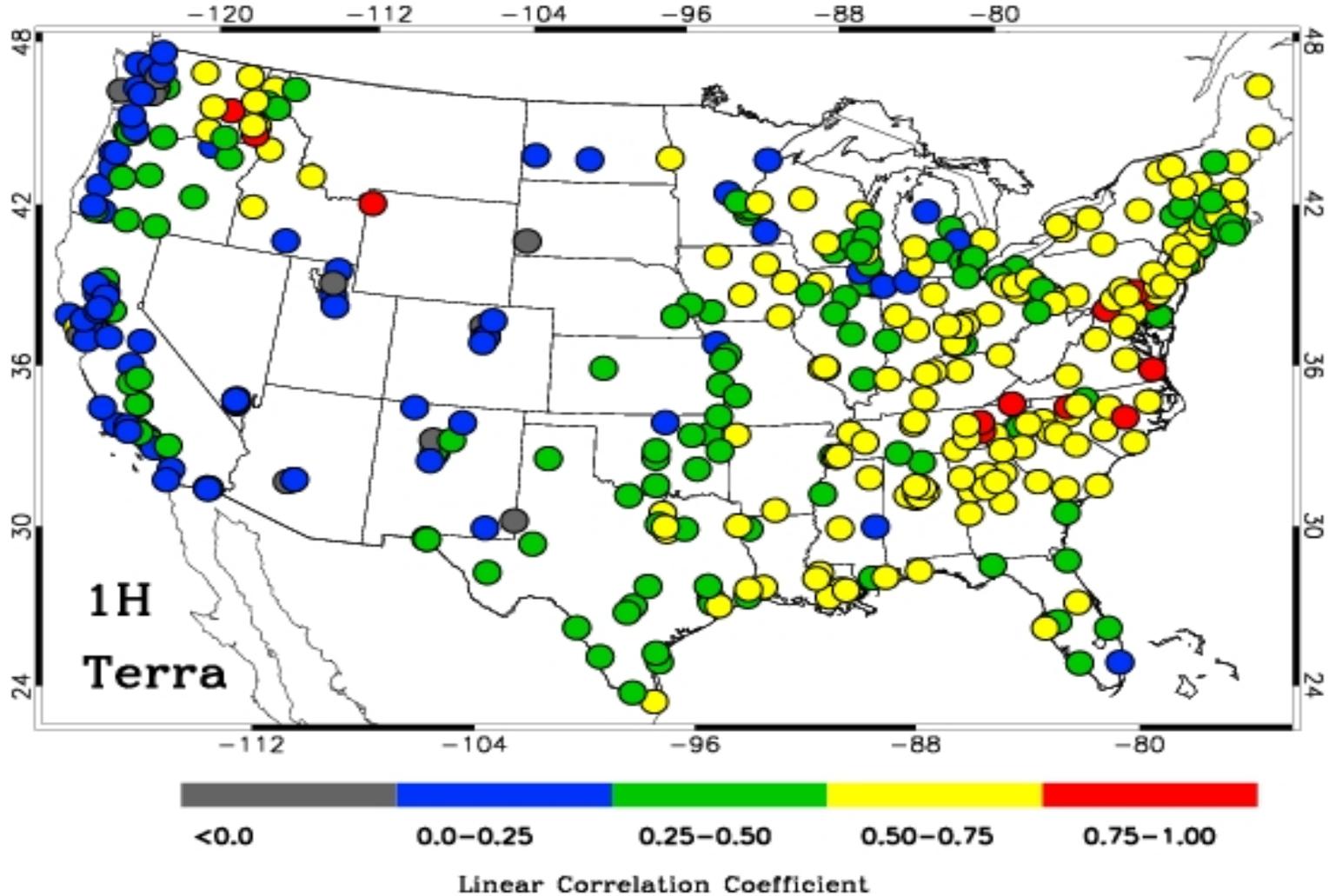


Source: Chu et al., 2003



Source: Wang et al., 2003

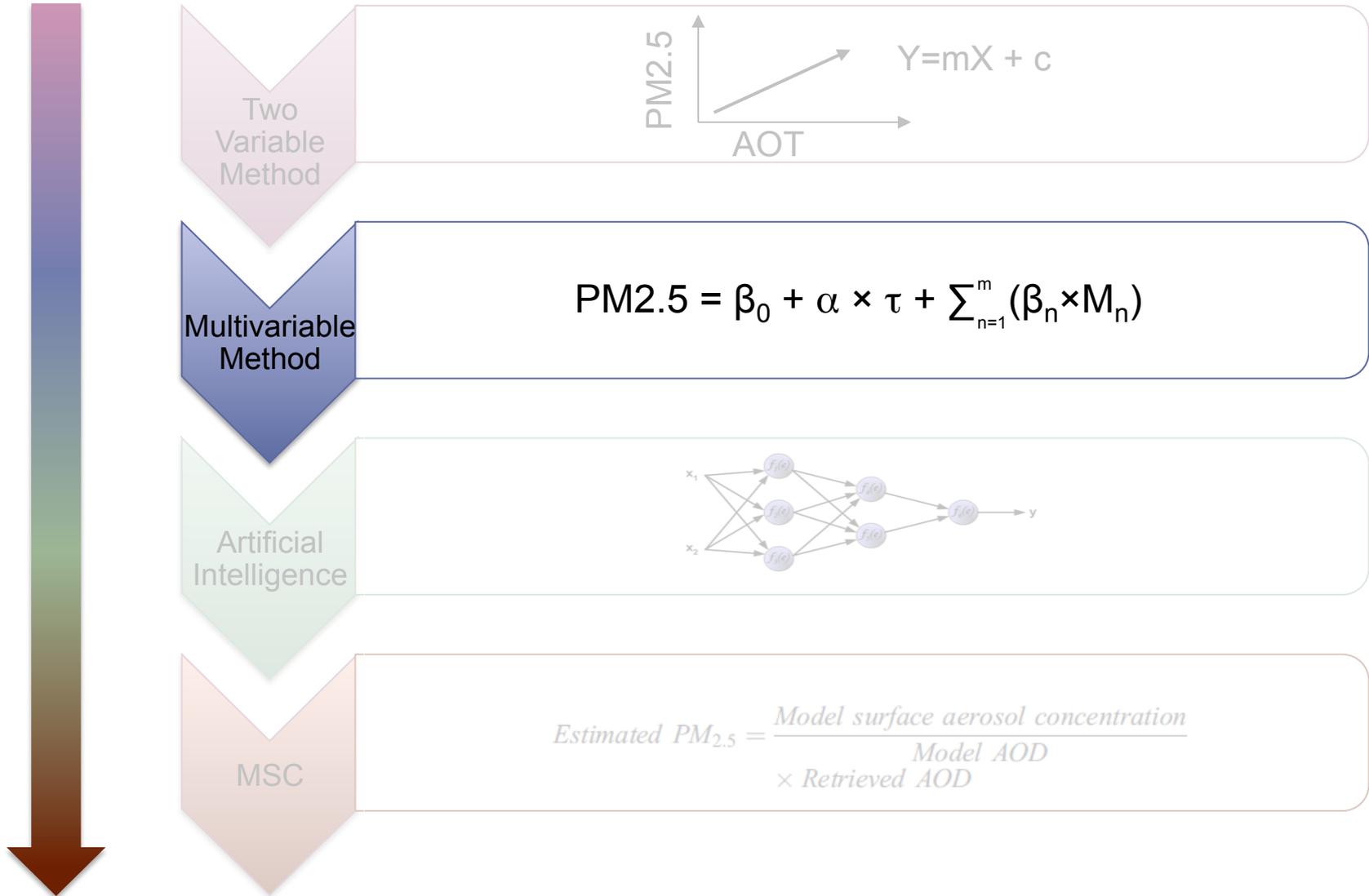
AOD-PM2.5 Relationship



Source: Gupta, 2008

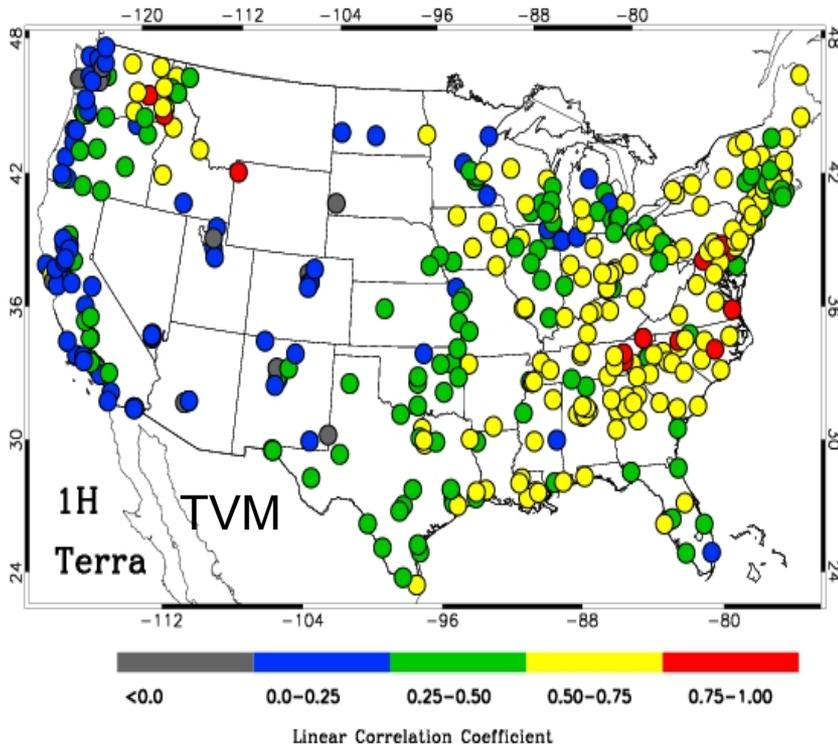
PM2.5 Estimation: Popular Methods

Difficulty Level

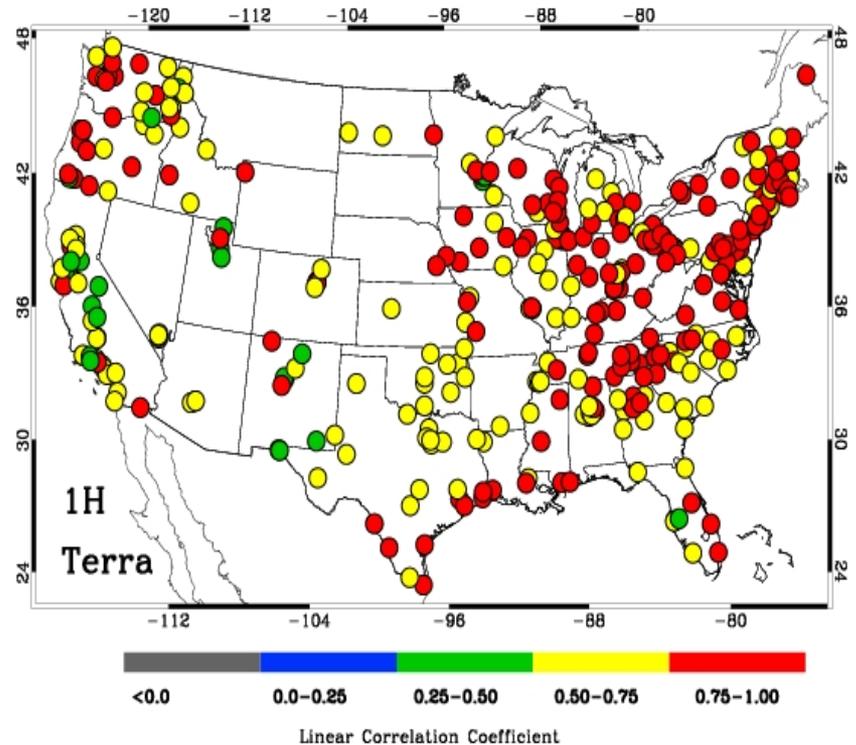


Multi-Variable Method

Predictor: AOD



Predictor: AOD + Meteorology

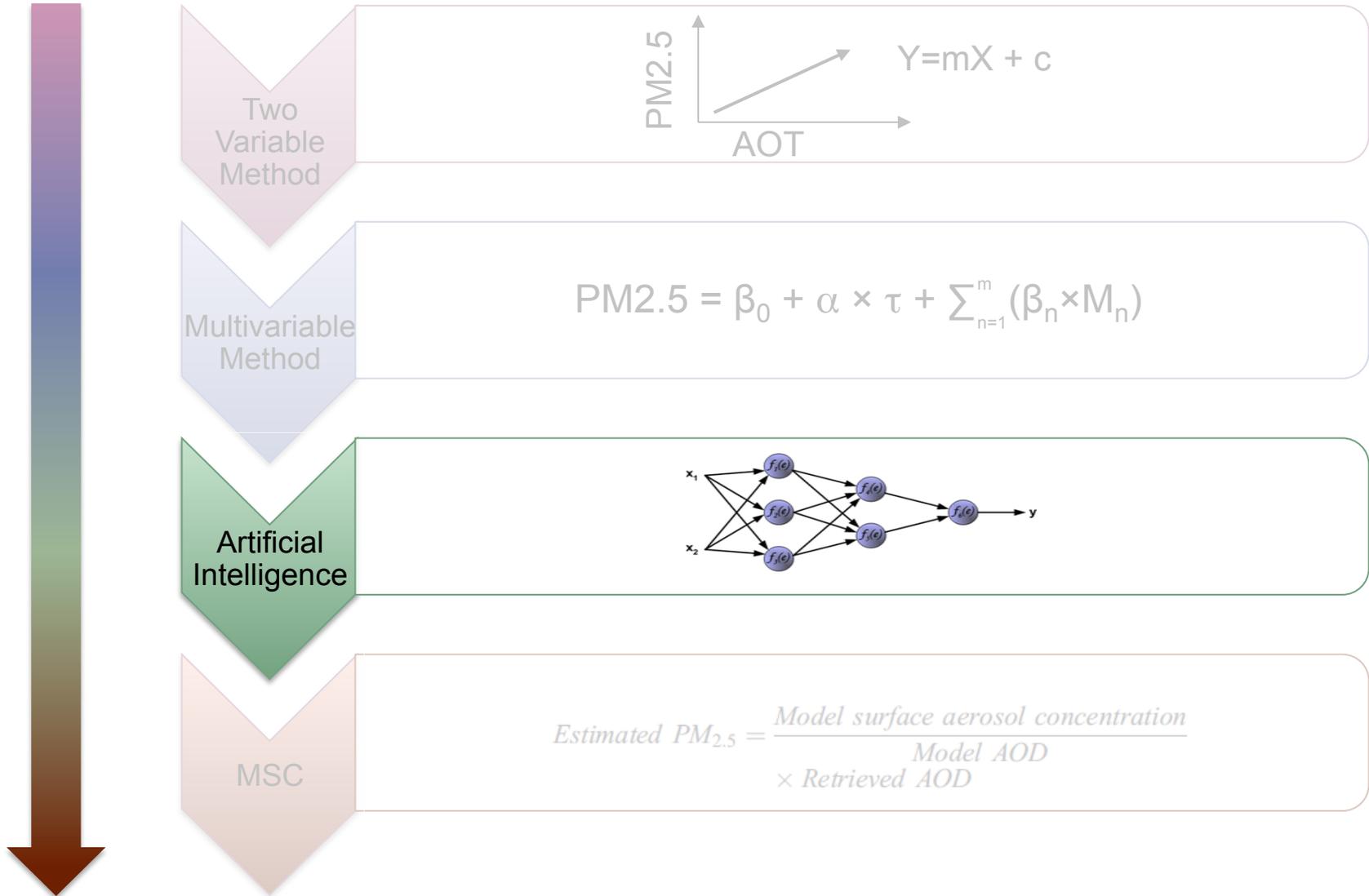


Linear correlation coefficient between observed and estimated PM_{2.5}

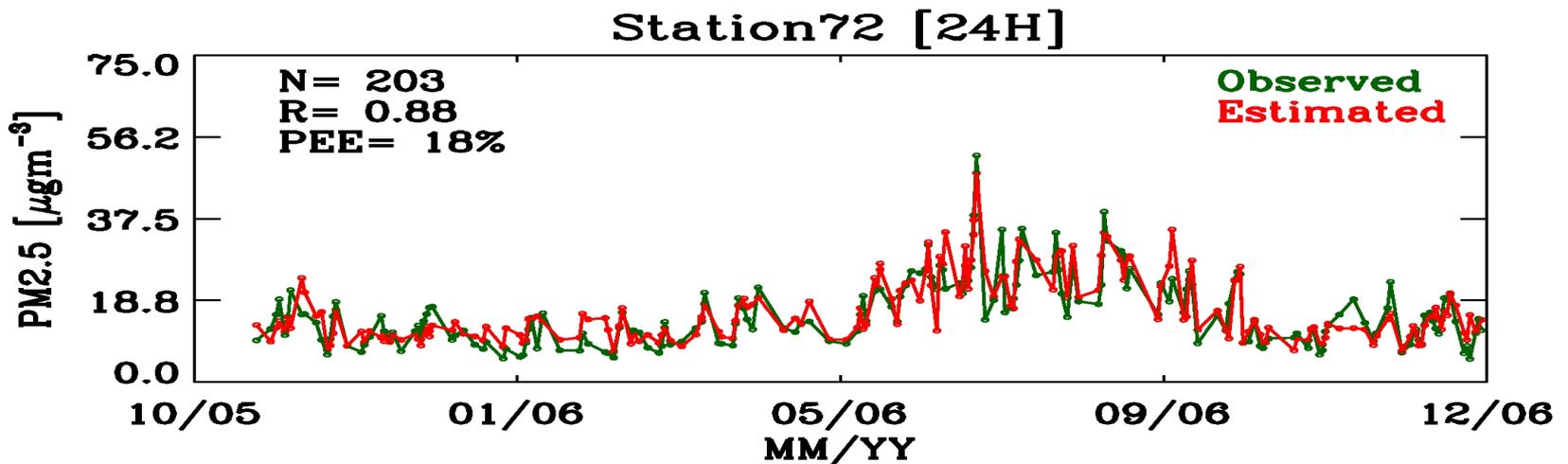
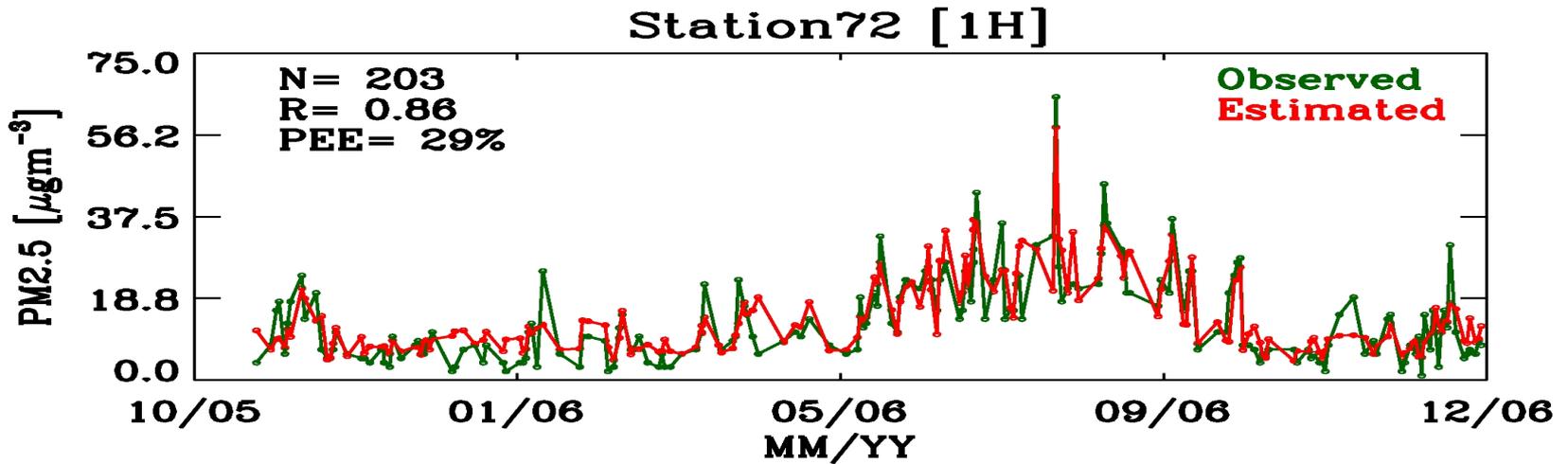
Source: Gupta, 2008

PM2.5 Estimation: Popular Methods

Difficulty Level



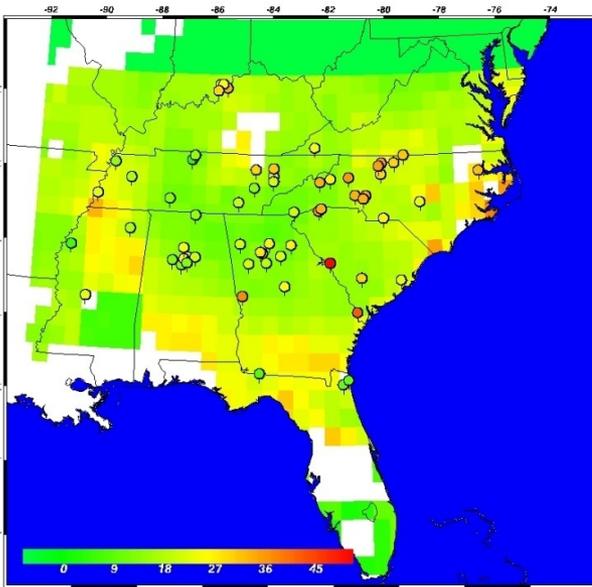
Time Series Examples of Results from ANN



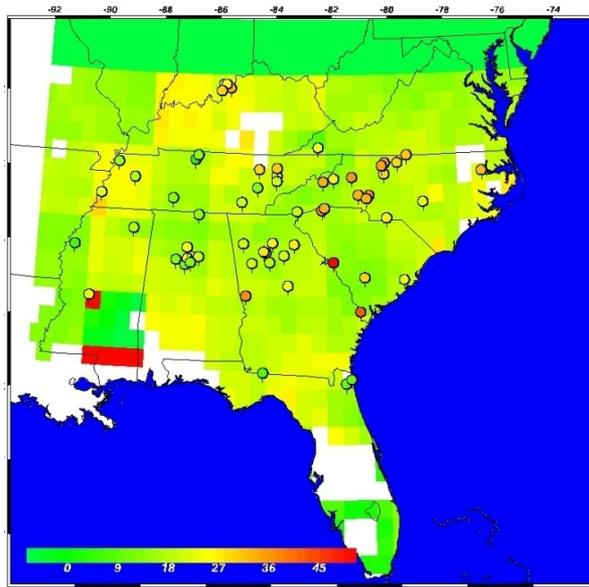
Source: Gupta, 2009

TVM vs. MVM vs. Artificial Intelligence

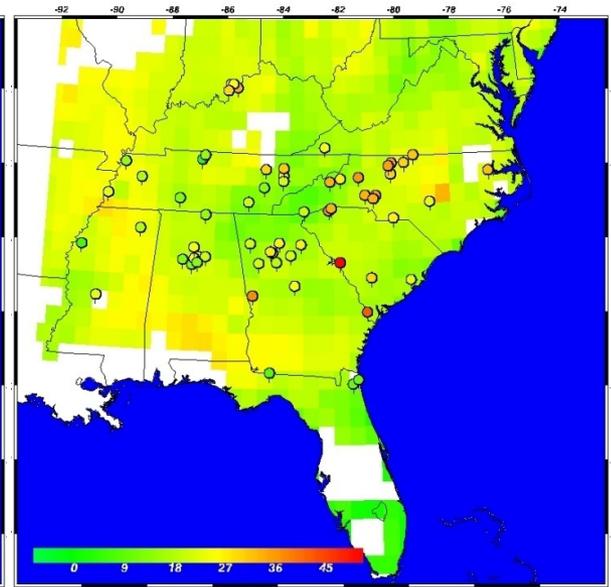
TVM



MVM



ANN



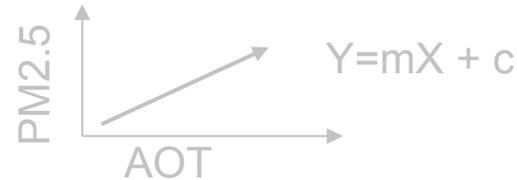
Source: Gupta, 2009

PM2.5 Estimation: Popular Methods

Difficulty Level



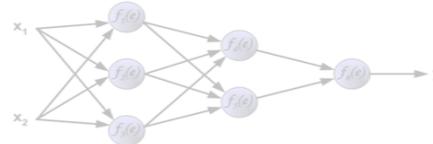
Two Variable Method



Multivariable Method

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

Artificial Intelligence

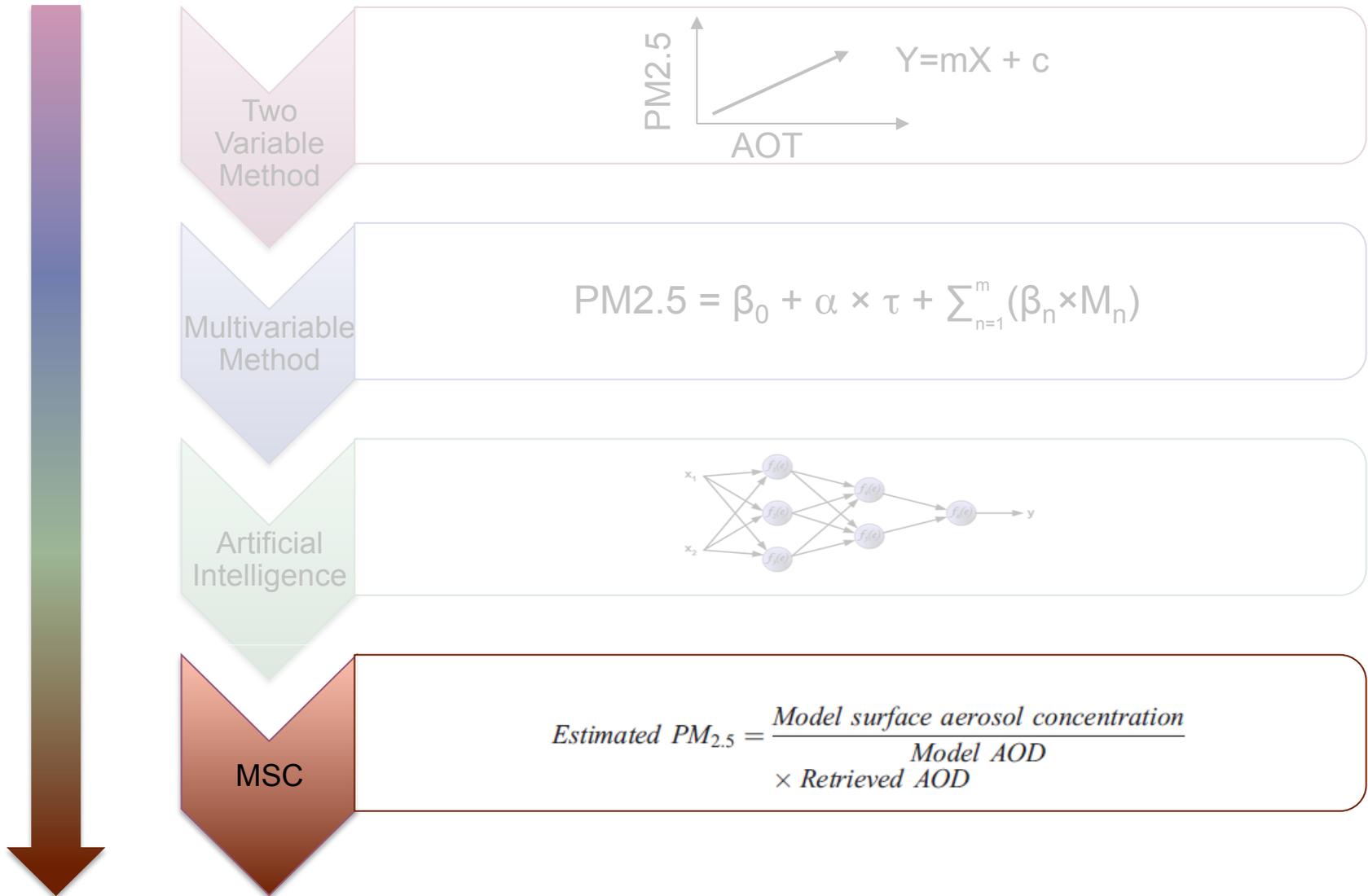


MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface aerosol concentration}}{\text{Model AOD}} \times \text{Retrieved AOD}$$

PM2.5 Estimation: Popular Methods

Difficulty Level



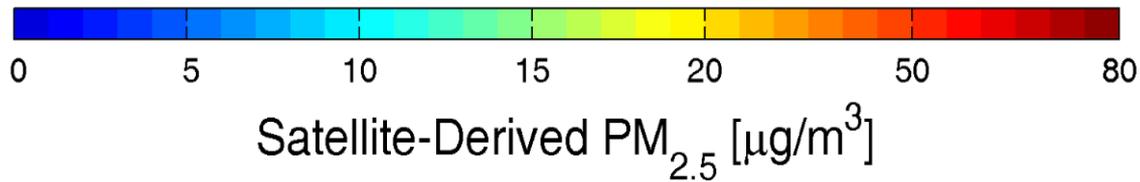
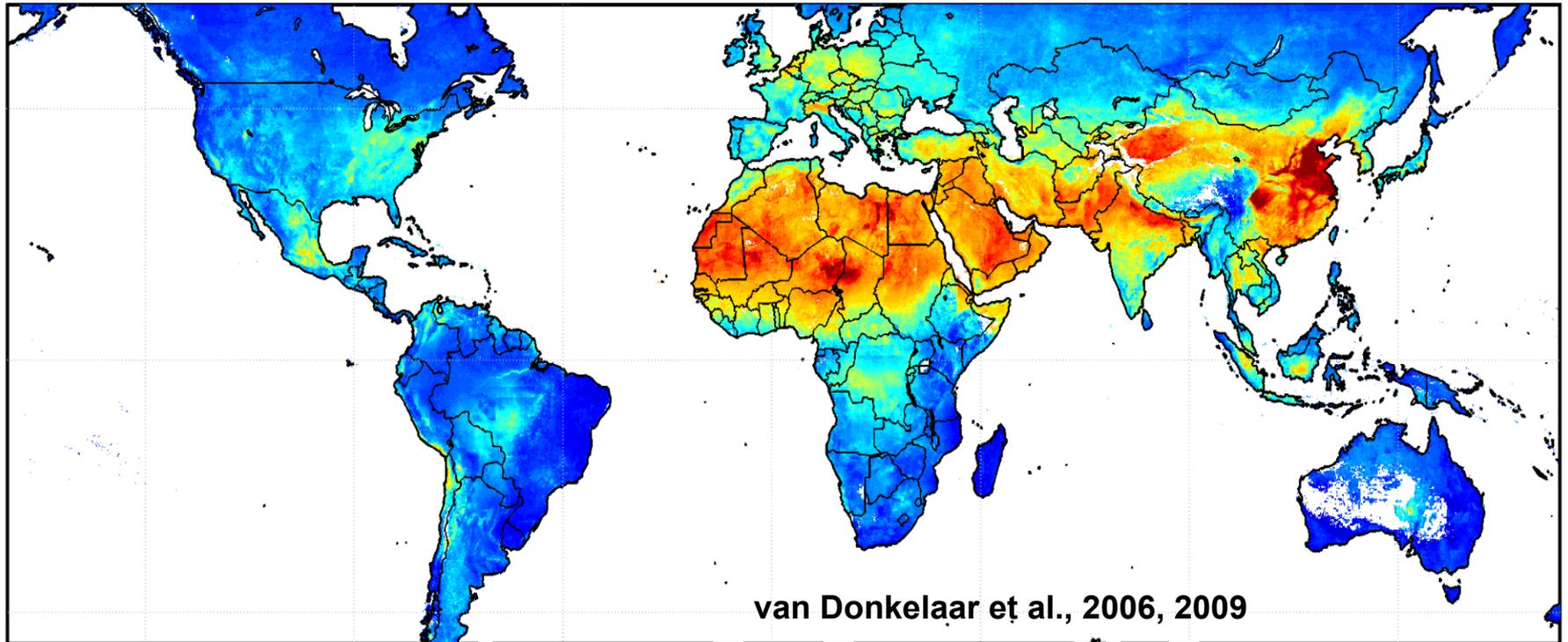
Scaling Approach

- 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

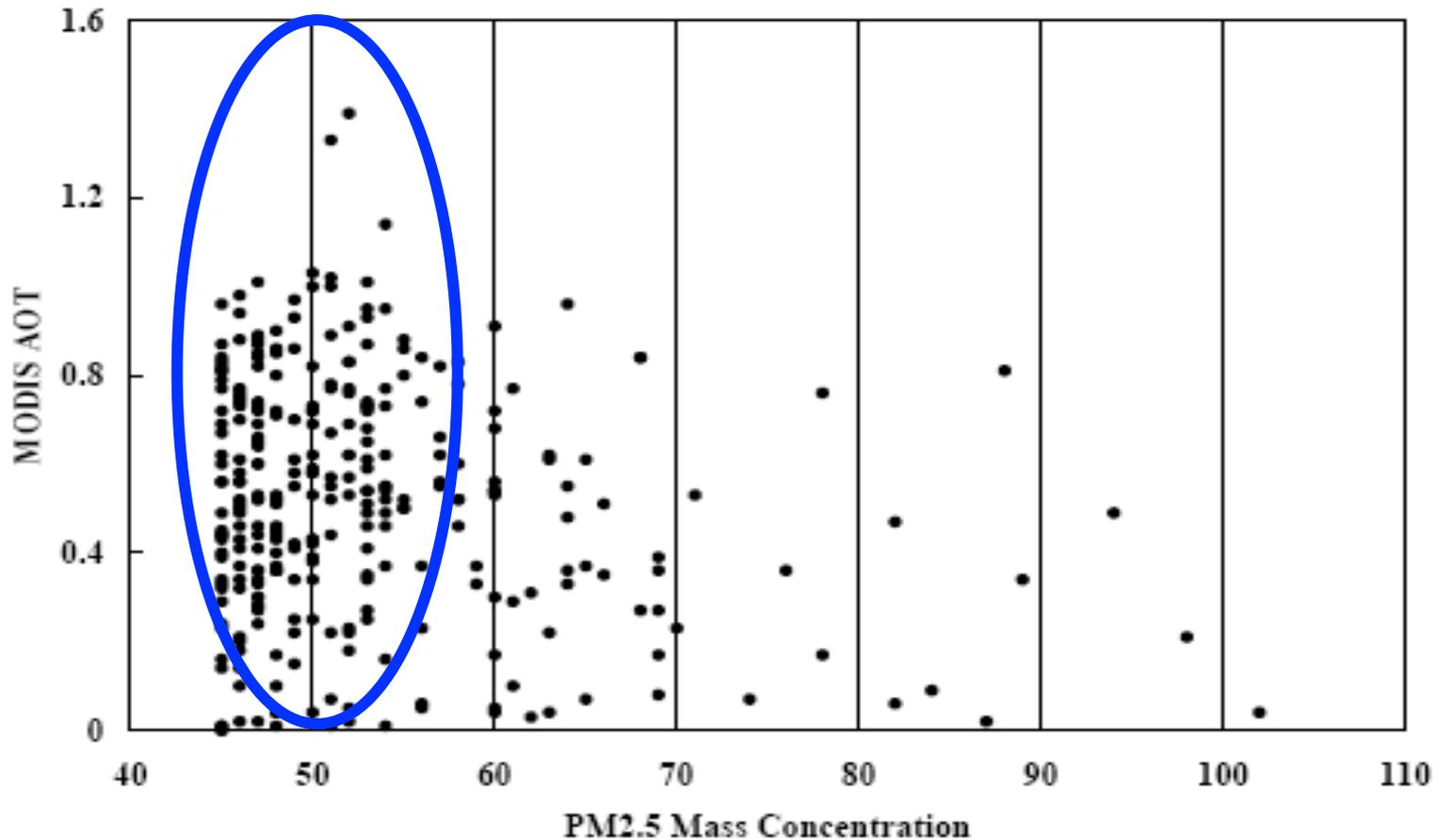
Annual Mean PM_{2.5} from Satellite Observations



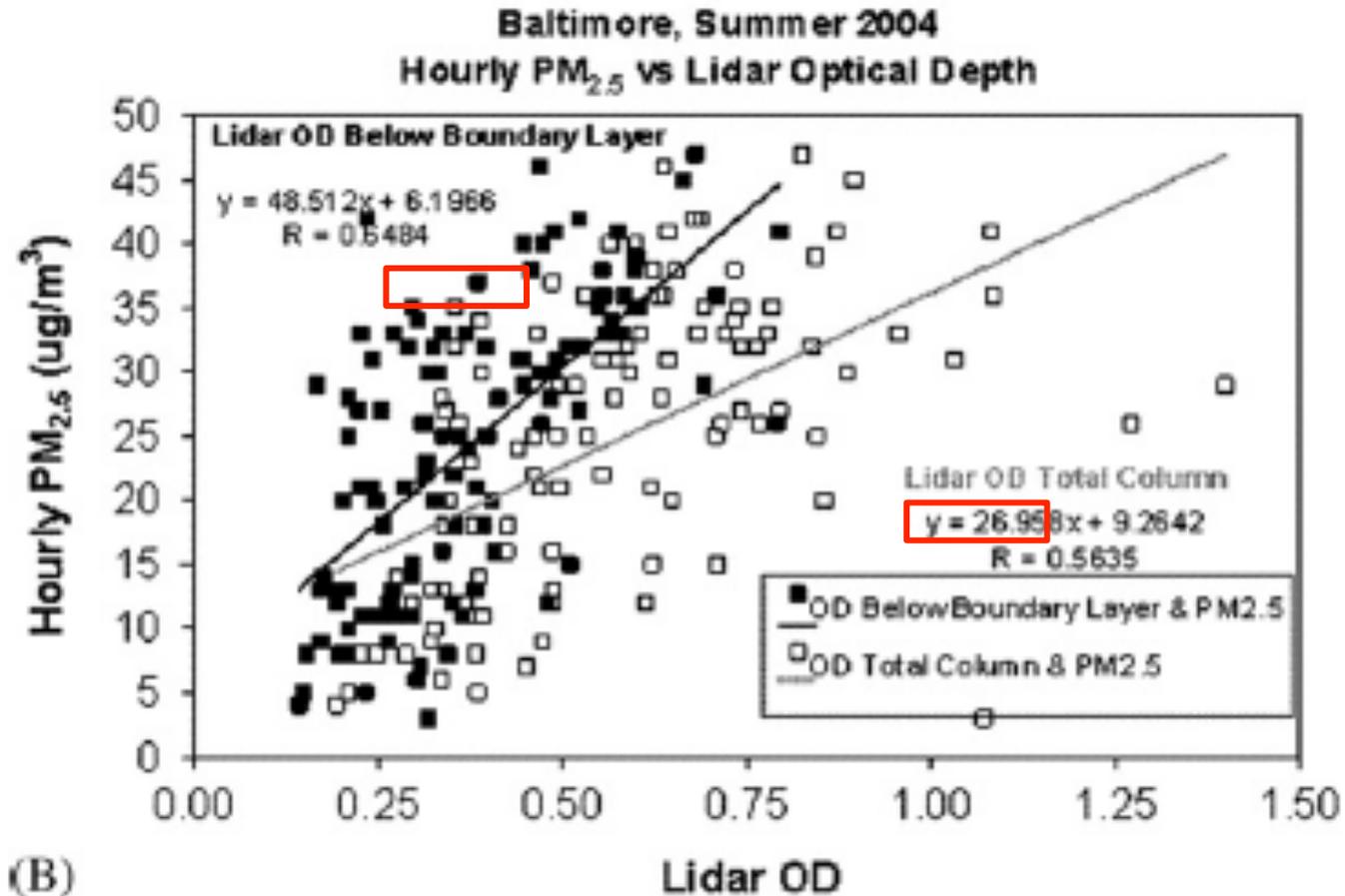
Questions to Ask: Issues

- How accurate are these estimates?
- Is the PM_{2.5}-AOD relationship always linear?
- How does AOD retrieval uncertainty affect 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 affect these estimates?

Limitation: Vertical Distribution of Aerosols



Vertical Distribution: Impact on AOD-PM2.5

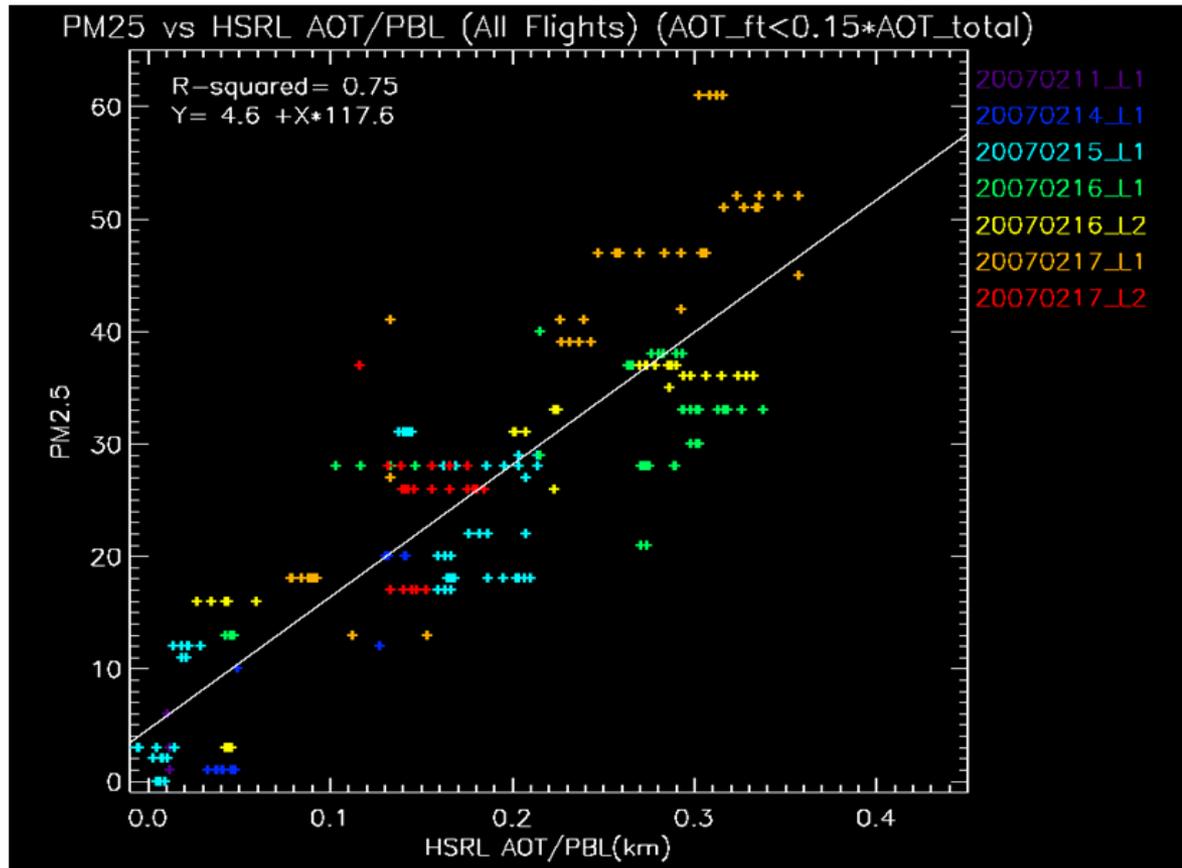


Source: Engel-Cox et al., 2006

Vertical Distribution: Impact on AOD-PM2.5

Correlation of Surface PM2.5 with HSRL AOD / PBL, All Flights

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

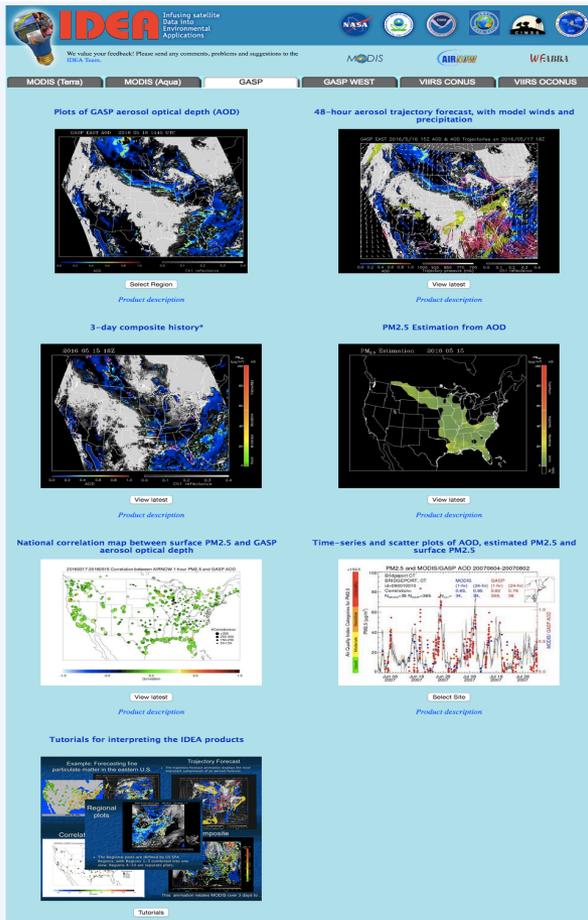
No textbook solution

Use of Satellite Data

- Currently for research
 - Spatial trends of PM2.5 on regional to national level
 - Variability of PM2.5 between years
 - Model calibration/validation
 - Exposure assessment for health effect studies
- Near-future research
 - Spatial trends at urban scale
 - Improved coverage and accuracy
 - Fused statistical-deterministic models
- For Regulation?

How Satellite Aerosol Data is Being Used

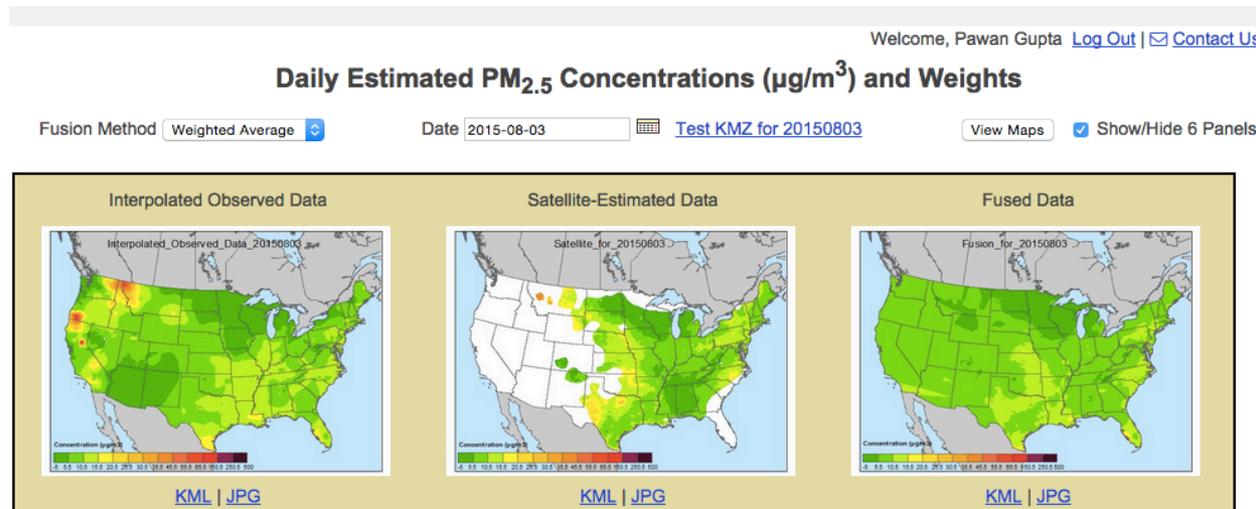
Infusing Satellite Data Into Environmental Applications



Objective: Near real-time product for state and local air quality forecasters

Goal: Improve accuracy of next day PM2.5 AQI forecasts during large aerosol events

AirNow Satellite Data Processor (ASDP)



Suggested Reading

2009 CRITICAL REVIEW

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



R.M. Hoff



Remote Sensing of Particles from Space: Have We Really Promised Land?

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-

dards (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 congress-

IMPLICATIONS

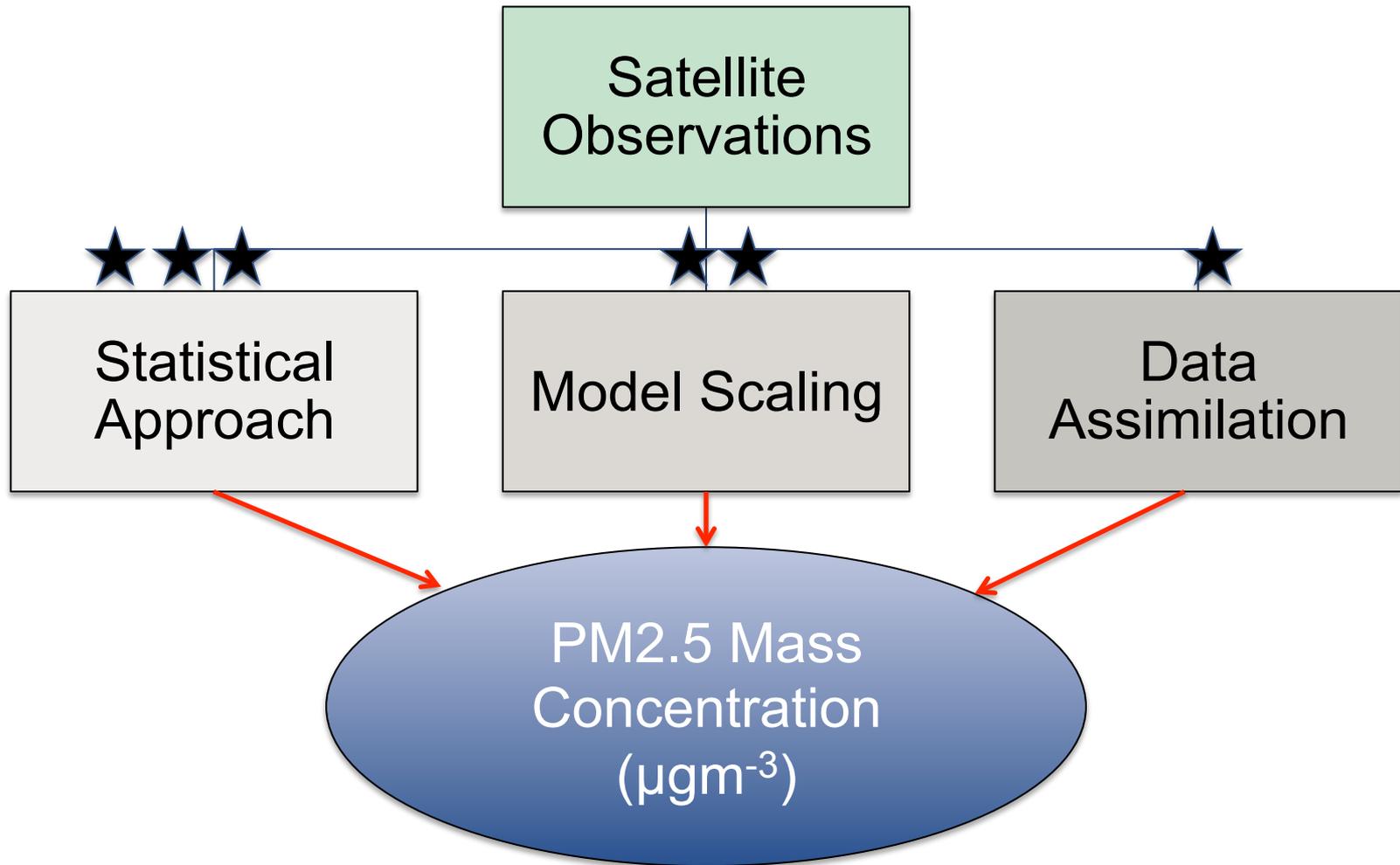
Satellite measurements are going to be an integral part of the Global Earth Observing System of Systems. Satellite measurements by themselves have a role in air quality studies but cannot stand alone as an observing system. Data assimilation of satellite and ground-based measurements into forecast models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

ellite 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.

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

Satellite Remote Sensing of PM2.5 - Summary



Questions and Discussion

- What are three differences between AOD and PM2.5 mass concentration ?
- List three advantages of using satellite observations for PM2.5 air quality monitoring
- What are the pros and cons of using scaling approach over regression method ?

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 PM2.5 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 PM2.5 using aerosol optical depth determined from satellite remote sensing. *J. Geophys. Res.*, 111, D21201, doi: 10.1029/2005JD006996, 2006.
- 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.



Questions
