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

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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

Spatial Gaps

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

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

Generated: March 7, 2018
Inferring AOD and PM2.5 from Visuals

Pittsburgh

PM$_{2.5}$ = 45 μgm$^{-3}$

July 2, 2001

PM$_{2.5}$ = 4 μgm$^{-3}$

July 18, 2001

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

AOD = ~0.8

AOD = ~0.1

Inferring AOD and PM2.5 from Visuals

Singapore

High AOD

Low AOD

Image Credit: Roslan Rahman/AFP/Getty Images
Surface vs. Satellite Measurements
AOD (or AOT) to PM
Aerosol Optical Depth from Satellites

Aerosols

Rayleigh Scattering

Ozone

Water vapor + other gases (absorption)

Surface

Column measurement 10 km
Aerosol Optical Depth from Satellites

- \( \text{AOT}(\tau) = \int \beta_{\text{ext}} \, dz \)
  - 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 km² resolution
- 3x3 km² 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 per unit volume of aerosol particles less than 2.5 µm in aerodynamic diameter at surface (measurement height) level

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

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

- $\tau$: 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

Hoff, R., & Christopher, S., 2009
PM$_{2.5}$ Estimation: Popular Methods

**Two Variable Method**

$Y = mX + c$

$PM_{2.5} = \beta_0 + \alpha \times \tau + \sum (\beta_n \times M_n)$

**Multivariable Method**

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

**Artificial Intelligence**

**MSC**
**PM$_{2.5}$ Estimation: Two Variable Method (TVM)**

**Two Variable Method**

- \( Y = mx + c \)

**Multivariable Method**

\[
PM_{2.5} = \beta_0 + \alpha \times \tau + \sum (\beta_n \times M_n)
\]

**Artificial Intelligence**

**MSC**

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

NASA’s Applied Remote Sensing Training Program
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)

Two Variable Method

PM$_{2.5}$ estimation:

- Two Variable Method:
  \[ Y = mX + c \]
  
- Multivariable Method:
  \[ PM_{2.5} = \beta_0 + \alpha \times \tau + \sum (\beta_n \times M_n) \]

Artificial Intelligence

MSC

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)**

**Two Variable Method**

\[ Y = mX + c \]

**Multivariable Method**

\[ PM_{2.5} = \beta_0 + \alpha \times \tau + \sum (\beta_n \times M_n) \]

**Artificial Intelligence**

\[ y = \sum w_j x_j \]

**MSC**

Estimated \( PM_{2.5} = \) \( \frac{\text{Model surface area concentration}}{\text{Model AOD}} \) x 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)**

**Two Variable Method**

![Graph showing linear relationship between PM$_{2.5}$ and AOT](image)

\[ Y = mX + c \]

**Multivariable Method**

\[ PM_{2.5} = \beta_0 + \alpha \times \tau + \sum (\beta_n \times M_n) \]

**Artificial Intelligence**

**MSC**

Estimated PM$_{2.5}$ = \[
\frac{\text{Model surface area concentration}}{\text{} \times \text{Satellite AOD}}
\]
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$_{2.5}$ from Satellite Observations

van Donkelaar et al., 2006, 2009

NASA’s Applied Remote Sensing Training Program
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)

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Daily Estimated PM$_{2.5}$ Concentrations ($\mu g/m^3$) and Weights

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<th>Fusion Method</th>
<th>Weighted Average</th>
<th>Date</th>
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Suggested Reading


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 mean annual values for each of the four seasons.

In 2007, the A&WMA Critical Review by Bachmann discussed the history of the National Ambient Air Quality Standards (NAAQS). 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. 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
A Review on Predicting Ground PM$_{2.5}$ Concentration Using Satellite Aerosol Optical Depth

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Satellite Remote Sensing of PM$_{2.5}$: Summary

Satellite Observations

- Statistical Approach
- Model Scaling
- Data Assimilation

PM$_{2.5}$ Mass Concentration ($\mu$g m$^{-3}$)
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