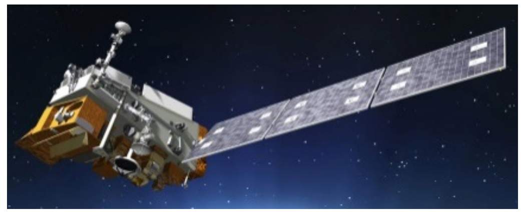
Environment and Climate Change Canada
Environnement et Changement climatique Canada

Canada



Potential Contribution of the Satellite Observations for Improving Atmospheric Deposition and Emission Estimates

Environment and Climate Change Canada
Air Quality Research Division
Ammonia Workshop
Albany, NY, USA
November 8th, 2018
Presenter: Mark Shephard

Satellite Observations of Near Surface Ammonia

Two most commonly used satellite instruments providing daily global coverage of ammonia are:

CrIS on the Suomi-NPP satellite

Cross-track Infrared Sounder (CrIS)

IASI on the MetOp-A satellite

Infrared Atmospheric Sounding Interferometer (IASI)

These sensors measure upwelling **infrared** radiation emitted by the surface and atmosphere.

For CrIS, the primary focus here:

- **Twice a day** temporal sampling: **~1:30 (night) and 13:30 (day)**
- **14-km (diameter)** spatial resolution (footprint on ground)
- Minimum detection of **~0.5 ppbv** (volume mixing ratio).
- **CrIS NH_3 algorithm** developed in collaboration between **Canada (ECCC)** and **USA (AER, Inc).**

Atmos. Meas. Tech., 8, 1323–1336, 2015

Cross-track Infrared Sounder (CrIS) satellite observations of tropospheric ammonia

M. W. Shephard[1] and K. E. Cady-Pereira[2]

[1]Environment Canada, Toronto, Ontario, Canada

[2]Atmospheric and Environmental Research, Inc., Lexington, MA, USA

Advantages

- **Global coverage** using consistent measurement methodology
- Ideal for detecting & tracking pollution and **hotspots**
- Re-flights of sensor enables **multi-decadal time series**

  IASI: 2006-**2021**; CrIS: 2012-**2038**; IASI-NG:2021-**2042**

Disadvantages

- Coverage is **not continuous**:
  - 2 measurements per day and not under clouds
- **Limited resolution** spatially (~10 km) and vertically (surface & boundary layer values are correlated)

Daily Spatiotemporal Variability of Surface NH_3 over North America in August 2013

Moderate Resolution **I**maging **S**pectroradiometer (MODIS)

- **Infrared:**
  - **Fire Detection (red)**
- **Visible:**
  - **Cloud (White)**
  - **Smoke (blue/gray)**

Cross-Track Infrared Sounder (CrIS)

- **Infrared:**
  - **Ammonia (NH_3)**

(Click here to view movie)

Captures daily spatial distributions of ammonia

- For example: episodic events (e.g. forest fires)
- Impact of the meteorology, cannot "see" through thick clouds

Monthly Spatiotemporal Variability of Surface NH_3 over North America in 2013

(Click here to view movie)

Captures expected temporal and spatial distributions of ammonia

- Spring fertilizer applications (May over Canada)
- Episodic events (e.g. Northern forest fires in middle of summer)

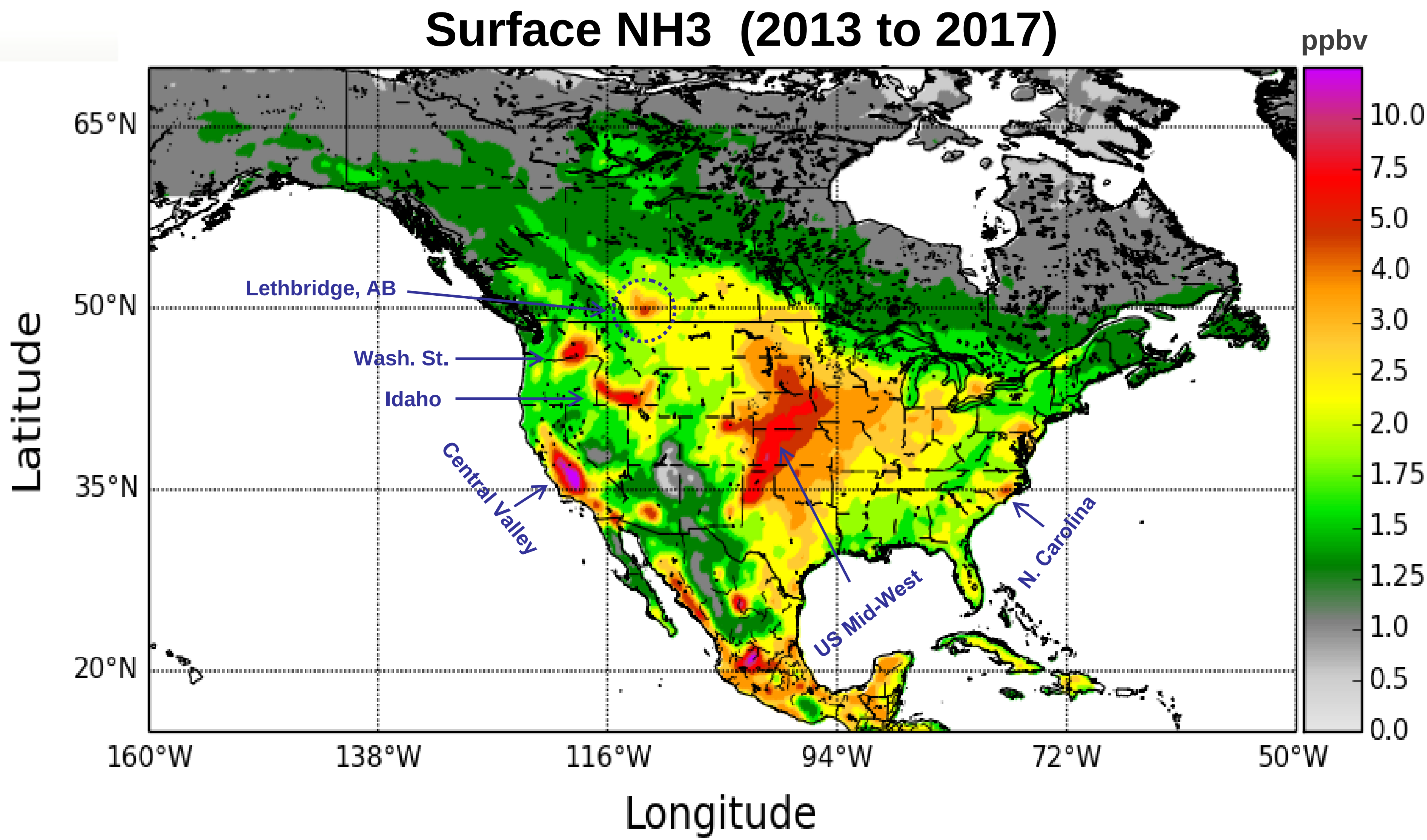
Annual Spatiotemporal Variability of Surface NH_3 over North America (2013-2017)

(Click here to view movie)

Interannual variability of ammonia over a 5-year period

– Can be used to evaluate the air quality model interannual variability, etc.

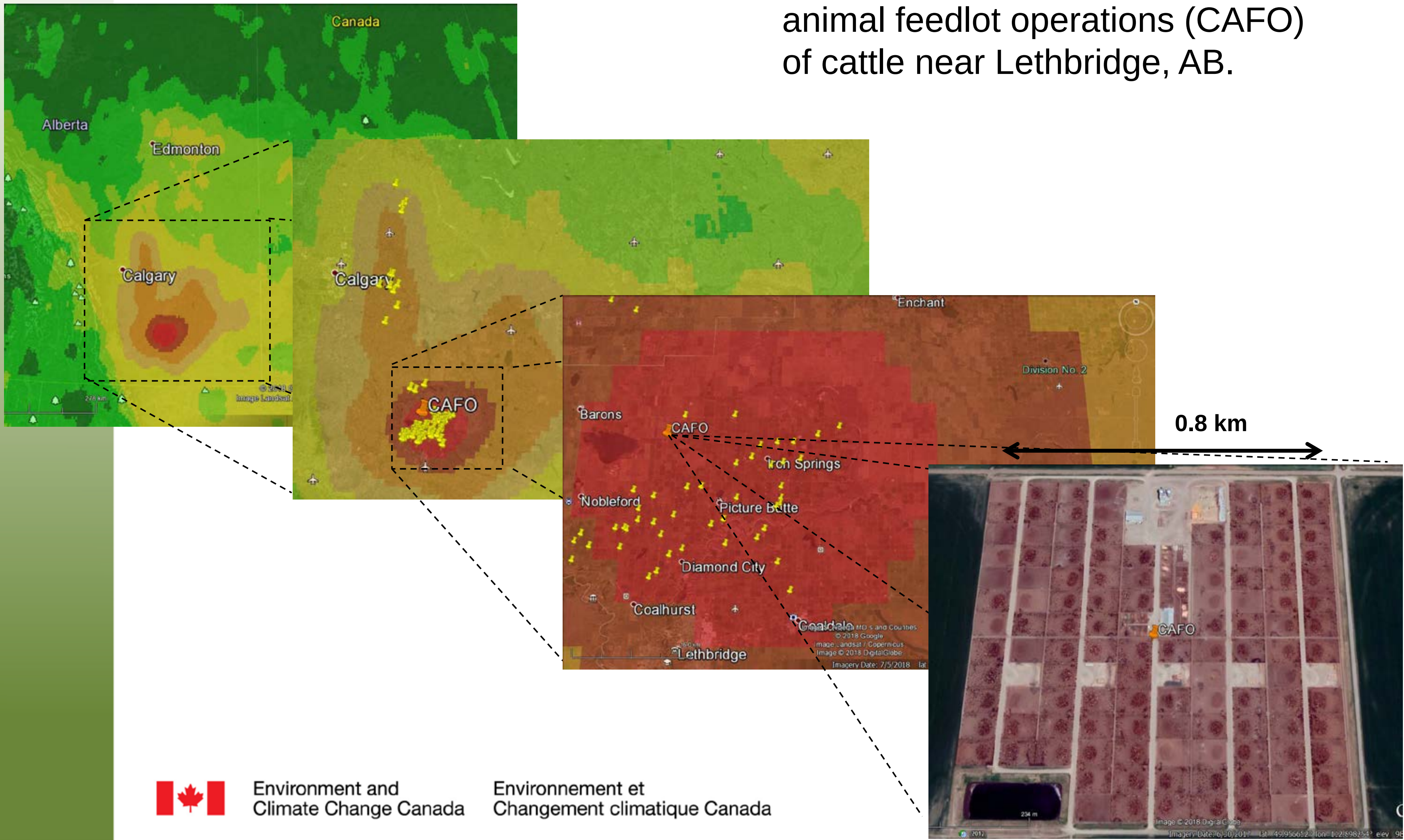
5-Year Mean of Surface NH_3



Captures spatial distributions of ammonia over expected "hot-spot" agriculture regions

CrIS NH_3 observations can be overlaid on Google Earth to help identify potential emission sources

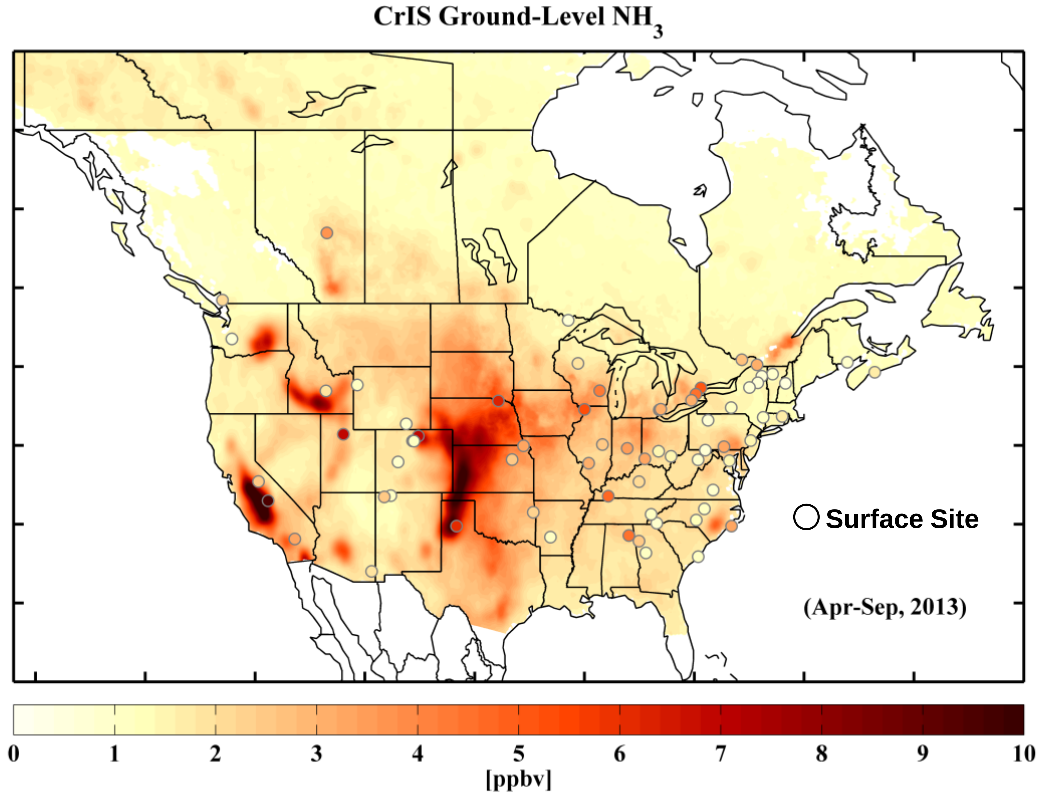
Large number of concentrated animal feedlot operations (CAFO) of cattle near Lethbridge, AB.



Environment and Climate Change Canada
Environnement et Changement climatique Canada

Satellite Ammonia Evaluation

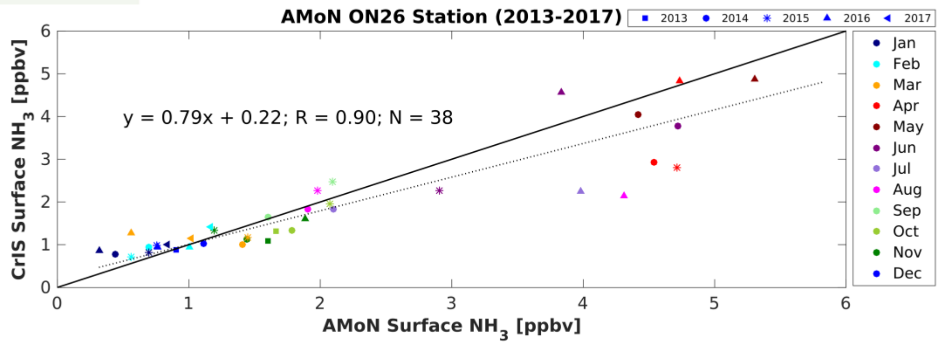
- Remotely sensed **satellite measurements require validation**
- Satellite provides global coverage, but at a lower spatial resolution than point source in-situ (e.g. ground- and aircraft-based) observations
  - **58** Ammonia Monitoring Network (AMoN) sites (**USA**) : **bi-weekly**
  - **10** National Air Pollution Surveillance Program (NAPS) sites (**Canada**) : **3-day**

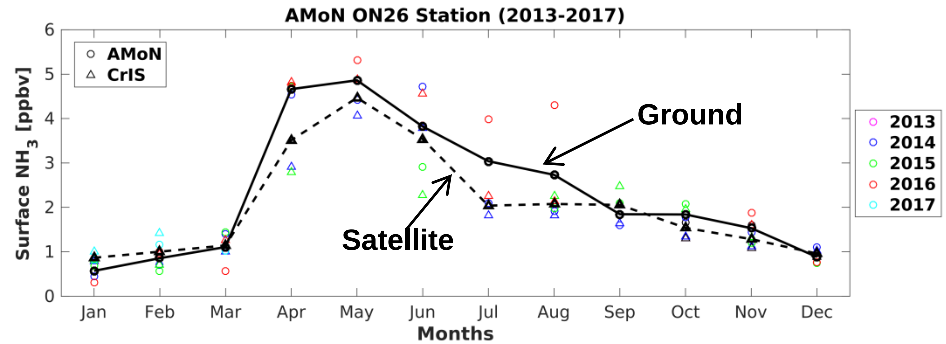


Demonstrates how satellite can potentially be used to help fill in network gaps
- Correlation of 0.76; Mean difference of +0.4 ppbv (~+15%)
- Next step is to updating with full timeseries

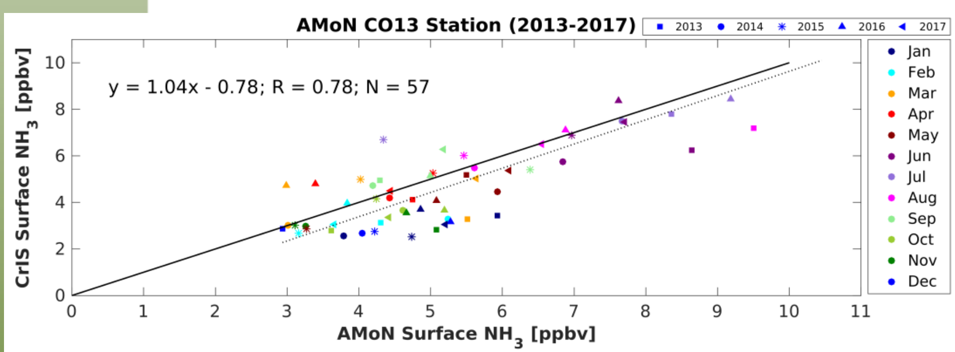
Satellite Ammonia Evaluation

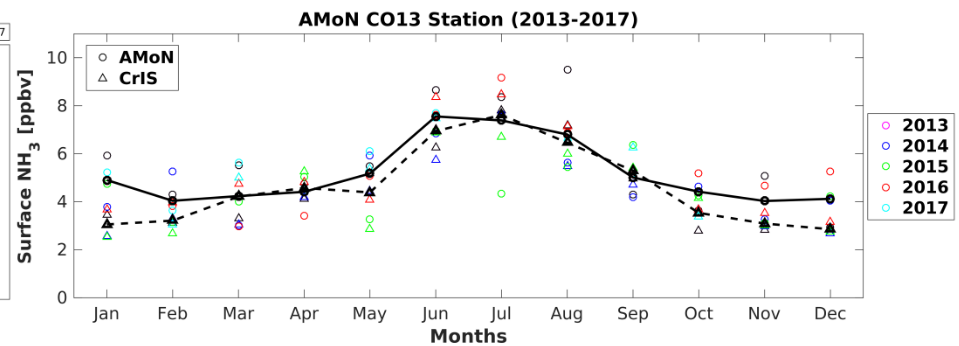
Longwoods, Southern Ontario, Canada





Fort Collins, Colorado



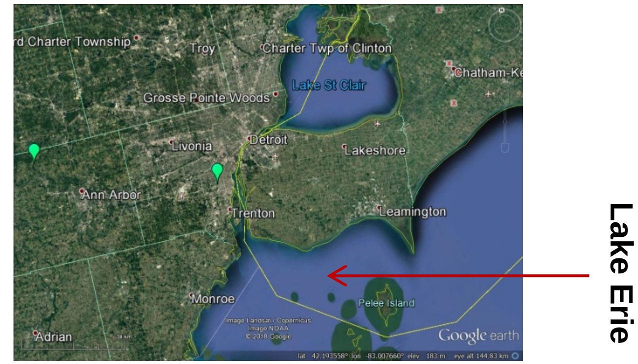


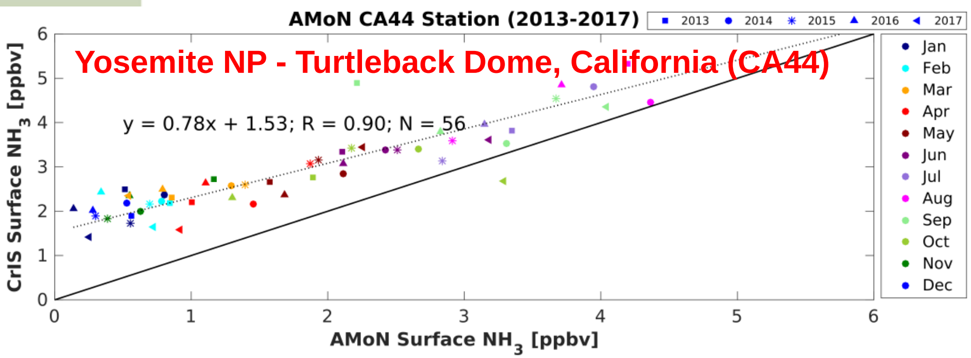
Examples of satellite and surface observations (AMoN) that **agree well despite potential sampling differences**

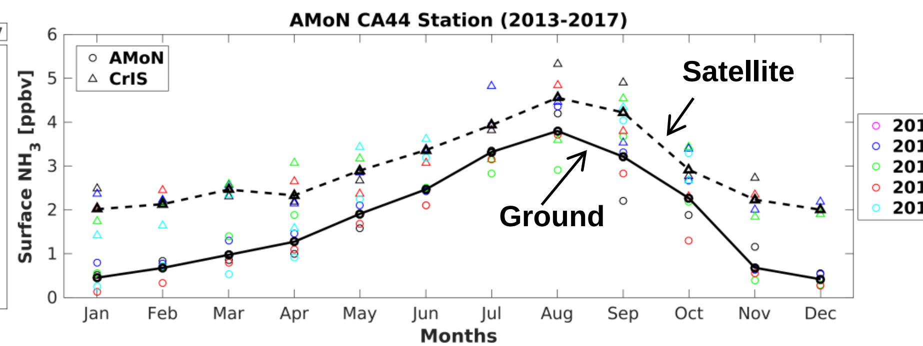
Satellite Ammonia Evaluation

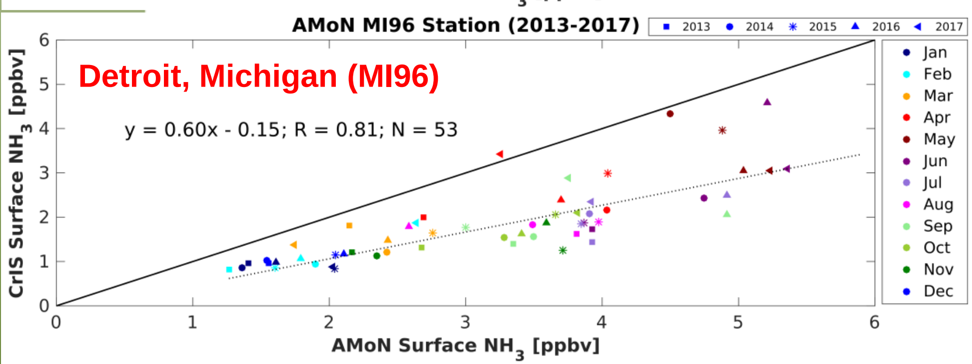
Yosemite NP - Turtleback Dome, California (CA44) (elevation at ~1.5 km)

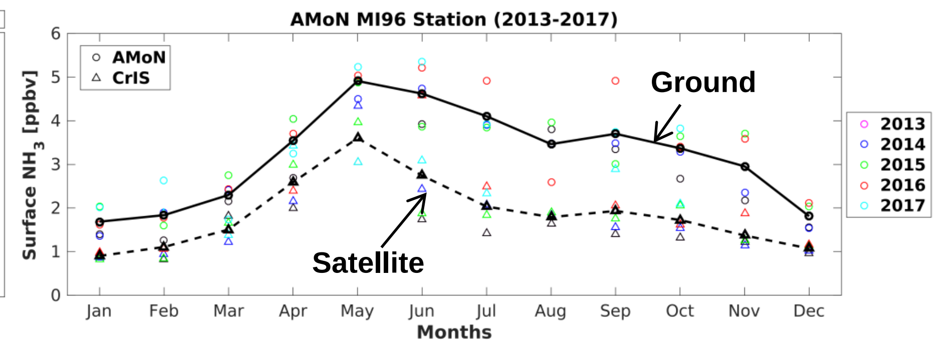
Detroit (MI96)









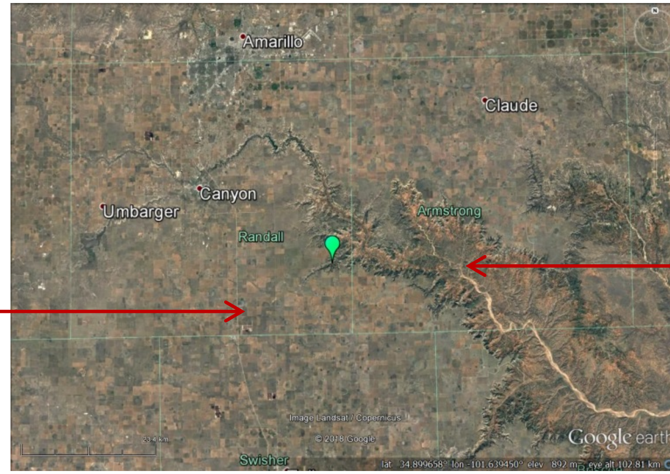


- Examples with similar seasonal patterns (correlated), but less agreement in magnitude
  - Potential sampling differences in less homogeneous conditions
  - Investigating making the satellite and ground-based comparisons more representative

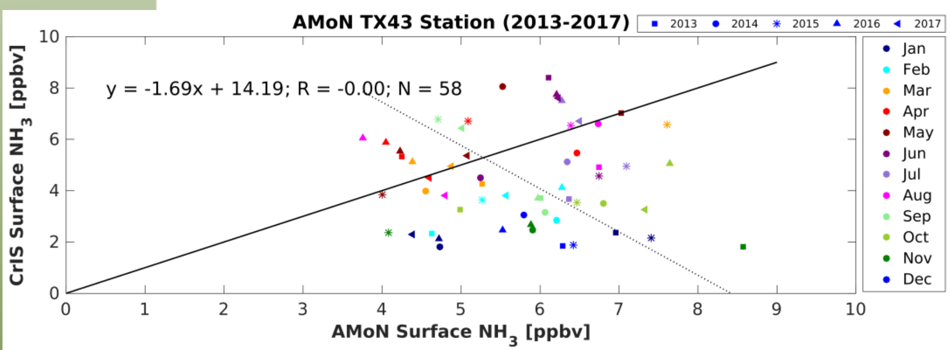
Satellite Ammonia Evaluation

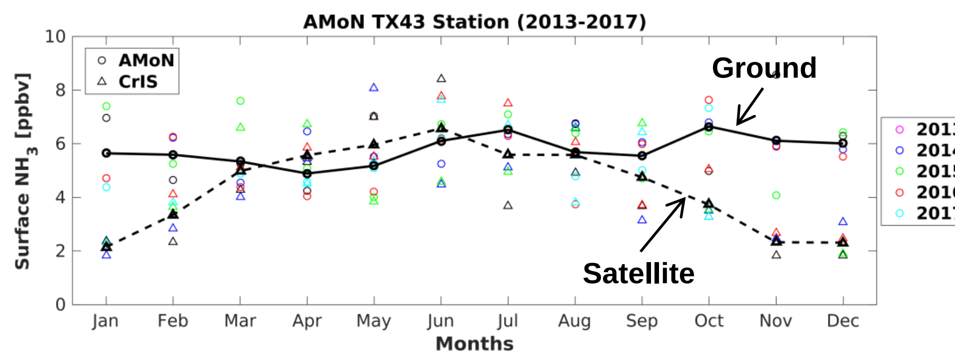
Cañónceta, Texas (TX43)

Lots of Agriculture



Beside a Canyon

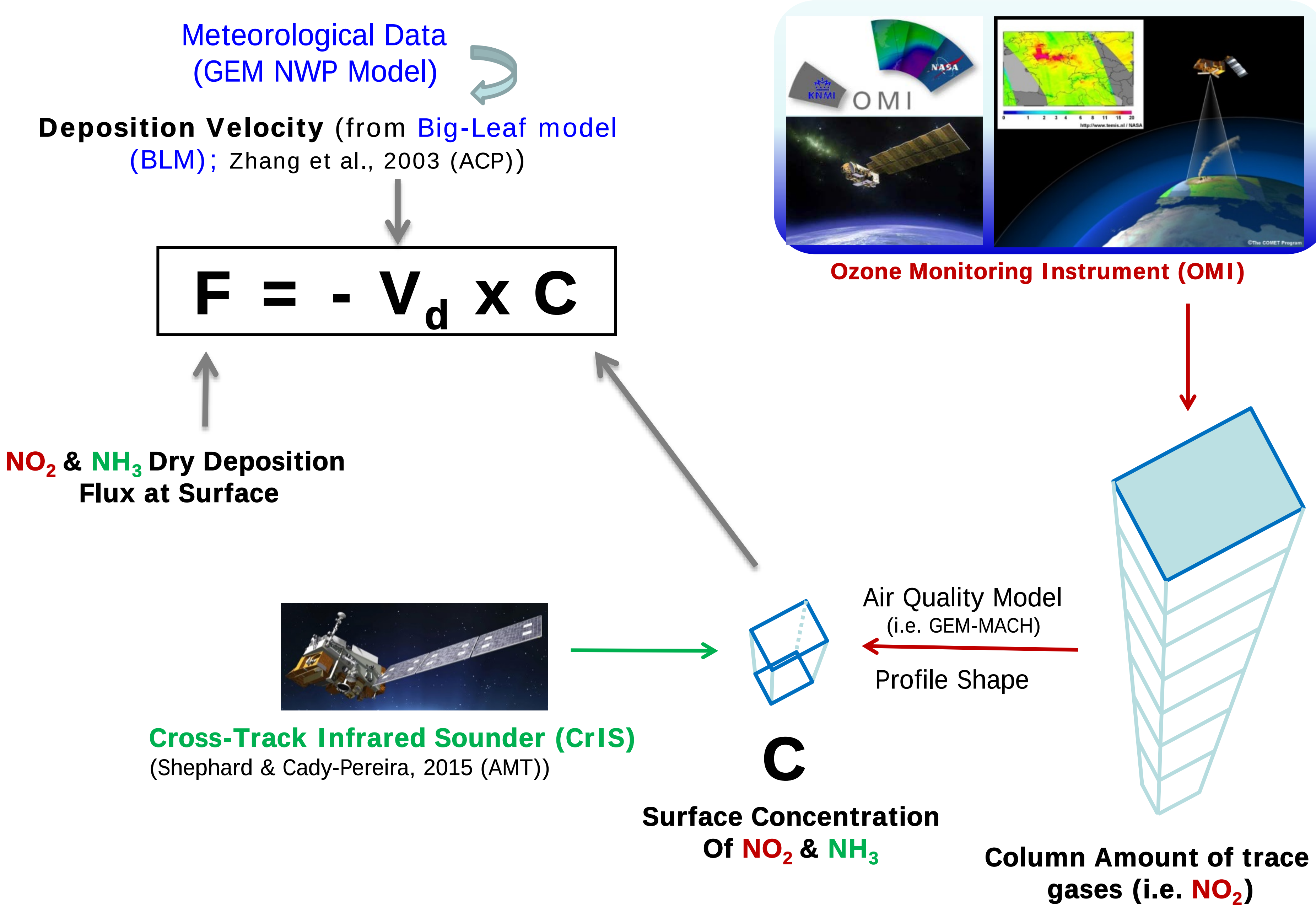




- Example with no correlation
    - No seasonality in the AMoN observations
    - Magnitude of the summertime values are similar

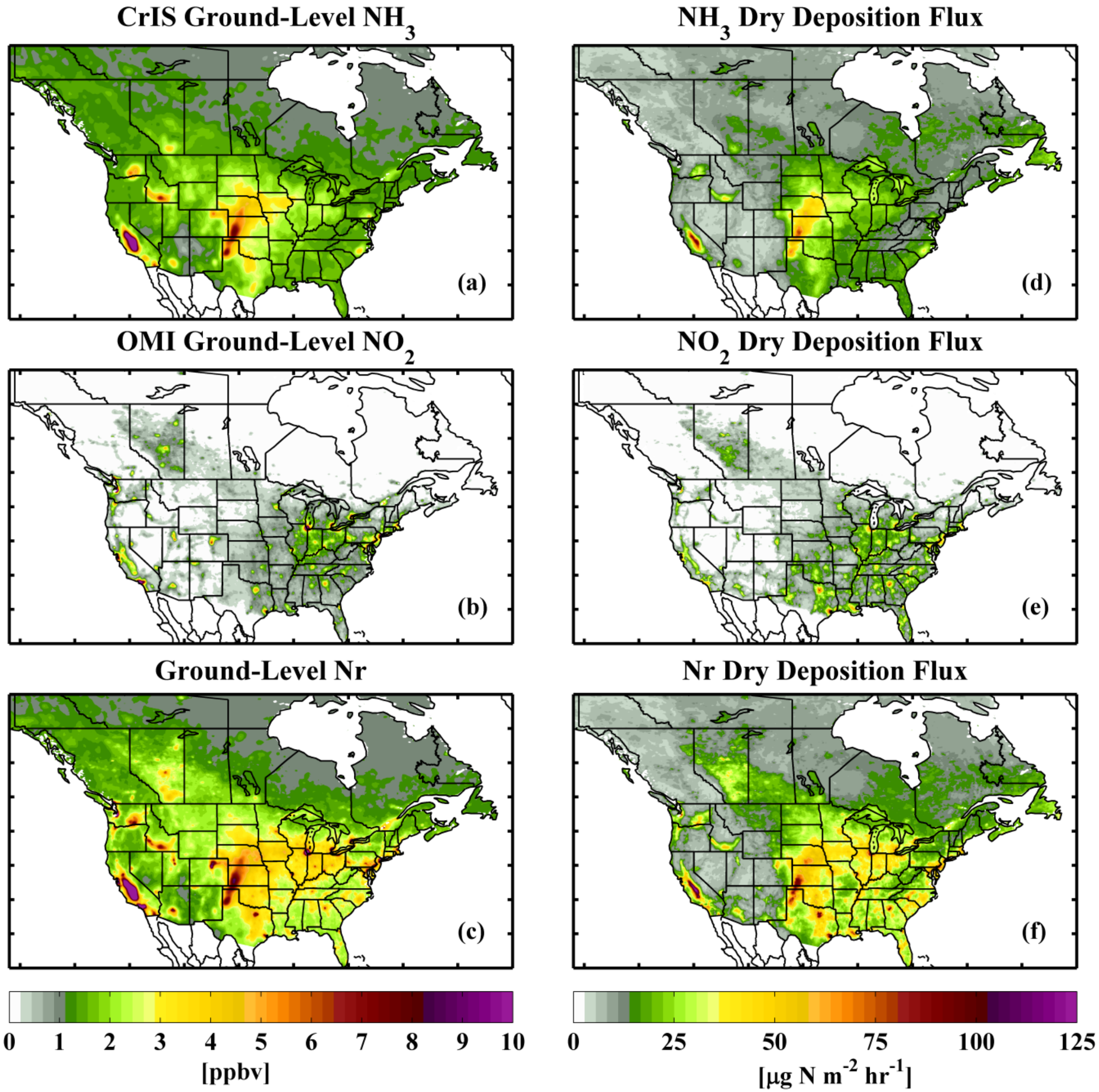
Applications

Satellite derived Dry Deposition Flux of NH_3 & NO_2



Satellite-derived reactive nitrogen (Nr) dry deposition over North America for 2013

Focused on the short-lived nitrogen species NH_3 & NO_2



NH_3 hot-spots are mainly located over agriculture regions

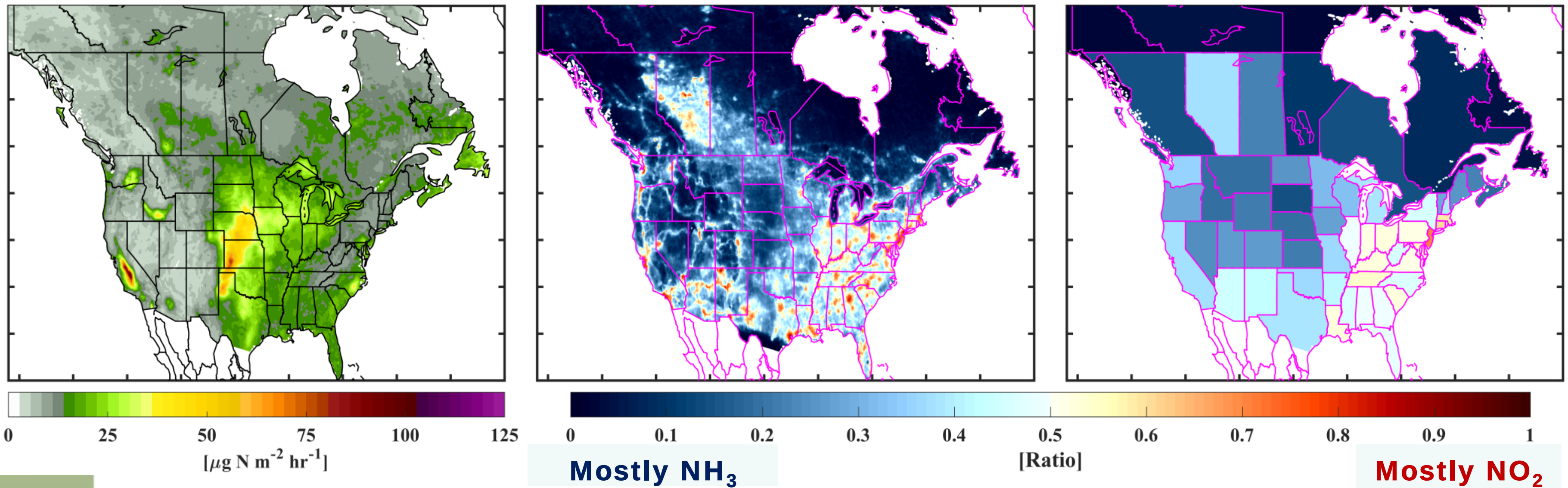
NO_2 hot-spots are mainly located over densely populated cities and power plants

Reactive Nitrogen
$Nr = NO_2 + NH_3$

Shailesh Kharol

Dry deposition flux over North America 2013

NH_3 Dry Deposition Flux | **Ratio, NO_2 / (NH_3 + NO_2) Dry Deposition Flux**



- **NH_3** dry deposition flux peaks in **agricultural** and remote regions
  - e.g. Mid-West
- **NO_2** dry deposition flux dominates in **urban** regions / power plants
  - e.g. North-East
- Repeat for multiple years (2013 to 2017) to look at **interannual variability**
- Need ground-based deposition measurements over a variety of conditions in North America for satellite validation!

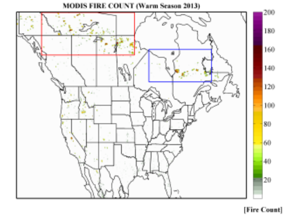
Environment and Climate Change Canada

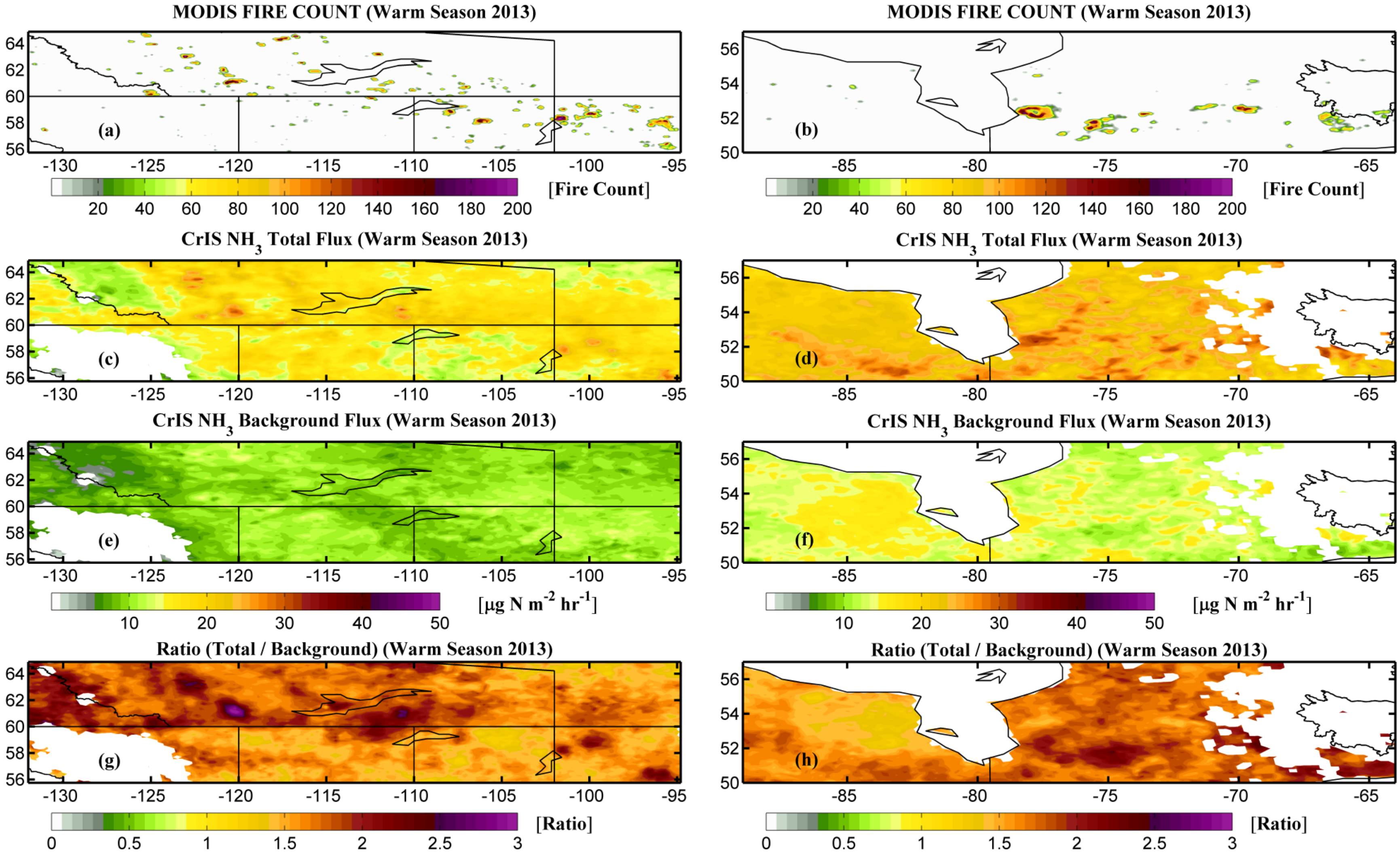
Shailesh Kharol

Dry deposition of reactive nitrogen from satellite observations of ammonia and nitrogen dioxide over North America

S. K. Kharol, M. W. Shephard, C. A. McLinden, L. Zhang, C. E. Sioris, J. M. O'Brien, R. Vet, K. E. Cady-Pereira, E. Hare, J. Siemons, N. A. Krotkov

Forest fires contribution to the dry deposition of NH_3 in Northern Canada (Warm Season: Apr-Sept)





Locations at northern latitudes affected by forest fires tend to have 2–3 times more dry deposition of ammonia relative to the local background

Satellite Derived Emissions: Fire Source

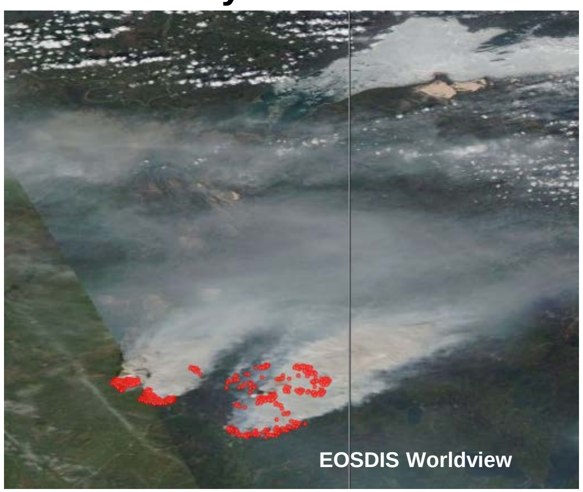
Emissions: mass / time

Mass in the box
Satellite *Column Density x Area x MolecMass*

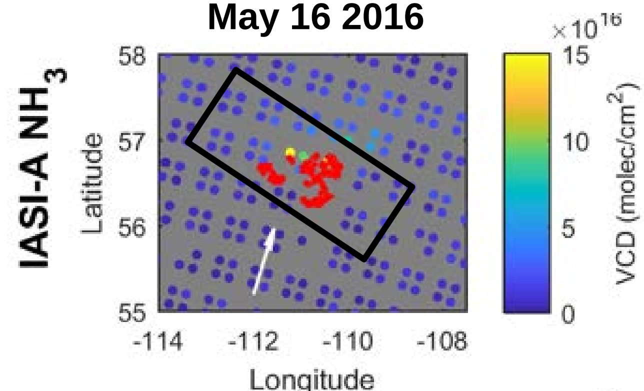
Rate mass leaves box
Winds *from Weather Prediction Model*

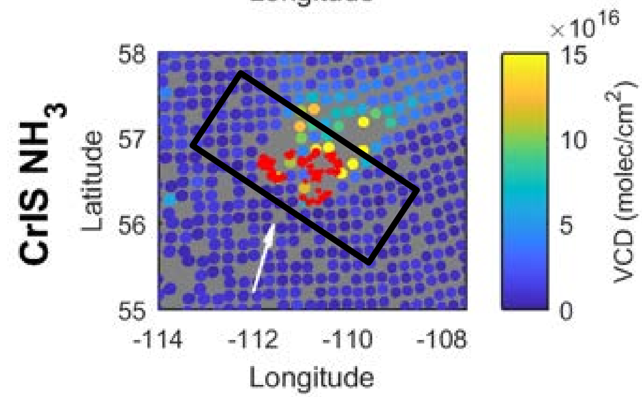
Satellite (MODIS) image of smoke and hotspots from Canadian Fort McMurray fires

May 16 2016



May 16 2016

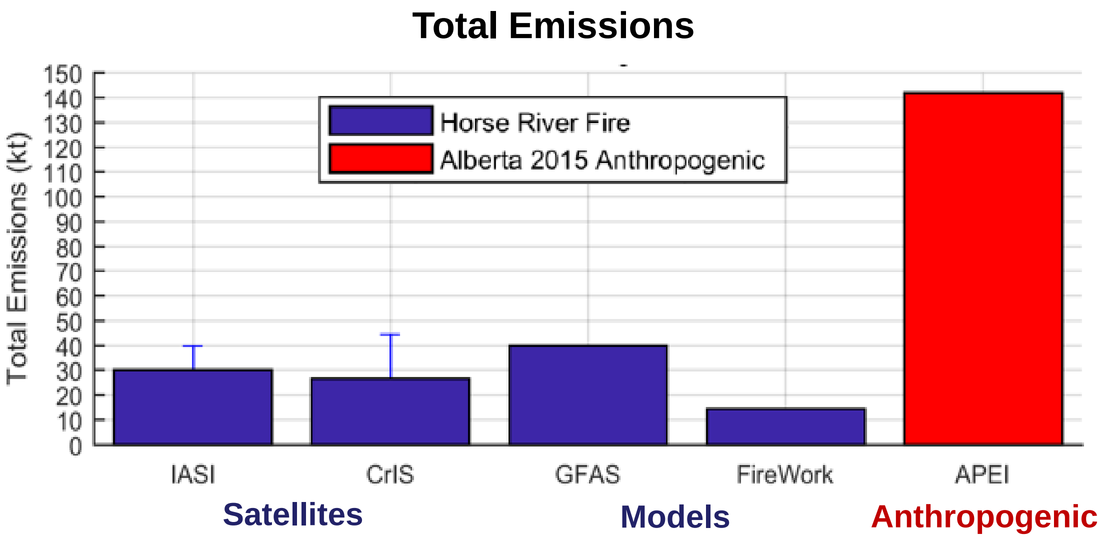




- **Combine satellite observations with model winds to derive fire emissions**

Environment and Climate Change Canada
Environnement et Changement climatique Canada
Cristen Adams
Canada

Satellite Derived Emissions: Fire Source



Fire Emission Models:

- **ECMWF Global Fire Assimilation System (GFAS)**
- **Fireworks: ECCC Fireworks model**

Emission Inventory:

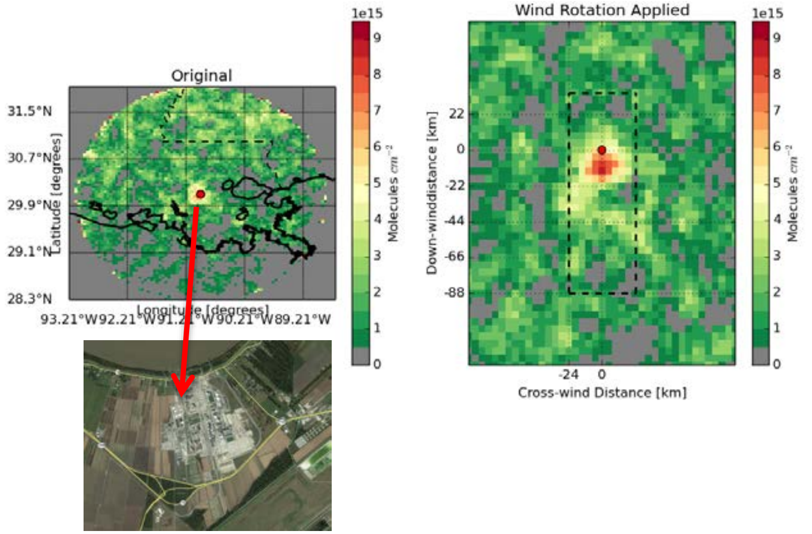
- **ECCC Air Pollutant Emissions Inventory (APEI)**

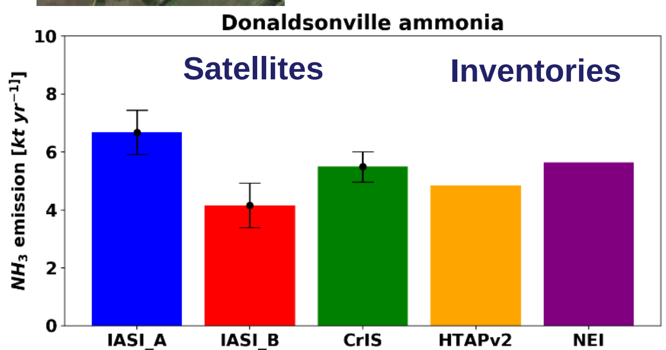
- **Satellite** and **model emissions agree pretty well** for the Fort McMurray fires
- **Total Fort McMurray fire emissions are significant compared with anthropogenic**
  - **~20% of the Alberta Anthropogenic emissions**
- Next steps include:
  - Apply method on more fires
  - Ultimate goal is to estimate national/global emissions from fires

acp-2018-913 Submitted on 31 Aug 2018
Satellite-derived emissions of carbon monoxide, ammonia, and nitrogen dioxide from the 2016 Horse River wildfire in the Fort McMurray area
Cristen Adams, Chris McLinden, Mark Shephard, Nolan Dickson, Enrico Dammers, Jack Chen, Paul Makar, Karen Cady-Pereira, Naomi Tam, Shailesh Kharol, Lok Lamsal, and Nickolay Krotkov

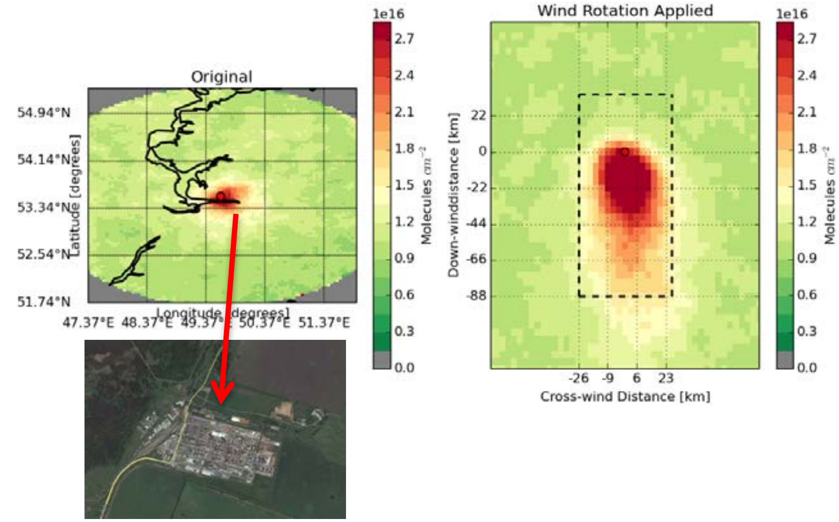
Satellite Derived Emissions: Point Source Examples

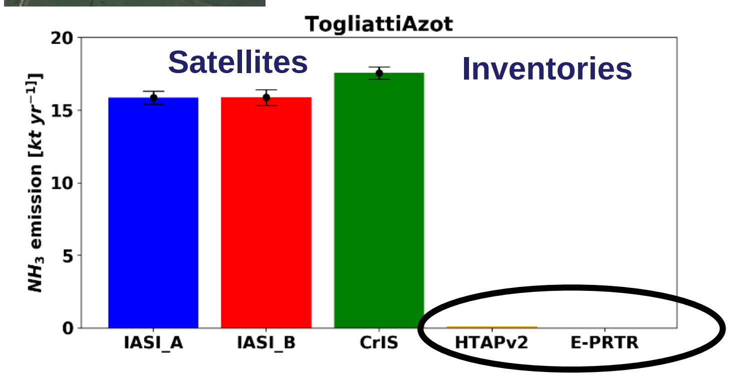
Donaldsonville ammonia, United States [IASI-A, 2013-2018]





TogliattiAzot, Russia [CrIS, 2013-2018]



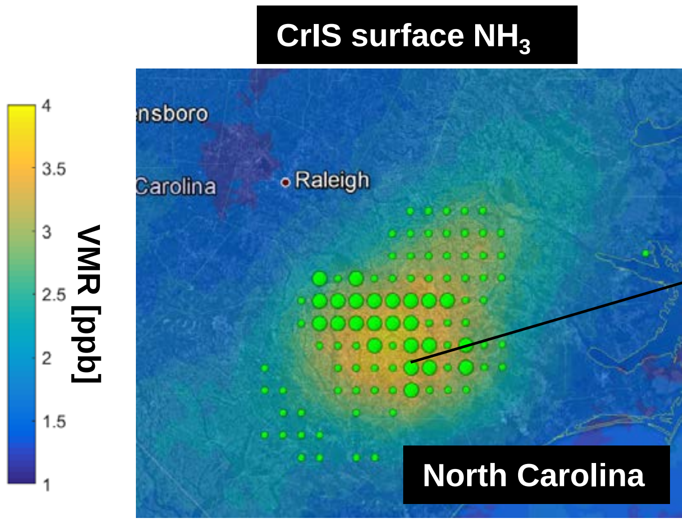


- **Satellite derived emissions agree well with inventories for some locations where others are completely missing in the current inventories**
- **Next step satellite derived emission estimates for all major point sources**

Environment and Climate Change Canada
Environnement et Changement climatique Canada
Enrico Dammers

Canada

Satellite Derived Emissions: Agriculture Sources



HTAP emissions inventory

Confined Animal Feedlot Operations

Anthropogenic Emissions

Six months (Apr-Sep) NH_3 emissions total

HTAP (annual /2)	= 42 kilotonnes
GEM-MACH	= 55 kilotonnes
CrIS *	**= 58±21 kilotonnes**

* Adjusted for assumed diurnal emissions profile

- **Preliminary example**
- **CrIS derived emission estimates and emission inventory are similar in this agriculture region of North Carolina**

Remarks

- Satellite measurements of ammonia in the lower troposphere are relatively new…just in the past **10-years**!

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L09801, doi:10.1029/2008GL033642, 2008

First satellite observations of lower tropospheric ammonia and methanol

Reinhard Beer,[1] Mark W. Shephard,[2] Susan S. Kulawik,[1] Shepard A. Clough,[3]

- Early stages of development and exploration of potential applications
  - Satellite NH_3 retrievals and applications look promising
    - Good initial comparisons of satellite with ground-based observations
      - AMoN, NAPS, FTIR
    - Presented initial satellite derived dry deposition and emission estimates
  - Requires more **validation**: concentrations and dry deposition
- Satellite remote sensing should be viewed as **complimentary to conventional surface and aircraft monitoring**
  - Has advantages (i.e. fill in gaps in surface networks) and disadvantages (i.e. more regional observations (~10km))
- An important applications we did not show here is the **use of satellite observations for air quality model evaluation** and data assimilation

Contributions

Satellite Ammonia	*Karen Cady-Pereira (AER), Enrico Dammers (ECCC), Shailesh Kharol (ECCC;UofT), Chris McLinden (ECCC), Chris Sioris (ECCC), Martin Van Damme (ULB), Simon Whitburn (ULB), Lieven Clarisse(ULB) Pierre Coheur (ULB)*
Observations/Monitoring	*Enrico Dammers (ECCC), Shailesh Kharol (ECCC;UofT) Jesse Thompson (ECCC,UofW), Andrew Kovachik (ECCC)*
Validations	*Enrico Dammers (ECCC), Shailesh Kharol (ECCC;UofT) Ed Hare (ECCC), Jason O'Brien (ECCC), Ewa Dabek (ECCC) AMoN and NAPS Data Providers*
Model Evaluation	*Shabtai Bittman (AAFC), Paul Makar (ECCC), Cynthia Whaley (ECCC), Junhua Zhang (ECCC) Leiming Zhang (ECCC)*
Dry Deposition	*Shailesh Kharol(ECCC;UofT); Leiming Zhang (ECCC)*
Emissions	*Cristen Adams(EMSD), Enrico Dammers(ECCC), Vitali Fioletov(ECCC), Chris McLinden(ECCC)*
+ others	

THANKS!

Agriculture and Agri-Food Canada (AAFC), British Columbia, Canada
Atmospheric and Environmental Research (AER), Lexington, MA, USA
Environment and Climate Change Canada (ECCC), Toronto, Ontario, Canada
Environmental Monitoring and Science Division, Government of Alberta, Edmonton, Alberta, Canada (EMSD)
University of Toronto, Toronto, Ontario, Canada(UofT)
University of Waterloo, Waterloo, Ontario, Canada (UofW)
University of Bremen, Bremen, Germany IUP-Bremen
Universite Libre Bruxelles, Brussels, Belgium (ULB)

Canada

BACKGROUND SLIDES

Satellite derived Dry Deposition Flux of NH_3 & NO_2

To convert the dry deposition flux to daily average, we followed the method developed by Nowlan et al. (2014) and calculated the 24 hr daily flux as follows:

$$\boldsymbol{F^{sat}} = -\frac{\boldsymbol{C^{sat}}}{24}\sum_{h=1}^{24} \boldsymbol{V_{d,h}} \times \boldsymbol{\gamma_h}$$

$\boldsymbol{F^{sat}}$ represents 24 h daily average flux
$\boldsymbol{C^{sat}}$ represents the satellite-derived ground-level concentration
$\boldsymbol{V_{d,h}}$ represents hourly dry deposition velocity
$\boldsymbol{\gamma_h}$ is a concentration diurnal scaling factor.

For NO_2: $\boldsymbol{\gamma_h = C_h^{GM} / C_{sat\ overpass}^{GM}}$

$\boldsymbol{C_h^{GM}}$ *and* $\boldsymbol{C_{sat\ overpass}^{GM}}$ represent hourly and satellite overpass time mean ground-level concentration from the GEM-MACH air quality model

For NH_3: $\boldsymbol{\gamma_h = 1}$

As there is relatively limited information on the NH_3 diurnal profile, which can vary significantly by region and season over North America, we presently assume that the mid-day NH_3 deposition flux can be representative of diurnal average (i.e., $\boldsymbol{\gamma_h = 1}$)

- New continuous measurements over Netherlands we are using to investigate this further

Shailesh Kharol

Continuous vs Satellite Overpass Sampling

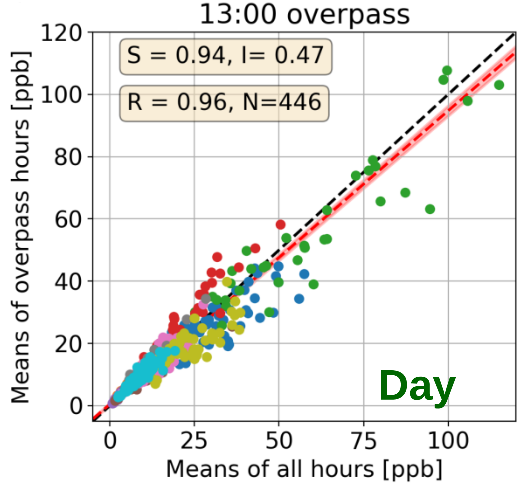
- Determine how well the satellite overpass sampling represent continuous sampling over a time period

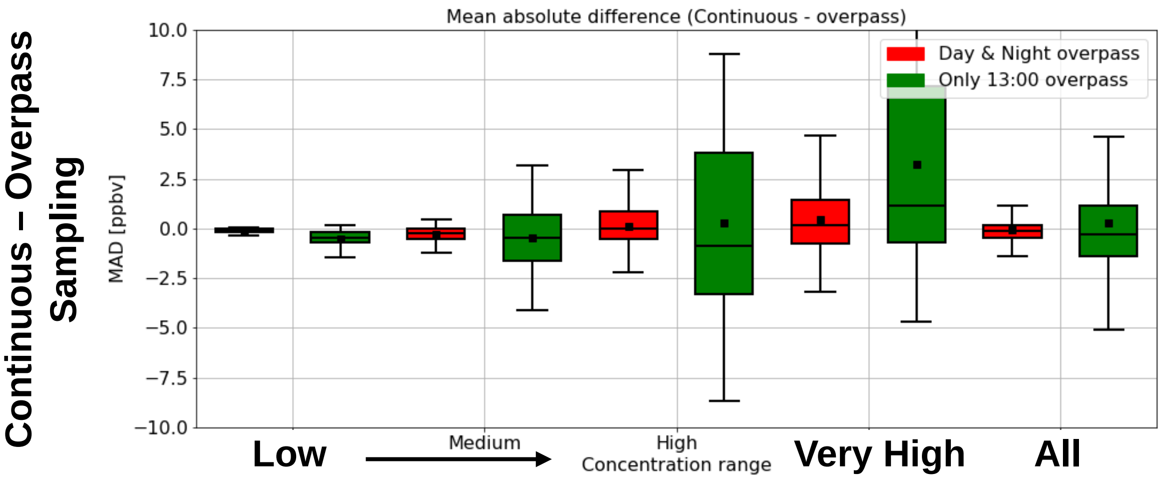
- Approach is to use continuous ground-based surface observations
  - Subset the data to only include surface observations the would correspond to satellite overpass times
  - Compare this subset to the whole continuous observations over various time periods (e.g. daily, 3-day, weekly, monthly, etc.)

- Dataset
  - Landelijk Meetnetwerk Luchtkwaliteit LML (National Measurement Network Air Quality) in the Netherlands
    - Hourly NH_3 observations using the AMOR instrument
    - Recently switched to mini-DOAS instruments in 2015.
  - 10 sites with NH_3 measurements (presently 6 are operating)

Continuous vs satellite overpass sampling from LML ground network only: Monthly comparison

Day + Night





Day + Night

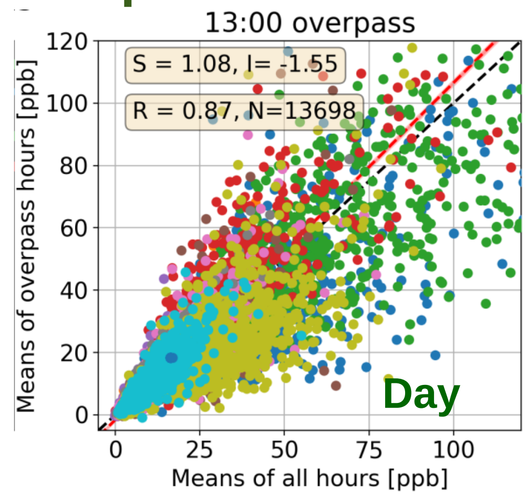
Day

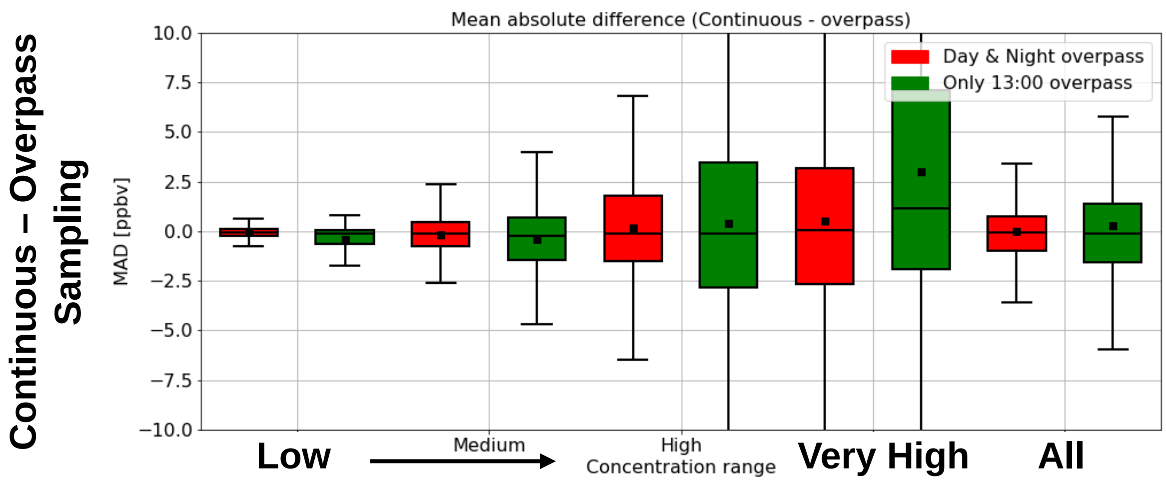
Sampling at overpass times (@~1:30 and 13:30) is a **good representation of monthly averaging of continuous** observations

- Overall **not a significant mean difference** (<-0.1 ppbv) with overpass sampling
- Some **dependency on amounts**: Low values : overpass sampling is overestimate
  Higher values: overpass sampling is underestimate
- Using both day + night overpasses shows less difference then day only (~0.3 ppbv)

Continuous vs satellite overpass sampling from LML ground network only: Daily comparison

Day & Night





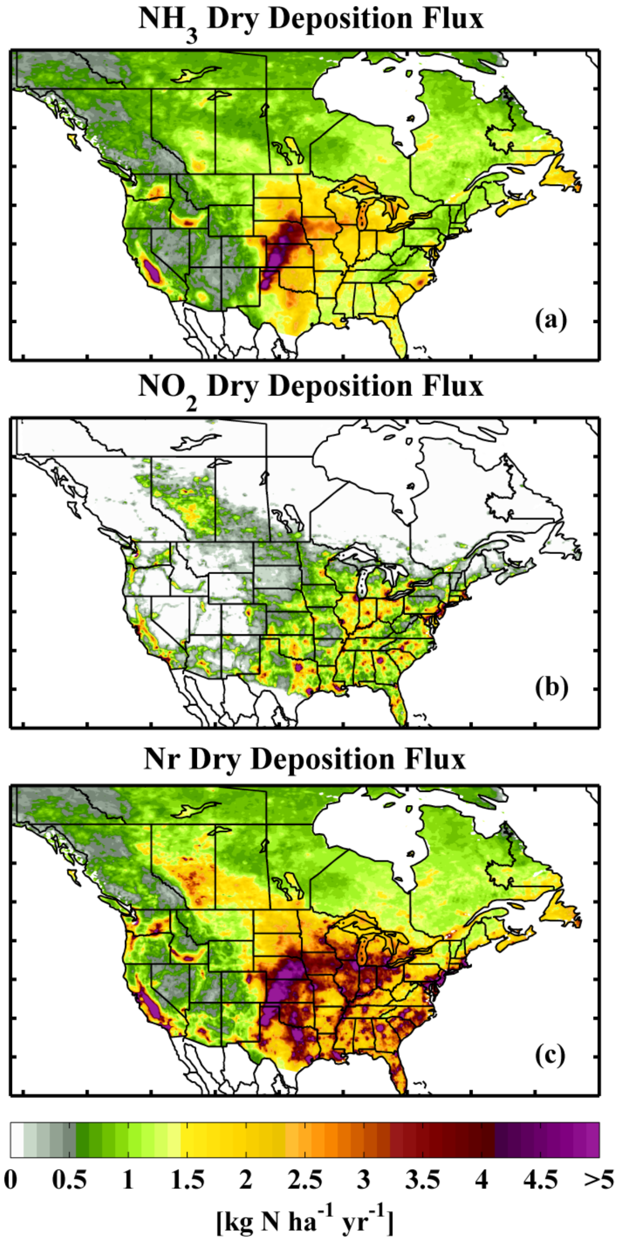
Day + Night

Day

Sampling at overpass times (@~1:30 and 13:30) is a **good representation of daily averaging of continuous** observations

- Overall **not a significant mean difference for day + night**
- Some **dependency on amounts**: Higher values: overpass sampling is underestimate
- Using both day + night overpasses shows less difference then **day** only (~0.3 ppbv)

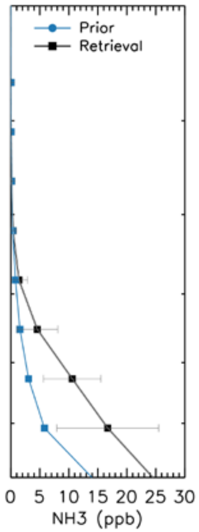
Satellite-derived reactive nitrogen (Nr) dry deposition over North America in 2013 (Total Amount)



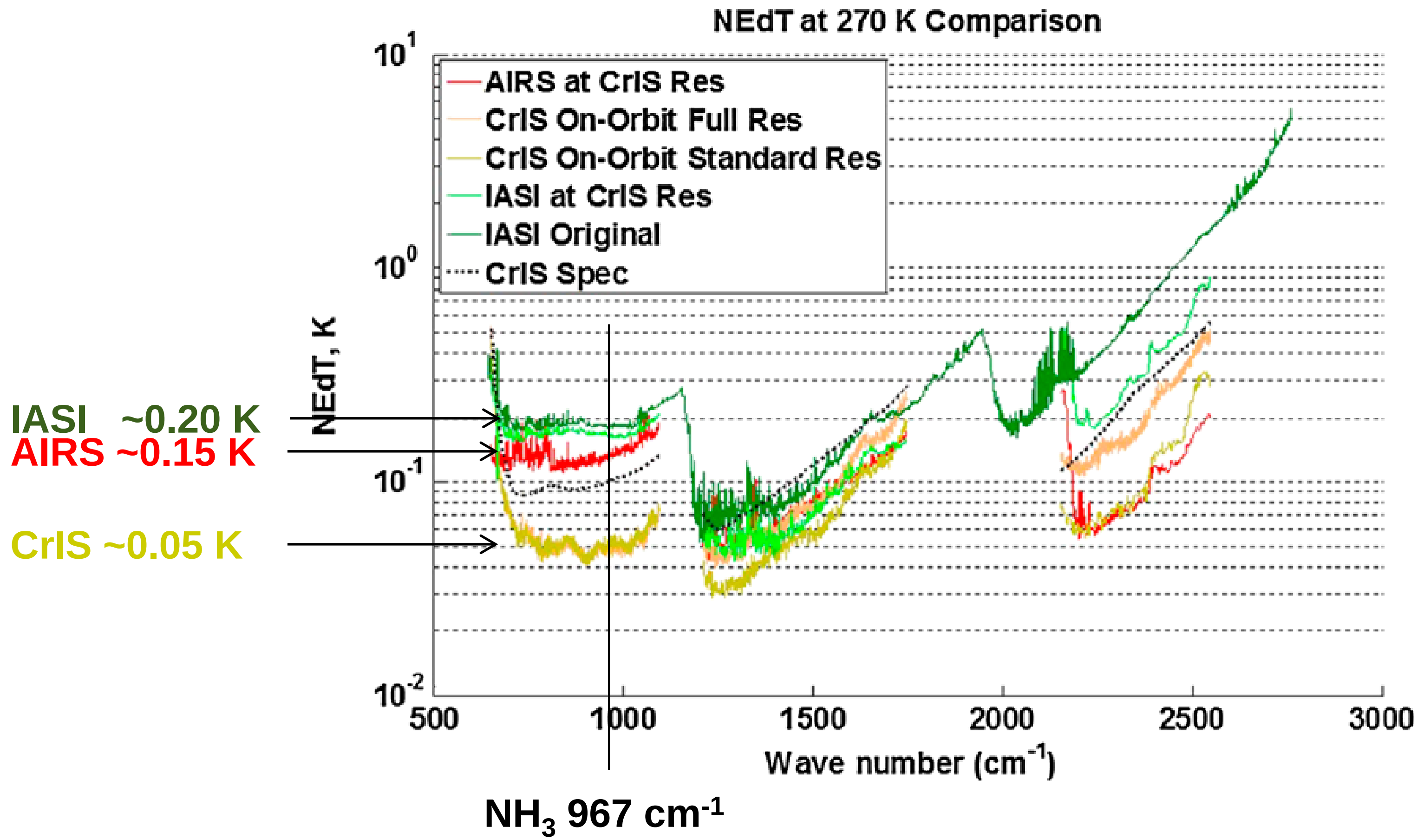
Canada

Cross-track Infrared Sounder (CrIS) Satellite

- Profiles: Concentrations at different levels
  - Reported as volume mixing ratio in ppbv
  - Errors and sensitivity (information content)
- Most sensitive to NH_3 in **boundary layer**
  - Not equally sensitive in the vertical and varies from profile-to-profile
    - Typically between **~0.5 to 3 km**(950 to 700 mb)
  - Surface retrieved values are driven by sensitivity in boundary layer
    - ~1 piece of independent information
- Detectability of NH_3 **~0.5 ppbv** (volume mixing ratio)



CrIS noise comparison with IASI and AIRS

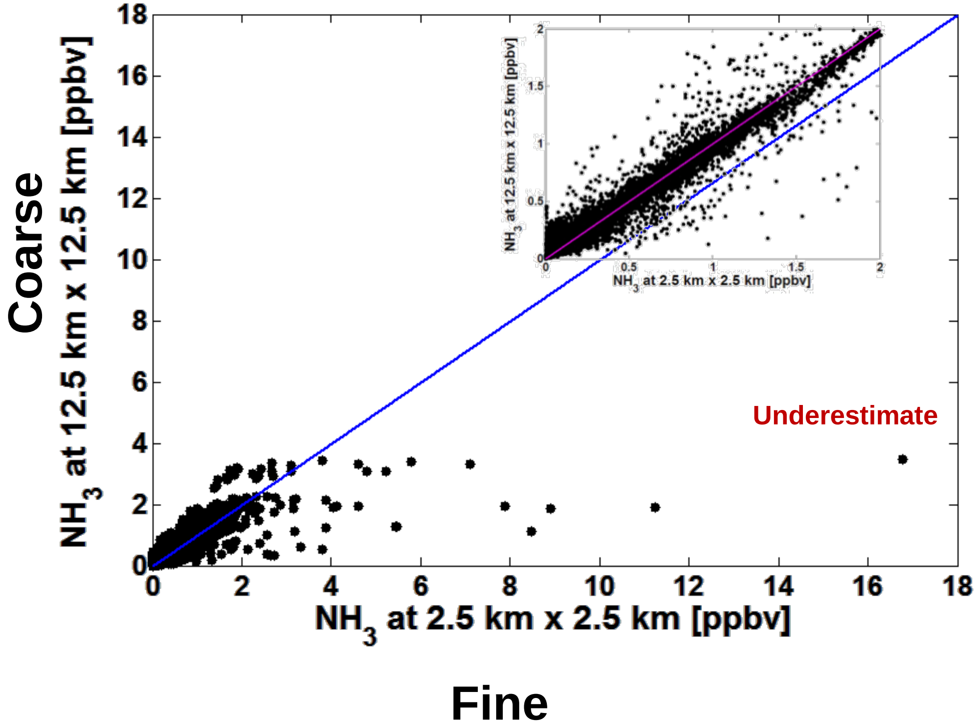


Reference: Zavyalov, V., et al. (2013), Noise performance of the CrIS instrument, J. Geophys. Res. Atmos., 118,13,108–13,120, doi:10.1002/2013JD020457.

Validation: Point vs Regional Spatial Sampling

Should we expect a 1:1 comparison of in-situ point sources and satellite footprint surface obs. of NH_3?

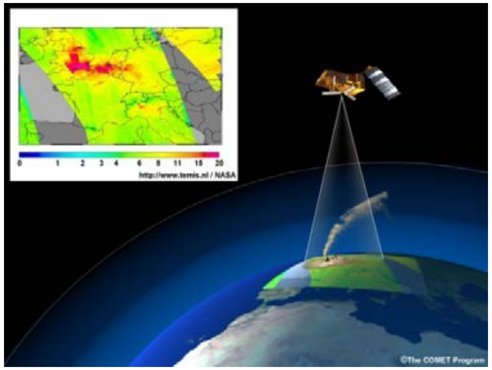
- Use high-resolution GEM-MACH model simulations to investigate the impact of sampling NH_3 surface fields over AB and SK with different spatial sampling resolutions.

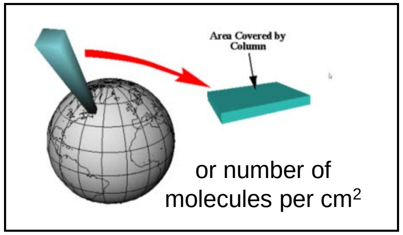


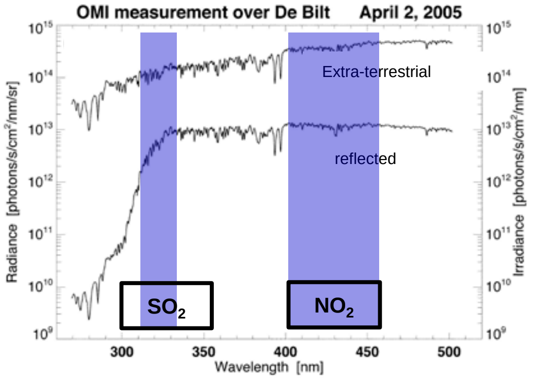
Larger spatial sampling @12kmx12km (similar to satellite) compared with **smaller 2.5km x 2.5km** (closer to smaller point source type observations) measurements will tend to **overestimate small values** and **underestimate larger values** under <u>inhomogenous</u> conditions even if both measurements were perfect.

Ozone Monitoring Instrument (OMI)

- The **Ozone Monitoring Instrument (OMI)** is a Dutch/Finnish instrument on the NASA Aura satellite, launched in 2004
- OMI measures nadir (upwelling**) UV/visible** radiances (surface reflected + scattered light)
- Complex algorithms are required to convert the measured spectra into tropospheric NO_2 and SO_2 **Vertical Column Densities**

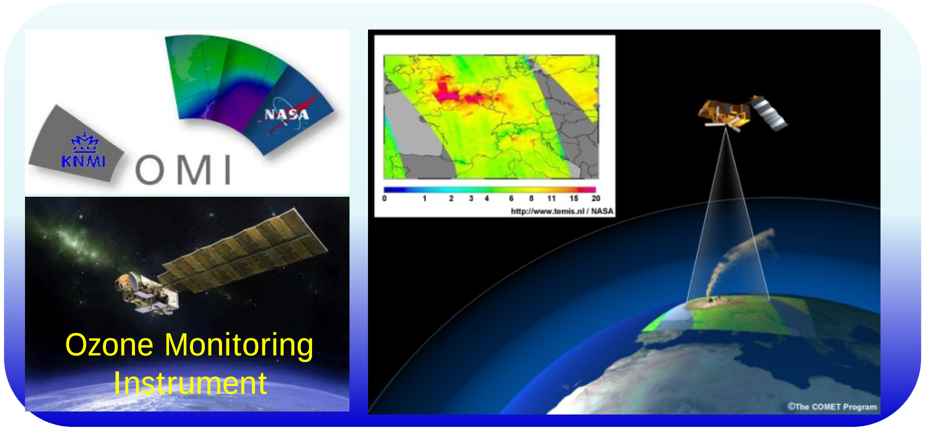






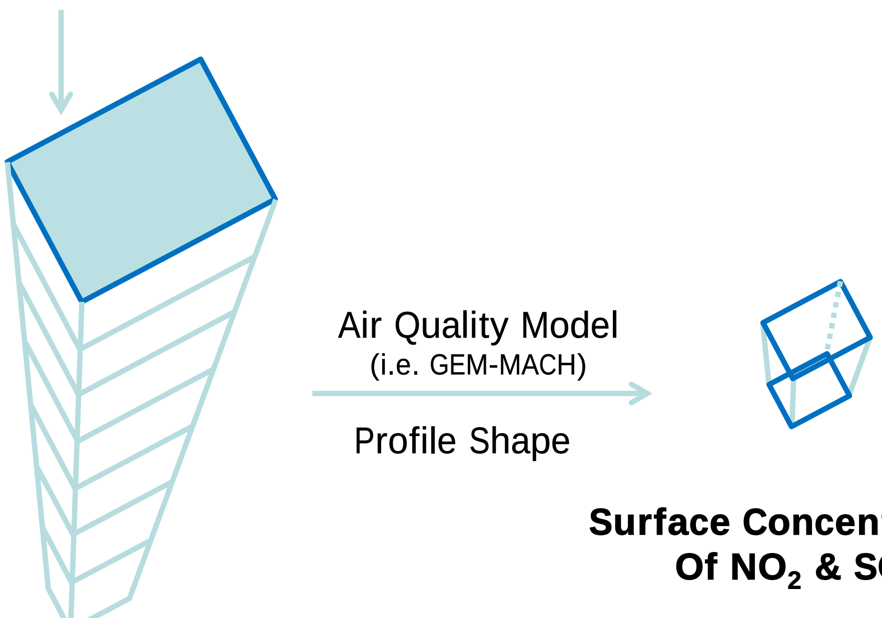
- OMI spatial resolution is about 15 x 30 km^2
- To correct systematic low biases in NASA and European products over the North America, Environment and Climate Change Canada has reprocessed data over North America

OMI Satellite derived Ground-level NO_2 & SO_2

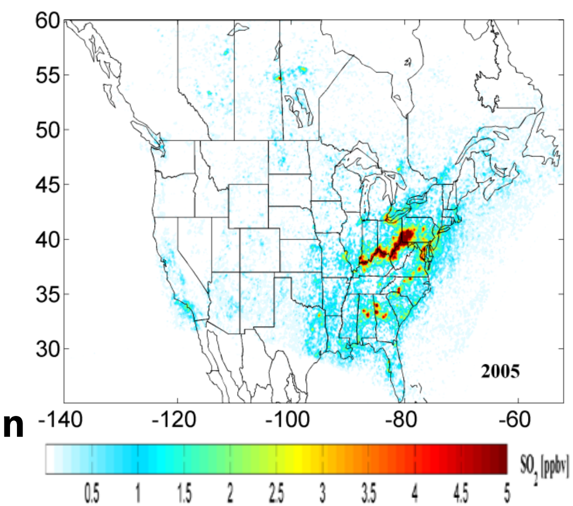


$$S_{OMI} = \Omega_{OMI} \times \frac{S_{Model}}{\Omega_{Model}}$$

Lamsal et al., 2008; 2010
McLinden et al., 2014



Surface Concentration Of NO_2 & SO_2



Column Amount of trace gases (i.e. NO_2 & SO_2)

Application to emissions

- Emissions are derived by **combining vertically-integrated profiles (columns) with winds** from a meteorological reanalysis (here ECMWF)
  - Combining concentrations and wind speed allows one to derive mass flux

$$\vec{F} = c(s,z)\vec{u}(s,z)$$

$$E = \oiint_C \left(\vec{F} \cdot \hat{n}\right) ds\, dz$$

c = Concentration (molec/cm^3)
u = wind speed (cm/s)
F = flux density (molec/cm^2/s)

- We consider two approaches:
  - Single overpass for **larger sources** ➔ **wild fires**
    (similar to Mebust et al., ACP, 2011)
  - Multiple overpasses for **smaller, more constant sources**
    ➔ **agricultural** sources (Fioletov et al., GRL, 2015)
    - requires the use of a rotation scheme in order to align the wind direction of all observations (Pommier et al., GRL, 2012)