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

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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
  - Bitumen found close to the surface may be mined; deeper deposits need to be heated and then pumped to surface
- 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?

### Aura-OMI
(Ozone Monitoring Instrument)

OMI provides tropospheric **vertical column densities** (VCDs)

- **NO\textsubscript{2}:** NASA SP v2.1 & KNMI DOMINO v2.0
- **SO\textsubscript{2}:** 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 NO\textsubscript{2} removal, and combined data appears to work best over Canada

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

### Aura-TES
(Tropospheric Emissions Spectrometer)

TES provides a **volume mixing ratio** (VMR) profile

- **Used recent Version 6 Lite products**
  - New CH\textsubscript{3}OH and HCOOH products
  - Significant amount has been reprocessed
- **NH\textsubscript{3}, CH\textsubscript{3}OH, 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 NO₂

Movie goes here
Evolution of OMI NO$_2$
Evolution of OMI NO$_2$
OMI SO₂ over the oil sands

- SO₂ emissions due to upgrading
  - converting bitumen to synthetic crude
- Only two significant SO₂ point sources, both in southern [S] mining region
- Northern [N] mines pipe bitumen off-site for upgrading

**Emissions and lifetime determined by fitting the downwind decay of SO₂**

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

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**2005 – 2013 average**

<table>
<thead>
<tr>
<th>Year</th>
<th>NPRI*</th>
<th>OMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-2007</td>
<td>~75 kt</td>
<td>~22 kt</td>
</tr>
<tr>
<td>2011-2013</td>
<td>100 kt SO₂/yr</td>
<td>89 kt SO₂/yr</td>
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*NPRI = National Pollutant Release Inventory
**OMI NO₂ over the oil sands**

- **NO₂ 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]**

**Emissions and lifetime determined by fitting the downwind decay of NO₂**

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

NOx / NO₂ = 1.35 from AQ model

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

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**2005 – 2013 average**

- **E(NPRI*) = 53 kt[NO₂]/yr**

*NPRI = National Pollutant Release Inventory

- **E(OMI) = 55 kt[NO₂]/yr**

**3-year averages**

**NOₓ Emissions [kt/yr]**

**Year**

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

NPRI = National Pollutant Release Inventory
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
- $2 \times 2^\circ$ grid averages
- Overall spatial gradient consistent with NPRI emissions database
- Potential decrease in NH$_3$ over the oil sands region?

NPRI Air Pollutant Emissions Data, 2008

Shephard Aura STM 2014
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?

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

Sept. 3rd, 2013 : Flight 18

Sept. 5th, 2013 : Flight 20

- Dedicated TES overpass spirals
- Clear conditions
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 CH₃Ol and HCOOH products

- Very preliminary TES/aircraft comparison results show:
  - ~20% NH₃
  - ~30% CH₃OH
  - ~40% HCOOH
  - ~10% CO

- Waiting on QC for aircraft NO₂ and SO₂ 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 $\text{NO}_2$ and $\text{SO}_2$ over the oil sands
    - comparable with medium-sized city (~1 M) or large power plant
    - distributions are consistent with location of sources
  - $\text{NO}_2$ increasing
    - possibly at a rate faster than NPRI emissions would suggest
  - $\text{SO}_2$ showing slight decline and consistent with NPRI
  - $\text{SO}_2$ analysis: possible due to improvements due to new PCA algorithm
  - Initial analysis of $\text{NH}_3$, CO, and VOCs ($\text{CH}_3\text{OH}$, and HCOOH) indicates:
    - TES does not detect large elevated concentrations directly over the oil sands mining regions
    - Potentially a decrease of $\text{NH}_3$ over oil sands region
      - In the presence of sulphur and NOx: $\text{NH}_3$ (gas) $\rightarrow$ $\text{NH}_4^+$ (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>
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</table>
| 2014 | **19631**  
**19695.**  
**19113.**  
**19138.**  
**19179.**  
**19252.**  
**19272.**  
**19285.**  |
|      | **19339**  
**19418.**  
**19441.**  
**19461.**  
**19502.**  
**18578.**  
**18601.**  |
|      | **19624**  
**19665.**  
**19728.**  
**19761.**  
**19781.**  
**19828.**  
**19901.**  |
|      | **19988.**  |  |
| 2013 | **16144.**  
**16188.**  
**16217.**  
**16252.**  
**16317.**  
**16399.**  
**16425.**  
**16486.**  
**16489.**  |
|      | **16473.**  
**16479.**  
**16502.**  
**16581.**  
**16590.**  
**16659.**  
**16759.**  
**16765.**  
**16829.**  |
|      | **16840.**  
**16851.**  
**16866.**  
**16878.**  
**17059.**  
**17079.**  
**17087.**  
**17094.**  
**17096.**  |
|      | **17097.**  
**17140.**  
**17201.**  
**17215.**  
**17235.**  
**17274.**  
**17340.**  
**17346.**  
**17363.**  |
|      | **17418.**  
**17497.**  
**17511.**  
**17578.**  |
| 2012 | **17551.**  
**17601.**  
**17644.**  
**17677.**  
**17700.**  
**17736.**  
**17746.**  
**17846.**  
**17869.**  |
|      | **17916.**  
**17920.**  
**18057.**  
**18064.**  
**18079.**  
**18102.**  
**18149.**  
**18168.**  
**18185.**  |
|      | **18220.**  
**18228.**  
**18287.**  
**18288.**  
**18314.**  
**18345.**  
**18347.**  
**18371.**  
**18371.**  |
|      | **18406.**  
**18410.**  
**18459.**  
**18460.**  
**18467.**  
**18468.**  
**18469.**  
**18713.**  
**18751.**  |
|      | **18751.**  
**18752.**  
**18758.**  |
| 2012 | **15857.**  
**15865.**  
**15866.**  
**15906.**  
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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

Shephard Aura STM 2014
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
**NOₓ Emissions**

- **NPRI**
- **OMI**

3-year averages

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

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

**NO₂ Lifetime**

- Trend = 0.9 ± 1.0%/yr

- Effective lifetime short, reflecting the very rapid drop-off in NO₂ from its source (near background ~40 km away) – suggests higher OH levels

- Some evidence for an increase in lifetime as NO₂ increases? This would suggest a transition towards a VOC-limited regime

E and τ determined by fitting the downwind decay of NO₂ [similar to Beirle et al., Science, 2011]

NOₓ / NO₂ = 1.35 assumed
Nice Features of the OE Approach

• **Retrieval Errors**
  - Straight-forward method of estimating retrievals 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 \( x_a \)
    \[
    x_r = A x + (I - A) x_a
    \]
  - \( A \rightarrow 1, \ x_r \rightarrow x \)
  - \( A \rightarrow 0, \ x_r \rightarrow x_a \)

• **DOFS** (degrees-of-freedom for signal):
  - Number of independent pieces of information in the measurement.
  - \( DOFS = \text{trace}(A) \)
  - 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

![Ideal Retrieval](image)

**Typical TES H\(_2\)O**

![Graph](image)
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

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

\[
\text{Air (TES obs): } \tilde{x}_{\text{air}} = A_{\text{sat}}x_{\text{air}} + (I - A_{\text{sat}})x_a
\]

Shephard Aura STM 2014
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 \(\text{NH}_3\) \(~800\ mb\)
  - DOFS = 0.83
  - RVMR = \(~5.0\ \text{ppbv}\)
  - \(~2-3\ \text{km vertical resolution}\)
  - Note: little sensitivity at surface
Challenges for Minor Trace Species: Example Ammonia (NH$_3$) from TES

Simulated TES spectra and NH$_3$ signal
18 ppbv at surface

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 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