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?

<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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**Aura-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

**Aura-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)

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

* Provided by Susan Kulawik

Shephard Aura STM 2014
Evolution of OMI NO$_2$

Movie goes here

Shephard Aura STM 2014
Evolution of OMI NO$_2$
Evolution of OMI NO$_2$
• 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]
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]

NPRI = National Pollutant Release Inventory

E(NPRI*) = 53 kt[NO$_2$/yr]
E(OMI) = 55 kt[NO$_2$/yr]

3-year averages

Emissions and lifetime determined by fitting the downwind decay of NO$_2$
[similar to Beirle et al., Science, 2011]
NOx / NO$_2$ = 1.35 from AQ model

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

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?

TES

NPRI Air Pollutant Emissions Data, 2008

kg/km$^2$

Surface mining

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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<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>
</tr>
</tbody>
</table>

- **Mountains**
- **Mountains**

![Image of Oil Sands Region and Mountains](image.png)

240 km
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 OM
  - 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

- Measurement every 2-7 days
- Over ~130 special observations over the oil sands to date
- OS Field Study • 9 overpasses
- TES transects of oil sands begun July 14, 2012
NO\textsubscript{x} Emissions

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

3-year averages

- E and \( \tau \) 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

- 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
Nice Features of the OE Approach

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

• 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
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 NH$_3$ ~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 (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