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Canada

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

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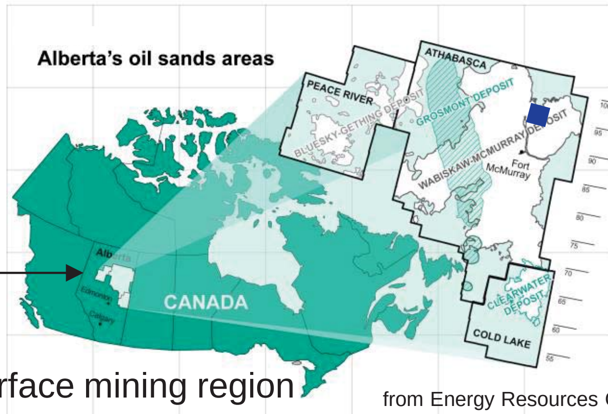
Aura Science Team Meeting, College Park, MD, USA, 15-18 September 2014

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

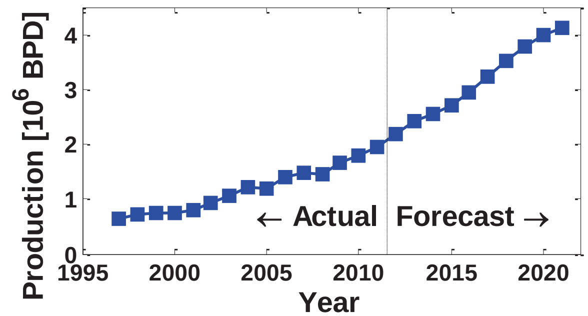
Province of Alberta



■ surface mining region

from Energy Resources Conservation Board, 2011

  - 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_2 : NASA SP v2.1 & KNMI DOMINO v2.0
- SO_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_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

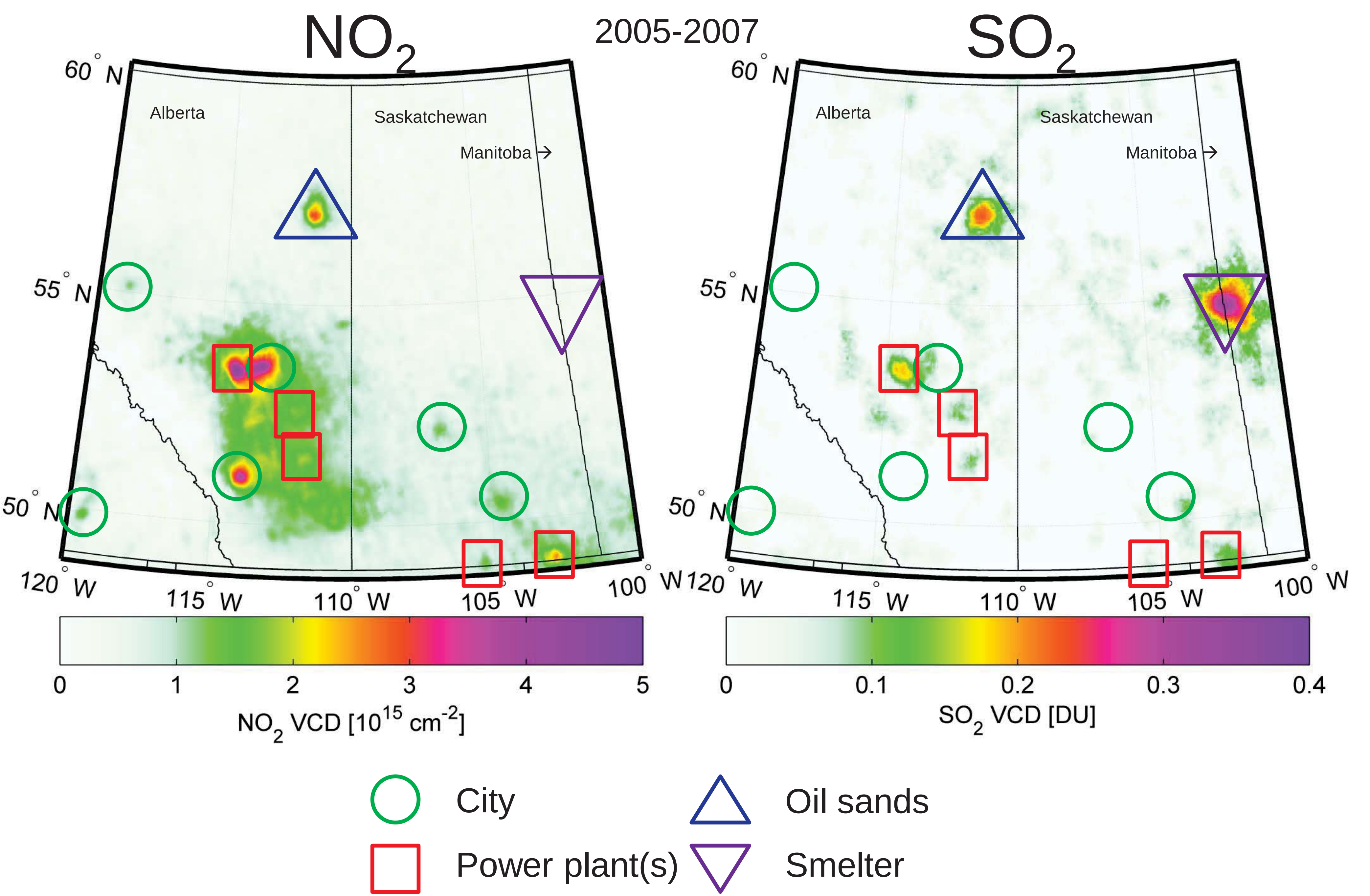
(Tropospheric Emissions Spectrometer)

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

- **Used recent Version 6 Lite products***
  - **New CH_3OH and HCOOH** products
  - significant amount has been reprocessed
- **NH_3, CH_3OH, 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)

* Provided by Susan Kulawik

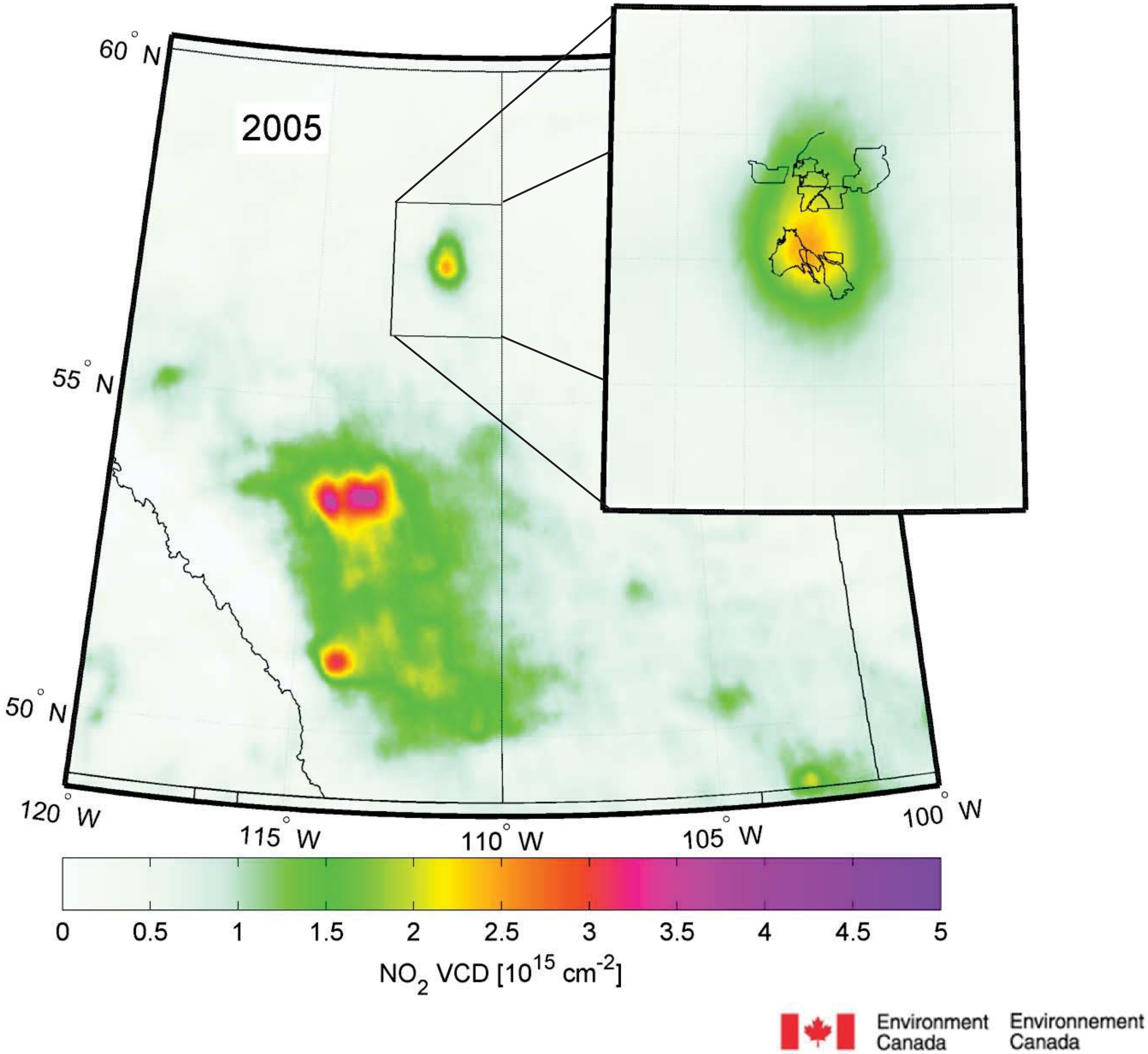
OMI view of Central Canada



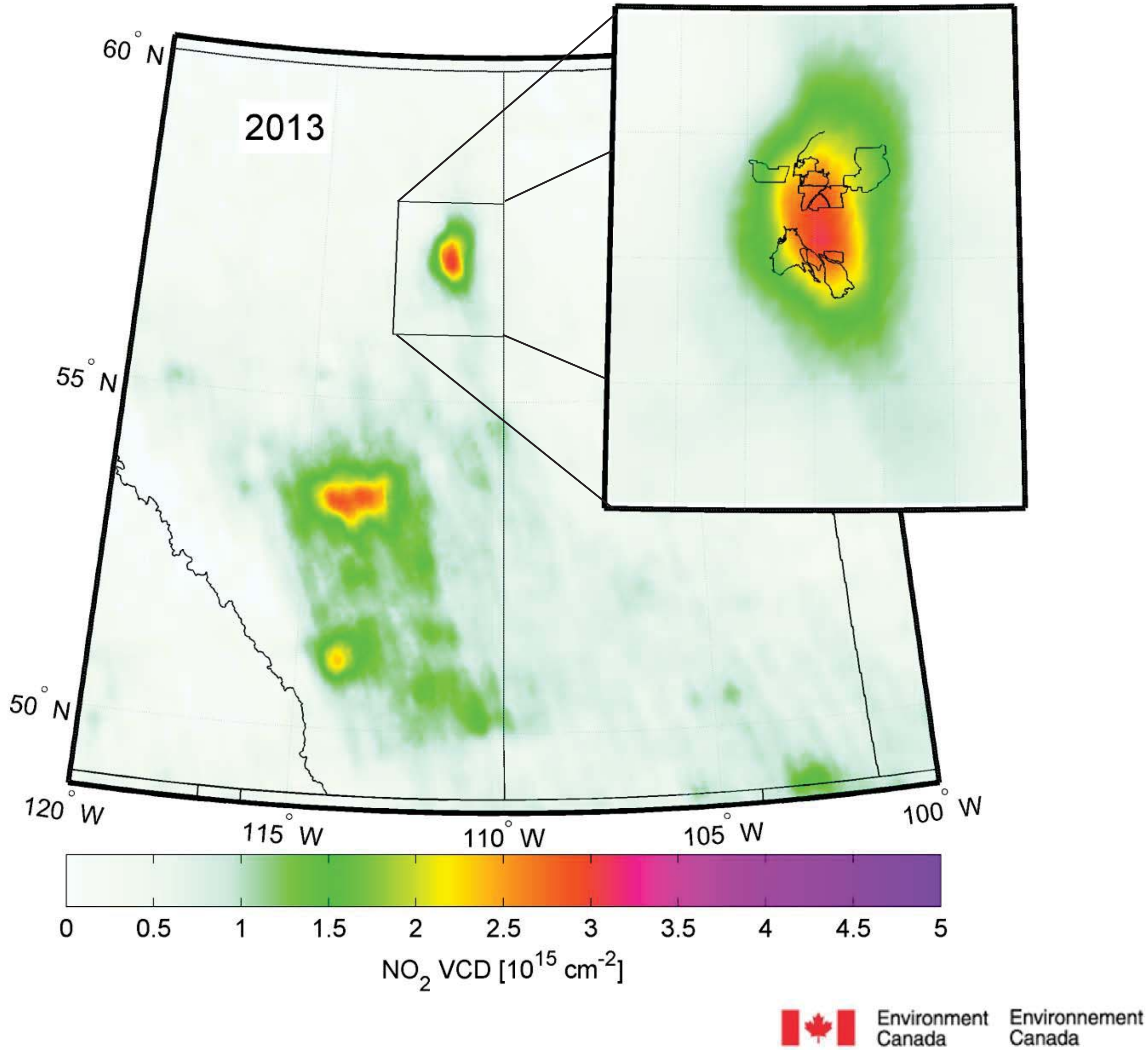
Evolution of OMI NO_2

Movie goes here

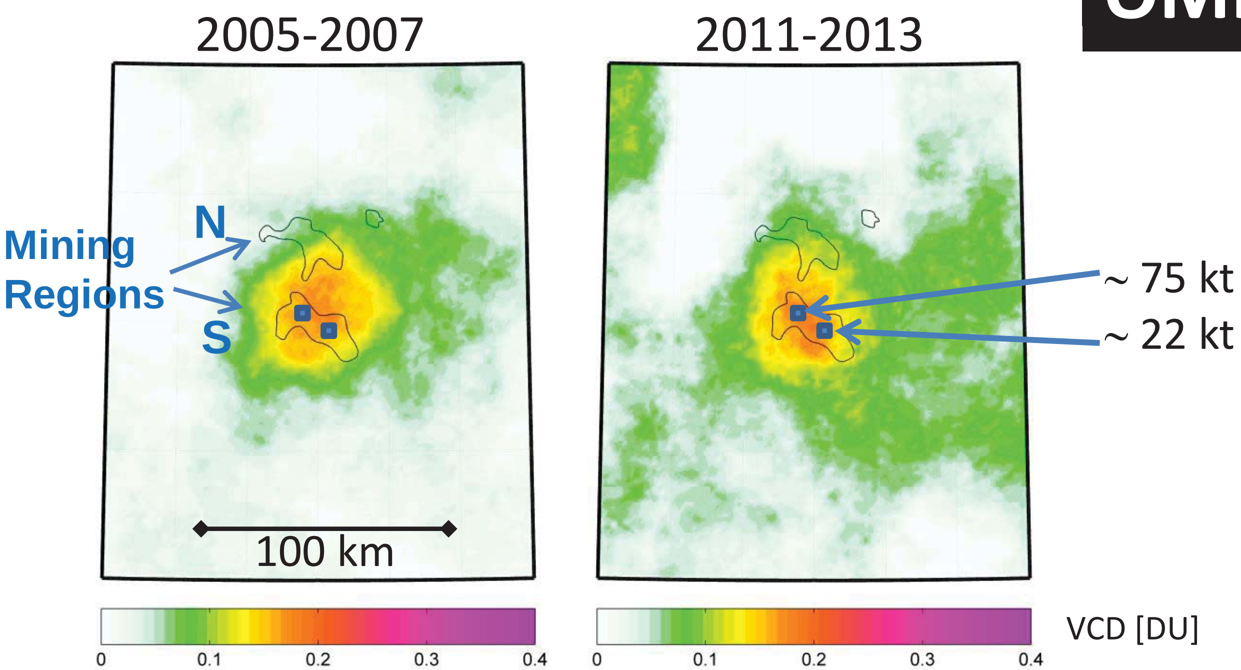
Evolution of OMI NO_2



Evolution of OMI NO_2

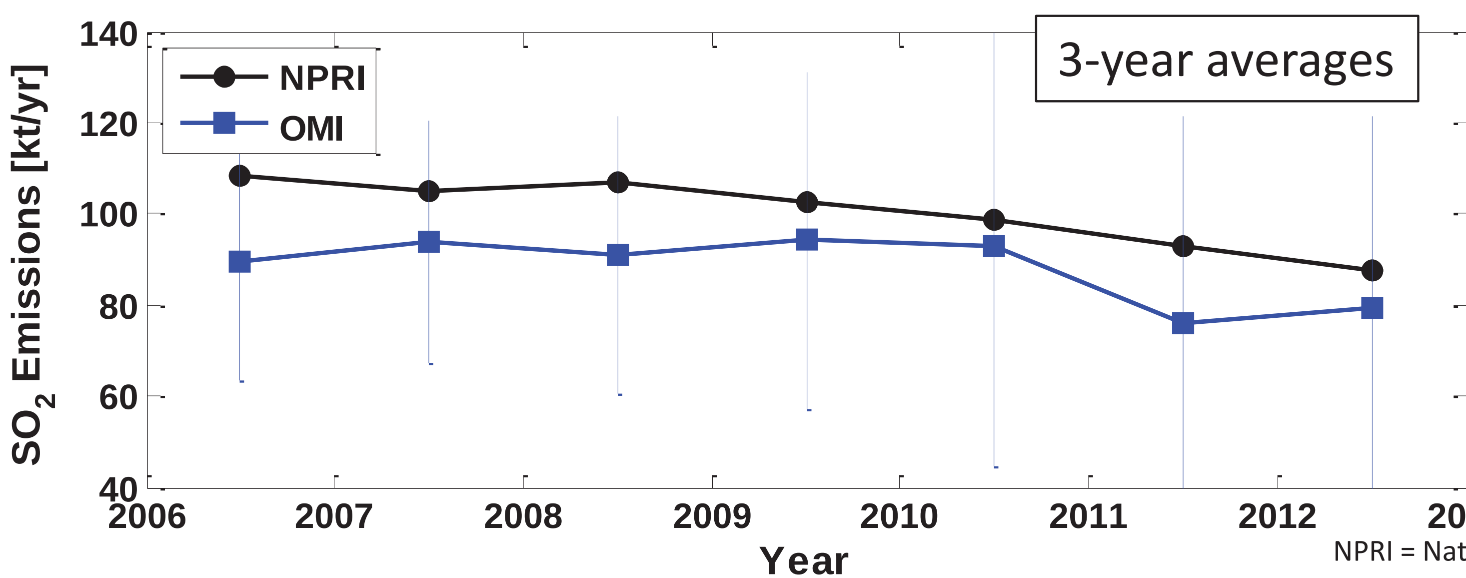


OMI SO_2 over the oil sands



- 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 average	E(NPRI*) = 100 kt[SO_2]/yr *NPRI = National Pollutant Release Inventory	E(OMI) = 89 kt[SO_2]/yr

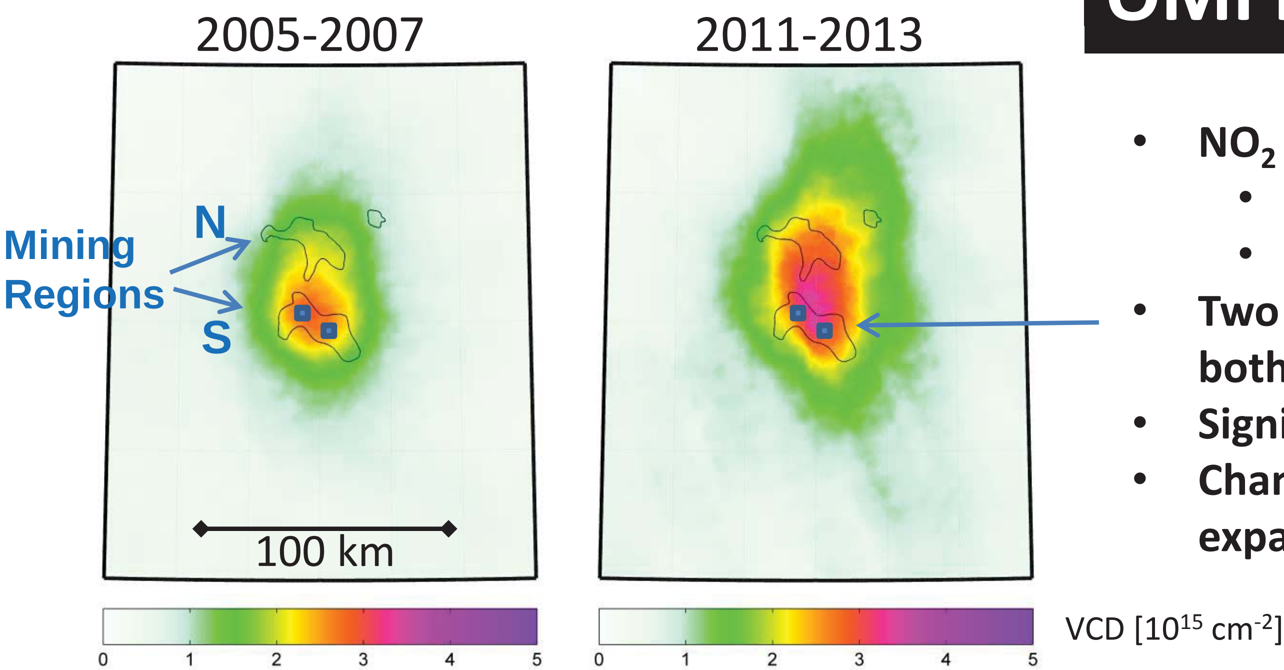


Emissions and lifetime determined by fitting the downwind decay of SO_2

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

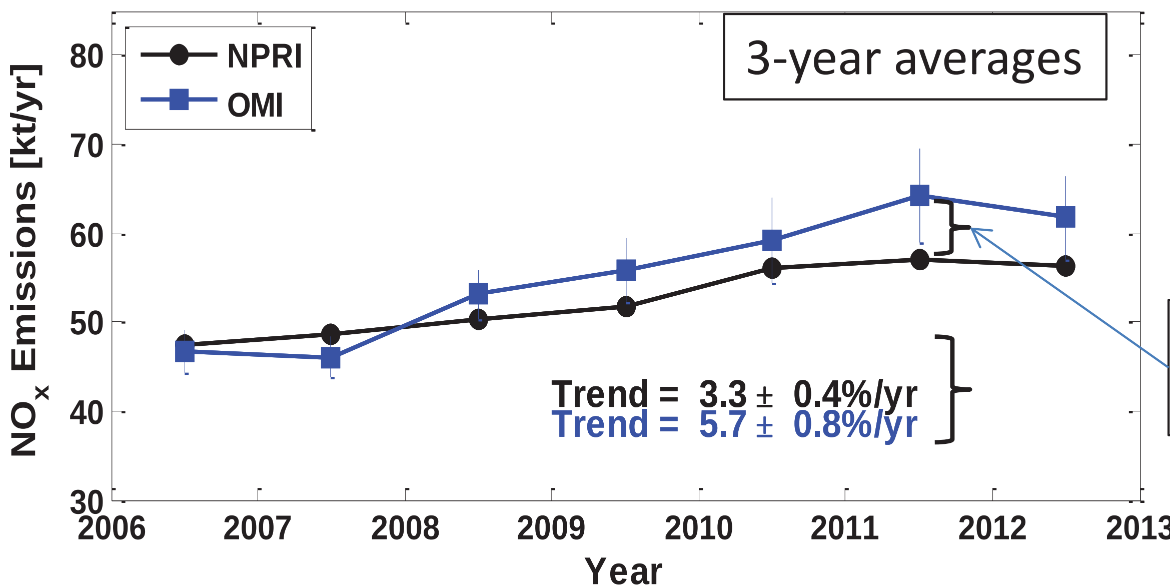
NPRI = National Pollutant Release Inventory

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(NPRI*) = 53 kt[NO_2]/yr** *NPRI = National Pollutant Release Inventory	**E(OMI) = 55 kt[NO_2]/yr**



Emissions and lifetime determined by fitting the downwind decay of NO_2

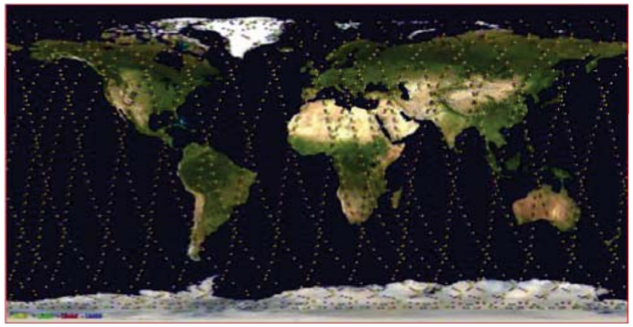
[similar to Beirle et al., Science, 2011]

$NOx / NO_2 = 1.35$ 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

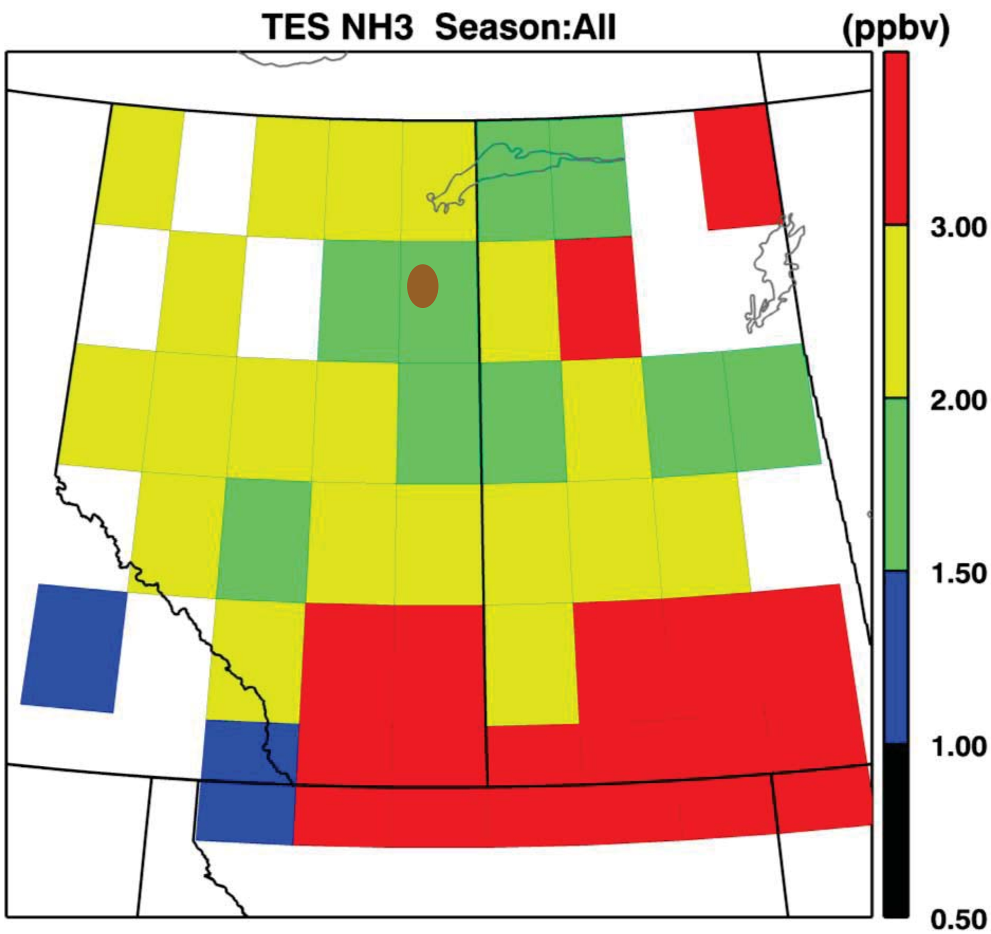
- Nadir pointing (16-day repeat cycle)
- Spacing of ~180 km along track
- No Global surveys taken after 2011

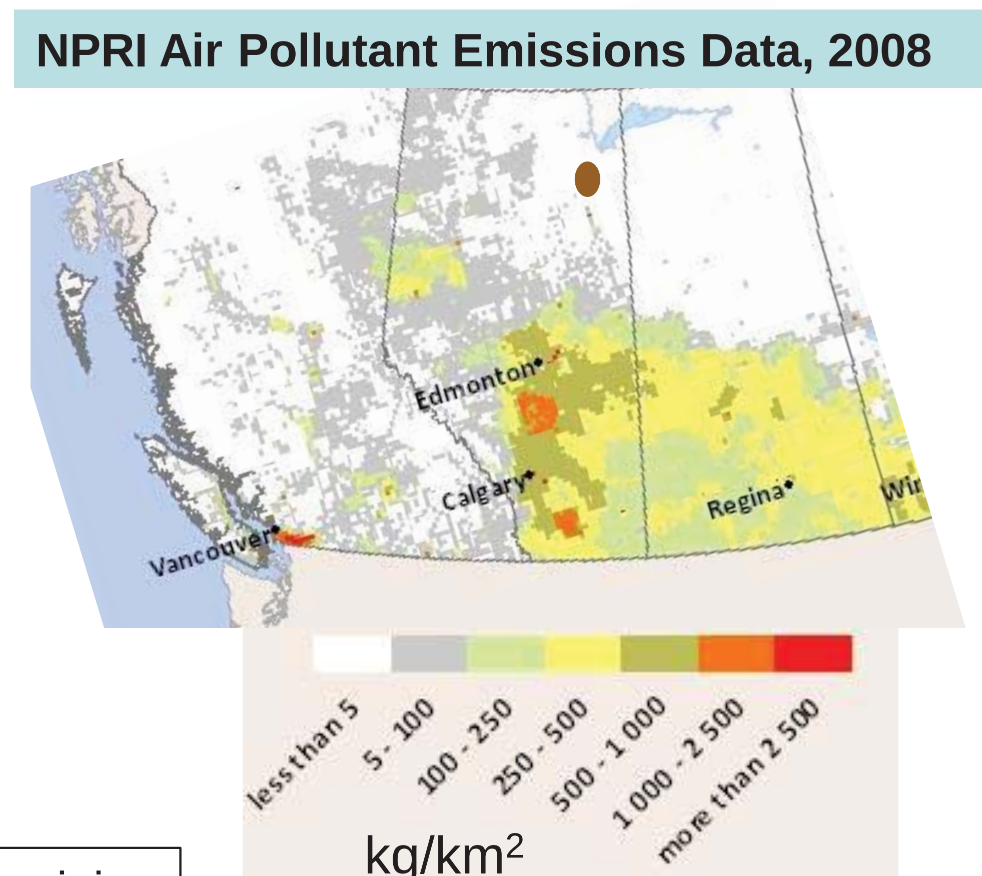
TES Special Observation (SO) Mode

- 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 56-58ºN 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



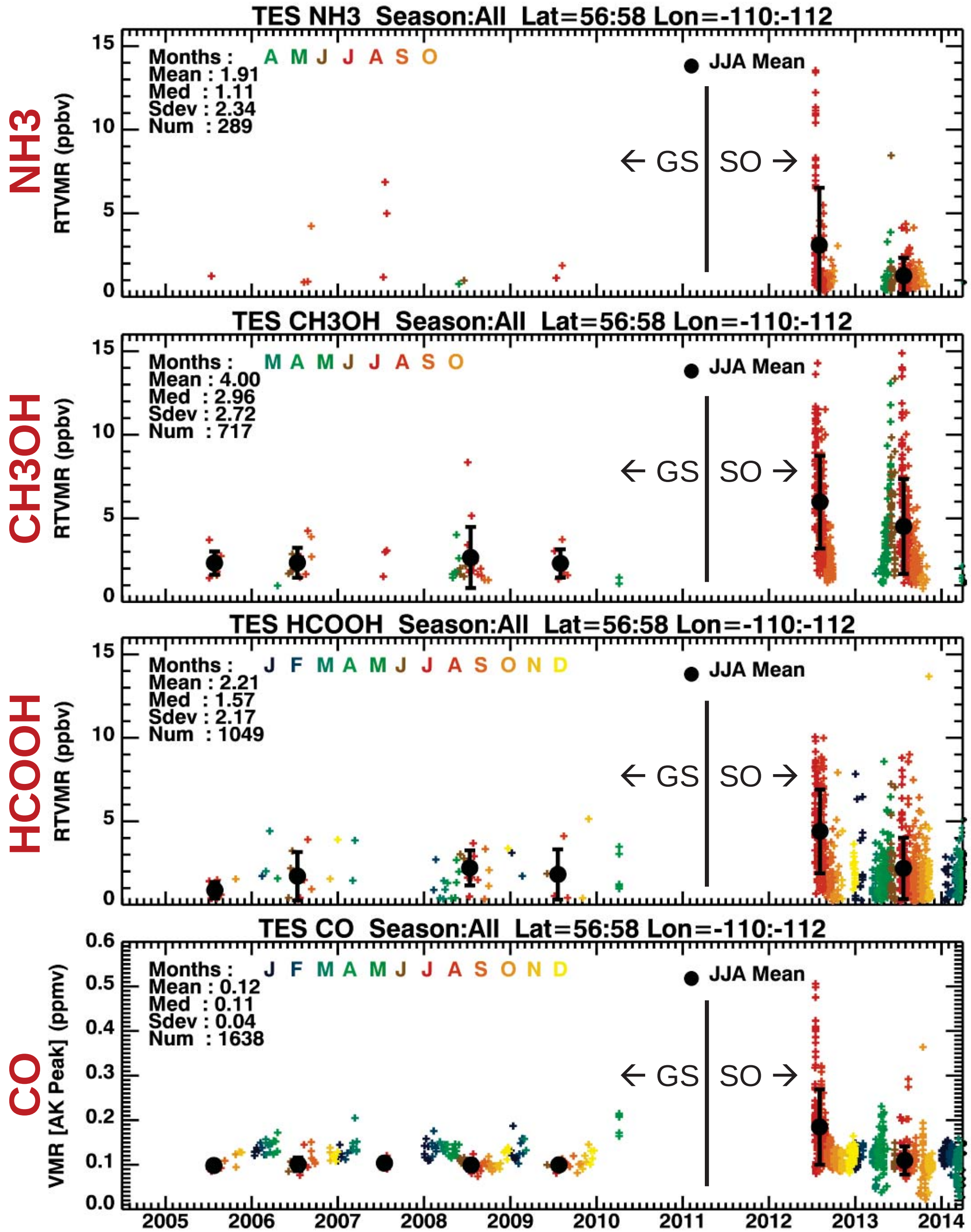


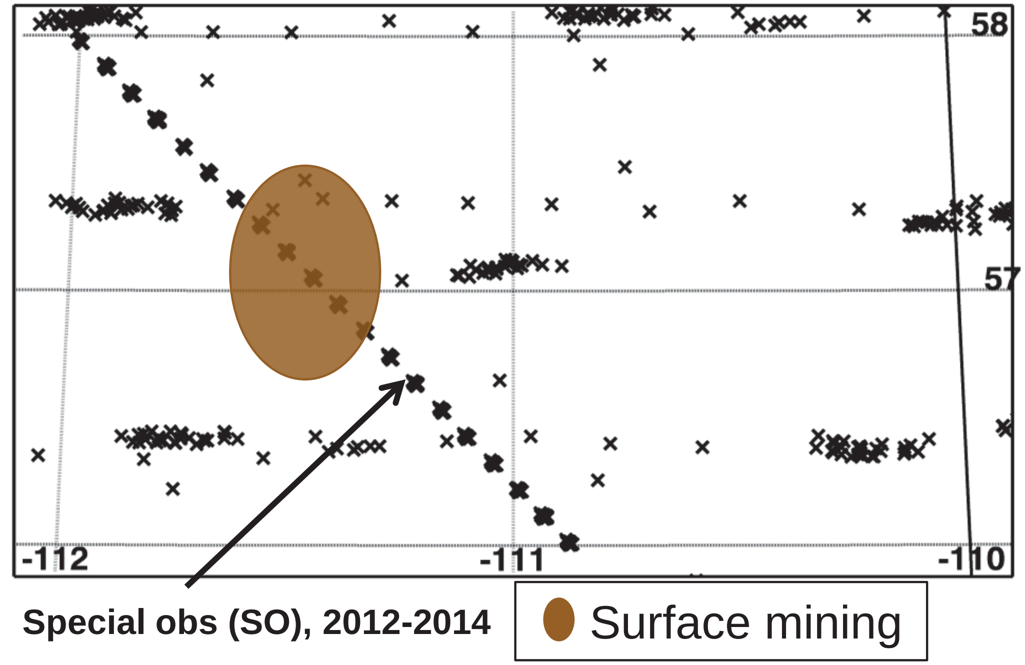
Surface mining

TES

- 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?





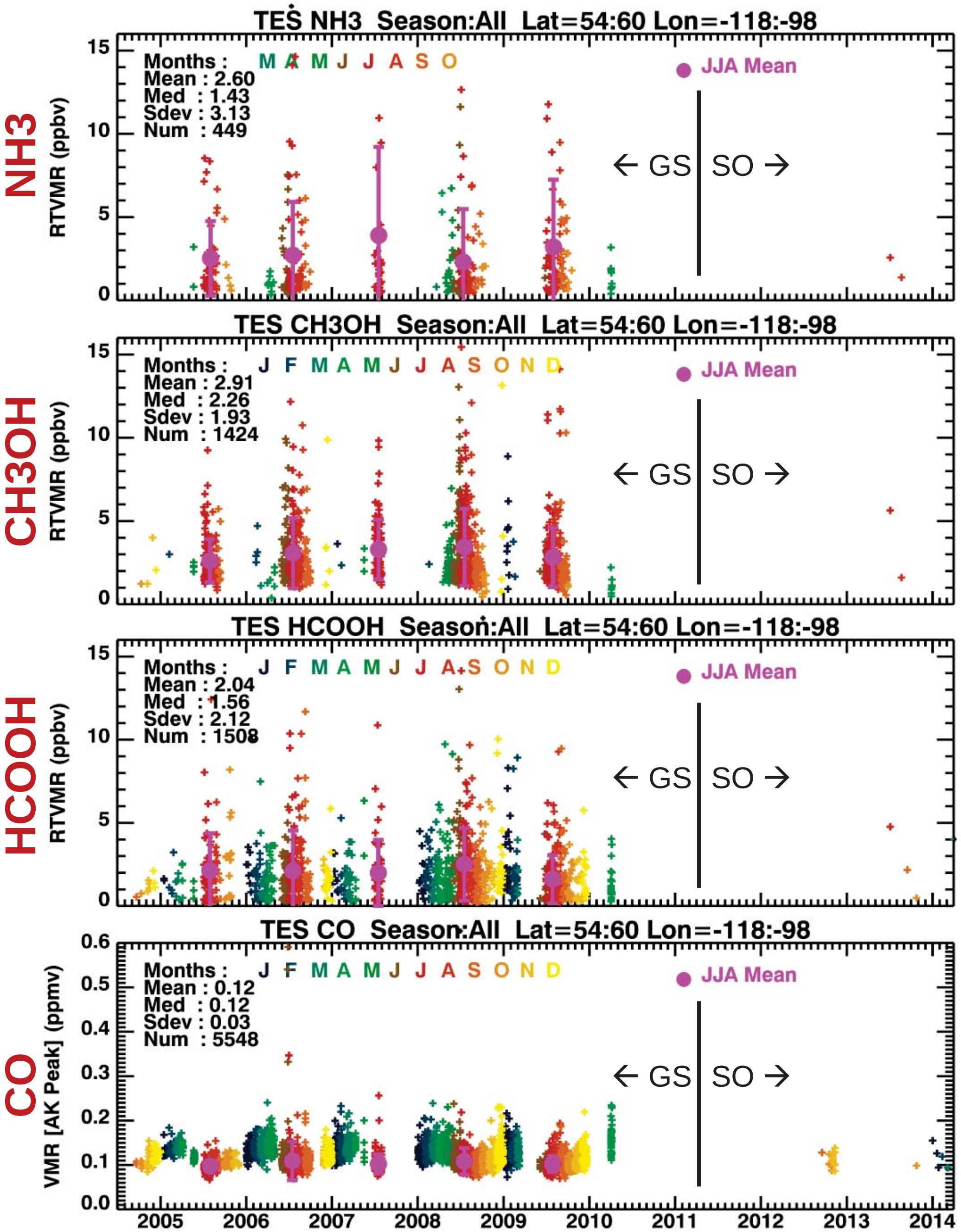
Approach: compare global survey (2004-2011) with special observations (2012-2014) over oil sands region

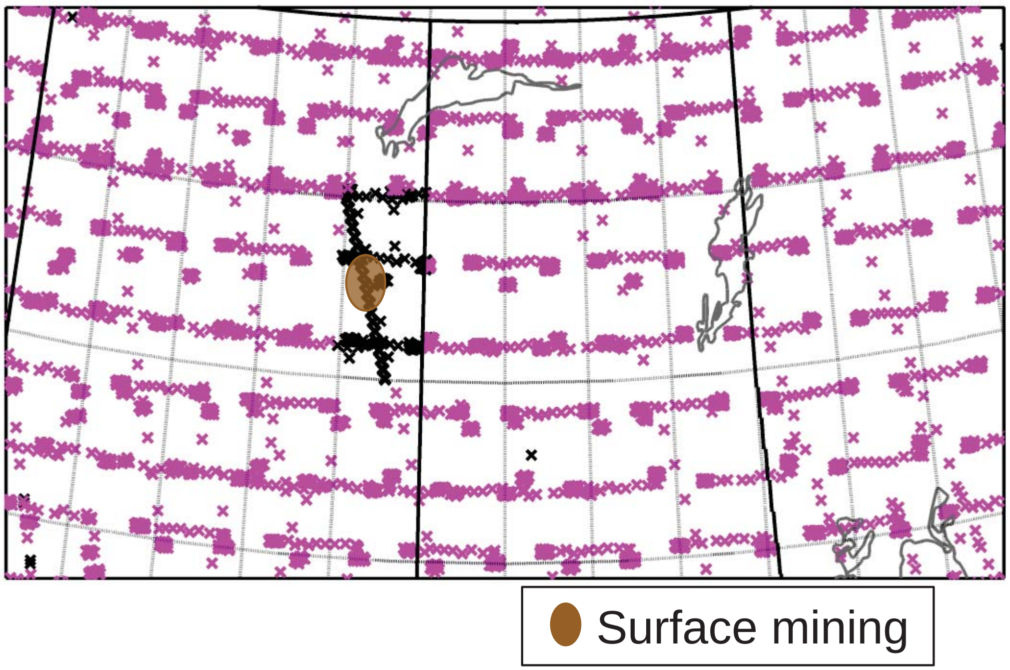
Challenging: Not many GS values over oil sands region (2004-2011)

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

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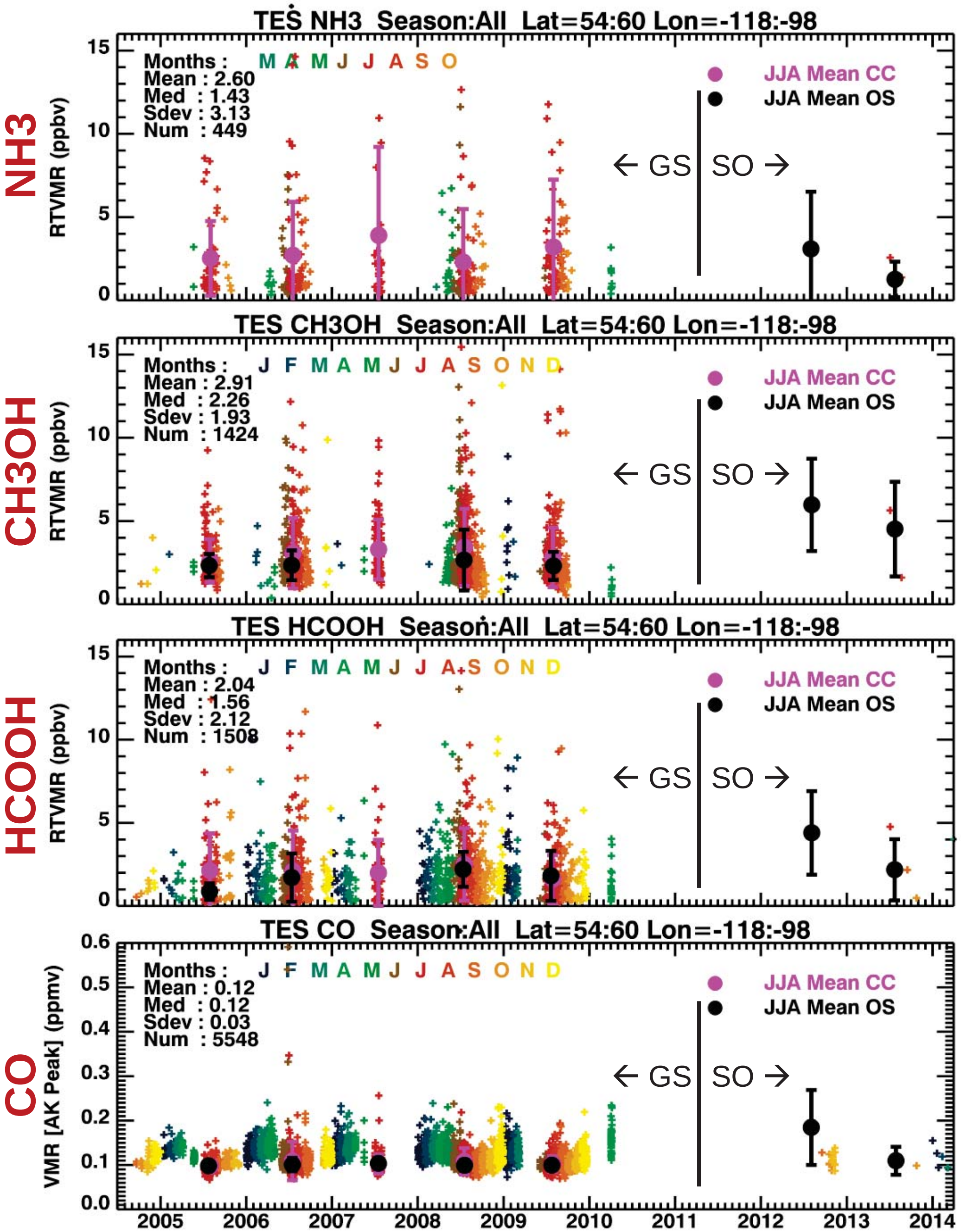

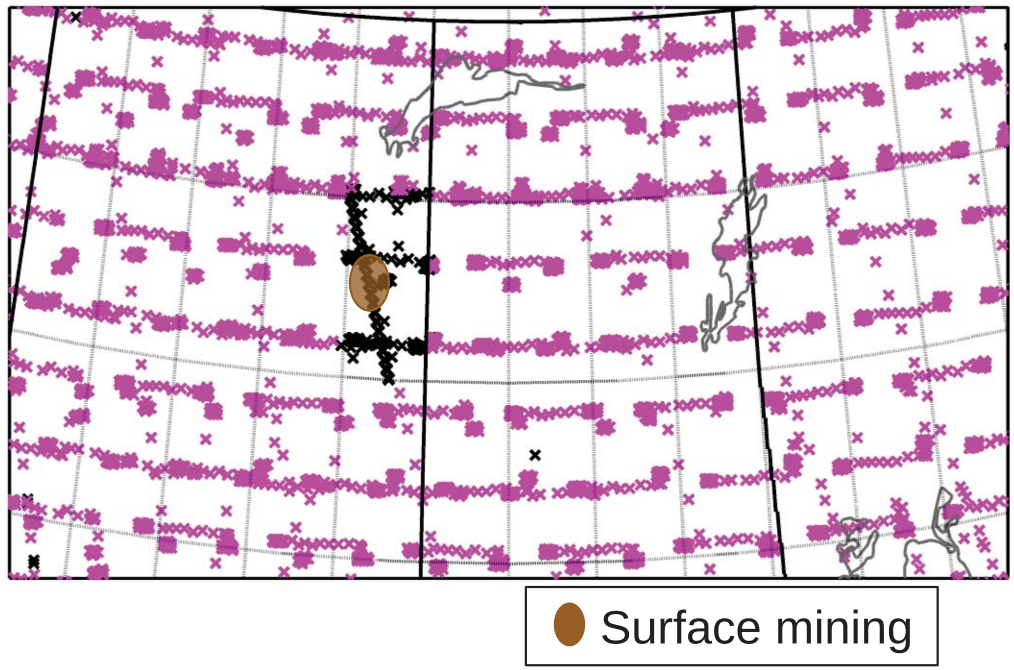

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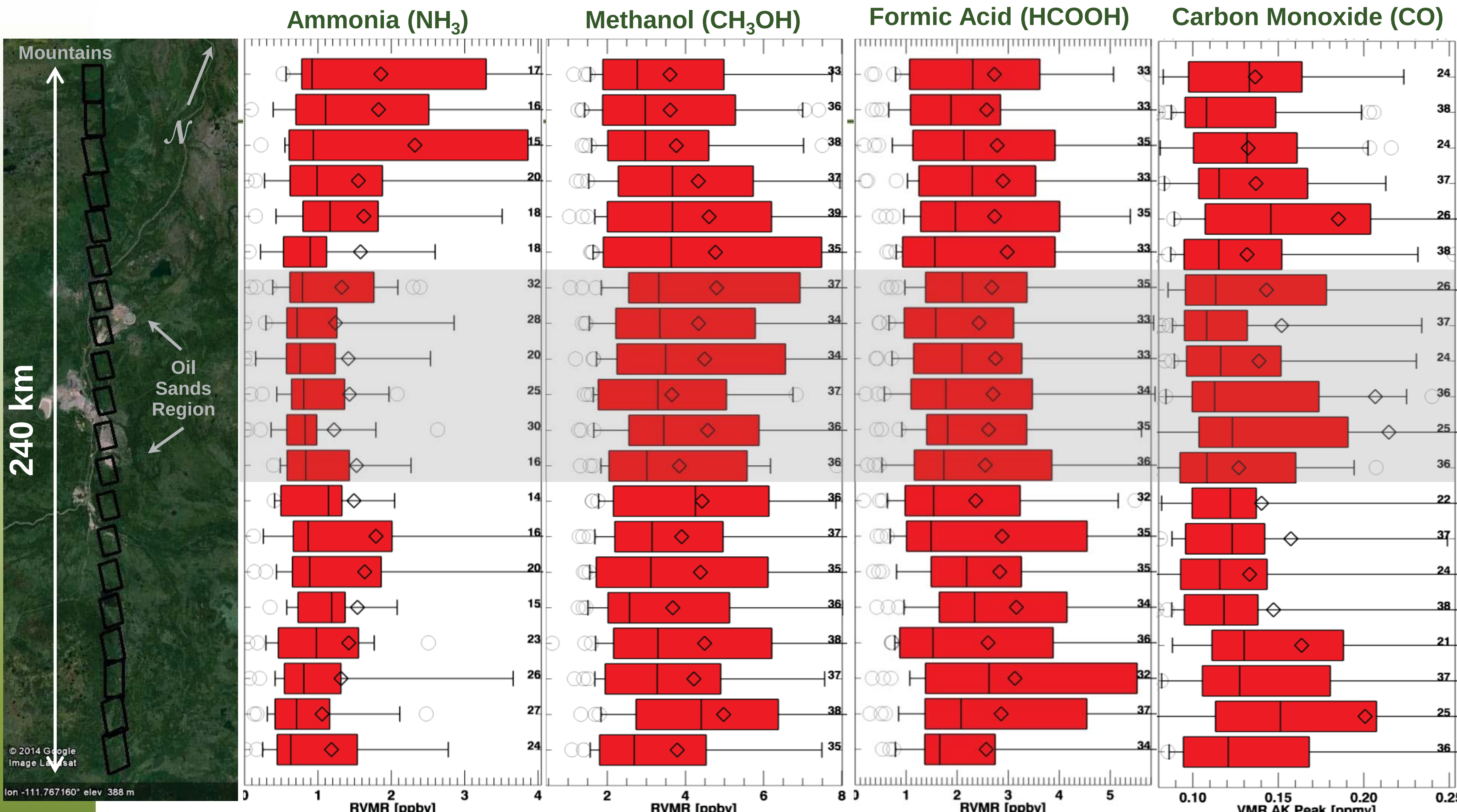
“Climatological” Oil Sand Region Satellite Observations:

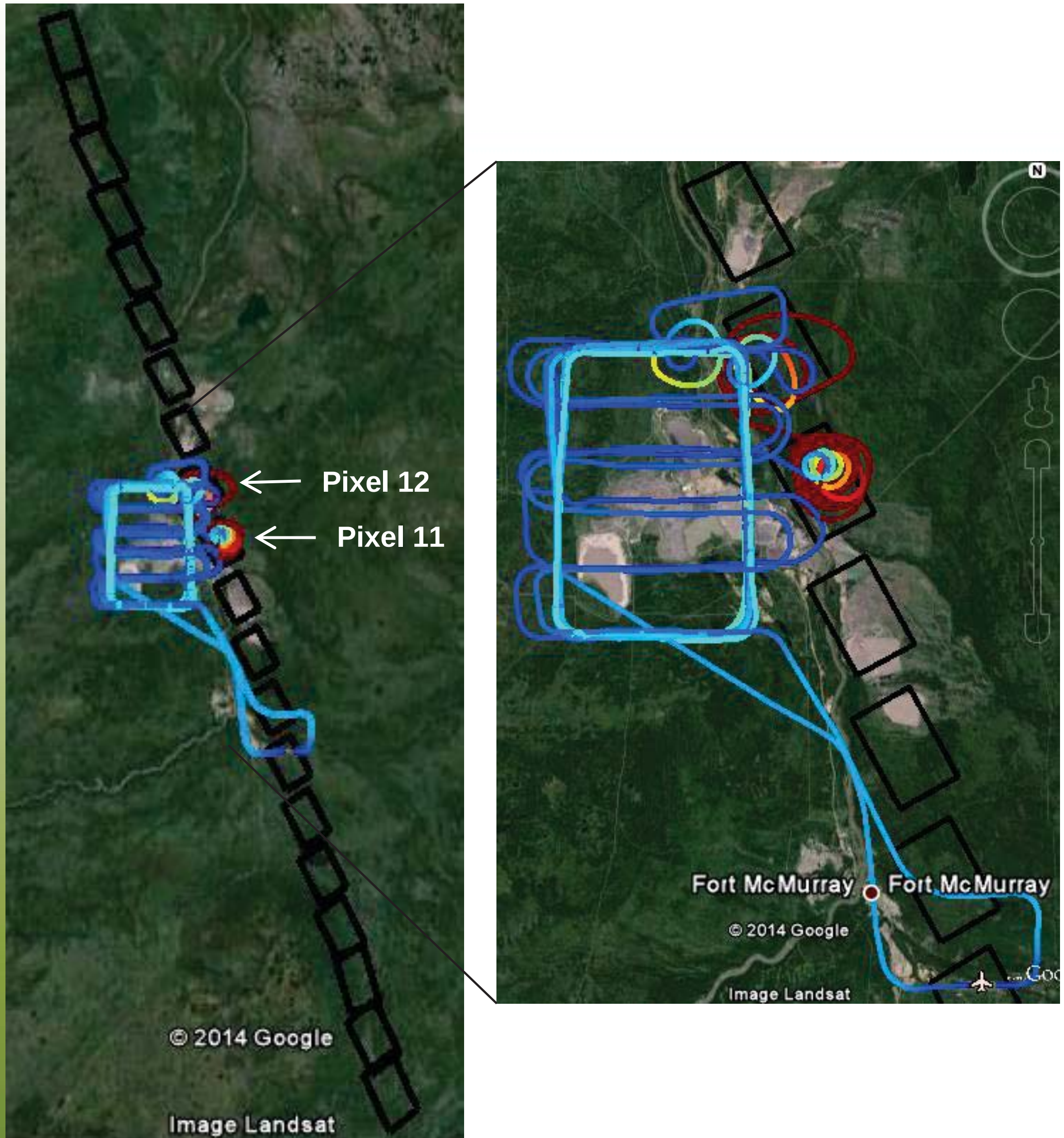
Period 2012/07/14 – 2014/04/03 (Warm Season: M-J-J-A-S)



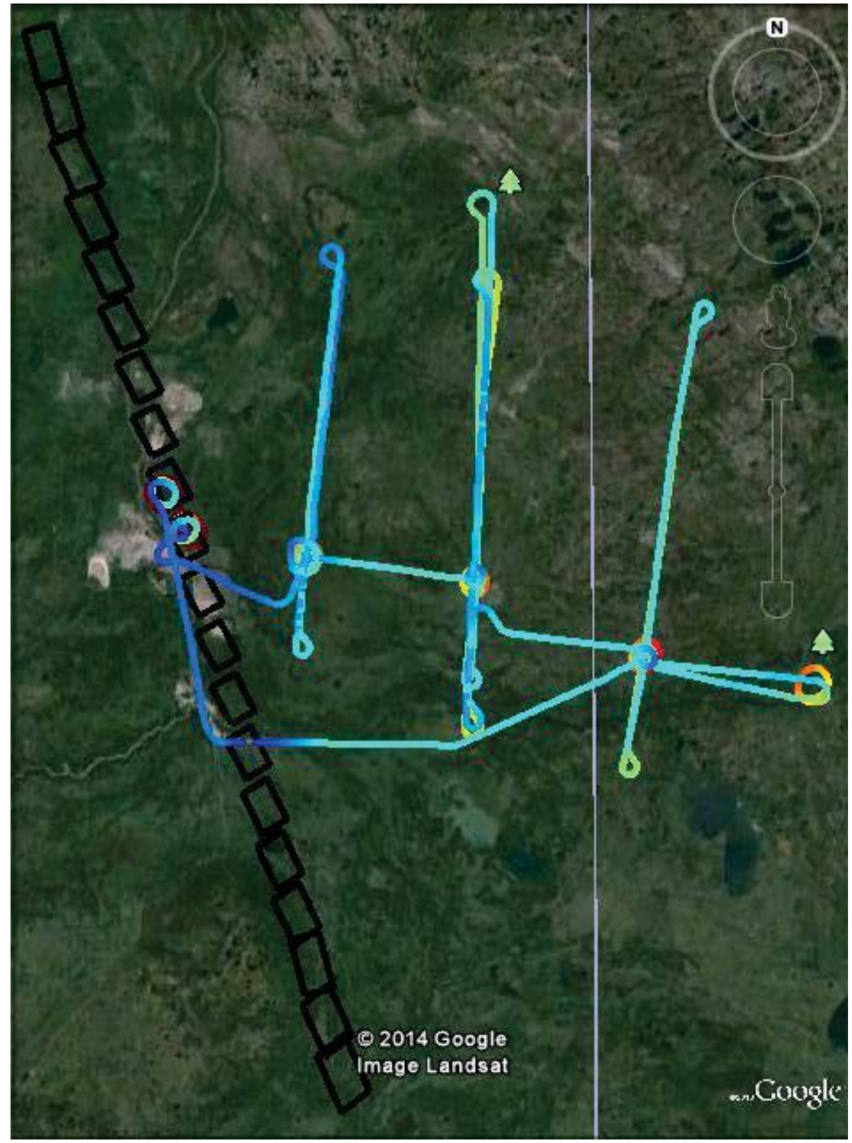
VMR (ppbv)	~1-2	~4-5	~2-3	~150-200
Pressure (hPa)	850-900	825	825	680
DOFS	0.65	0.6	0.75	1.1

Satellite Validation: 2013 Intensive Oil Sands Field Campaign

Sept. 3rd, 2013 : Flight 18



Sept. 5th, 2013 : Flight 20



- Dedicated TES overpass spirals
- Clear conditions

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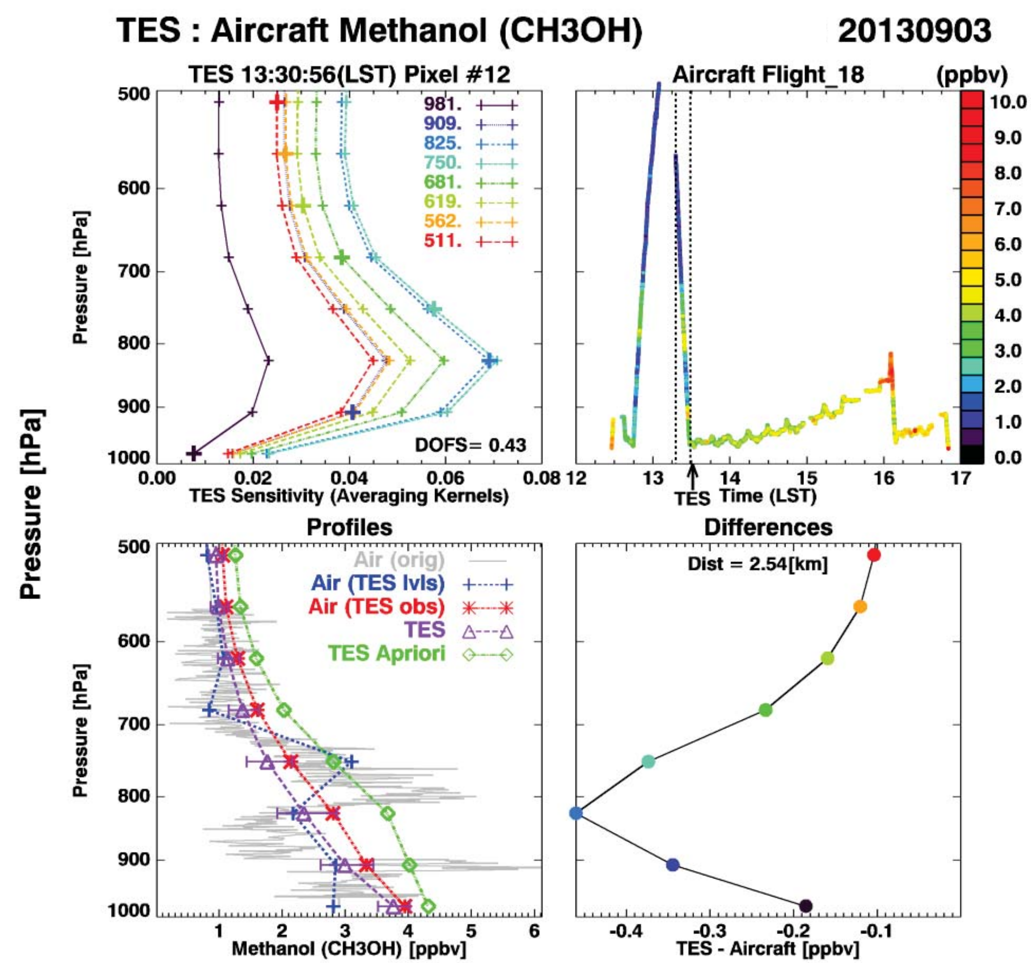
Satellite Validation:
2013 Intensive Oil Sands Field Campaign

- **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_3OH and HCOOH products**

- **Very preliminary TES/aircraft comparison results show:**
  - **~20% NH_3**
  - **~30% CH_3OH**
  - **~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 NO_2 and SO_2 over the oil sands**
    - comparable with medium-sized city (~1 M) or large power plant
    - distributions are consistent with location of sources
  - **NO_2 increasing**
    - possibly at a rate faster than NPRI emissions would suggest
  - **SO_2 showing slight decline and consistent with NPRI**
  - SO_2 analysis : possible due to improvements due to **new PCA algorithm**
  - **Initial analysis of NH_3, CO, and VOCs (CH_3OH, and HCOOH) indicates**:
    - TES does not detect large elevated concentrations directly over the oil sands mining regions
    - Potentially a decrease of NH_3 over oil sands region
      - In the presence of sulphur and NOx : NH_3 (gas) → 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

Over ~130 special observations over the oil sands to date

- Measurement every 2- 7 days

OS Field Study

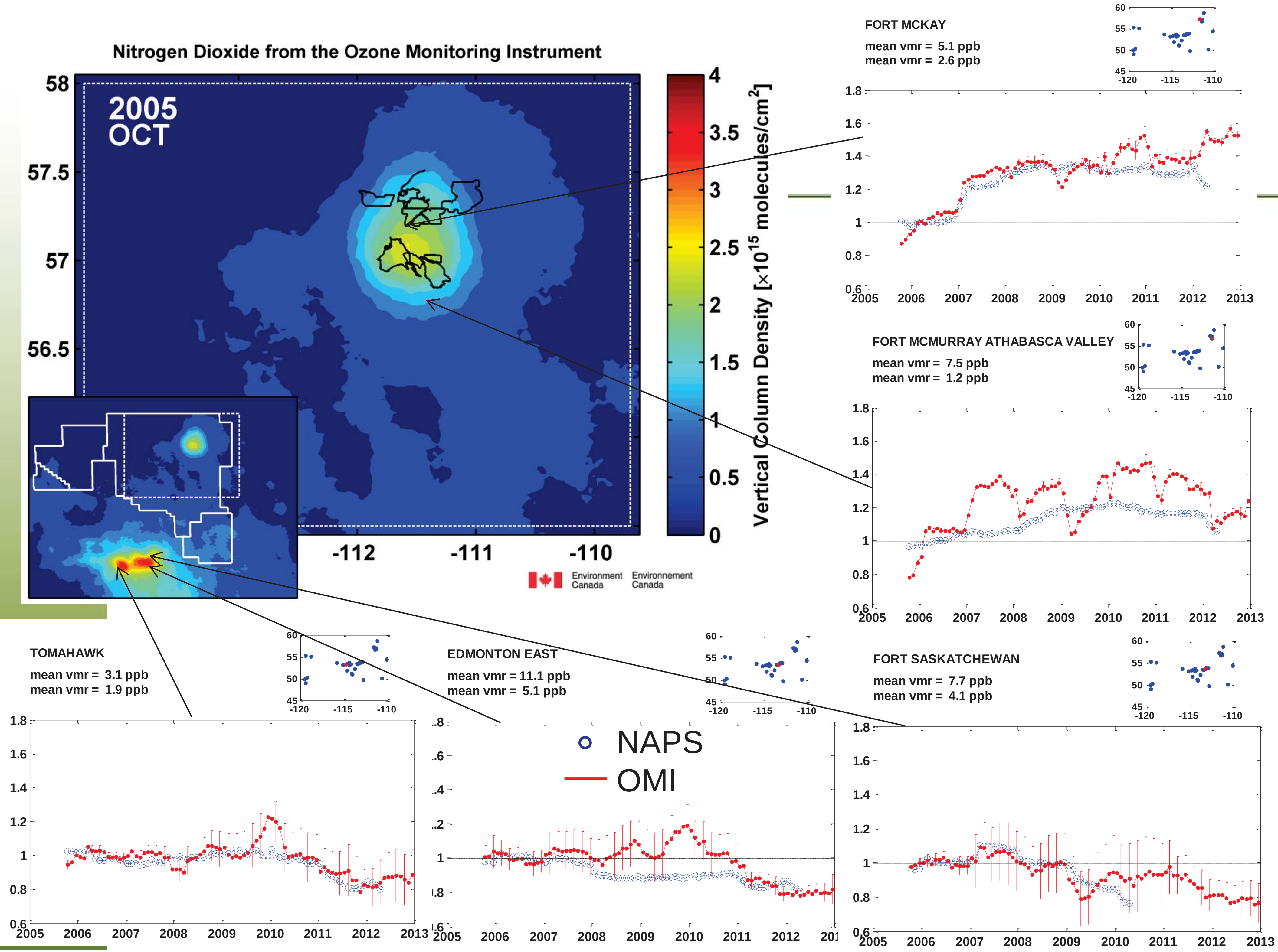
- **9 overpasses**

TES transects of oil sands begun July 14, 2012

2014					
• 2014-01-02: 19031. • 2014-01-09: 19095. • 2014-01-11: 19118. • 2014-01-13: 19138. • 2014-01-18: 19179. • 2014-01-25: 19252. • 2014-01-27: 19272. • 2014-01-29: 19295.	• 2014-02-03: 19339. • 2014-02-10: 19418. • 2014-02-12: 19441. • 2014-02-14: 19461. • 2014-02-19: 19502. • 2014-02-26: 19578. • 2014-02-28: 19601.	• 2014-03-02: 19624. • 2014-03-07: 19665. • 2014-03-14: 19738. • 2014-03-16: 19761. • 2014-03-18: 19781. • 2014-03-23: 19828. • 2014-03-30: 19901.	• 2014-04-08: 19988.		

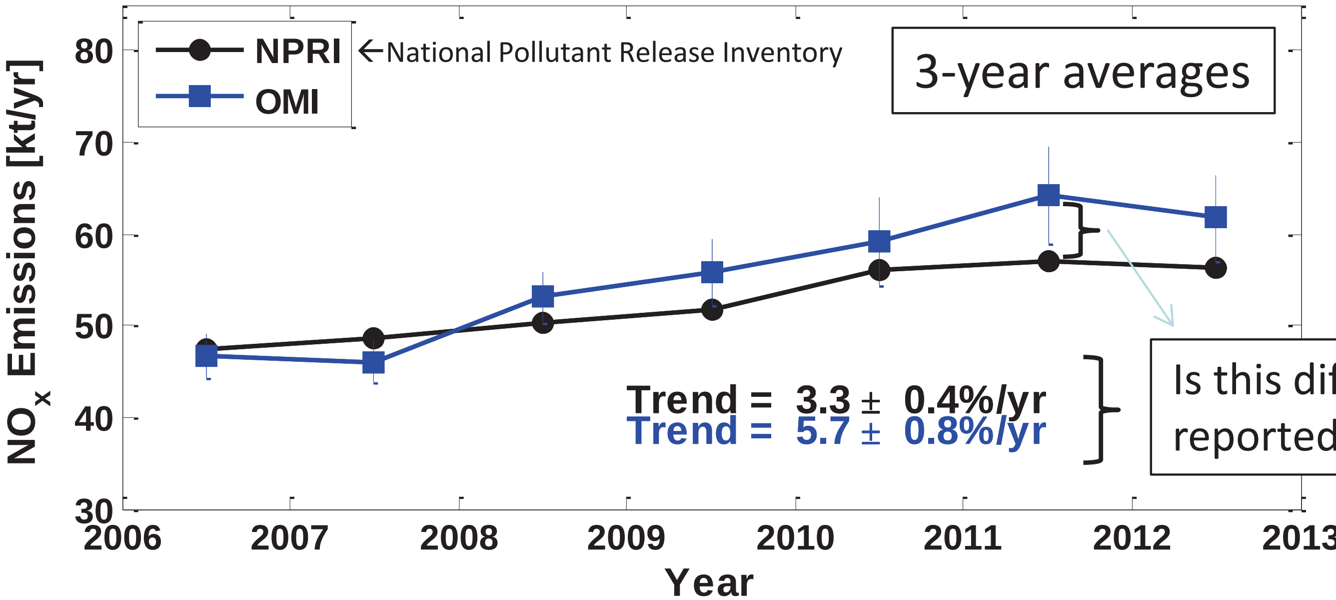
2013					
• 2013-01-01: 16144. • 2013-01-06: 16188. • 2013-01-08: 16217. • 2013-01-10: 16252. • 2013-01-15: 16317. • 2013-01-22: 16399. • 2013-01-24: 16425. • 2013-01-26: 16436. • 2013-01-31: 16459.	• 2013-02-02: 16473.	• 2013-03-15: 16739. • 2013-03-20: 16765. • 2013-03-27: 16829. • 2013-03-29: 16840. • 2013-03-31: 16851.	• 2013-04-05: 16886. • 2013-04-12: 16950. • 2013-04-14: 16964. • 2013-04-21: 16998. • 2013-04-28: 17059. • 2013-04-30: 17079.	• 2013-05-02: 17096. • 2013-05-07: 17140. • 2013-05-14: 17201. • 2013-05-16: 17218. • 2013-05-18: 17235. • 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: 17575.
• 2013-07-01: 17651. • 2013-07-03: 17677. • 2013-07-05: 17700. • 2013-07-10: 17735. • 2013-07-17: 17826. • 2013-07-19: 17846. • 2013-07-21: 17869. • 2013-07-26: 17916.	• 2013-08-02: 17992. • 2013-08-04: 18015. • 2013-08-06: 18035. • 2013-08-11: 18079. • 2013-08-13: 18102. • 2013-08-18: 18148. • 2013-08-20: 18168. • 2013-08-22: 18185. • 2013-08-27: 18220.	• 2013-09-03: 18287. • 2013-09-05: 18307. • 2013-09-12: 18371. • 2013-09-14: 18394. • 2013-09-19: 18450. • 2013-09-28: 18476.	• 2013-10-05: 18546. • 2013-10-07: 18566. • 2013-10-14: 18618. • 2013-10-21: 18679. • 2013-10-23: 18699. • 2013-10-25: 18713. • 2013-10-30: 18751.	• 2013-11-06: 18827. • 2013-11-08: 18850. • 2013-11-10: 18870. • 2013-11-15: 18911. • 2013-11-22: 18978.	

2012					
• 2012-07-14: 15057. • 2012-07-16: 15068. • 2012-07-18: 15079. • 2012-07-23: 15108. • 2012-07-25: 15119.	• 2012-08-01: 15165. • 2012-08-03: 15188. • 2012-08-10: 15237. • 2012-08-17: 15289. • 2012-08-19: 15303. • 2012-08-26: 15358.	• 2012-09-02: 15410. • 2012-09-04: 15424. • 2012-09-11: 15464. • 2012-09-16: 15502. • 2012-09-20: 15537. • 2012-09-27: 15574.	• 2012-10-02: 15603. • 2012-10-06: 15637. • 2012-10-13: 15677. • 2012-10-18: 15710. • 2012-10-20: 15733. • 2012-10-22: 15747. • 2012-10-27: 15789.	• 2012-11-03: 15837. • 2012-11-05: 15848. • 2012-11-07: 15853. • 2012-11-23: 15907. • 2012-11-30: 15944.	• 2012-12-05: 15967. • 2012-12-07: 15990. • 2012-12-09: 16001. • 2012-12-16: 16038. • 2012-12-21: 16079. • 2012-12-23: 16090. • 2012-12-25: 16101. • 2012-12-30: 16133.



Nitrogen Dioxide from the Ozone Monitoring Instrument
2005
OCT
Vertical Column Density [×10^15 molecules/cm^2]
Environment Canada
Environnement Canada
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
FORT SASKATCHEWAN
mean vmr = 7.7 ppb
mean vmr = 4.1 ppb
TOMAHAWK
mean vmr = 3.1 ppb
mean vmr = 1.9 ppb
EDMONTON EAST
mean vmr = 11.1 ppb
mean vmr = 5.1 ppb
NAPS
OMI

NO_x Emissions

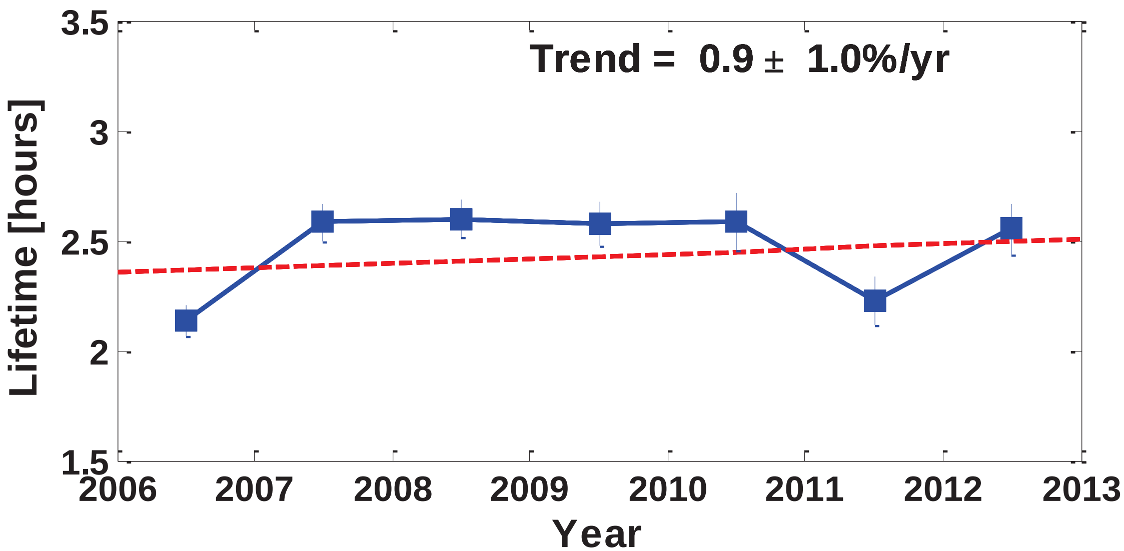


E and τ determined by fitting the downwind decay of NO_2 [similar to Beirle et al., Science, 2011]

NOx / NO_2 = 1.35 assumed

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

NO_2 Lifetime



- 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 NO_2 increases? This would suggest a transition towards a VOC-limited regime

Nice Features of the OE Approach

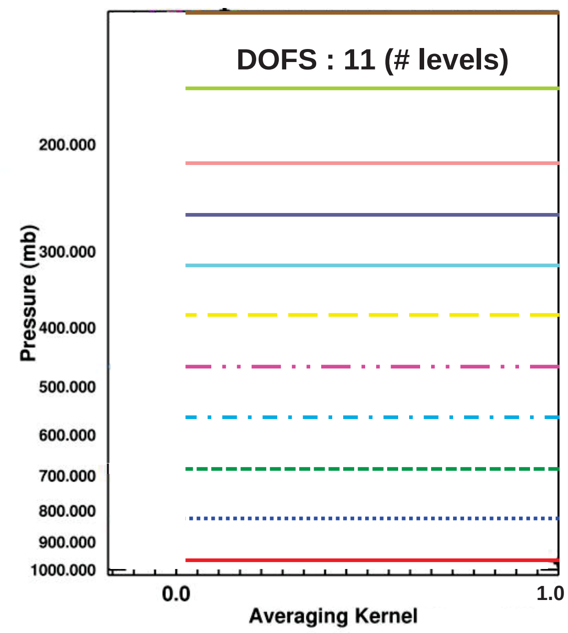
- **Retrieval Errors**
  - Straight-forward method of estimating retrievals errors
  - $E=\{K^T S_m^{-1} K + S_a^{-1}\}^{-1} \rightarrow$ total error
- **Averaging Kernels (A)**
  - $A=\{K^T S_m^{-1} K + S_a^{-1}\}^{-1} K^T S_m^{-1} K$
  - Describes the relative weighting of the retrieved product, x_r to the "true" atmosphere, **x, and a priori** x_a

$$x_r = Ax + (I - A)\, x_a$$

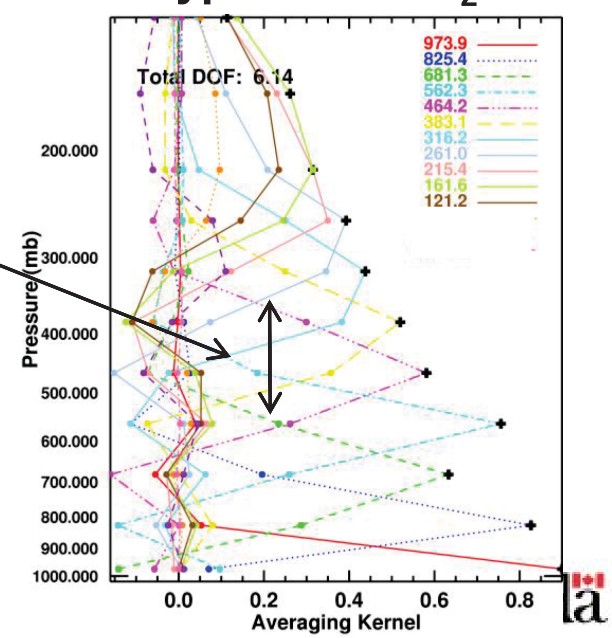
$$A \rightarrow 1\,,\; x_r \rightarrow x$$
$$A \rightarrow 0\,,\; x_r \rightarrow x_a$$

  - **DOFS** (degrees-of-freedom for signal):
    - Number of **independent pieces of information** in the measurement.
    - DOFS=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



Typical TES H_2O

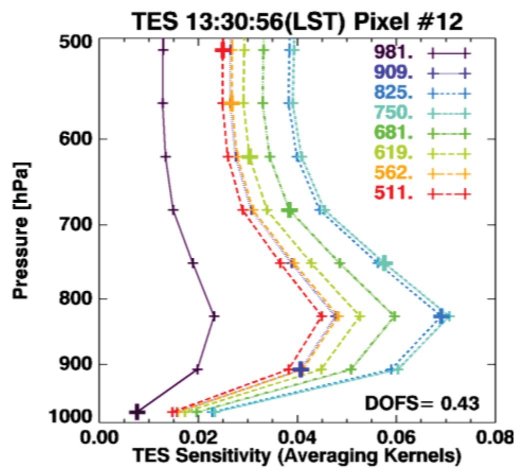


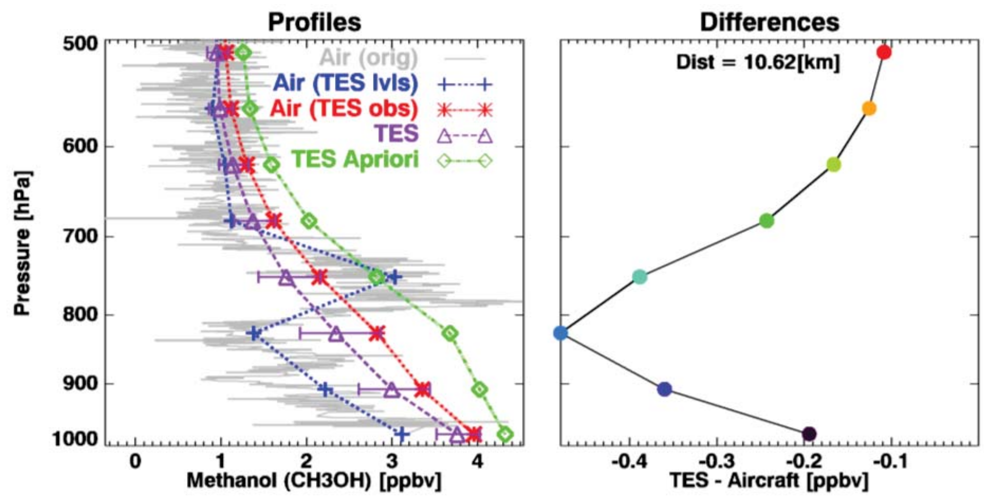
Comparison Methods : Apply the Observational Operator

- **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) : $\hat{x}_{air} = A_{sat}x_{air} + (I - A_{sat})x_a$





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$x_r - \hat{x}_{air}$

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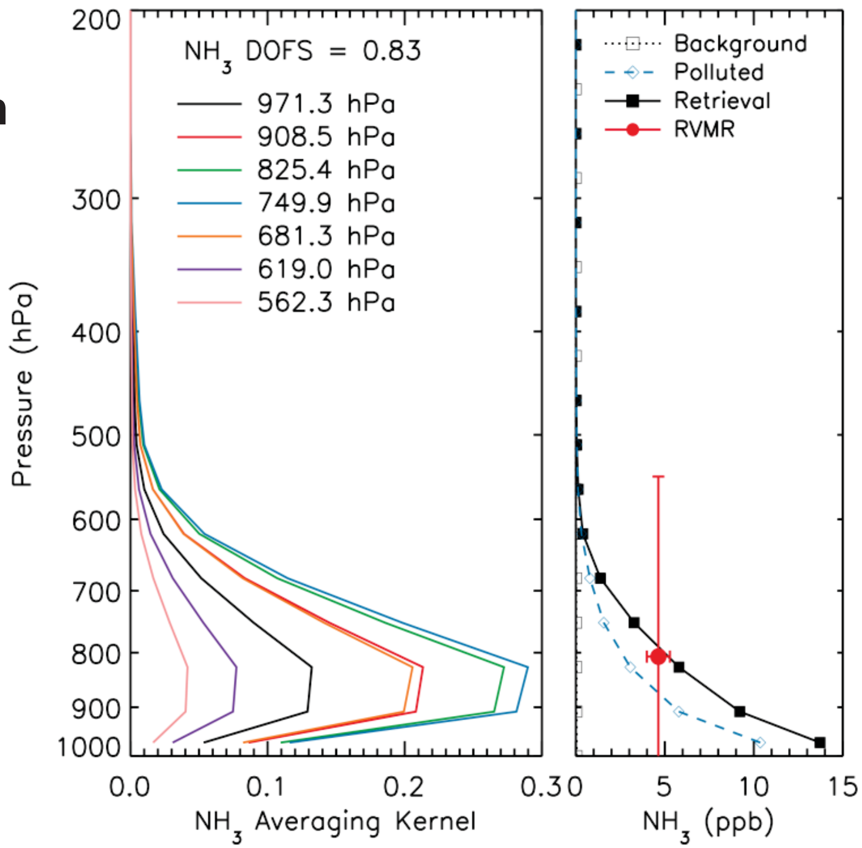
Comparison Methods: Representative Volume Mixing Ratio (RVMR)

- **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.**

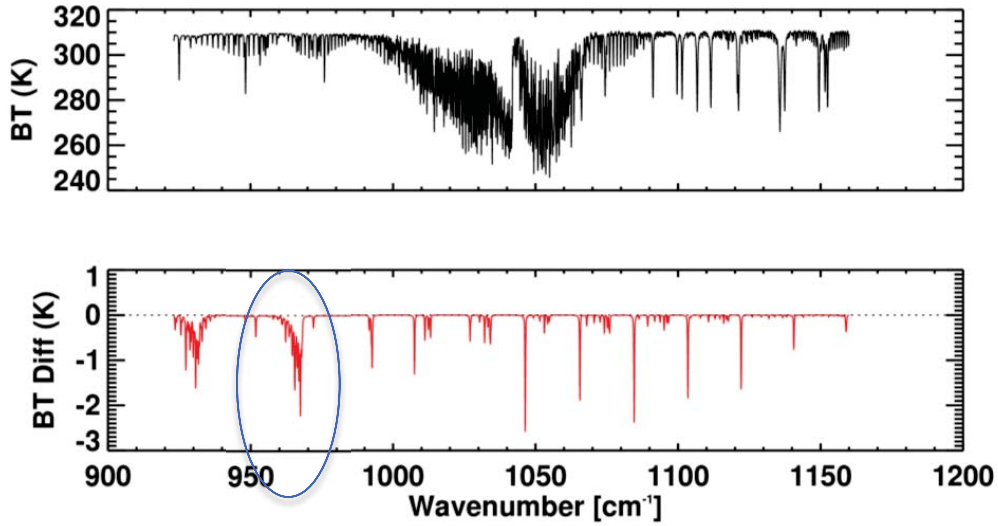
- **As an example :**
  - **TES is most sensitive to NH_3 ~800 mb**
  - **DOFS = 0.83**
  - **RVMR = ~5.0 ppbv**
  - **~2-3 km vertical resolution**
  - **Note: little sensitivity at surface**

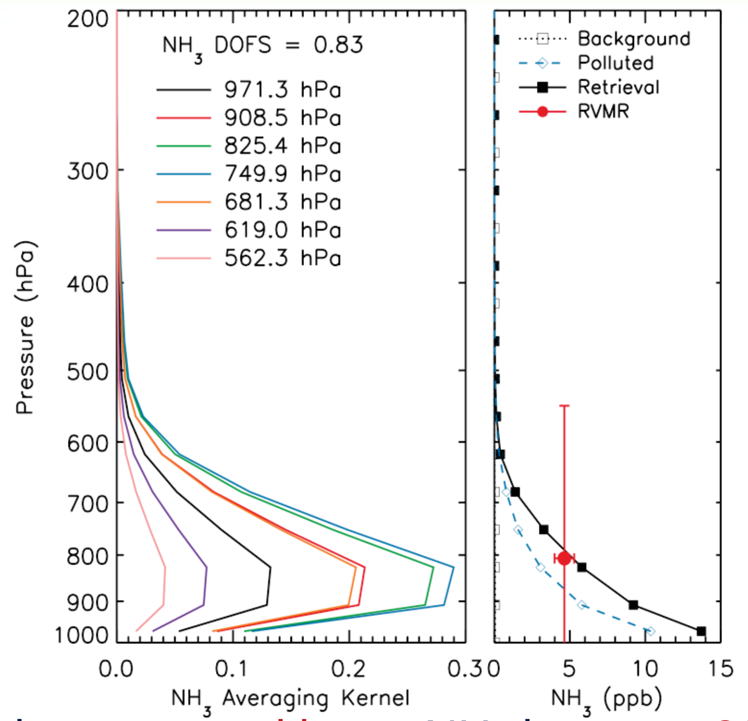


Challenges for Minor Trace Species:
Example Ammonia (NH_3) from TES

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