MUli-SpEctra, MUli-SpEcies, Multi-SEnsors
Retrievals of Trace Gases: Updates on Validation and Science Applications

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Measurements from TIR (LW) are sensitive to the free-tropospheric trace gases. Measurements from UV-Vis-NIR (SW) are sensitive to the column abundances of trace gases. Joint LW/SW or ultra-high spectral resolution measurements can distinguish upper/lower troposphere.
JPL MUSES algorithm delivers both retrieved trace gas concentration profiles and observation operators needed for trend analysis, climate model evaluation, and data assimilation.

E.g., a data assimilation system applies an observation operator \( \mathbf{H} \)

\[
\mathbf{y}^s = \mathbf{H}(\mathbf{x}) = \mathbf{x}_a + \mathbf{A}(\mathbf{x}_{\text{model}} - \mathbf{x}_a)
\]

\( \mathbf{y}^s \) is the model profiles; \( \mathbf{x}_a \) is an a priori profiles used in the retrievals; \( \mathbf{A} \) is the averaging kernels of satellite observations.

After applying observation operator to model profiles, the satellite-model differences \( (\mathbf{y}^o - \mathbf{y}^s) \) is not biased by the a priori used in the retrievals.

\[
\Delta \mathbf{y} = \mathbf{y}^o - \mathbf{y}^s = \mathbf{A}(\mathbf{x}_{\text{true}} - \mathbf{x}_{\text{model}}) + \mathbf{e}
\]
The AIRS/OMI O$_3$ retrievals have been configured in two modes.

- **Global survey mode**
  - Provides profile data with a spatial sampling similar to TES global survey
  - 22-month data have been processed including:
    - 2006 Jun – Aug
    - 2010 Jan – May
    - 2016 Mar – Jun
  - All of 2006 GS data will be available in weeks.
  - December 2017, an estimated release date of AIRS/OMI ozone v1 data

- **Regional mapping mode**
  - Processes all available measurements for flight campaigns including:
    - KORUS-AQ, Apr – Jun 2016
    - ORACLES, Aug, Sept 2016
    - POSIDON, Sept, Oct 2016

Data products have been saved in Hierarchical Data Format, a common format used in the NASA Earth Observation System level 2 products.
### AIRS/OMI Vs. TES v5 GS O$_3$ Profile Data on August 2006

<table>
<thead>
<tr>
<th></th>
<th>AIRS/OMI O$_3$ VMR</th>
<th>TES O$_3$ v5 VMR</th>
<th>a priori</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 mbar</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>510 mbar</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>750 mbar</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Tropospheric DOFS</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Combined AIRS single footprint L1B radiances to OMI measurements for retrieving O$_3$ profiles.
Joint AIRS/OMI vs. TES GS O$_3$ During Summer 2006

- Relative bias < 2-5%. Standard deviation of the differences < the estimated uncertainty.

<table>
<thead>
<tr>
<th></th>
<th>316 mbar</th>
<th></th>
<th></th>
<th>510 mbar</th>
<th></th>
<th></th>
<th>750 mbar</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
</tr>
<tr>
<td>Correlation Coefficient (r)</td>
<td>0.85</td>
<td>0.85</td>
<td>0.84</td>
<td>0.83</td>
<td>0.82</td>
<td>0.80</td>
<td>0.81</td>
<td>0.77</td>
<td>0.75</td>
</tr>
<tr>
<td>Mean Diff. (Joint-TES) ppb</td>
<td>-7.4</td>
<td>-6.2</td>
<td>-4.0</td>
<td>-3.4</td>
<td>-3.3</td>
<td>-2.9</td>
<td>-1.8</td>
<td>-1.5</td>
<td>-1.8</td>
</tr>
<tr>
<td>100 x (Joint-TES)/TES %</td>
<td>-4.8</td>
<td>-4.4</td>
<td>-3.8</td>
<td>-1.9</td>
<td>-2.1</td>
<td>-2.7</td>
<td>-0.8</td>
<td>-0.4</td>
<td>-1.6</td>
</tr>
<tr>
<td>Standard Deviation of Diff. ppb</td>
<td>20.5</td>
<td>17.7</td>
<td>14.3</td>
<td>10.9</td>
<td>10.0</td>
<td>8.5</td>
<td>7.6</td>
<td>7.3</td>
<td>7.0</td>
</tr>
<tr>
<td>100 x (Joint-TES)/TES %</td>
<td>24.6</td>
<td>22.5</td>
<td>19.5</td>
<td>21.0</td>
<td>19.7</td>
<td>16.8</td>
<td>19.6</td>
<td>19.4</td>
<td>17.9</td>
</tr>
<tr>
<td>AIRS/OMI Total Uncertainty %</td>
<td>27.8</td>
<td>27.8</td>
<td>27.6</td>
<td>22.5</td>
<td>22.5</td>
<td>22.3</td>
<td>24.1</td>
<td>23.9</td>
<td>23.5</td>
</tr>
<tr>
<td>TES v5 Total Uncertainty %</td>
<td>22.0</td>
<td>22.0</td>
<td>22.2</td>
<td>19.5</td>
<td>19.5</td>
<td>19.7</td>
<td>23.9</td>
<td>23.9</td>
<td>23.5</td>
</tr>
</tbody>
</table>
Comparisons to WOUDC Ozonesondes

### Coincident criteria
- Passed retrieval quality check
- Distance within 300 km
- Time diff. within 4 hours
- June, July, August 2006

<table>
<thead>
<tr>
<th>Pressure (mbar)</th>
<th>316 mbar</th>
<th>510 mbar</th>
<th>750 mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>AIRS/OMI</td>
<td>1.9</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td>15.8</td>
<td>18.3</td>
<td>-0.7</td>
</tr>
<tr>
<td><strong># of Sites</strong></td>
<td>21</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td><strong># of Pairs</strong></td>
<td>93</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td><strong>100 x (Satellite - Sonde_AppliedAK)/Sonde_AppliedAK</strong></td>
<td>AIRS/OMI</td>
<td>1.9</td>
<td>4.0</td>
</tr>
<tr>
<td>TES</td>
<td>6.6</td>
<td>22.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Korea-US Air Quality study (KORUS-AQ) - International Cooperative Air Quality Field Study

- Total ozone shows strong latitudinal dependence, dominated by stratospheric ozone.
- The pattern of enhancement (Upper tropospheric > Lower tropospheric) over Korean peninsula <-> Japan suggests either lofting and transport of pollution from the surface or the influence of stratosphere-troposphere exchange.

Three-day averaged May 18-20, 2016.
Joint AIRS/OMI ozone profiles have been assimilated into CHASER system.

CHASER system assimilated the OMI (NO$_2$), GOME-2 (NO$_2$) MLS (HNO$_3$ and O$_3$), MOPITT (CO) for KORUS-AQ, recently assimilated AIRS/OMI ozone profile data.
Fire Influence on Regional and Global Environments Experiment (FIREX) is to study the impact of biomass burning of western North America fires on climate and air quality.

JPL/UW-Madison team will combine high vertical/spatial resolution O₃ and CO data with chemical data assimilation to provide a critical synoptic context for quantifying the role of fires on atmospheric composition and air quality.

JPL MUSES algorithm will provide

- CrIS CO profile data
  - nine times higher spatial resolution vs. the CrIS operational data products
- Joint CrIS/OMPS O₃ profile data
  - could distinguish upper/lower troposphere, similar to AIRS/OMI O₃, but 3X spatial coverage
- Both CO and O₃ profile data products provide full observation operators readily for data assimilation/model evaluation

UW-Madison Real time Air Quality Modeling System (RAQMS) will provide

- Real-time assimilation
  - Aura-MLS stratospheric ozone profiles (>50mb)
  - Aura-OMI total ozone column (cloud cleared)
  - MODIS aerosol optical depth
- Real-time fire detection via MODIS data
- Will assimilate JPL CrIS CO and joint CrIS/OMPS O₃ profile data
Plume of biomass burning observed on August 5, 2017
CrIS CO profiles were retrieved using single footprint CrIS full spectral resolution data.
MUSES algorithm retrieves trace gases profiles, cloud optical depths, surface properties and temperature profiles.
Comparisons of MUSES-CrIS and RAQMS CO Data

- Used CrIS single footprint full spectral resolution L1B radiances in the retrievals
- MUSES CrIS CO data show agreement to the RAQMS model fields that were applied the observation operators of CrIS CO.
- Collaborating with Dr. Pierce at UW-Madison for assimilating CrIS CO data into the RAQMS model

<table>
<thead>
<tr>
<th>Applying MUSES CrIS CO Observation Operator to RAQMS Predicted CO Fields</th>
<th>Correlation Coefficient</th>
<th>Mean Diff x10^{18}</th>
<th>%</th>
<th>RMS x10^{18}</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>With</td>
<td>0.68</td>
<td>-0.15</td>
<td>6.9</td>
<td>0.27</td>
<td>11.1</td>
</tr>
<tr>
<td>Without</td>
<td>0.40</td>
<td>-0.15</td>
<td>6.6</td>
<td>0.45</td>
<td>25.7</td>
</tr>
</tbody>
</table>
In October 13, 2017, ESA Sentinel 5 Precursor (S5P) launched successfully, forming a satellite constellation with Suomi-NPP satellite.

It provides an unique opportunity to extend and improve the MOPITT joint TIR/NIR CO data, via combining CrIS/TROPOMI measurements [Fu et al., AMT, 2016]

**XCO maps**: near surface partial column averaged VMR [surface to ~750 hPa]
MUSES retrieval algorithm can combine radiances measured from long wavelength (TES, AIRS, CrIS) and short wavelength (OMI, OMPS, TROPOMI) space sensors to retrieve the vertical concentration profiles of primary gaseous pollutants including O₃ and CO.

- Joint AIRS/OMI and CrIS/OMPS retrieved O₃ profiles can distinguish the abundances in the upper troposphere from the lower troposphere.
- Joint CrIS/TROPOMI would help in extending the MOPITT CO profile data.

The observation operators of joint AIRS/OMI data products enable data assimilation, e.g., “CHASER-DA”, demonstrating the significant impacts on ozone distributions.

The O₃ and CO data products from MUSES algorithm could help in the quantitative attribution of anthropogenic emissions and natural influences of pollutants for NASA KORUS-AQ and NOAA FIREX.

Thank you for attention!

Questions?