Using Models and Satellite Data for Air Quality Studies: Challenges and Needs

Mian Chin
NASA Goddard Space Flight Center
Introduction

• PM2.5 (particulate matter, or aerosol particles, with diameter less than 2.5 µm) is a key component determining air quality
• Remote sensing capability of atmospheric aerosol optical depth (AOD) could lead to a quantum leap in our ability of air quality monitoring and prediction, especially for regions where surface monitoring network does not exist
• I will discuss:
  – What are the advantages and limitations of using the current satellite data for regional AQ (PM2.5) studies?
  – Can we use data assimilation to improve PM2.5 prediction?
  – What are the critical data needs?
Q1. What are the advantages and limitations of using the current satellite data for regional AQ (PM2.5) studies?
<table>
<thead>
<tr>
<th>Sat.</th>
<th>Instr.</th>
<th>Pros</th>
<th>Cons</th>
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</thead>
<tbody>
<tr>
<td>Terra &amp; Aqua</td>
<td>MODIS</td>
<td>• Daily near global coverage</td>
<td>• Large uncertainties or not data over bright surfaces</td>
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<td></td>
<td>(0.47 – 2.13 µm)</td>
<td>• Morning and afternoon observations</td>
<td>• No vertical information</td>
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<td>• Size information (fine/coarse)</td>
<td>• No speciation</td>
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<td></td>
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<td>• High spatial resolution (1 – 10 km)</td>
<td>• No data when cloudy</td>
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<tr>
<td>Terra</td>
<td>MISR</td>
<td>• High accuracy over land</td>
<td>• Limited area coverage (global coverage every ~7 days)</td>
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<tr>
<td></td>
<td>(0.45 – 0.87 µm)</td>
<td>• Size information</td>
<td>• Hit or miss – difficult for daily AQ monitoring</td>
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<td>• Air mass differentiation</td>
<td>• Almost no vertical information</td>
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<td>• Plume height information in some cases</td>
<td>• No speciation</td>
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<tr>
<td></td>
<td></td>
<td>• (Particle shape information)</td>
<td>• No data when cloudy</td>
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<tr>
<td>Aura</td>
<td>OMI</td>
<td>• Daily near global coverage</td>
<td>• No vertical information</td>
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<td></td>
<td>(0.27 – 0.50 µm)</td>
<td>• Detecting aerosol over bright land surface</td>
<td>• No speciation</td>
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<td></td>
<td>• Aerosol absorption (thus information of BC or dust)</td>
<td>• ???</td>
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<td>• Aerosol Index detecting aerosol in clouds</td>
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<td>• Precursor measurements (SO₂, NO₂)</td>
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<tr>
<td>IceSat</td>
<td>GLAS</td>
<td>• Vertical distributions</td>
<td>• Very limited space and time coverage</td>
</tr>
<tr>
<td></td>
<td>(0.532 &amp; 1.064 µm)</td>
<td>• Cloud information</td>
<td>• Uncertainties in retrieving extinction profiles</td>
</tr>
<tr>
<td>Calipso</td>
<td>CALIOP</td>
<td>• Vertical distributions</td>
<td>• Limited space and time coverage</td>
</tr>
<tr>
<td>(not launched)</td>
<td></td>
<td>• Cloud information</td>
<td>• Uncertainties in retrieving extinction profiles</td>
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MODIS AOD tracks PM2.5, providing guidance for PM2.5 forecasts

(Figures from Al-Saadi et al., BAMS 2005)
Can satellite AOD data be quantitatively used to predict surface PM2.5?

- Yes, if aerosol composition and vertical distribution do not vary much
- No, if aerosol composition and vertical distribution vary a lot
- Maybe so, if the AOD are supplemented with vertical data or a reliable chemistry-transport model

Engel-Cox et al. (2004) show that the correlation coefficients between the MODIS AOD and surface PM2.5 measurements vary with locations: better correlated in the eastern US than in the western US for the period of 4/1 – 9/30/2002.
AOD and PM2.5 is better correlated in the eastern half of the U.S. than in the western.
AOD and PM2.5 is better correlated in September than in April.
This is mainly because the change in composition and/or vertical structure.

GOCART model shows a similar relationship between AOD and PM2.5.
Composition and vertical distribution

Sulfate is the major aerosol type for both seasons.

Aerosols are mostly located within the boundary layer for both seasons.
Composition and vertical distribution: Example: Western U.S.

Aerosol composition changes with seasons

Aerosols vertical distribution changes with seasons
Smoke mixing in Maryland 20-22 July 2004

(Engel-Cox et al., Atmos. Environ., 2006)

Figures from: Ray Hoff, Ray Rodgers, Jill Engel-Cox (UMBC)
Q1. What are the advantages and limitations of using the current satellite data for regional AQ (PM2.5) studies?

R1.

- **Advantages:**
  - Providing very useful guidance – "big picture"
  - When aerosol composition and vertical profiles are relatively stable (e.g., eastern US in summer/fall), AOD is proportional to PM2.5
  - Profiling data (e.g. GLAS) can provide vertical information

- **Limitations:**
  - Quantitative use is not always possible, especially at places (e.g. western US) where aerosol composition and vertical profile have large variations
  - Satellite data are not always available (e.g., no data when cloudy, sparse temporal/spatial coverage)
  - Retrieval uncertainties

- **Best use:**
  - MODIS (and OMI):
    - Daily guidance for PM2.5 prediction
    - Scaling to PM2.5 for selected time and locations
  - MISR:
    - Gathering long-term data (e.g. monthly average for multiple years) for research
    - Selecting specific time/location for specific case studies
  - GLAS (and CALIOP):
    - Interpreting AOD-PM2.5 relationships (including plume height)
Q2. Can we use data assimilation to improve PM2.5 prediction?
What to assimilate? That is the question

- Assimilating AOD alone is not sufficient
  - What type of aerosols? Different aerosol types have different mass extinction efficiency
  - Where is the aerosol located? Aerosol aloft does not affect surface AQ
  - What about those gaps and bias?
- Assimilating surface PM2.5 and chemical composition may not be consistent with column AOD
- Assimilating radiance (directly measured by satellite) is very challenging
  - Particle shape
  - Surface albedo
  - Mixing state
  - Satellite viewing geometry, etc etc etc
- Multi-dimensional (3-D plus information on composition) assimilation may be the best, but currently has little data
AOD from MODIS, MISR, AERONET:

MODIS-AERONET

MISR-AERONET

Monthly avg AOT MODIS-AERONET 200104

Monthly avg AOT MODIS-AERONET 200109

Monthly avg AOT MISR-AERONET 200104

Monthly avg AOT MISR-AERONET 200109
Optimal integration ("fake" assimilation) of MODIS, MISR, and GOCART

- Weighing uncertainties in both satellite and model to obtain a best and complete description of AOD distributions (Yu et al., 2003)
  - Over land: mostly MISR-GOCART integration
  - Over ocean: mostly MODIS-GOCART integration
- Using aerosol compositions and vertical profiles from the model to "retrieve" PM2.5 from the integrated AOD product:

\[
PM2.5_{\text{corrected}} = PM2.5_{\text{model}} \frac{AOD_{\text{assim}}}{AOD_{\text{model}}}
\]
MO_MI_GO improves the agreement with AERONET measurements of column AOT...

Optimal integration of MODIS, MISR, GOCART

CONUS
...but does not translate to a better agreement with IMRPOVE PM2.5
**Q2.** Can we use data assimilation to improve PM2.5 prediction?

**R2.**

- Using aerosol assimilation of satellite data may not improve PM2.5 prediction compared with using model only, due to lack of constraints of vertical profile and composition.
- 3-D assimilation (e.g. AOD+lidar) is likely to significantly enhance the PM2.5 estimation but may not be practical for daily forecasts.
- Without (a) high quality model(s) the quality of assimilation cannot sustain.
- Model development and improvement is the key to integrate the knowledge and data for forecasts, assessments, analyses, and observation designing.
Q3. What are the critical needs?

R3.

- Space sensor for global or near global coverage:
  - Vertical profile measurement to resolve BL
  - Composition
  - Daily revisit (minimum)
- Ground-based networks for diurnal variation, detailed composition, and for satellite validation (mostly likely over North America and Europe):
  - AERONET type + lidar
  - Chemical composition (IMPROVE type)
- In-situ measurements (once in a while) in key areas
- These data provide critical information for model evaluation, improvement, and development
Combination of model and data can:

- Fill the gaps of observations
- Provide “inside” information of unmeasurable quantities
- Link data from different platforms (space, ground, aircraft)
- Derive relationships between remote-sensed data (AOD, extinction etc) to surface concentrations and apply these relationships to regions where AQ measurement is none (e.g. developing countries)
- Provide AQ forecast, assessment, and management strategy