An investigation of transboundary PM over northeast Asia

Park, Mi Eun, Jeong Hoon Cho, Sang-Sam Lee, Hee Choon Lee, Sun-Young Kim, Sang Boom Ryoo, Chul Han Song*

Asian Dust Research laboratory
National Institute of Meteorological Research, KMA, KOREA

*School of Environmental Science and Engineering, GIST, KOREA

mieun@korea.kr

17 June, 2015
Research backgrounds I

Transboundary air pollution between countries

- Cause of serious international problems in Europe, Asia, and North America
  e.g., acid precipitation, regional-scale formation of ground-level ozone and particles, visibility impairment

- Efforts to manage transboundary air pollution
  - [Europe] Convention on Long-Range Transboundary Air Pollution (CLRTAP) supported by UNECE (United Nations Economic Commission for Europe) and European Monitoring and Evaluation Programme (EMEP)
  - [Northeast Asia] Long-range Transboundary Air pollutants (LTP) in northeast Asia conducted as part of international joint research among Korea, Japan, and China
• Quantitative evaluations of Long-Range Transport (LRT)
  – Chemistry-transport model (CTM) simulations
    • Large uncertainties in the emission rates
    • Uncertainties related to the CTM and meteorological model simulations
    • Uncertainties in atmospheric secondary particle formation and particle generation/transport
  
  – Combination of CTM simulations with remote-sensing data
    • Data assimilation
    • Utilization of AOD as a proxy for surface-level PM concentrations
  
  – Geostationary Ocean Color Imager (GOCI)
    • High temporal resolution (every ~1 hour interval during the daytime)
    • Level-2 AOD data converted by “Yonsei aerosol retrieval algorithm”
Research objectives

- To evaluate transboundary **long-range transport PM pollution** using AODs as a proxy for PM concentrations over **northeast Asia**

- To obtain more accurate AODs, by combining **hourly GOCI-retrieved** and CMAQ-simulated AODs through a data assimilation technique
Modeling descriptions

Modeling domain
- 95-145°E; 20-50°N
- 30km×30km (137×113)
- 14 vertical layers

Modeling periods
- 1\textsuperscript{st} April – 31\textsuperscript{st} May, 2011

US EPA/CMAQ v4.5.1
- Meteorological fields from PSU/MM5
- Emission inventories
  - Output for the year 2011, using the projection factors based on the GAINS emission scenarios (CO, NO\textsubscript{x}, VOC, SO\textsubscript{2}, NH\textsubscript{3}, CO\textsubscript{2}, CH\textsubscript{4}, PM\textsubscript{2.5}) (In collaboration with Prof. Woo at Kunkuk Univ.)
  - Inclusion of Fire Inventory from NCAR (FINN) (Wiedinmyer et al., 2011)
Observation data

Satellite observations
- Hourly AOD data retrieved from the COMS/GOCI (09:00 – 16:00 LST) sensor through Yonsei aerosol retrieval algorithm (In collaboration with Prof. Kim at Yonsei Univ.)

Ground-based observations from AERONET
- 5 sites (Korea & Japan)
- AOD: Level 2.0 (quality-assured)
## Aerosol optical property (AOP) retrievals from geostationary satellites

<table>
<thead>
<tr>
<th>Satellite &amp; Sensor</th>
<th>GMS5&lt;sup&gt;1&lt;/sup&gt; VISSR&lt;sup&gt;7&lt;/sup&gt;</th>
<th>MTSAT-1 R&lt;sup&gt;2&lt;/sup&gt; JAMI&lt;sup&gt;8&lt;/sup&gt;</th>
<th>MSG&lt;sup&gt;3&lt;/sup&gt; SEVIRI&lt;sup&gt;9&lt;/sup&gt;</th>
<th>GOES&lt;sup&gt;4&lt;/sup&gt; GOES-8</th>
<th>COMS&lt;sup&gt;5&lt;/sup&gt; GOCI&lt;sup&gt;10&lt;/sup&gt;</th>
<th>GOES-R ABI&lt;sup&gt;11&lt;/sup&gt;</th>
<th>GEO-KOMPSAT&lt;sup&gt;6&lt;/sup&gt; &amp; ABI &amp; GOCI-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>MET&lt;sup&gt;13&lt;/sup&gt; sensor</td>
<td>MET sensor</td>
<td>MET sensor</td>
<td>MET sensor</td>
<td>Ocean color imager</td>
<td>MET sensor</td>
<td>Environ. &amp; Ocean color imager</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>1 hour</td>
<td>30 min</td>
<td>15 min</td>
<td>15 min</td>
<td>1 hour</td>
<td>TBD&lt;sup&gt;17&lt;/sup&gt;</td>
<td>1 hour (GEMS)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>1.25 km / b) 5 km</td>
<td>1.25 km / 5 km</td>
<td>1 km / 3 km</td>
<td>1 km / 4 km</td>
<td>0.5 km / 0.5 km</td>
<td>0.5 km / 2 km</td>
<td>0.25 km / 1 km</td>
</tr>
<tr>
<td>Number of bands</td>
<td>1 VIS&lt;sup&gt;14&lt;/sup&gt; / 3 IR&lt;sup&gt;16&lt;/sup&gt;</td>
<td>1 VIS / 4 IR</td>
<td>2 VIS/ 2 NIR / 8 IR</td>
<td>1 VIS / 4 IR</td>
<td>6 VIS / 2 NIR&lt;sup&gt;15&lt;/sup&gt;</td>
<td>2 VIS / 4 NIR / 10 IR</td>
<td>13 VIS/NIR</td>
</tr>
<tr>
<td>Covering region</td>
<td>East Asia &amp; West Pacific Ocean</td>
<td>East Asia &amp; West Pacific Ocean</td>
<td>Central Europe</td>
<td>Eastern US</td>
<td>Northeast Asia</td>
<td>US</td>
<td>East, Southeast &amp; Central Asia</td>
</tr>
<tr>
<td>Launch year</td>
<td>March 1995</td>
<td>February 2005</td>
<td>August 2002</td>
<td>April 1994</td>
<td>June 2010</td>
<td>Schedule to be launched in 2015</td>
<td>Schedule to be launched in 2018</td>
</tr>
<tr>
<td>References</td>
<td>Wang et al., 2003, Masuda et al., 2002</td>
<td>Kim et al., 2008</td>
<td>Popp et al., 2007</td>
<td>Knapp et al., 2002, Christopher et al., 2002, Knapp et al., 2005</td>
<td>Lee et al., 2010, this study</td>
<td>Laszlo et al., 2008</td>
<td></td>
</tr>
</tbody>
</table>

1) GMS: Geostationary Meteorological Satellite  
2) MTSAT-1R: Multi-functional Transport Satellite  
3) MSG: Meteosat Second Generation  
4) GOES: Geostationary Operational Environmental Satellite  
5) COMS: Communication, Ocean, and Meteorological Satellite  
6) GEO-KOMPSAT: Geostationary Earth Orbit KOREA Multi-Purpose SATellite  
7) VISSR: Visible and Infra-Red Spin Scan Radiometer  
8) JAMI: Japanese Advanced Meteorological Imager  
9) SEVIRI: Spinning Enhanced Visible and Infra-Red Imager  
10) GOCI: Geostationary Ocean Color Imager  
11) ABI: Advanced Baseline Imager  
12) GEMS: Geostationary Environment Monitoring Spectrometer  
13) MET: Meteorological  
14) VIS: VISible  
15) NIR: Near Infra-Red  
16) IR: Infra-Red  
17) TBD: To Be Determined  

a) Resolution for the visible channels  
b) Resolution for the infra-red channels
Evaluation of GOCI-retrieved AOD
AOD assimilation: Optimal Interpolation (OI)

\[ \tau_m' = \tau_m + K \left( \tau_o - H \tau_m \right) \]

\[ K = BH^T \left( H B H^T + O \right)^{-1} \]

\[ O = \left[ (f_o \tau_o)^2 + (\varepsilon_o)^2 \right] I \]

\[ B(d_x, d_z) = \left[ (f_m \tau_m)^2 + (\varepsilon_m)^2 \right] \exp \left( -\frac{d_x^2}{2l_{mx}^2} \right) \exp \left( -\frac{d_z^2}{2l_{mz}^2} \right) \]

Statistical Parameters

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>This study</th>
<th>Experiment ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional error coefficient in model ( \tau ) ( f_m )</td>
<td>0.20-1.80</td>
<td></td>
</tr>
<tr>
<td>Fractional error coefficient in observation ( \tau ) ( f_o )</td>
<td>0.20-1.80</td>
<td></td>
</tr>
<tr>
<td>Minimum RMS error in model ( \tau ) ( \varepsilon_m )</td>
<td>0.00-0.05</td>
<td></td>
</tr>
<tr>
<td>Minimum RMS error in observation ( \tau ) ( \varepsilon_o )</td>
<td>0.00-0.05</td>
<td></td>
</tr>
<tr>
<td>Horizontal correlation length for errors in model ( \tau ) ( L_m )</td>
<td>30 km</td>
<td></td>
</tr>
<tr>
<td>Horizontal correlation length for errors in observation ( \tau ) ( L_o )</td>
<td>0 km</td>
<td></td>
</tr>
</tbody>
</table>

Assumptions

1. The errors are Gaussian distributed.
2. The errors in model and data are uncorrelated.

\( \tau_m \) : modeled values of AOD

\( \tau_o \) : observed values of AOD

\( H \) : linear operator for interpolation from the model grid to the location of the observation

\( K \) : Kalman gain matrix (Kalman filter)

[Collins et al., 2001; Yu et al., 2003; Adhikary et al., 2008; Chung et al., 2010; Park et al., 2011]
Spatial and temporal distributions of AODs

LRT case

(a) CMAQ AOD
(b) GOCI AOD
(c) Assimilated AOD
(d) HYSPLIT backward trajectories
Spatial and temporal distributions of AODs

Non-LRT case

(a) CMAQ AOD
(b) GOCI AOD
(c) Assimilated AOD
### Statistical analysis of AODs

<table>
<thead>
<tr>
<th>AOD</th>
<th>N(^1)</th>
<th>R(^2)</th>
<th>RMSE(^3)</th>
<th>MNGE(^4)</th>
<th>MB(^5)</th>
<th>NMB(^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAQ</td>
<td>946</td>
<td>0.47</td>
<td>0.31</td>
<td>46.52</td>
<td>-0.09</td>
<td>-14.51</td>
</tr>
<tr>
<td>GOCI</td>
<td>499</td>
<td>0.84</td>
<td>0.19</td>
<td>42.42</td>
<td>-0.03</td>
<td>-15.15</td>
</tr>
<tr>
<td>Assimilation</td>
<td>695</td>
<td>0.63</td>
<td>0.28</td>
<td>35.75</td>
<td>-0.04</td>
<td>-6.50</td>
</tr>
</tbody>
</table>

1) \(N\): number of data

\[
\sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M} - \text{AOD}_{i,O}}{\text{AOD}_{i,O}} \right)
\]

2) \(R\): correlation coefficient =

\[
\sqrt{\frac{\sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M}}{N} \right)^2 - \left( \frac{\sum_{i=1}^{N} \text{AOD}_{i,M}}{N} \right)^2}{\sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,O}}{N} \right)^2 - \left( \frac{\sum_{i=1}^{N} \text{AOD}_{i,O}}{N} \right)^2}}
\]

3) RMSE: Root Mean Square Error =

\[
\sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M} - \text{AOD}_{i,O}}{\text{AOD}_{i,O}} \right)^2}
\]

4) MNGE: Mean Normalized Gross Error (%) =

\[
\frac{1}{N} \sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M} - \text{AOD}_{i,O}}{\text{AOD}_{i,O}} \right) \times 100
\]

5) MB: Mean Bias =

\[
\frac{1}{N} \sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M} - \text{AOD}_{i,O}}{\text{AOD}_{i,O}} \right)
\]

6) MNB: Mean Normalized Bias (%) =

\[
\frac{1}{N} \sum_{i=1}^{N} \left( \frac{\text{AOD}_{i,M} - \text{AOD}_{i,O}}{\text{AOD}_{i,O}} \right) \times 100
\]
Time-series analysis of AODs at five AERONET sites

\[
\frac{\text{AOD}_{\text{LRT}} - \text{AOD}_{\text{non-LRT}}}{\text{AOD}_{\text{non-LRT}}} \times 100 \text{ } (\%)
\]
Time-series analysis of PM at five AERONET sites

- Baengnyeong
- Yonsei_ Univ (Seoul)
- Gwangju_GIST
- Gosan_SNU
- Osaka

(Bar graphs showing PM concentration over time at each location.)
## Comparison analysis of the assimilated AOD for LRT & non-LRT events

<table>
<thead>
<tr>
<th></th>
<th>Non-LRT events</th>
<th>LRT events</th>
<th>Data fraction of LRT events</th>
<th>3) AOD increase during LRT events</th>
<th>4) Ratio of AOD increase during LRT events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1) N</td>
<td>2) σ</td>
<td>Avg.</td>
<td>Max.</td>
<td>1) N</td>
</tr>
<tr>
<td>Baengnyeong</td>
<td>849</td>
<td>0.12</td>
<td>0.22</td>
<td>0.98</td>
<td>606</td>
</tr>
<tr>
<td>Yonsei_Univ (Seoul)</td>
<td>821</td>
<td>0.21</td>
<td>0.30</td>
<td>1.13</td>
<td>634</td>
</tr>
<tr>
<td>Gwangju_GIST</td>
<td>1024</td>
<td>0.16</td>
<td>0.27</td>
<td>1.22</td>
<td>431</td>
</tr>
<tr>
<td>Gosan</td>
<td>967</td>
<td>0.12</td>
<td>0.22</td>
<td>1.14</td>
<td>488</td>
</tr>
<tr>
<td>Osaka</td>
<td>1247</td>
<td>0.11</td>
<td>0.21</td>
<td>0.90</td>
<td>208</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>0.15</td>
<td>0.24</td>
<td>1.22</td>
<td>0.40</td>
</tr>
</tbody>
</table>

1) N: the number of data for non-LRT or LRT events for the entire modeling period
2) Standard deviation
3) AOD increase by LRT events above the average background AOD calculated during non-LRT periods
4) \[ \frac{AOD_{LRT} - AOD_{non-LRT}}{AOD_{non-LRT}} \]
Time-series plots of AODs over the three sub-regions of the Korean peninsula.
To more accurately monitor and evaluate transboundary PM pollution, this research combined two AOD products (as a proxy for surface-level PM conc.) from GOCI and CTM simulations through a data assimilation technique.

The transboundary PM pollution from China to the Korean peninsula was quantitatively evaluated for a period from 1 April to 31 May, 2011. The average AOD increases of 117-265% at five AERONET sites and the average AOD increases of 121% over the entire Korean peninsula were found.

This study is a preceding investigation for full-scale analysis with data from GOCI-2 and GEMS aboard GEO-KOMPSAT that is scheduled to be launched in 2018.
Application plans for data assimilation of aerosols at KMA
Improvements in Initial Conditions with DA

Model-predicted PM$_{10}$ compositions + Measured PM$_{10}$ compositions → Data assimilation [3D OI] → Initial conditions (ICs) of model

- With surface PM$_{10}$, AOD would be also assimilated with satellite (or ground)-observed AOD and vertical information.
- More sophisticated techniques (3DVAR, 4DVAR, KF) would be adopted for the data assimilation of aerosols.
Improvements in Initial Conditions with DA

- Preliminary results of DA for surface PM$_{10}$
  - Case: Haze (10-16 Jan, 2013)
  - Modeling periods: 8-16 Jan, 2013
  - 3D OI: 9-12 Jan, 2013 (3hr-interval)
Thank you for your attention!

Any question and comment will be appreciated!