Improved Ozone Profile Retrievals Using Multispectral Measurements from NASA "A Train" Satellites

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Introduction

Knowledge of the vertical distribution of ozone over the long term is essential for investigating multiple science objectives, e.g., impacts of tropospheric ozone on air quality and climate; response of ozone to rapid industrialization in Asia; reductions in ozone precursor emissions in North America and Europe; changes in burning due to climate and agricultural practices.

The Aura Tropospheric Emission Spectrometer (TES) :

- provides well-validated global survey record of tropospheric ozone
- has advanced a number of science objectives including increased tropospheric ozone trends over Asia possibly connected to local ozone precursor emissions (NOx) [Figure 1].

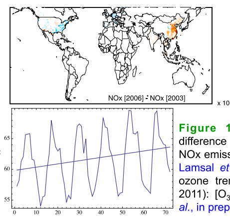


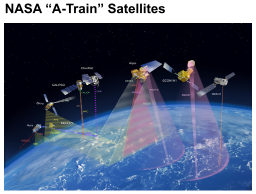
Figure 1. (Upper panel) the spatial difference between bottom-up anthropogenic NOx emissions (1° × 1.25° grid) [Figure 1 of Lamsal *et al.*, 2011]; (Bottom panel) TES ozone trend over Asia (Jan. 2005 – Jan. 2011): [O_3] record over Asia [Verstraten *et al.*, in preparation 2013].

- Temporal/spatial availability of TES data: **(1)** 2005 – 2009 within designed life time provides consistently high sampling; **(2)** 2010 – 2012 exceeded designed life time did not cover high latitude; **(3)** 2012 – focused on targeted observations
  - Limits the full potential of using TES measurements to assess long-term changes in ozone and its relationship to climate.

There are needs for creating a new global decadal tropospheric ozone profile products [Table 1] by combining collocated measurements from NASA "A-Train" (within ~10 minutes) of

- Aura Ozone Monitoring Instrument (OMI)
- Aqua Atmospheric Infrared Sounder (AIRS)
- Aura Microwave Limb Sounder (MLS)

NASA "A-Train" Satellites



- Afternoon constellation
- Sun-synchronous orbit
- Altitude: ~ 690 Km
- Daily crosses equator time
  - ~1:30 pm
  - ~1:30 am

Figure 2. Artist's Concept of the A-Train constellation of satellites. **Credit:** NASA.

Table 1. The Temporal and Spatial Coverage together with the Vertical Sensitivity of Retrieved Ozone Profiles among NASA "A Train" Satellites.

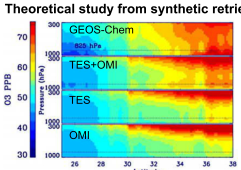
Data Set	Year Coverage	Repeat Cycle	[O_3] Degrees of Freedom		Data Product	Reference
		Day	Trop.	Stra.	Ver./Year	
OMI/AIRS/MLS	2004 – Present	1	3.6	9.1	V1.0; 2016	This Work
TES	GS[1] 2004 – 2008 SO[1] 2004 – Now	16	1.5	3.0	V5.0; 2013	Worden, *et al.*, 2007a; Boxe *et al.*, 2010
TES/OMI	GS 2004 – 2008 SO 2004 – Now	1	N/A	9.0	V3.4; 2013	Fu *et al.*, 2013
MLS	2004 – Present	1	1.0	5.0	V3.0; 2013	Livesey *et al.*, 2008 and 2013
OMI[2]	2004 – Present	1	0.5	1.0	V6.0; 2013	Liu *et al.*, 2010 a/b; Kroon *et al.*, 2011
AIRS	2004 – Present	16	2.0	5.0	V1.0; 2014	Susskind *et al.*, 2003

(1) GS: global survey; SO: special observations for regions

Retrieval Algorithm Inheritance

The multi-spectral retrieval is a rapidly maturing technique [Worden *et al.*, 2007b; Landgraf and Hasekamp 2007; Fu *et al.*, 2013; Worden *et al.*, 2013; Cuesta *et al.*, 2013].

Theoretical study from synthetic retrievals



Synthetic estimated ozone from joint OMI/TES closely represent the GEOS-CHEM fields.

Figure 3. (first panel) A Curtain Plot of the GEOS-CHEM ozone fields used for the study. (2nd, 3rd and 4th panels) The synthetic estimated ozone from joint OMI/TES, TES alone and OMI alone accordingly [Worden *et al.*, 2007].

Evaluations of retrievals using TES/OMI measured radiances: Comparing the sonde measurements

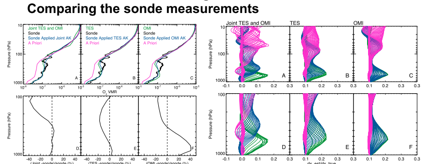
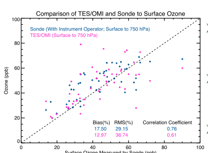


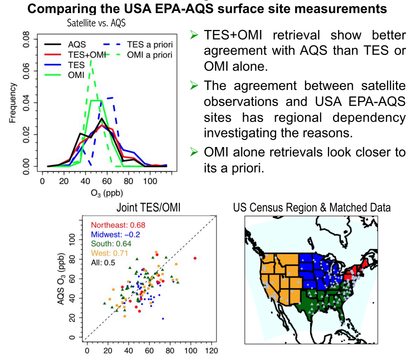
Figure 4. Left: (A-C panels) ozone profiles; (D-F panels) differences beween satellite estimates and sonde profiles **Right:** (A-C panels) Averaging kernels from surface to 10 hPa; (D-F panels) zoom in view of surface to 100 hPa [Fu *et al.*, 2013]



- Surface and boundary layer ozone sonde measurements are well-correlated.
- Moderate bias and significant RMS reflect in part lateral mixing.
- TES+OMI correlation and bias consistent with precision.

Figure 5. Correlation between TES/OMI and Sonde measurements.

Evaluations of retrievals using TES/OMI measured radiances: Comparing the USA EPA-AQS surface site measurements



- TES+OMI retrieval show better agreement with AQS than TES or OMI alone.
- The agreement between satellite observations and USA EPA-AQS sites has regional dependency investigating the reasons.
- OMI alone retrievals look closer to its a priori.

Figure 6. Correlation among joint TES/OMI, TES alone, OMI alone and EPA in-situ measurements over USA During August 2008.

Retrieval Algorithm Inheritance

Multi-spectral retrieval algorithm has already been developed for IASI-GOME2 instruments on MetOp satellite, an European satellite in the Sun-synchronous orbit.

- Joint IASI/GOME-2 ozone retrievals have a strong spatial correlation with CHIMERE in the planetary boundary layer.

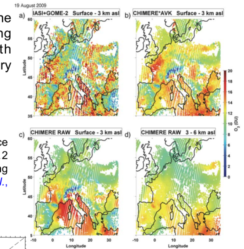
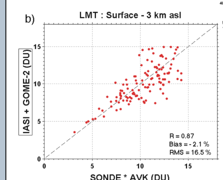


Figure 7. Ozone fields near surface estimated from IASI+GOME2 measurements and simulated using CHIMERE model [Cuesta *et al.*, 2013].



- Strong correlation with ozone sondes in the planetary boundary layer, similar to TES +OMI.

Figure 8. Correlation between IASI +GOME2 estimated ozone and sonde measurements [Cuesta *et al.*, 2013].

Development of Joint OMI/AIRS/MLS Retrieval Algorithm

The joint OMI/AIRS/MLS retrieval algorithm, which applies the optimal estimation method [Rodgers, 2000], is being developed from TES/ OMI work and combines: **(1)** measured OMI/AIRS spectral radiances; **(2)** a priori ozone constraints in the upper troposphere and stratosphere provided by MLS assimilated ozone fields. It minimizes the following cost function to find the best estimate state vector **X**.

$$C(\mathbf{x}) = \underbrace{\|\mathbf{x}-\mathbf{x}_a\|^2_{\mathbf{S}_a^{-1}}}_{a\ priori} + \underbrace{\|\mathbf{x}-\mathbf{x}_{\mathrm{MLS}}\|^2_{\mathbf{S}^{-1}_{\mathrm{MLS\_posterior}}}}_{\mathrm{MLS}} + \underbrace{\|\mathbf{L}_{\mathrm{obs\_OMI}}-\mathbf{L}_{\mathrm{sim\_OMI}}(\mathbf{x})\|^2_{\mathbf{S}^{-1}_{\mathrm{e\_OMI}}}}_{\mathrm{OMI}} + \underbrace{\|\mathbf{L}_{\mathrm{obs\_AIRS}}-\mathbf{L}_{\mathrm{sim\_AIRS}}(\mathbf{x})\|^2_{\mathbf{S}^{-1}_{\mathrm{e\_AIRS}}}}_{\mathrm{AIRS}}$$

Equation 1

- Joint AIRS/OMI [Figure 9]
  - differ from the a priori profile (**purple**)
  - closely match to sonde profiles (**green** and **black**)
  - has similar vertical resolution to Aura TES
  - has similar error characteristics to Aura TES
  - has slightly different biases

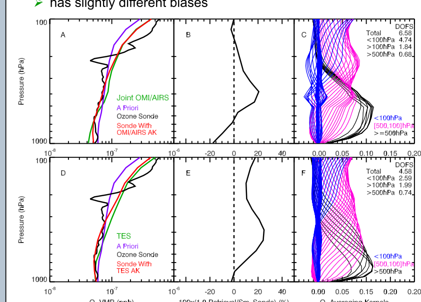


Figure 9. Ozone measurements over Huntsville, USA on August 16th, 2008.

Development of Joint OMI/AIRS/MLS Retrieval Algorithm

- Joint OMI/AIRS/MLS
  - incorporates the assimilated Aura MLS ozone profiles [Stajner *et al.*, 2008; Wargan *et al.*, 2010] into the joint retrievals (**Equation 1**)
  - The vertical resolution and error characteristics can be substantially improved, compared to joint OMI/AIRS measurements (**Figure 10**).
  - This increased sensitivity is critical for evaluating the radiative response of ozone to surface emissions and the role of stratospheric/tropospheric exchange, long range transport, and tropical fires (or pyro-convection) on the tropospheric ozone distribution.

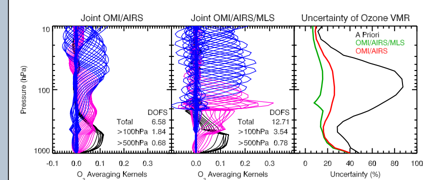


Figure 10. Ozone soundings with improved vertical sensitivity and reduced measurement uncertainty using multi-spectral observations over Huntsville, USA on August 16th, 2008.

- The joint OMI/AIRS/MLS data products, which we are planning to create, consist of two categories: "global survey" (GS) and "regional maps" (RM). Both categories will have temporal coverage from 2004 to present day.

Summary and Future Work

- This work presented an approach/algorithm to retrieve decadal global ozone record using NASA "A Train" measurements.
- The sample retrievals over Huntsville, USA on August 16th, 2008 indicated the feasibility of obtaining high vertical resolution ozone profiles in both stratosphere and troposphere by combining multiple sensors on NASA "A Train" satellites.
- This new algorithm, which is inherited from the validated joint TES/OMI retrieval algorithm, is being developed/optimized/test.

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