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Canada

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

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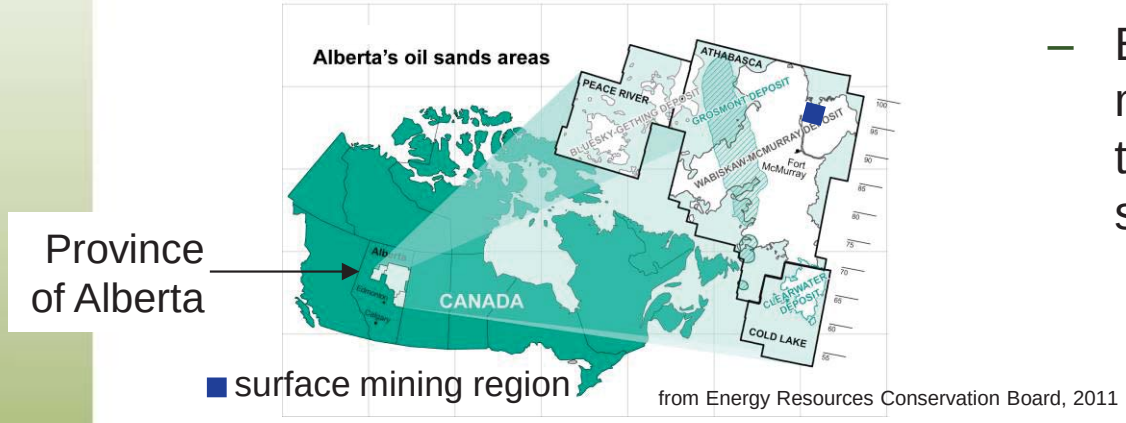
Aura Science Team Meeting, College Park, MD, USA, 15-18 September 2014

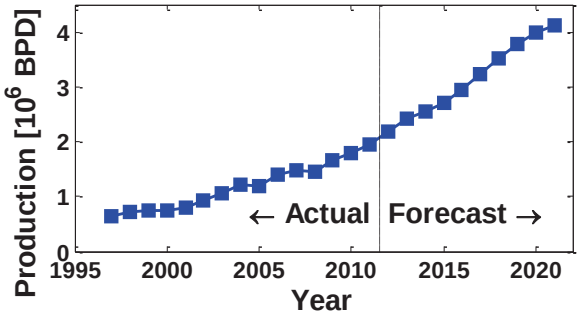
Introduction

- "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



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

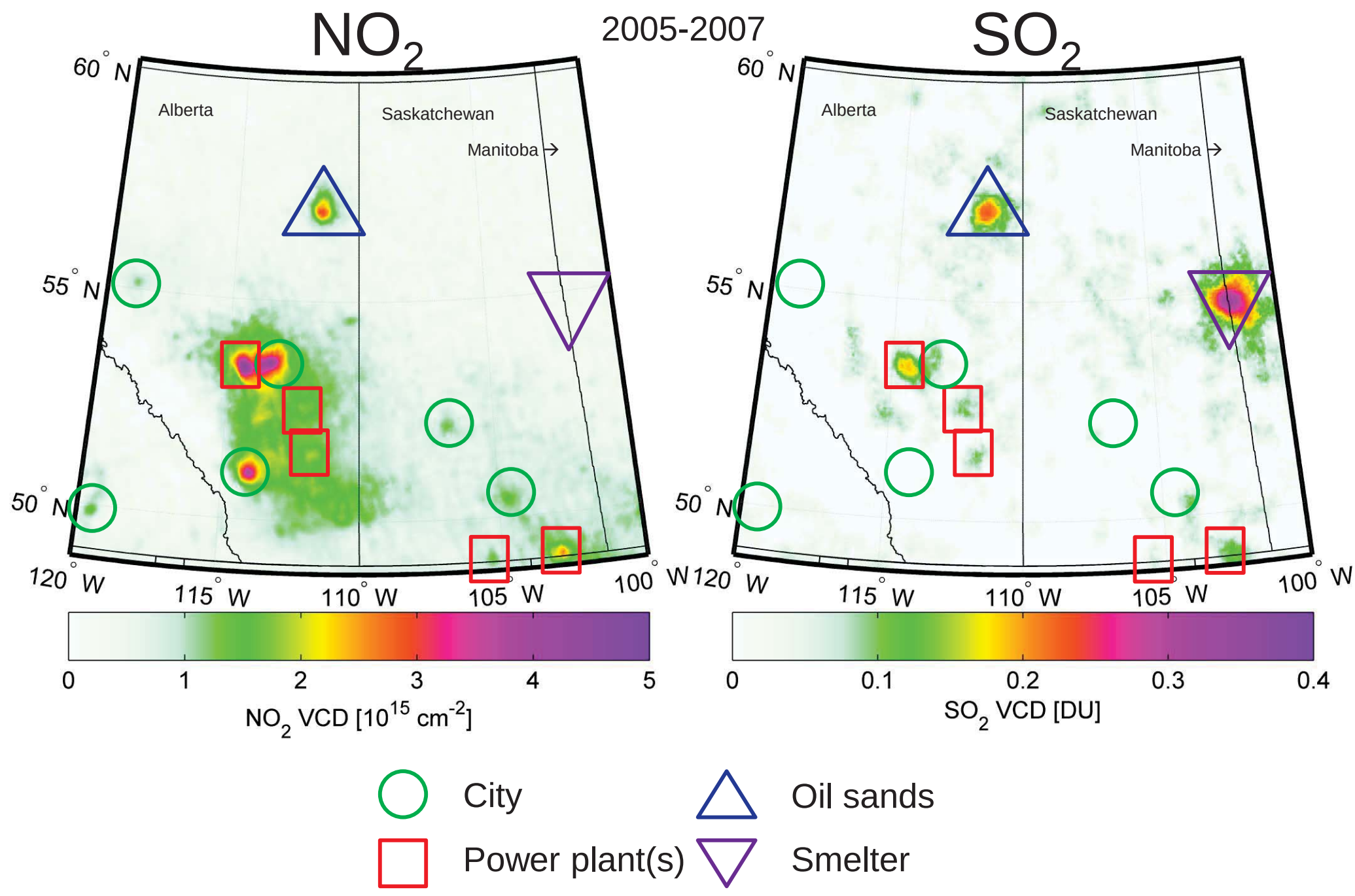
* Principle Component Analysis method, Li et al., GRL, 2013, product being evaluated; See Nick Krotkov talk

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)

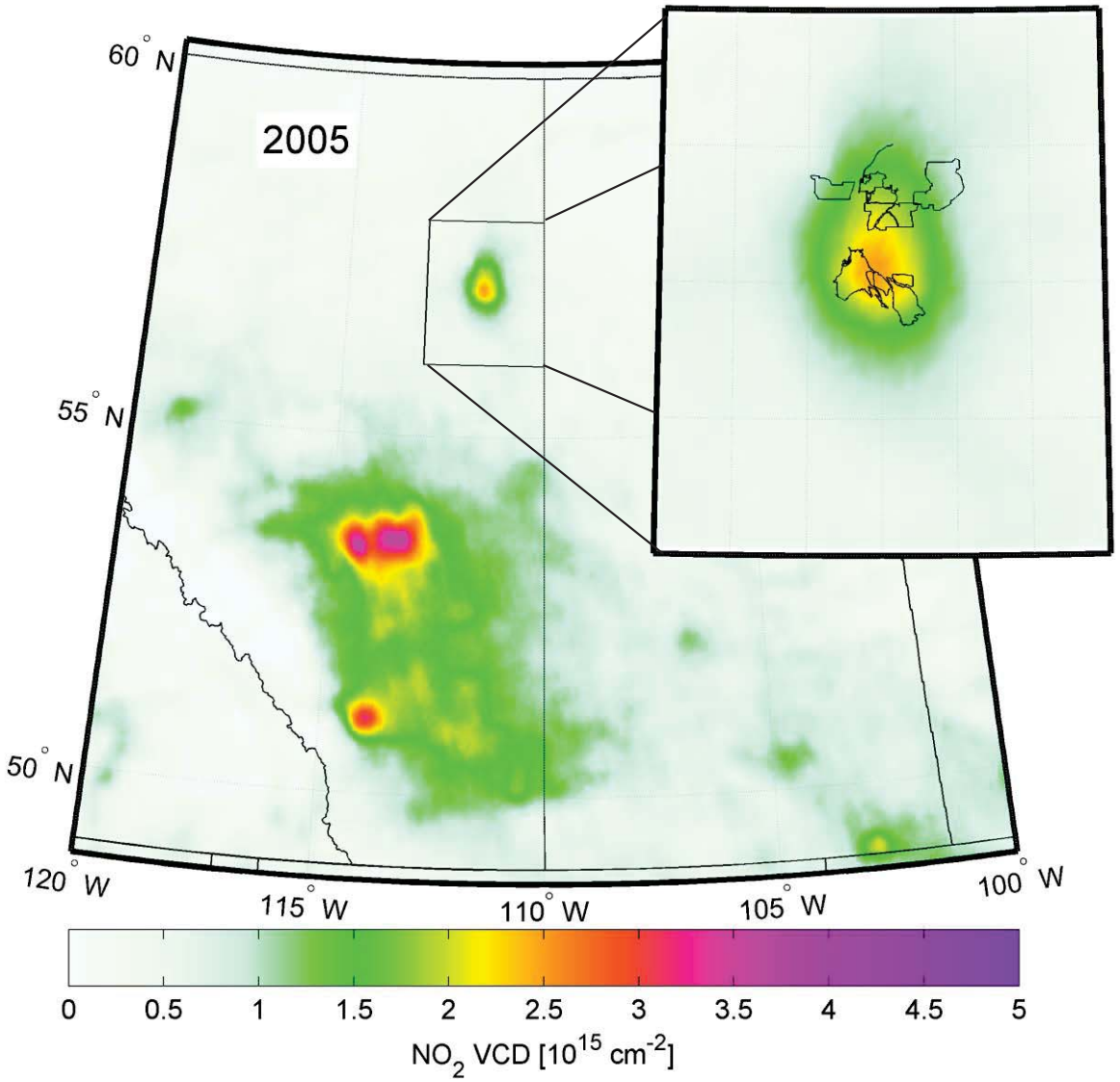
OMI view of Central Canada



Evolution of OMI NO_2

Movie goes here

Evolution of OMI NO_2



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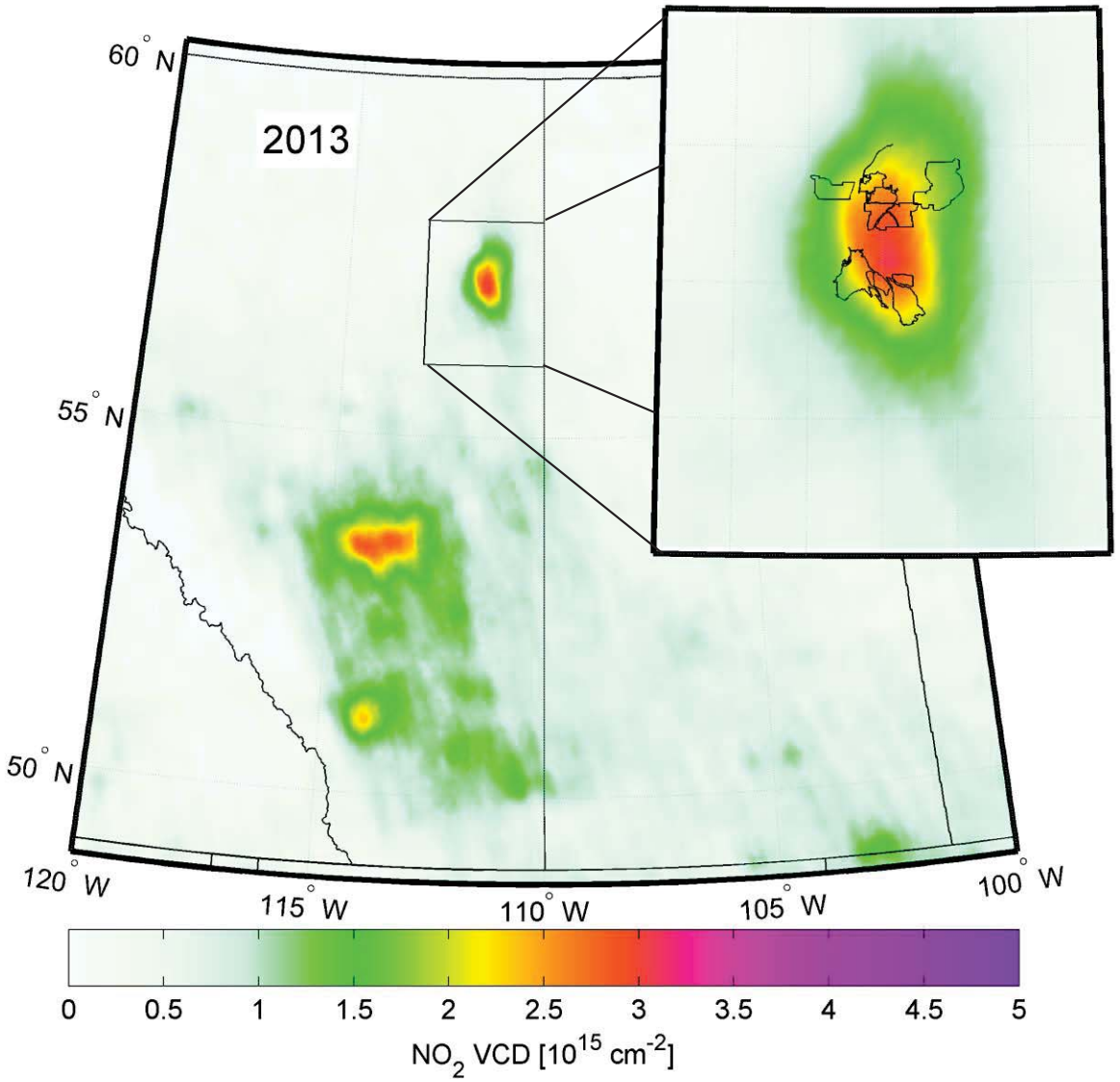
Evolution of OMI NO_2



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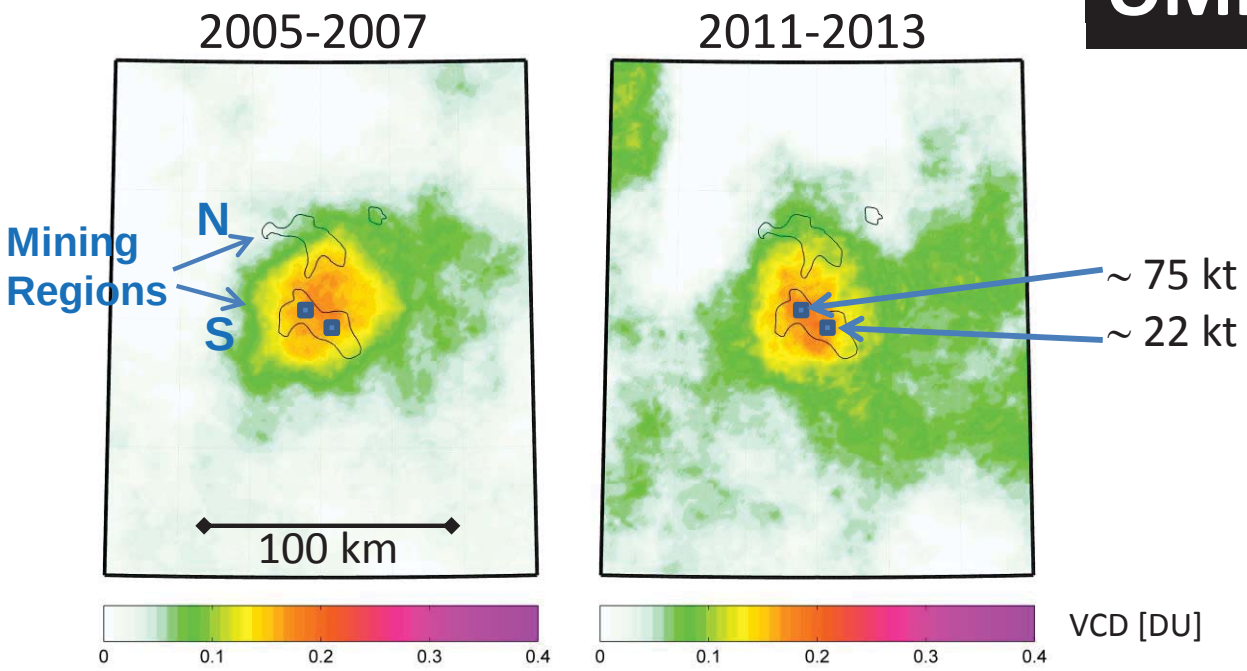
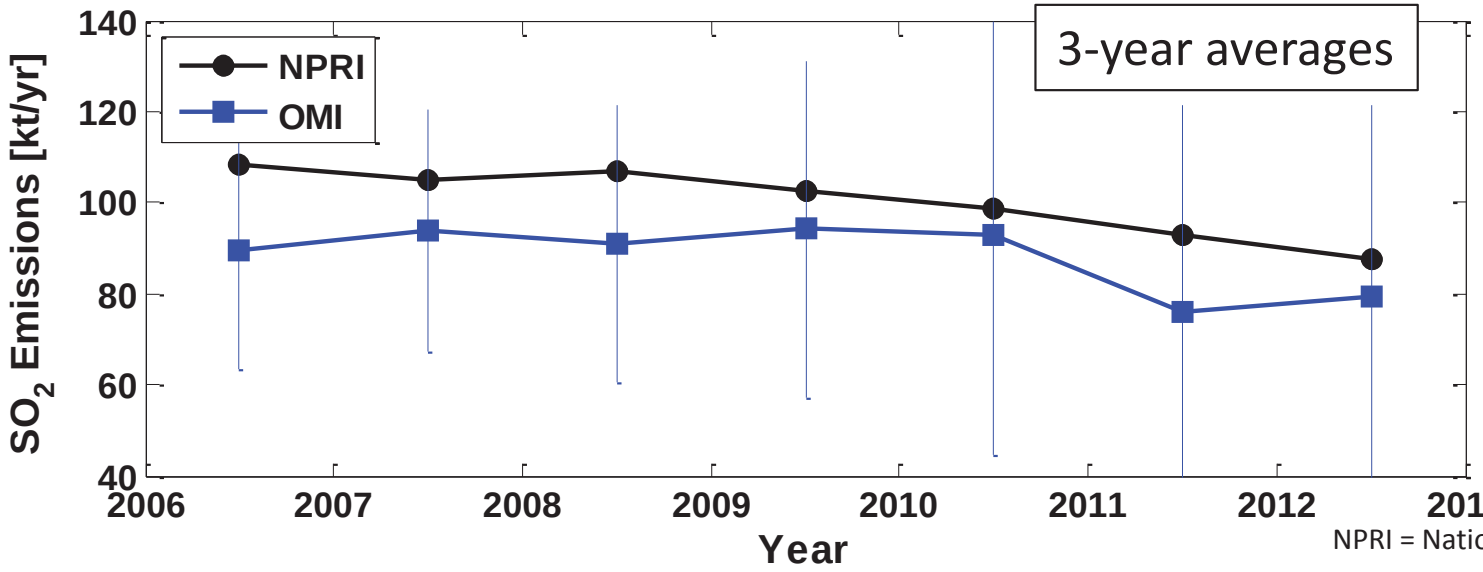
OMI SO_2 over the oil sands



- **SO_2 emissions due to upgrading**
  - converting bitumen to synthetic crude
- **Only two significant SO_2 <u>point</u> sources, both in southern [S] mining region**
- **Northern [N] mines pipe bitumen off-site for upgrading**

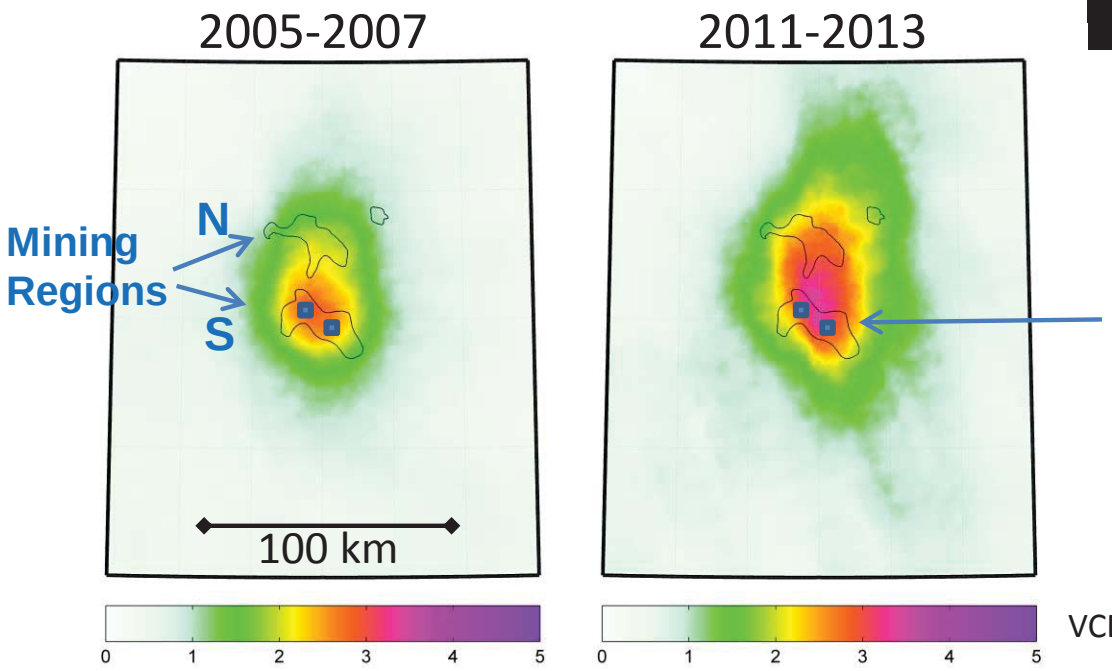
2005 – 2013 average	E(NPRI*) = 100 kt[SO_2]/yr *NPRI = National Pollutant Release Inventory	E(OMI) = 89 kt[SO_2]/yr



Emissions and lifetime determined by fitting the downwind decay of SO_2
[similar to Beirle et al., Science, 2011]

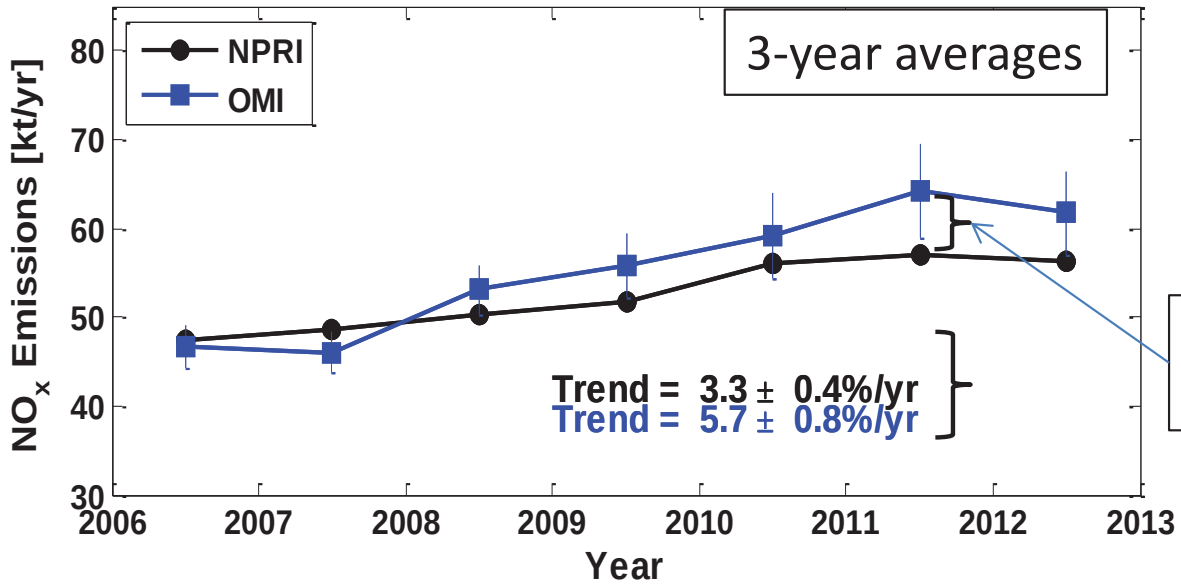
NPRI = National Pollutant Release Inventory

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



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

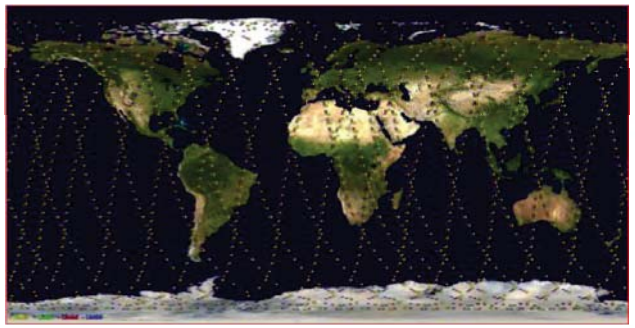
Is this difference real, from sources not reported to the NPRI (e.g., construction)?

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

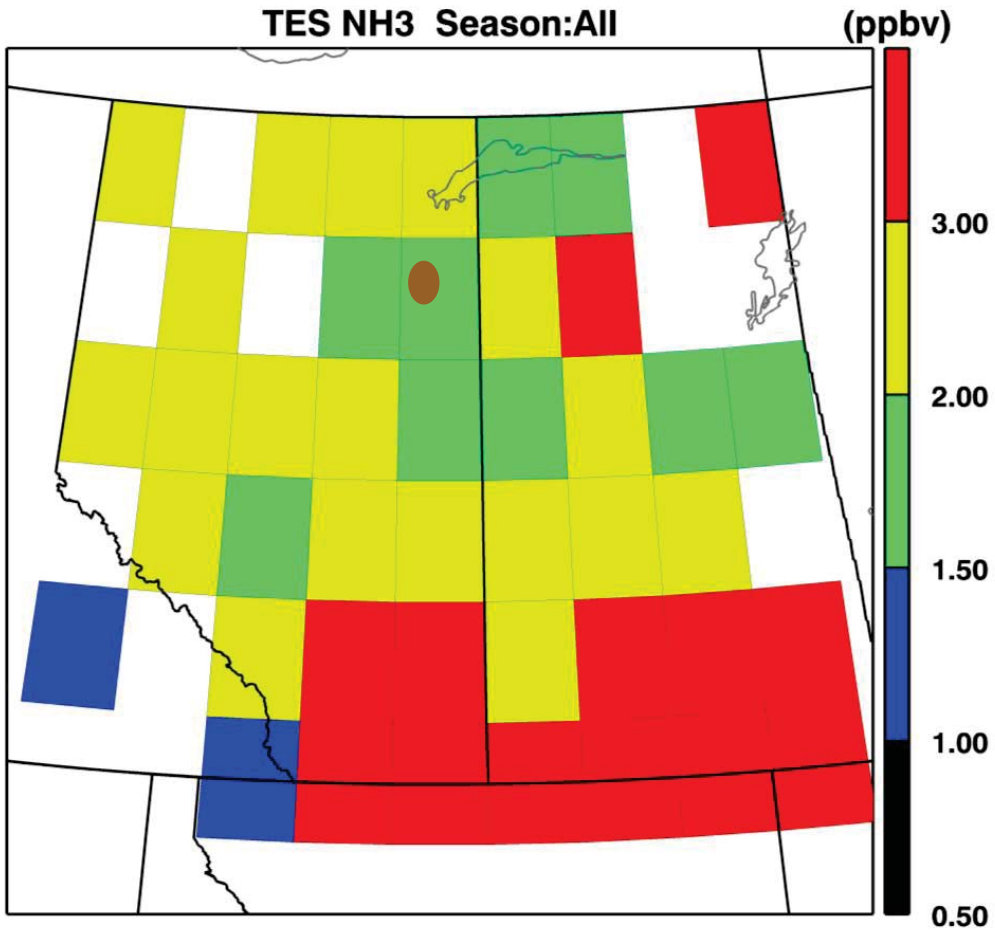


TES Special Observation (SO) Mode

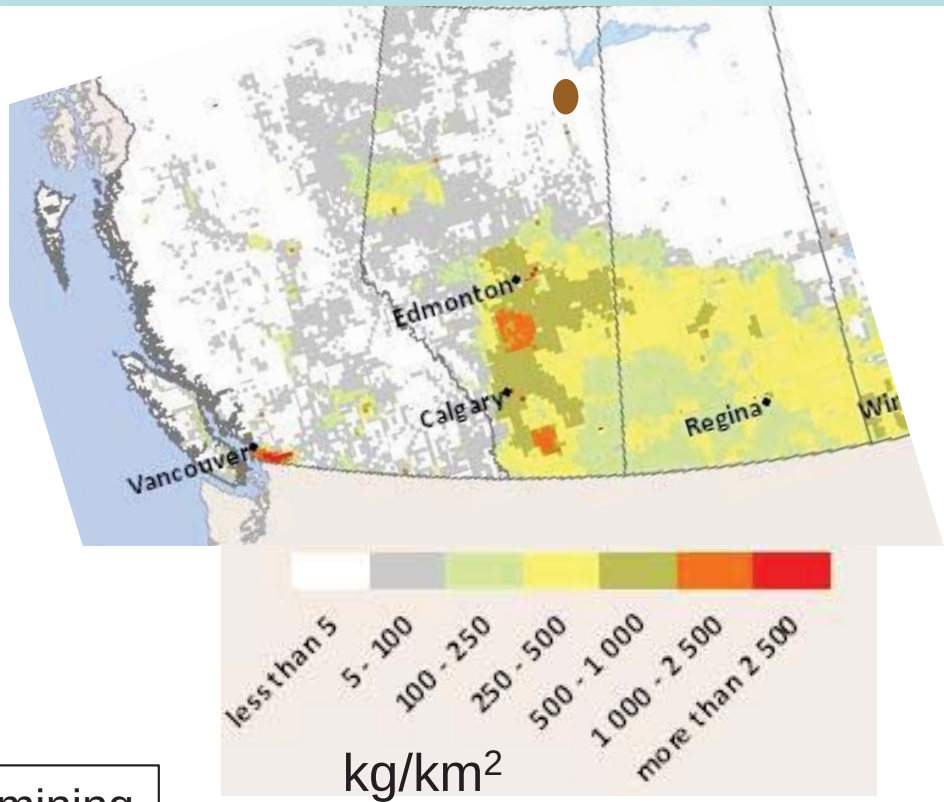
- Higher sampling density over shorter tracks
  - Transect: regional pollution studies
    - Over the Oil Sands:
      - Begun July 14, 2012 (over 2-years)
      - Observations every 2-7 days
        - » Over 125 SO to date
      - 20 contiguous targets
      - 12-km sampling along track
      - Between 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



NPRI Air Pollutant Emissions Data, 2008

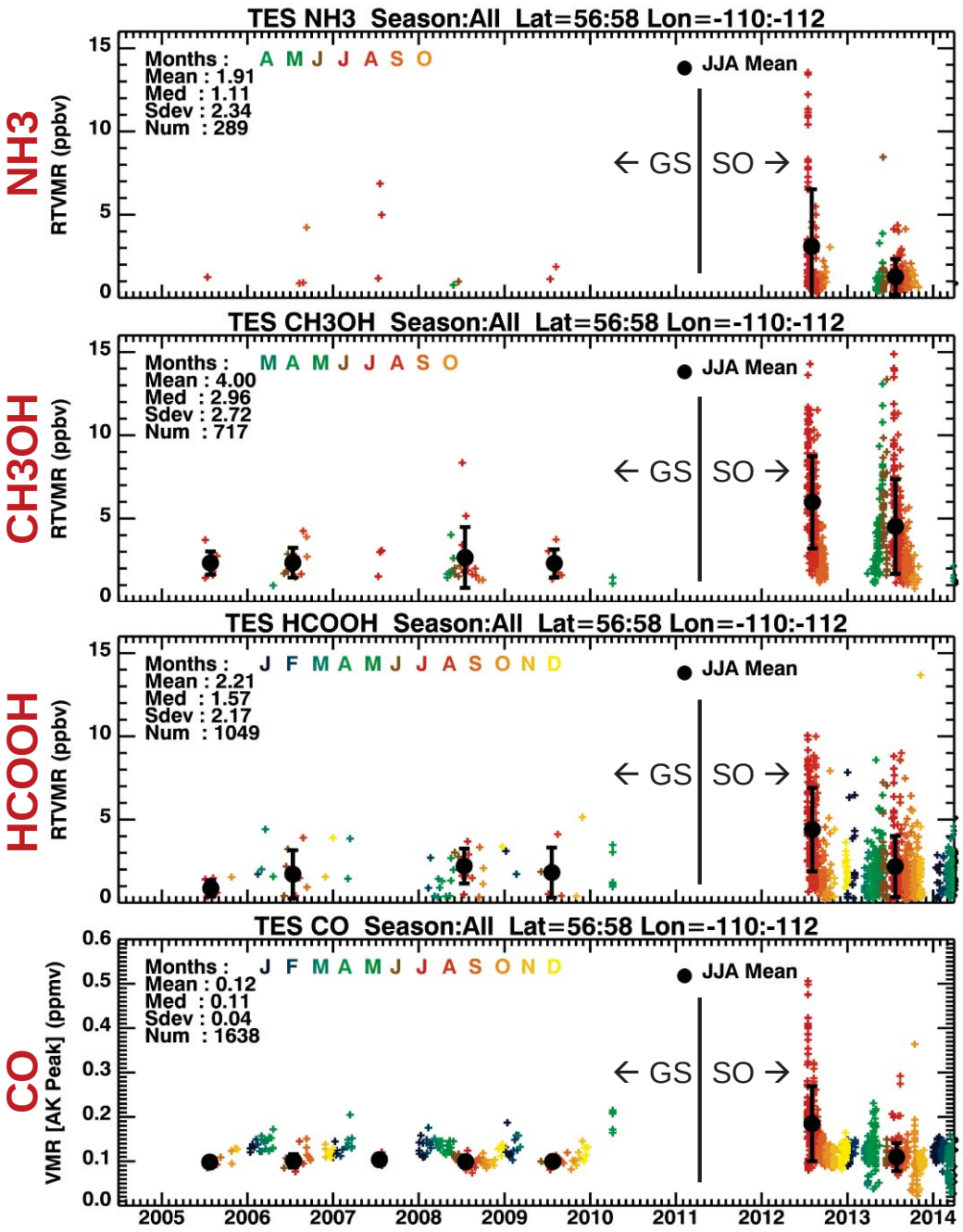


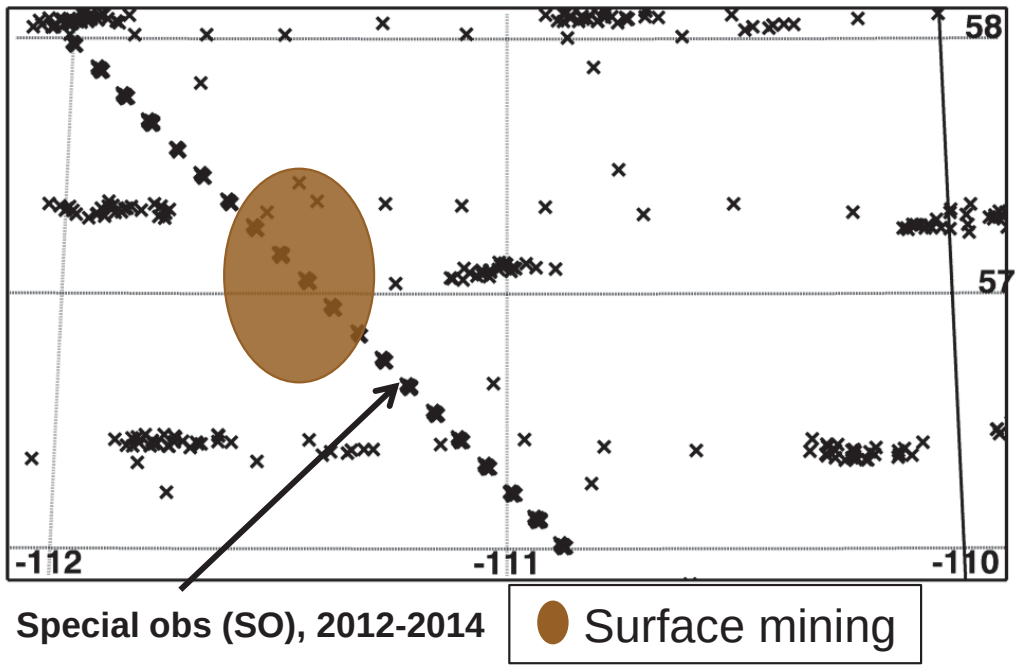
Surface mining

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?





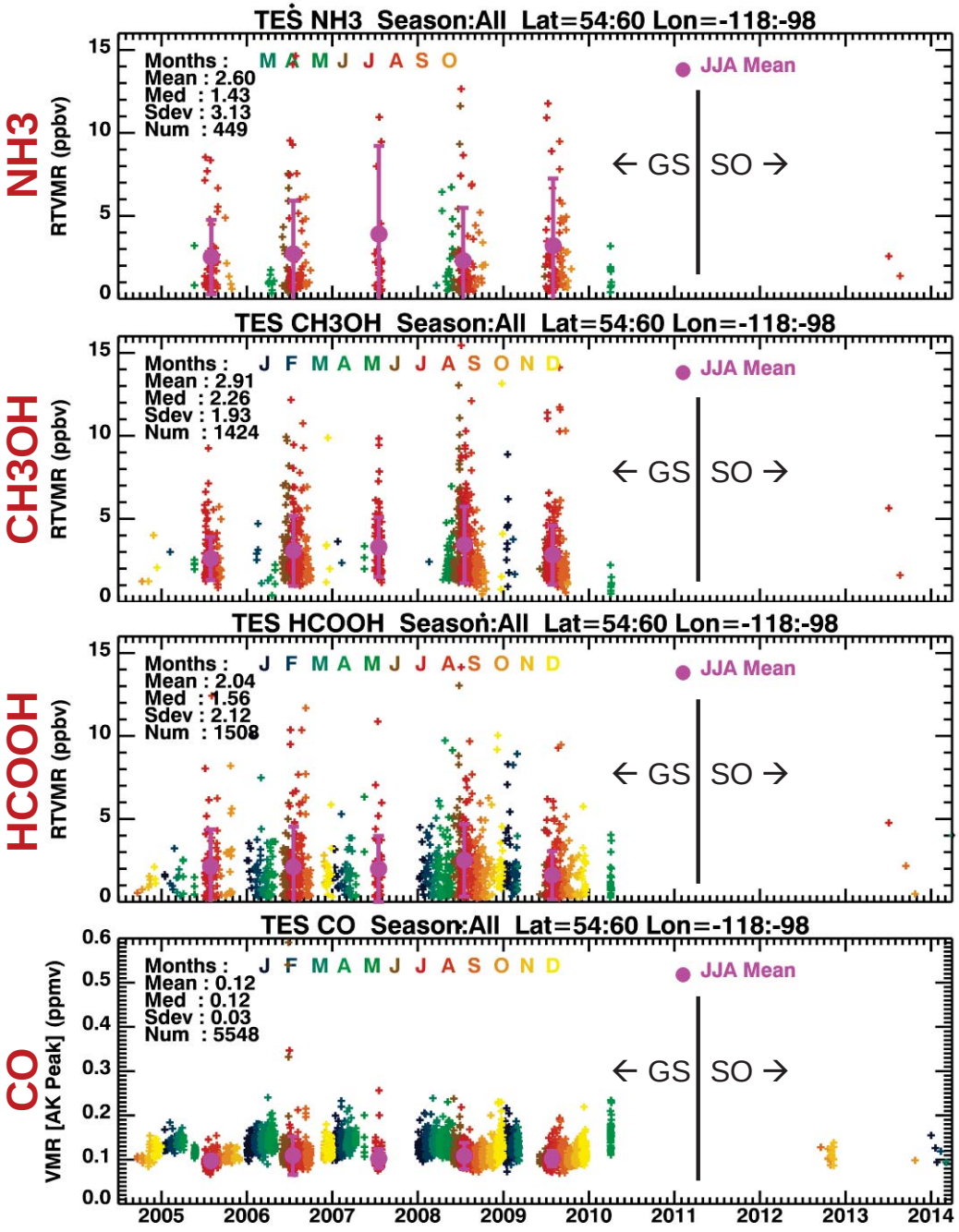
Approach: compare global survey (2004-2011) with special observations (2012-2014) over oil sands region

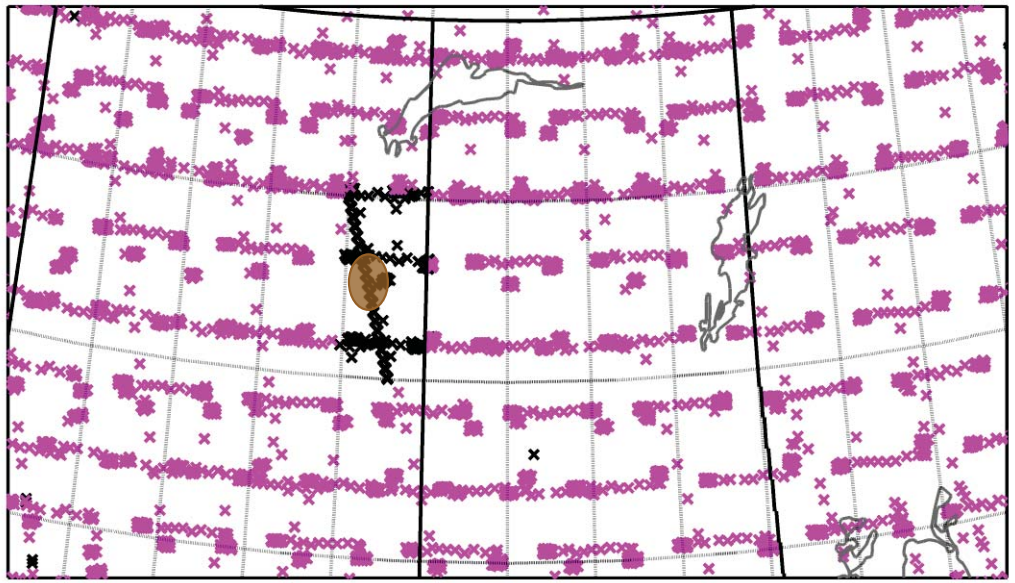
Challenging: Not many GS values over oil sands region (2004-2011)

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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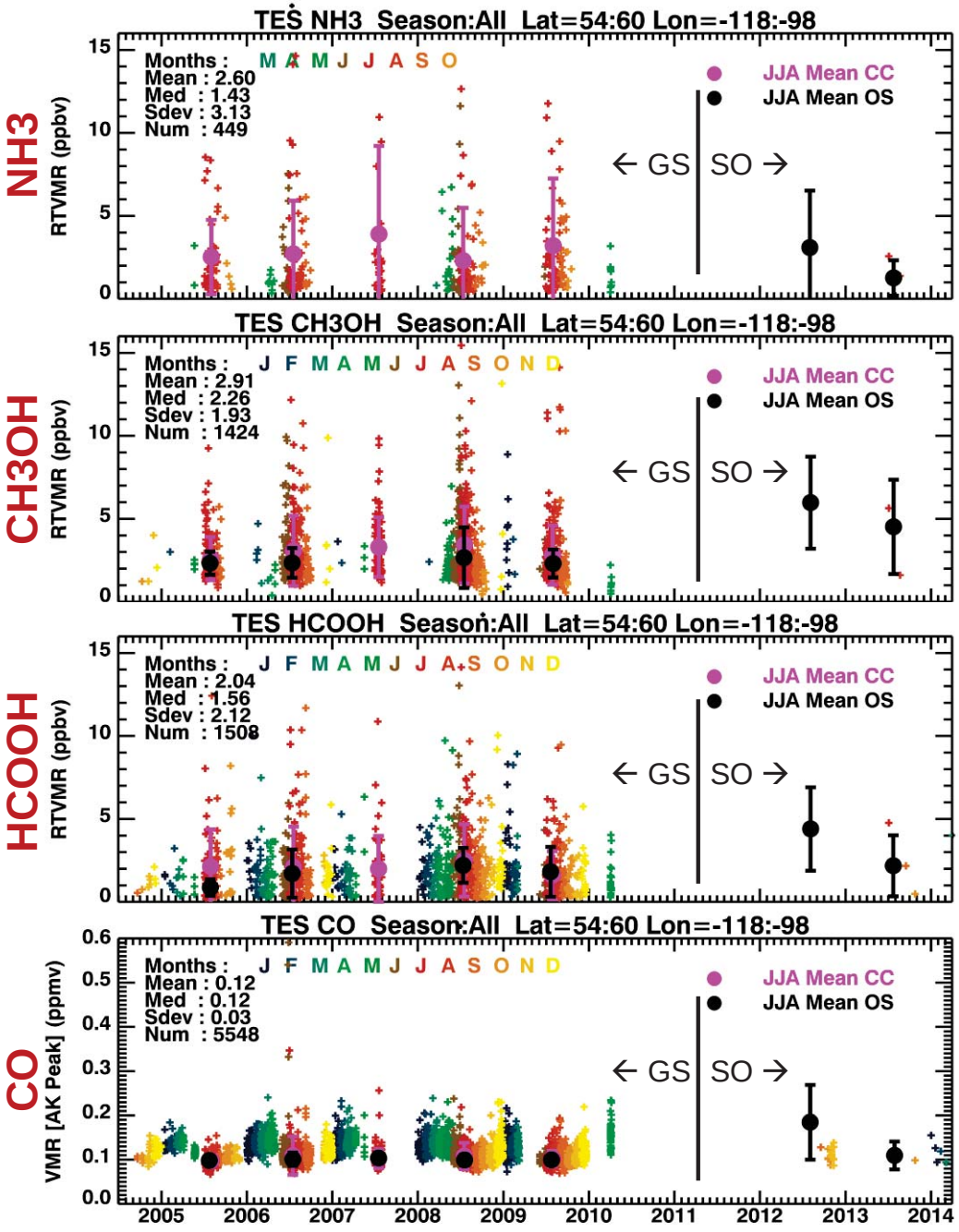

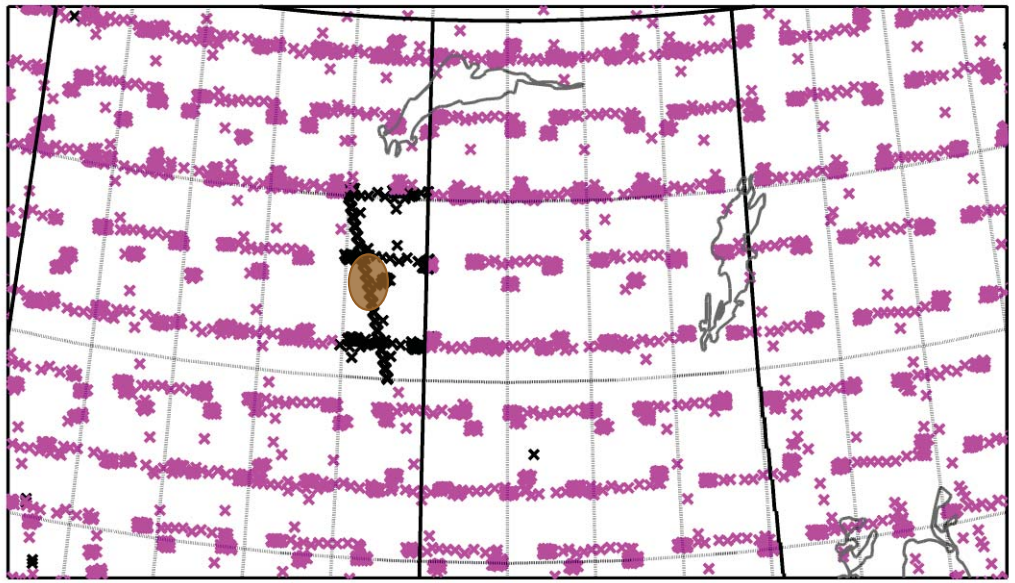

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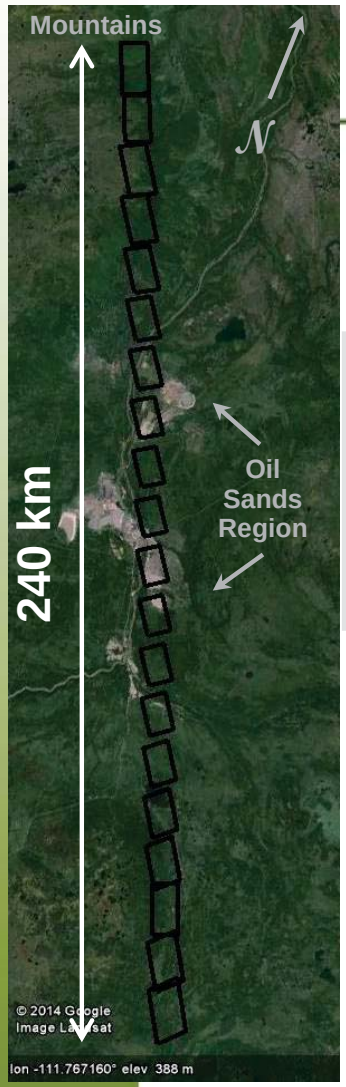
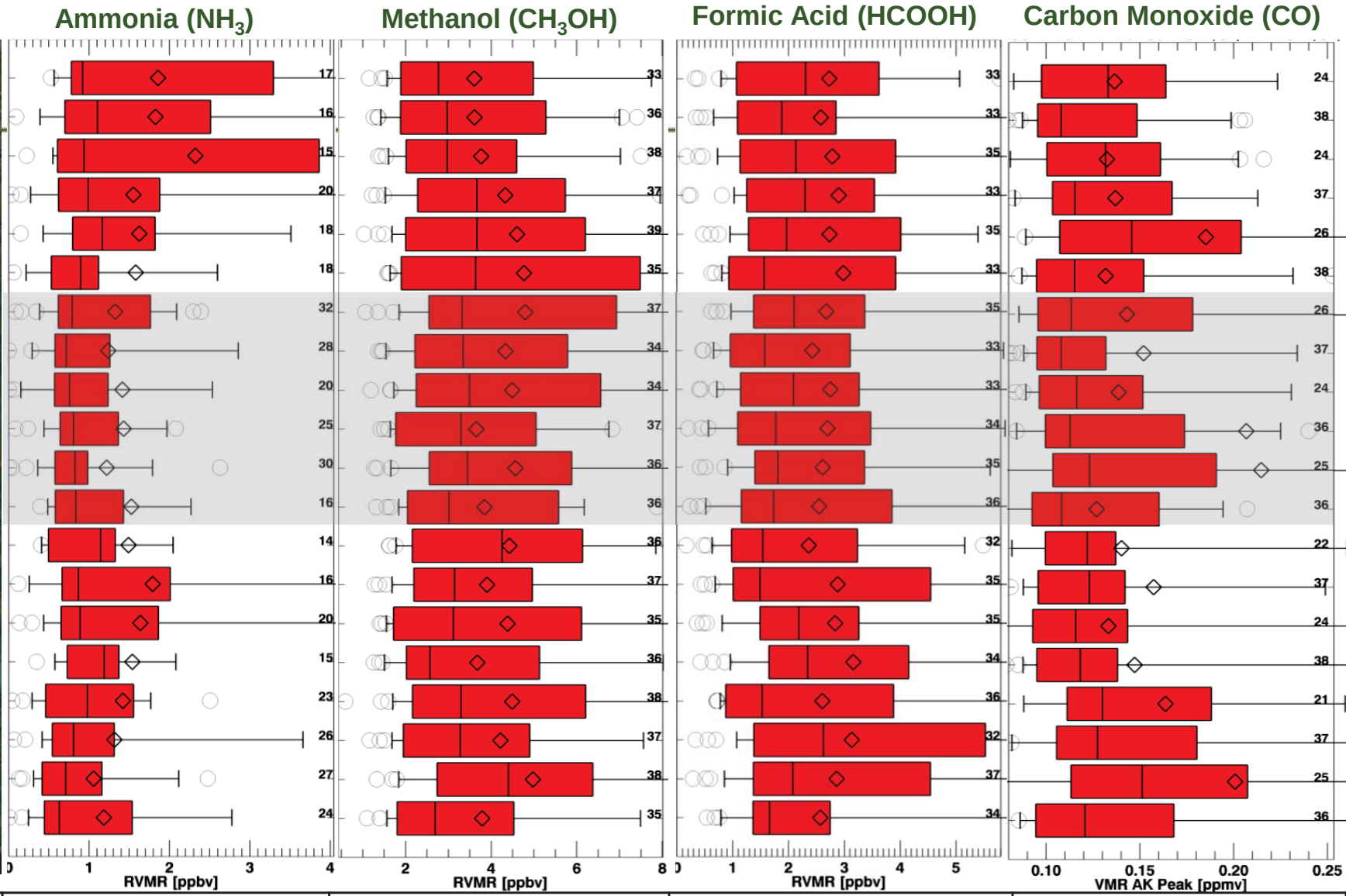
“Climatological” Oil Sand Region Satellite Observations:

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

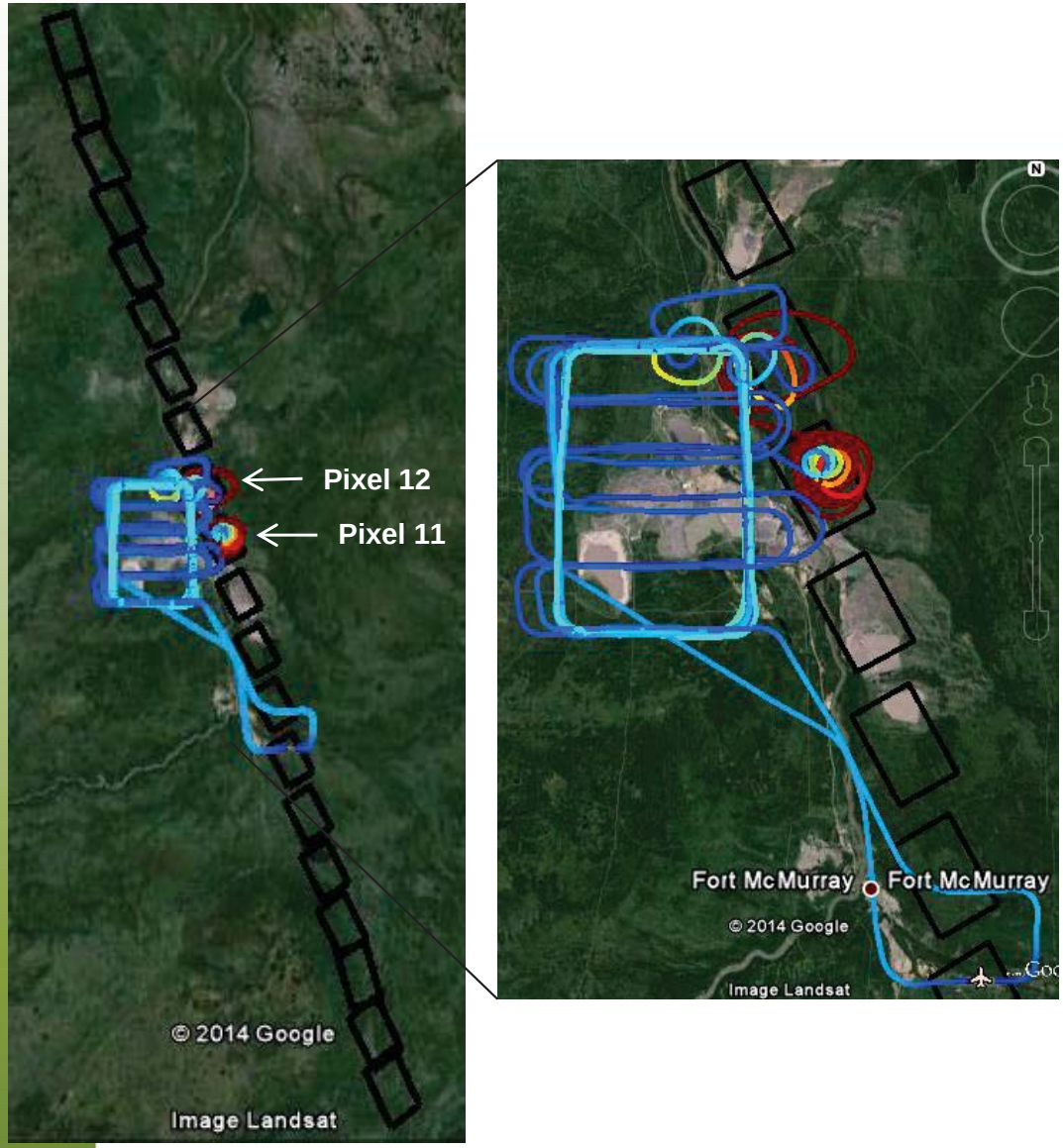




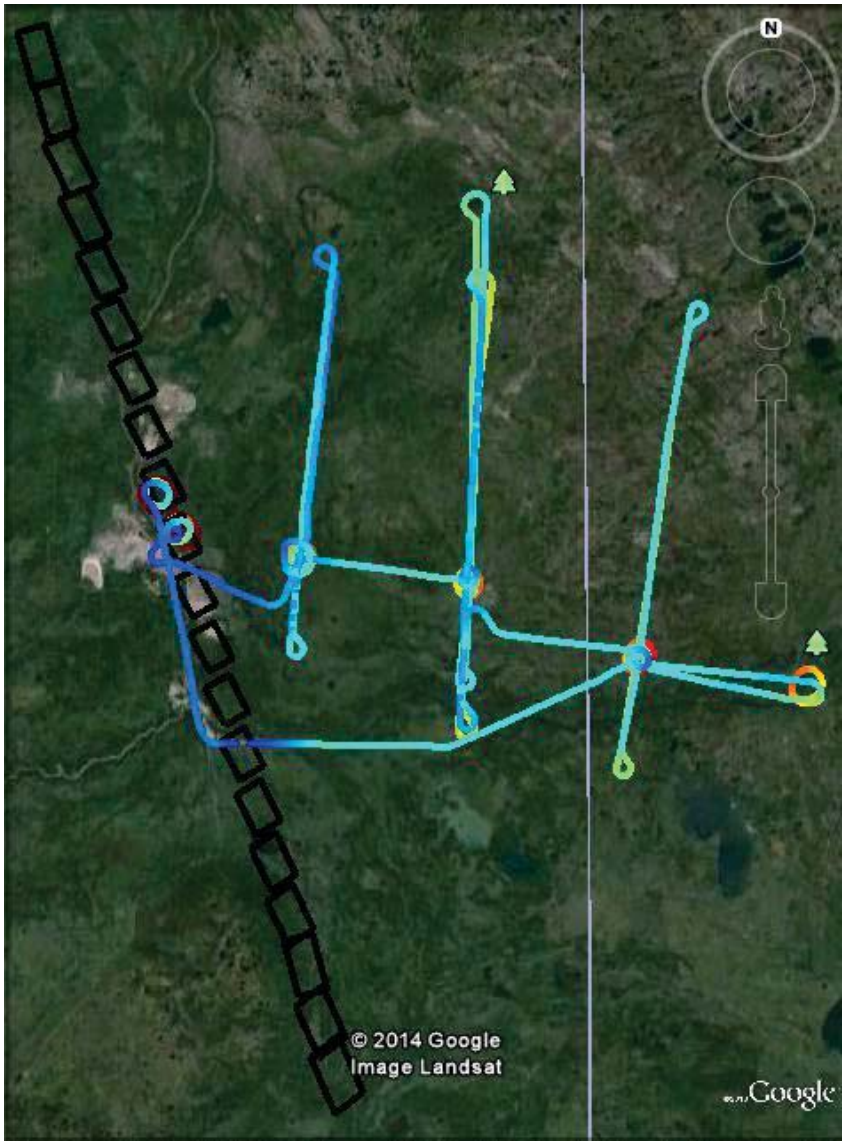
VMR (ppbv)	~1-2	~4-5	~2-3	~150-200
Pressure (hPa)	850-900	825	825	680
DOFS	0.65	0.6	0.75	1.1

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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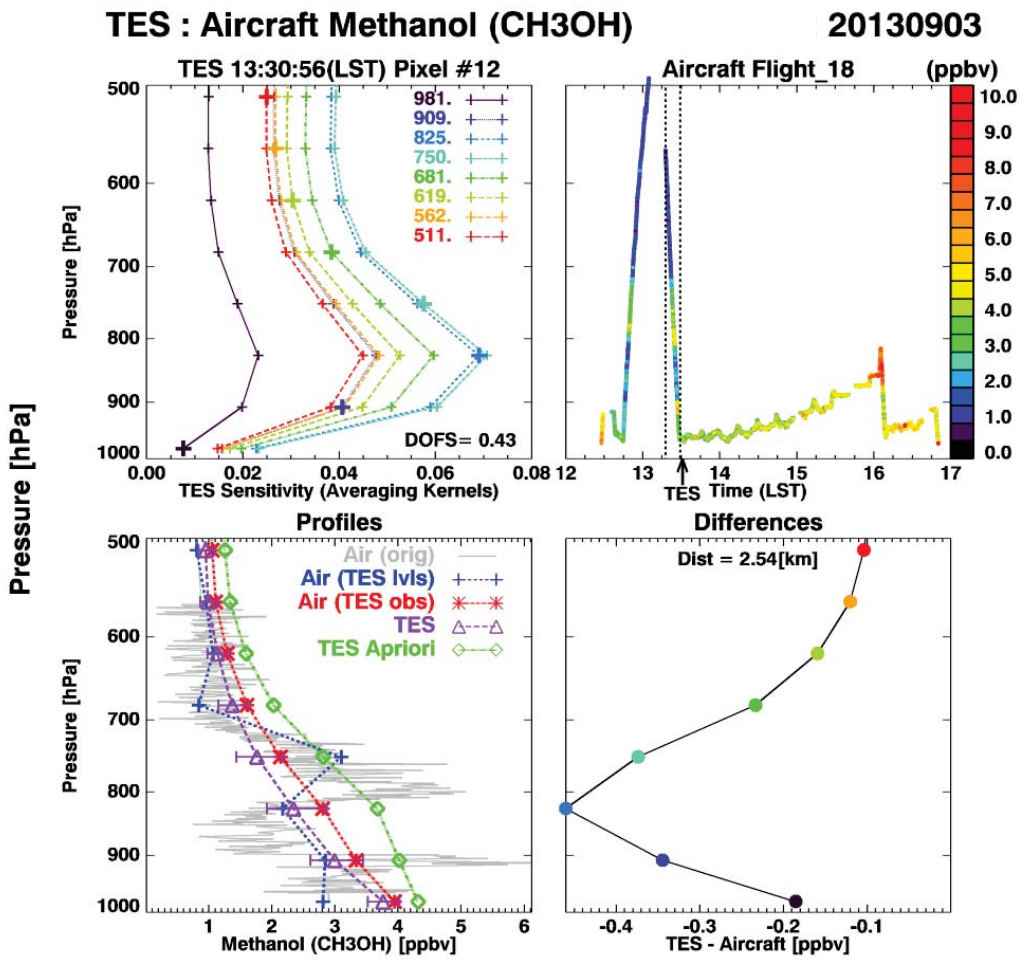
Satellite Validation:
2013 Intensive Oil Sands Field Campaign

- **Comparisons of TES and OM**
  - **Period from Aug. to Sept. 201**
  - **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.
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- 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.
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- 2013-07-10: 17735.
- 2013-07-17: 17826.
- 2013-07-19: 17846.
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- 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.
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- 2013-09-12: 18371.
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- 2013-09-19: 18450.
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- 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.
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- 2012-09-04: 15424.
- 2012-09-11: 15464.
- 2012-09-16: 15502.
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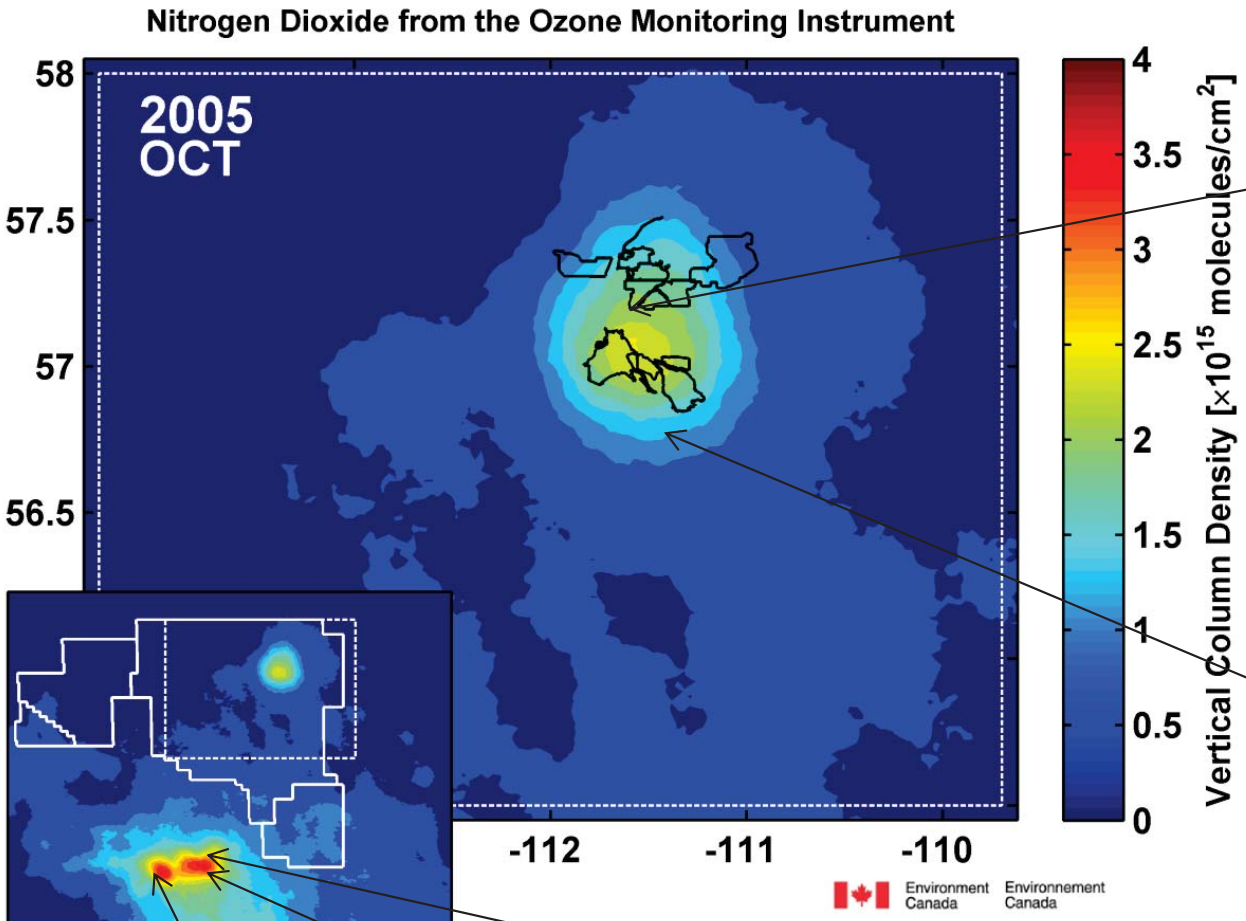
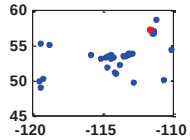
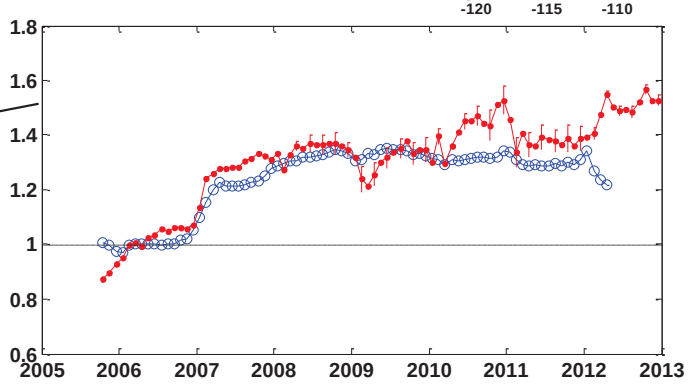


FORT MCKAY

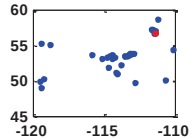
mean vmr = 5.1 ppb
mean vmr = 2.6 ppb

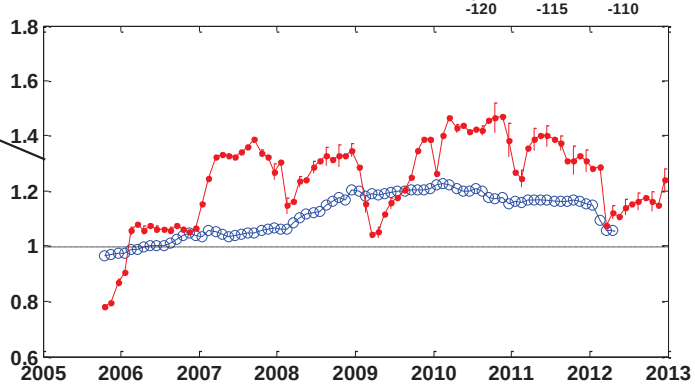




FORT MCMURRAY ATHABASCA VALLEY

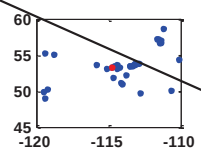
mean vmr = 7.5 ppb
mean vmr = 1.2 ppb

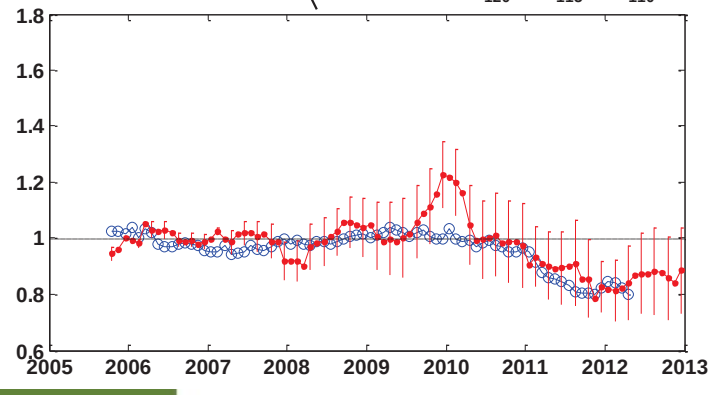




TOMAHAWK

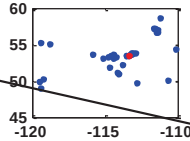
mean vmr = 3.1 ppb
mean vmr = 1.9 ppb

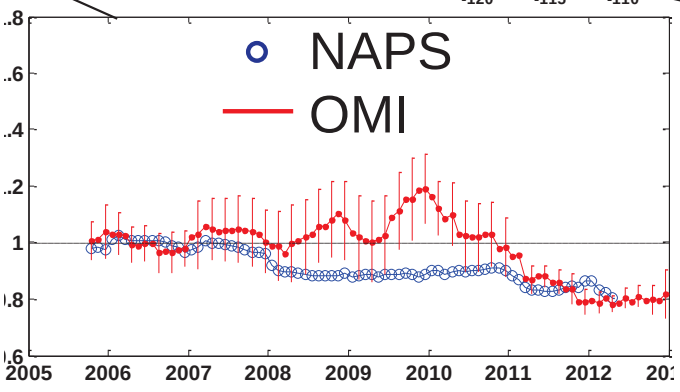




EDMONTON EAST

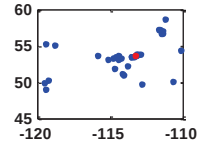
mean vmr = 11.1 ppb
mean vmr = 5.1 ppb

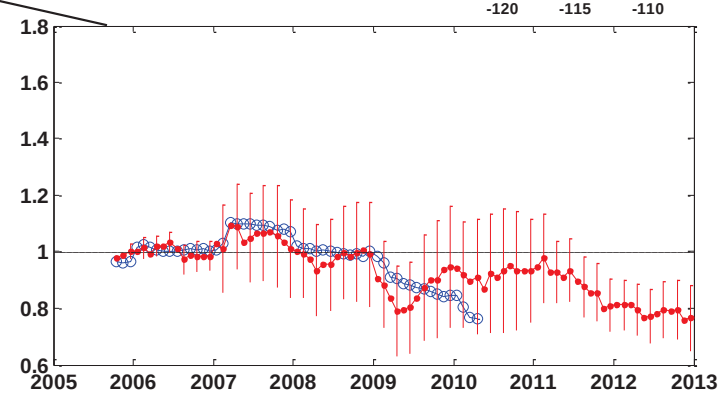




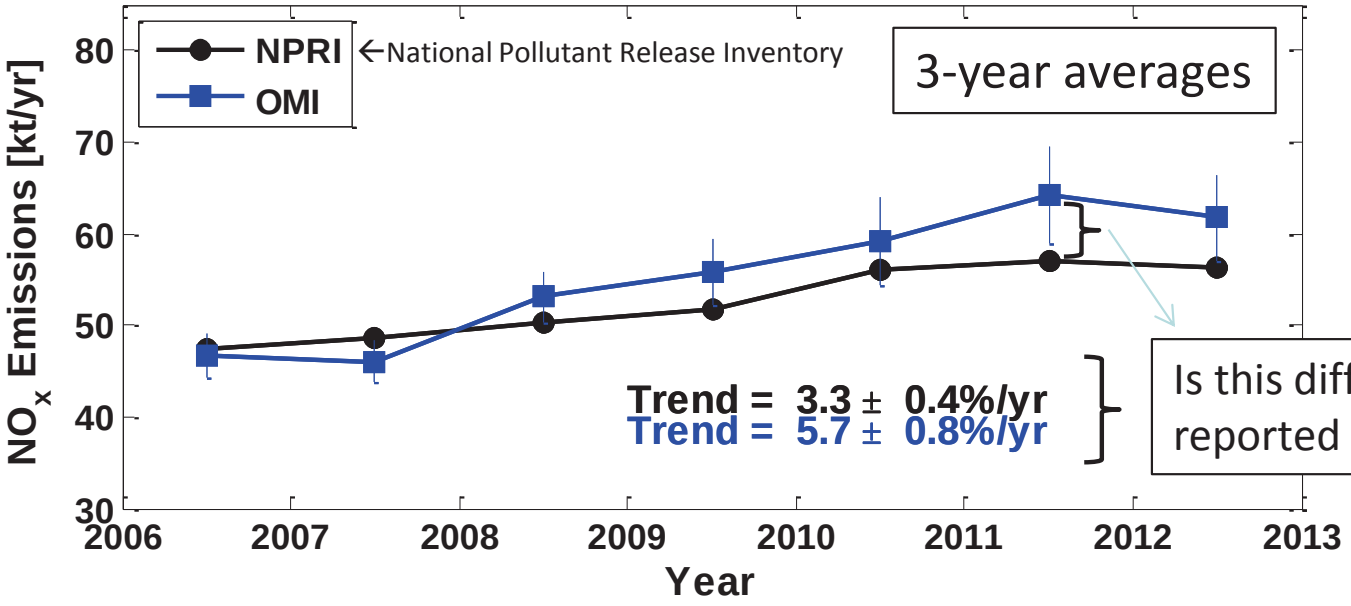
FORT SASKATCHEWAN

mean vmr = 7.7 ppb
mean vmr = 4.1 ppb





NO_x Emissions

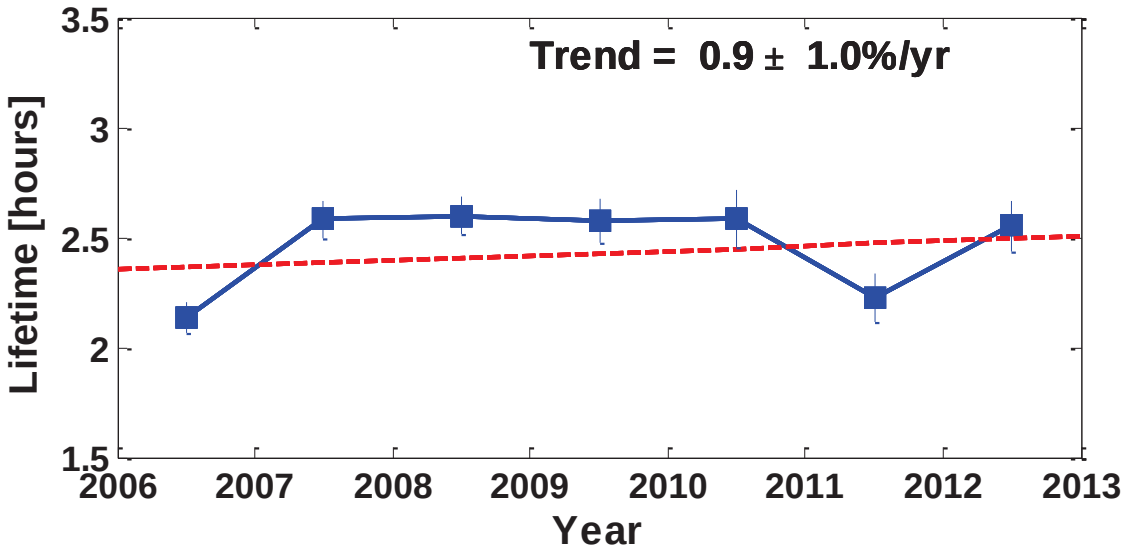


E and τ determined by fitting the downwind decay of NO_2 [similar to Beirle et al., Science, 2011]

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

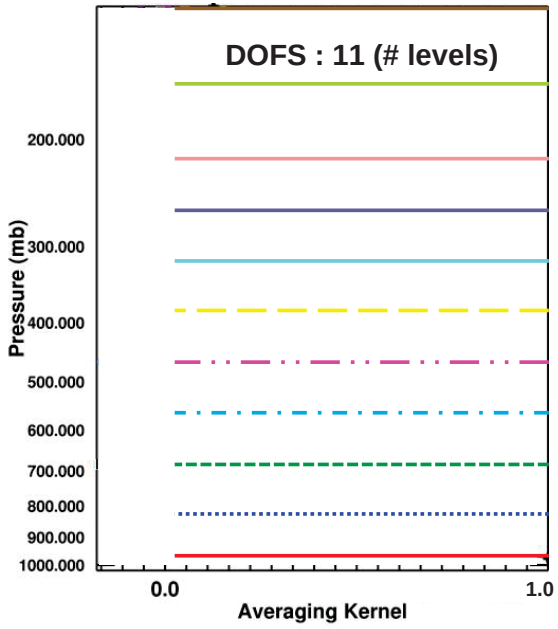
$$x_r = Ax + (I - A)\, x_a$$

$A \rightarrow 1$, $x_r \rightarrow x$

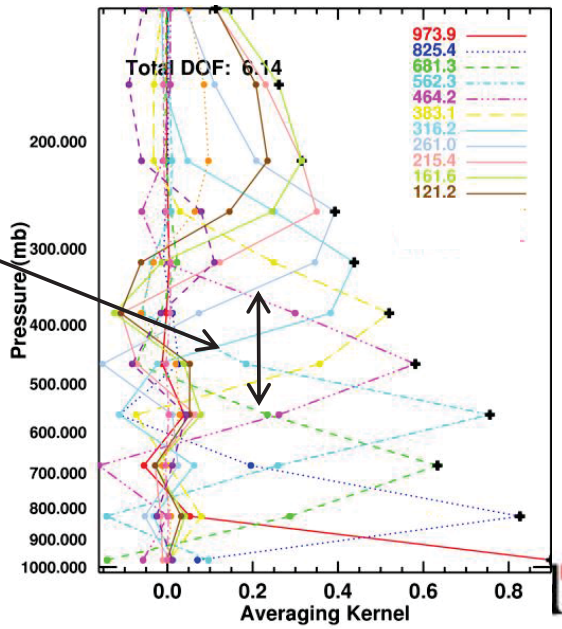
$A \rightarrow 0$, $x_r \rightarrow x_a$

  - **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

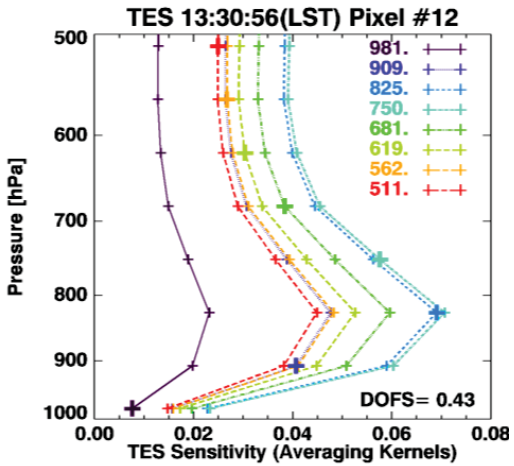


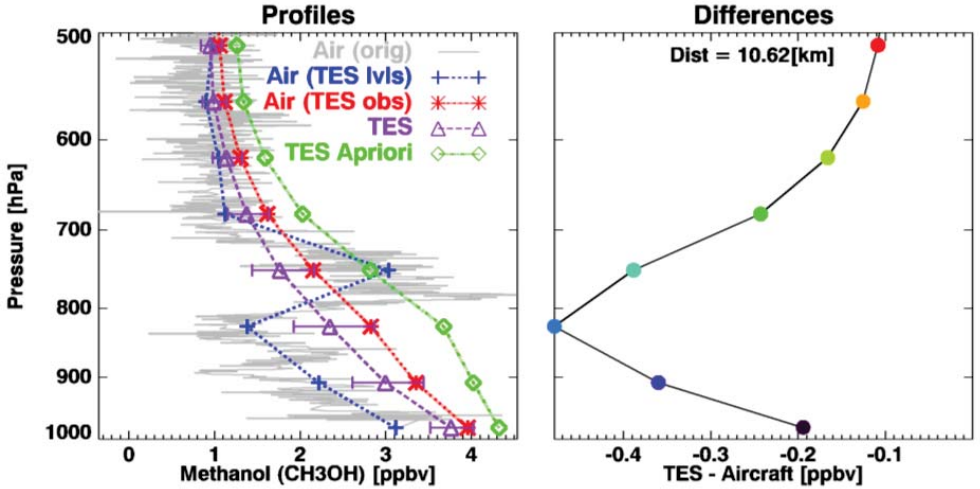
Comparison Methods : Apply the Observational Operator

- **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**

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

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





Environment Canada Environnement Canada

Shephard Aura STM 2014

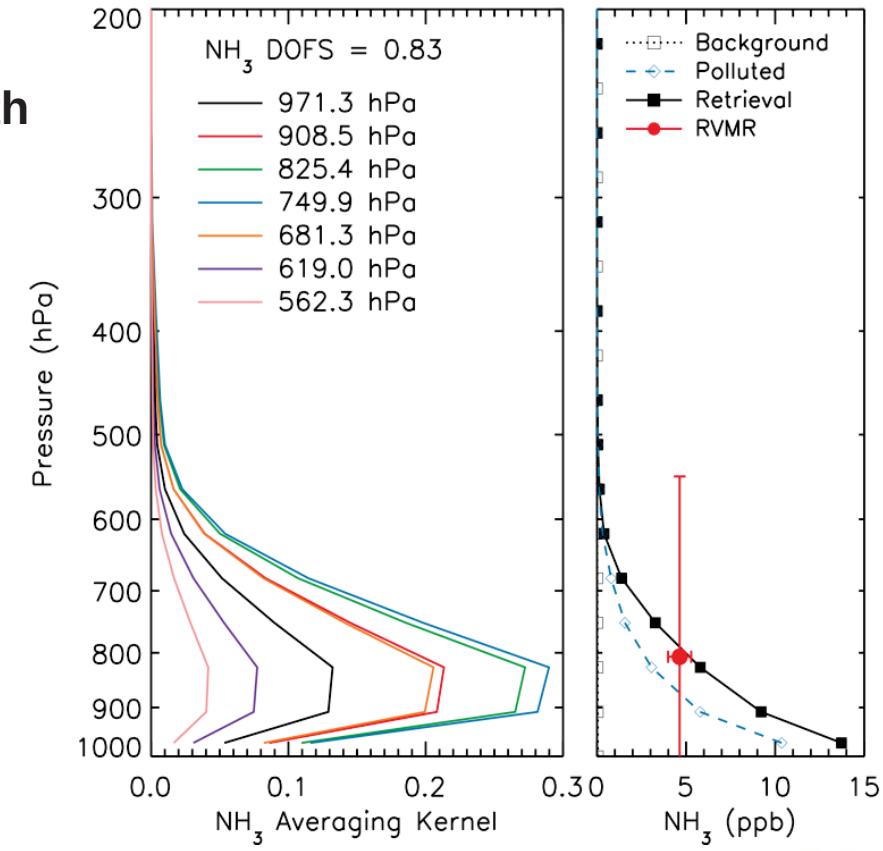
$x_r - \hat{x}_{air}$

Canada

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.**

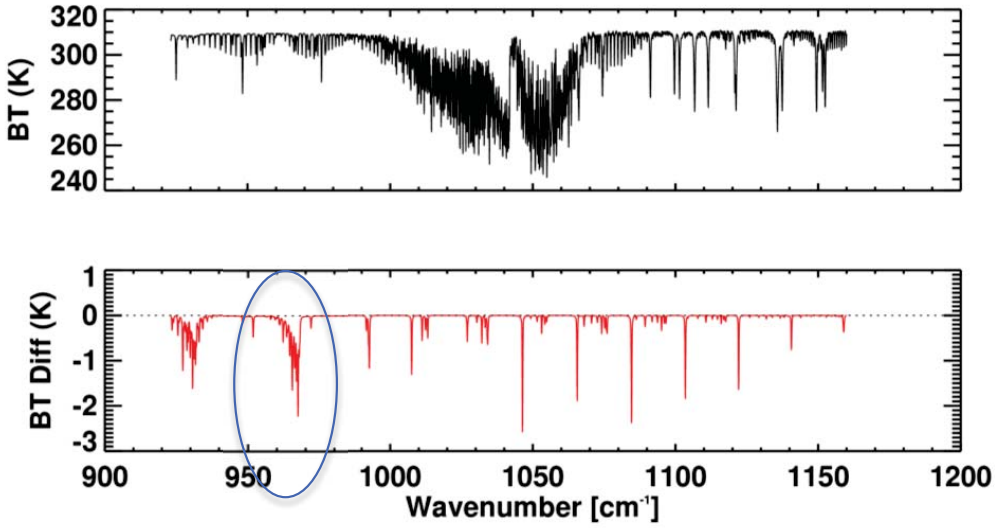
- **As an example :**
  - **TES is most sensitive to NH_3 ~800 mb**
  - **DOFS = 0.83**
  - **RVMR = ~5.0 ppbv**
  - **~2-3 km vertical resolution**
  - **Note: little sensitivity at surface**

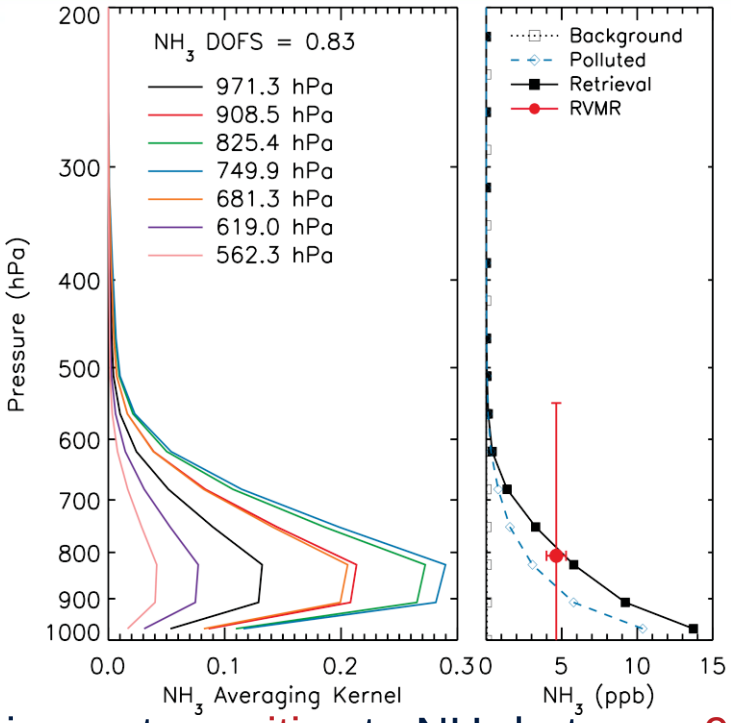


Challenges for Minor Trace Species:
Example Ammonia (NH_3) from TES

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