Satellite Monitoring Over the Canadian Oil Sands: Highlights from Aura OMI and TES

Mark W. Shephard\textsuperscript{a}, Chris McLinden\textsuperscript{a}, Vitali Fioletov\textsuperscript{a}, Karen E. Cady-Pereira\textsuperscript{b}, Nick A. Krotkov\textsuperscript{c}, Folkert Boersma\textsuperscript{d}, Can Li\textsuperscript{e}, Ming Luo\textsuperscript{f}, P.K Bhartia\textsuperscript{c}, and Joanna Joiner\textsuperscript{c}

\textsuperscript{a}Environment Canada (EC)
\textsuperscript{b}Atmospheric and Environment Research (AER), Inc.
\textsuperscript{c}NASA Goddard Space Flight Center
\textsuperscript{d}Royal Netherlands Meteorological Institute (KNMI)
\textsuperscript{e}Earth System Science Interdisciplinary Center, University of Maryland
\textsuperscript{f}Jet Propulsion Laboratory (JPL)
Introduction

- “Oil sands” is a type of petroleum deposit in which the oil is very thick and sticky (called “bitumen”) and mixed with sand/water/clay
- Proven reserve of ~170 billion barrels
- Production expected to double by 2020
- Additional monitoring needed to better understand the emissions of the oil sands region and its impacts
  - Joint Canada and Alberta plan for monitoring of the air, water, and wildlife in and around the oil sands
  - Satellites provide large scale spatial and temporal coverage and extent
What insights can Aura provide on Air Quality in the Oil Sands?

<table>
<thead>
<tr>
<th>Aura-OMI</th>
<th>Aura-TES</th>
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<tbody>
<tr>
<td>(Ozone Monitoring Instrument)</td>
<td>(Tropospheric Emissions Spectrometer)</td>
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</table>

**OMI provides tropospheric vertical column densities (VCDs)**
- **NO₂**: NASA SP v2.1 & KNMI DOMINO v2.0
- **SO₂**: NASA PCA*-beta release
  - Largely eliminates artifacts and 2x reduction in noise compared to operational product
- For all products original AMFs replaced by new Environment Canada AMFs that are based on higher resolution input data [Mclinden et al., ACP, 2014]
- SP and DOMINO datasets combined since remaining difference is primarily stratospheric NO₂ removal, and combined data appears to work best over Canada

**TES provides a volume mixing ratio (VMR) profile**
- **Used recent Version 6 Lite products***
  - New CH₃OH and HCOOH products
  - Significant amount has been reprocessed
- **NH₃, CH₃OH, HCOOH**
  - Peak sensitivity varies between 1-2 km
  - Typically 1 DOFS or less
  - Not much vertical “profiling”
  - Reported as a RVMR
    - Boundary layer weighted averaged VMR value where TES is most sensitive
- **CO**
  - Peak sensitivity typically ~3-km
  - Typically 1-2 DOFS
  - For comparison purposes we report the VMR at the peak vertical sensitivity in the troposphere defined by the averaging kernel (AK Peak)

* Principle Component Analysis method, Li et al., GRL, 2013, product being evaluated; See Nick Krotkov talk

* Provided by Susan Kulawik
Evolution of OMI NO$_2$
Evolution of OMI NO₂
OMI SO$_2$ over the oil sands

- SO$_2$ emissions due to upgrading
  - converting bitumen to synthetic crude
- Only two significant SO$_2$ point sources, both in southern [S] mining region
- Northern [N] mines pipe bitumen off-site for upgrading

2005 – 2013

<table>
<thead>
<tr>
<th>Year</th>
<th>2005-2007</th>
<th>2011-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPRI</td>
<td>~ 75 kt</td>
<td>~ 22 kt</td>
</tr>
<tr>
<td>OMI</td>
<td></td>
<td></td>
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</table>

3-year averages

Emissions and lifetime determined by fitting the downwind decay of SO$_2$
[similar to Beirle et al., Science, 2011]
OMI NO$_2$ over the oil sands

- NO$_2$ emissions sources:
  - upgrading (50%)
  - large vehicles (50%, more uncertain)
- Two significant point sources (upgraders), both in southern [S] mining region,
- Significant area sources in [S] and [N]
- Change in distribution consistent with expansion into the [N]

2005 – 2013 average

\[ E(\text{NPRI}^*) = 53 \text{ kt}[\text{NO}_2]/\text{yr} \]

\[ E(\text{OMI}) = 55 \text{ kt}[\text{NO}_2]/\text{yr} \]

\[ \text{*NPRI} = \text{National Pollutant Release Inventory} \]

Emissions and lifetime determined by fitting the downwind decay of NO$_2$

[similar to Beirle et al., Science, 2011]

\[ \text{NO}_x / \text{NO}_2 = 1.35 \text{ from AQ model} \]

Is this difference real, from sources not reported to the NPRI (e.g., construction)?
TES Infrared Satellite Observations:

TES Global Survey (GS) Mode
- Nadir pointing (16-day repeat cycle)
- Spacing of ~180 km along track
- No Global surveys taken after 2011

TES Special Observation (SO) Mode
- Higher sampling density over shorter tracks
  - Transect: regional pollution studies
    - Over the Oil Sands:
      - Begun July 14, 2012 (over 2-years)
      - Observations every 2-7 days
        » Over 125 SO to date
      - 20 contiguous targets
      - 12-km sampling along track
      - Between 56-58°N covering 240 km
        » Centred on the oil sands
      - Each target is 5x8 km

Used recently produced TES Version 6 Lite Products (Susan Kulawik).
Ammonia : Central Canada

- Period from 2004-2014
  - mostly GS before 2011 and SO over the OS after
- 2x2° grid averages
- Overall spatial gradient consistent with NPRI emissions database
- Potential decrease in NH$_3$ over the oil sands region?
Trends in TES Over Oil Sands Region?

Approach: compare global survey (2004-2011) with special observations (2012-2014) over oil sands region

Challenging: Not many GS values over oil sands region (2004-2011)

Any trends?
- Large values in summer 2012 potentially due to biomass burning?
- Need to identify (and filter)
Are OS Values Different than Across Central Canada?

Approach: compare global survey oil sands with larger central Canada region
- Seasonal cycle in GS and SO
- Global survey (2004-2011) values used to define “typical” values from a large region in central Canada.
- GS (2004-2011) values over central Canada are similar to the (relatively few) GS values over OS
Are OS Values Different than Across Central Canada?

Approach: compare global survey oil sands with larger central Canada region
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"Climatological" Oil Sand Region Satellite Observations:

<table>
<thead>
<tr>
<th>Component</th>
<th>VMR (ppbv)</th>
<th>Pressure (hPa)</th>
<th>DOFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia (NH₃)</td>
<td>~1-2</td>
<td>850-900</td>
<td>0.65</td>
</tr>
<tr>
<td>Methanol (CH₃OH)</td>
<td>~4-5</td>
<td>825</td>
<td>0.6</td>
</tr>
<tr>
<td>Formic Acid (HCOOH)</td>
<td>~2-3</td>
<td>825</td>
<td>0.75</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>~150-200</td>
<td>680</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Satellite Validation: 2013 Intensive Oil Sands Field Campaign

Sept. 3rd, 2013: Flight 18

• Dedicated TES overpass spirals
• Clear conditions

Sept. 5th, 2013: Flight 20
Satellite Validation: 2013 Intensive Oil Sands Field Campaign

- Comparisons of TES and OMI
  - Period from Aug. to Sept. 2013
  - Aircraft
  - Surface
    - In-situ / Remote (Pandora)
  - AQ model
    - GEM-MACH: 2.5 x 2.5 km

- Validation of new TES CH$_3$OI and HCOOH products

- Very preliminary TES/aircraft comparison results show:
  - ~20% NH$_3$
  - ~30% CH$_3$OH
  - ~40% HCOOH
  - ~10% CO

- Waiting on QC for aircraft NO$_2$ and SO$_2$ observations
Final Remarks

• The **10-years** of the Aura OMI and TES satellite observations are providing valuable insight on the air quality in and around the Canadian oil sands region.

• Some highlights presented include:
  - **OMI** sees clear enhancements in **NO₂** and **SO₂** over the oil sands
    - comparable with medium-sized city (~1 M) or large power plant
    - distributions are consistent with location of sources
  - **NO₂** increasing
    - possibly at a rate faster than NPRI emissions would suggest
  - **SO₂** showing slight decline and consistent with NPRI
  - **SO₂** analysis: possible due to improvements due to new PCA algorithm
  - **Initial analysis of NH₃, CO, and VOCs (CH₃OH, and HCOOH)** indicates:
    - TES does **not** detect large elevated concentrations directly over the oil sands mining regions
    - Potentially a decrease of NH₃ over oil sands region
      - In the presence of sulphur and NOx: NH₃ (gas) → NH₄⁺ (aerosol)
    - **Initial TES/aircraft validations** show general agreement
Background Slides
Status and Availability of Infrared Satellite Obs.  
TES Special Observations over the OS for the past ~2 years

<table>
<thead>
<tr>
<th>Year</th>
<th>Observations</th>
</tr>
</thead>
</table>
| 2014 | • 2014-01-02: 190631  
• 2014-01-09: 190985  
• 2014-01-11: 191113  
• 2014-01-12: 191138  
• 2014-01-18: 191779  
• 2014-01-25: 192522  
• 2014-01-27: 192772  
• 2014-01-29: 192865 | • 2014-02-03: 193539  
• 2014-02-10: 194118  
• 2014-02-12: 194411  
• 2014-02-14: 194661  
• 2014-02-19: 195092  
• 2014-02-26: 196758  
• 2014-02-28: 196901  
• 2014-03-05: 19988 |  
| 2013-01-01: 16144  
2013-01-06: 16188  
2013-01-08: 16217  
2013-01-10: 16252  
2013-01-15: 16317  
2013-01-22: 16399  
2013-01-24: 16425  
2013-01-26: 16456  
2013-01-31: 16489 | 2013-02-02: 164728  
2013-03-01: 164738  
2013-03-20: 16765  
2013-03-27: 168289  
2013-03-29: 168408  
2013-03-31: 16851 | 2013-03-10: 16986  
2013-04-12: 16950  
2013-04-14: 16984  
2013-04-21: 16998  
2013-04-26: 17059  
2013-04-30: 17079  
2013-05-02: 17096  
2013-05-07: 17140  
2013-05-14: 17201 | 2013-05-16: 17218  
2013-05-18: 17255  
2013-05-23: 17279  
2013-05-30: 17340  
2013-06-01: 17363  
2013-06-03: 17383  
2013-06-08: 17418  
2013-06-15: 17497  
2013-06-17: 17511  
2013-06-24: 17578  |

Over ~130 special observations over the oil sands to date  
- Measurement every 2-7 days

OS Field Study  
• 9 overpasses

TES transects of oil sands begun July 14, 2012
Nitrogen Dioxide from the Ozone Monitoring Instrument

FORT MCKAY
mean vmr = 5.1 ppb
mean vmr = 2.6 ppb

FORT McMURRAY ATHABASCA VALLEY
mean vmr = 7.5 ppb
mean vmr = 1.2 ppb

EDMONTON EAST
mean vmr = 11.1 ppb
mean vmr = 5.1 ppb

FORT SASKATCHEWAN
mean vmr = 7.7 ppb
mean vmr = 4.1 ppb

TOMAHAWK
mean vmr = 3.1 ppb
mean vmr = 1.9 ppb

NAPS
- NAPSS
- OMI
**NO\textsubscript{x} Emissions**

- Trend = 3.3 ± 0.4\%/yr
- Trend = 5.7 ± 0.8\%/yr

**3-year averages**

Is this difference real, from sources not reported to the NPRI (e.g., construction)?

**NO\textsubscript{2} Lifetime**

- Trend = 0.9 ± 1.0\%/yr

- Effective lifetime short, reflecting the very rapid drop-off in NO\textsubscript{2} from its source (near background ~40 km away) – suggests higher OH levels
- Some evidence for an increase in lifetime as NO\textsubscript{2} increases? This would suggest a transition towards a VOC-limited regime

E and τ determined by fitting the downwind decay of NO\textsubscript{2} [similar to Beirle et al., Science, 2011]

NO\textsubscript{x} / NO\textsubscript{2} = 1.35 assumed
Nice Features of the OE Approach

• **Retrieval Errors**
  - Straight-forward method of estimating retrieval errors
  - \( E = \left\{ K^T S_m^{-1} K + S_a^{-1} \right\}^{-1} \rightarrow \) total error

• **Averaging Kernels (A)**
  - \( A = \left\{ K^T S_m^{-1} K + S_a^{-1} \right\}^{-1} K^T S_m^{-1} K \)
  - Describes the relative weighting of the retrieved product, \( x_r \) to the “true” atmosphere, \( x \), and a priori \( x_a \)
    - \( A \rightarrow 1, \ x_r \rightarrow x \)
    - \( A \rightarrow 0, \ x_r \rightarrow x_a \)

• **DOFS** (degrees-of-freedom for signal):
  - Number of independent pieces of information in the measurement.
  - \( \text{DOFS}=\text{trace}(A) \)
  - Estimate of the **vertical resolution**: FWHM
  - AK varies from profile-to-profile depending:
    - Instrument (i.e. noise, nadir/limb viewing)
    - Atmospheric state
      - i.e. temperature, trace gases, clouds
    - Constraints
Comparison Methods:
Apply the Observational Operator

- Provides the best “apples-to-apples comparisons
  - Requires a comparison profile
- Comparisons the satellite measurement information only
  - Essentially how TES would “see” the atmosphere measured by the aircraft
  - Put the high resolution data (aircraft) on the low resolution (satellite)
  - Removes the influence of the retrieval a priori when subtracted

Satellite: \( x_r = A_{sat}x + (I - A_{sat})x_a \)

Air (TES obs): \( \tilde{x}_{air} = A_{sat}x_{air} + (I - A_{sat})x_a \)
Comparison Methods: Representative Volume Mixing Ratio (RVMR)

- Collapse all information to a subset of level(s) where the retrieval is most sensitive
  - Reduces the influence of the a priori
- Useful for retrievals with limited information
  - ~1 DOFS or less
- Useful generating maps, or comparing with non-profile single values (i.e. surface)
- Can be thought of as a “boundary layer” weighted average VMR where the satellite is most sensitive.

- As an example:
  - TES is most sensitive to NH₃ ~800 mb
  - DOFS = 0.83
  - RVMR = ~5.0 ppbv
  - ~2-3 km vertical resolution
  - Note: little sensitivity at surface
Challenges for Minor Trace Species: Example Ammonia ($\text{NH}_3$) from TES

Relatively Weak Atmospheric IR Signal
~ tenth’s to a couple degrees BT signal compared to a background of ~300 K

Detectability
- ~ 0.5 - 1 ppbv under ideal conditions
- thermal contrast plays a role

• TES is most sensitive to $\text{NH}_3$ between 900 and 700 mb
  - ~2 km vertical resolution
• 1 piece of information or less: DOFS<1.0
• Representative Volume Mixing Ratio (RVMR)
  - Collapse all information to a single point that represents the information content:
  - Easier to compare with *in situ* measurements