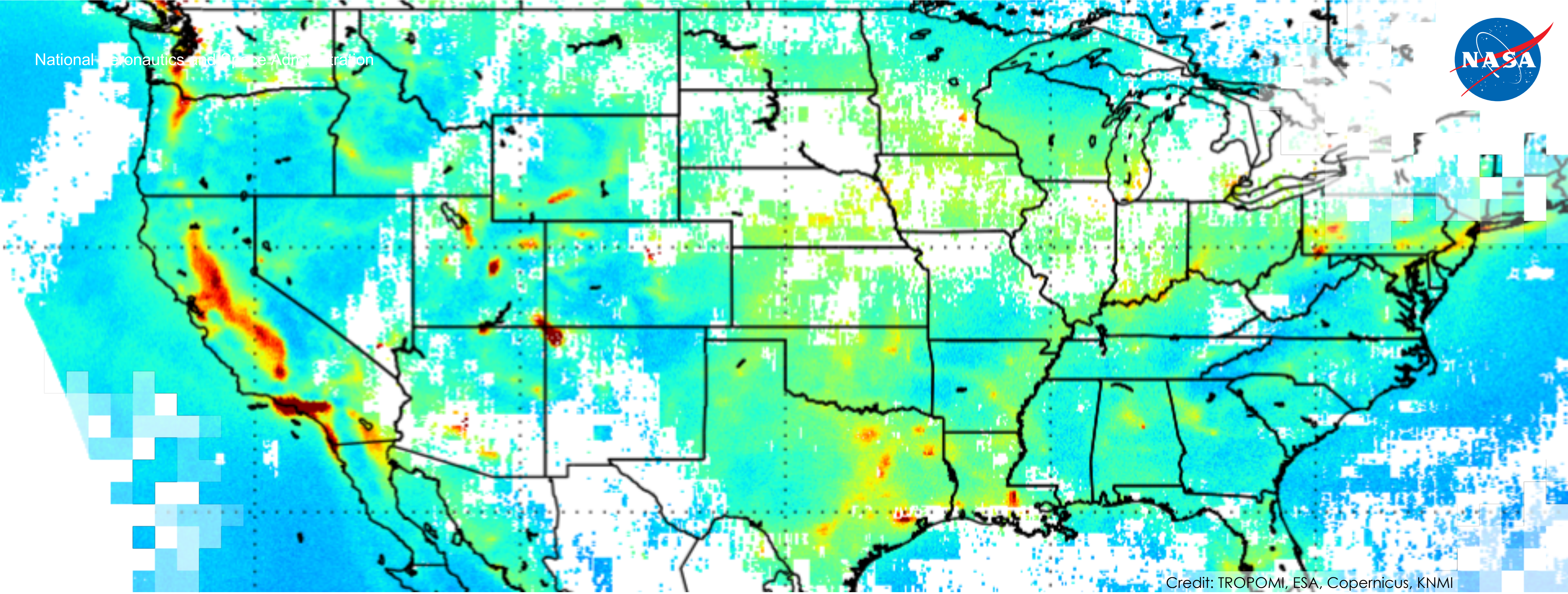
National Aeronautics and Space Administration



Credit: TROPOMI, ESA, Copernicus, KNMI

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

Pawan Gupta, and Melanie Follette-Cook

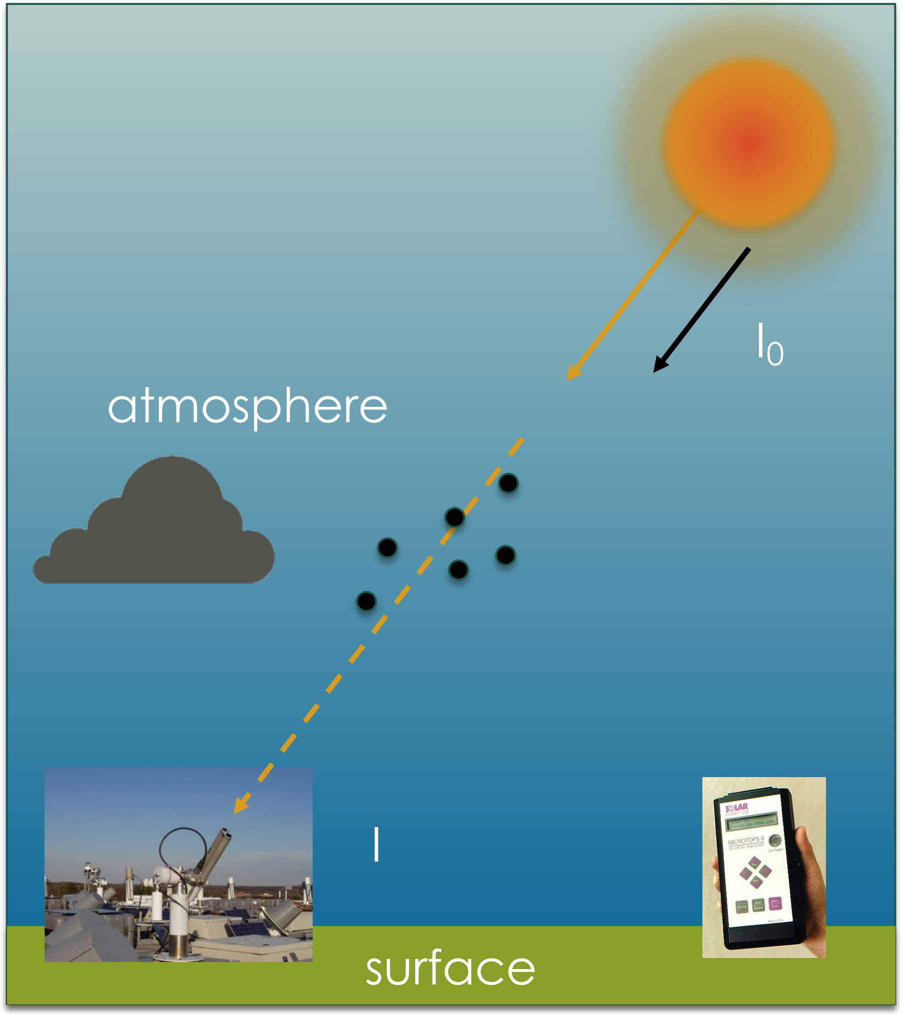
Application of Satellite Observations for Air Quality and Health Exposure, October 9-11, 2019

Objectives

By the end of this presentation, you will have understanding of:

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

Optical Depth



The optical depth expresses the quantity of light removed from a beam by **scattering** or/and **absorption** during its path through a medium

optical depth τ as:

$$I = I_o e^{-m\tau}$$
$$m = \sec\theta_0$$
$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$

$PM_{2.5}$

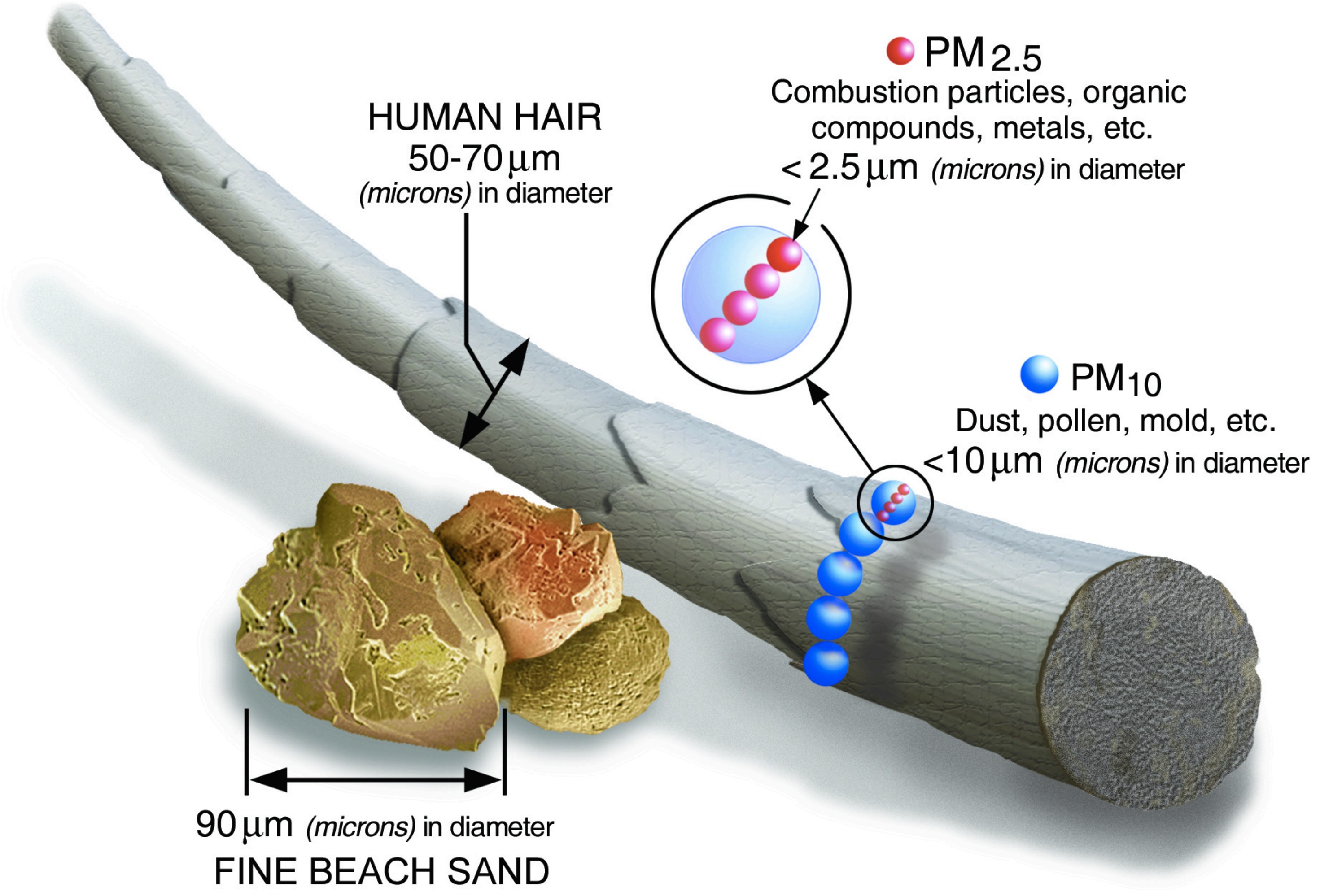


Image Credit: U.S. EPA

Surface vs. Satellite Measurements

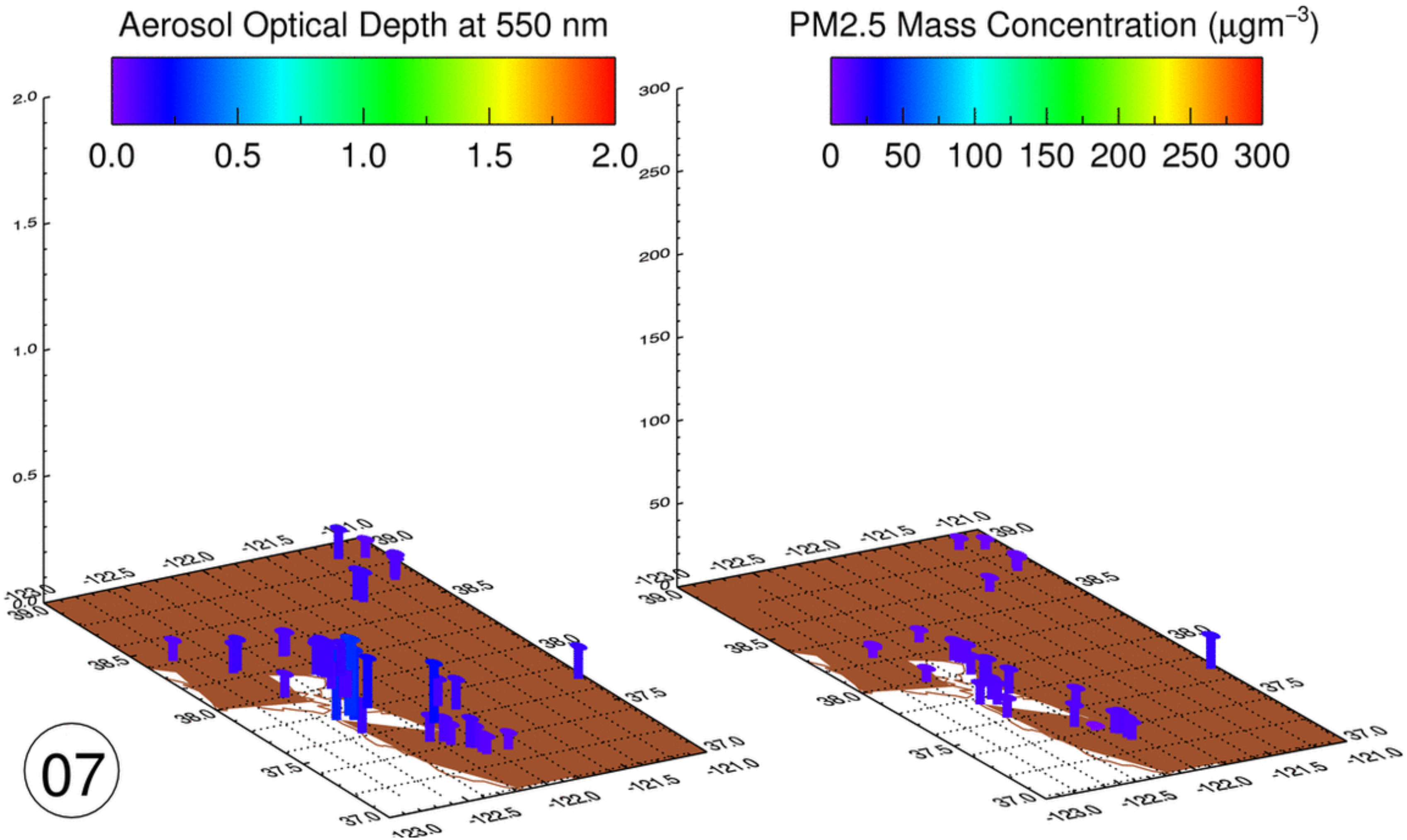
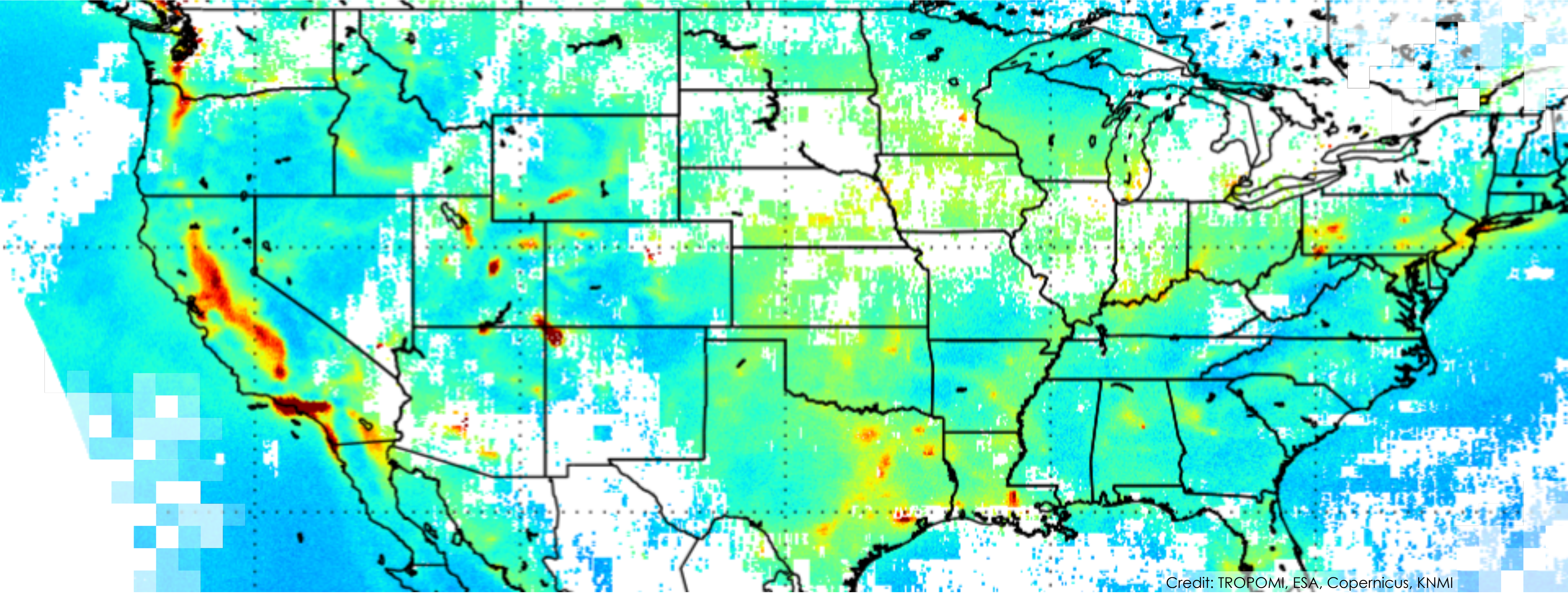
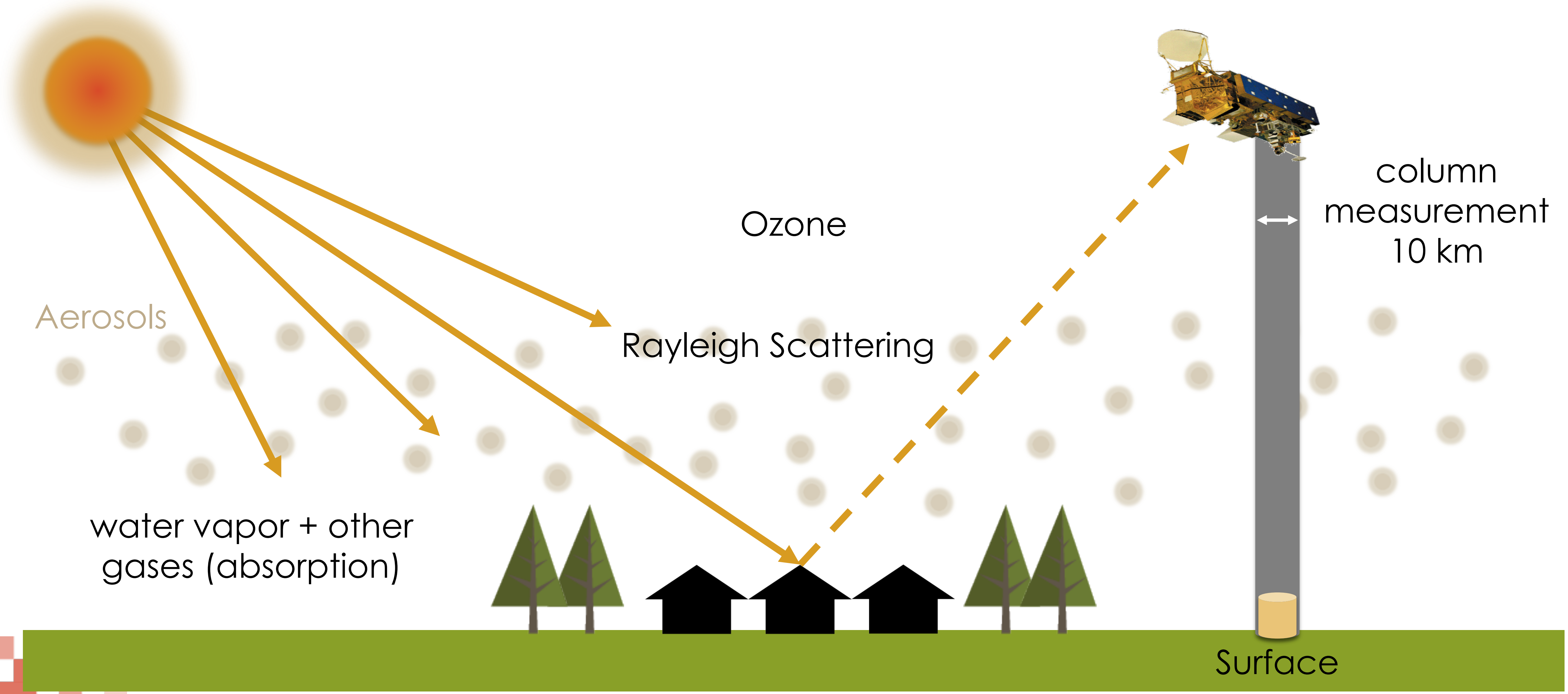


Image Credit: Gupta et al., 2018

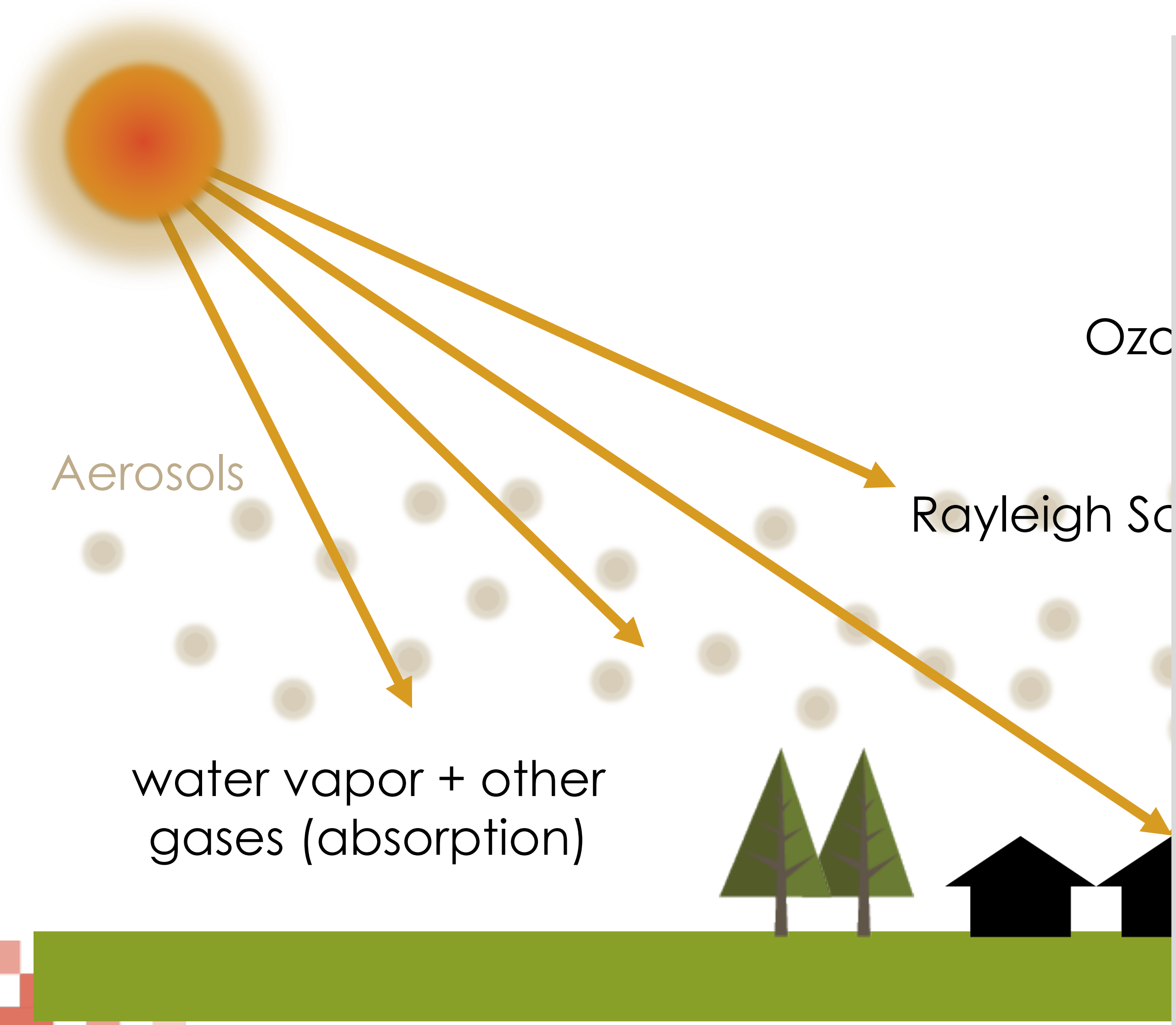


AOD (or AOT) to PM

Aerosol Optical Depth from Satellites



Aerosol Optical Depth from Satellites

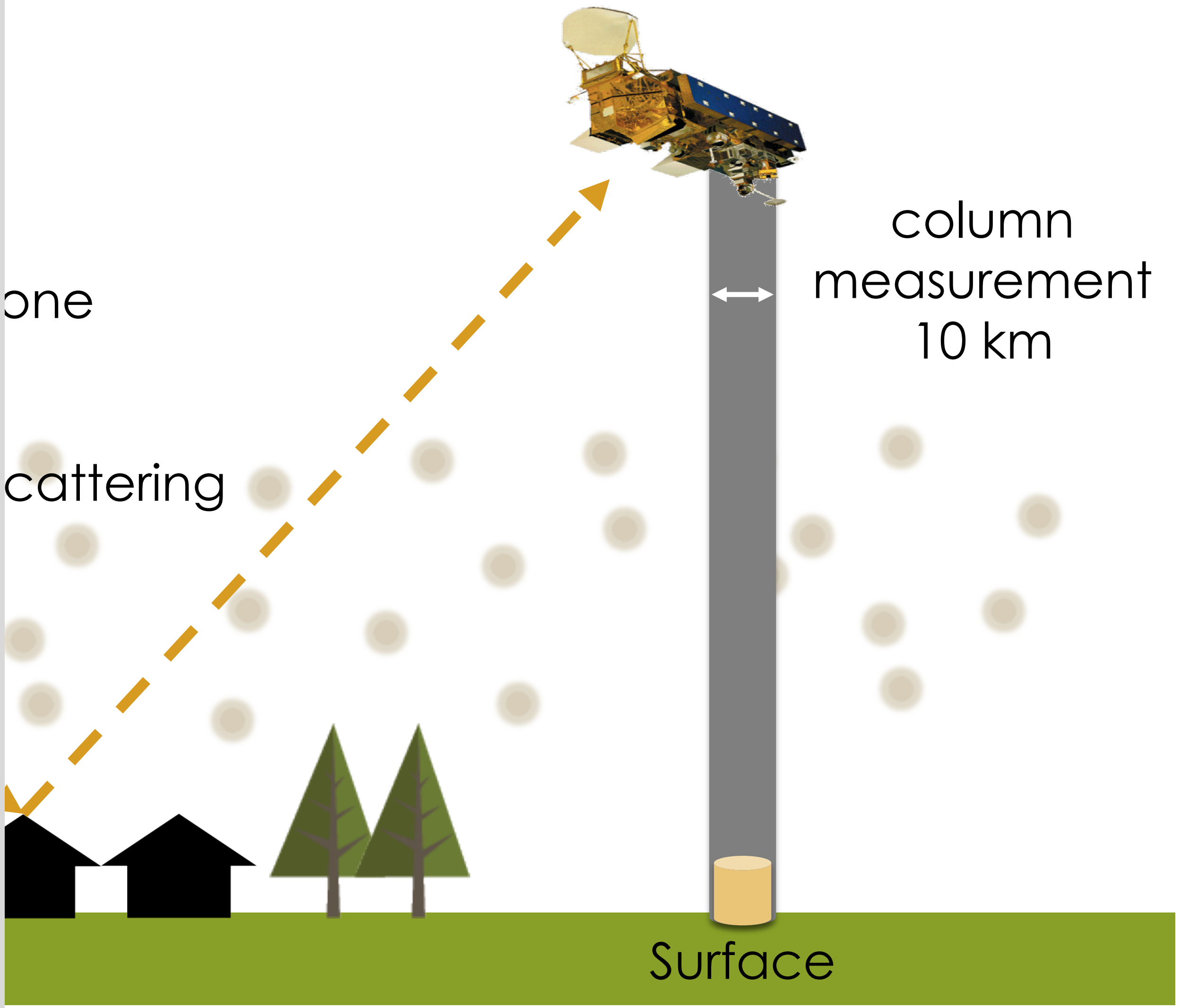


- $AOT(\tau) = \int \beta_{ext}\, dz$
  - particle size
  - composition
  - water update
  - vertical distribution

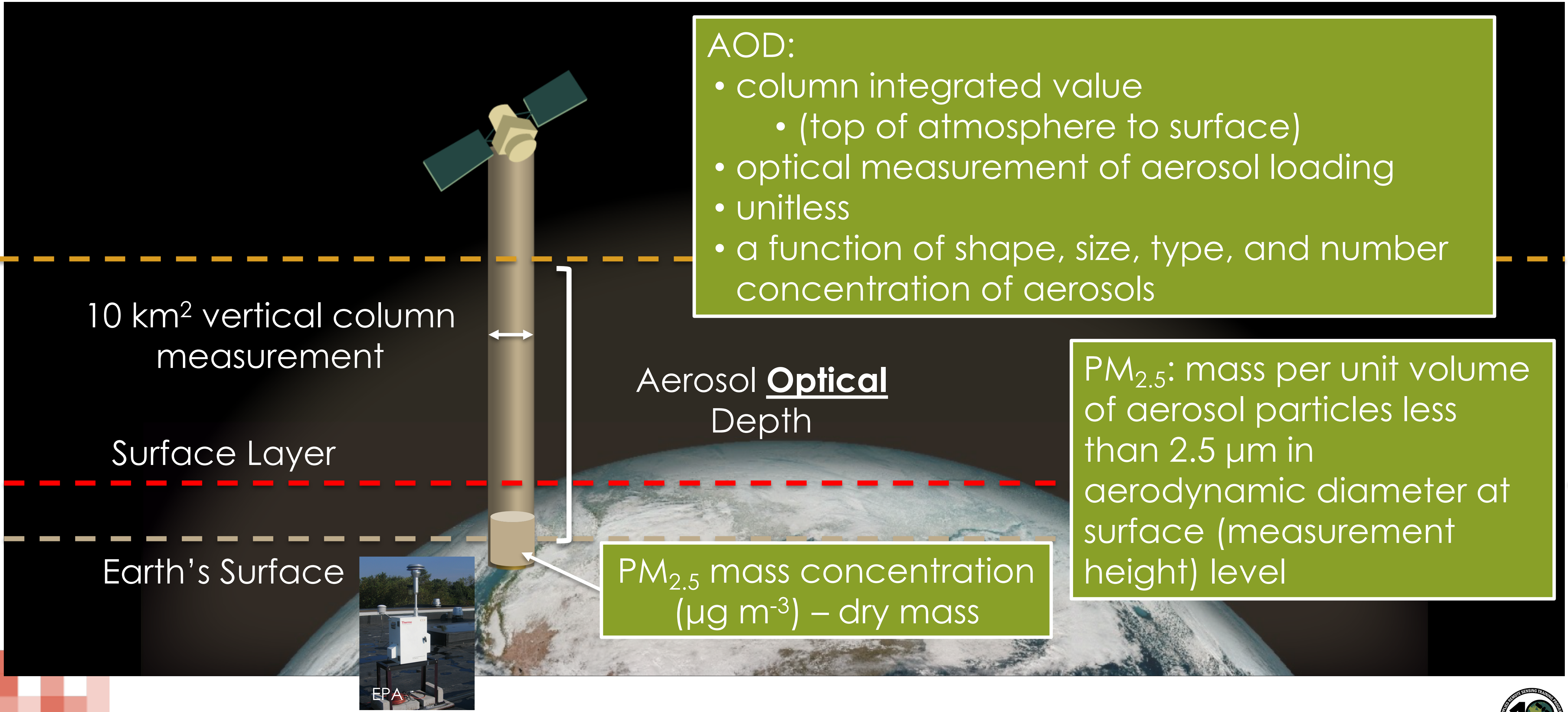
- There are satellite retrieval issues: inversion (e.g. aerosol model, background)

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



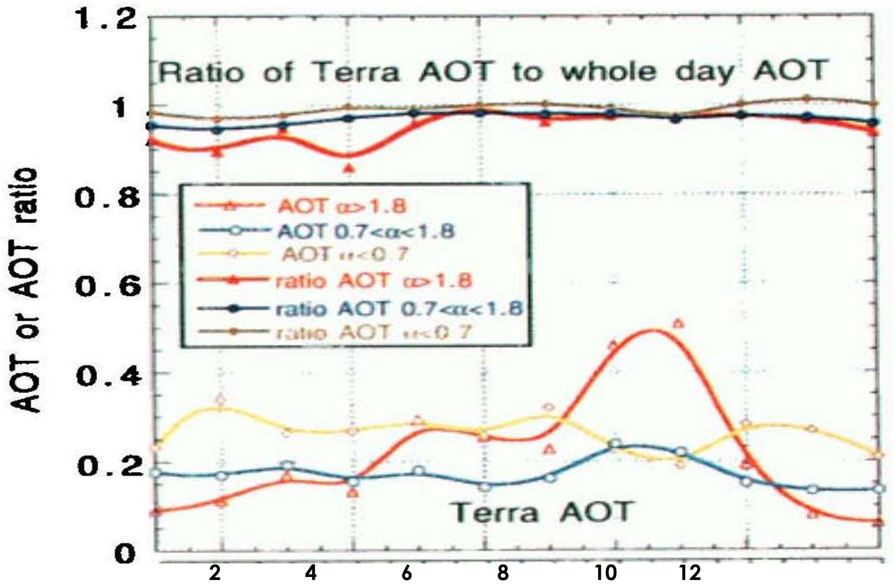
AOD:
- column integrated value
  - (top of atmosphere to surface)
- optical measurement of aerosol loading
- unitless
- a function of shape, size, type, and number concentration of aerosols

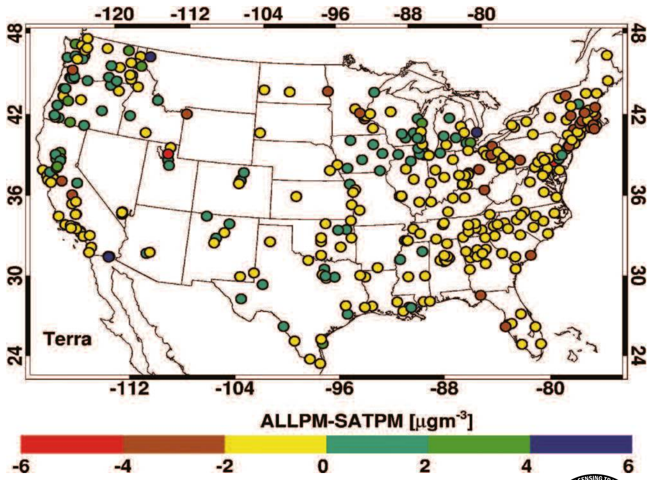
$PM_{2.5}$ mass concentration ($\mu g\ m^{-3}$) – dry mass

$PM_{2.5}$: 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

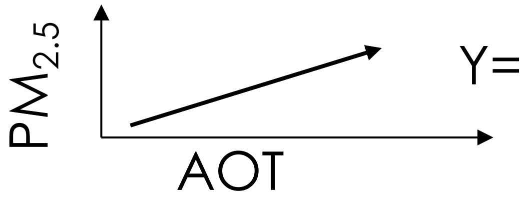
- H: mixing height
- *ƒ(RH)*: how aerosol scattering changes with changing relative humidity

Source: Hoff, R. & Christopher, S., 2009

$PM_{2.5}$ Estimation: Popular Methods

Difficulty Level

Two-Variable Method

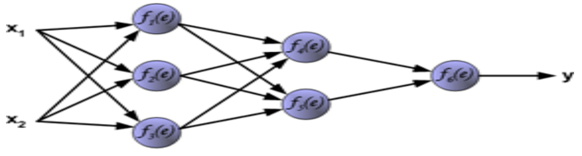


$Y = mX + c$

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)

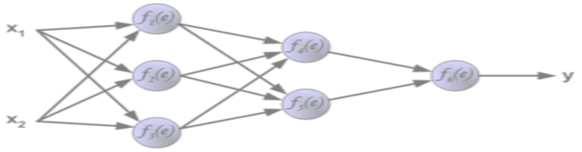
Difficulty Level

Two-Variable Method

Multivariable Method

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

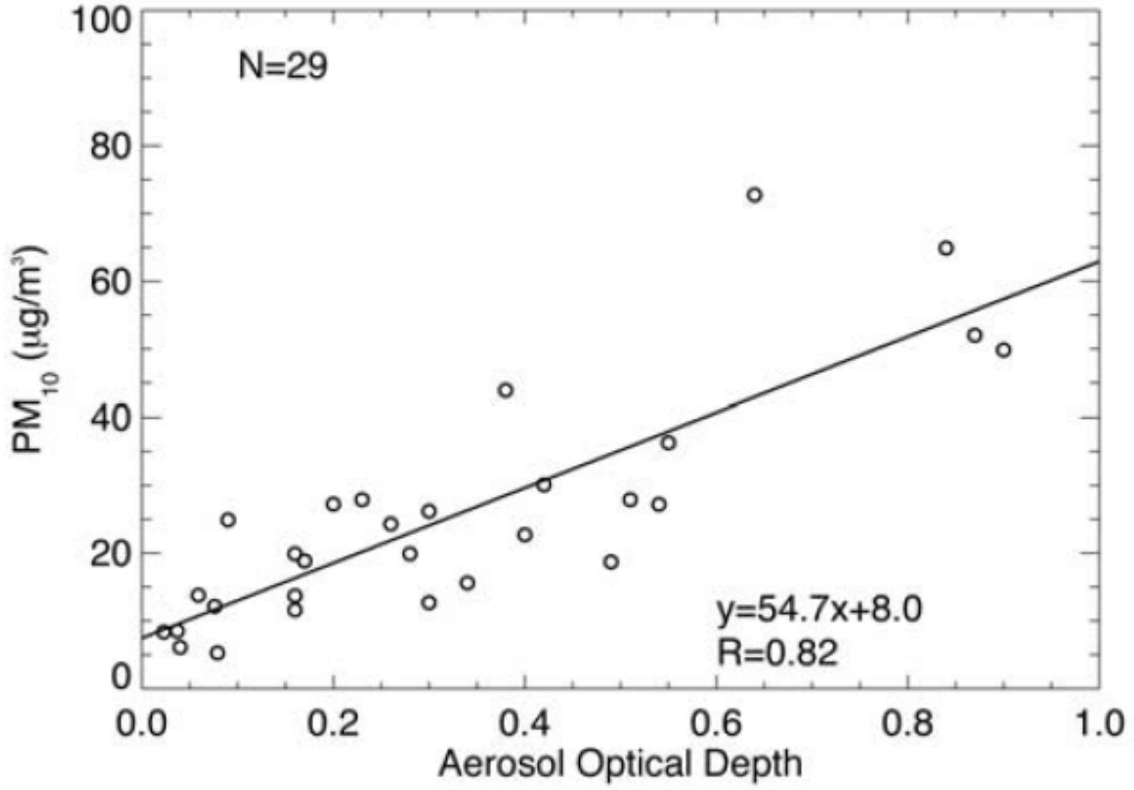
Artificial Intelligence

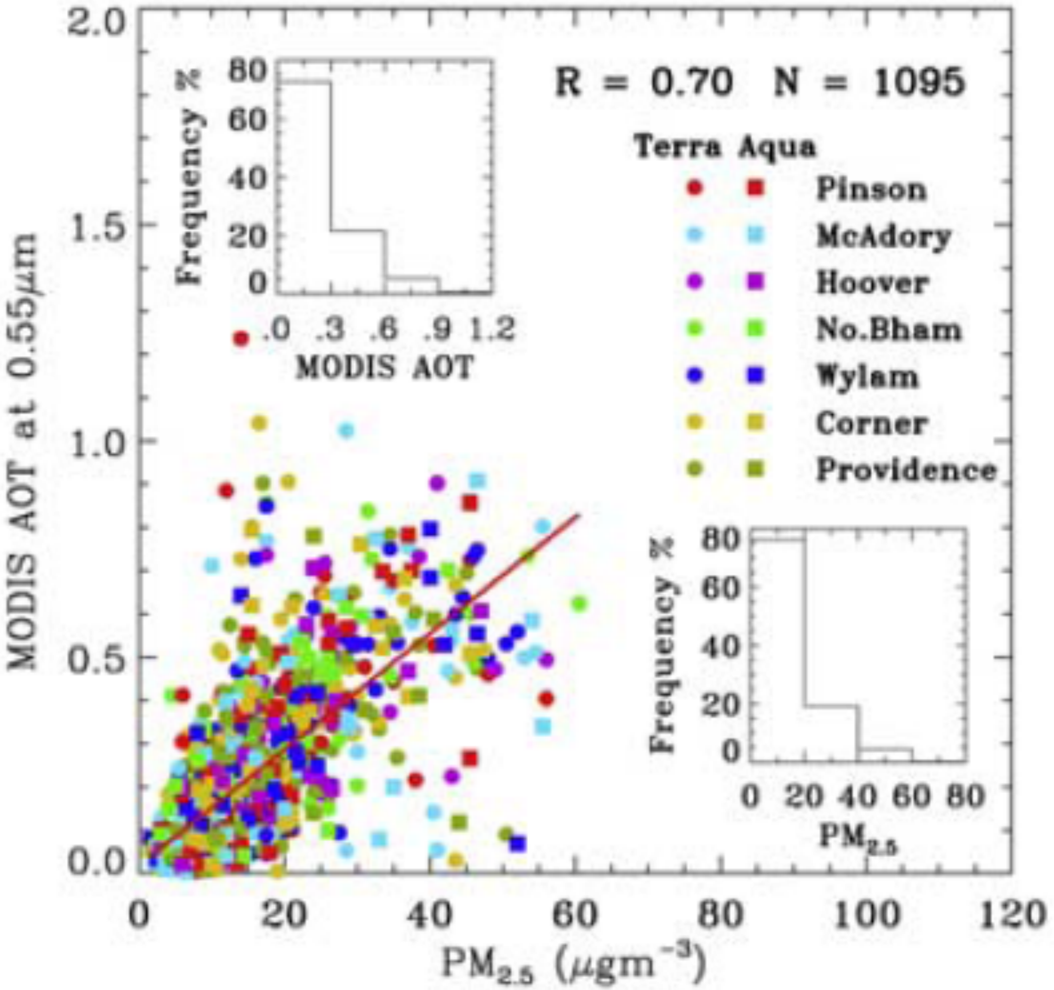


MSC

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

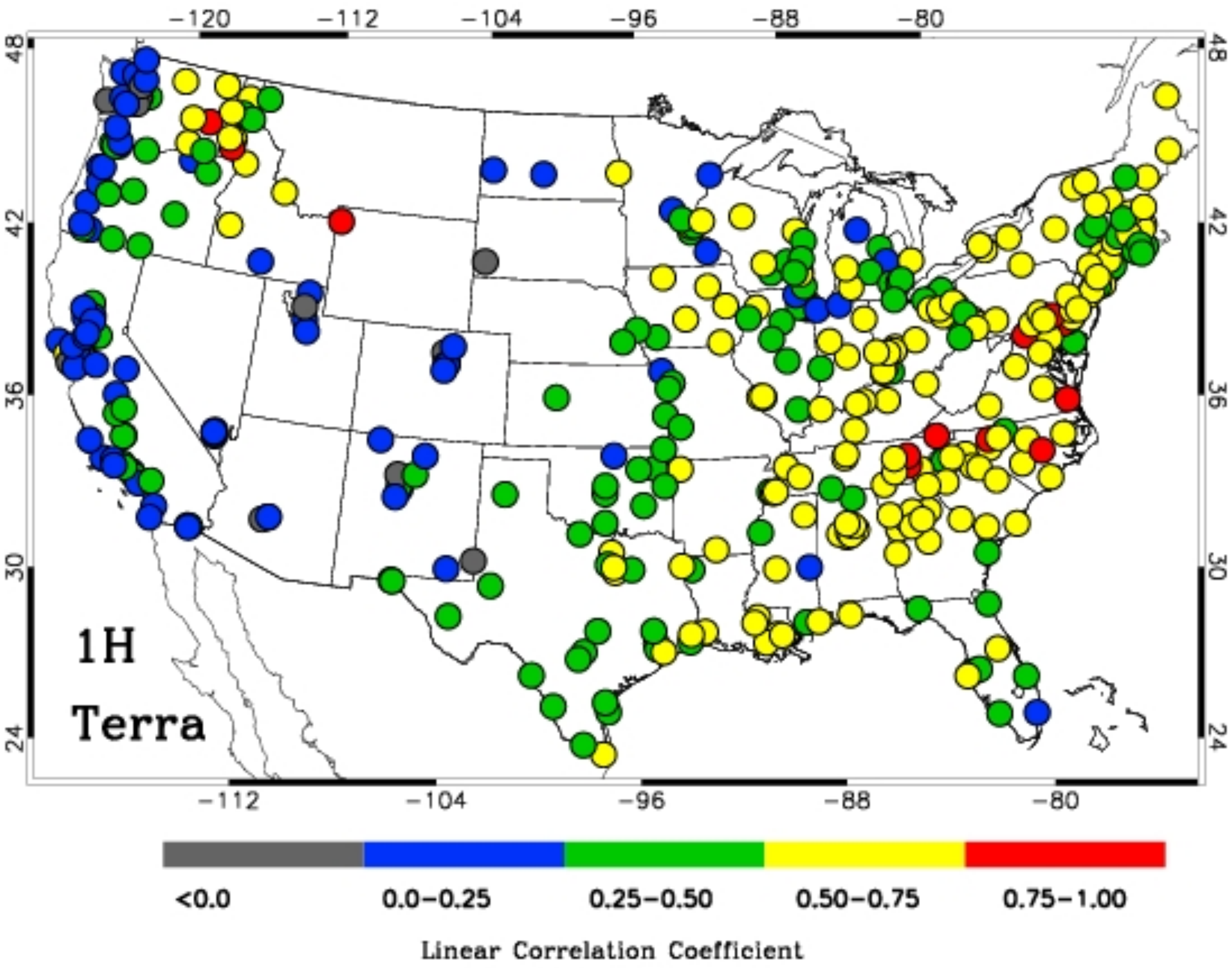
Simple Models from Early Days





(Left) Chu et al., 2003; (Right) Wang et al., 2003

AOD-$PM_{2.5}$ Relationship



Source: Gupta et al., 2008

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

Difficulty Level

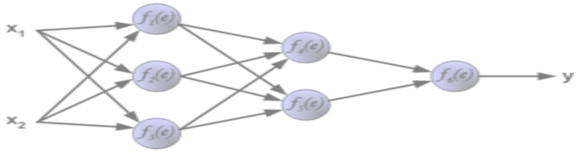
Two-Variable Method

$$Y = mX + c$$

Multivariable Method

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

Artificial Intelligence

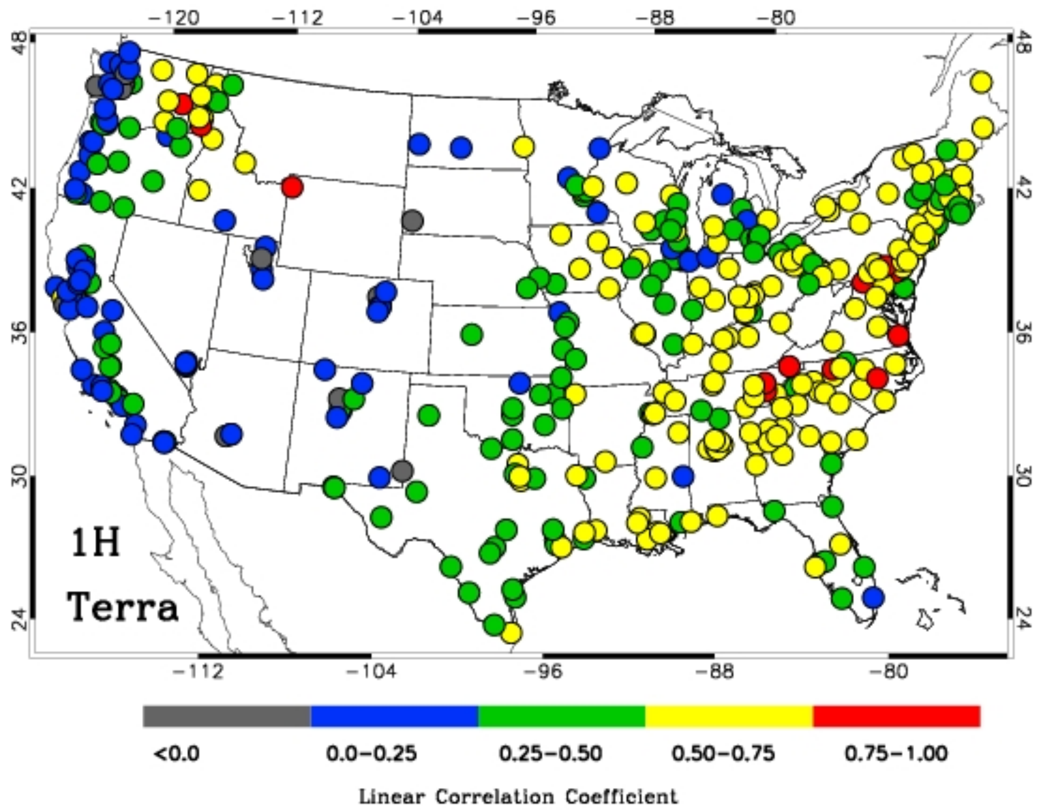


MSC

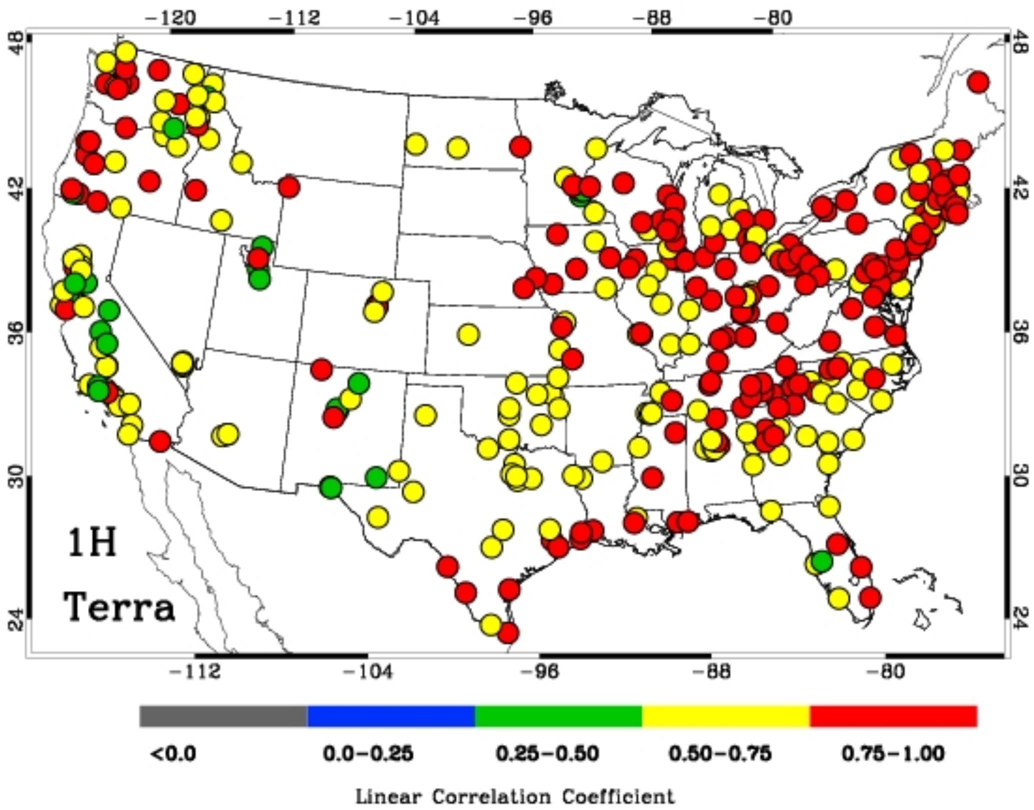
$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface area concentration}}{\text{Model AOD}} \times \text{Satellite AOD}$$

Multivariable Method (MVM)

Predictor: AOD



Predictor: AOD + Meteorology



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

Source: Gupta et al., 2008

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

Difficulty Level

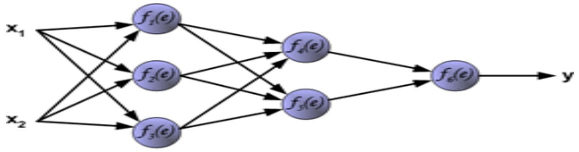
Two-Variable Method

$$Y = mX + c$$

Multivariable Method

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

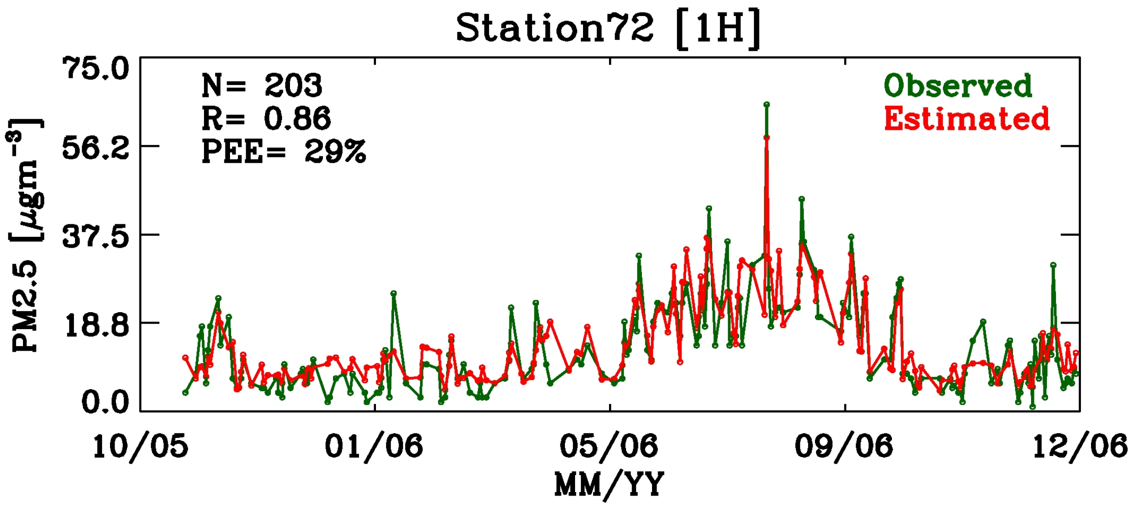
Artificial Intelligence

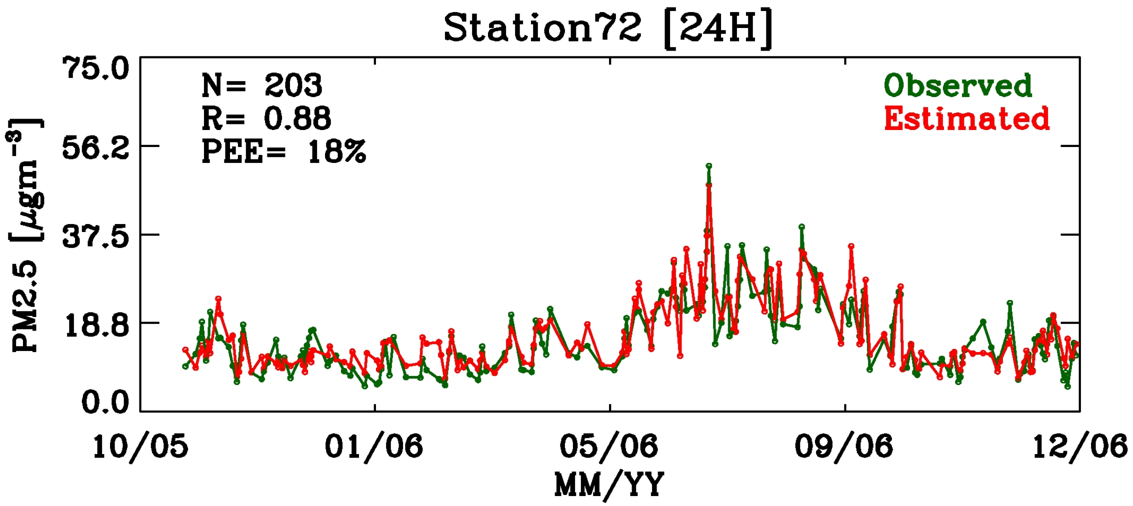


MSC

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

Time Series Examples of Results from ANN





Source: Gupta 2009

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

Difficulty Level

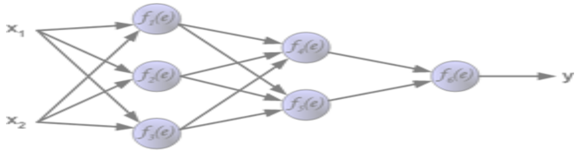
Two-Variable Method

$$Y = mX + c$$

Multivariable Method

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

Artificial Intelligence



MSC

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

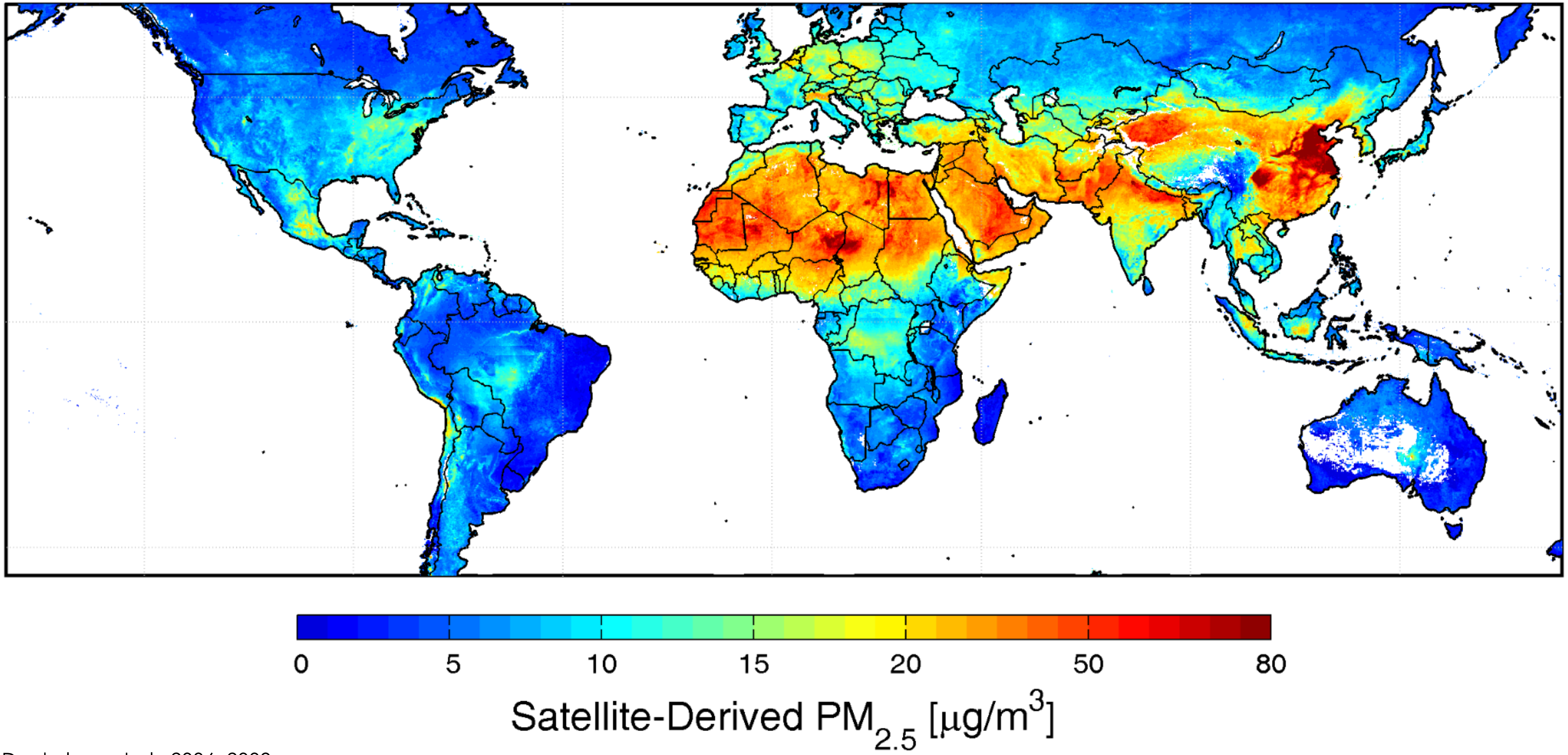
Scaling Approach

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

Source: Liu et al., 2006

Annual Mean $PM_{2.5}$ from Satellite Observations

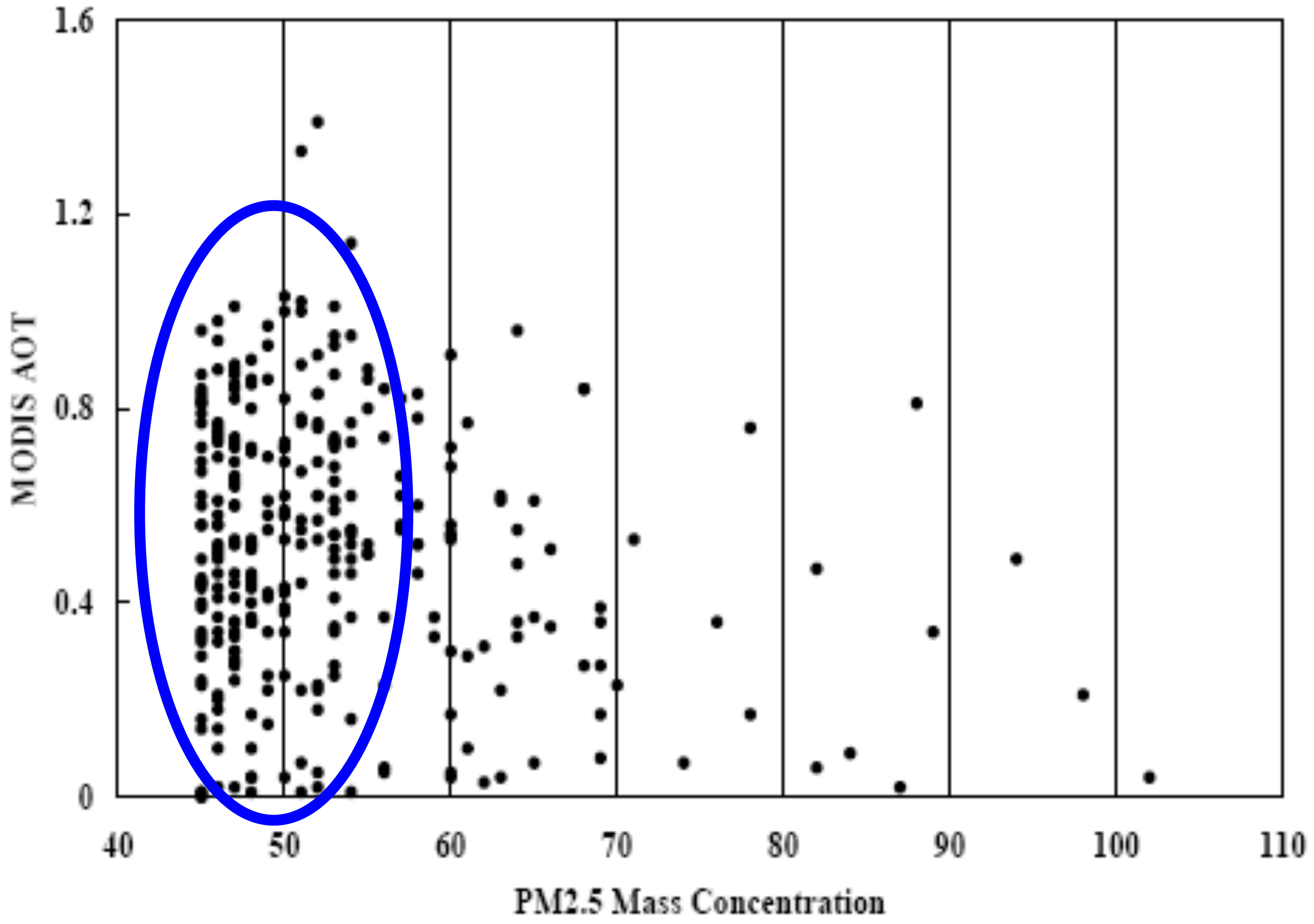


Source: von Donkelaar et al., 2006, 2009

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?

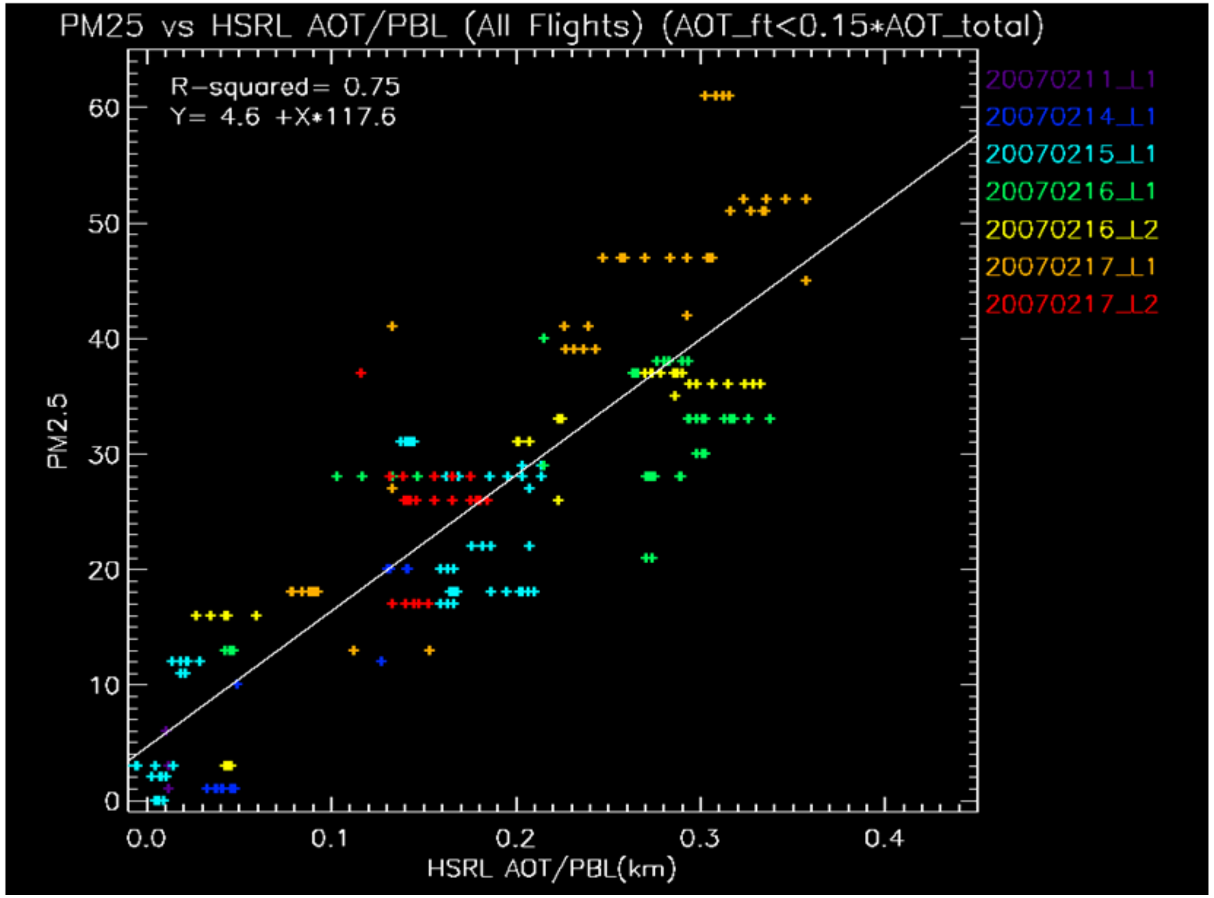
Limitation: Vertical Distribution of Aerosols



Source: Gupta et al., 2009

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

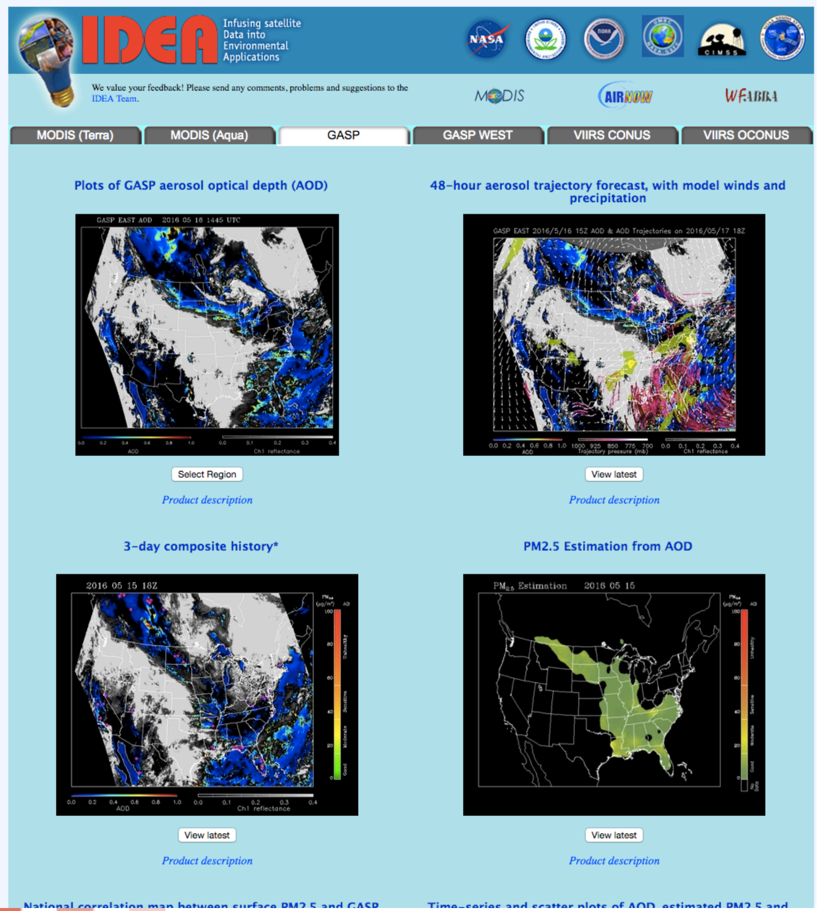
No textbook solution

Use of Satellite Data

- Currently for Research
  - Spatial distribution of $PM_{2.5}$ on 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?

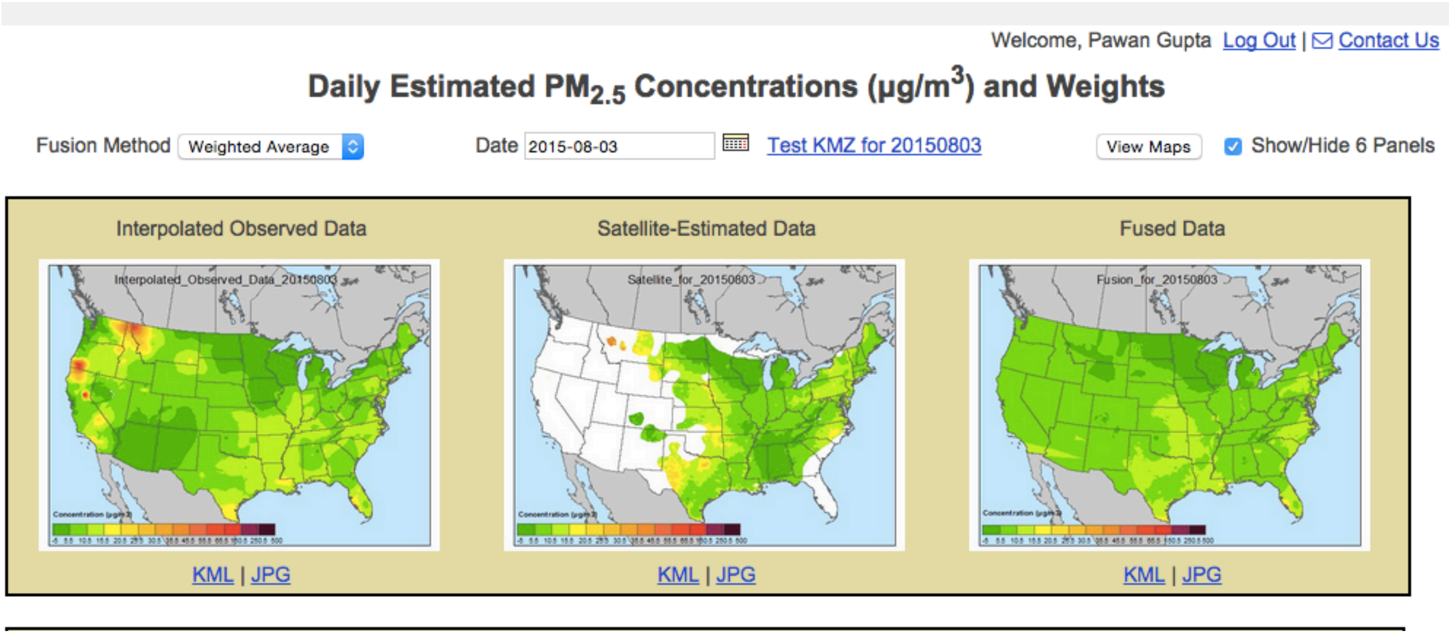
How Satellite Aerosol Data is Used

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

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?

Raymond M. Hoff
Department of Physics and the Joint Center for Earth Syste... and Technology Center, University of Maryland, Baltimore ...

Sundar A. Christopher
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,*]

1 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.); zfmao@126.com (Z.M.); aries_c_7@163.com (X.C.); 2012302170047@whu.edu.cn (N.L.); melodyrren@163.com (M.R.); 2015203050008@whu.edu.cn (F.L.)

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

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

4 International Baccalaureate Diploma Program, Wuhan Foreign Languages School, Wan Song Yuan Road, Wuhan 430022, China; hansonlu_hl@hotmail.com

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

6 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.)

7 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

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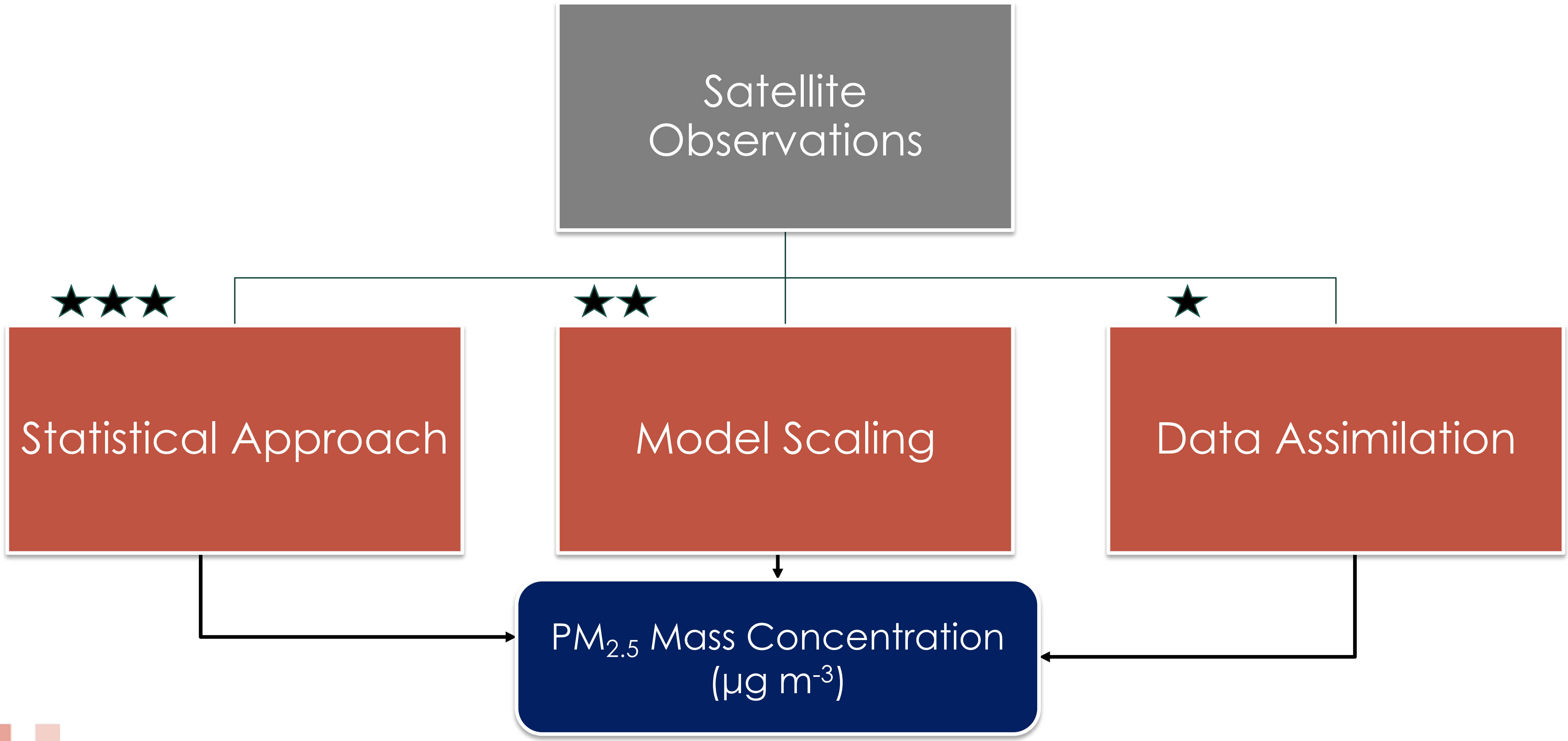
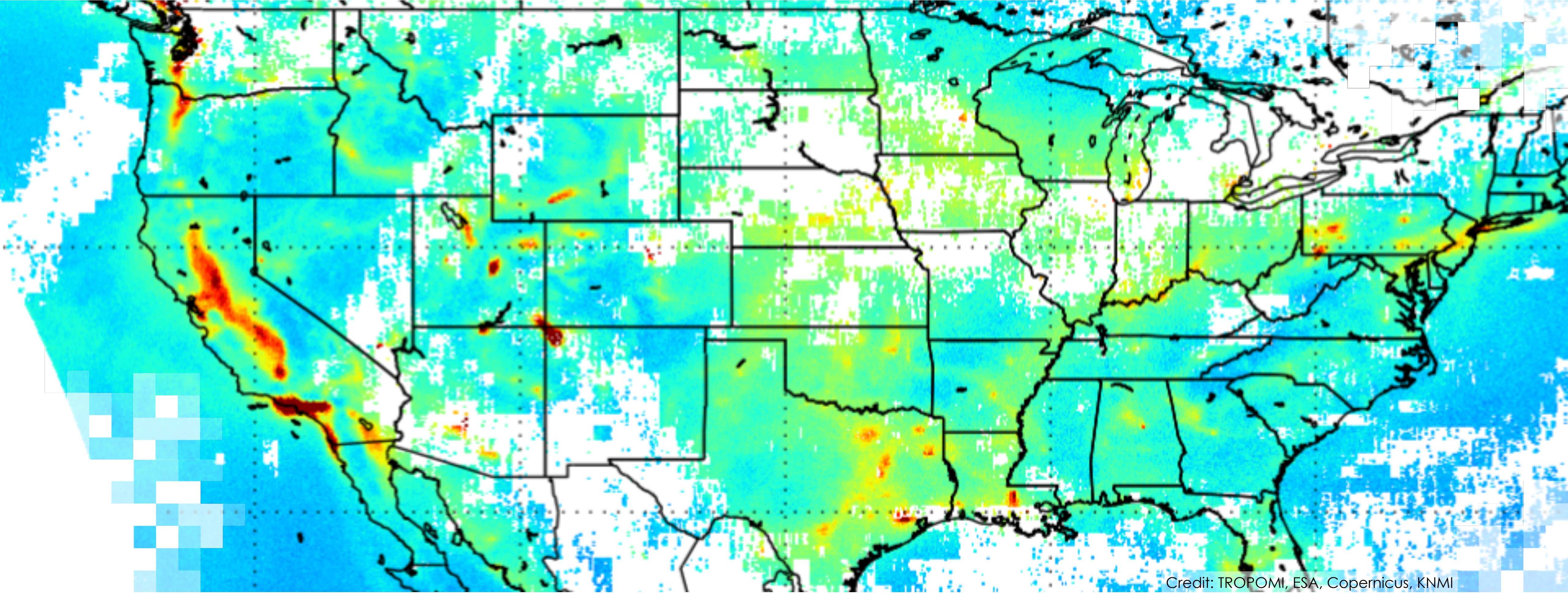
Satellite Remote Sensing of $PM_{2.5}$: Summary



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?



Questions