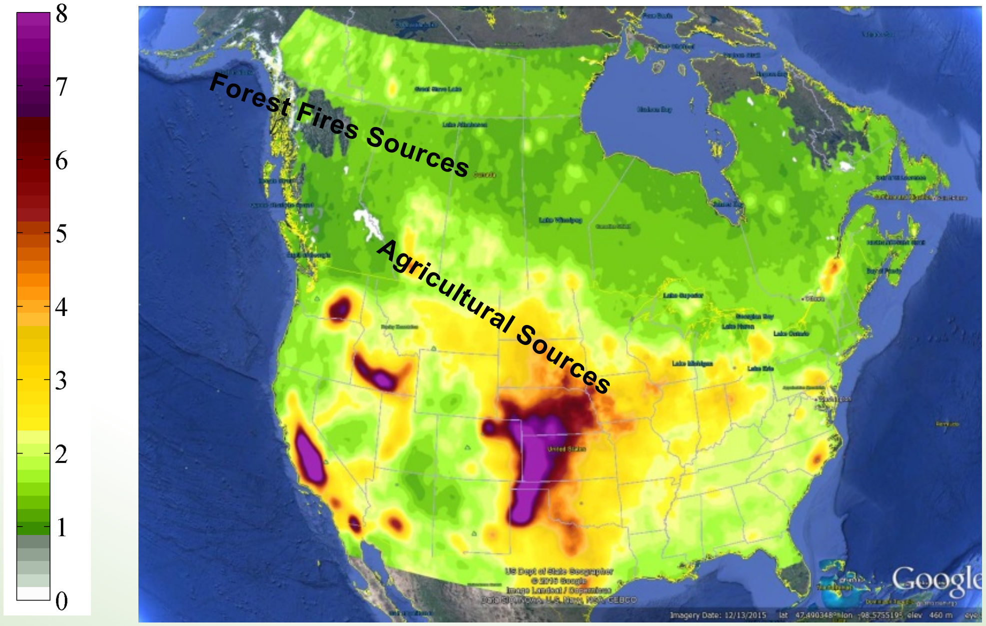
CrIS Observations of Ammonia: Retrievals, Validation and Spatiotemporal Variability



***Karen E. Cady-Pereira*[1] ,** *Mark W. Shephard*[2], *Shailesh K. Kharol*[2], *Enrico Dammers*[2], *Cynthia Whaley*[2], *Cristen Adams*[2], *Jesse Thompson*[2] , *Nolan Dickson*[2], *Ed Hare*[2], *Matt Alvarado*[1] *and Chantelle Lonsdale*[1]

[1]*Atmospheric and Environmental Research (AER), Lexington, Massachusetts, USA*
[2] *Environment and Climate Change Canada (ECCC), Toronto, Ontario, Canada*

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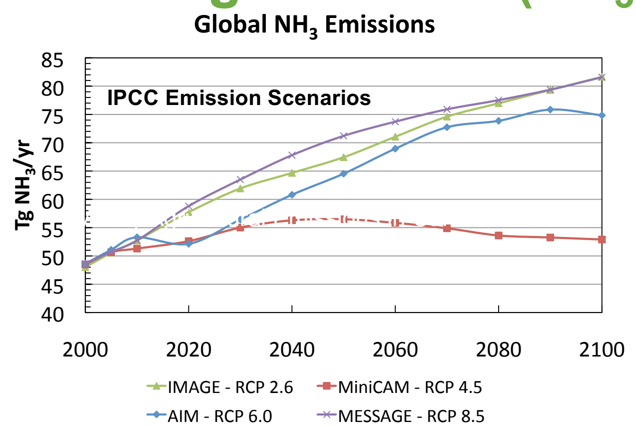
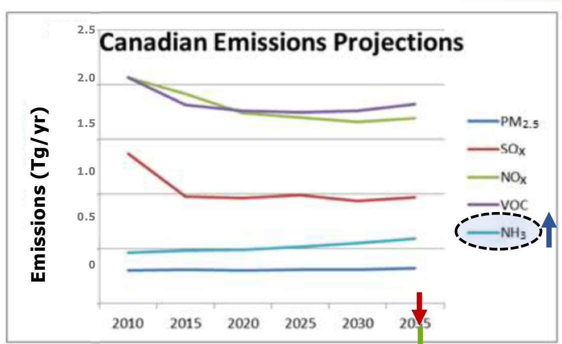
Why are we interested in measuring ammonia (NH_3)?

- Global (NH_3) emissions are forecast to increase:
  - Demand for more and better food in developing countries
    - More livestock production
    - Greater use of fertilizer



- From 1990 to 2015 Canada's ammonia emissions have increased by 22%, driven mainly by crop production

- SO_x, NO_X in general have been decreasing due to increased emission controls
  - Catalytic converters on vehicles (NOx)
  - Scrubbers installed in power plant stacks (SOx)



Canada-USA Transboundary Particulate Matter Science Assessment, 2013

Ammonia (NH_3) is the only $PM_{2.5}$ precursor that is both currently increasing and expected to continue to increase in the future

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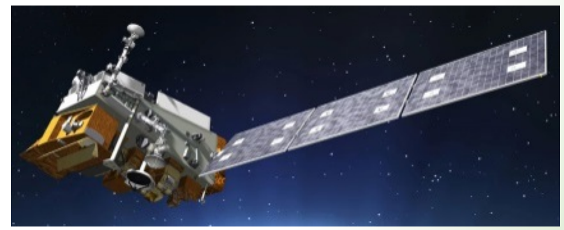
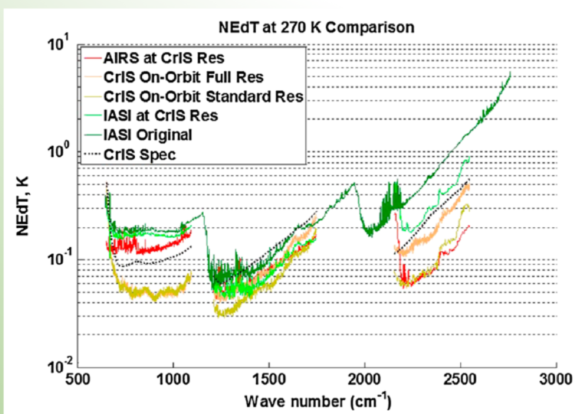
Cross-Track Infrared Sounder (CrIS)

- Launched in fall 2011 on S-NPP
- Also now flying on JPSS1: three more to follow through 2038
- Spatial Resolution = 14 km (diameter)
- ~1:30 and 13:30 overpass: ideal for NH_3
- Global spatial coverage
- Spectral Resolution (cm^{-1}) @ 970 cm^{-1} = 0.625
- Excellent noise
  - NEdT ~0.05K at 270K
  - ~4x better noise than similar sensors
- TES-like sensitivity with IASI/AIRS-like spatial coverage





Atmos. Meas. Tech., 8, 1323–1336, 2015
www.atmos-meas-tech.net/8/1323/2015/
doi:10.5194/amt-8-1323-2015

Atmospheric Measurement Techniques
Open Access

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

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

Correspondence to: M. W. Shephard (mark.shephard@ec.gc.ca)

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CrIS Fast Physical Retrieval (CFPR) Algorithm for NH_3

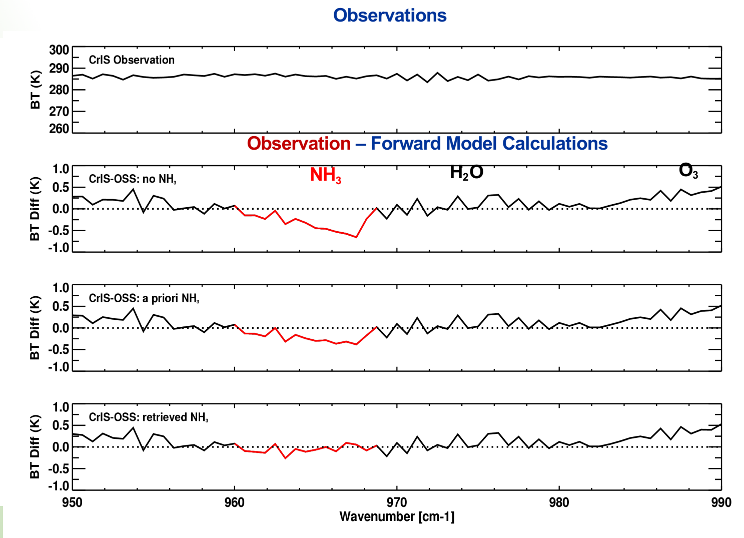
- developed in collaboration between Canada (ECCC) and USA (AER)
- TES heritage
- optimal estimation (Rodgers, 2000) implemented in IDL
- OSS as forward model

CrIS Obs

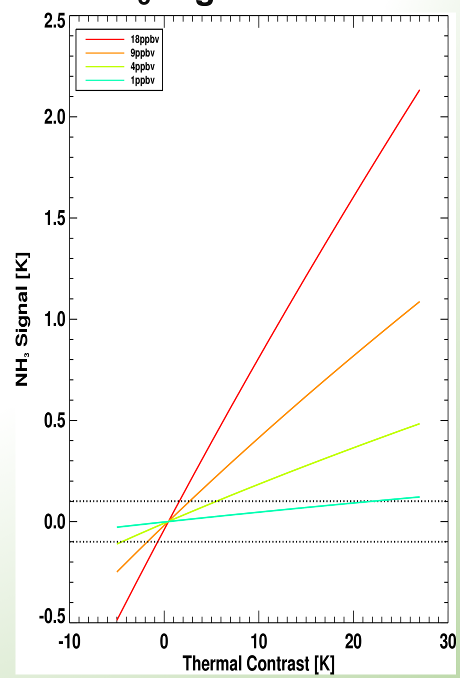
No NH_3

Initial Guess

Retrieval



NH_3 Signal vs TCON



Thermal Contrast: Surface- Air Temperature

- Detectability is ~ 0.25 ppbv under ideal conditions
- Thermal contrast plays an important role

For more details see: Shephard M.W. and K. E. Cady-Pereira, AMT, 2015

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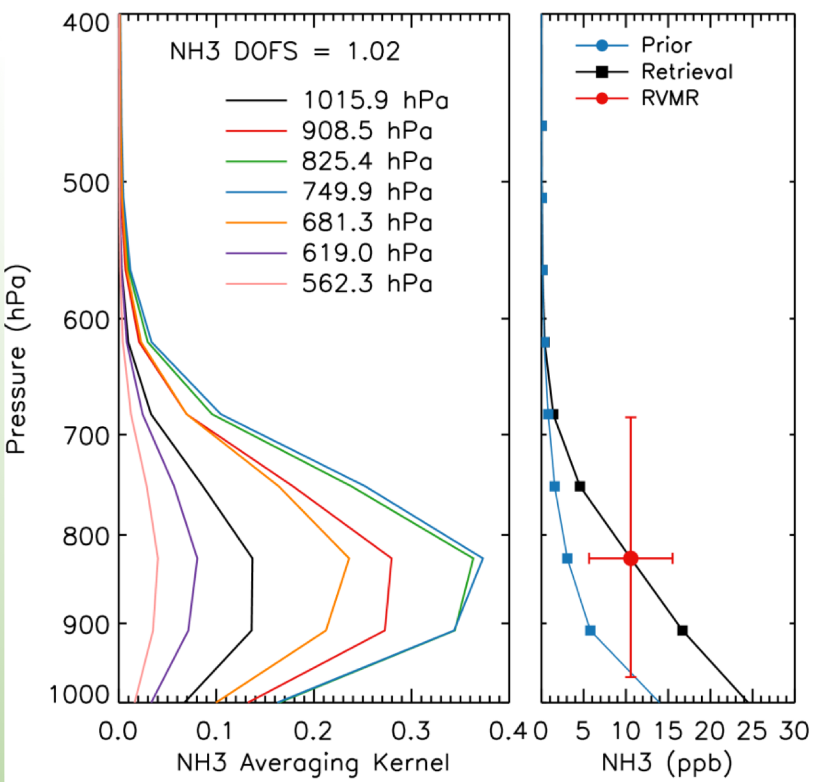
CrIS Fast Physical Retrieval (CFPR) for NH_3



- CrIS most sensitive to NH_3 between 950 and 700 mb (~0.5 to 3 km)
- Sensitivity varies from profile-to-profile
- Surface retrieved values are driven by sensitivity in boundary layer
- ~1 piece of information:
  - DOFS~1

For more details see: Shephard M.W. and K. E. Cady-Pereira, AMT, 2015

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How do CrIS NH_3 retrievals compare with other measurements?

- **CrIS**: an instantaneous profile over a footprint at least 14 km in diameter
- Most **ground measurements**: point data at the surface
  - Often a bi-weekly average:
    - Ammonia Monitoring Network (AMoN)
    - Canadian Air and Precipitation Monitoring Network (CAPMoN)
- **Ground-based Fourier Transform InfraRed (FTIR)**
  - Profile and total column measurements
  - Instantaneous cloud-free sampling (middle of the day)
- **Aircraft**: profiles of point data
  - DISCOVER-AQ campaigns in California and Colorado
- **All measurements** come with large uncertainties:
  - NH_3 is sticky, highly reactive and has high spatial and temporal variability

→ validation is not straightforward

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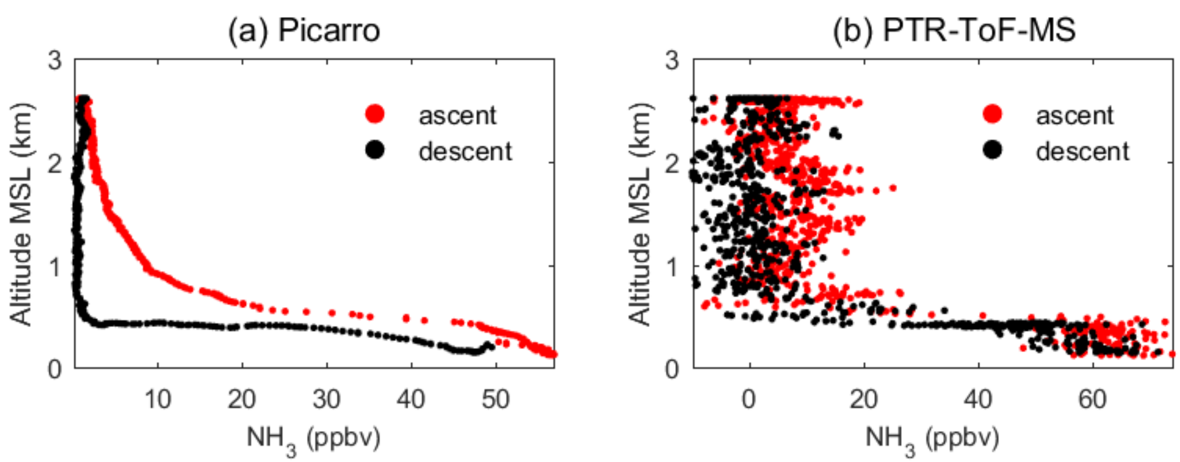
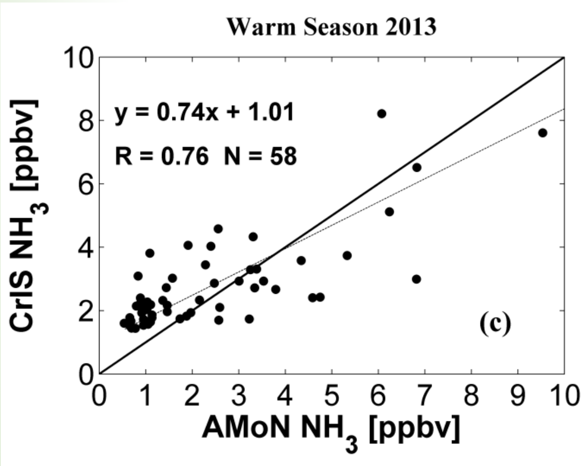
Validation: Uncertainty in aircraft profiles

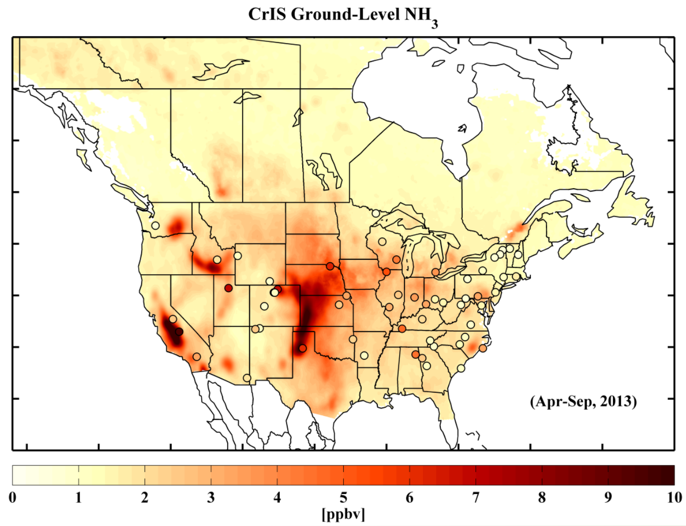
Sample profiles from the California DISCOVER AQ campaign January-February 2013



- **Picarro slow response leads to hysteresis:**
  - **Overestimates on ascent and underestimate on descent**
- **PTR-ToF-MS signal is very noisy**

Surface NH_3 from CrIS and the AMoN Network





Initial assessment shows that the satellite and AMoN surface obs agree well despite sampling differences

- **Correlation of 0.76**
- **Mean difference of +0.4 ppbv (~+15%)**

Shailesh Kharol et al., in preparation, 2018

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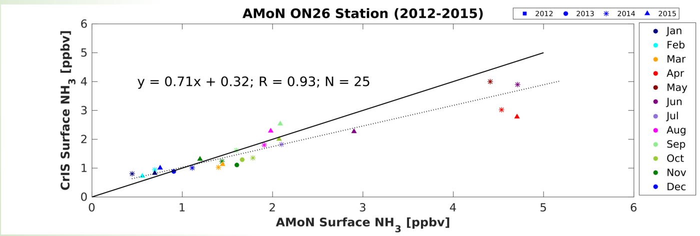
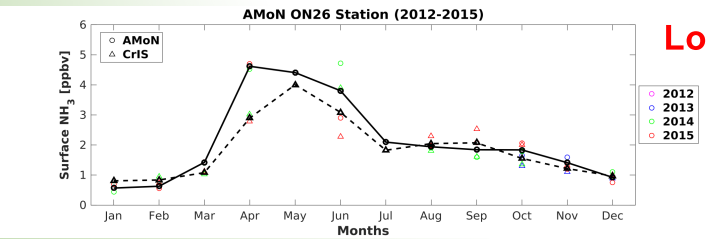
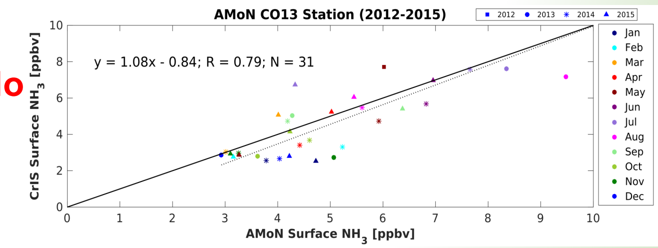
Surface NH_3 from CrIS and the AMoN Network

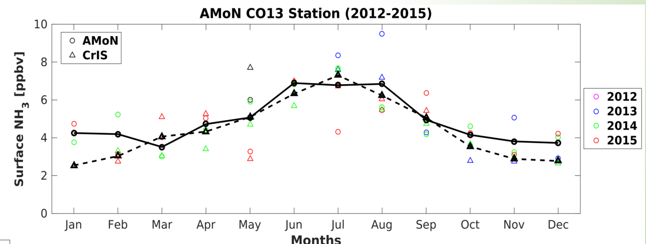




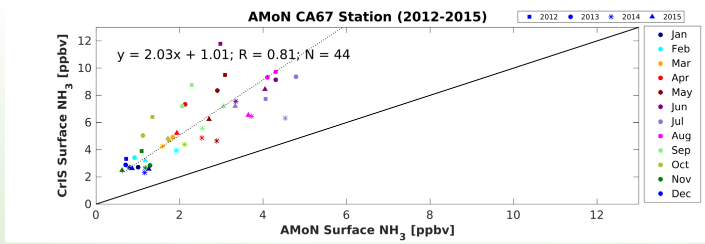
Longwoods, Ontario

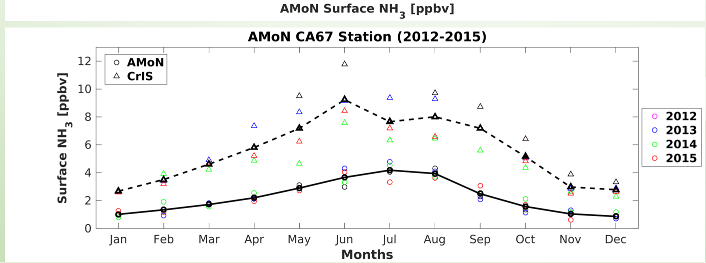
Fort Collins, Colorado





Joshua Tree National Park
Black Rock, California





Shailesh Kharol et al., in preparation, 2018

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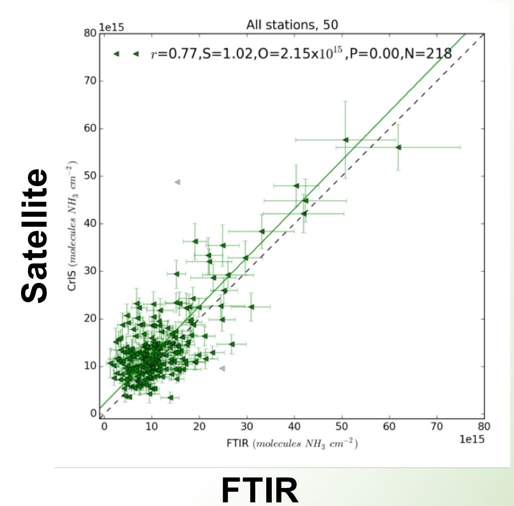
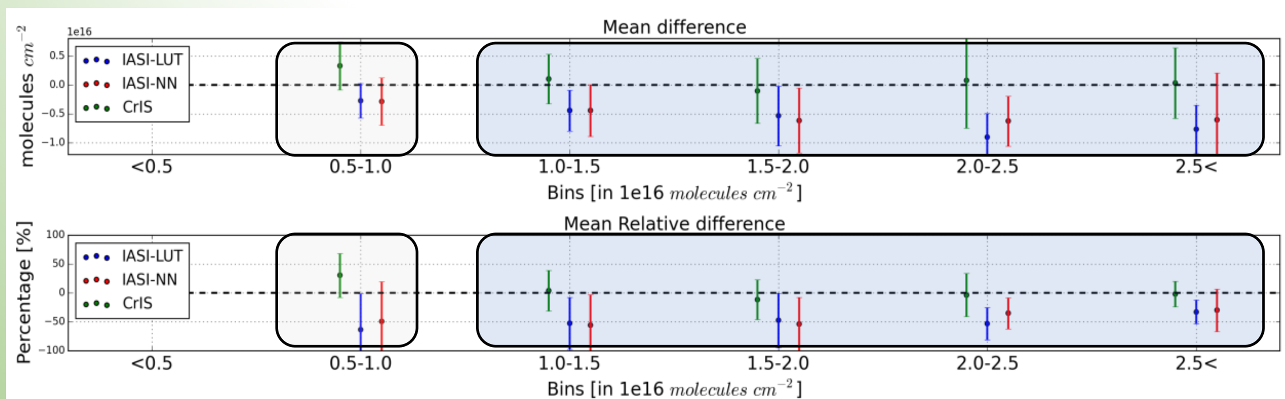
CrIS and ground-based FTIR

- **Total column comparisons with ground-based Fourier Transform InfraRed (FTIR) obs. at several locations globally**
  - **Bremen, Germany; Toronto Canada; Boulder USA, Pasadena USA, Wollongong, Australia; Lauder, New Zealand, Mexico City, Mexico**



- **Results look good with mean relative column differences of ~0 to -5% for the medium to large values**
  - **CrIS shows slight overestimate of smaller values**



Enrico Dammers et al., Validation of the CrIS fast physical NH3 retrieval with ground-based FTIR, Atmos. Meas. Tech., 10, 2645-2667, https://doi.org/10.5194/amt-10-2645-2017, 2017.

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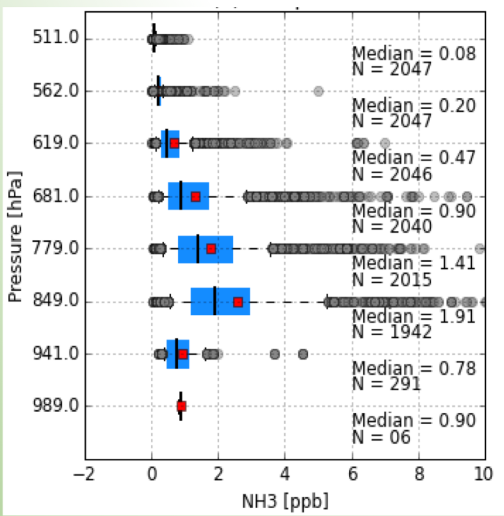
Satellite Validation: Ground-based FTIR profiles

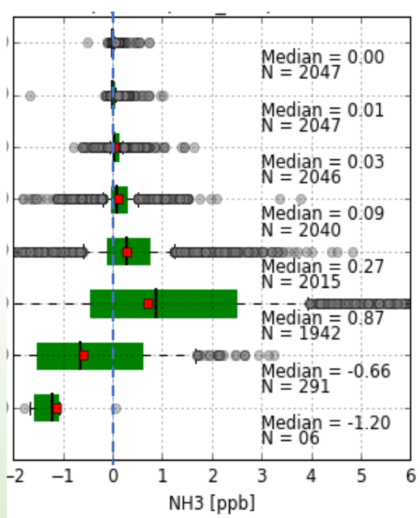
Profile comparisons done by applying the FTIR instrument operator

$$X_{est} = X_a + AVK * (X_{true} - X_a)$$

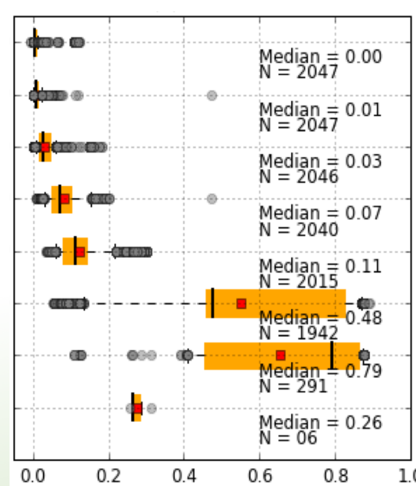
CrIS



CrIS-FTIR



FTIR AVK



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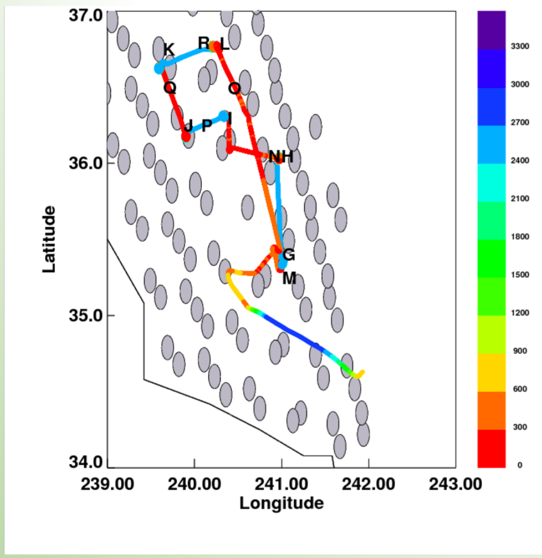
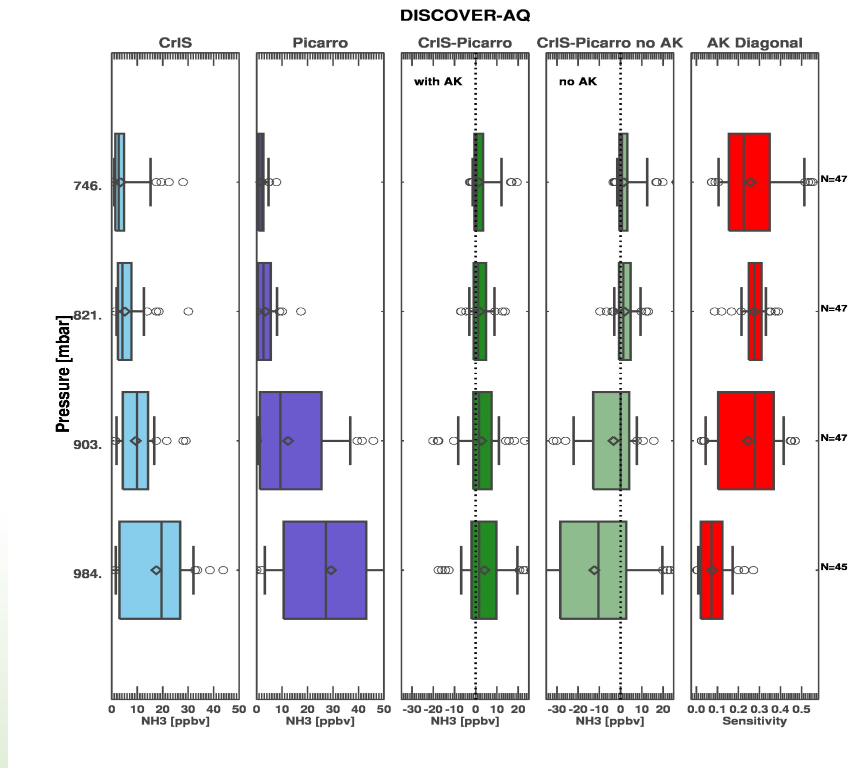
CrIS during DISCOVER-AQ California 2013

What does NOT applying the instrument operator tell you?

Jan 30 NASA P3B flight





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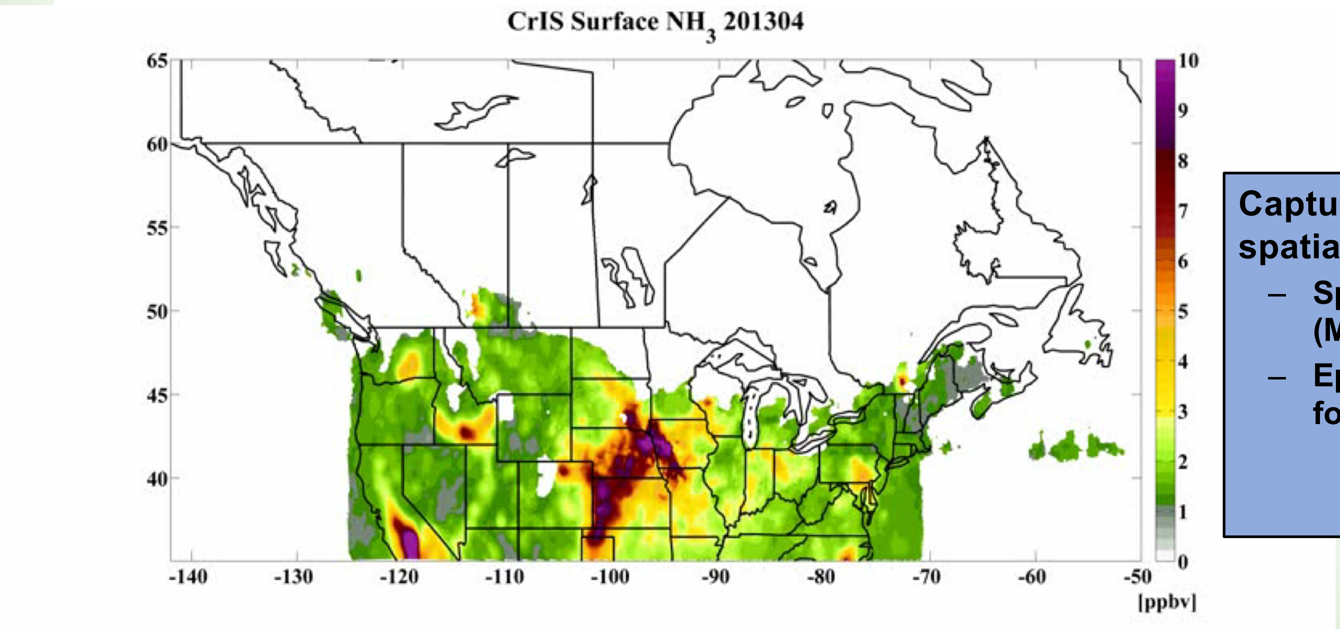
CrIS NH_3 North America
2013 Monthly Averages: April to October



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)**

- **White regions indicative of values near detection limit**
  - **Cold background surface**

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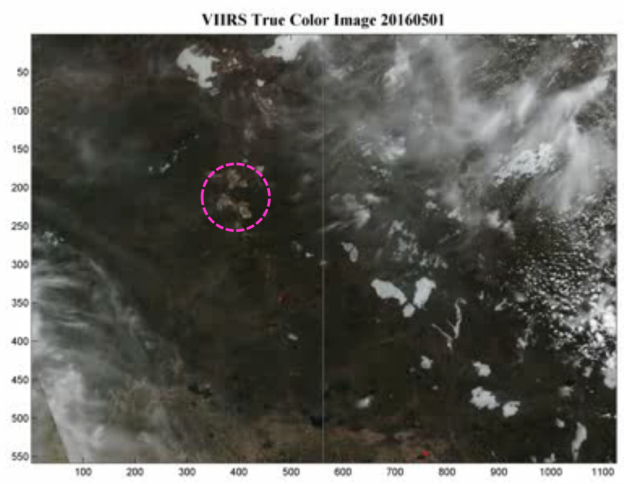
Satellite data over Fort McMurray forest fires: Daily values in May 2016

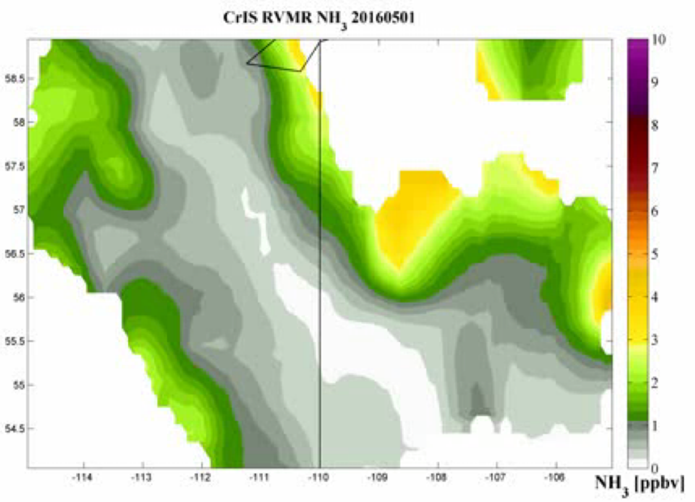
VIIRS

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



CrIS

Infrared: Ammonia (NH_3)



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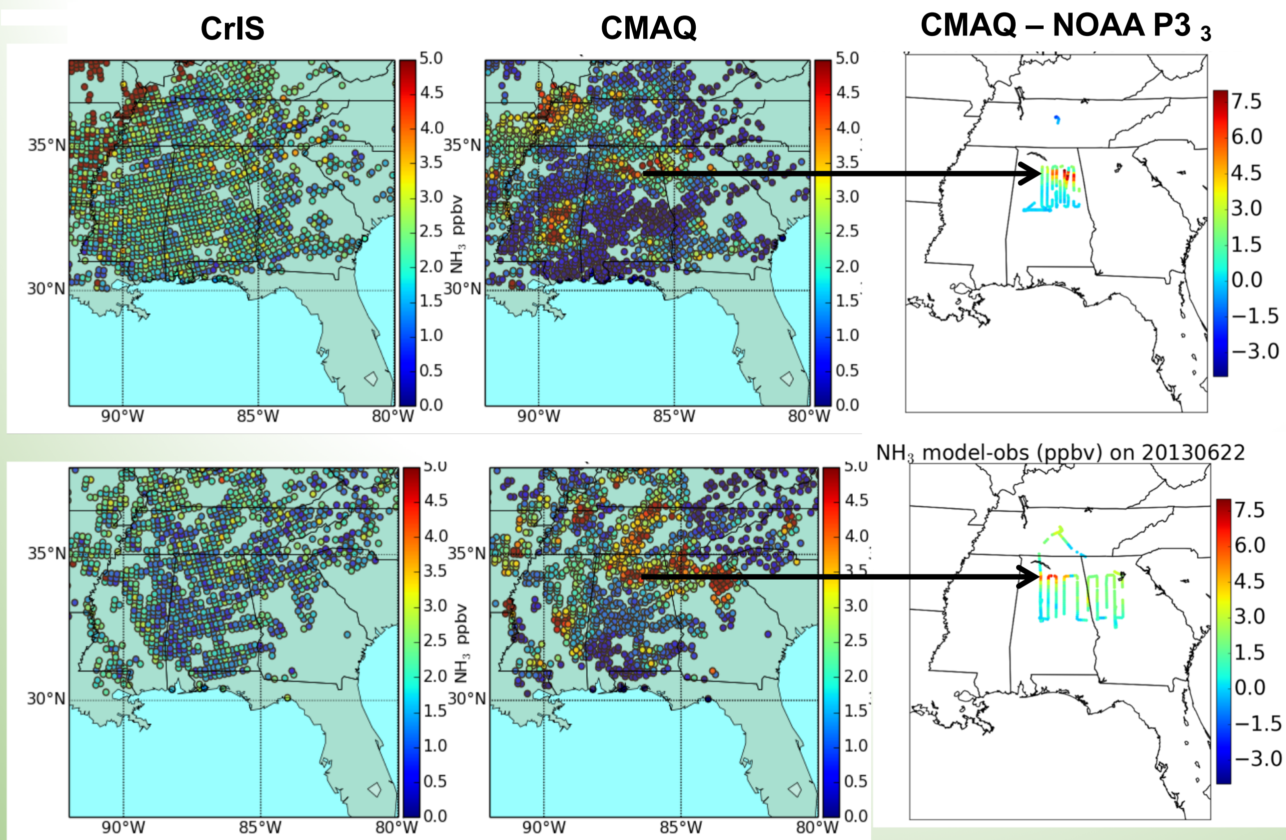
Surface NH_3 during SENEX Campaign



- **CrIS and aircraft data both indicate that CMAQ is overestimating NH3**

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Satellite derived dry deposition flux of nitrogen from ammonia (NH_3)

Applying an approach similar to Caroline Nowlan, Randall Martin, et. al, (2014) used for NO_2 and SO_2

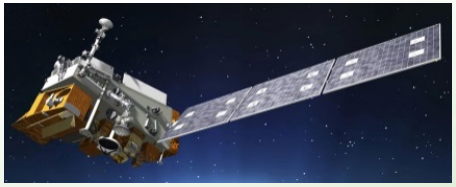
Meteorological Data
(GEM Model)

Deposition Velocity (from Big-Leaf model (BLM); (Leiming Zhang et al., 2003 (ACP))

$$F = -V_d \times C$$

Surface Concentration of NH_3 (from **CrIS Satellite**)

NH_3 Dry Deposition Flux at Surface



CrIS (NASA/NOAA)
(Shephard & Cady-Pereira, 2015 (AMT))

Geophysical Research Letters
AN AGU JOURNAL
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Research Letter

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

Accepted manuscript online: 8 November 2017 Full publication history

DOI: 10.1002/2017GL075832 View/save citation

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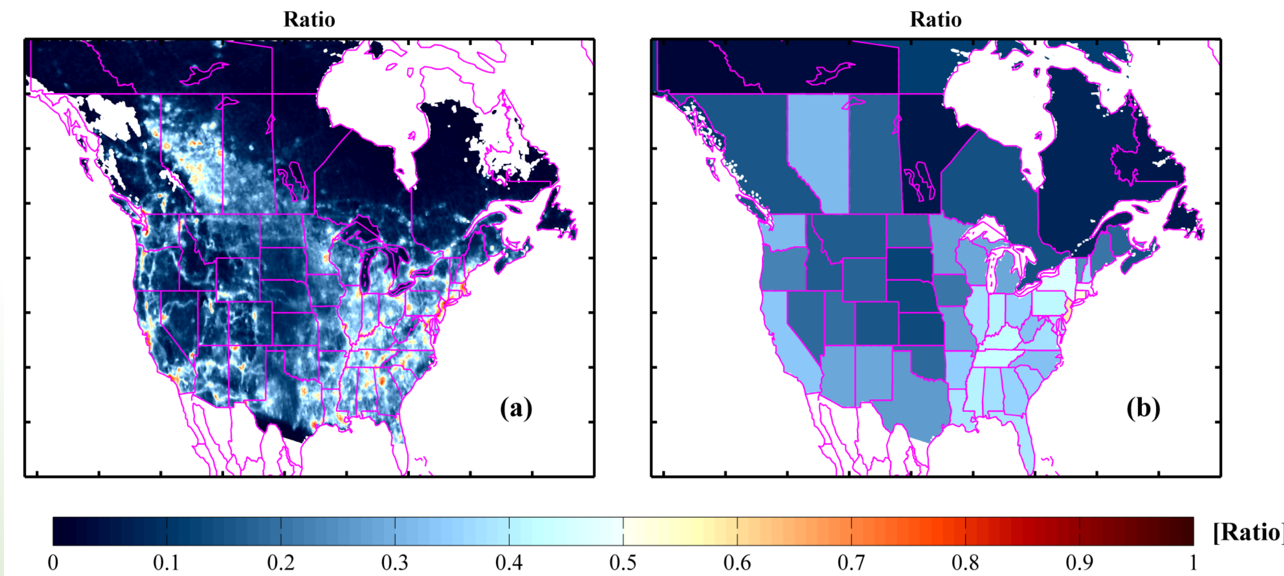
Ratio of Nr dry deposition flux over North America

Ratio = NO_2 Flux / (NO2 + NH3) Flux



Mostly NH_3 **Mostly NO_2**

- NO_2 dry deposition flux hot-spots dominates in urban regions and power plants (e.g. North-East).
- NH_3 dry deposition flux dominates mostly in agricultural and remote regions (e.g. Mid-West)
- Decreasing trends in NO_2 emissions +increasing trends in NH_3 ➡ NH_3 dominates N_r dry deposition over most regions.

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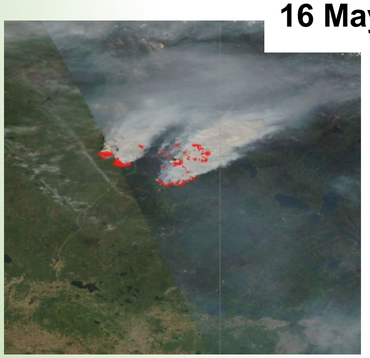
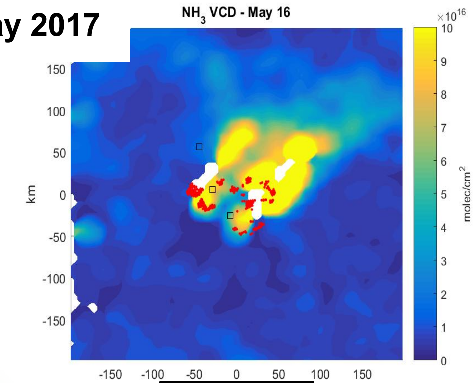
NH_3 Emissions from Wildfires Fort McMurray : May 2016

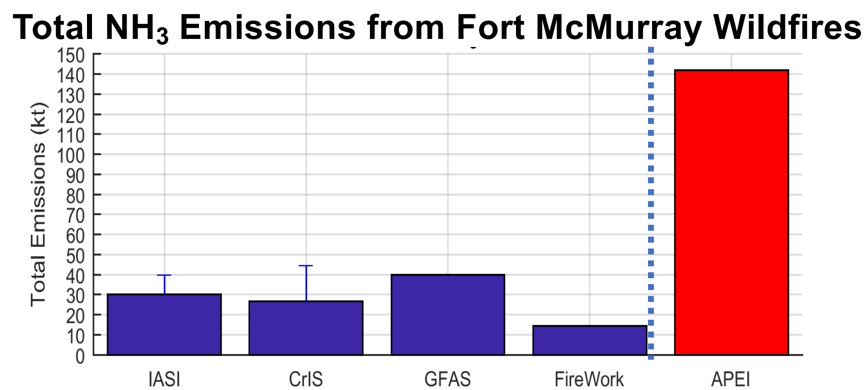
16 May 2017

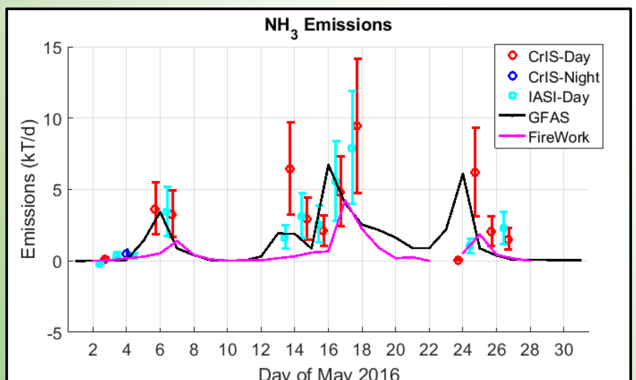


MODIS - Aqua



CrIS – NH_3





$$E = \frac{m}{\tau \cdot \left(1 - e^{-\frac{t_c}{\tau}}\right)}$$

M = mass of NH_3 (from CrIS)

τ = NH_3 lifetime

t_c = time in box = f(wind speed, box size)

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GFAS: Global Fire Assimilation System

Canada's wildfire smoke model

Adams et al., in preparation, 2018

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Operational algorithm currently under implementation at the SNPP SIPS

- **ESSPA software: FORTRAN retrieval code with OSS as forward model**
- **Same a priori profiles/constraints/selection as CFPR**

First guess emissivity from University of Wisconsin database

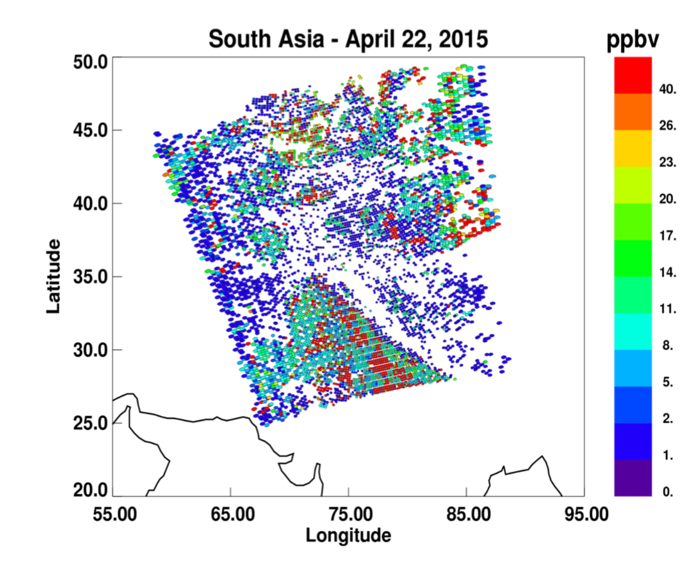
From each observation:
- Radiances
- Noise estimate

Use radiances for
- a priori selection from three possible profiles
- Cloud screening

From previous retrievals (CLIMCAPS):
- Water vapor profiles
- Temperature profiles
- Surface temperature

Optimal estimation first step
- Refinements of
  - Surface temperature
  - Emissivity

Optimal estimation second step
- NH_3 profiles
- Error estimates
- Averaging kernels



For more details see: Shephard M.W. and K. E. Cady-Pereira, AMT, 2015

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Ongoing Work

- Add FOV surface temperature retrieval to ESSPA processing for NH3
- Averaging kernel and error covariance
  - Add output to ESSPA
  - Investigate options for compressed storage
- Validate ESSPA product
  - Against DISCOVER-AQ data in California and Colorado
  - Against fire data from WE_CAN
    - Determine if fire scenes need different a priori
- Use CrIS NH_3 over India and China to better constrain emissions over these regions

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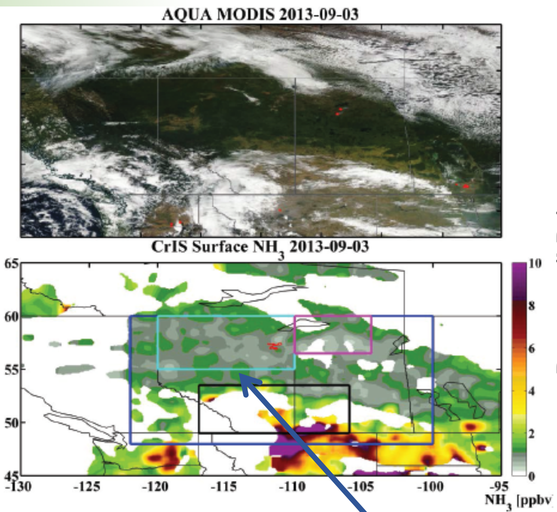
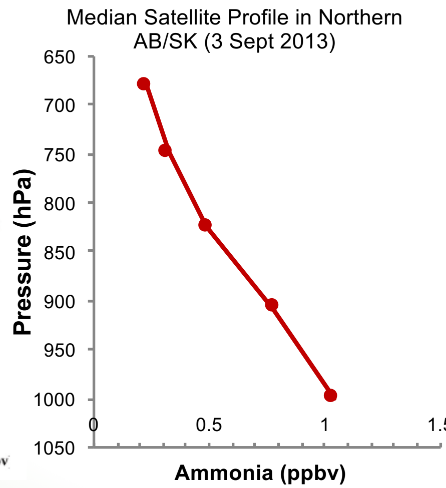
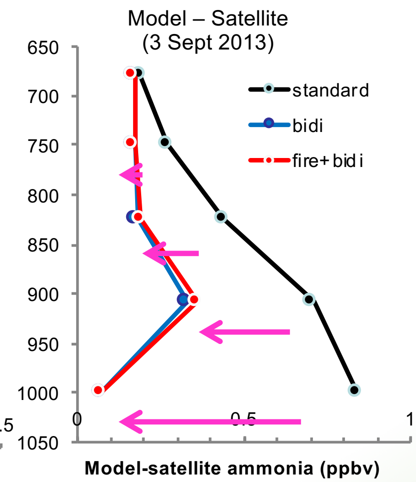
Model Evaluation: Bidi Flux Example – Sep 3, 2013







CrIS observations suggest that the bidirectional flux scheme is working well in northern Alberta and Saskatchewan

Large study region around the oil sands (cyan box):

- **Cloud-free day example: over 800 profiles.**
- **Relatively small influence from forest fires**
- **During intensive field campaign in Aug/Sept 2013**

Whaley et al., Contributions of natural and anthropogenic sources to ambient ammonia in the Athabasca Oil Sands and north-western Canada, Atmos. Chem. Phys., 18, 2011-2034, https://doi.org/10.5194/acp-18-2011-2018, 2018

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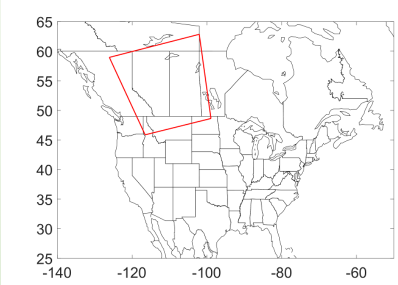
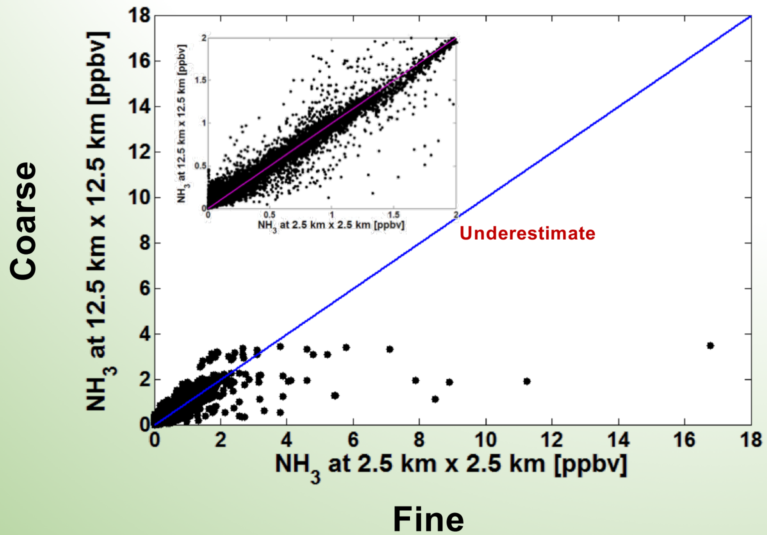
Validation: Point vs Regional Spatial Sampling



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 point observations) measurements will tend to **overestimate small values** and **underestimate larger values** under inhomogenous conditions even if both measurements were perfect.

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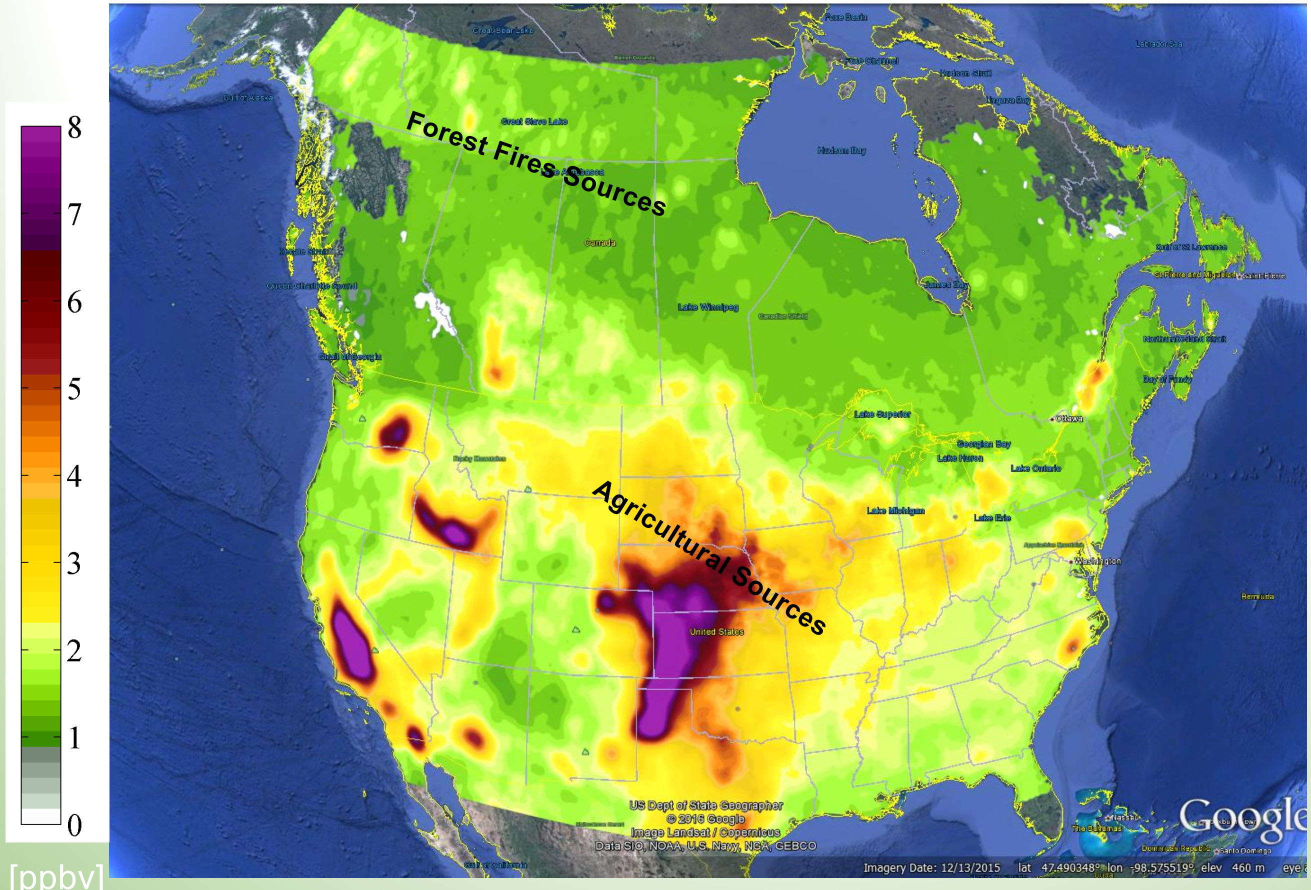
CrIS North America Warm Season Average 2013



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