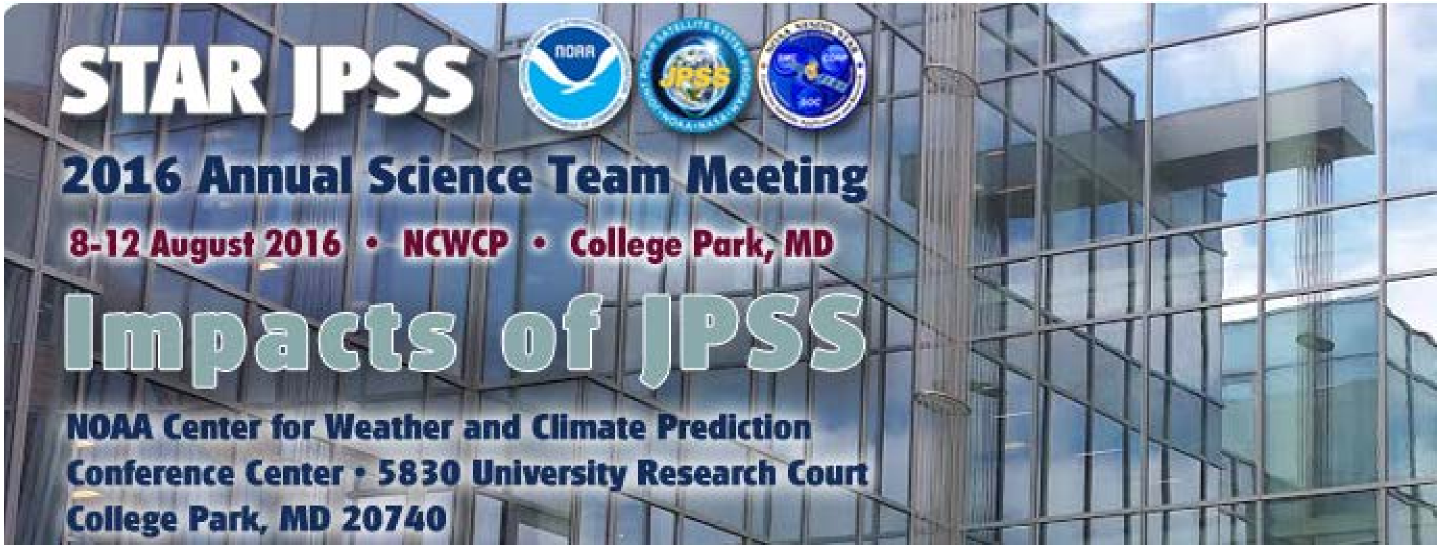


Session 11: Trace Gases
Chairs: Antonia Gambacorta and Monika Kopacz
NCWCP 2552-53

Agenda:

8:30 – 12:10 **NUCAPS**
12:10 – 13:20 Lunch
13:20 – 14:45 **Applications (carbon, methane, HCHO, NO_2)**
14:45 – 15:30 Break (no posters)
15:30 – 17:00 **SO_2 presentations**

AC4 Program and JPSS

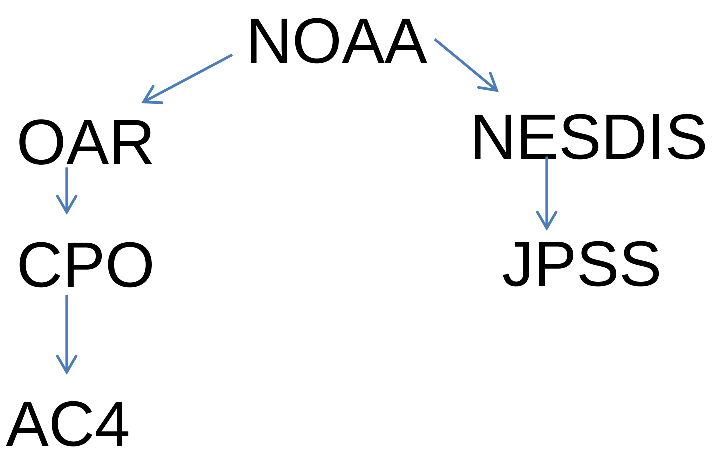
Monika Kopacz, Kenneth Mooney
AC4 Program Managers

August 11, 2016

Atmospheric Chemistry, Carbon Cycle and Climate (AC4) Program

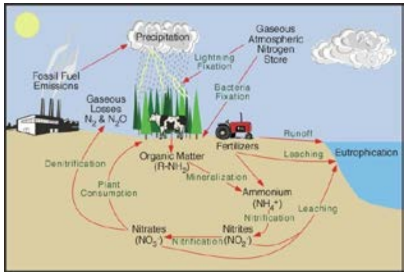
AC4 is a competitive research program which manages a portfolio of multi-year projects

AC4 Goal: Determine the processes governing atmospheric concentrations of greenhouse gases and aerosols in the context of the Earth System and climate



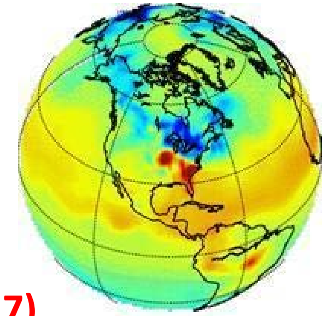
FY13-FY16 Atmospheric Chemistry, Carbon Cycle, and Climate (AC4) Research Portfolio

Nitrogen Cycle (FY13,15)



Atmospheric composition from space (FY16)

CarbonTracker (FY13)



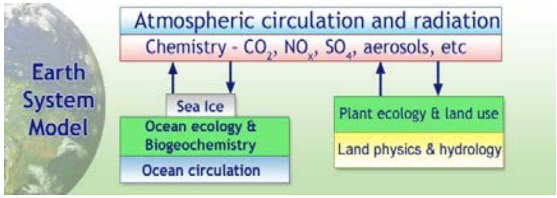
Emissions and Chemistry of Wildfires (FY16-17)

Urban Emissions (FY13,14,17)

Oil & Gas Emissions (FY 14,17)

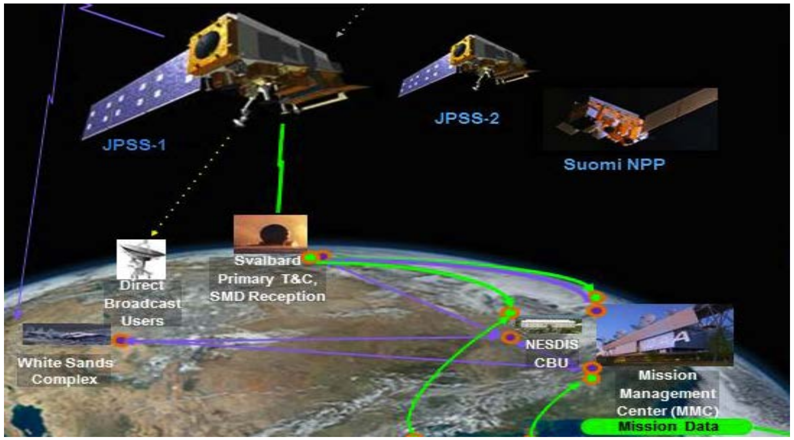
ESRL/CSD, PMEL, ARL Field Campaigns

GFDL Nitrogen Modeling



ESRL/GMD Monitoring

Atmospheric Composition from space

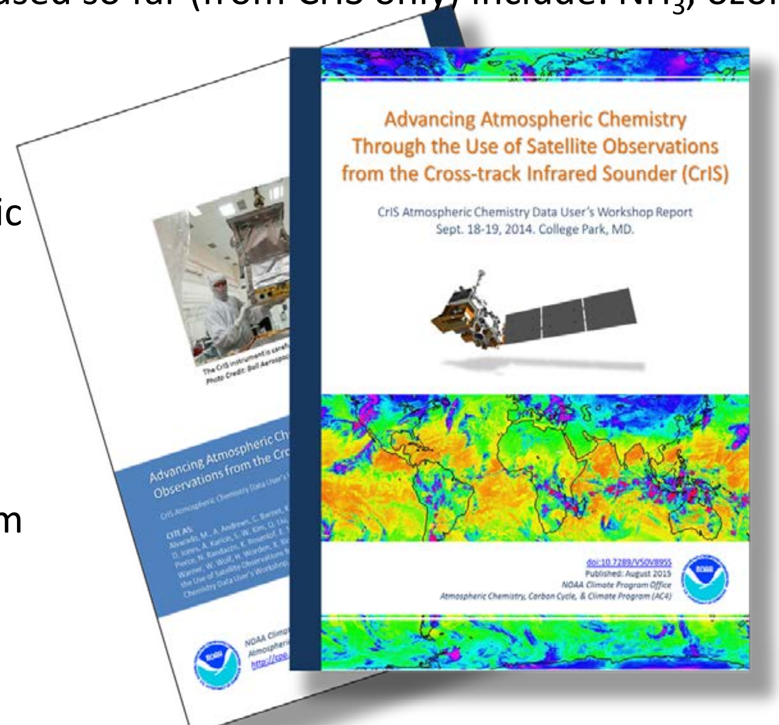


Data from JPSS instruments and AC4 program science:

- AC4 typically supports field and laboratory data, which can be complemented by JPSS data
- CrIS, OMPS and VIIRS composition products (trace gases and aerosols) can all supply relevant products
- Retrievals are used in connection with global and Earth System models
- Data used so far (from CrIS only) include: NH_3, ozone

AC4 current and future activities:

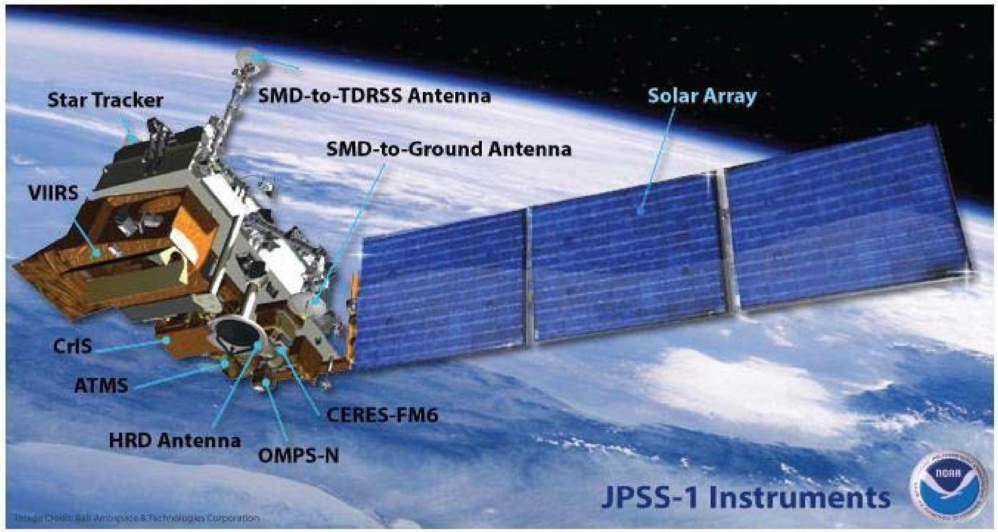
- CrIS data users workshop, focused on atmospheric composition took place September 18-19, 2014; report published August 2015
- Three projects include NH_3 data product development, validation and application
- Upcoming project on CrIS/OMPS ozone retrieval
- Ongoing interest in atmospheric composition from space, with special emphasis on monitoring and field campaign support/complement



Thank you.

ATMOSPHERIC COMPOSITION FROM SPACE

Useful tropospheric observations have been obtained from space since 1999. In 2011, NOAA-NASA partnership resulted in a launch of SNPP satellite, the first in the JPSS series. Aboard SNPP, and later also JPSS-1 and JPSS-2, there are several instruments relevant to atmospheric chemistry: CrIS, VIIRS, ATMS and OMPS. Together, they can provide data on trace gases (e.g. CO, O_3, CH_4, NH_3, CO_2 etc.) and aerosols.



CrIS instrument focus in AC4:

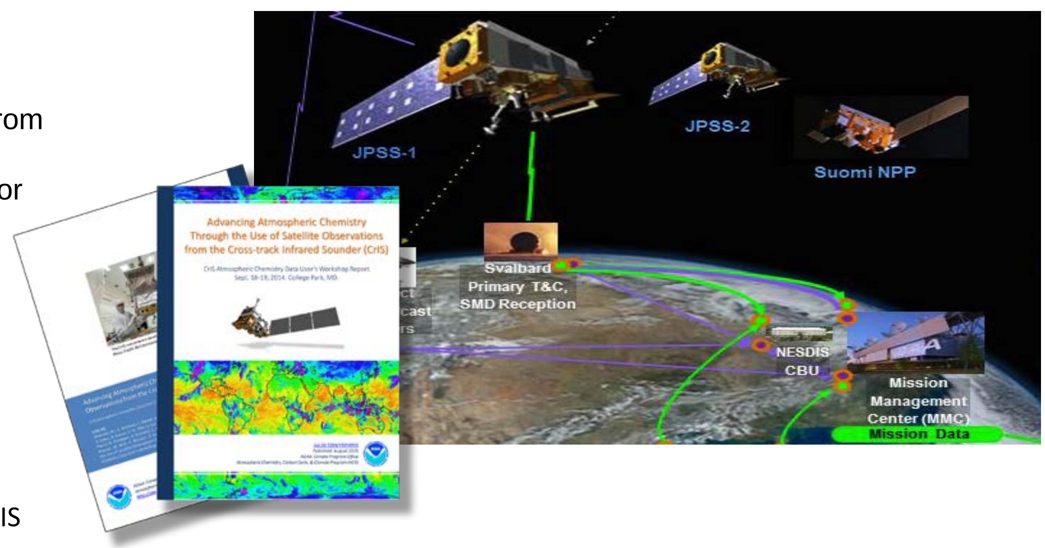
- CrIS is an infrared sounder, similar in observing characteristics to MOPITT, AIRS and TES instruments that have provided data since 1999, 2002 and 2004, respectively
- Mid-tropospheric data from CrIS include: CO, CH_4, O_3, CO_2, NH_3, dust
- Scheduled to be launched on SNPP, JPSS-1 and JPSS-2, CrIS can provide at least 20 years of continuous measurements

NOAA NESDIS activities:

- Development and validation of composition products from CrIS: CO, CO_2 and CH_4 so far
- JPSS call for proposals (LOIs due January 12, 2015) for proving ground included atmospheric chemistry focus

AC4 current and future activities:

- CrIS data users workshop, focused on atmospheric composition took place September 18-19, 2014; report published August 2015
- Two projects funded include NH_3 data product development, validation and application
- Future plans: inclusion in program announcement(s) CrIS data applications



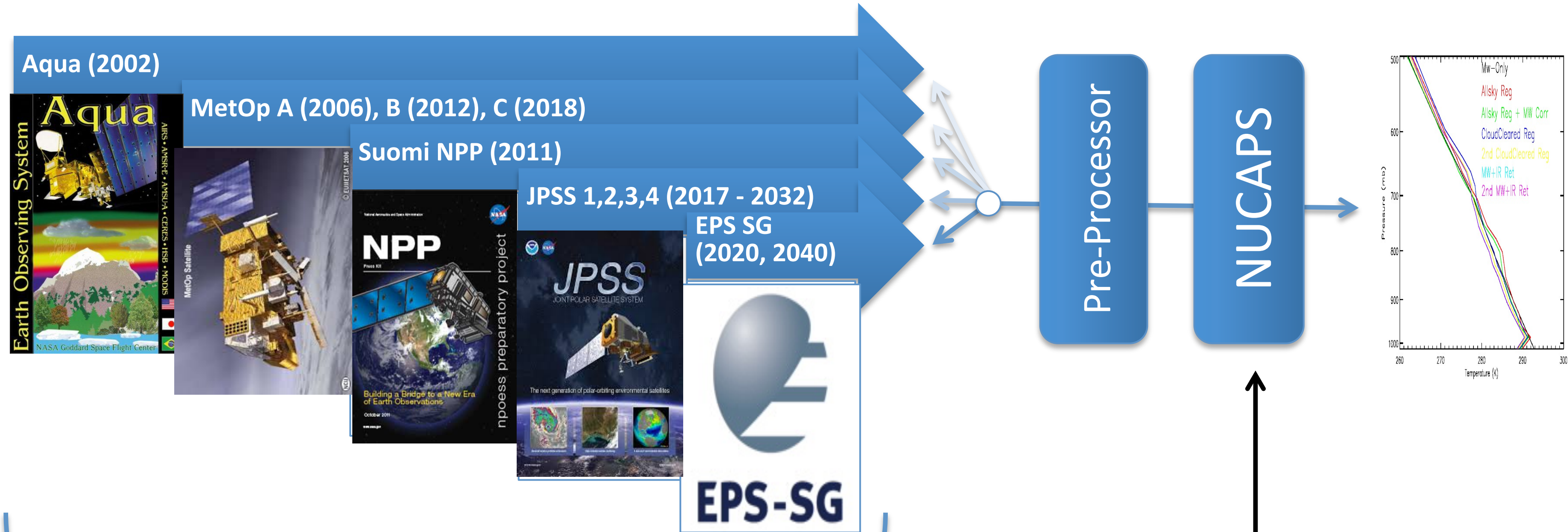
NOAA Long-term Strategy of trace gases from hyper-spectral thermal sounders

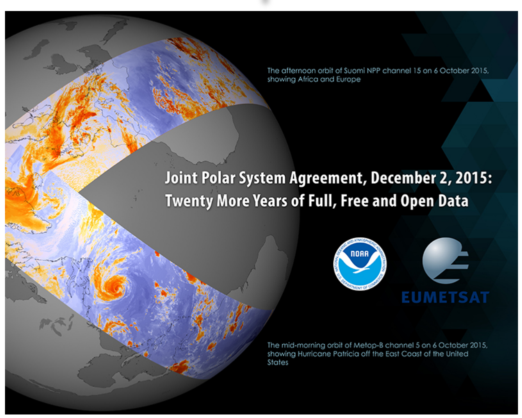
Antonia Gambacorta (1), Chris Barnet (1), Nadia Smith (1), Jonathan Smith (1), Walter Wolf (2), Mark Liu (2), Tony Reale (2), Tom King (2), Michael Wilson (2), Letitia Suillard (2), Nick Nalli (2), Bomin San (2), Kexin Zhang (2), Changyi Tan (2), Flavio Iturbide-Sanchez (2), Xiaozhen Xiong (2), Mitch Goldberg (3)

3rd JPSS Annual Meeting
August 11, 2016

1. Science and Technology Corporation, STC
2. NOAA NESDIS STAR
3. NOAA JPSS Project Scientist

NOAA long-term strategy of trace gases from hyper spectral sounders





The NOAA Unique Combined Atmospheric Processing System (NUCAPS)

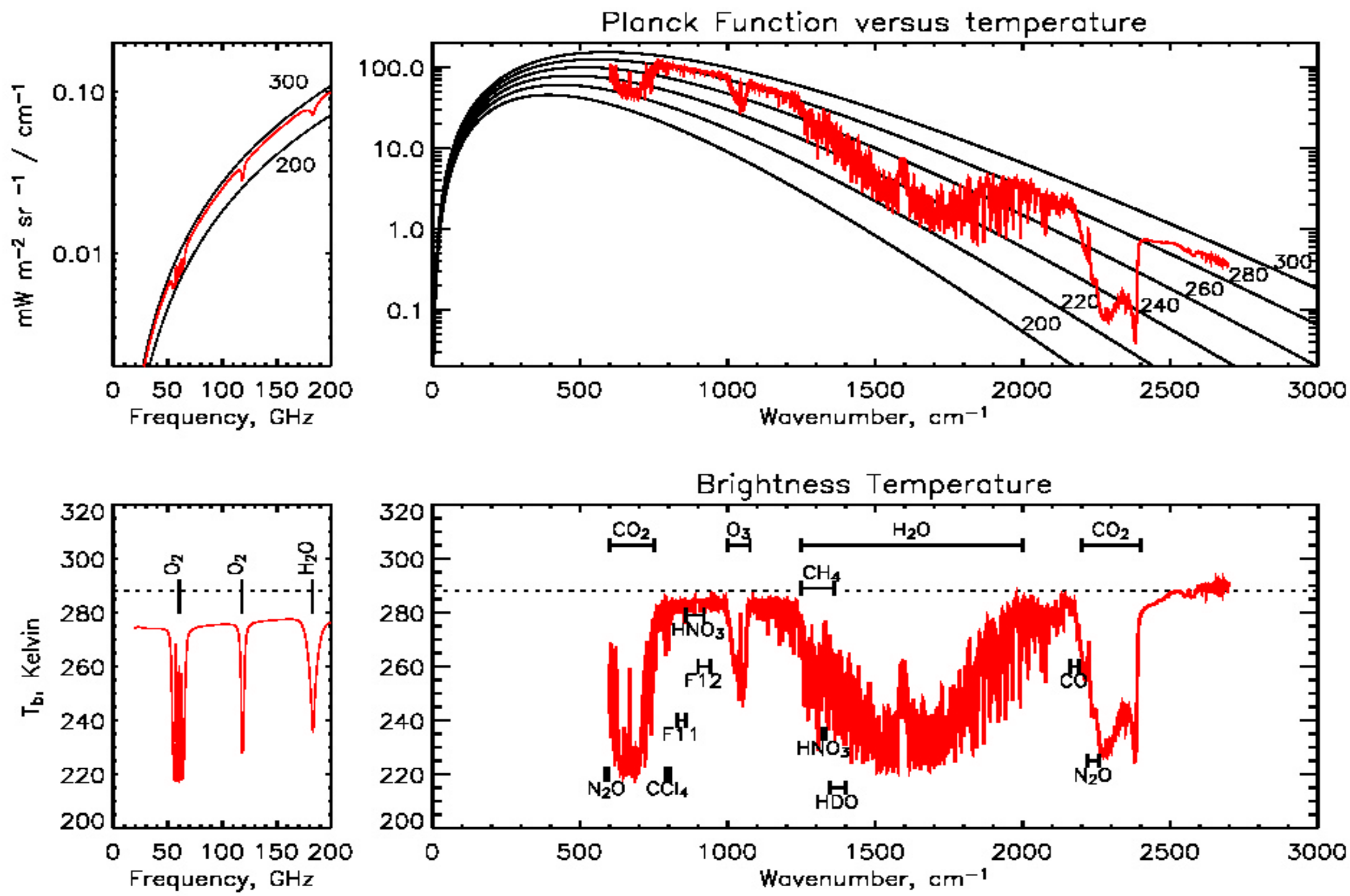
Same exact executable
Same underlying Spectroscopy
Same look up table methodology for all platforms

Philosophy of NUCAPS

- **The challenge**: high computationally efficiency and sophisticated inversion methods to maximize utilization of large volumes of data for real time weather and long-term climate applications

- **Philosophy of NUCAPS**: developing a mathematically sound and globally applicable (land/ocean, day/night, all season, all sky, TOA-surface) retrieval algorithm that can fully exploit all available satellite assets (infrared, microwave, visible) to retrieve the full suite of surface temperature and vertical profiles of temperature, moisture and trace gases. These are among the essential metrics defining a modern, physical and independent data record of atmospheric variables, suitable for both weather and climate applications.

Hyper spectral sounders sensitivity to trace gases



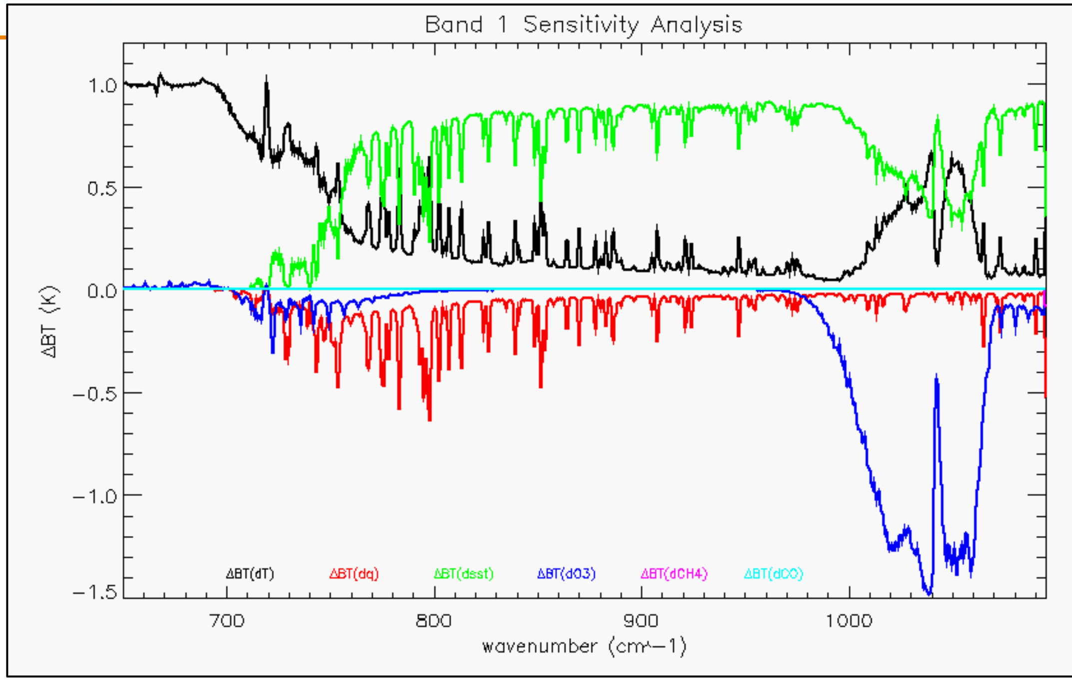
Summary of products from NUCAPS

gas	Range (cm^{-1})	Precision	d.o.f.	Interfering Gases
T	**650-800** **2375-2395**	**1K/km**	**6-10**	**H2O,O3,N2O** **emissivity**
H_2O	**1200-1600**	**15%**	**4-6**	**CH4, HNO3**
O_3	**1025-1050**	**10%**	**1+**	**H2O,emissivity**
CO	**2080-2200**	**15%**	**≈ 1**	**H2O,N2O**
CH_4	**1250-1370**	**1.5%**	**≈ 1**	**H2O,HNO3,N2O**
CO_2	**680-795** **2375-2395**	**0.5%**	**≈ 1**	**H2O,O3** **T(p)**
Volcanic **SO_2**	**1340-1380**	**50% ??**	**< 1**	**H2O,HNO3**
HNO_3	**860-920** **1320-1330**	**50% ??**	**< 1**	**emissivity** **H2O,CH4,N2O**
N_2O	**1250-1315** **2180-2250**	**5% ??**	**< 1**	**H2O** **H2O,CO**
$CFCl_3$ (F11)	**830-860**	**20%**	**-**	**emissivity**
CF_2Cl (F12)	**900-940**	**20%**	**-**	**emissivity**
CCl_4	**790-805**	**50%**	**-**	**emissivity**

The challenge of trace gas retrievals from hyper spectral sounders

- Retrieving trace gases from hyper spectral sounders is a highly non linear and ill-conditioned problem
- Trace gas signals are small and characterized by strong spatial and seasonal variability
- In some cases trace gases are physically correlated with other geophysical variables – for example in respiration of soil CO_2 is correlated with surface temperature; Ts/CH_4; CO/CH_4/O_3;
- Most of geophysical correlations in nature are non-linear.
- With trace gases geophysical *a-priori* information is limited.
- Lack of information content is problematic especially in presence of cloudy, cold, isothermal scenes.
- Trace gases are highly spectrally correlated (CO_2,O_3,H_2O in 15 um band, etc.)
- Errors in spectroscopy and geophysical state.
  - All trace gases dependent on temperature profile.
  - CO_2 and temperature are intimately correlated since CO_2 absorption is used to derive temperature
  - CO_2 can be correlated with clouds both in the retrieval and geophysical sense.
- Stitching satellite instruments together with different
  - Spatial sampling,
  - Spectral sampling, and
  - Noise characteristics
- Ground truth
  - Need full atmospheric state – up to ≥ 30 km.

Spectral Sensitivity Analysis (LW band)



Perturbation Applied

SST	**1K**
T	**1K**
H2O	**10%**
O3	**10%**
CH4	**2%**
CO	**1%**

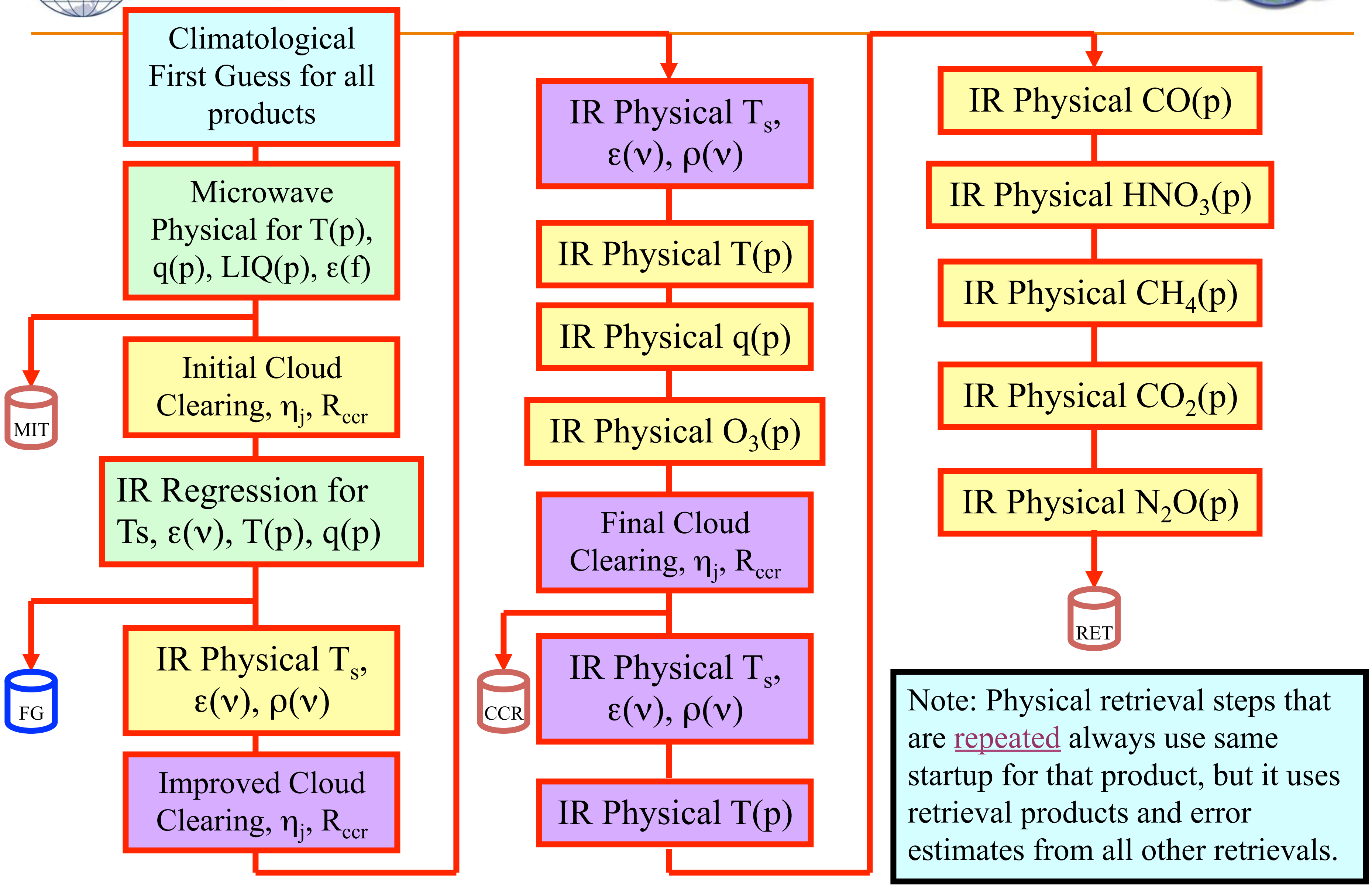
Brightness temperature difference (ΔBT) terms represent the sensitivity of each channel to a given perturbation species and are indicative of the degree of "spectral purity" of each channel.

- For each atmospheric species, we select channels with:
    - the highest degree of spectral purity (the highest sensitivity to the species of interest and the lowest sensitivity to all other interfering species).
    - the lowest noise sources (NEDT, calibration & apodization corr., RTA errors. See ahead.)
    - unique spectral features (to capture atmospheric variability, maximize vertical resolution)

NUCAPS long-term strategy of trace gases from hyper spectral sounders

- A minimum dependence on the geophysical a priori and full exploitation of the measurement and knowledge of the physics of radiative transfer.
  - Channel selection aimed at maximizing spectral purity and information content.
  - Spectral correlation, cloud clearing errors and instrument noise used as terms of the measurement error covariance in a weighted least square minimization
- A sequential approach, solving for most linear (including cloud clearing) or high S/N parameters first and a formal error propagation from one step to the next
- A retrieval is a signal averaging process over many channels and only makes changes where we have information content. Vertical averaging kernels, $A_{j,j}$, define where the instrument has skill.
- Users need to know vertical and spatial error covariance and vertical weighting functions.
  – Many of the "signals" we see have seasonal or spatial variability in the information content.
  – Broad vertical weighting functions tend to mix stratospheric and upper tropospheric contributions together.
    - Trace gas retrievals are sensitive to stratospheric-tropospheric exchange.
- Reprocessing capability to study long-term stability of algorithm.
  – All archived data ("granule" processing)
  – Global "gridded" data sub-sets (for rapid evaluation of algorithm modifications)
  – All validation datasets (including radio-sonde, aircraft match up datasets)

NUCAPS Flow Diagram



The path forward

- We have built a retrieval system aimed at making the best use of hyper spectral data.
- Previous validation efforts have proven that we can meet requirements.
- With temperature and water vapor, users are clearly identifiable.
- What defines the operational need for these trace gas products instead?
  - Just because we can do it, it does not mean that we shall do it.
  - We would like to support any project supported by the NOAA AC4 Program to engage new potential users and gain insights on the applicability of our products. This will ultimately lead to a user requirement to justify the effort of transitioning products into operations.
  - NOAA JPSS is funding an unprecedented list of Proving Ground and Risk Reduction (PGRR) initiatives to demonstrate the operational need of our products. This is not validation in the traditional sense, it is developing new user's applications.
- What defines a trace gas operational user?
  - We need a real time, vetted, institutional user: EPA, National Forest Service, DOA, etc.
  - We need users that need archived consistent products: NUCAPS CO_2 might serve as forecast climatology for the National Weather Service.

Main goal of this session

- This session should discuss what trace gases should be explored in a research sense and what trace gases should be distributed operationally.
- NASA and NOAA have different research mandates, goals and intended users.
  - NASA's focus is primarily on new instrument concepts and fundamental research.
  - NOAA leverages on NASA's research to develop a real time, operational and archival product, intended for specific end users applications of societal benefits.
- We are now looking for those user applications that will (1) verify the applicability of our trace gas products, (2) educate us on the need for new or improved products, QCs and formatting, (3) justify new efforts for algorithm improvements and transition to operations.
- The ultimate result is a continued and intelligent use of hyper-spectral trace gas products, both for real time and long-term applications.

Back Up slides

Why are CO_2 averaging functions broad while T(p) functions have profile information?

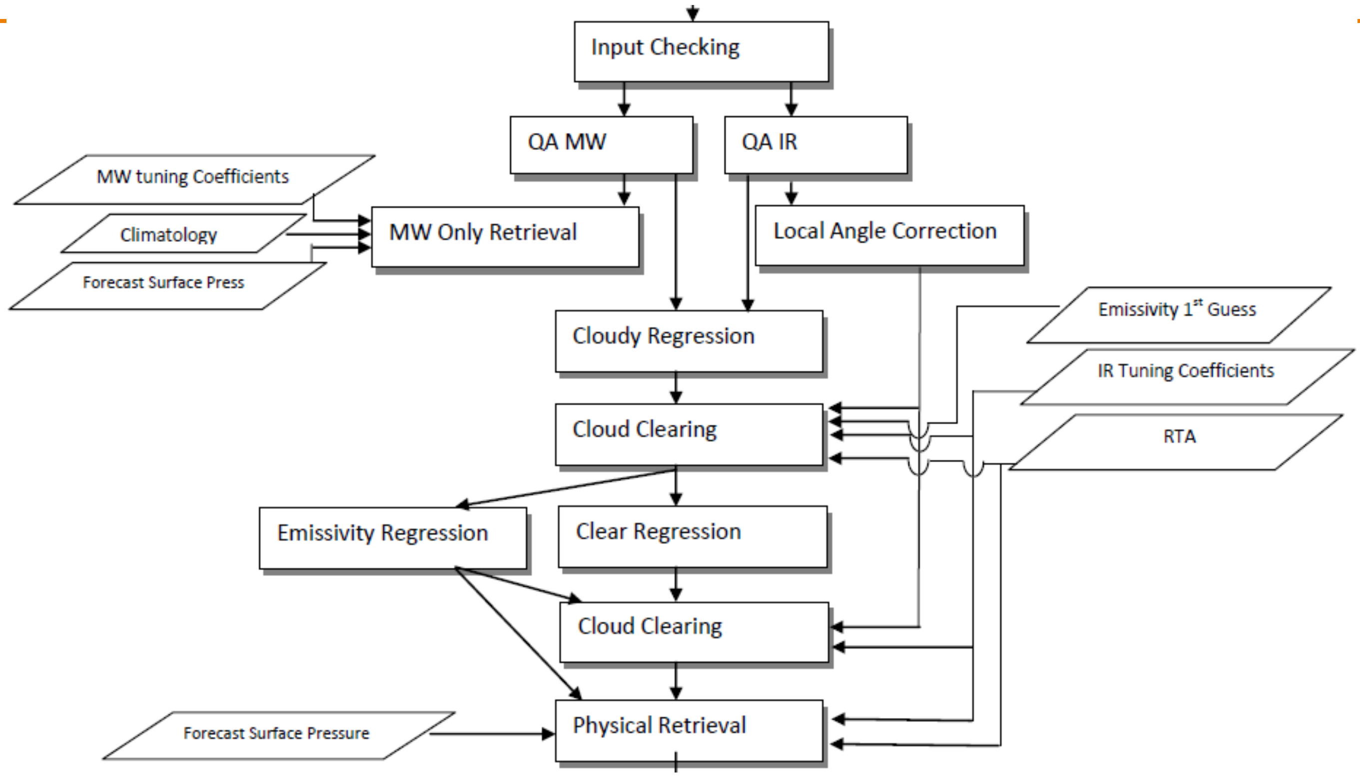
- Spectroscopy: The CO2 lines are strong narrow lines. Temperature affects the width (and hence the channel transmittance) while # of CO2 molecules affects the strength. Once the line is saturated (near the surface, where p is large) we loose sensitivity.

$$\kappa_i(\nu, p, T, \theta) \simeq \sum_{j=1}^{J} \frac{N_i \cdot S_{ij}}{\pi} \frac{\gamma_{ij}}{(\nu - \nu_{ij})^2 + (\gamma_{ij})^2} \cdot \sec(\theta) \qquad \gamma_{ij} \simeq \gamma_{ij}^0 \cdot \frac{p}{P_0} \cdot \sqrt{\frac{T}{T_0}}$$

- Radiative transfer: The temperature enters both in the absorption coefficient and in the Planck function.

$$R_n(\vec{X}) \simeq \int_{\nu} \Phi_n(\nu) \int_{p} B_\nu(T(p)) \cdot \frac{\partial \exp\left(-\int_{z'=\infty}^{z(p)} \sum_i \kappa_i(\vec{X}, p, \ldots) dz'\right)}{\partial p} \cdot dp \cdot d\nu$$

NUCAPS Flow Chart



- **I. A microwave retrieval module** which computes Temperature, water vapor and cloud liquid water (Rosenkranz, 2000)
- **II. A fast eigenvector regression** retrieval that is trained against ECMWF and CrIS all sky radiances which computes temperature and water vapor (Goldberg et al., 2003)
- **III. A cloud clearing module** (Chahine, 1974)
- **IV. A second fast eigenvector regression** retrieval that is trained against ECMWF analysis and CrIS cloud cleared radiances
- **V. The final infrared physical retrieval** based on a regularized iterated least square minimization: temperature, water vapor, trace gases (O3, CO, CH4, CO2, SO2, HNO3, N2O) (Susskind, Barnet, Blaisdell, 2003)

Ammonia (NH_3) Distributions and Recent Trends by 13-year AIRS Measurements

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Y. Wang[4], Q. Liang[5, 6]

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*Published in ACP: **The Global Tropospheric Ammonia Distribution as seen in the 13-year AIRS Measurement Record**

*Ready to Submit: **Increases in Atmospheric Ammonia over Major Agricultural Areas from Space Measurements**

* Funded by NASA's The Science of Terra and Aqua Program (NNX11AG39G), and the Atmospheric Composition Program (NNX07AM45G).

Why Ammonia

- Ammonia (NH_3) plays an increasingly important role in the global biogeochemical cycle of reactive nitrogen as well as in aerosol formation and climate.

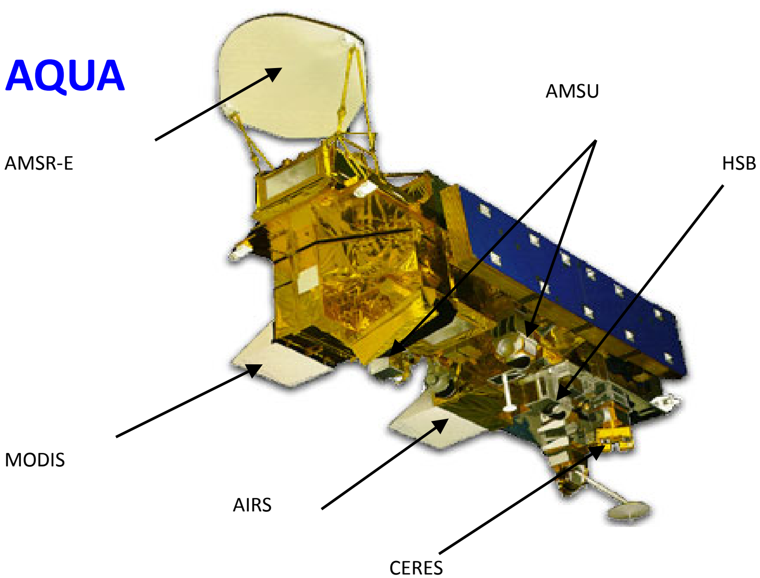
- Measurements with daily and large global coverage are challenging and have been lacking partly because the lifetime of NH_3 is relatively short and partly because it requires high sensitivity for the retrievals that can be only obtained from areas with high thermal contrasts near the surface (Clarisse *et al.*, 2010).

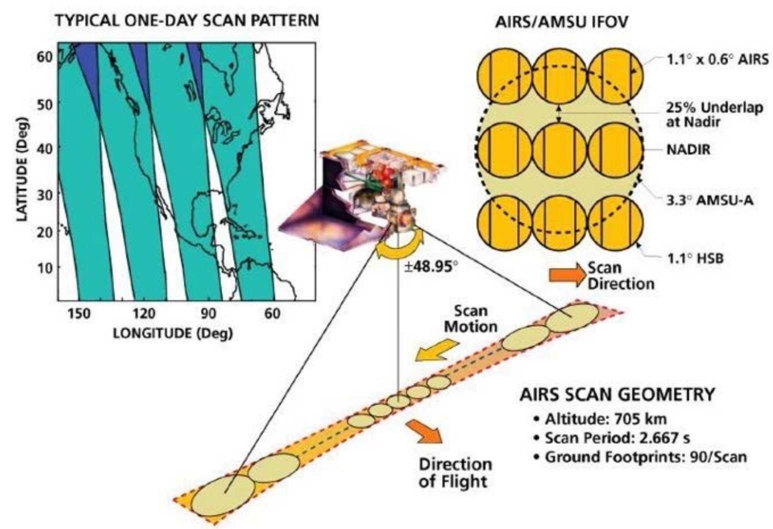
- AIRS afternoon overpasses (1:30pm) are best correlated with the daily emission peak time and during the daily period with the highest thermal contrast. Additionally, AIRS large coverage with wide swaths and cloud-clearing provide daily NH_3 maps. The 13-year data records makes AIRS the best sensor for NH_3 trends and variability studies (to date).

Atmospheric Infrared Sounder

Launched May 2002

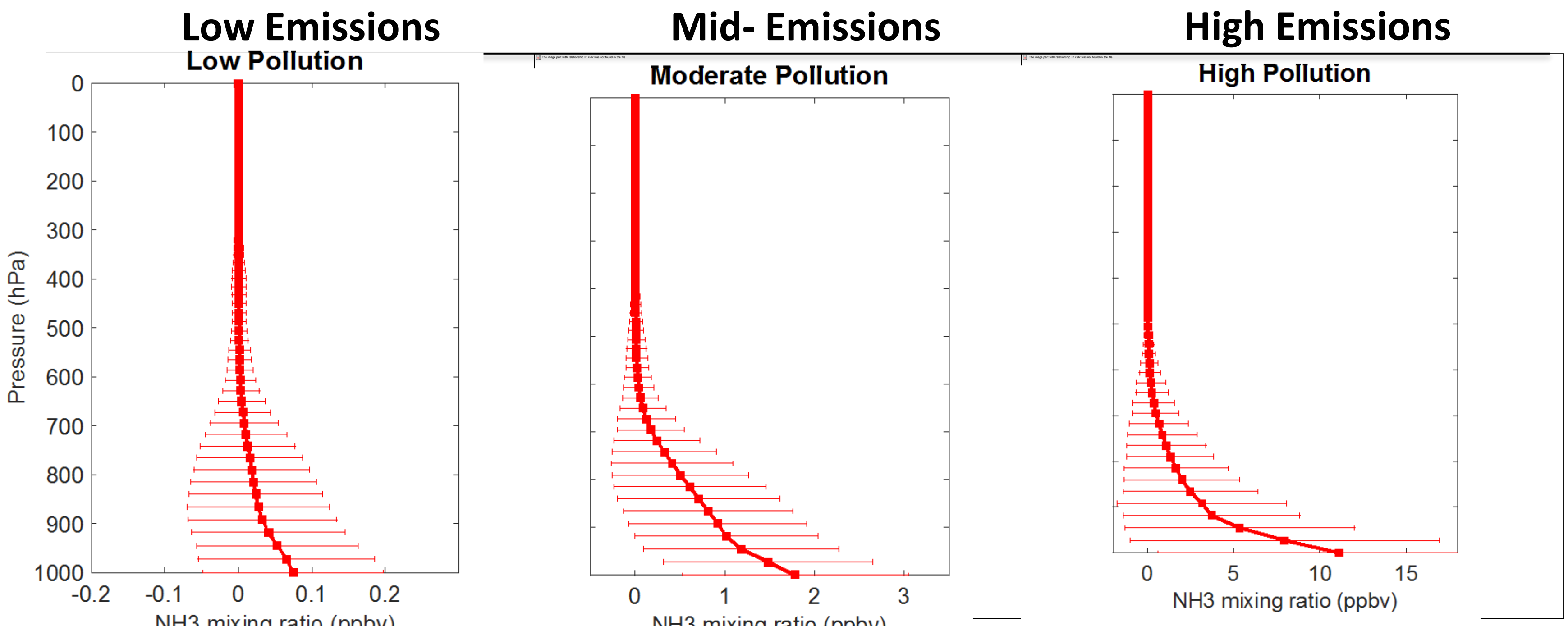
- A grating spectrometer originally designed to improve weather forecast and now also used for climate and air quality studies.
- Spectral resolution at □1200 (~ 0.5 cm^{-1})
- Covers 650-2665 in three bands with a total of 2378 channels
- Spatial resolution 13.5 km^2 (with retrievals at ~45 km^2)
- Wide swaths and cloud clearing provide daily global coverage
- Very high Signal-to-Noise accuracies of 1K over 1 km-layer.





AIRS NH_3 Algorithm

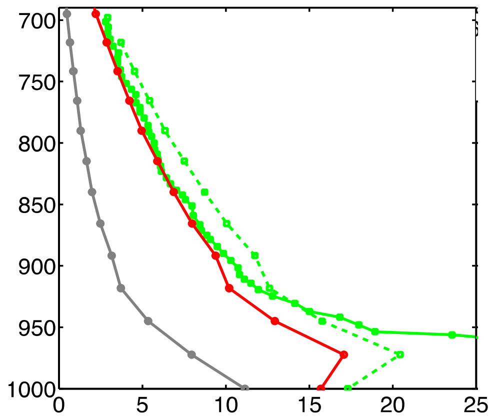
- AIRS NH3 retrievals use Optimal Estimation (OE) technique (Rodgers, 2000);
- CCRs and SARTA are used as in AIRS algorithm for other species;
- The *a priori* levels are computed from GEOS-chem;
- Globally one set *a priori*.
- Select *a priori* levels based on brightness temperature differences weighted by noise (dbti);



Validation vs CRDS/Picarro in DISCOVER-AQ CA

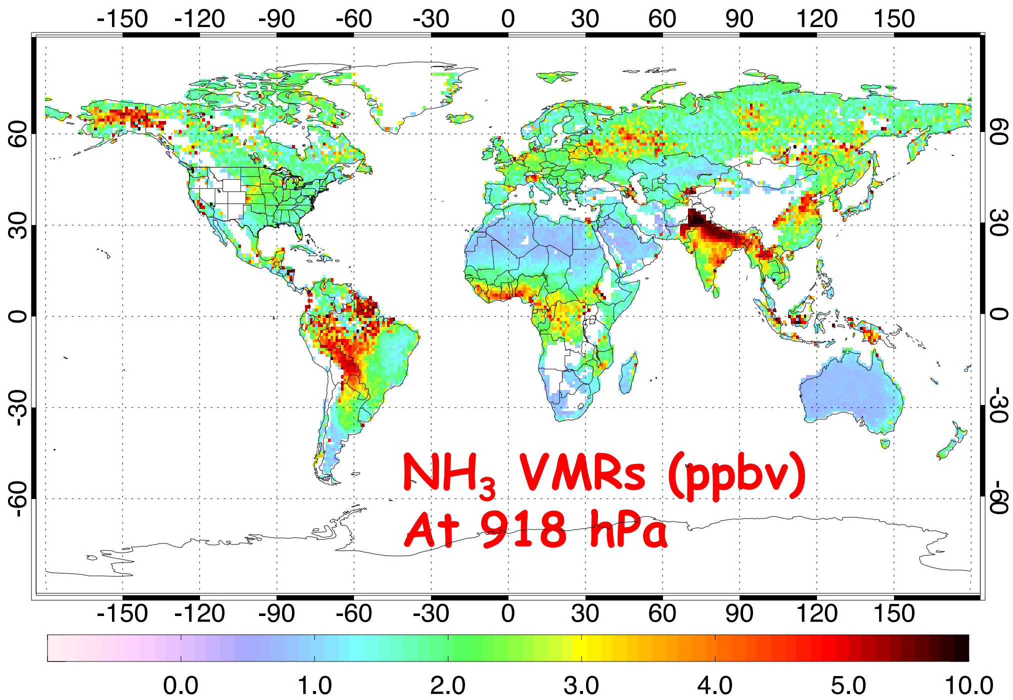
Spiral Profiles Only - 01/16 to 02/06, 2013

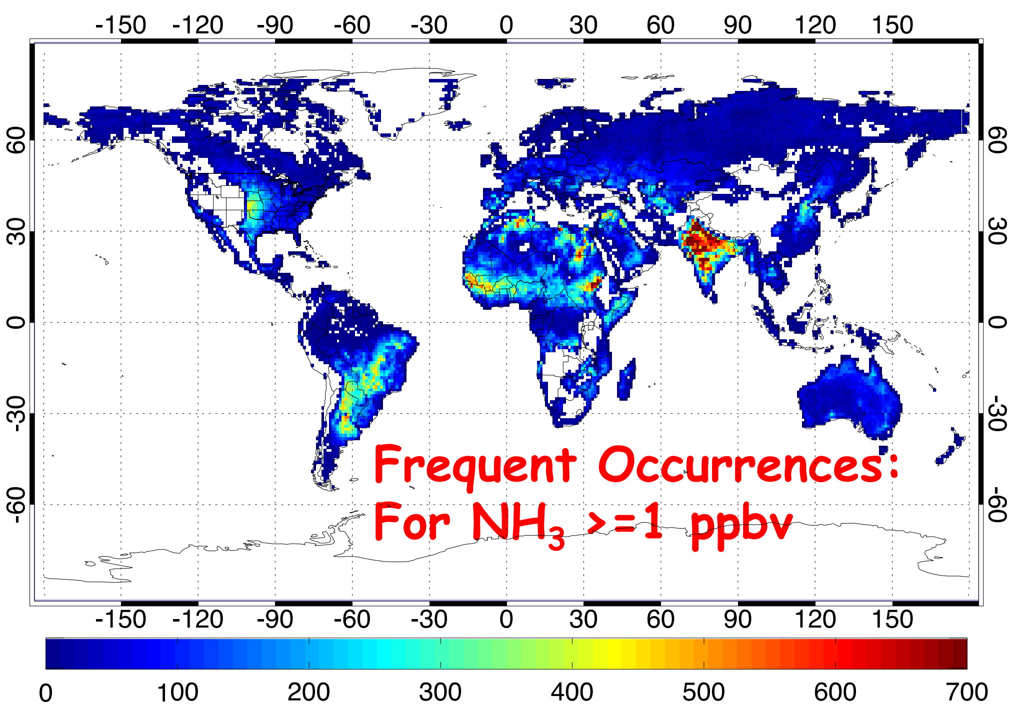
CRDS/Picarro data courtesy of Co-author J. Nowak



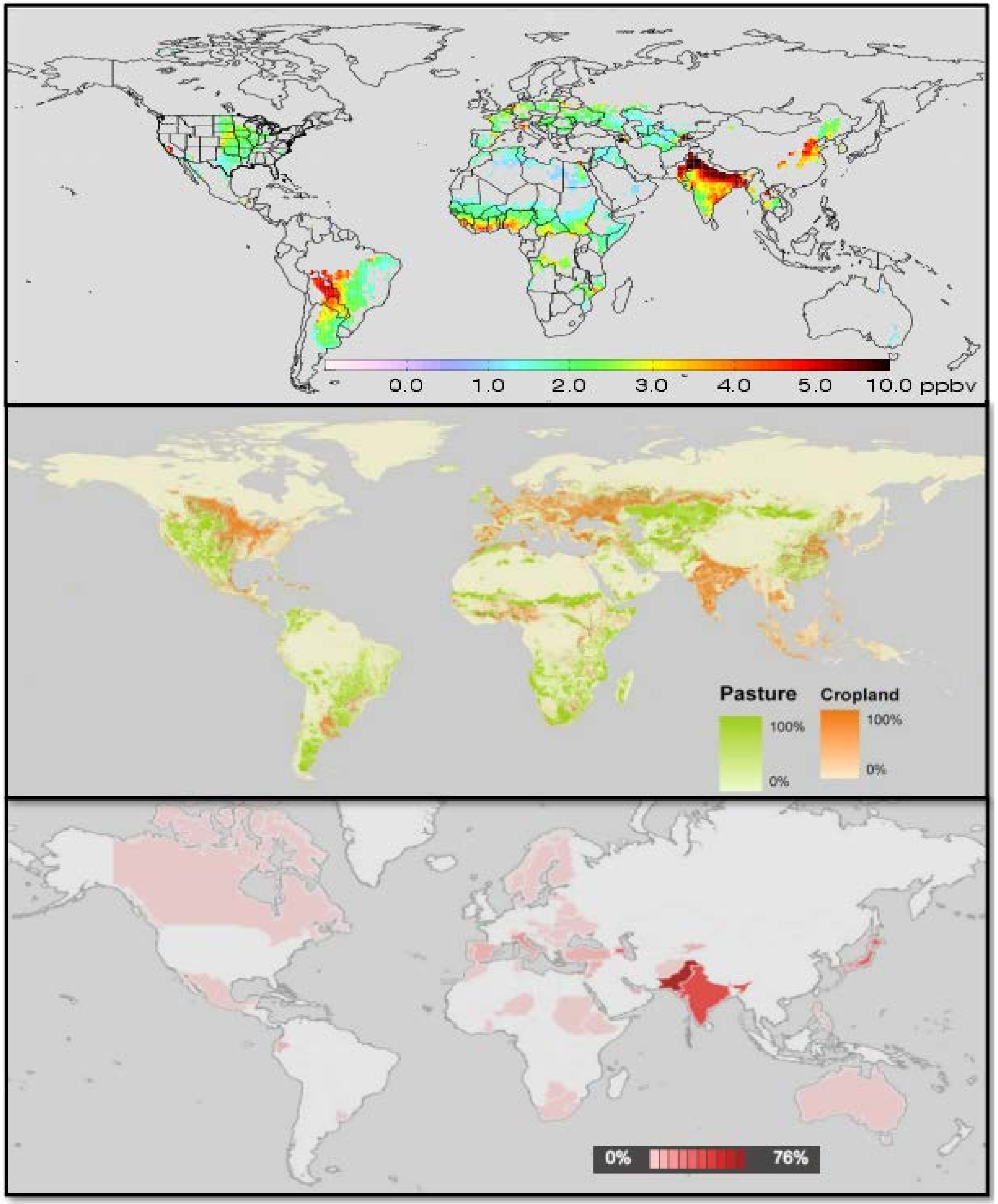
- Gray – a priori; Red – retrievals; Green solid – in situ; and Green dashed – convolved in situ.
- AIRS L2 pixel sizes are ~45 km^2, can coincide with multiple in situ profiles.
- AIRS NH_3 measurements are most sensitive at 850-950 hPa layer.

Global NH_3 in 2002-2015





- AIRS NH_3 at 918 hPa for daytime and land only averaged over Sept. 2002 to Aug. 2015;
- Use Q0; DOFS ≥ 0.1;
- High concentrations are mainly due to human activities and fires;
- Use occurrences of higher emissions (lower) to distinguish between the two major sources: agricultural (high VMRs & high frequencies); BB emissions (high VMRs & low frequencies);
- Sources are seen in valleys (e.g., San Joaquin Valley, California in the U.S., the Po Valley, Italy, Fergana Valley, Uzbekistan, and the Sichuan Basin in China); Agricultural especially in irrigated lands (e.g., Azerbaijan, Nile Delta and near Nile River in Egypt, the Mid-West U.S., in the Netherlands, in Mozambique and Ethiopia, Africa, and especially the Indo-Gangetic Plain of South Asia).

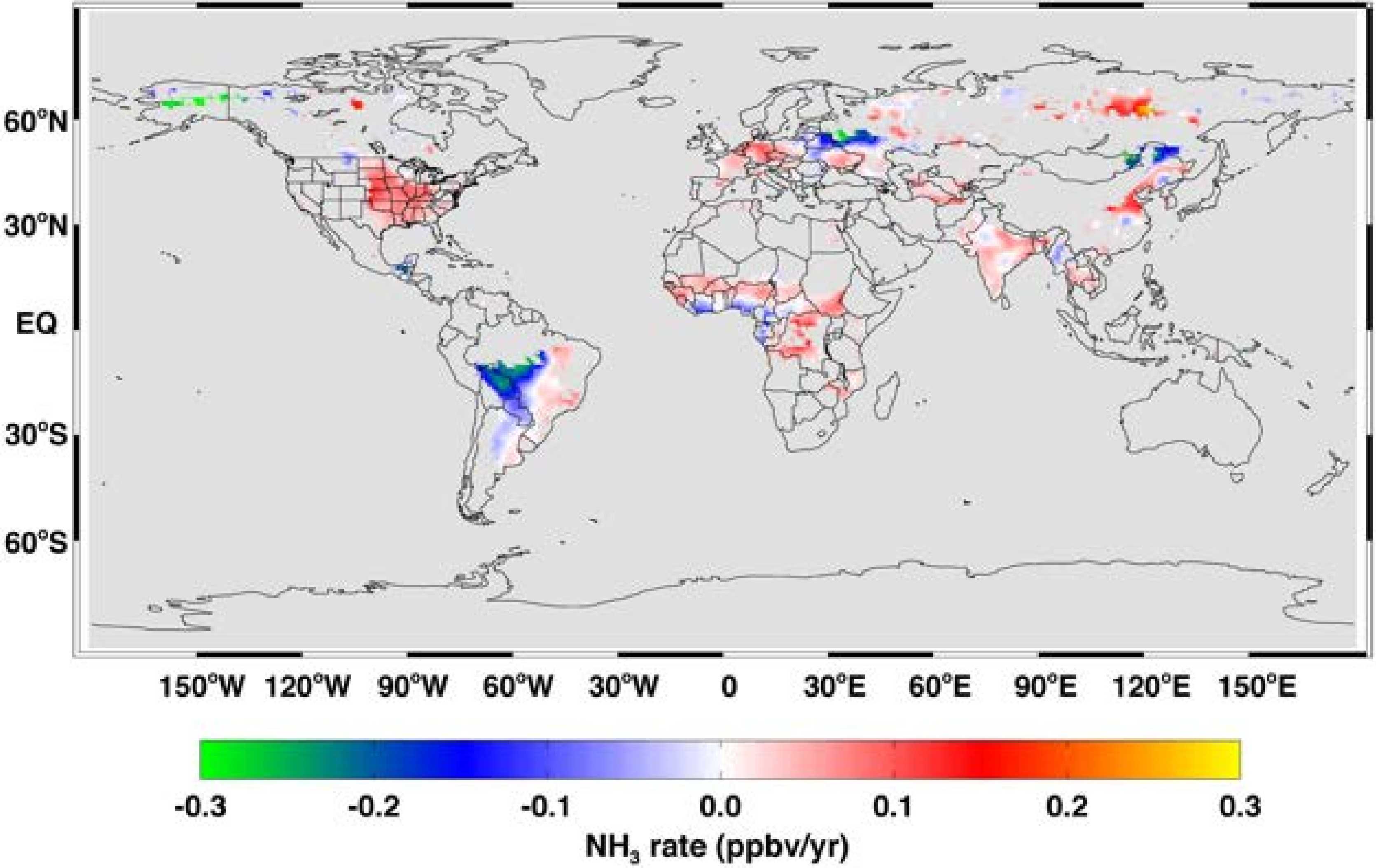


Top panel: The NH_3 VMRs from the persistent sources filtered with the collocated occurrences of elevated emissions (≥ 1.4 ppbv) using a threshold of 40 days;

Middle panel: Pasture and Cropland Map

<u>Bottom panel: </u>irrigated agricultural land areas.

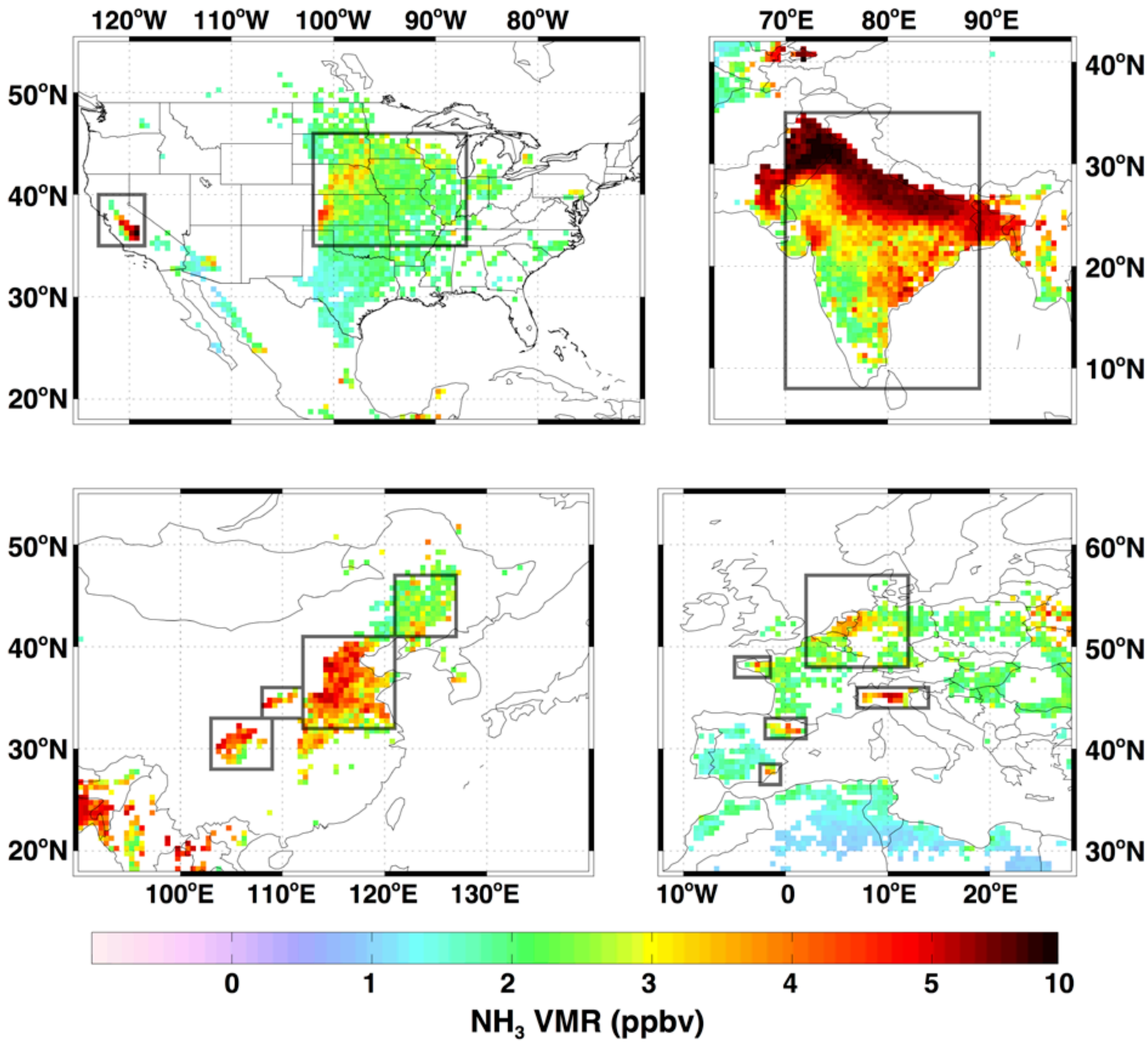
NH_3 Trends - Last 13 years



- Concentrations of anthropogenic emissions increased and BB decreased
- Trends due to BB are not conclusive due to the short record.

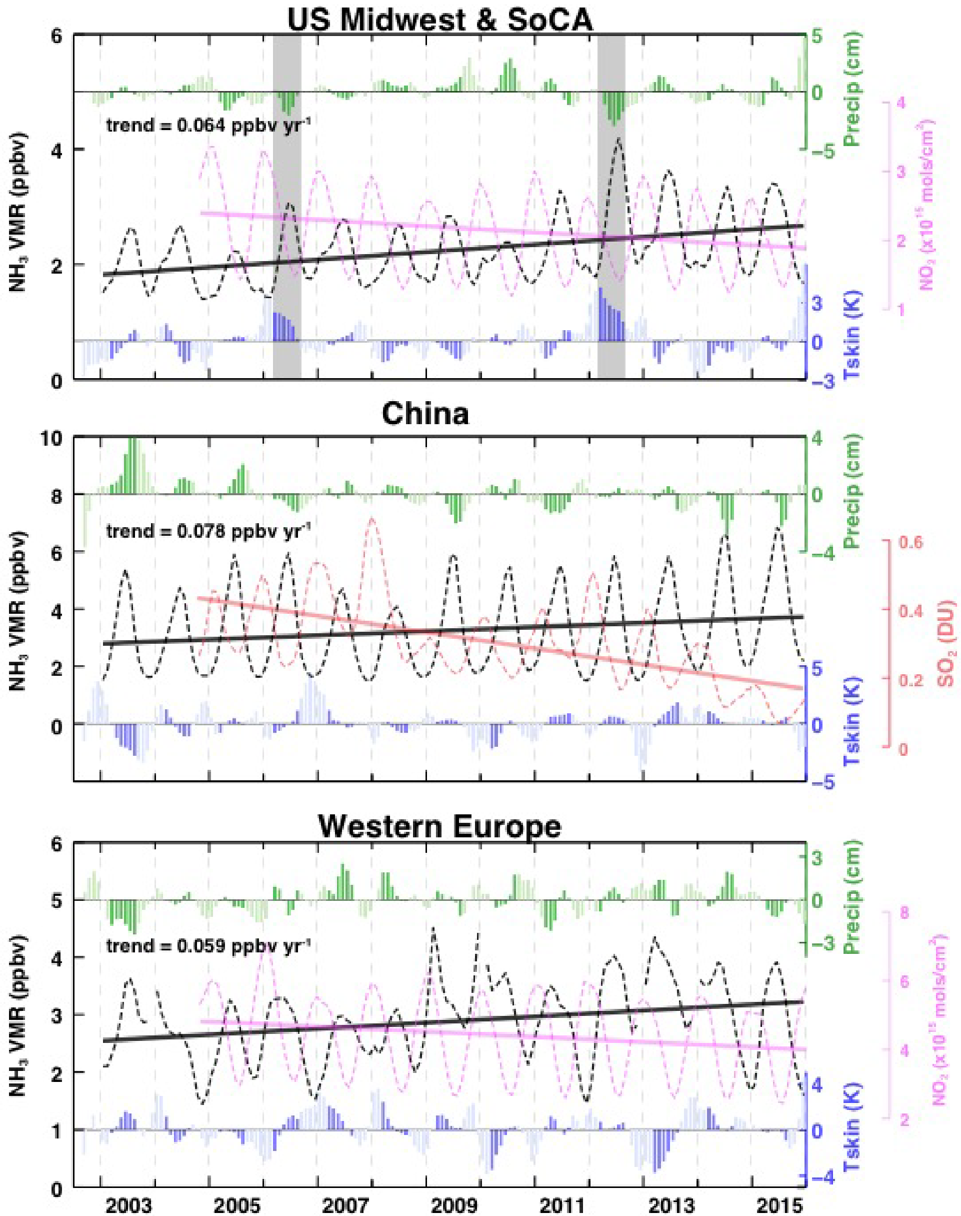
NH_3 over USA, China, India, and Europe

Using high concentration and high frequencies



Black boxes are regions used for follow up trend studies.

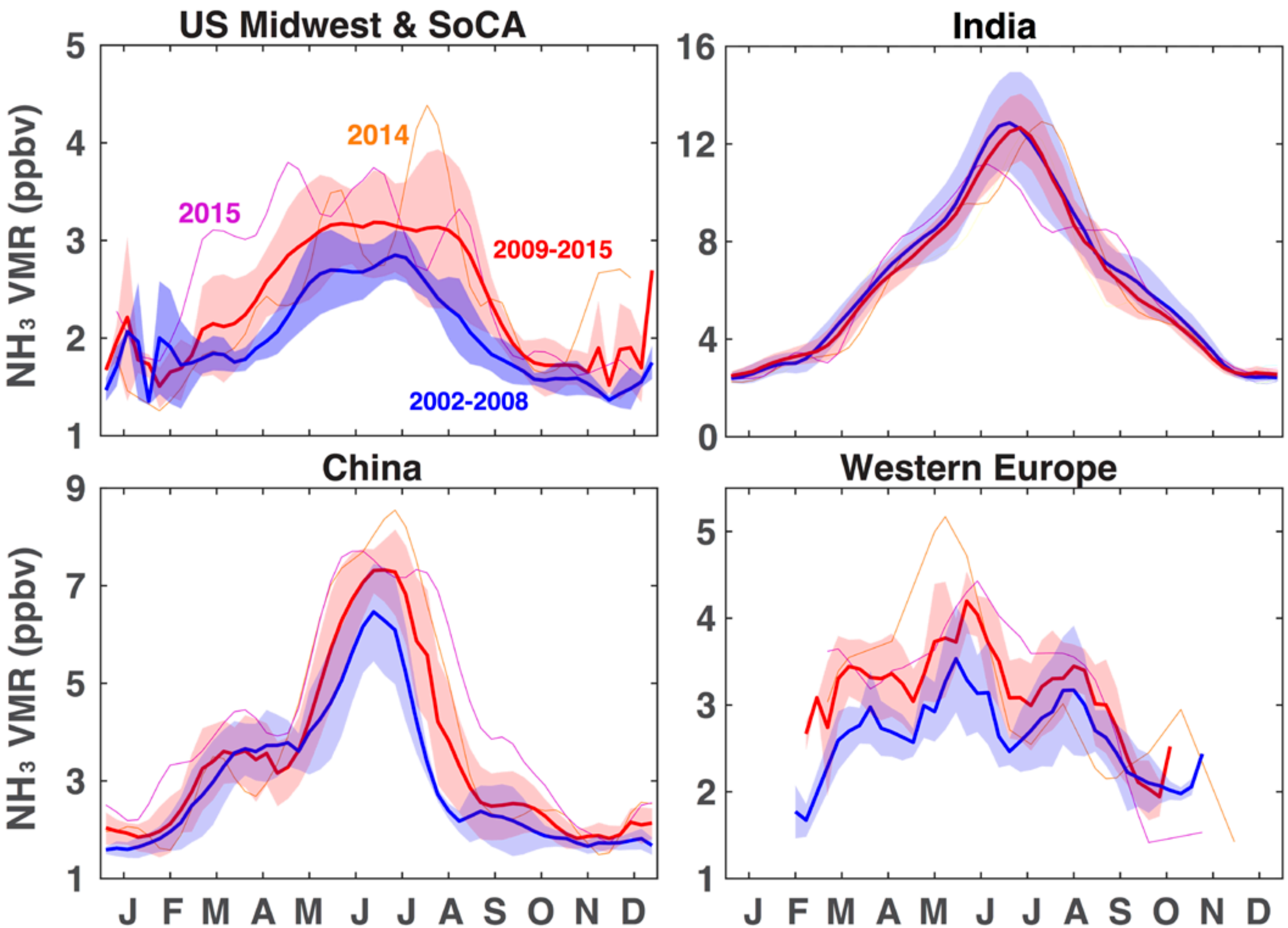
AIRS NH_3 vs OMI NO_2 for US (top), SO_2 for China (middle) and NO_2 for Western Europe (lower)



- All 3 regions show increasing NH_3 trends in the last 13 years, in black.
- Decreased SO_2 from OMI largely explains the reason of NH_3 increases in Midwest U.S. (not shown), China, and Europe (not shown).
- OMI NO_2 decreasing explains winter NH_3 increasing over the US and Europe.
- Meteorological conditions also affect NH_3 concentrations (high surface temperatures and low precipitation), see top panel shaded areas.

AIRS NH_3 Seasonal Variation

- over USA, China, Europe, and India

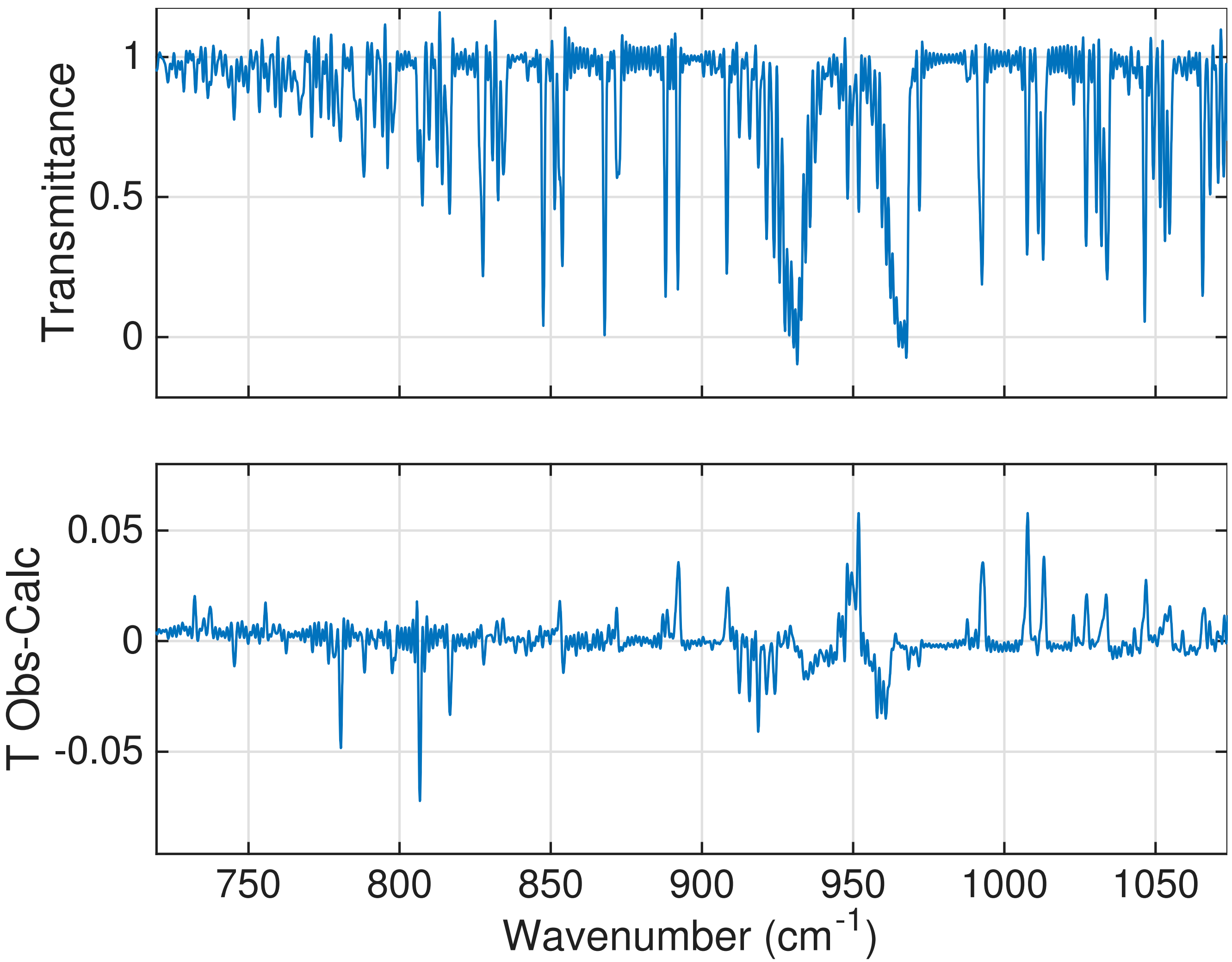


- The highest NH_3 concentrations in average occur in India/Pakistan, and China. Note scales.
- NH_3 in India seasonal variation are broad and no obvious increasing/decreasing trends;
- NH_3 for USA, China and Europe have increased, with peaks in both spring and summer;
- Clear increasing trends over US Midwest, China, and Western Europe.

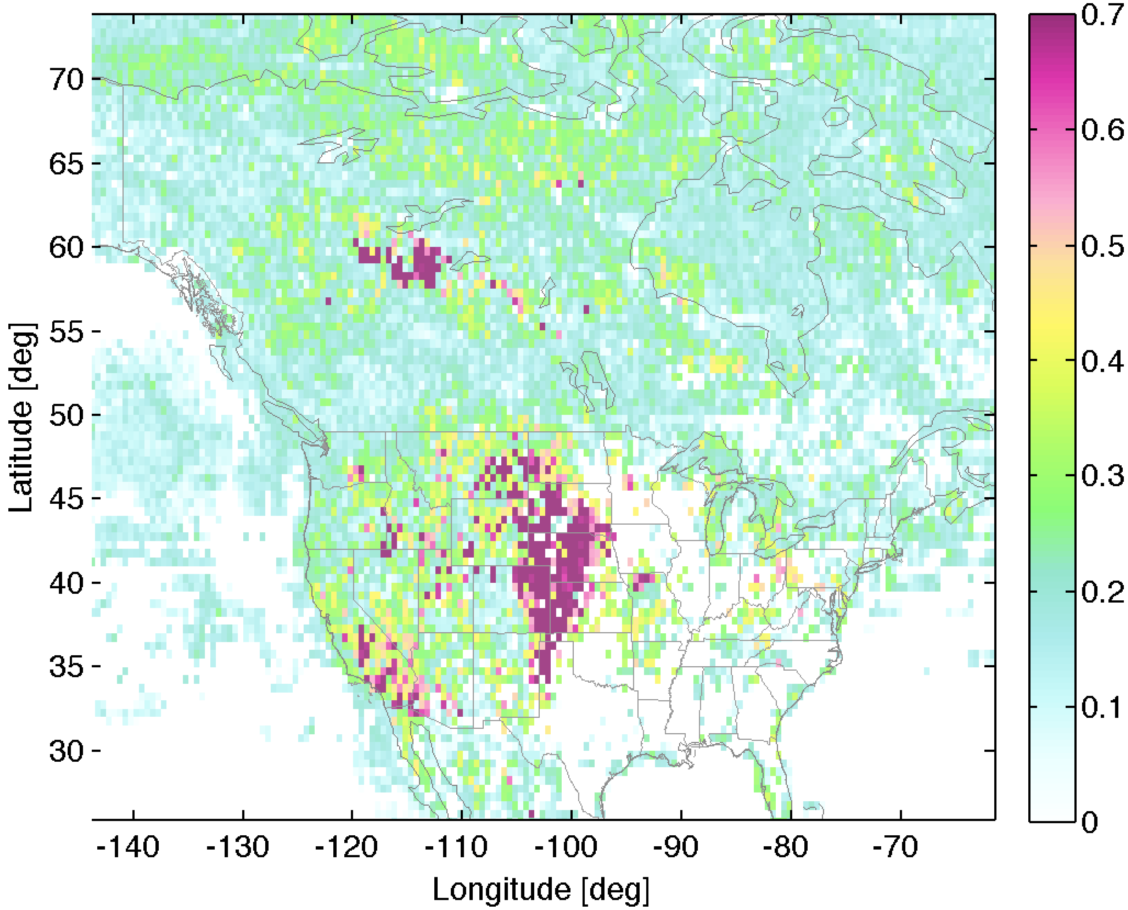
Summary

- AIRS NH_3 products not only include 13 years data record, it also provide daily maps!
- AIRS retrieved vertical profiles show good agreement (~5 – 15%) with in situ profiles from the 2013 DISCOVER-AQ field campaign in central California.
- AIRS daily measurements captures the strong continuous NH_3 emission sources from the anthropogenic (agricultural) source regions, as well as emissions from biomass burning (BB).
- Ammonia trends increase over agriculture regions, where fertilizers are used as routine practice, decrease over BB regions (with insufficient records).
- Ammonia increases resulted primarily from dramatic decreases in concentrations of acidic aerosols (sulfate and nitrate), an unintended consequence of effective controls of NO_x and SO_2 emissions.

CrIS NH3 (TVAC Gas Cell)

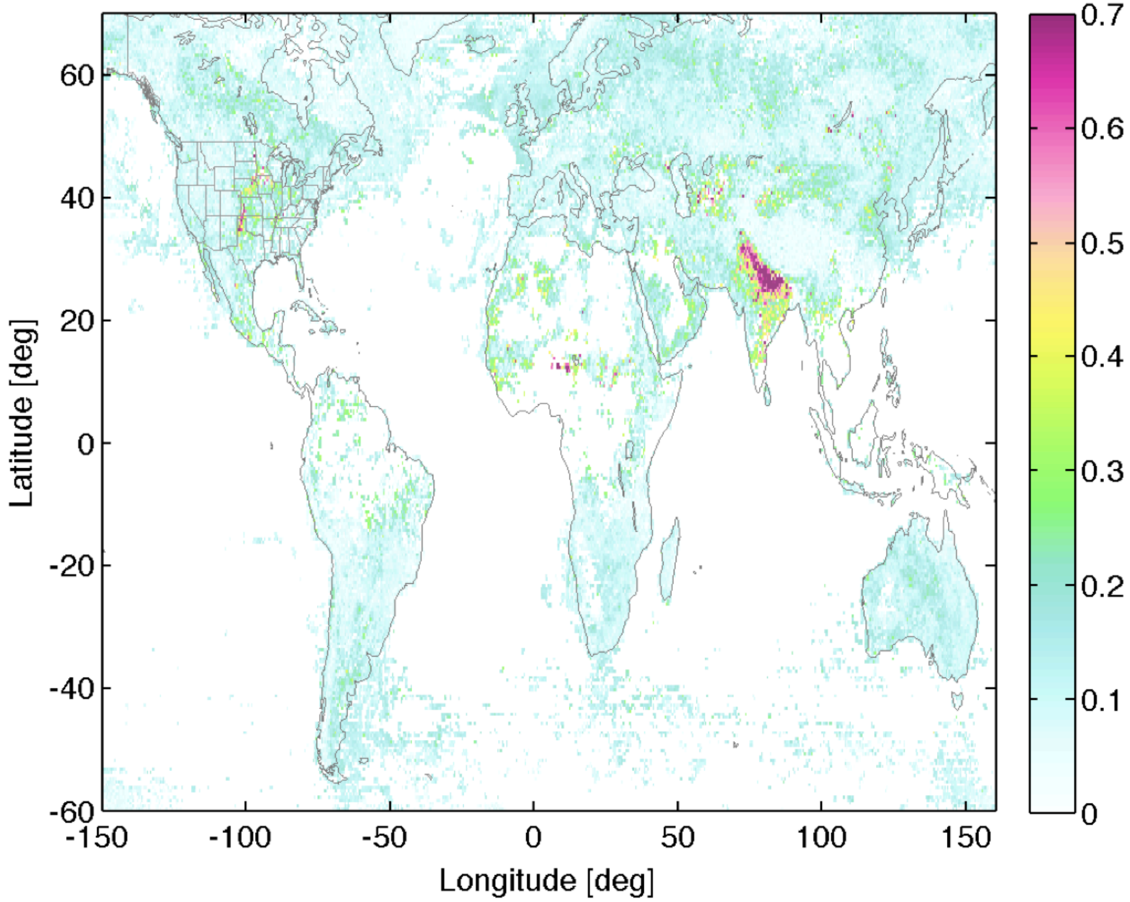


CrIS NH3 B(T) Signals (on/off line)



July 2012

CrIS NH3 B(T) Signals



May 2012

Validation of SNPP NUCAPS trace gas EDRs: O_3, CO, and CO_2

Nicholas R. Nalli[1,2], Q. Liu[2], C. Tan[1,2], A. Gambacorta[3], C. D. Barnet[3], F. Iturbide-Sanchez[1,2], J. W. Smith[3,4], X. Xiong[1,2], *et al.*

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2016 STAR JPSS Annual Meeting
College Park, Maryland, USA
August 2016

Acknowledgments

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- **SNPP Sounder EDR Validation Dataset collection**
  - **NOAA AEROSE:** E. Joseph, V. R. Morris, M. Oyola (HU/NCAS); D. Wolfe (NOAA/ESRL)
    - AEROSE works in collaboration with the NOAA PIRATA Northeast Extension (PNE) project (R. Lumpkin, G. Foltz and C. Schmid), and is supported by the NOAA Educational Partnership Program (EPP) grant NA17AE1625, NOAA grant NA17AE1623, JPSS and STAR
  - **CalWater/ACAPEX:** R. Spackman (STC); R. Leung (PNNL); C. Fairall, J. Intrieri (NOAA); N. Hickmon, M. Ritsche, A. Haruta, and the ARM Mobile Facility 2 (AMF2)
  - **NASA Sounder Science Team:** E. Olsen (for his expertise and assistance with the AIRS v6 EDR products), T. Pagano, E. Fetzer (NASA/JPL)
  - **World Ozone and Ultraviolet Radiation Data Centre (WOUDC)** data contributors (DWD-GRUAN, & INPE, & KNMI, & NASA-WFF, & SMNA. http://www.woudc.org
  - **SHADOZ: Southern Hemisphere ADditional Ozonesondes** (A. Thompson et al.)

- **NUCAPS validation effort (past and present)**: M. Wilson, T. King, W. W. Wolf, A.K. Sharma (STAR)

Outline

- **JPSS Sounder Trace Gas EDR Cal/Val Overview**
  - JPSS Level 1 Requirements
  - Validation Hierarchy
  - NUCAPS Algorithm
    - v1.5 (operational, CrIS nominal res)
    - v1.8.1. (CrIS full-res)
- **NUCAPS IR Ozone Profile EDR Product Evaluation**
  - v1.5 (operational)
    - Global Focus Day
    - Ozonesonde ensemble
  - v1.8.1 (CrIS full-res)
    - Global Focus Day
- **NUCAPS Trace Gas EDR Product Evaluation Versus AIRS v6 (Preliminary)**
  - Basic Methodology
  - Carbon Monoxide (CO)
    - v1.5 (operational)
    - v1.8.1 (full-res CrIS)
  - Carbon Dioxide (CO_2)
    - v1.5 (operational)
    - v1.8.1 (full-res CrIS)
- **Summary and Future Work**

JPSS Specification Performance Requirements
CrIS Trace Gas EDR Uncertainty (O_3, CO, CO_2, CH_4)

CrIS Infrared Trace Gases Specification Performance Requirements		
PARAMETER	**THRESHOLD**	**OBJECTIVE**
O_3 (Ozone) Profile Precision, 4–260 hPa (6 statistic layers)	20%	10%
O_3 (Ozone) Profile Precision, 260 hPa to sfc (1 statistic layer)	20%	10%
O_3 (Ozone) Profile Accuracy, 4–260 hPa (6 statistic layers)	±10%	±5%
O_3 (Ozone) Profile Accuracy, 260 hPa to sfc (1 statistic layer)	±10%	±5%
O_3 (Ozone) Profile Uncertainty, 4–260 hPa (6 statistic layers)	25%	15%
O_3 (Ozone) Profile Uncertainty, 260 hPa to sfc (1 statistic layer)	25%	15%
CO (Carbon Monoxide) Total Column Precision	35%, or full res mode 15%	3%
CO (Carbon Monoxide) Total Column Accuracy	±25%, or full res mode ±5%	±5%
CO_2 (Carbon Dioxide) Total Column Precision	0.5% (2 ppmv)	1.05 to 1.4 ppmv
CO_2 (Carbon Dioxide) Total Column Accuracy	±1% (4 ppmv)	NS
CH_4 (Methane) Total Column Precision	1% (≈20 ppbv)	NS
CH_4 (Methane) Total Column Accuracy	±4% (≈80 ppmv)	NS

Source:
(L1RD, 2014, pp. 45-49)

Validation Methodology Hierarchy

(e.g., *Nalli et al., JGR Special Section,* 2013)

1. **Numerical Model (e.g., ECMWF, NCEP/GFS) Global *Comparisons***
   - Large, truly global samples acquired from Focus Days
   - Useful for sanity checks, bias tuning and regression
   - Limitation: *Not* independent truth data

2. **Satellite Sounder EDR (e.g., AIRS, ATOVS, COSMIC) *Intercomparisons***
   - Global samples acquired from Focus Days (e.g., AIRS)
   - Consistency checks; merits of different retrieval algorithms
   - Limitation: Similar error characteristics; must take rigorous account of averaging kernels of both systems (e.g., *Rodgers and Connor,* 2003)

3. **Conventional RAOB Matchup *Assessments***
   - WMO/GTS operational sondes launched ~2/day for NWP
   - Representation of global zones, long-term monitoring
   - Large samples after a couple months (e.g., *Divakarla et al.,* 2006; *Reale et al.* 2012)
   - Limitations:
     - Skewed distribution toward NH-continents
     - Mismatch errors, potentially systematic at individual sites
     - Non-uniform, less-accurate and poorly characterized radiosondes
     - RAOBs assimilated , by definition, into numerical models

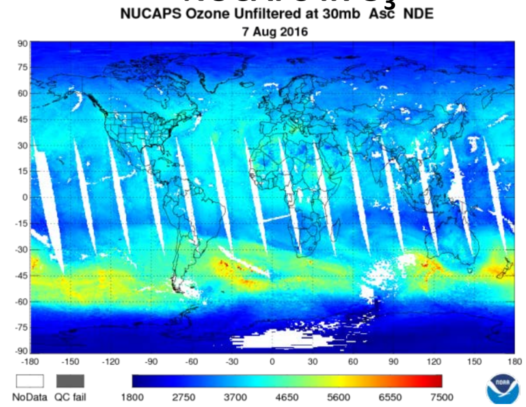
4. **Dedicated/Reference RAOB Matchup *Assessments***
   - *Dedicated* for the purpose of satellite validation
     - Known measurement uncertainty and optimal accuracy
     - Minimal mismatch errors
     - Atmospheric state “best estimates” or “merged soundings”
   - Reference sondes: CFH, **GRUAN** corrected RS92/RS41
     - Traceable measurement
     - Uncertainty estimates
   - Limitation: Small sample sizes and limited geographic coverage
   - E.g., **ARM sites** (e.g., *Tobin et al.,* 2006), **AEROSE**, **CalWater/ACAPEX ,** BCCSO, PMRF

5. **Intensive Field Campaign *Dissections***
   - Include dedicated RAOBs, some *not* assimilated into NWP models
   - Include ancillary datasets (e.g., ozonesondes, lidar, M-AERI, MWR, sunphotometer, etc.)
   - Ideally include funded aircraft campaign using IR sounder (e.g., NAST-I, S-HIS)
   - Detailed performance specification; state specification; SDR cal/val; case studies
   - E.g., **SNAP, SNPP-1,-2, AEROSE, CalWater/ACAPEX**, JAIVEX, WAVES, AWEX-G, EAQUATE

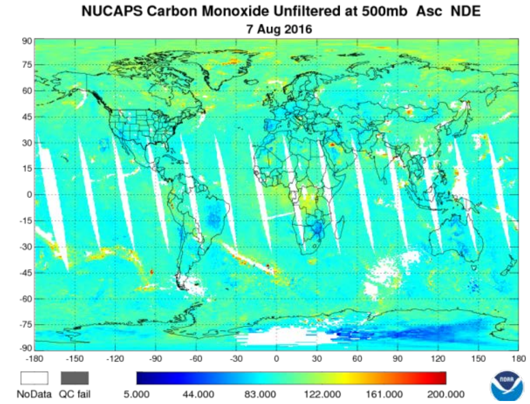
NOAA Unique Combined Atmospheric Processing System (NUCAPS) Algorithm (1/2)

- **Operational algorithm**
  - Unified Sounder Science Team (AIRS/IASI/CrIS) retrieval algorithm (*Susskind, Barnet and Blaisdell,* IEEE 2003; *Gambacorta et al.,* 2014)
  - Global non-precipitating conditions
  - Atmospheric Vertical Temperature , Moisture Profiles (**AVTP**, **AVMP**) and **trace gas** (**O_3, CO, CO_2, CH_4**)
  - Validated Maturity for AVTP/AVMP, Sep 2014
- **Users**
  - **Weather Forecast Offices (AWIPS)**
    - Nowcasting / severe weather
    - Alaska (cold core)
  - NOAA/CPC (OLR)
  - NOAA/ARL (IR ozone, trace gases)
  - TOAST (IR ozone)
  - Basic and applied science research (e.g., *Pagano et al.,* 2014)
    - Via NOAA Data Centers (e.g., CLASS)
    - Universities, peer-reviewed pubs

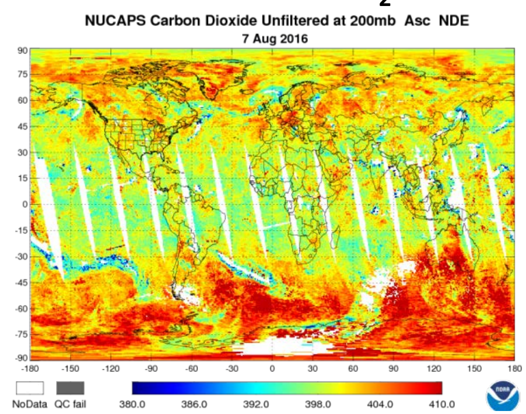
NUCAPS IR O_3



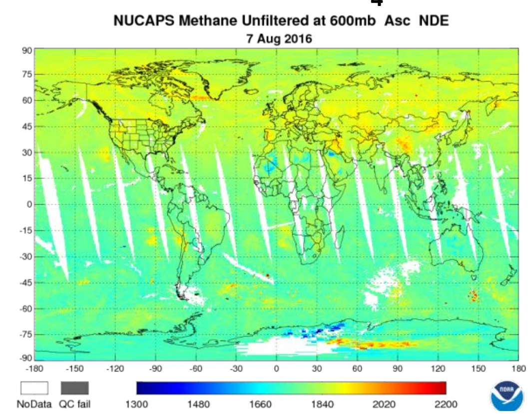
NUCAPS CO



NUCAPS CO_2



NUCAPS CH_4



Long Term Monitoring

http://www.star.nesdis.noaa.gov/jpss/EDRs/products_Soundings.php

http://www.ospo.noaa.gov/Products/atmosphere/soundings/nucaps/index.html

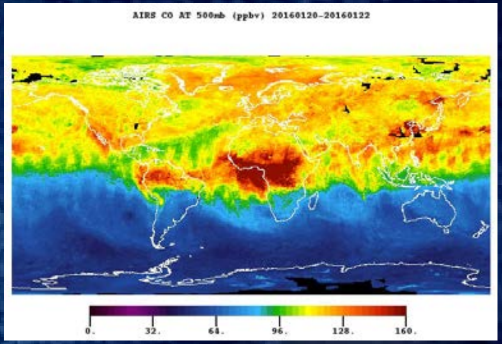
NOAA Unique Combined Atmospheric Processing System (NUCAPS) Algorithm (2/2)

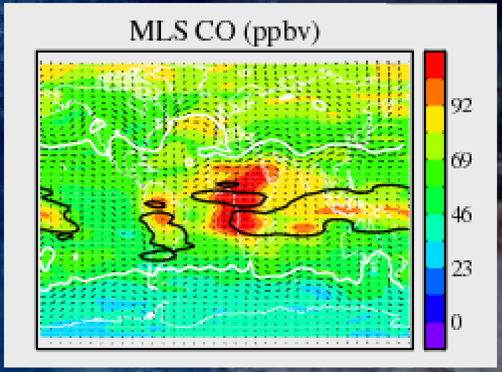
- **NUCAPS Offline Code Versioning**
  - **Version 1.5**
    - **Current operational system**
    - Runs on **nominal CrIS spectral resolution** data
  - **Version 1.8.1**
    - **Offline experimental** algorithm
    - Runs on **CrIS full spectral resolution** data
    - Uses conventional regression algorithm for the IR/MW first guess (as opposed to MW retrieval as in v1.7 full-res)
    - Upgrades
      - Updated IR radiative transfer algorithm (RTA) bias correction coefficients (based on the best combination resulted after testing the use of several atmospheric states and trace gaseous profiles)
      - IR emissivity threshold decreased from 1.05 to 1.0 in the `temp_cris.nl` namelist.
      - Replaced the Taylor expansion to the Exponential formula in the `fasttau_co2.F` program.
      - Updated MW bias correction (as in v1.6)
      - Updated MW RTA model error coefficients (as in v1.6)
      - Removal of MW channel 16 (as in v1.6)

From the Critical Design Review (CDR) Meeting
4 February 2016

Validation of Products
NUCAPS EDR: Trace Gases (1/2)

- **Satellite Intercomparisons** (Hierarchy Method #2)
  - » **Aqua AIRS** (NASA A-Train)
    - – Launched in 2002, the satellite sounder community has the experience of 13+ years of AIRS processing and AIRS has been well tested and validated
    - – The Aqua satellite is in the same orbit as SNPP, thereby facilitating collocations with SNPP CrIS/ATMS
    - – AIRS produces the same trace gas products as NUCAPS: **O_3, CO, CO_2, CH_4**
  - » **Orbiting Carbon Observatory (OCO)-2** (NASA A-Train)
    - – Launched in July 2014
    - – Provides **CO_2 observations**
  - » **Microwave Limb Sounder (MLS)** (NASA A-Train)
    - – Launched in July 2004
    - – Provides **CO observations**





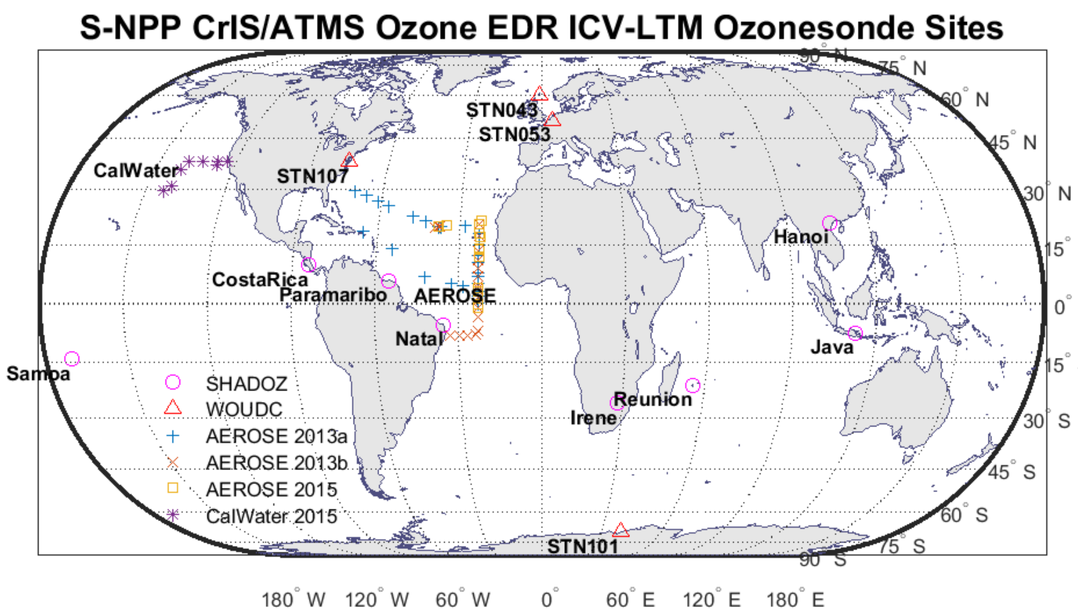
Validation of SNPP NUCAPS trace gas EDRs

IR OZONE PROFILE EDR

IR Ozone Profile EDR Validation (1/8)

In Situ Truth Datasets

- **Collocated ozonesondes** for **O_3 (ozone) profile EDR**
  - **Dedicated Ozonesondes**
    - **NOAA AEROSE** (*Nalli et al.* 2011)
    - **CalWater/ACAPEX 2015**
  - **Sites of Opportunity**
    - **SHADOZ** (*Thompson et al.* 2007)
      - Costa Rica
      - Hanoi
      - Irene
      - Java
      - Natal
      - Paramaribo
      - Reunion
      - American Samoa
    - **WOUDC**
      - STN043
      - STN053
      - STN107
      - STN101

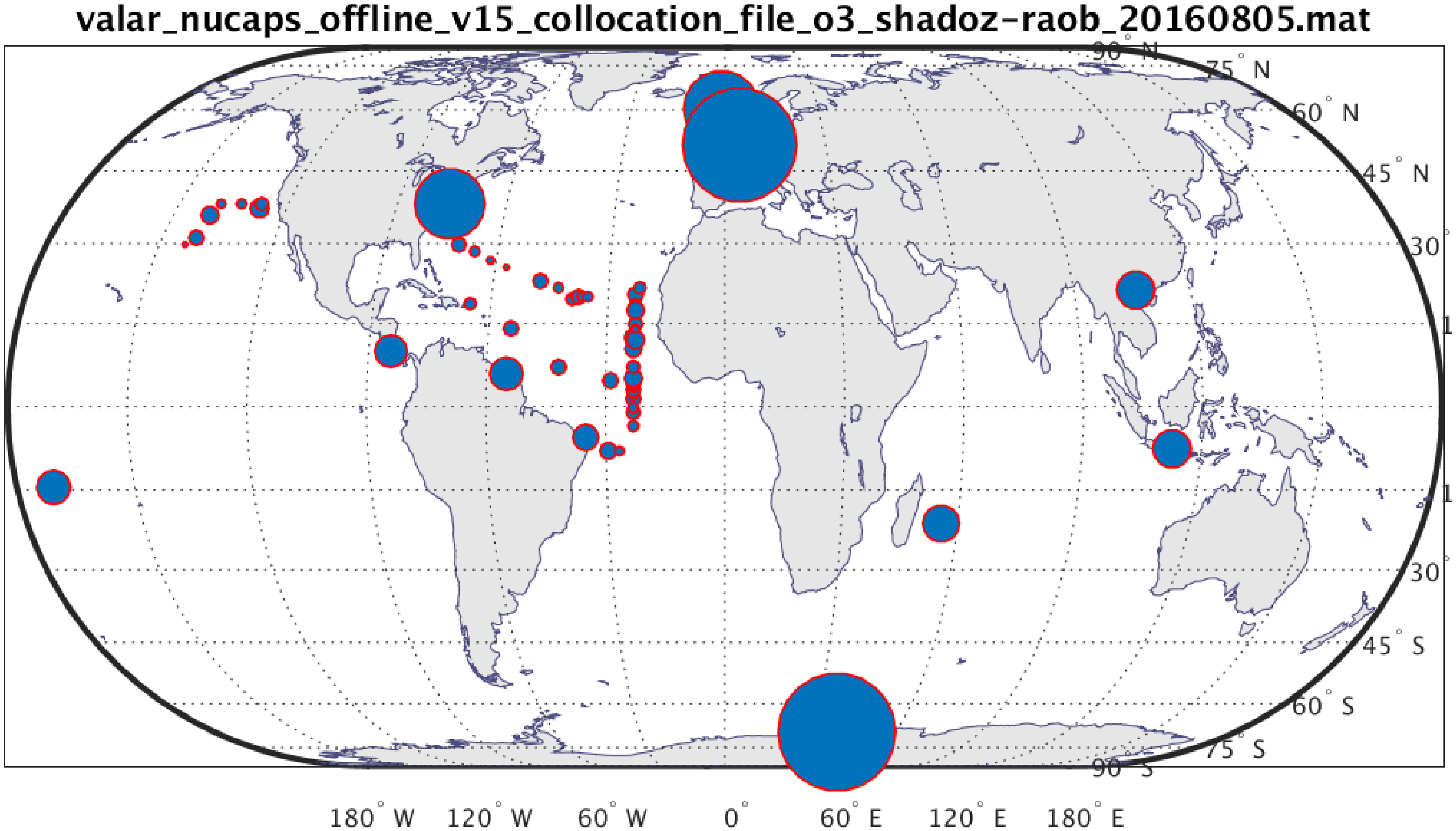


IR Ozone Profile EDR Validation (2/8)

VALAR Ozonesonde-FOR Collocation Sample (*n* = 6024)

Geographic Histogram (Equal Area)

FOR Collocation Criteria: δ*x* ≤ 125 km, −240 < δ*t* < +120 min

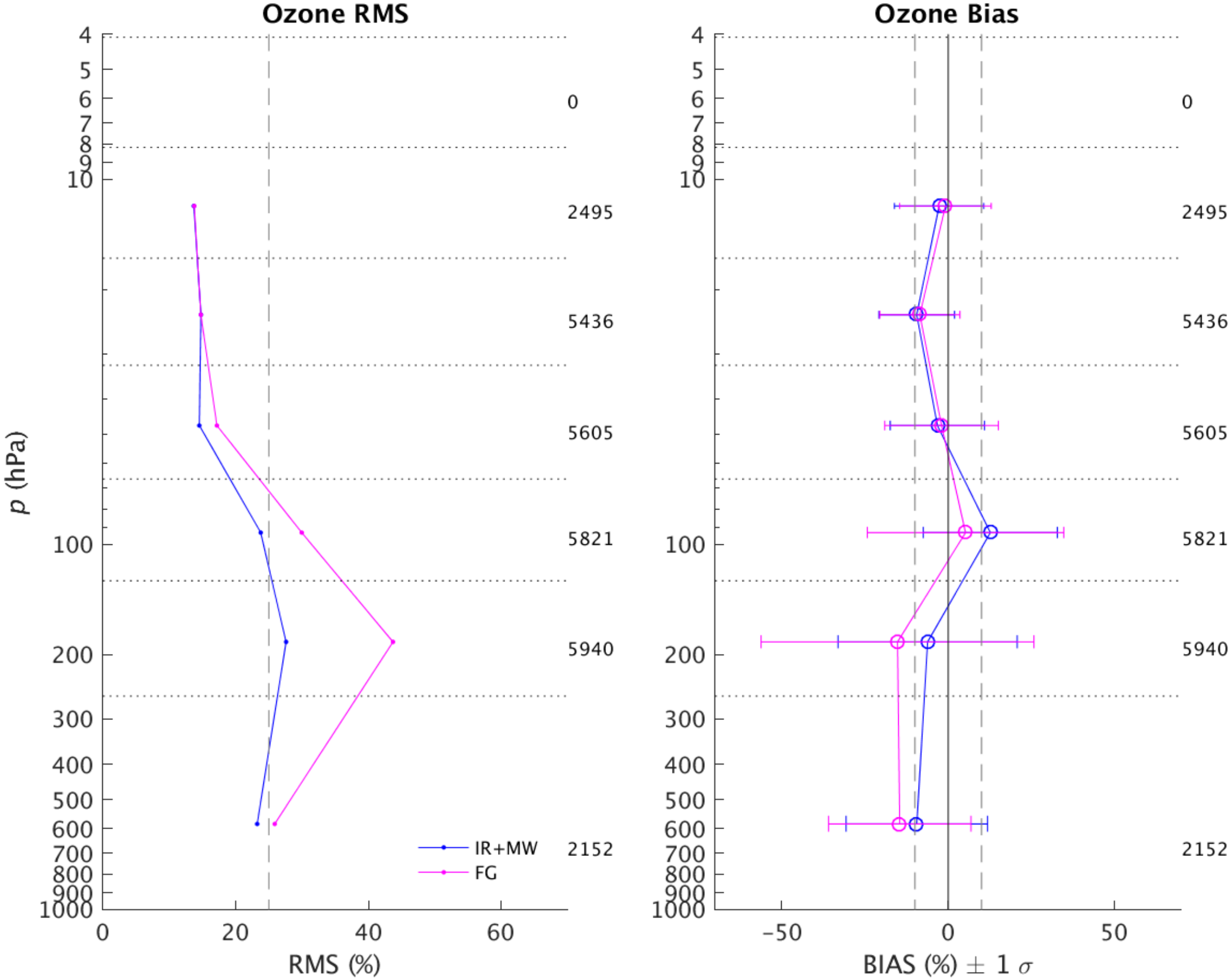


IR Ozone Profile EDR Validation (3/8)

NUCAPS Offline (v1.5) versus Global Ozonesondes

Retrieval and *A Priori* First Guess

IR+MW Yield = 62.2%

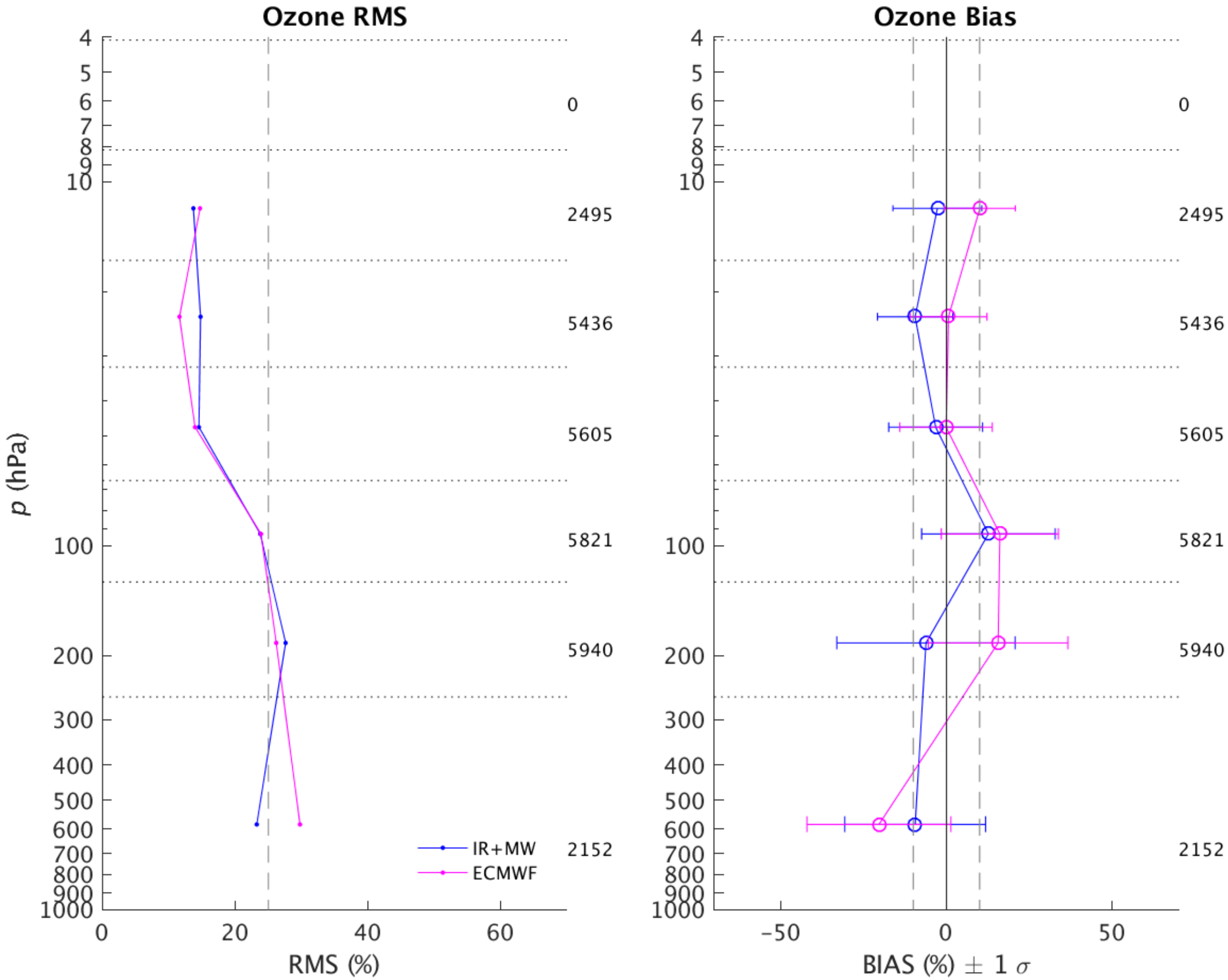


IR Ozone Profile EDR Validation (4/8)

NUCAPS Offline (v1.5) versus Global Ozonesondes

Retrieval and **ECMWF**

IR+MW Yield = 62.2%



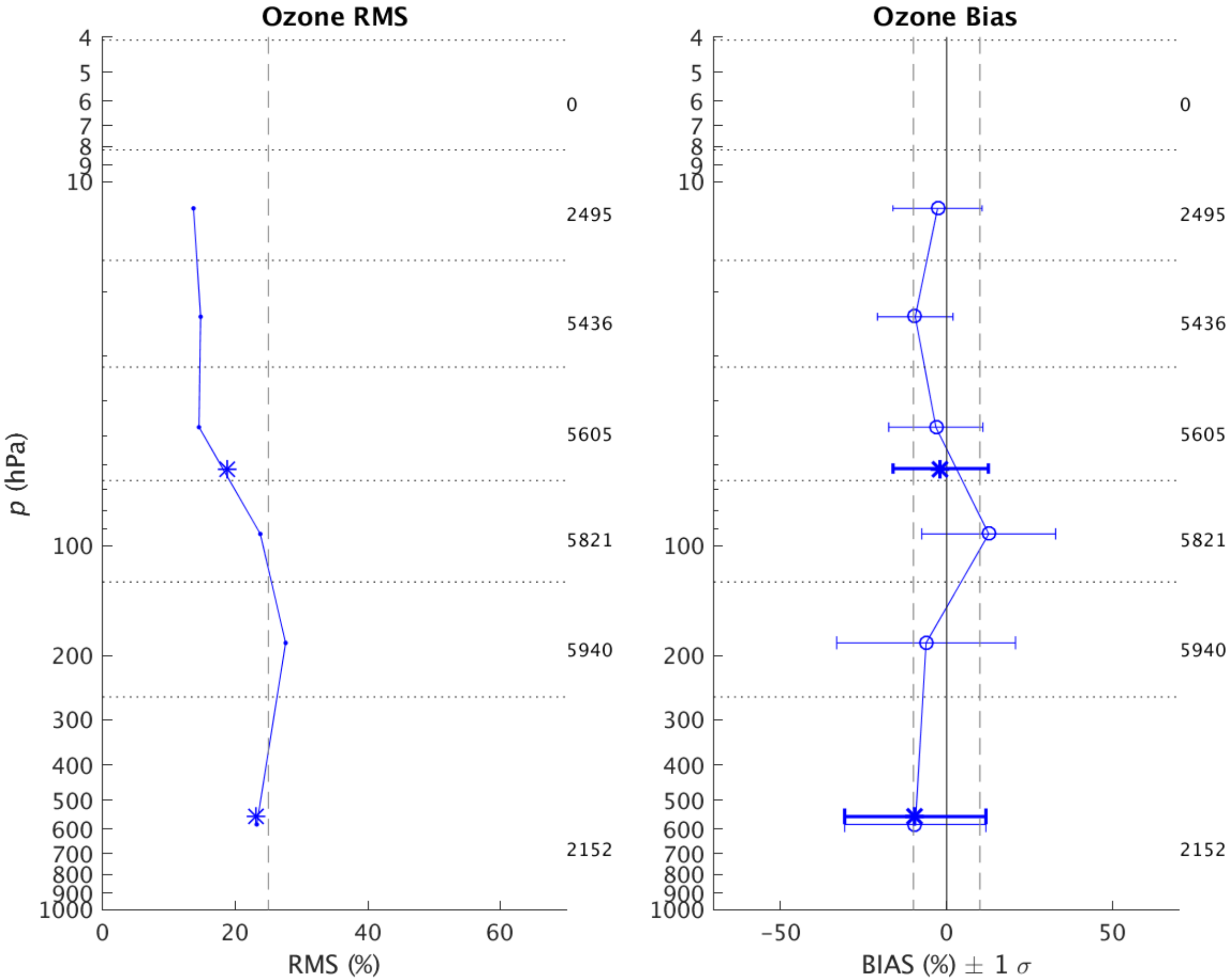
IR Ozone Profile EDR Validation (5/8)

NUCAPS Offline (v1.5) versus Global Ozonesondes

*** Broad-Layer Statistics**

(Per JPSS Level 1 Requirements)

IR+MW Yield = 62.2%



IR Ozone Profile EDR Validation (6/8)

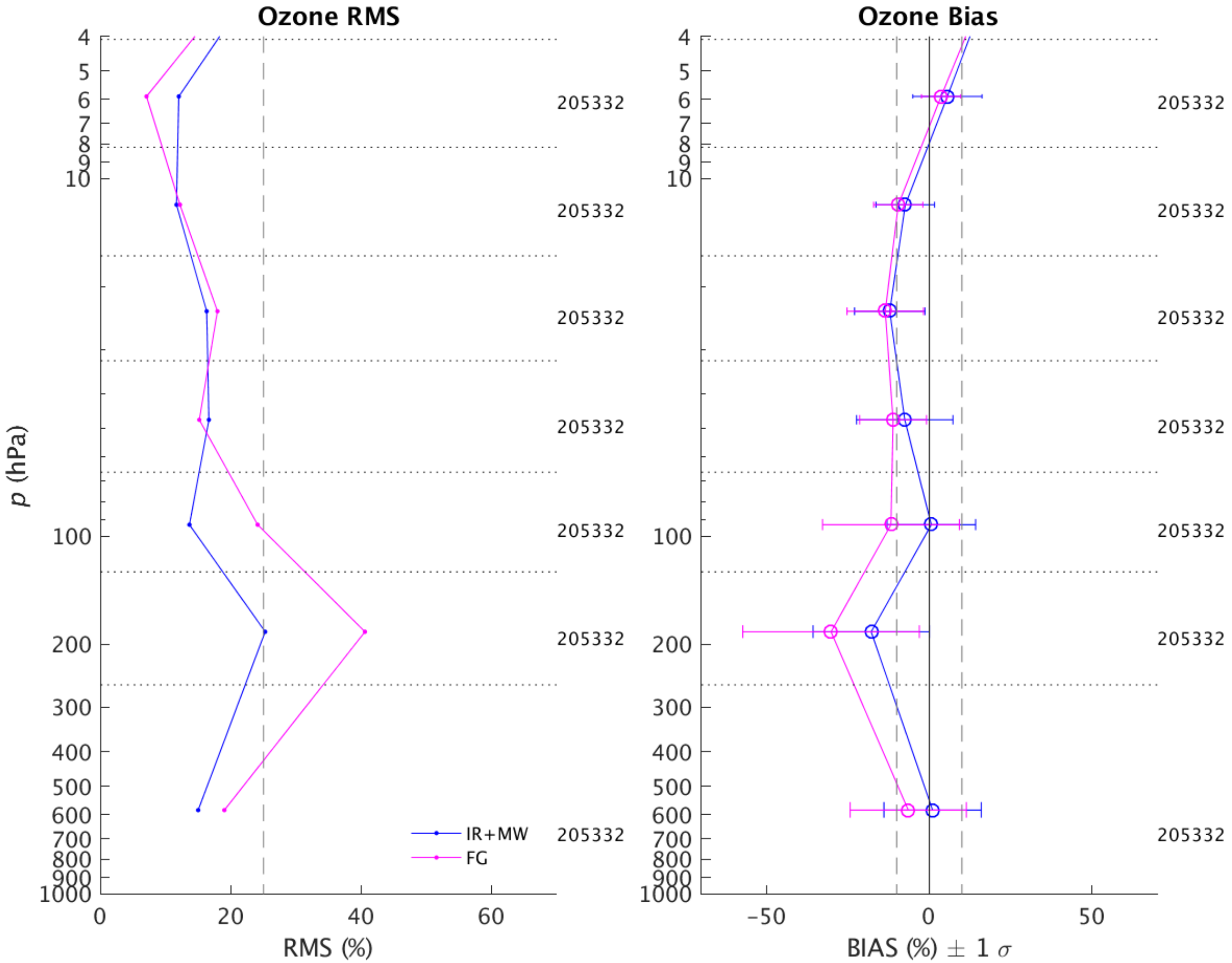
NUCAPS Offline (v1.5) versus Global Focus Day 17-Feb-2015

O_3 Versus ECMWF

IR+MW

First Guess

NUCAPS v1.5
Yield = 63.4%



IR Ozone Profile EDR Validation (7/8)

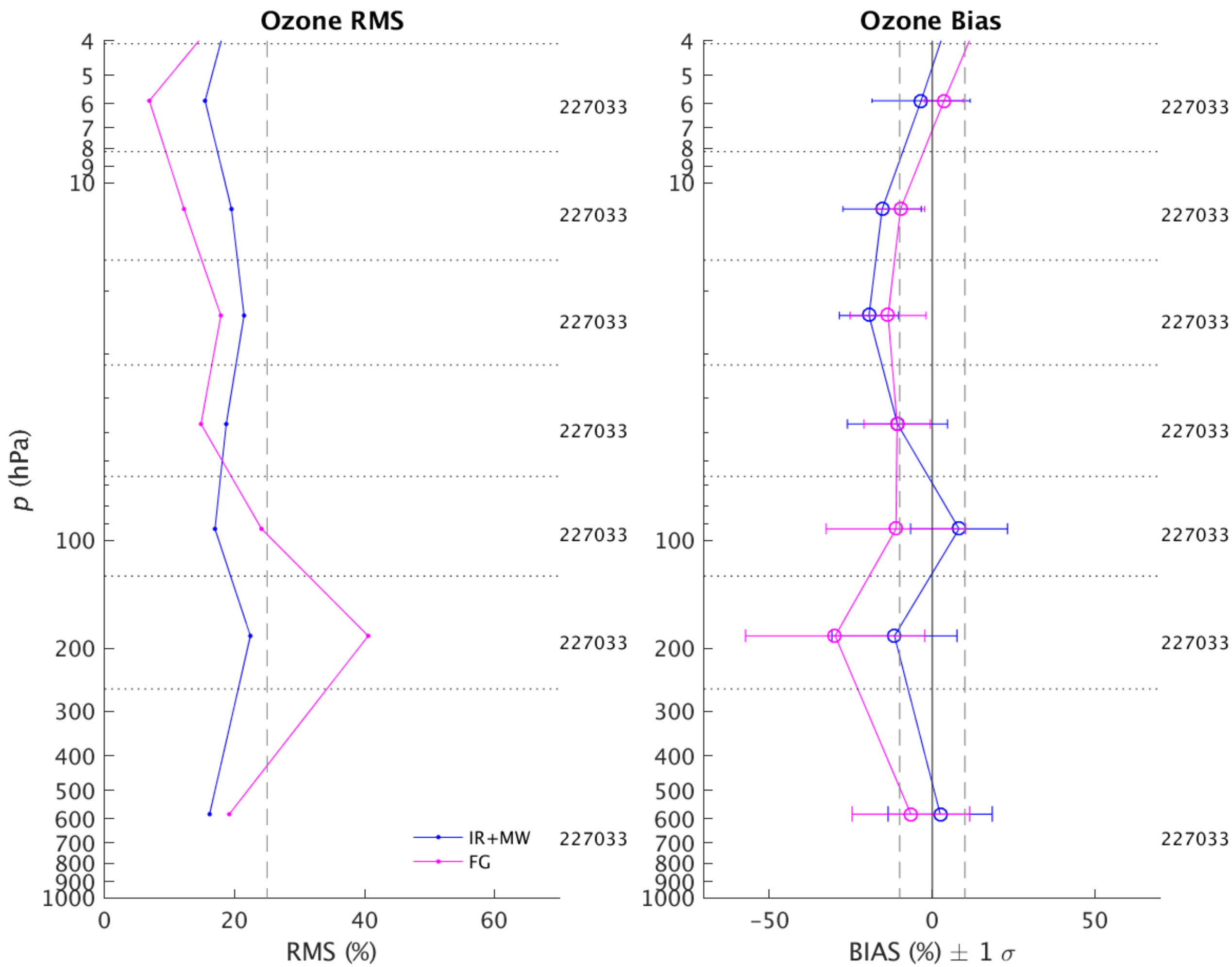
NUCAPS Offline (v1.8.1) versus Global Focus Day 17-Feb-2015

O_3 Versus ECMWF

IR+MW

First Guess

NUCAPS v1.8.1
Yield = 70.1%



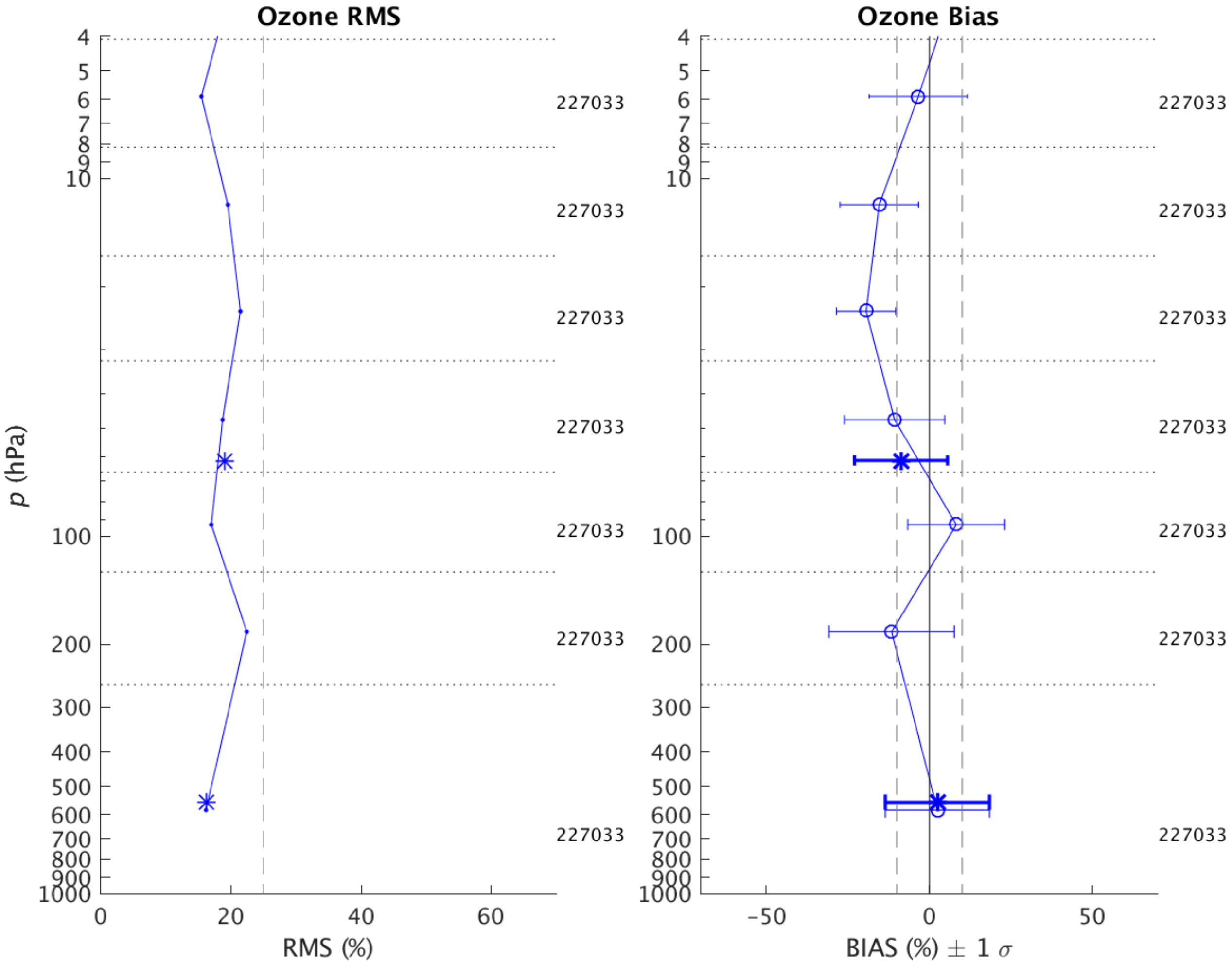
IR Ozone Profile EDR Validation (8/8)

NUCAPS Offline (v1.8.1) versus Global Focus Day 17-Feb-2015

* Broad-Layer Statistics

(Per JPSS Level 1 Requirements)

NUCAPS v1.8.1
Yield = 70.1%



Validation of SNPP NUCAPS trace gas EDRs

CARBON MONOXIDE (PRELIMINARY)

Basic Methodology for CO and CO_2

- The **AIRS v6 standard products** were obtained for the global Focus day 17 February 2015
  - Total column integrated CO and CH_4
  - The AIRS Team provided us offline runs for CO_2
- AIRS and NUCAPS were divided into ascending (ASC) and descending (DES) orbits
- Linear interpolations of FOR (lat/lon) were then performed for each orbit (ASC and DES) to create a one-to-one correspondence of collocation data points
  - AIRS CO was interpolated to NUCAPS
  - NUCAPS CO_2 was interpolated to the more sparse AIRS

- **NUCAPS offline runs for** global **Focus Day 17 February 2015**
  - **v1.5 (nominal CrIS res)**
  - **v1.8.1 (full CrIS res)**

- **For NUCAPS CO,** profile EDRs on 100 RTA layers are integrated to obtain total column abundances (molecules/cm2) according to *Nalli et al.* (2013)

$$\Sigma_x(z) \equiv \int_{z_t}^{z} N_x(z')\,\mathrm{d}z'$$

$$\Longrightarrow \quad \Sigma_x(z) \approx \Sigma_{x,\mathcal{L}} \equiv \sum_{\mathcal{L}}^{n_{\mathcal{L}}} \overline{N}_{x,\mathcal{L}}\,\delta z_{\mathcal{L}}$$

with stats being computed relative to the AIRS v6 total column product

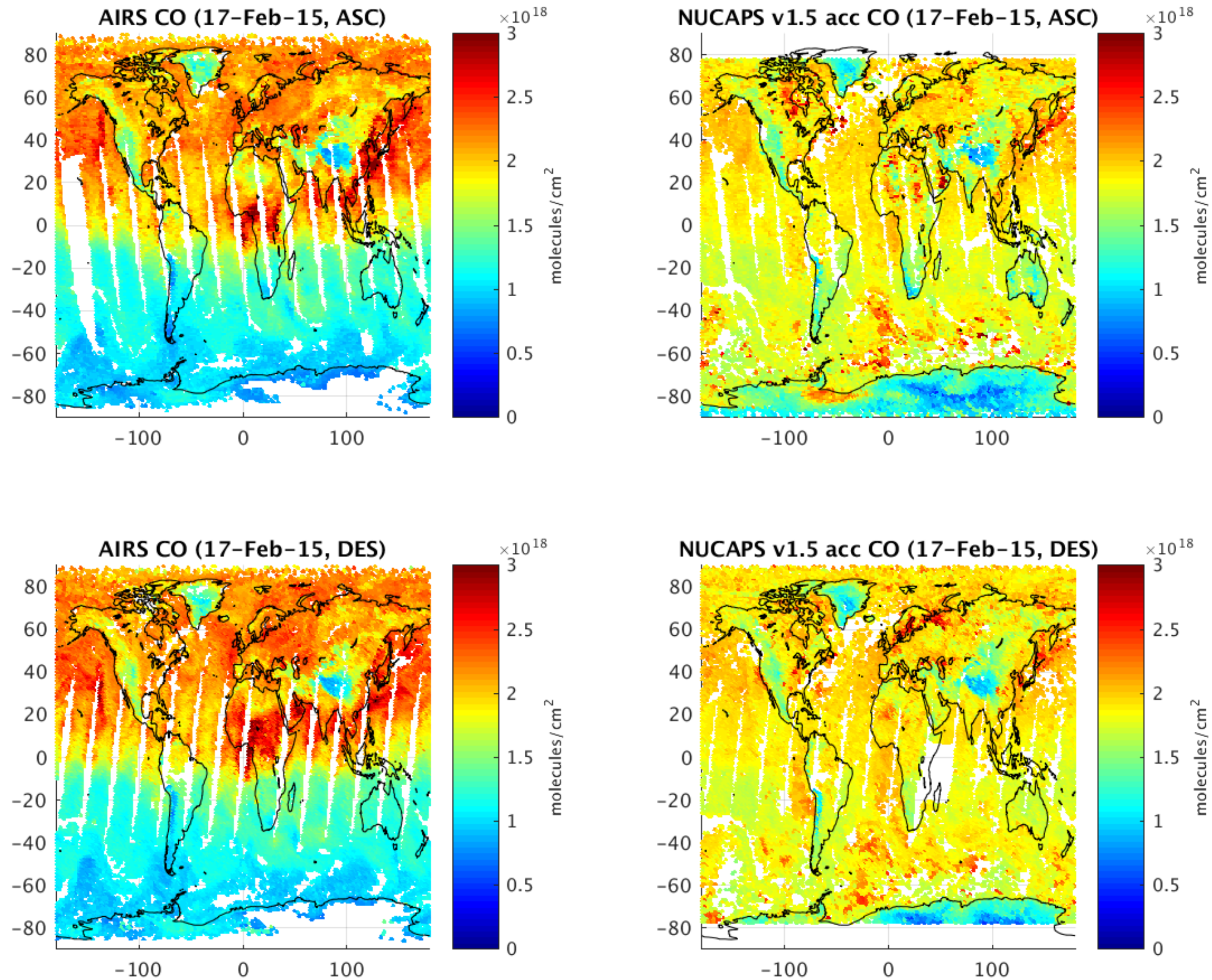
- **For NUCAPS CO_2**, stats are performed simply for atmospheric column averages (in PPMV)

Total Column Carbon Monoxide (CO) EDR (1/2)

17 Feb 2015 Focus Day, NUCAPS v1.5 and AIRS v6 Accepted Cases

Preliminary

AIRS v6 | **NUCAPS v1.5**



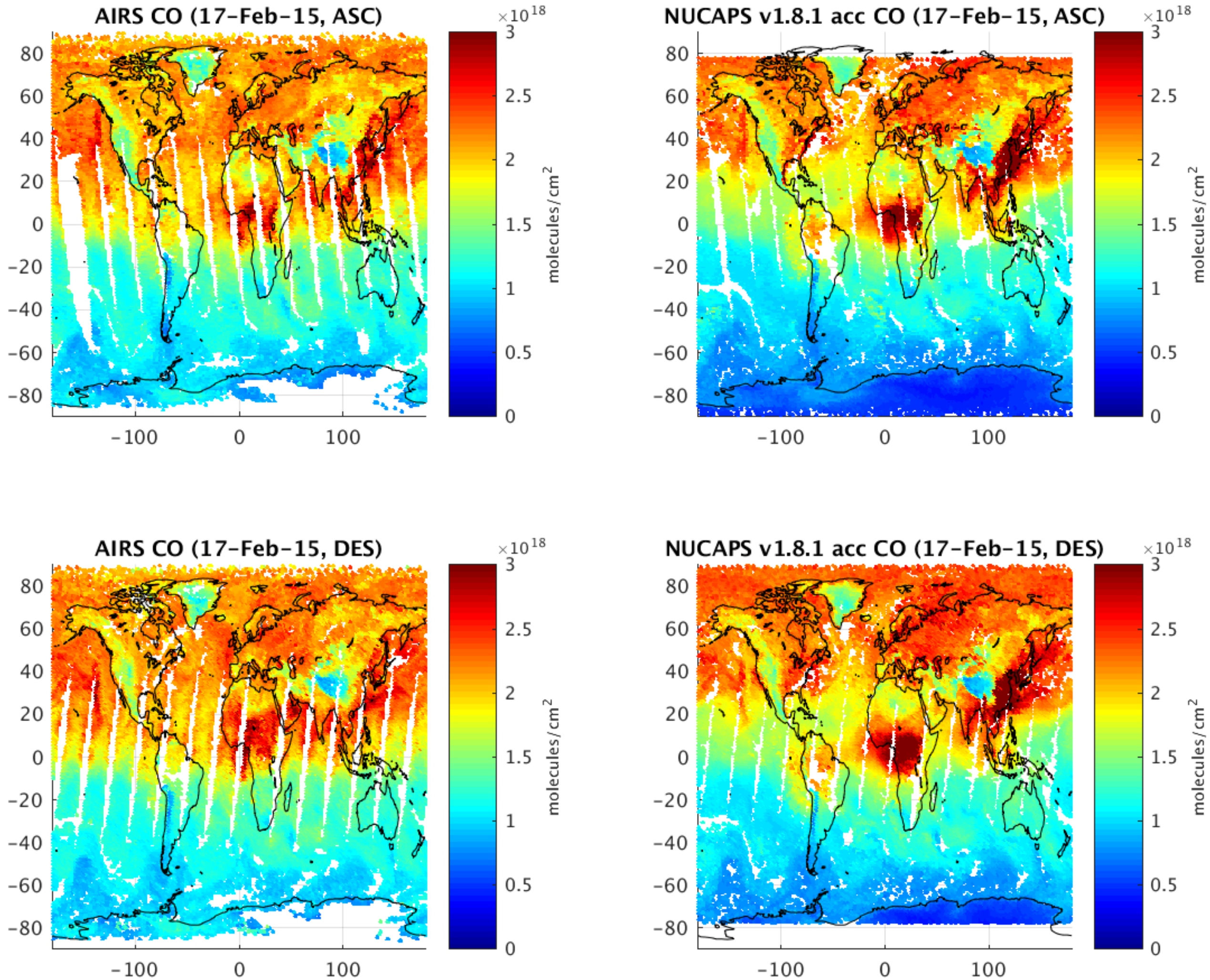
NUCAPS v1.5
Yield = 63.4%

Total Column Carbon Monoxide (CO) EDR (2/2)

17 Feb 2015 Focus Day, NUCAPS v1.8.1 and AIRS v6 Accepted Cases

Preliminary

AIRS v6 | **NUCAPS v1.8.1**



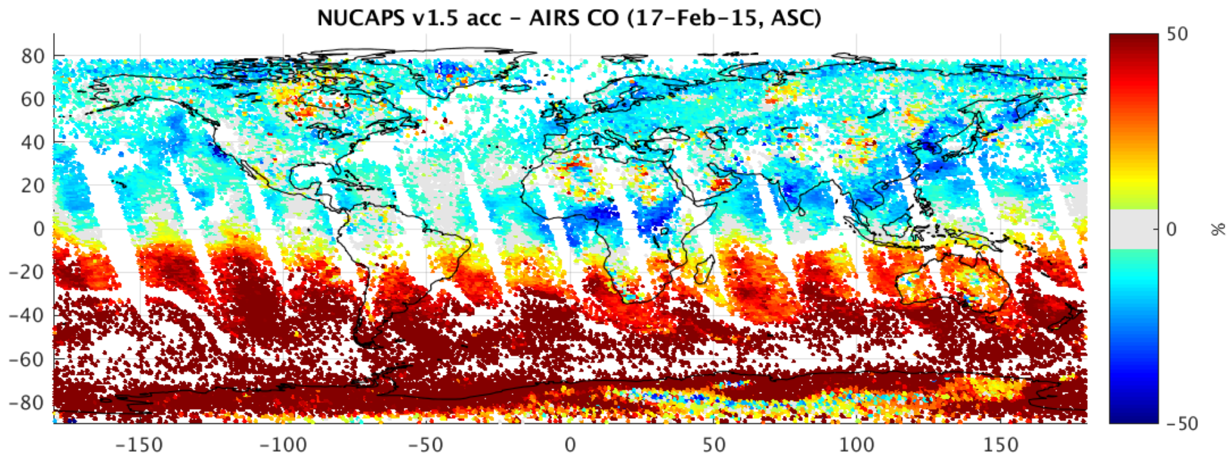
NUCAPS v1.8.1
Yield = 70.1%

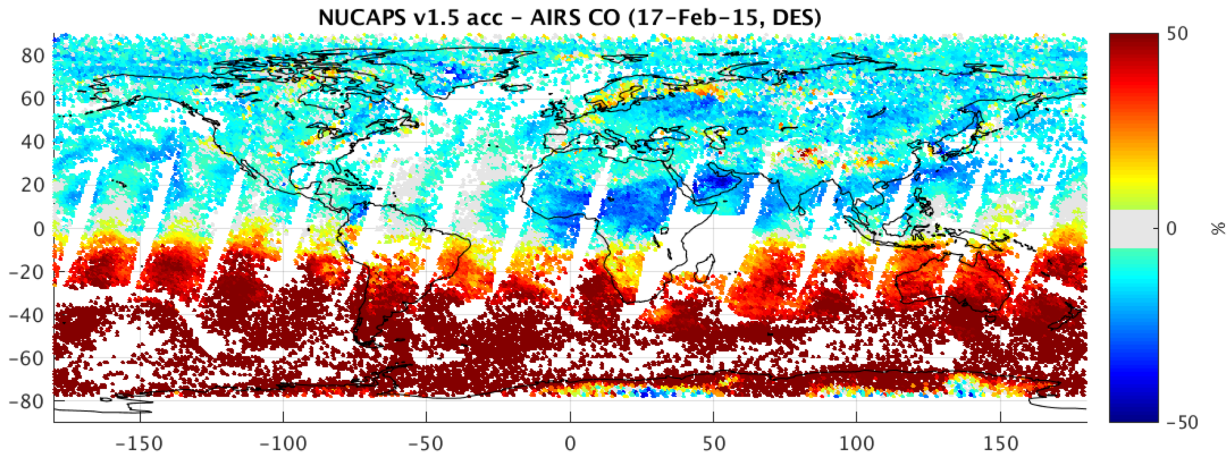
NUCAPS v1.5 CO – AIRS v6 CO

17 Feb 2015 Focus Day, Accepted Cases

Preliminary

NUCAPS v1.5 (Nominal CrIS Resolution)



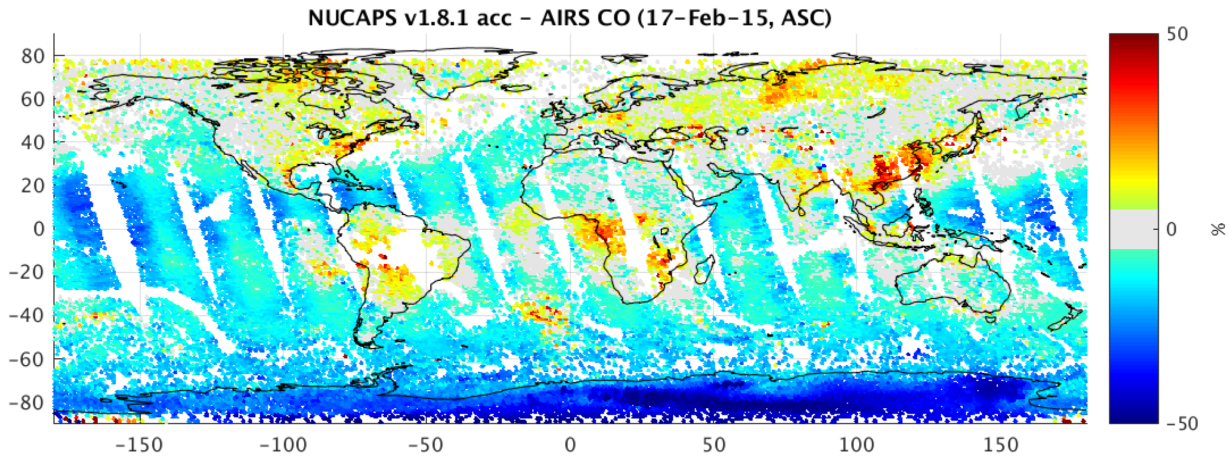


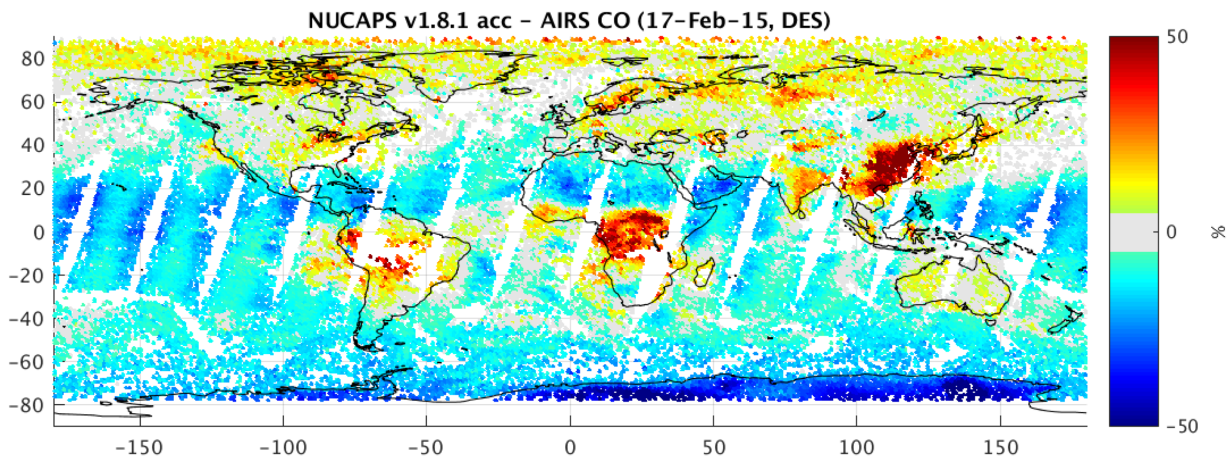
NUCAPS v1.8.1 CO – AIRS v6 CO

17 Feb 2015 Focus Day, Accepted Cases

<u>Preliminary</u>

NUCAPS v1.8.1 (Full CrIS Resolution)





Validation of SNPP NUCAPS trace gas EDRs

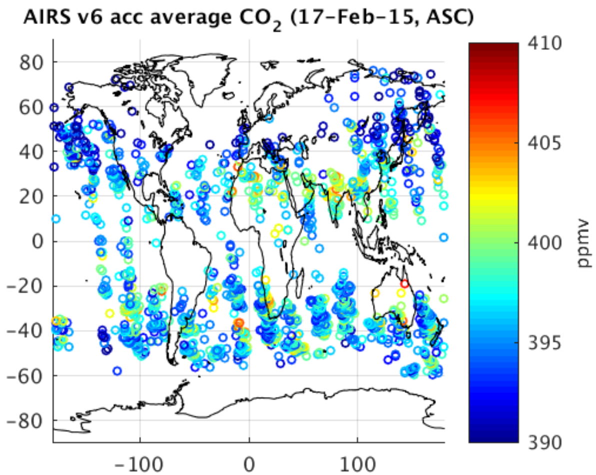
CARBON DIOXIDE (PRELIMINARY)

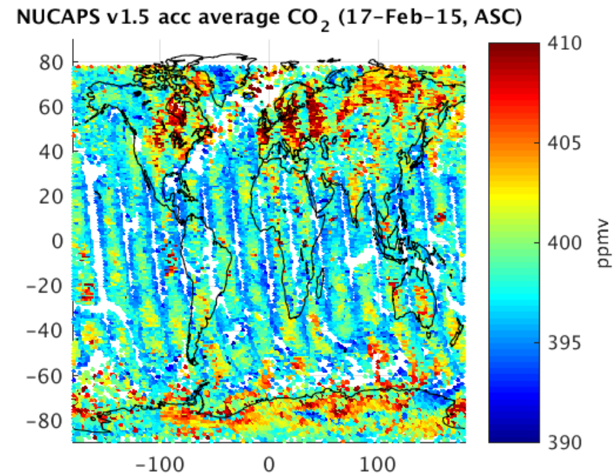
Mean Column Carbon Dioxide (CO_2) EDR (1/2)

17 Feb 2015 Focus Day, NUCAPS v1.5 and AIRS v6 Accepted Cases

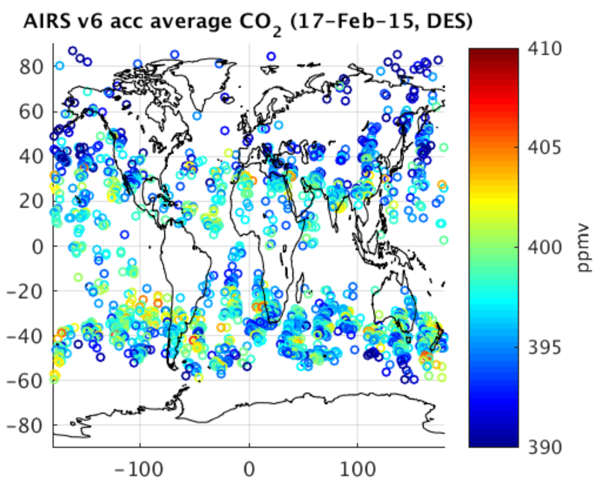
Preliminary

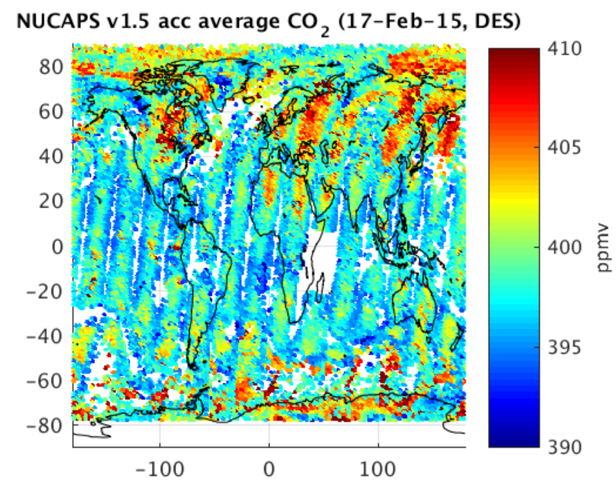
AIRS v6 | **NUCAPS v1.5**





NUCAPS v1.5
Yield = 63.4%



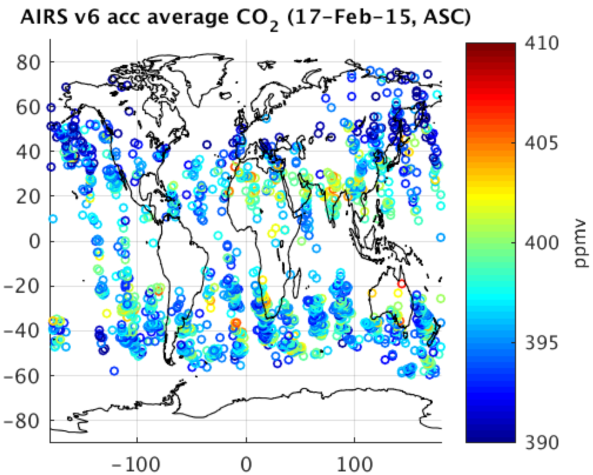


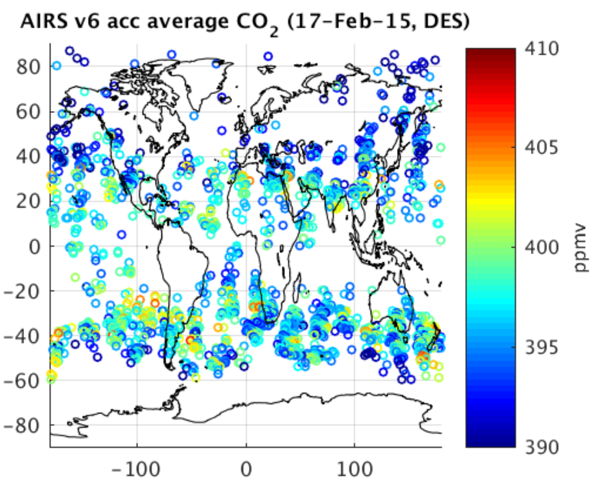
Mean Column Carbon Dioxide (CO_2) EDR (1/2)

17 Feb 2015 Focus Day, NUCAPS v1.8.1 and AIRS v6 Accepted Cases

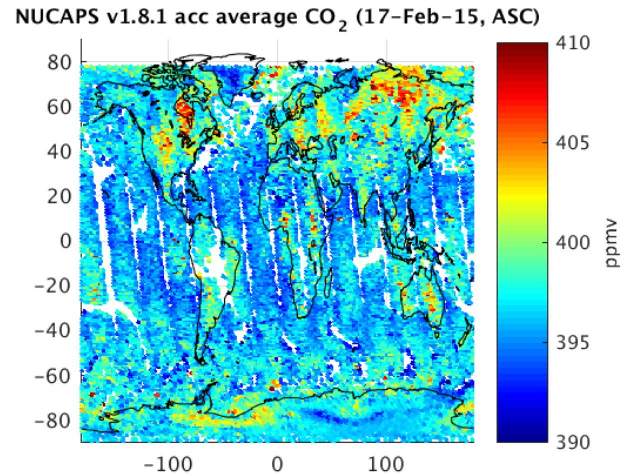
<u>Preliminary</u>

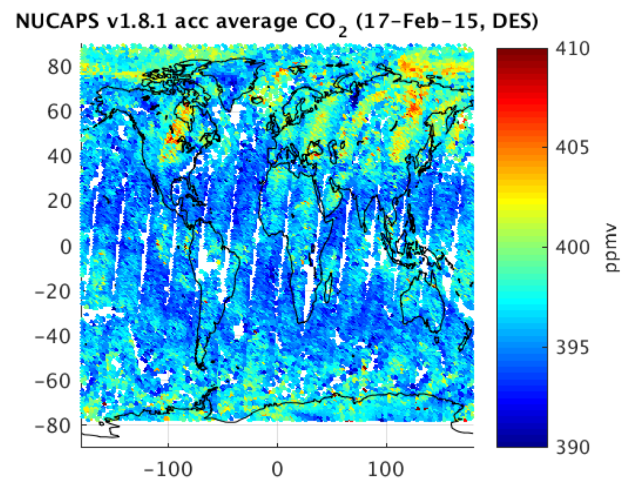
AIRS v6





NUCAPS v1.8.1





NUCAPS v1.8.1
Yield = 70.1%

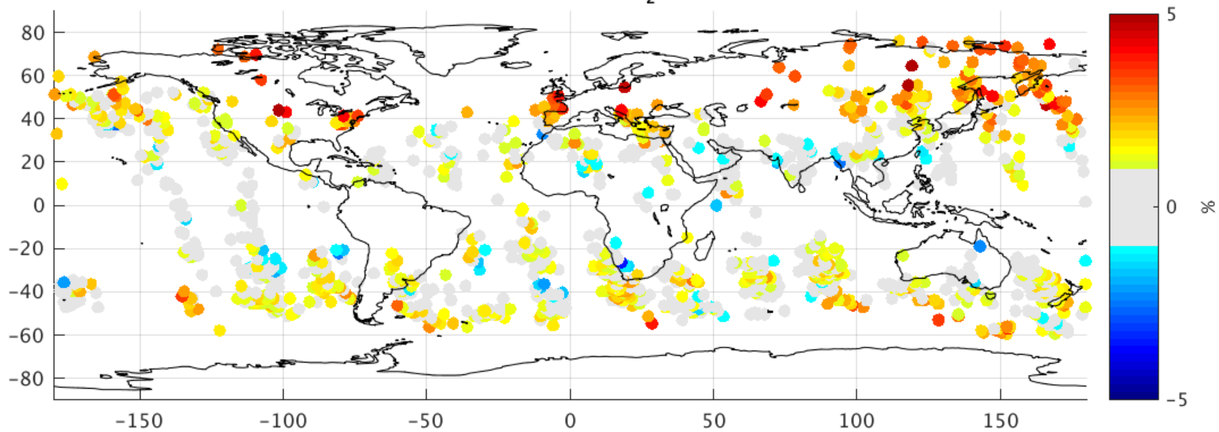
NUCAPS v1.5 CO_2 – AIRS v6 CO_2

17 Feb 2015 Focus Day, NUCAPS and AIRS Accepted Cases

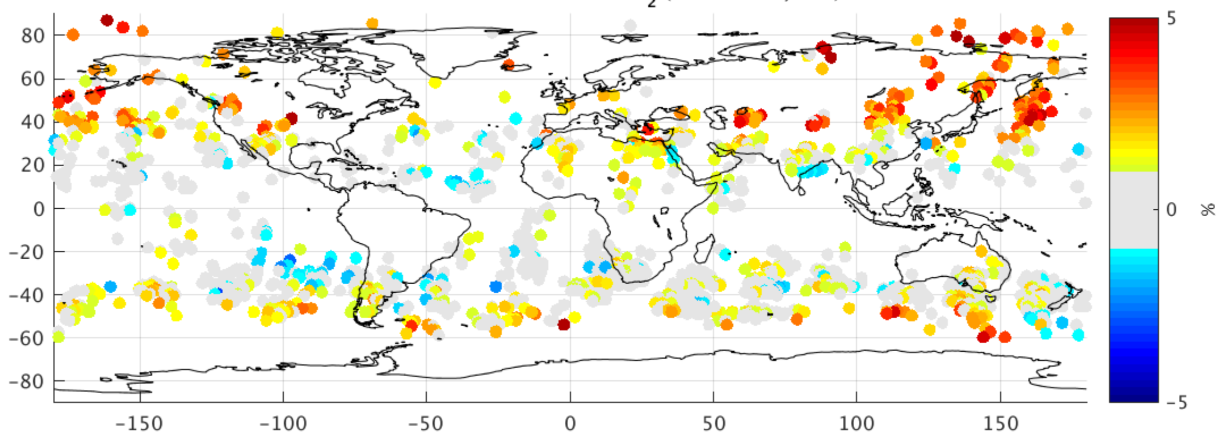
Preliminary

NUCAPS v1.5 (Nominal CrIS Resolution)

NUCAPS v1.5 acc – AIRS v6 acc CO_2 (17–Feb–15, ASC)



NUCAPS v1.5 acc – AIRS v6 acc CO_2 (17–Feb–15, DES)

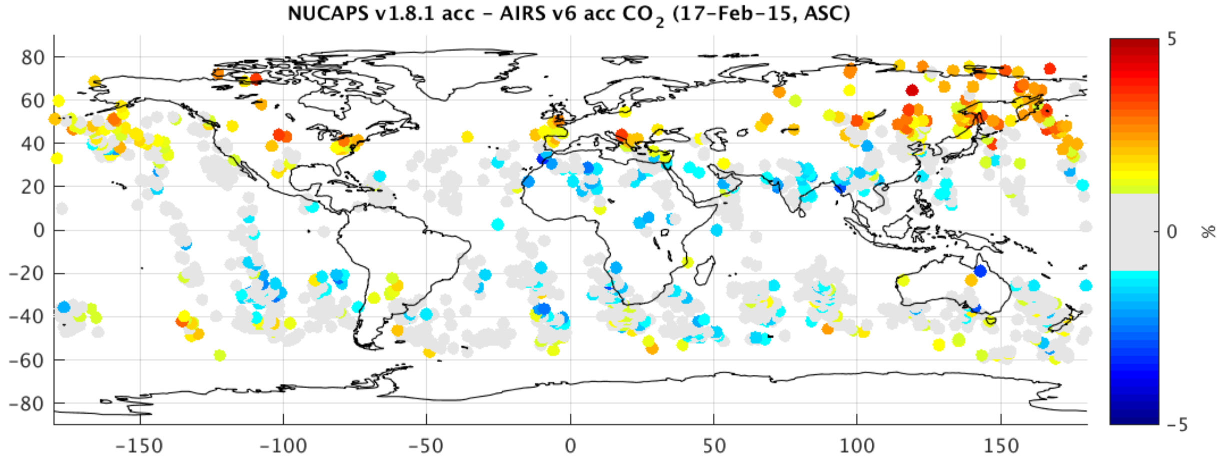


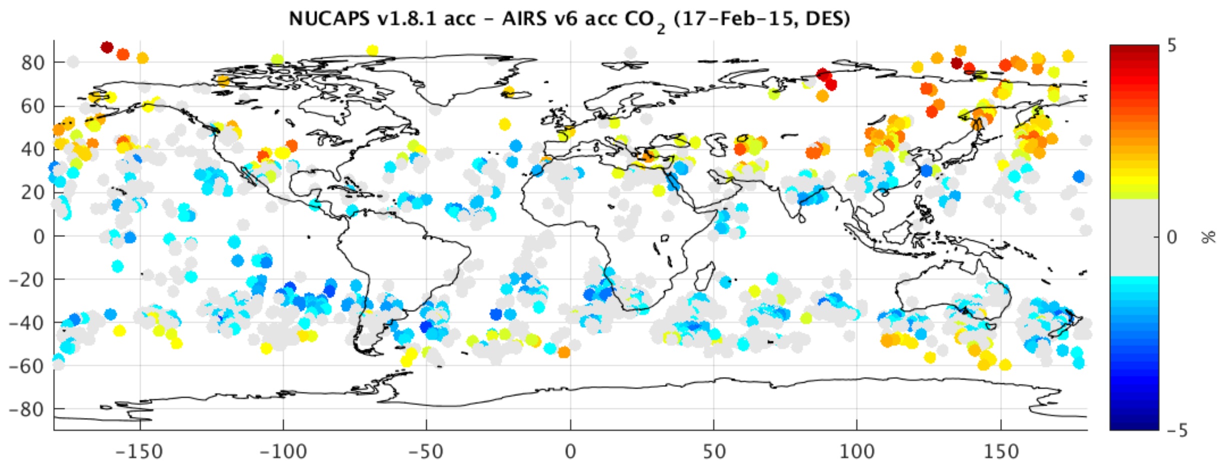
NUCAPS v1.8.1 CO_2 – AIRS v6 CO_2

17 Feb 2015 Focus Day, NUCAPS and AIRS Accepted Cases

Preliminary

NUCAPS v1.8.1 (Full CrIS Resolution)





Preliminary Global Statistics NUCAPS versus AIRS
(accepted cases)

	V1.5 CrIS Nom Res			V1.8.1 CrIS Full Res		
Trace Gas EDR	BIAS (%)	STD (%)	RMS (%)	BIAS (%)	STD (%)	RMS (%)
CO (asc)	**+21.7** (±25.0)	**41.5** (35.0)	46.8	**−10.3** (±5.0)	**28.1** (15.0)	17.8
CO (des)	**+11.0** (±25.0)	**33.4** (35.0)	35.1	**−3.2** (±5.0)	**14.8** (15.0)	15.7
CO_2 (asc)	**+0.9** (±1.0)	**1.1** (0.5)	1.4	**+0.2** (±1.0)	**1.1** (0.5)	1.4
CO_2 (des)	**+0.8** (±1.0)	**1.2** (0.5)	1.5	**−0.2** (±1.0)	**1.2** (0.5)	1.4

O_3, CO, CO_2 Trace Gas Summary

- The **NUCAPS IR ozone (O_3) profile EDR products are shown to meet JPSS Level 1 requirements**
  - The **offline v1.5 (nominal CrIS resolution) ozone EDR** has reached **“Validated Maturity”** based upon coarse/broad layer statistical analyses versus
    - Collocated **global ozonesondes**, including **dedicated ozonesondes** (Validation Hierarchy Method #4)
    - **Global Focus Day** (17 February 2015) **ECMWF** output (Validation Hierarchy Method #1)
  - The **offline v1.8.1 (full CrIS resolution) also meets Level 1 requirements** based upon coarse/broad layer statistical analyses versus
    - **Global Focus Day ECMWF** output
    - **Statistics are comparable to the ozonesonde-validated NUCAPS v1.5**

- For validation of **NUCAPS carbon monoxide (CO)** and **carbon dioxide (CO_2) EDRs**, we rely on satellite EDR Intercomparisons (Validation Hierarchy Method #2) versus **collocated AIRS v6**
  - **AIRS flown on Aqua is in the same orbit as SNPP** and is thus ideal for collocations with SNPP
  - **NUCAPS v1.5 CO** and **CO_2** retrievals **meet the relaxed JPSS Level 1 requirements for BIAS**
  - **NUCAPS v1.5 and v1.8.1 CO descending orbit currently meet JPSS Level 1 requirements**

- **Future Work**
  - **Perform “spot-checks” of AIRS and NUCAPS EDRs using *in situ* datasets of opportunity**
  - Utilize a larger data sample (e.g., month) for the CO_2 validation, apply other techniques for QA (e.g., considering DOF, applying AKs, etc.)
  - Further optimization of NUCAPS full-resolution algorithm
  - Investigate improvements in the ozone *a priori*

SNPP NUCAPS Validation

THANK YOU! QUESTIONS?

Retrieval of Trace Gases using CrIS Full Spectrum Data

Xiaozhen (Shawn) Xiong[1,2], Q. Liu[2],
A. Gambacorta[3], C. Tan[1,2] ,
and other NUCAPS Team members

[1]**IMSG Inc.**
[2]**NOAA/NESDIS/STAR**
[3]**Science and Technology Corporation**

JPSS Annual Meeting, College Park, 8/11/2016

Outline

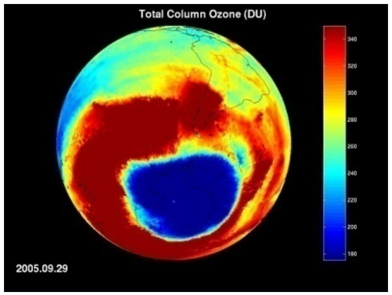
- **Part I: Lessons Learned from AIRS and IASI Trace Gases Retrievals**
  - AIRS and IASI provide measurements of trace Gases (O_3, CO_2, CO, CH_4, N_2O since 2002);
  - Valuable information of gases distribution in Mid-Upper troposphere can be observed (examples) :
    1) Enhancement of upper troposphere CH_4 over south Asia during Monsoon season;
    2) Stratospheric Intrusion and its impact to CH_4 and O_3;
  - One more study to examine the possibility to combine AIRS and IASI data to make a long-term product;

- **Part II: Preliminary Assessment to CrIS Trace Gases Retrievals and Improvements**
  1) Preliminary assessment to current trace gases retrieval in NUCAPS (DOF, Averaging Kernels) and Improvements;
  2) Monitoring the leakage of CH_4 from California **Aliso Canyon Oil Field and Gas Storage Facility;**

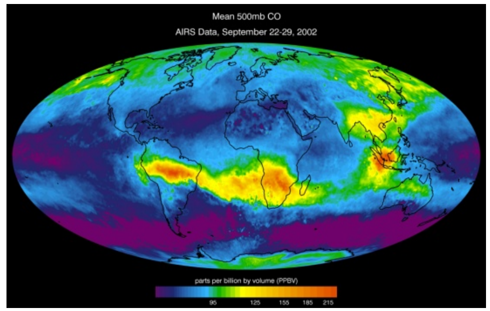
- **Summary and Future Works**

Trace Gases Products

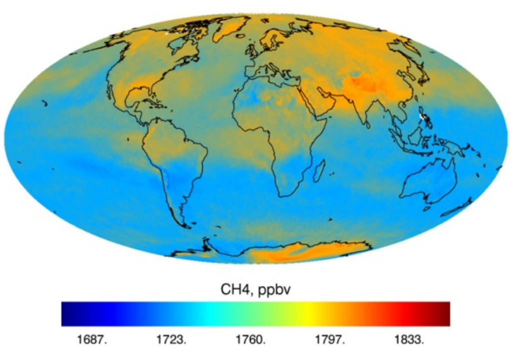
Ozone



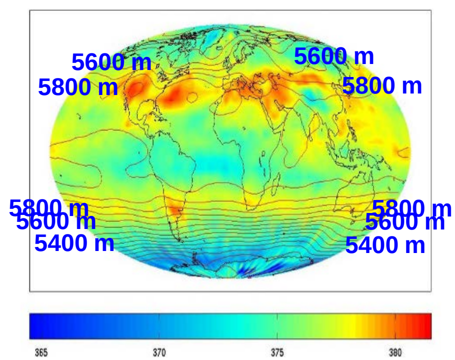
CO



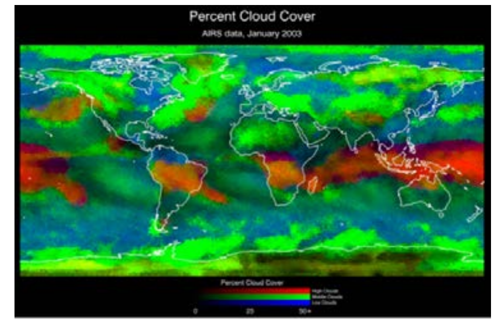
Methane



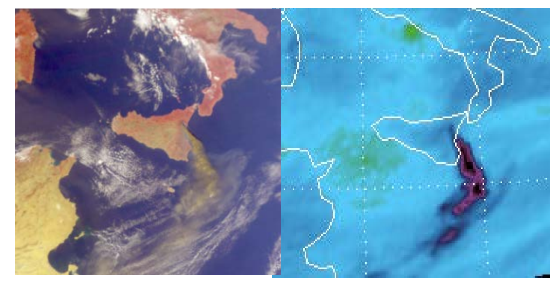
CO2



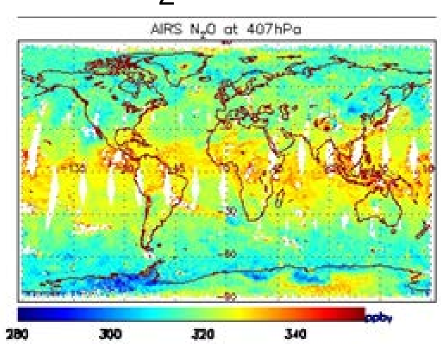
Clouds



SO_2

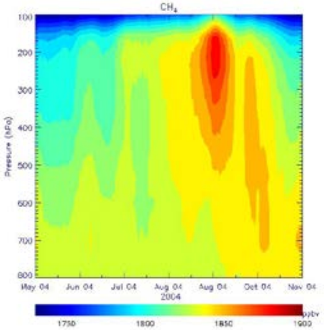


N_2O

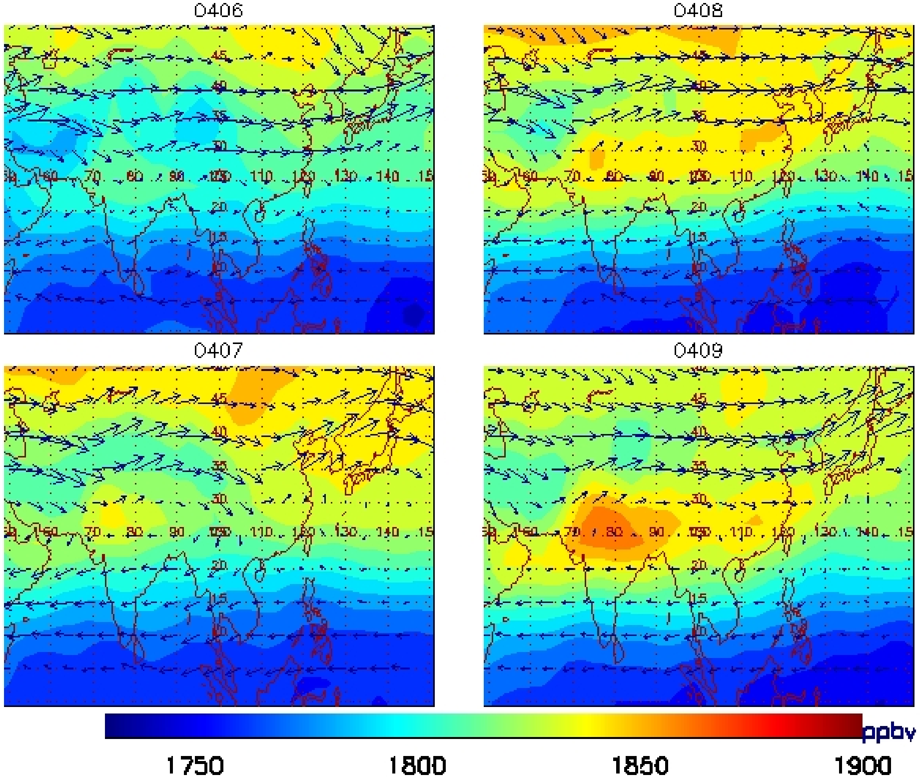


CO_2, CO and CH_4 are listed as Level-1 requirement of products of JPSS

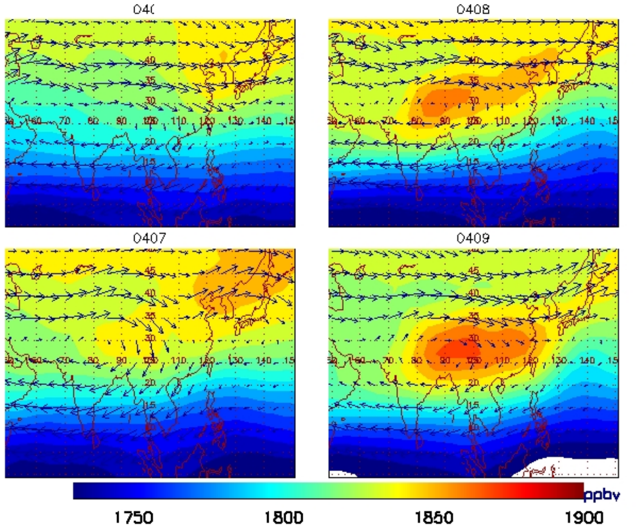
1. AIRS Observed CH_4 Enhancement over South Asia During Monsoon Season (JJAS)



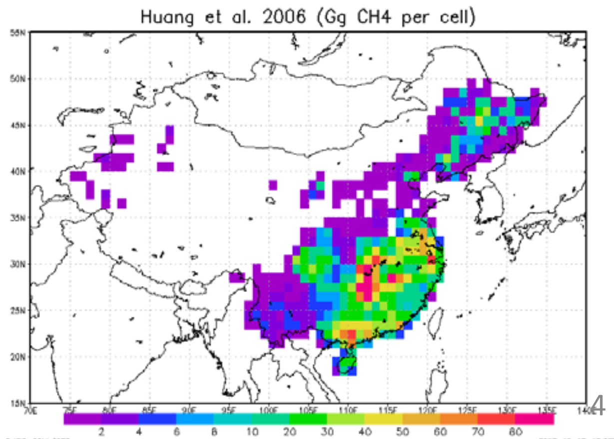
AIRS



Model

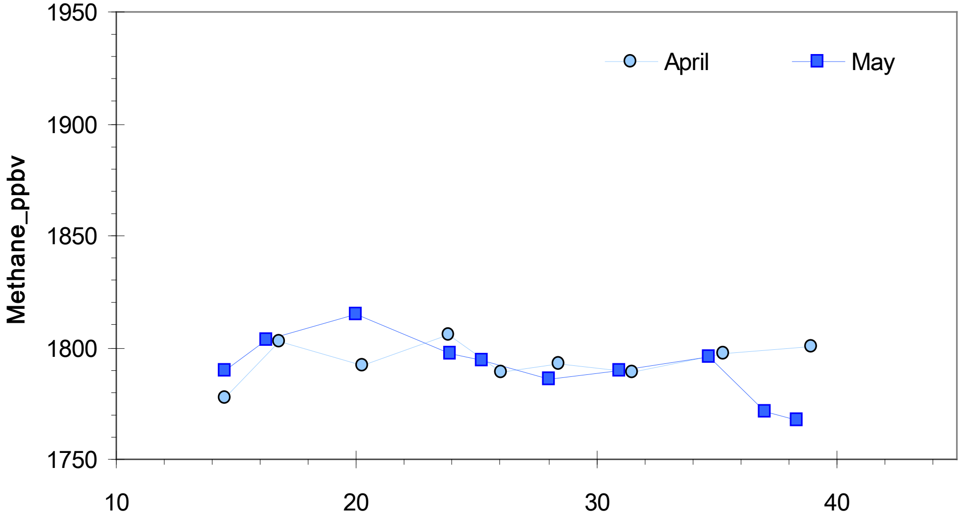


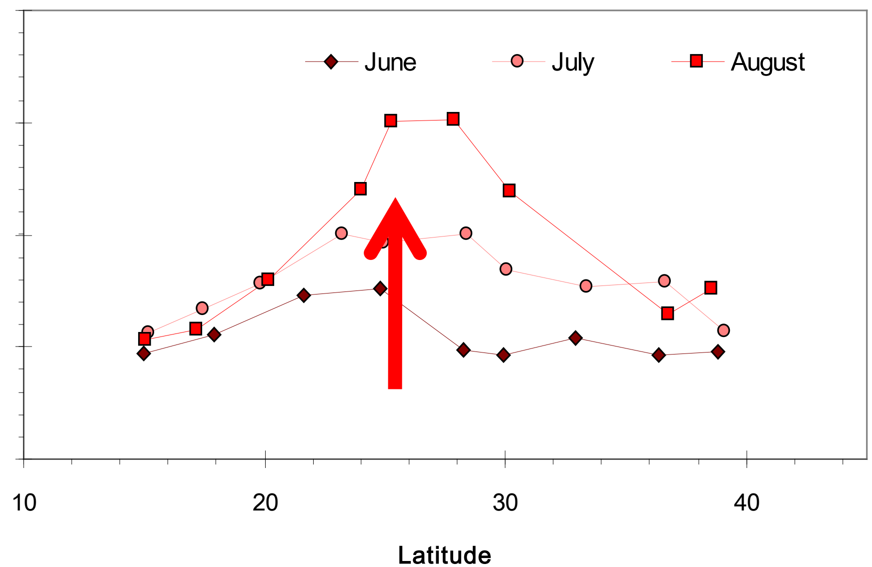
CH4 emission from rice paddies

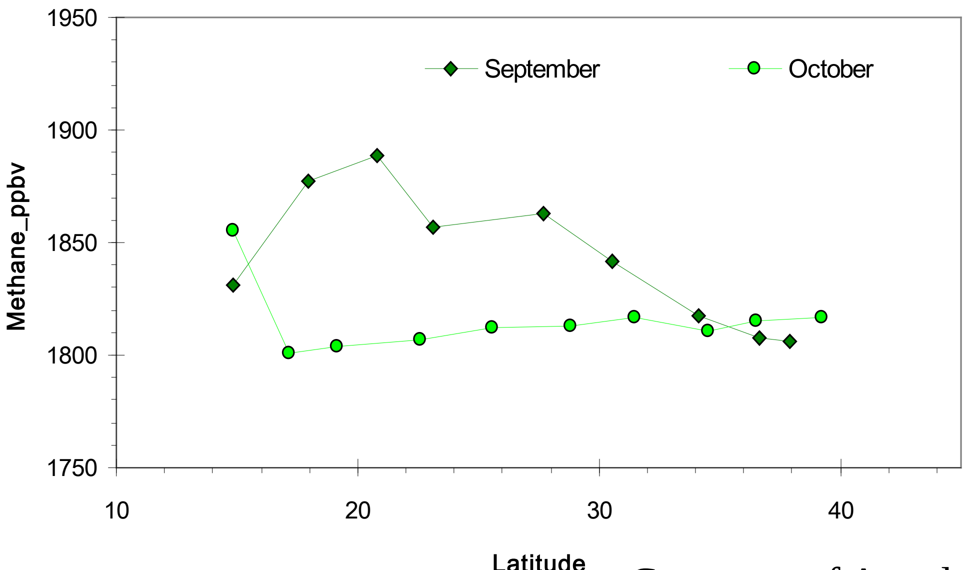


Xiong et al., Methane Plume over South Asia during the Monsoon Season: Satellite Observation and Model Simulation, ACP., 9, 783-794, 2009 .

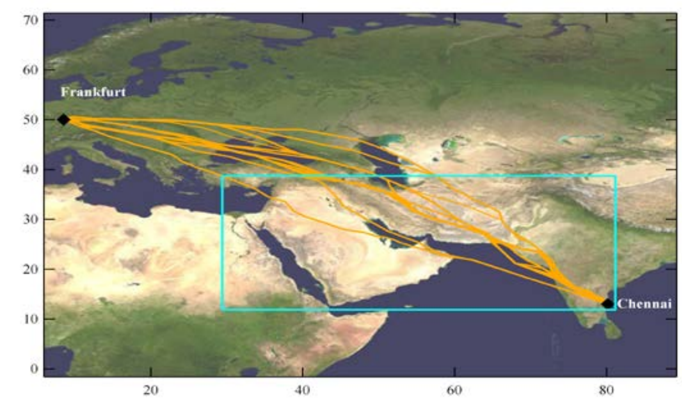
CARIBIC aircraft measurements proved significant increase of CH_4 as AIRS observed in the same time over South Asia







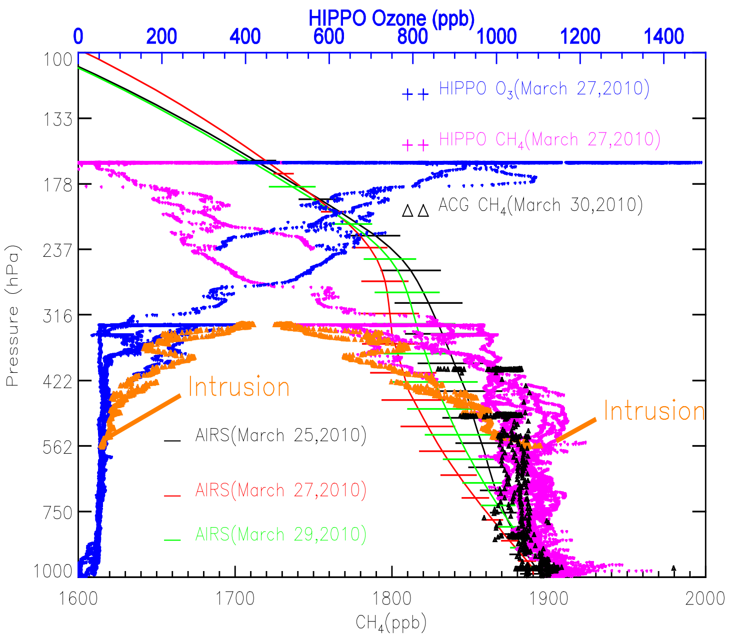
CARIBIC



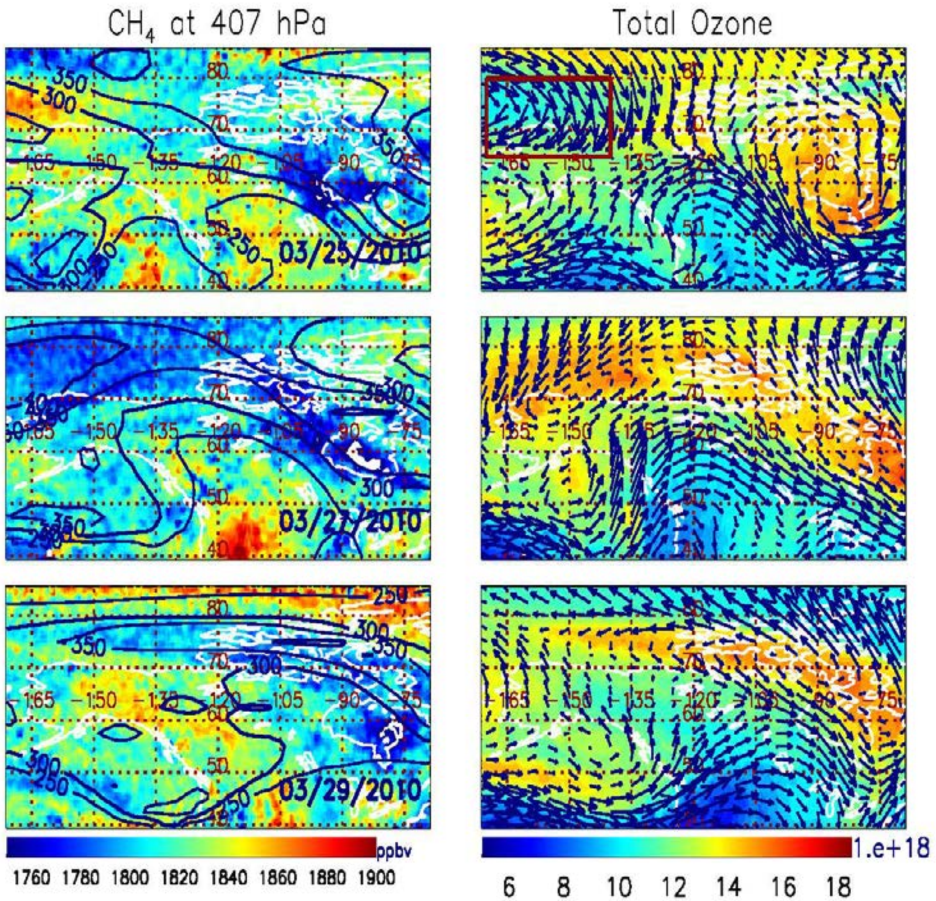
Courtesy of Angela Baker and Tanja Schuck(Schuck et al., 2010, ACP)

2. AIRS Observed the Impact of Stratospheric Intrusion to CH_4 and O_3

Aircraft Measurements



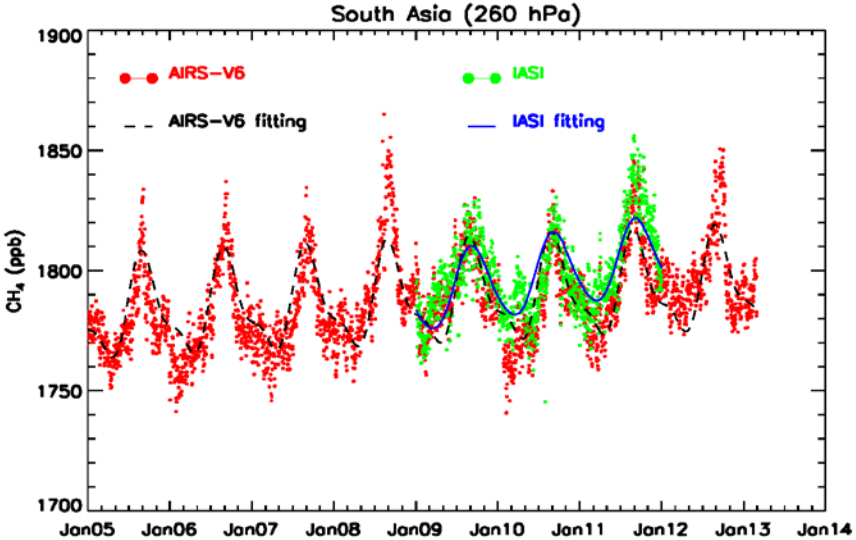
3/25, 3/27, 3/29/2010, Alaska



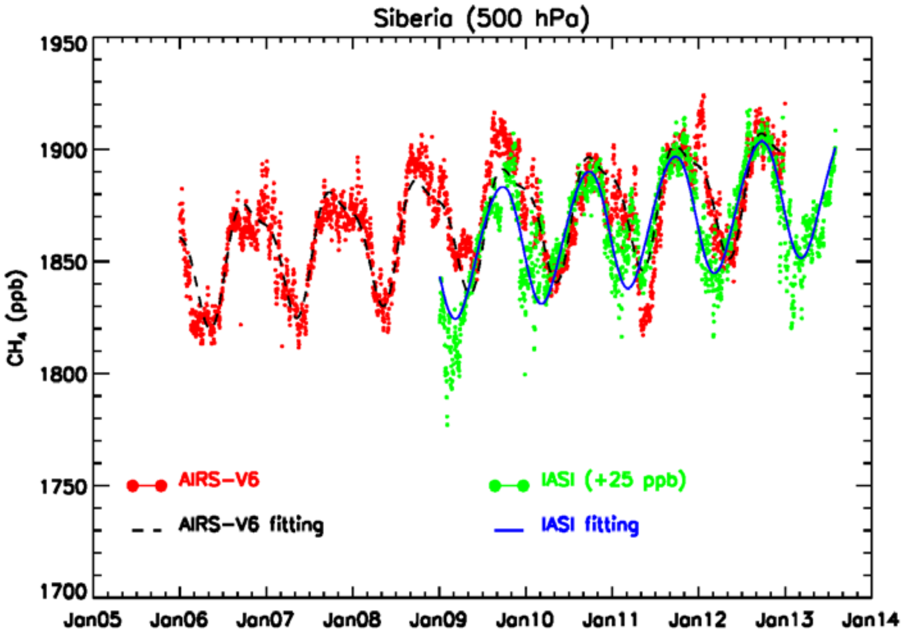
Xiong, X. , Barnet, C. D., Maddy, E., et al., 2013, Detection of Methane Depletion Associated with Stratospheric Intrusion by Atmospheric Infrared Sounder (AIRS), *GEOPHYSICAL RESEARCH LETTERS*, VOL. 40, Issue 10, Pages: 2455–2459, doi:10.1002/grl.50476, 2013.

One more study: to make a long-term product by combing AIRS and IASI CH_4 Products

South Asia: repeatable increase of CH_4 during Monsoon Season



Arctic: similar seasonal cycles from AIRS and IASI but has large difference in the cold season



Xiong et al., 2016, Comparison of Atmospheric Methane Retrievals from AIRS and IASI, IEEE JSTARS, 10.1109/JSTAR.2016.2588279

- The above examples shows that AIRS and IASI can be used to observe gases distribution in Mid-Upper troposphere, and it is likely to combine AIRS and IASI data to make a long-term product;

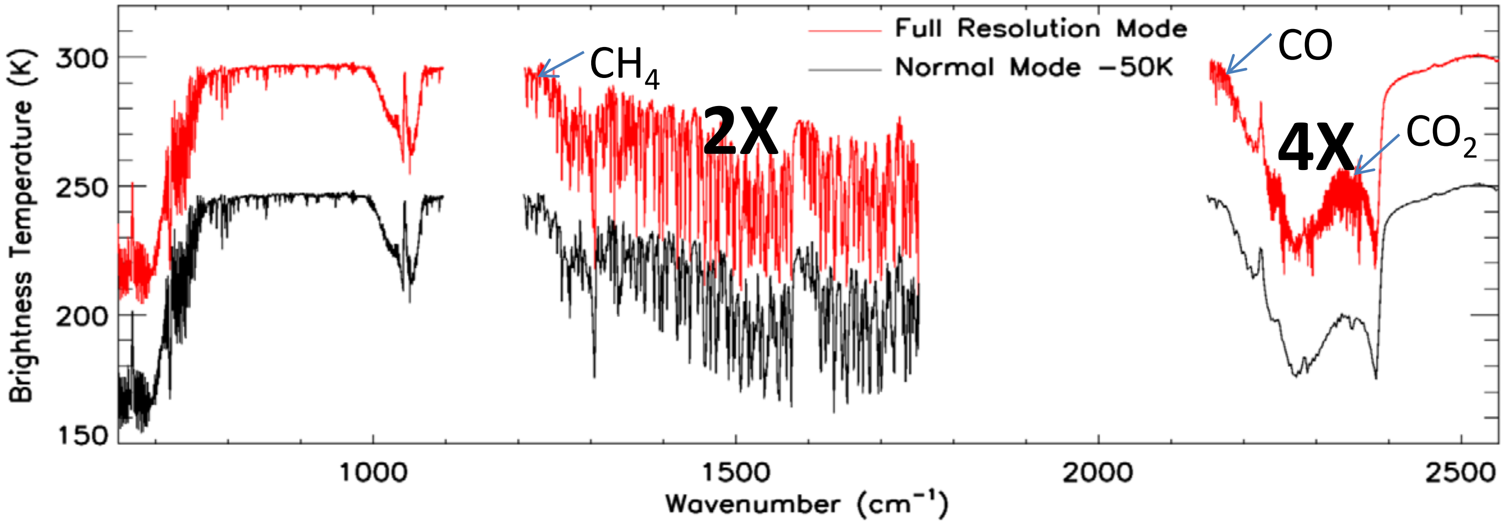
- **CrIS started to operate in the full spectral resolution (FSR) mode since Dec.4, 2014 → making it possible to retrieve trace gases .**

CrIS Normal Resolution and Full Resolution SDR

- **CrIS FSR data are available from NOAA/NESDIS/STAR, and it has 2211 channels as compared to 1305 channels in normal mode**

ftp://ftp2.star.nesdis.noaa.gov/smcd/xxiong/ **Red: Full resolution**

Frequency Band	Spectral Range (cm^{-1})	Number of Channel (unapodized)	Spectral Resolution (cm^{-1})	Effective MPD (cm)
LWIR	650 to 1095	713* (717)	0.625	0.8
MWIR	1210 to 1750	433* (437)	1.25	0.4
		865* (869)	0.625	0.8
SWIR	2155 to 2550	159* (163)	2.5	0.2
		633* (637)	0.625	0.8

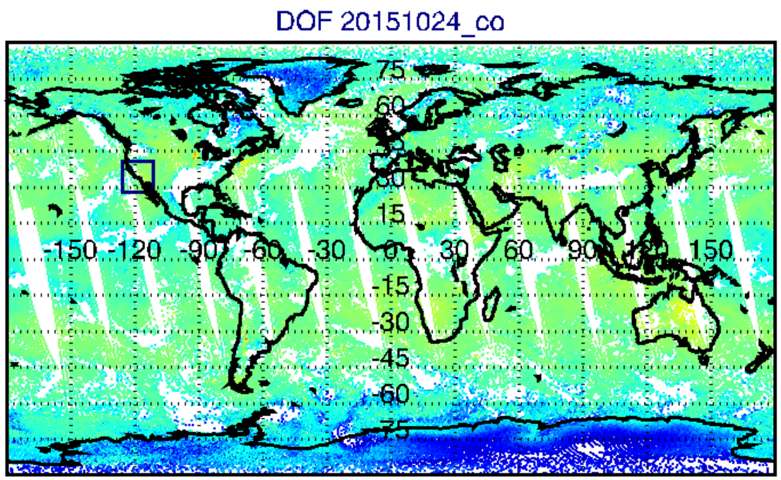


Part 2: Preliminary Assessment to CrIS Trace Gases Retrievals and Improvements

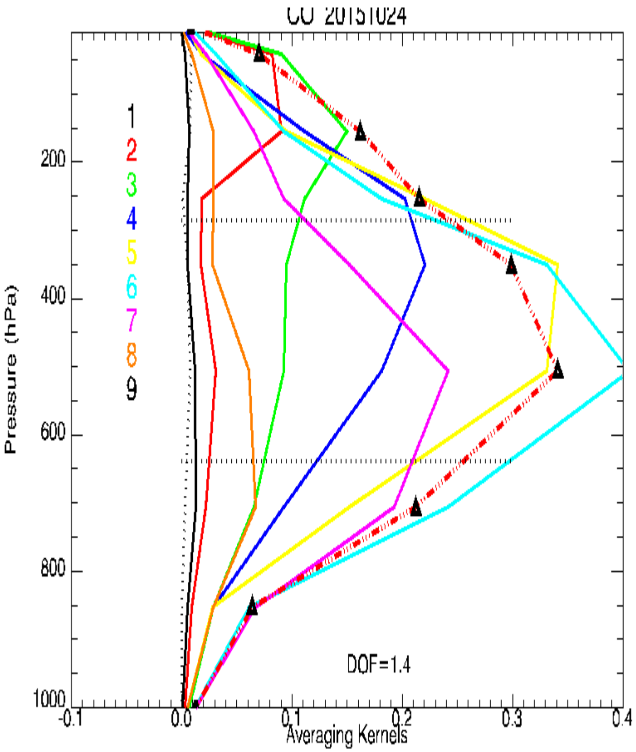
- **First check to NUCAPS trace gases retrieval averaging kernels and DOFs indicated the DOFs are much lower than AIRS and IASI;**
- **Improvements can be made after re-selection of channels, as well as the update to QC;**
- **Historically largest gas leakage in California provides a good case to test if NUCAPS can capture this leakage;**

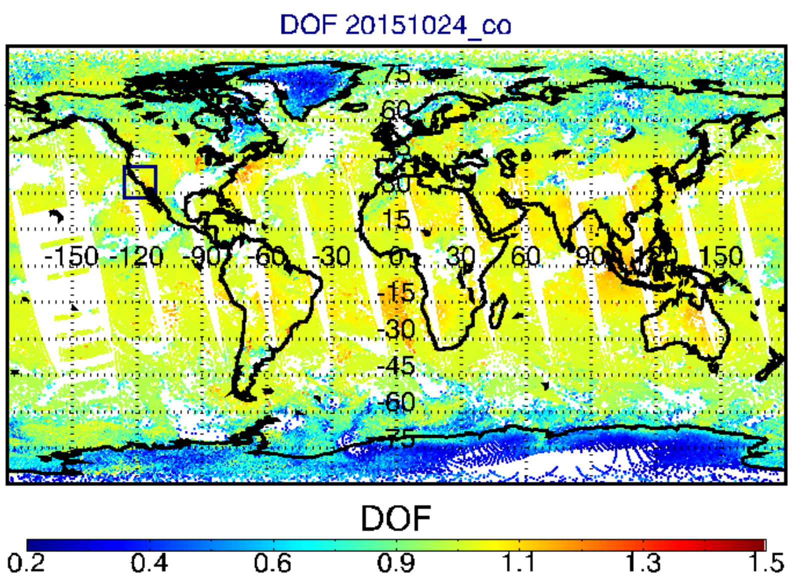
Averaging Kernels and Degree of Freedoms (DOFs) before and after Improvement for CO

Major Sensitivity: 300-650 hPa



current



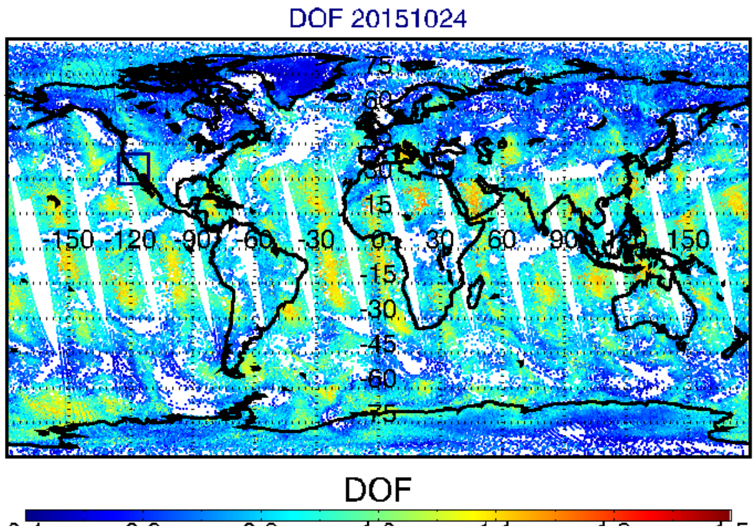


after

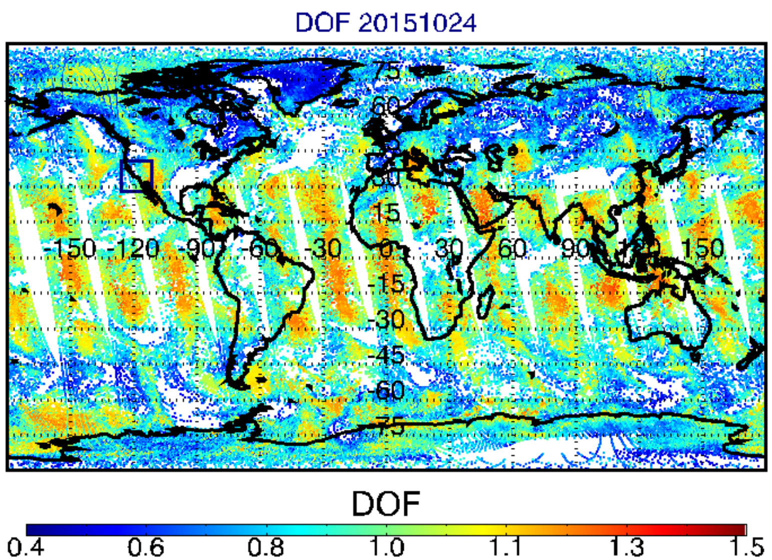
DOFs increase after the re-selection of channels

Averaging Kernels and DOFs Changes for CH_4

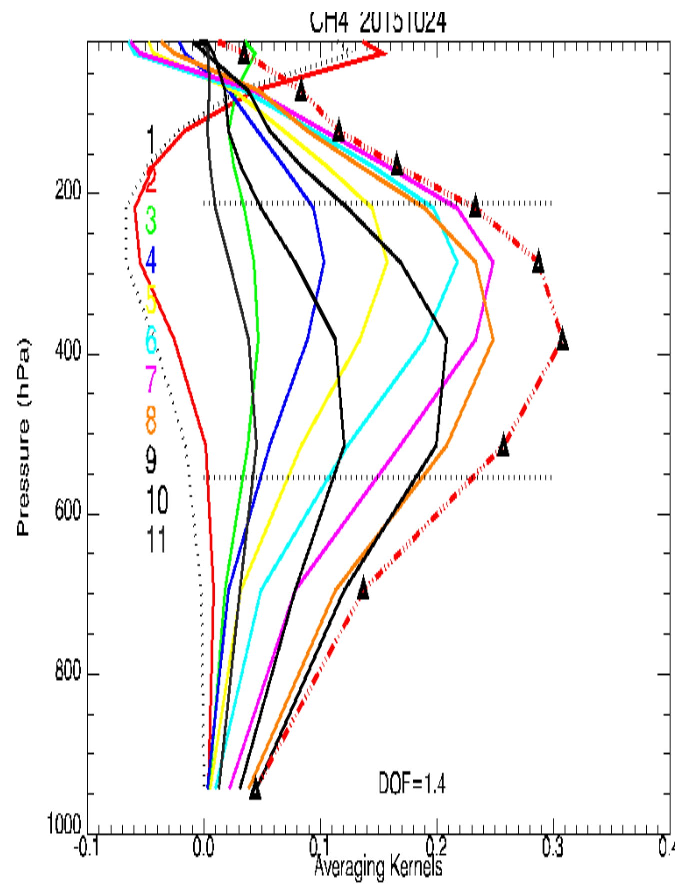
Major sensitivity: 200-550 hPa



current

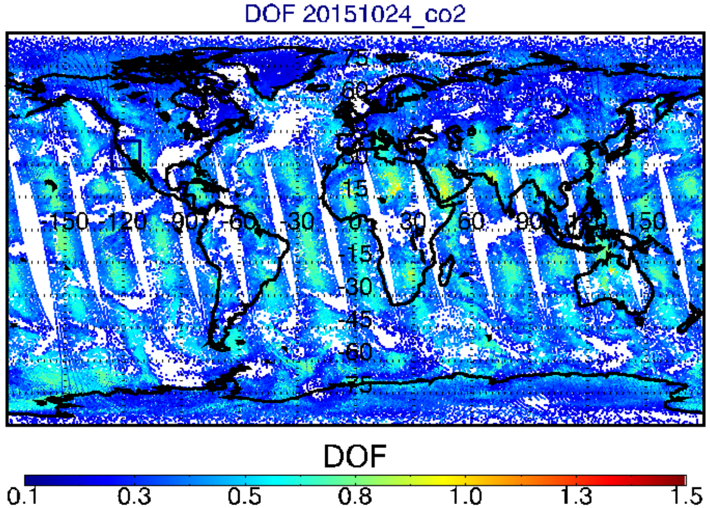


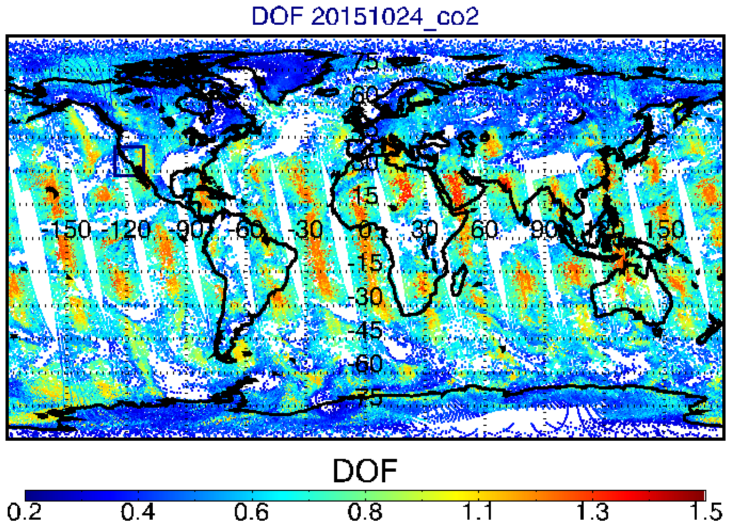
after



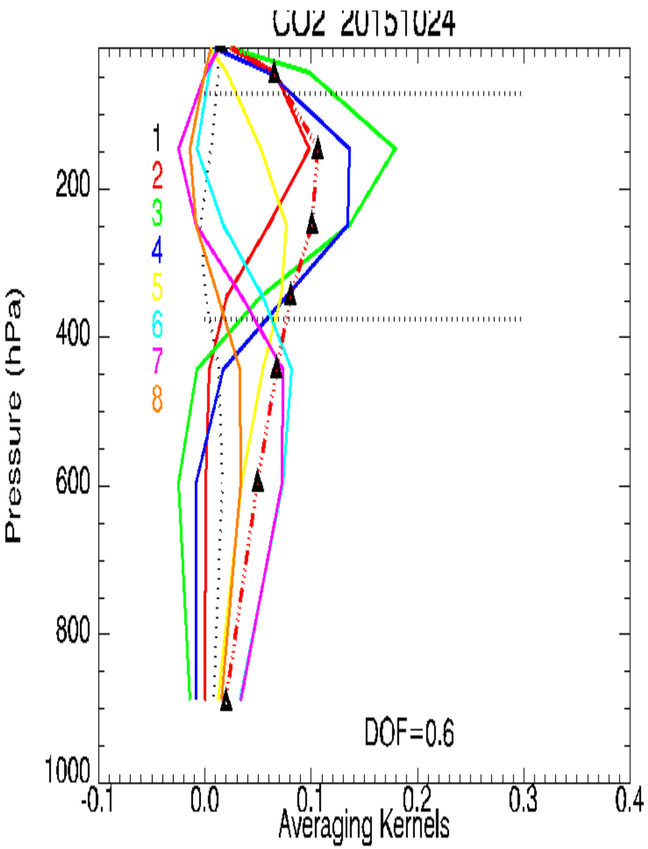
DOFs increase after the re-selection of channels

Averaging Kernels and DOFs – CO_2



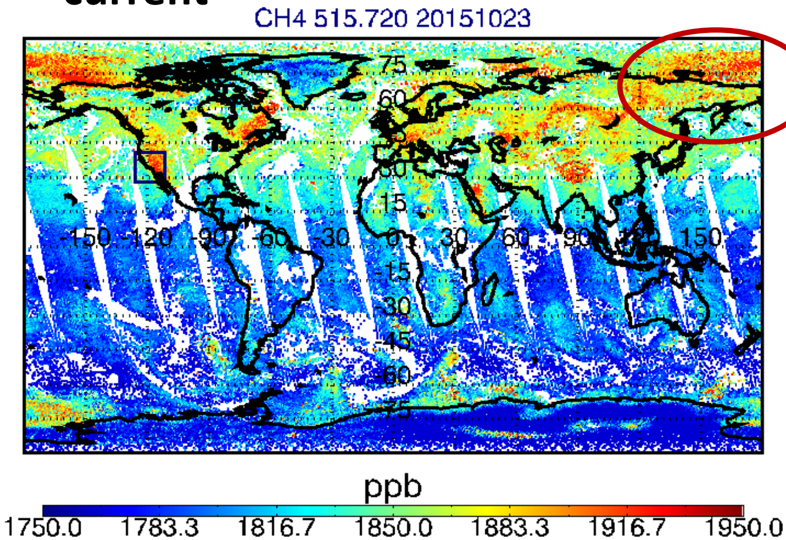


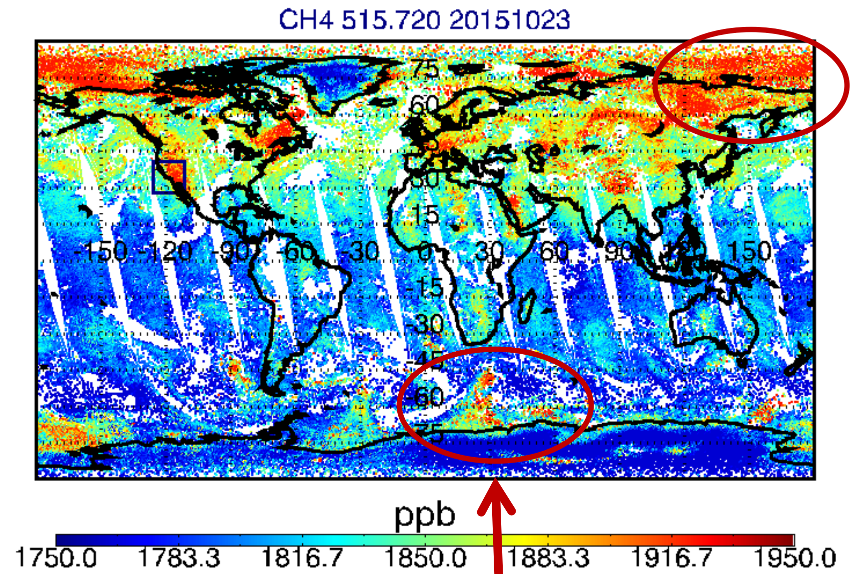
More works need to be done for CO_2



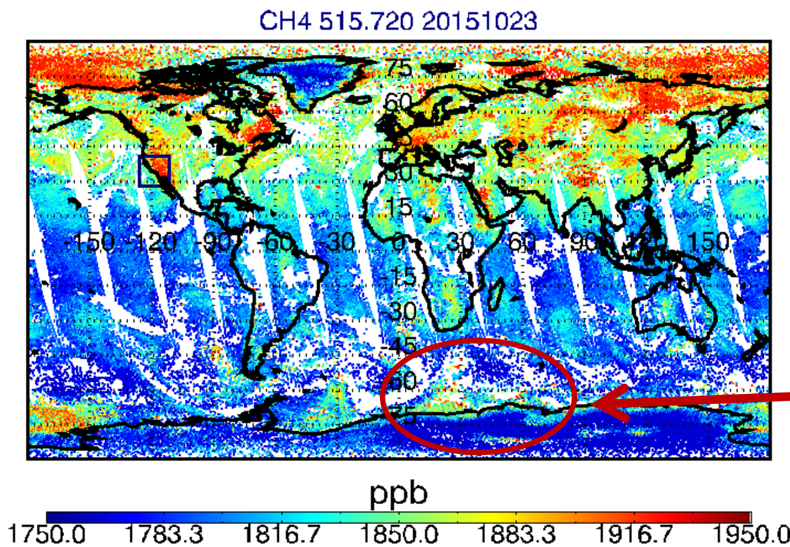
Changes of CH_4 Distribution after the re-selection of channels and update of QC (+10 ppb)

current

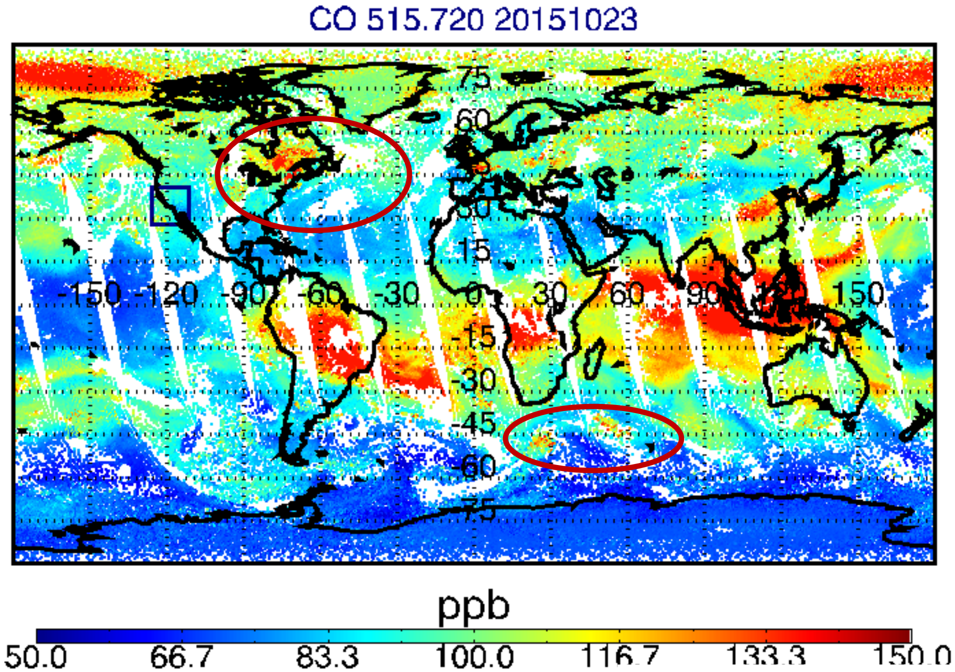




after the re-selection of channels

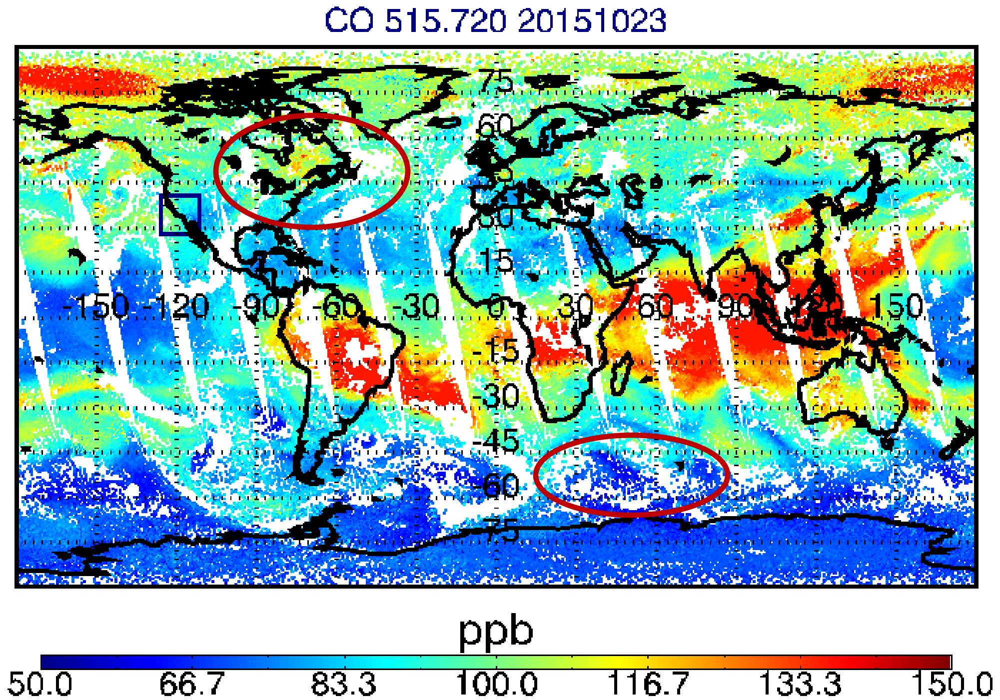


New QC



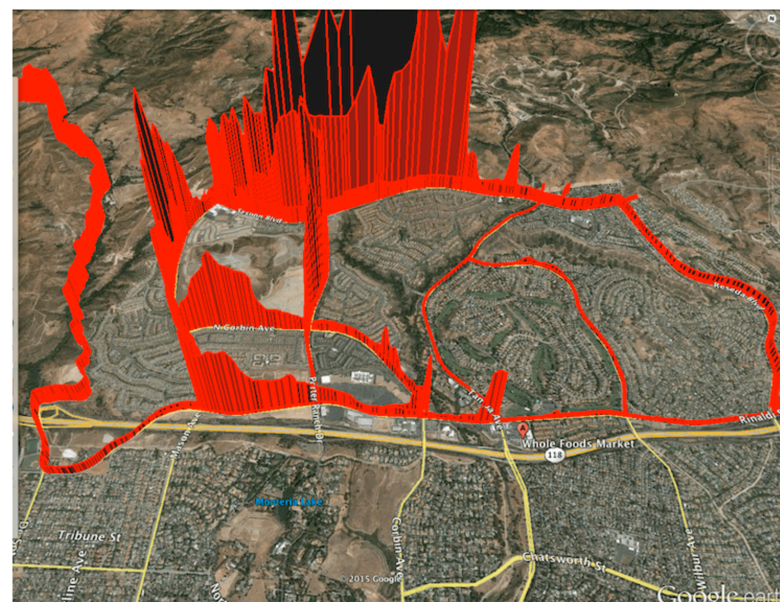
Change of CO distribution after re-selection of channels and update of QC

After



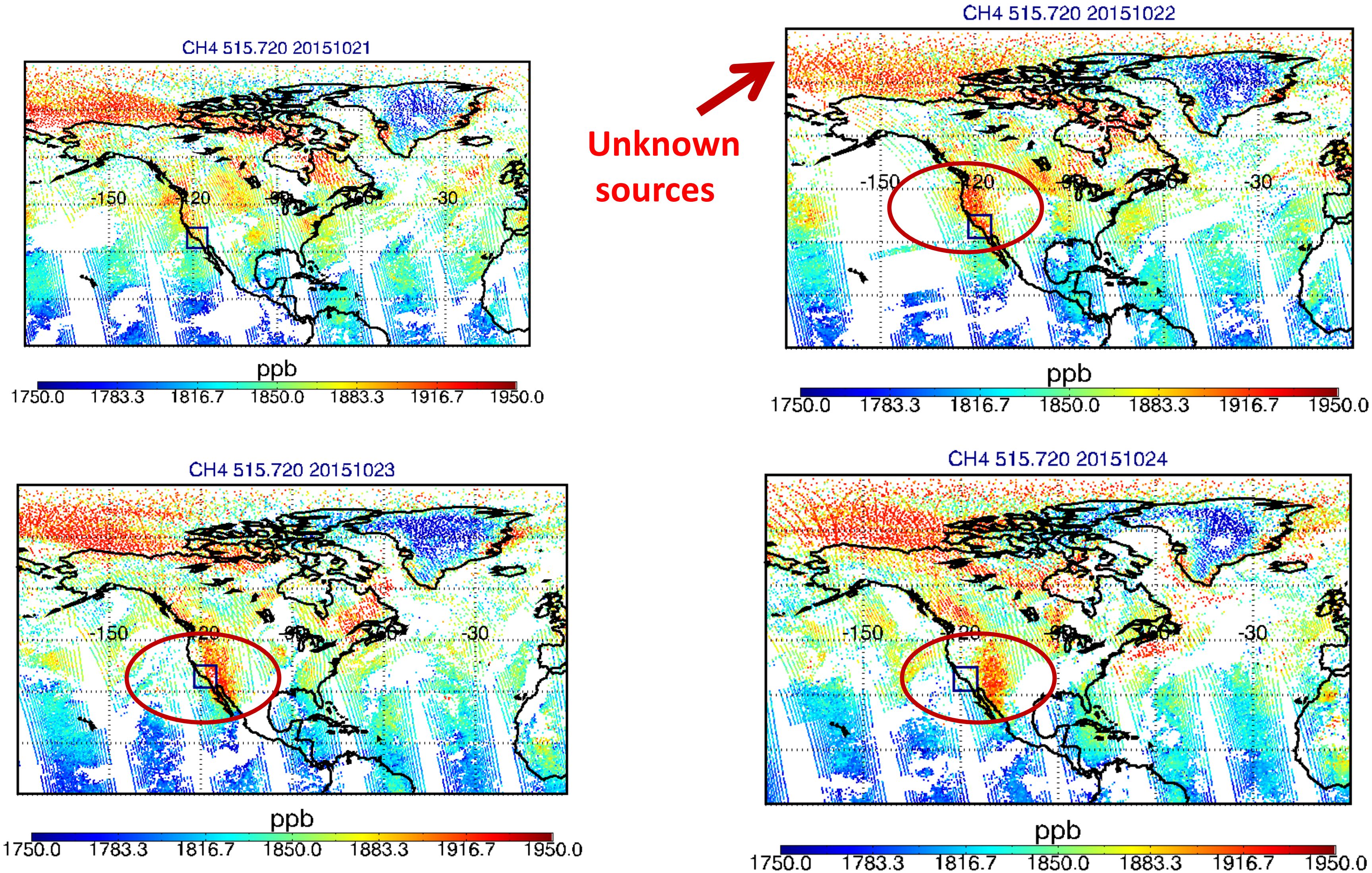
Aliso Canyon Gas Leakage (10/23/2015- 2/18/2016)

CH_4 increase from ground measurement

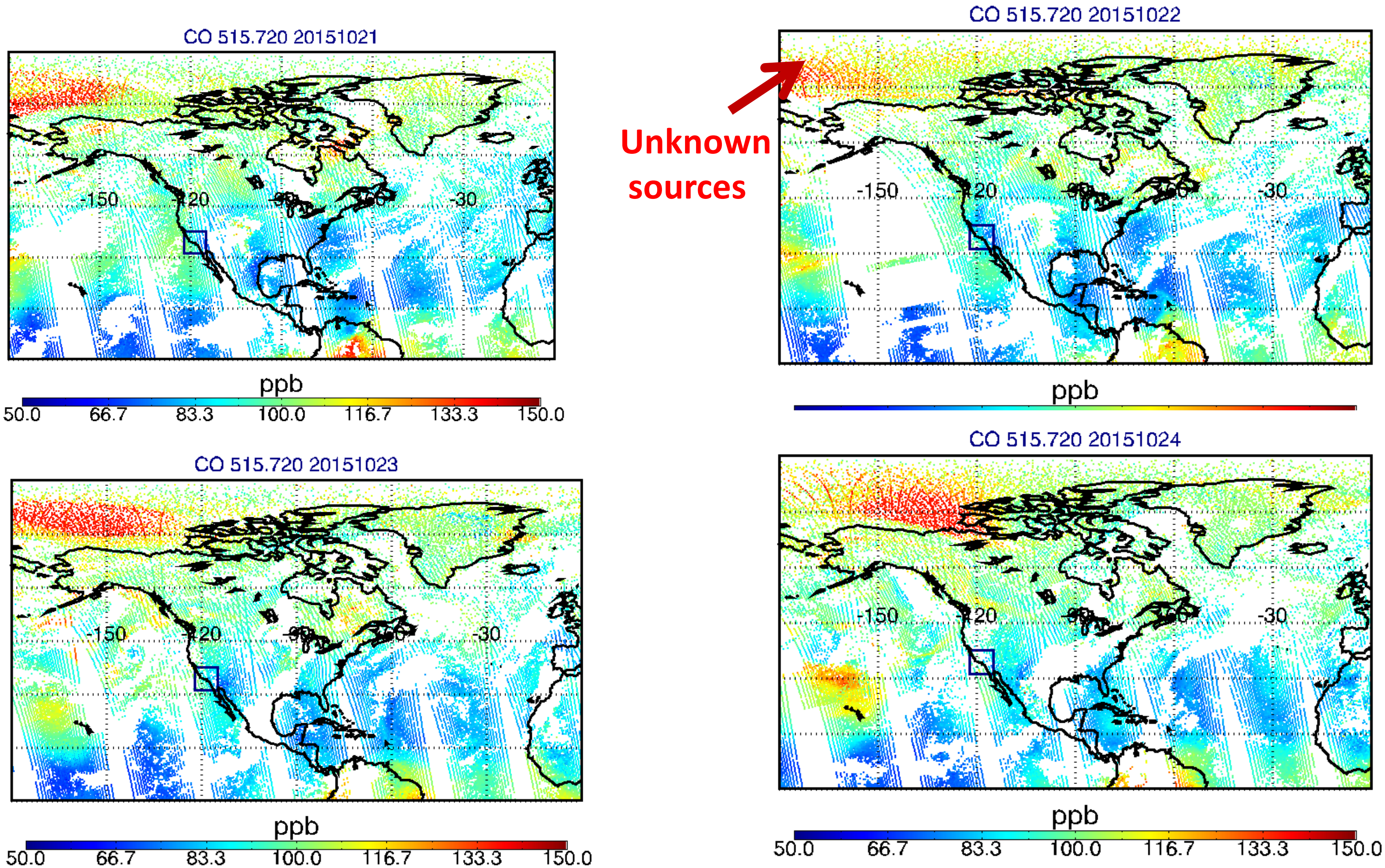


- Historically largest gas leakage -- a good case to test if NUCAPS can capture this leakage;
- CrIS retrievals for two days before the leakage (10/23/2015) and 1 week after have been made in this analysis;

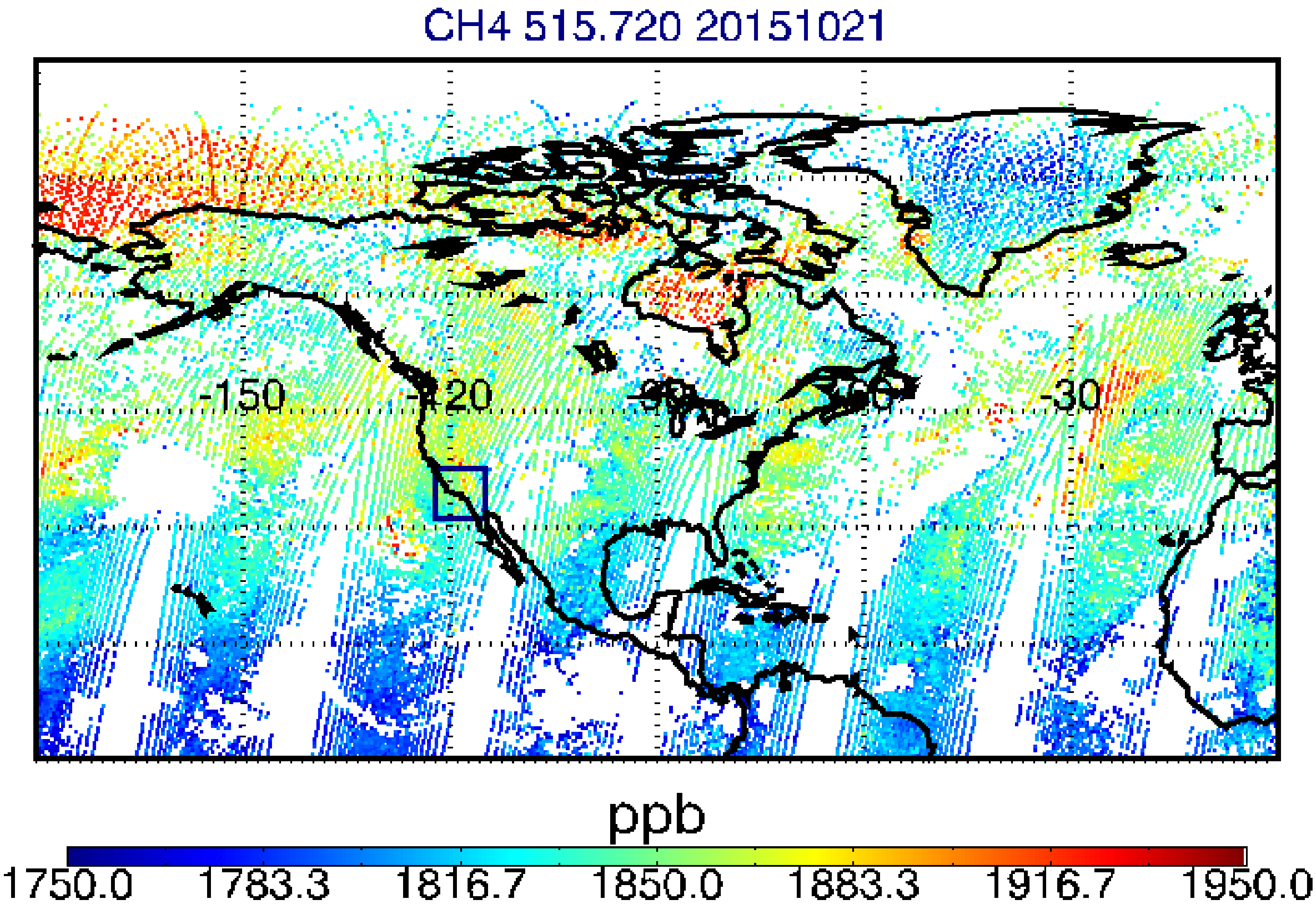
CH_4 from Ascending Node – enhanced CH_4 started in Oct.22,2015



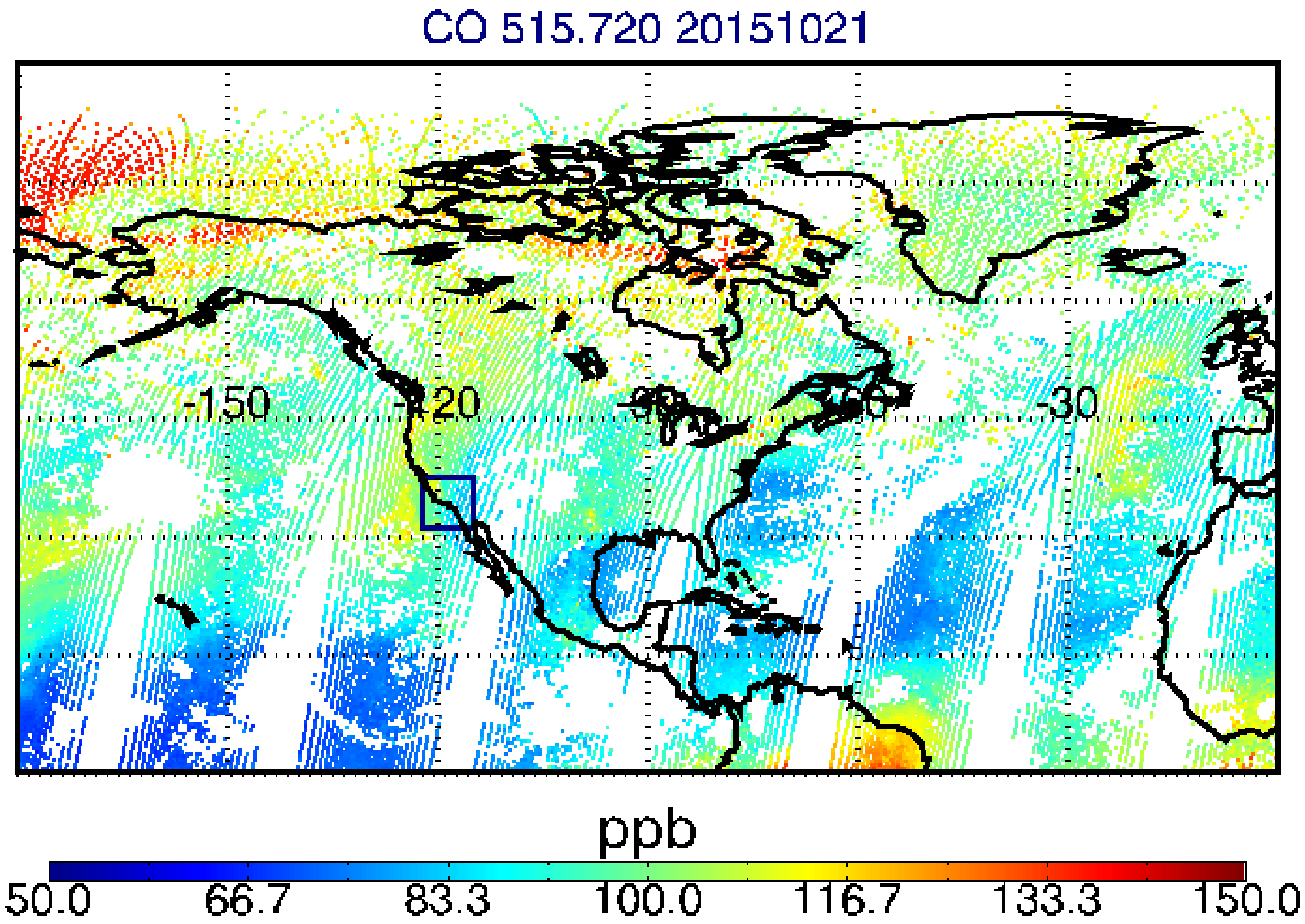
CO from Ascending Node – similar transport of CO, but sources are unknown



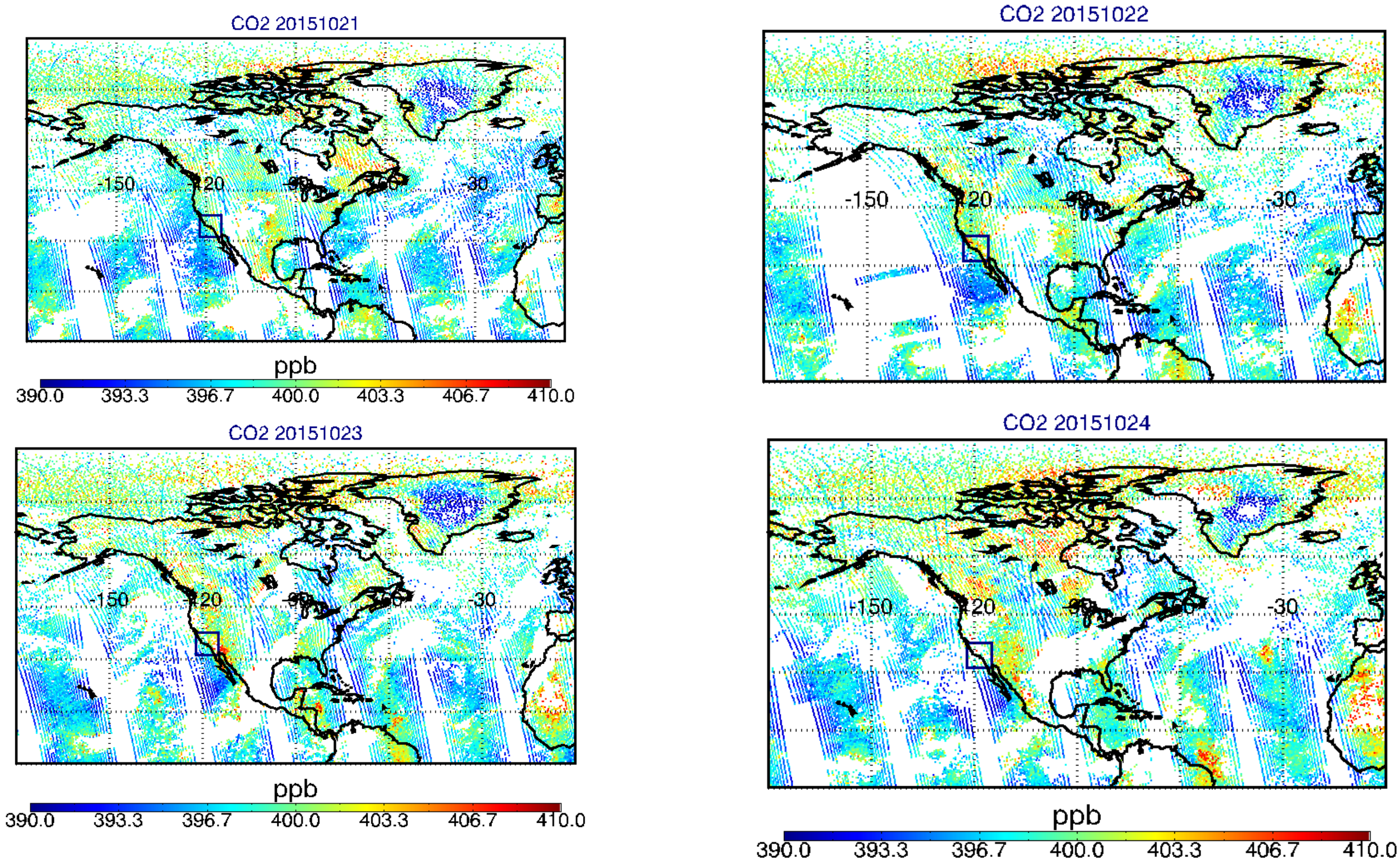
CH_4 from 10/21 – 10/29/2015



CO from 10/21 – 10/29/2015



CO_2 from Ascending Node



Summary and Future Works

1. CrIS full spectrum data can be used to retrieve trace gases with similar DOFs as AIRS and IASI, with its major sensitivity in the ***mid-upper troposphere***; however, to combine these three sensors to make a consistent product from 2002 to beyond need more works (***larger disparity existed in the Arctic between AIRS and IASI retrievals***);

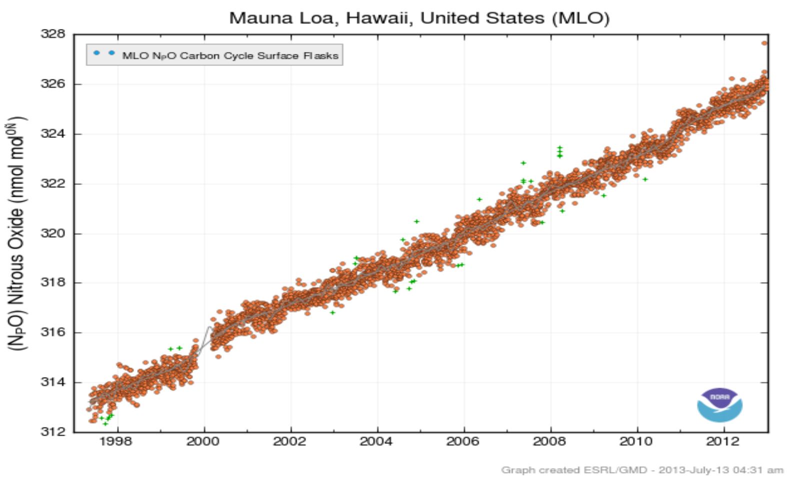
2. It is promising to use CrIS full Spectrum data to detect the leakage of CH_4 during the historically largest Gas leakage from **Aliso Canyon Oil Field and Gas Storage Facility in 2015. However,** more checks to other possible uncertainties need to be done (cloud-clearing, transport);

3. Preliminary improvements in channels selection and QC have been made, which show positive impacts to the retrieval products;

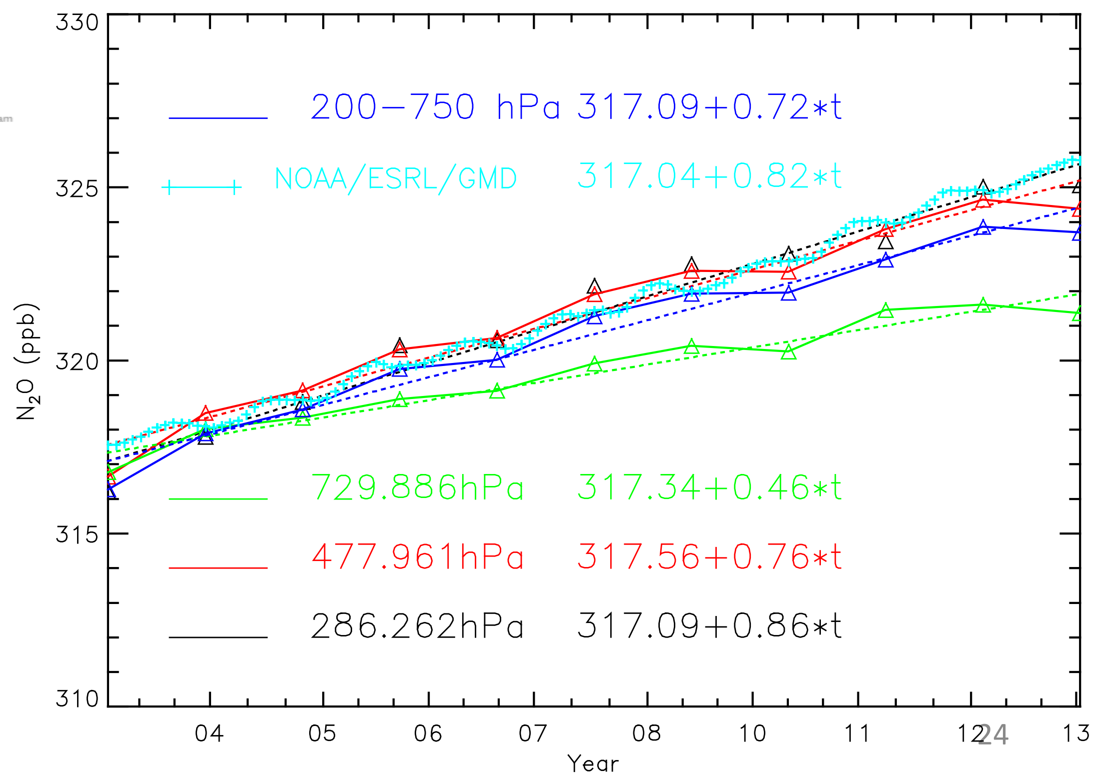
4. Validation is a key step but hampered due to lack of the measurements of trace gases profiles. Improvement to QC will be one focus of future works.

Questions/Suggestions

3. Monitoring of N_2O trend using AIRS

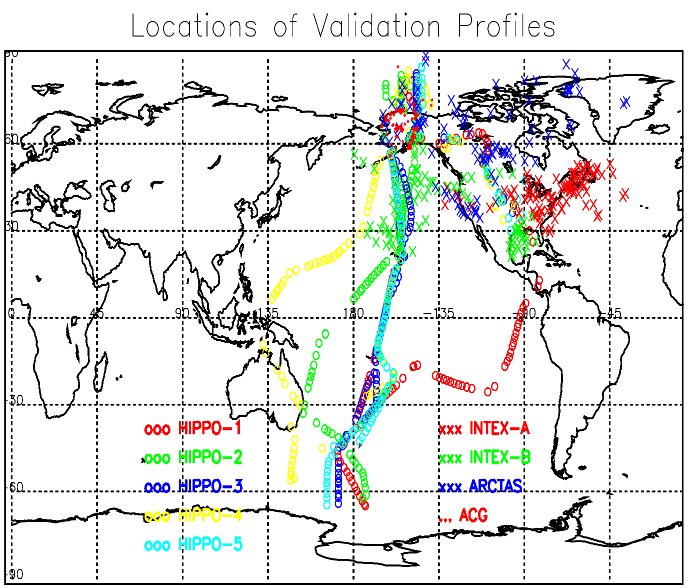


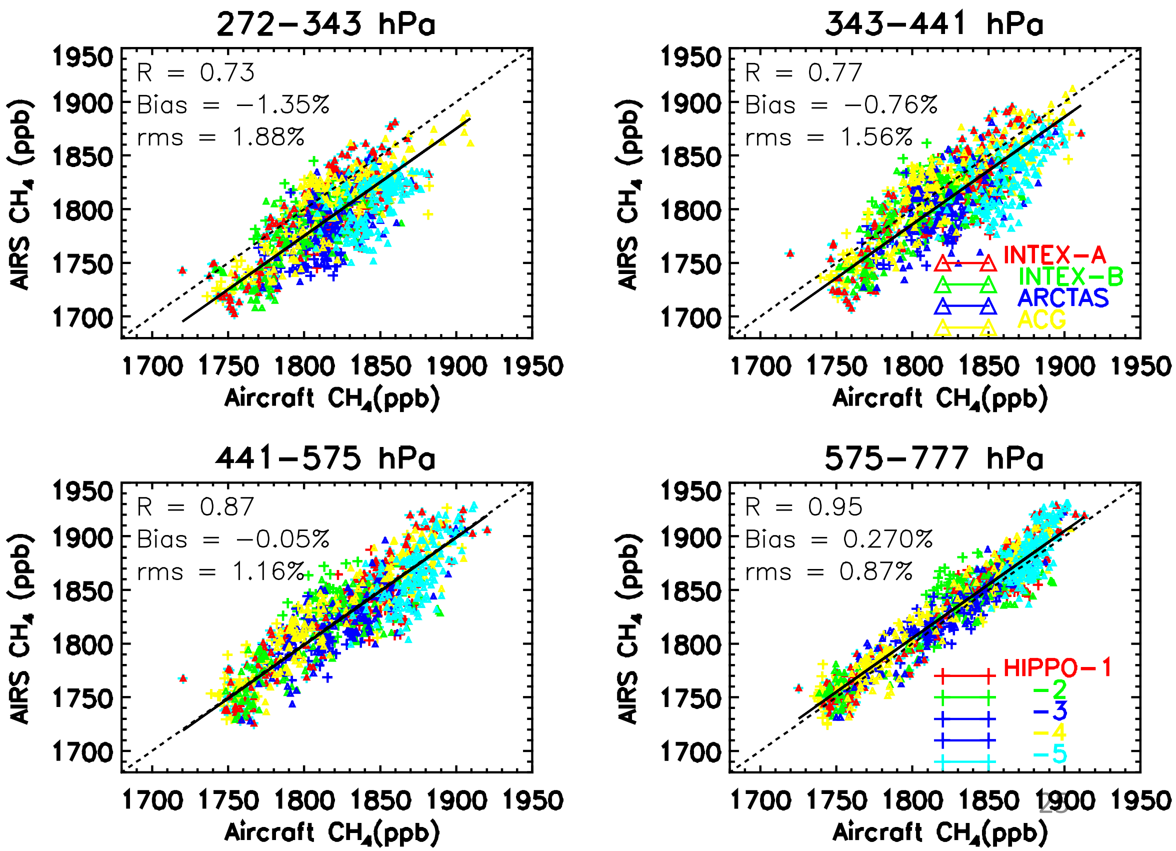
Xiong, X. et al., 2014, Retrieval of Nitrous Oxide from Atmospheric Infrared Sounder: Characterization and Validation, JGR-atmosphere, 119, doi:10.1002/2013JD021406.



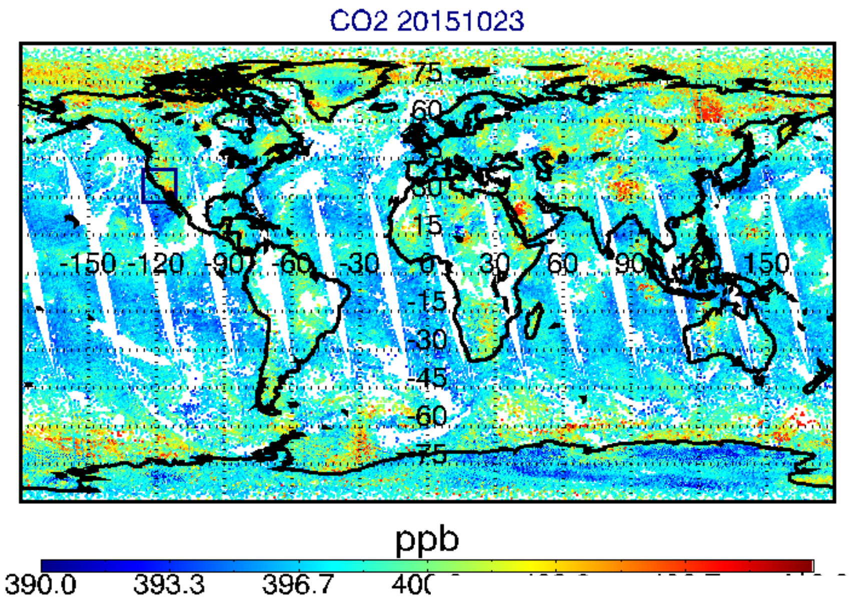
Validation: one Key step to evaluate the trace gases products

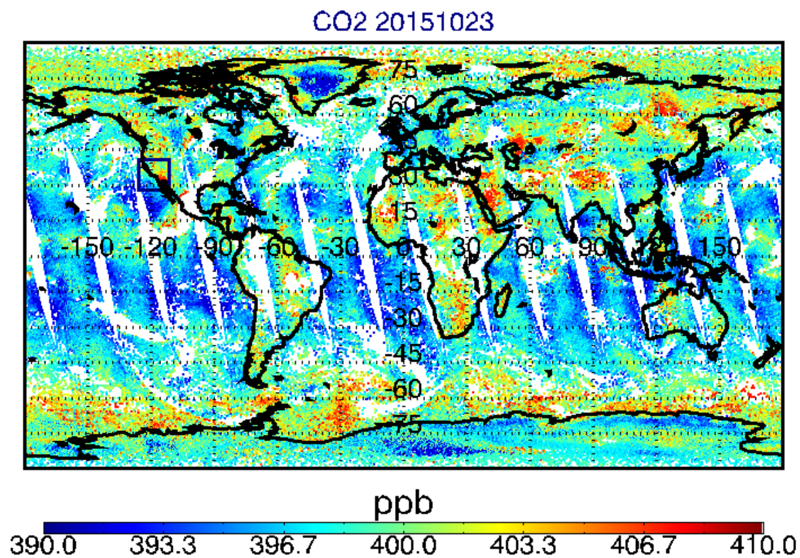
AIRS-V6 CH_4



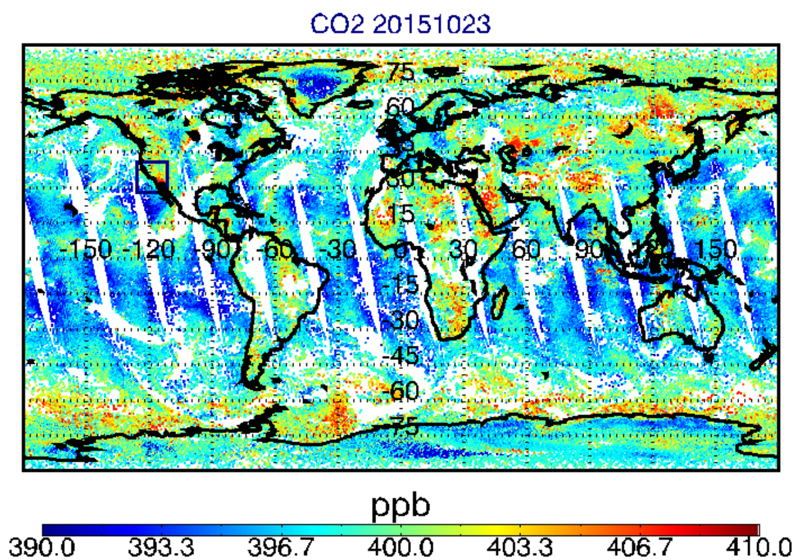


Change of CO_2

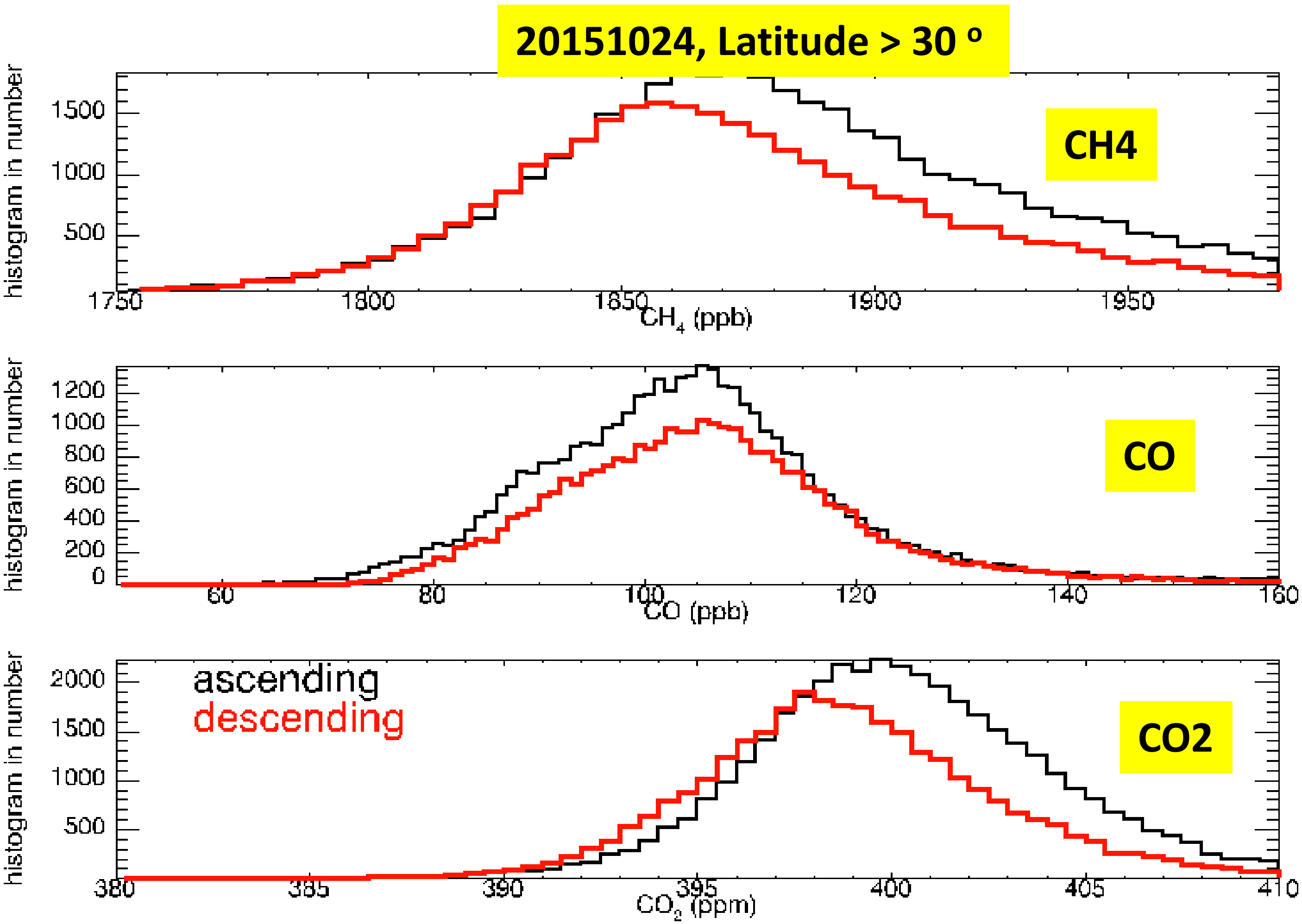




More works need to be done for CO_2



Day-night Difference



Daytime CH4 and CO2 are larger than night time, but not CO

The NOAA Operational High-Resolution CrIS Channel Selection: Impacts On NUCAPS Trace Gas Retrievals

Jonathan W. Smith[1]
Antonia Gambacorta[1], Chris Barnet[1], Nadia Smith[1], Brad Pierce[2], Walter Wolf[2], Mitch Goldberg[3]
Thursday, August 11, 2016

[1] Science and Technology Corporation
[2] NOAA/NESDIS STAR
[3] NOAA JPSS Program

Introduction

- **The Cross-Track Infrared Sounder (CrIS)** is a Fourier spectrometer covering the longwave (655-1095 cm-1, "LW"), midwave (1210-1750 cm-1, "MW"), and shortwave (2155-2550 cm-1, "SW") infrared spectral regions.

- **NUCAPS Phase I, II and III operations:**
  - Maximum geometrical path difference *L* = 0.8 cm (LW), 0.4 cm (MW) and 0.2 cm (SW)
  - Nyquist spectral sampling (*1/2L*): 0.625 cm-1, 1.25 cm-1 and 2.5 cm-1
  - Total number of channels: 1305

- **NUCAPS Phase IV operations:**
  - Maximum geometrical path difference *L* = 0.8 cm in all three bands
  - Nyquist spectral sampling (*1/2L*): 0.625 cm-1 in all three bands
  - Total number of channels: 2211 + 12 guard channels

- **<u>Motivation for a channel selection:</u>**
  - Assimilation of full radiance spectra is not computationally efficient for near real time data processing.
  - A channel selection is required to expedite both data assimilation and retrieval processes.
  - Attention must be paid to minimizing the loss of information content such that the final retrieval quality is not deteriorated.

Channel Selection Methods: Two Schools of Thought

Jacobians or Physical method

- physically-based methodology
  - channels are selected upon their spectral properties
  - each atmospheric species, we perform a spectral sensitivity analysis and retain the spectrally purest channels.
- Other than spectral purity, priority is given to:
  - vertical sensitivity properties,
  - instrumental noise
  - RTA errors.
- Jacobian method is suited for sequential steps retrieval methodologies
- works for simultaneous optimal estimation retrieval techniques.

Rodgers method

- follows a statistical iterative approach
  - channels are incrementally added after being tested against an increase in degree of freedom.
- This methodology is suited for simultaneous optimal estimation retrieval techniques.

Both methods:

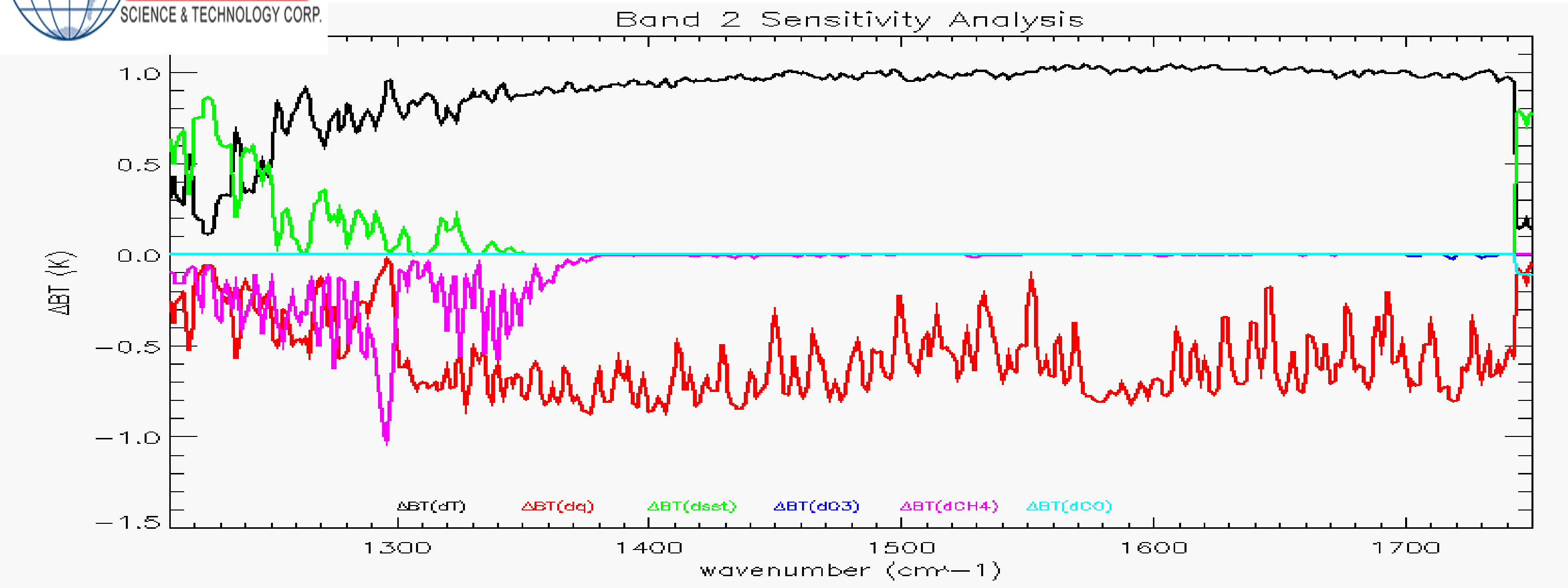
- a constant channel selection is normally used
- derived as an average from multiple optimal selections computed over different geophysical regimes (polar, mid latitudes, tropical, land, ocean, desert).

Why do we use the Jacobians method?

- NUCAPS required all sky operational products:
  - Cloud cleared radiances
  - Cloud top pressure and fraction
  - Surface temperature
  - Vertical temperature
  - Water vapor
  - Trace gases: O_3, CH_4, CO, CO_2, SO_2, N_2O, HNO_3
    - Future candidates:
      - NH_3 (Ammonia), HCO_2H (Formic Acid), $CH_3COOONO_2$ ("PAN")
- Most channels are largely contaminated by clouds, temperature and water vapor signals.
- A "**trace gas"** is a gas which makes up less than 1% of the volume of the Earth's atmosphere.
- Trace gas radiative signals are in the range of the instrument noise.
- Answer: *Spectral purity combined with a sequential retrieval approach is essential for the retrieval of the full list of NUCAPS products, particularly for trace gases, under all sky conditions.*
- In depth description available in:

A.Gambacorta and C.Barnet, Methodology and information content of the NOAA NESDIS operational channel selection for the Cross-Track Infrared Sounder (CrIS), IEEE Transaction on geoscience and remote sensing.
Vol. 51, No. 6, 2013. DOI: 10.1109/TGRS.2012.2220369

Spectral Purity Analysis (band 2)



SST	1K
T	1K
H_2O	10%
O_3	10%
CH_4	2%
CO	1%

Brightness temperature difference (ΔBT) terms represent the sensitivity of each channel to a given perturbation species and are indicative of the degree of *"spectral purity"* of each channel.

- Perturb these gases (left column) by that amount or percentage (right column), you obtain a perturbation (ΔBT) in brightness temperature (figure above).

- The magnitude of ΔBT describes how sensitive a channel is to the perturbed species.

- You select those channels that tend to be sensitive to only your species of interest with minimum interference from the other species.

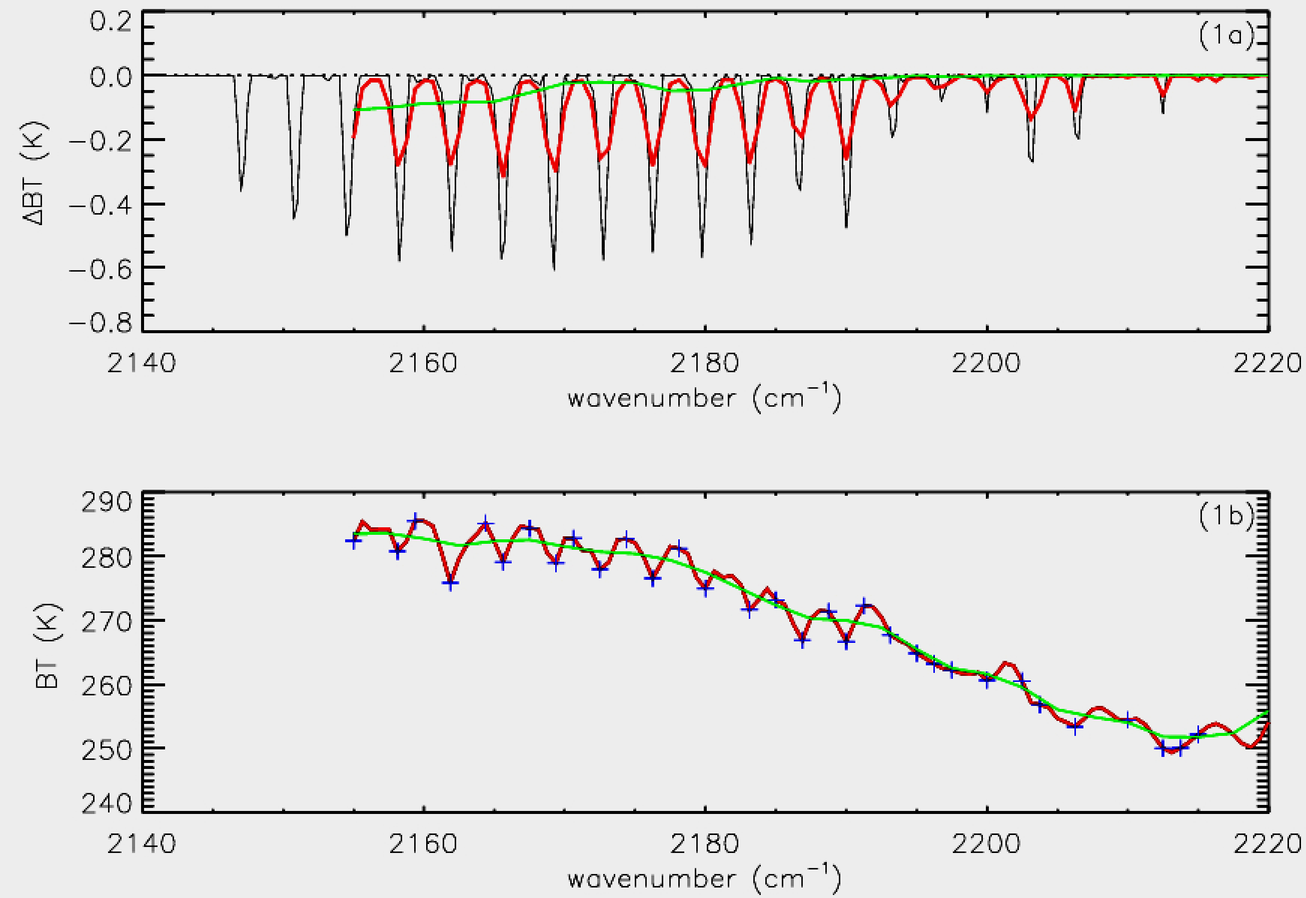
- You still account for the residual interference as an error term in the retrieval measurement error covariance.

CO Channel Selection

A test case study from the 1 May 2016 (Ft. McMurray, Alberta Fire Case)

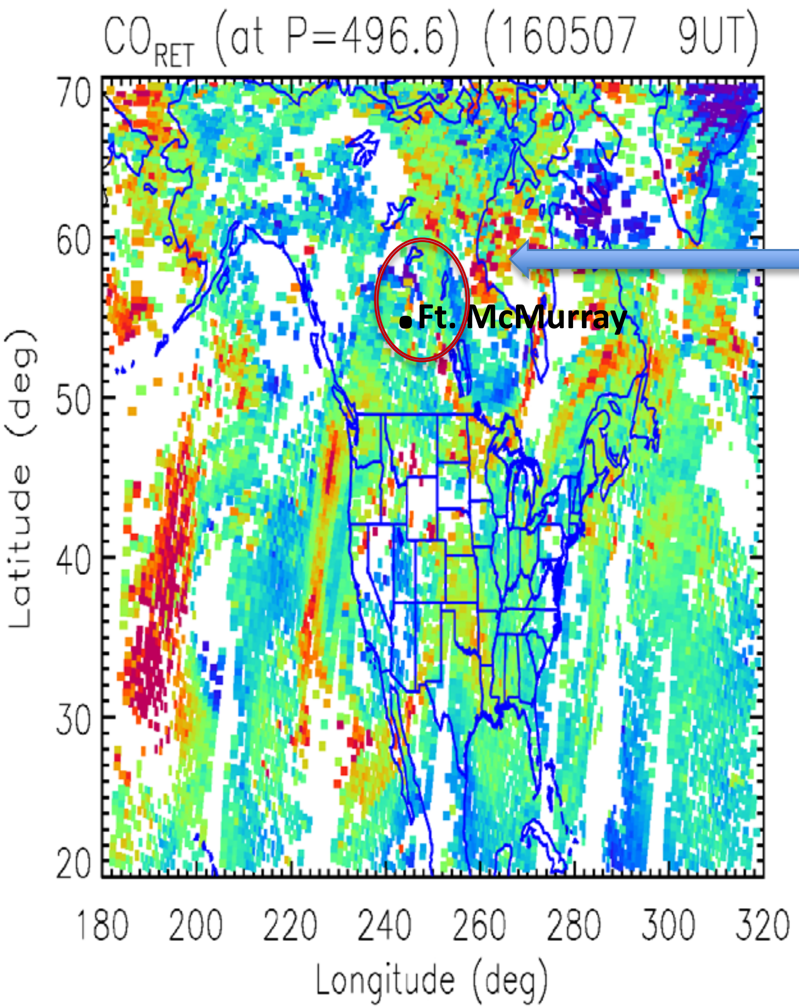
Sensitivity Analysis to 1% CO perturbation

2.5cm^-1 0.625 cm^-1 0.25cm ^-1



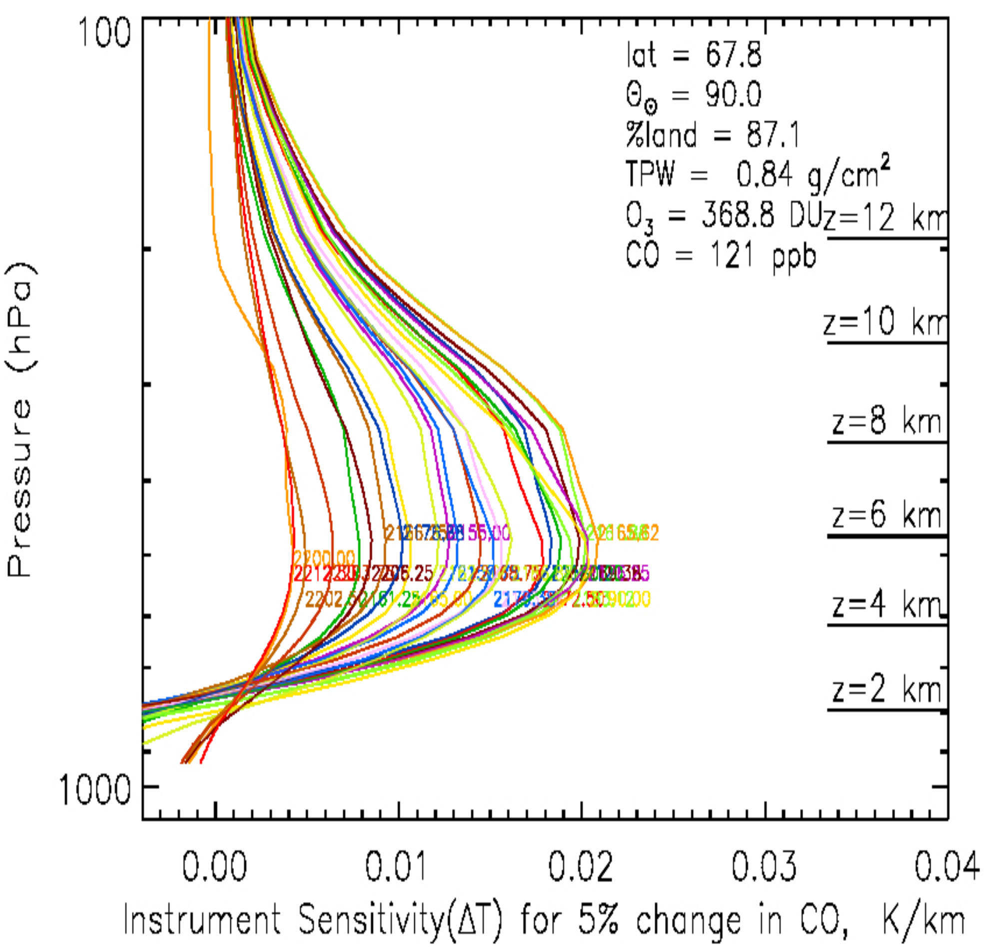
- Why you are showing the CO case?
  - Only when switched to high spectral resolution, CrIS spectrum (red curve, bottom part) shows the distinctive signature of CO absorption (red and black curve, top figure).
  - Blue cross symbols: CO high resolution channel selection.

Fire Case Study



- 7 May 2016 NUCAPS retrieval over North America
- Highlighting the Ft. McMurray, Alberta Fire
- Pressure level: 496.62 hPa
- 120+ ppbv over fire

CO channel selection for Ft. McMurray, Alberta fire case



- The selection was made on multiple geophysical regimes (polar, mid-latitude, tropics, and fire) to
  - ensure global applicability.
  - examine polluted vs relatively clear regimes.
- We are testing CO selection over focus areas to ensure global optimality and to serve users needs

NUCAPS High Res Trace Gas Product Evaluation

- Initiative is based on 2 recently funded JPSS proposals.
  1. Greg Frost: "Understanding emissions and tropospheric chemistry using NUCAPS and VIIRS"
  2. Brad Pierce: "High Resolution Trajectory-Based Smoke Forecasts using VIIRS Aerosol Optical Depth and NUCAPS Carbon Monoxide Retrievals "

- Models are used to interpolate the sparse aircraft observations to the satellite temporal, spatial, and vertical sampling characteristics for detailed validation

- NUCAPS (and AOD f/ VIIRS) will be used within IDEA (Infusing Satellite Data into Envir. AQ Applications)

  http://www.star.nesdis.noaa.gov/smcd/spb/aq/

Future Work: Maintenance and Optimization

- *We will re optimize and deliver the channel selection once the new version of the RTA is delivered*
- Expected improvements
  - NON LTE and water vapor regions
- Continue to run NUCAPS various global cases
- Channel selection for IASI
- Continue to ensure that users obtain the best products

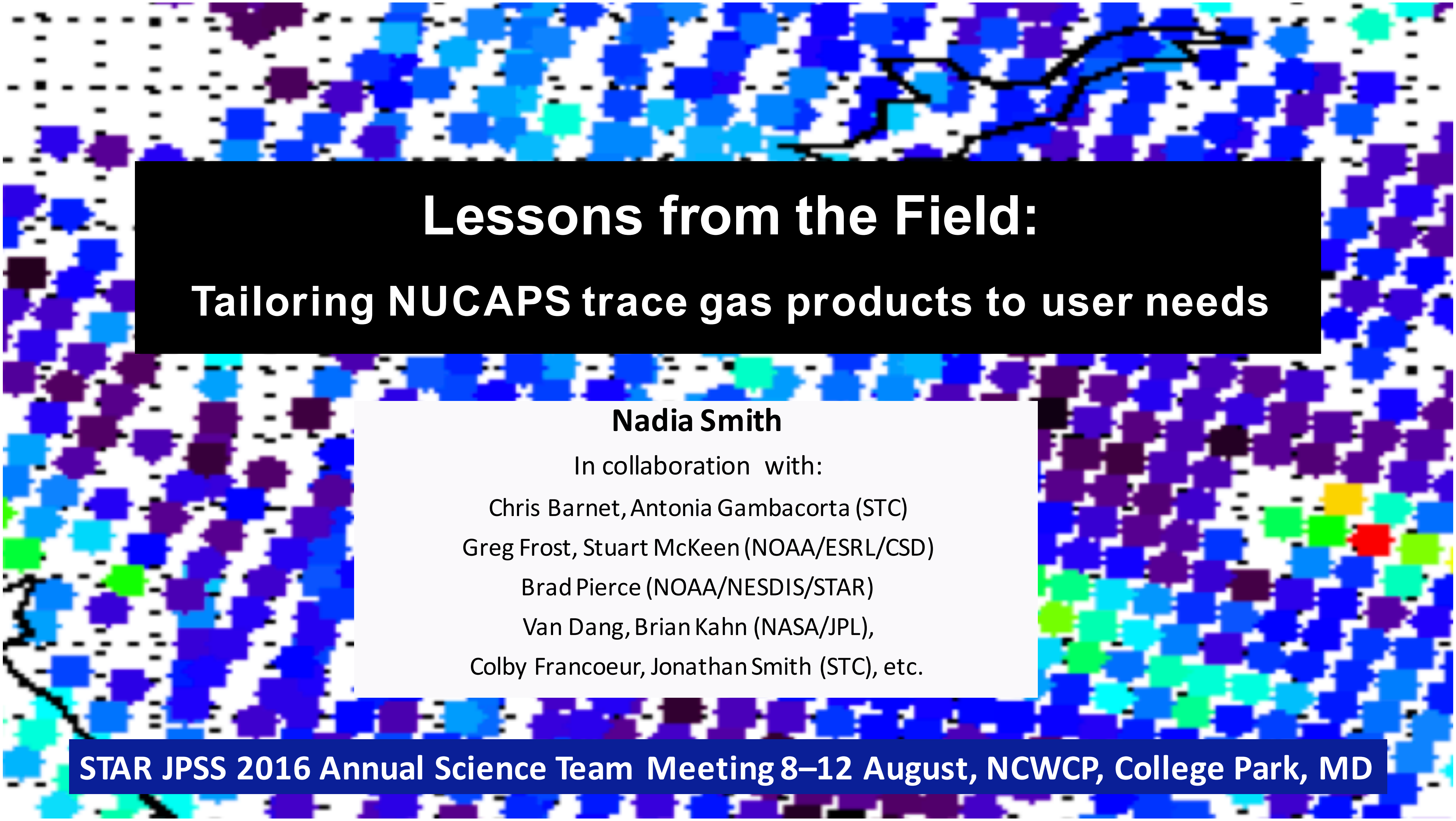
Acknowledgements

Walter Wolf

Larabee Strow

Tom King

Lihang Zhou



Lessons from the Field:

Tailoring NUCAPS trace gas products to user needs

Nadia Smith

In collaboration with:

Chris Barnet, Antonia Gambacorta (STC)

Greg Frost, Stuart McKeen (NOAA/ESRL/CSD)

Brad Pierce (NOAA/NESDIS/STAR)

Van Dang, Brian Kahn (NASA/JPL),

Colby Francoeur, Jonathan Smith (STC), etc.

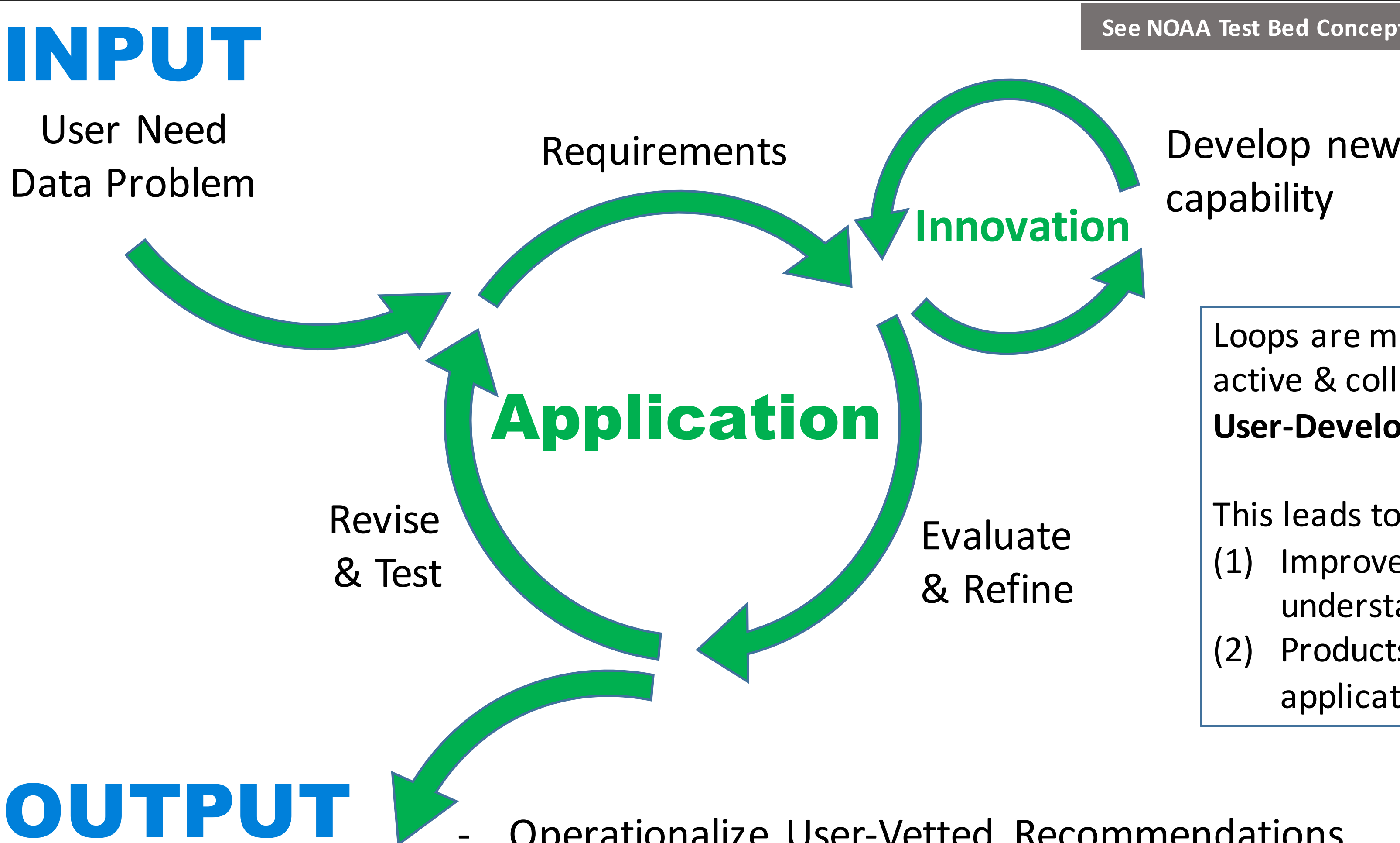
STAR JPSS 2016 Annual Science Team Meeting 8–12 August, NCWCP, College Park, MD

Doing Science within an Operational Framework

- Who cares about this problem?
- Can we find a **robust**, **stable** scientifically credible solution?
- Is the solution **operationally viable**, i.e. cost effective?

Sounding Initiative: A User-Oriented Approach to Development

See NOAA Test Bed Concept in Ralph et al. 2013 BAMS



Loops are maintained by active & collaborative **User-Developer Partnerships**

This leads to:

(1) Improved user/developer understanding

(2) Products tailored to user applications

- Operationalize User-Vetted Recommendations
- Develop/Enhance Applications

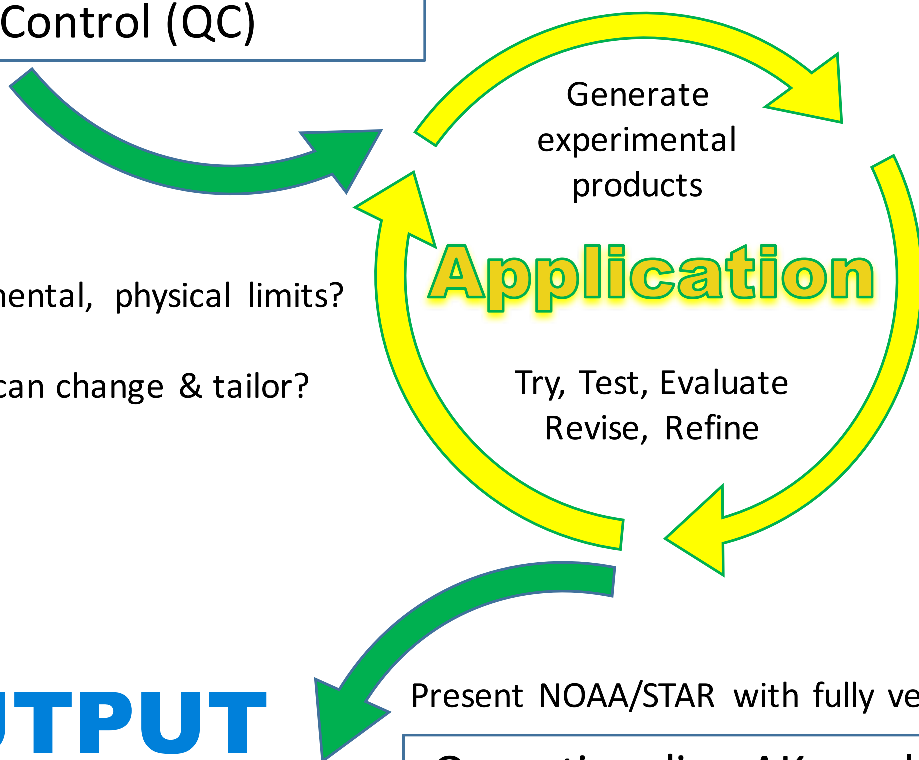
NOAA PGRR Sounding Initiative: NUCAPS CO and CH4

INPUT

Need for Averaging Kernels (AK) and Quality Control (QC)

What are the fundamental, physical limits?

What are things we can change & tailor?



STC NUCAPS Team in collaboration with:

NESDIS/STAR
NOAA/ESRL/CSD
CIRES + CIMSS

Working with multiple users in multiple applications to ensure that everyone benefits

OUTPUT

Present NOAA/STAR with fully vetted recommendations and solutions

Operationalize AK product and QC changes

Auxiliary Data Distribution – Averaging Kernels

Our primary partners in this initiative:

Brad Pierce (PGRR PI): High resolution trajectory-based smoke forecasts

Greg Frost (PGRR PI): Understanding emissions and tropospheric chemistry using NUCAPS and VIIRS

- At present, the NUCAPS trace gas user community is largely made up of scientists, not forecasters or air quality monitoring agencies yet
- Users have need for Auxiliary products that are not available in Operational CLASS product to cast light on the quality of products and aid in evaluation/characterization – Specifically the Averaging Kernels (AK) and Degrees of Freedom (DOF), both metrics of uncertainty and information content
- We developed the capability to distribute AK and DOF to users in netCDF files.

  NUCAPS stores all the building blocks with which to calculate AK and DOF in binary files (that are currently discarded for operational products, but available when run off-line)

  For each granule of measurement and a target parameter (e.g., CO, CH_4), we generate a netCDF file that contains all the relevant retrieval and auxiliary information that enables users to do meaningful characterization.

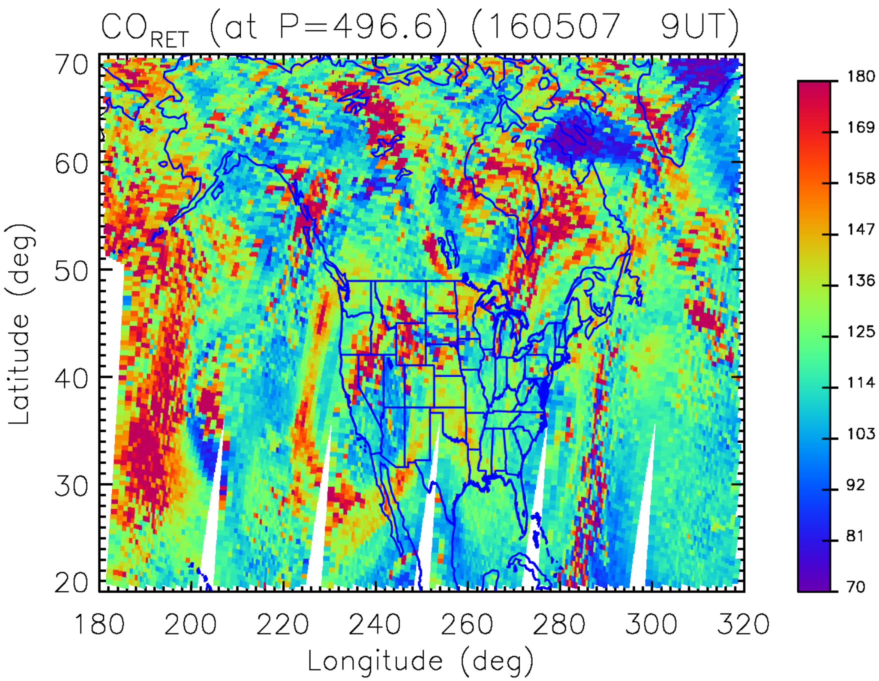
  Each netCDF files is ~2.5MB in size

  These netCDF files are experimental products and available only upon user request.

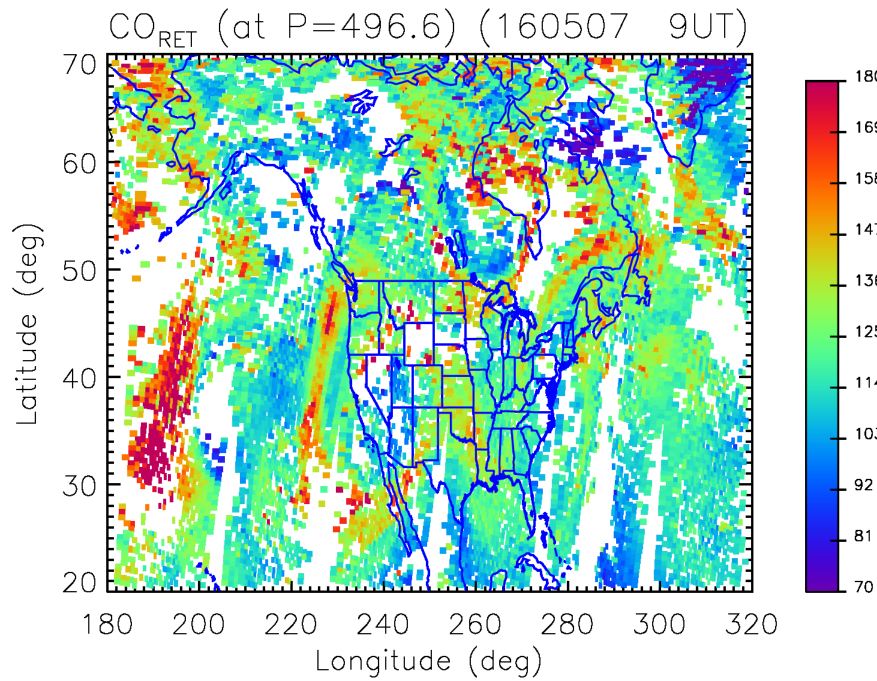
  We will evaluate product value, fine tune its design and eventually make recommendations for operationalization

Quality Control – A necessary step in using Satellite Data

NUCAPS CO without QC



NUCAPS CO with QC

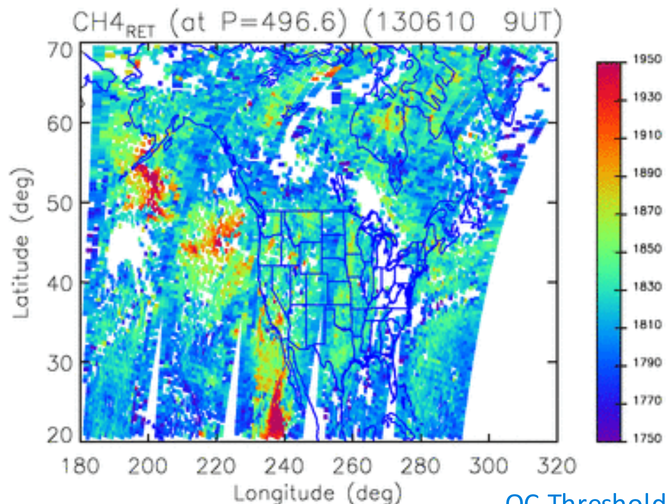


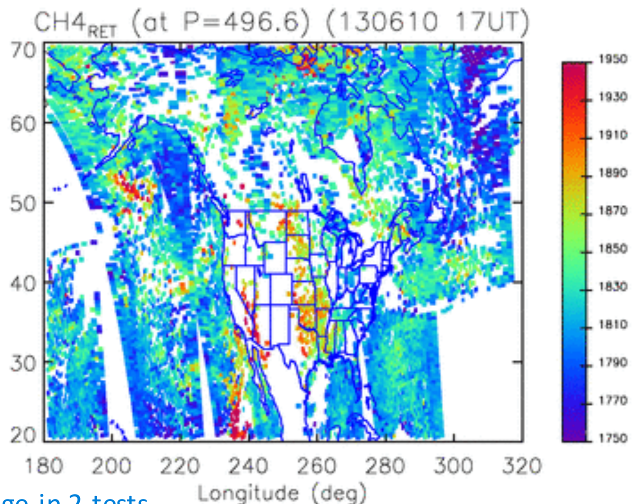
NUCAPS QC indicates quality of T/q from IR and MW retrieval steps
Designed to meet system requirements for global retrieval statistics; 1K T and 10% q

Can we adjust NUCAPS QC and improve Retrieval Yield?

Night Time
AM orbit
(~01h30)

NUCAPS has 17 QC tests throughout retrieval process

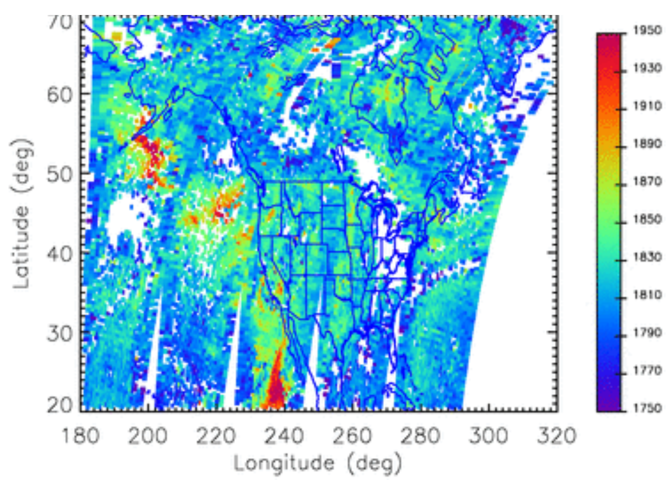


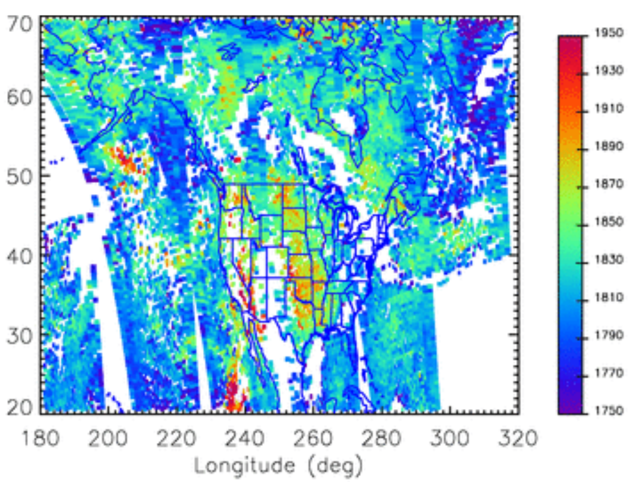


Day Time
PM orbit
(~13h30)

QC Threshold Change in 2 tests

~4% increase in retrieval yield





~12% increase in retrieval yield

Can we tailor QC to specific parameters? – CO

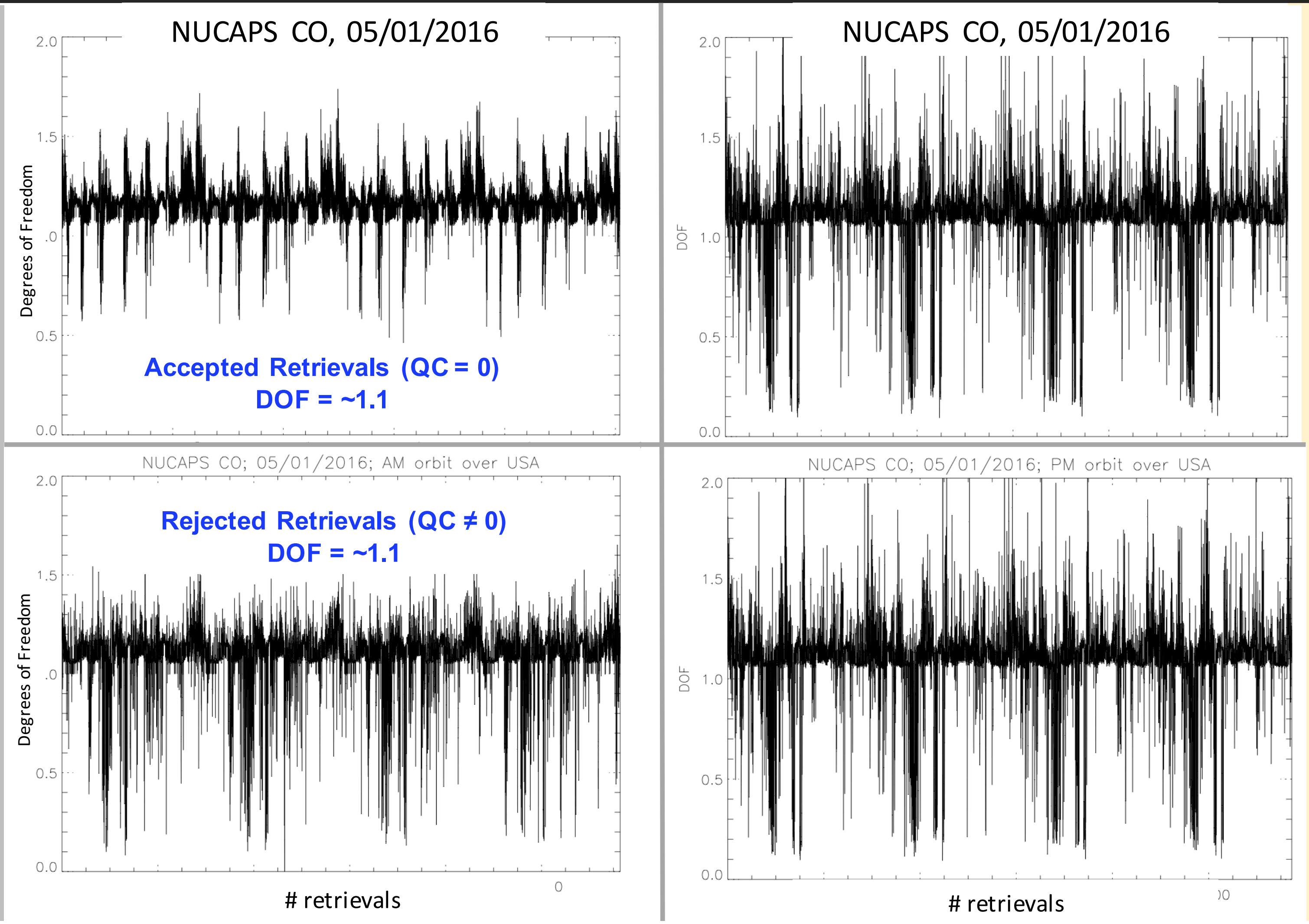
Night Time
AM orbit
(~01h30)

Night time DOF for accepted cases has less variation

There is a clear difference between night time DOF for accepted vs rejected cases

QC should typically filter out those retrievals with low DOF (or quality) and retain those with high DOF

The larger the DOF, the more information is available in the radiances



Day Time
PM orbit
(~13h30)

Degrees of Freedom (DOF) as indicator of information content

Mean DOF = 1.2
No matter what the time of day or QC

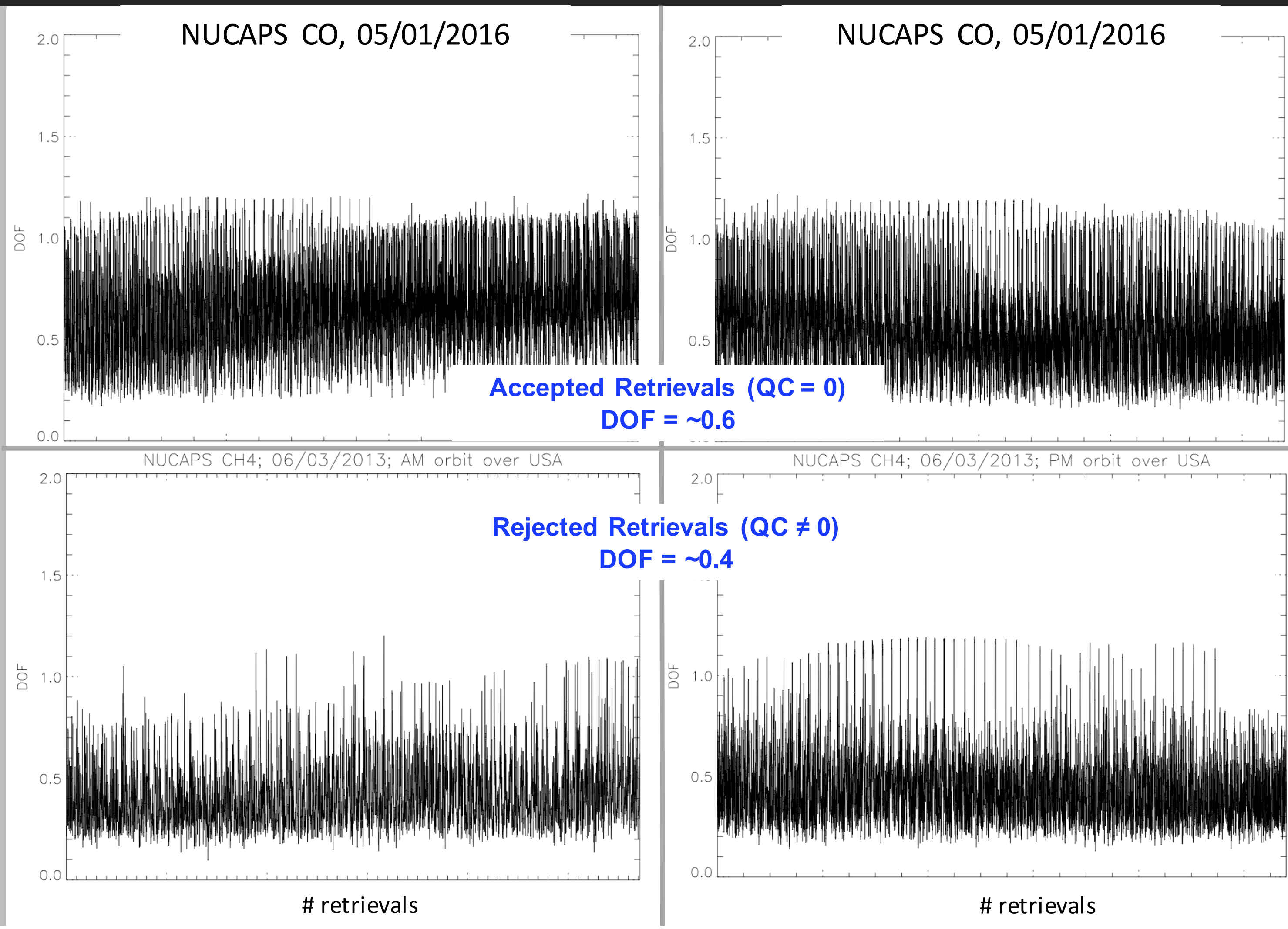
Daytime DOF has the same variation and systematic patter irrespective of QC

There are many CO retrievals with DOF > 1 in rejected cases (and vice versa) suggesting opportunity to develop CO-tailored QC. The quality of NUCAPS CO appears to be largely independent of T/q QC

Can we tailor QC to specific parameters? – CH4

Night Time
AM orbit
(~01h30)

DOF for rejected cases has less variation and the average is lower than the DOF for accepted cases suggesting that current QC successfully filters out the low quality CH4 retrievals



Day Time
PM orbit
(~13h30)

Accepted retrievals have higher DOF than rejected cases for both day and night time suggesting a stronger dependence of CH4 on T/q QC

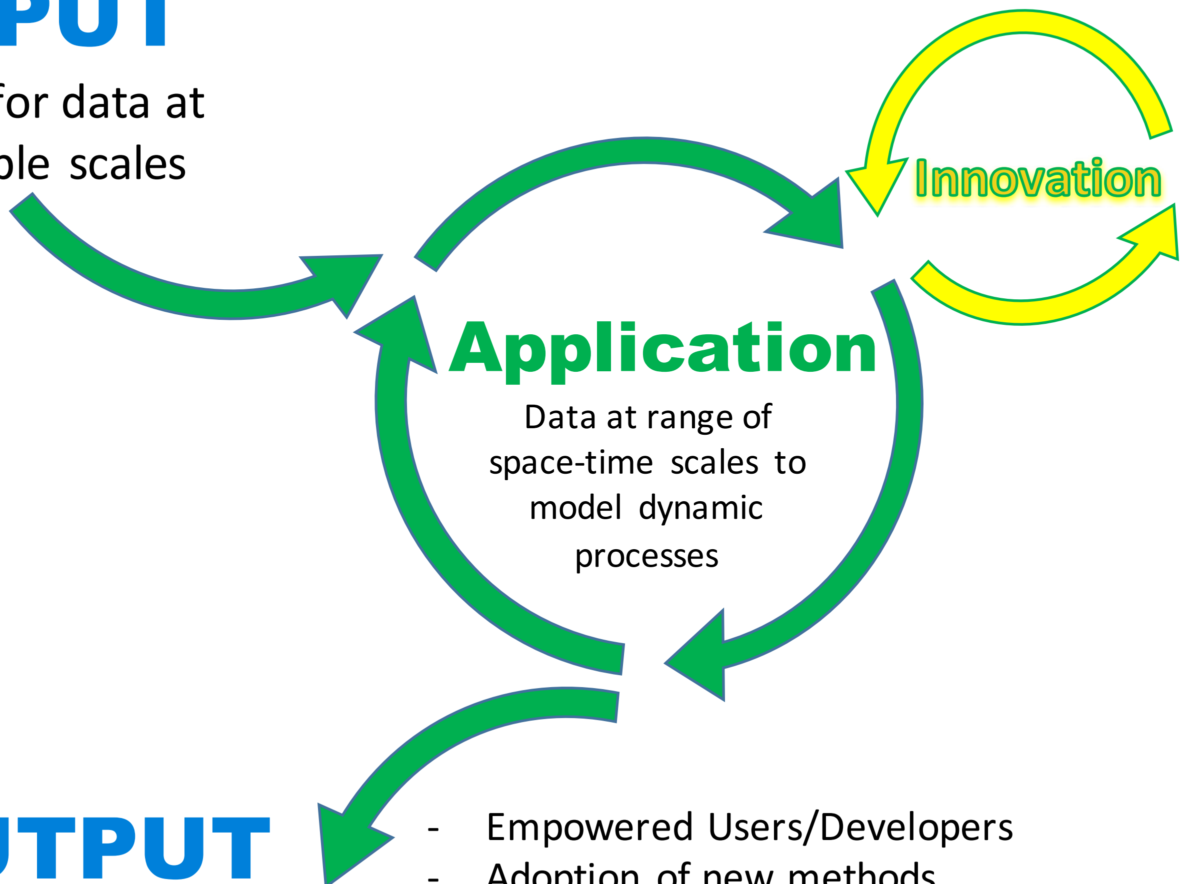
Accepted retrievals have high DOF variability suggesting a strong dependence on prevailing atm conditions

There are some CO retrievals with DOF > 0.5 in rejected cases suggesting opportunity to tailor QC for CH4

NOAA PGRR Initiative: NUCAPS CO and CH4

INPUT

Need for data at multiple scales



Develop objective methods for non-uniform data

STC NUCAPS Team in collaboration with:

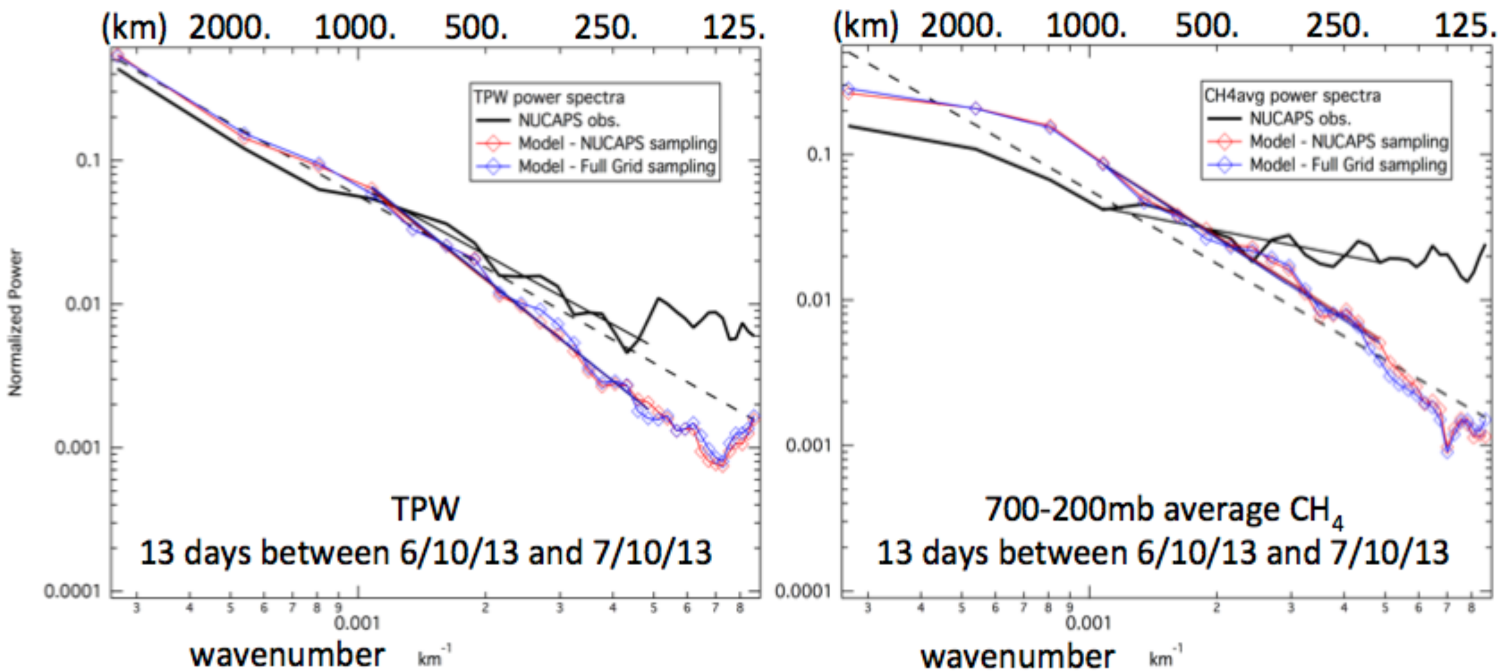
NOAA/ESRL/CSD
CIRES
NASA/JPL, etc.

OUTPUT

- Empowered Users/Developers
- Adoption of new methods
- Improved Trace Gas Climatologies, etc

Characterizing Atmospheric Chemistry

The objective is to understand how NUCAPS trace gases scale with respect to TPW in order to constrain the modeling of emission, chemistry and transport.



Average **normalized power spectra** for TPW (left) and 700-200 mb average CH_4 (right) for the NUCAPS data and the WRF-Chem model output. Dashed line is the -5/3 power law, and length scale is shown on the top axis. Thin lines are regression fits between 200 and 1000 km length scales.

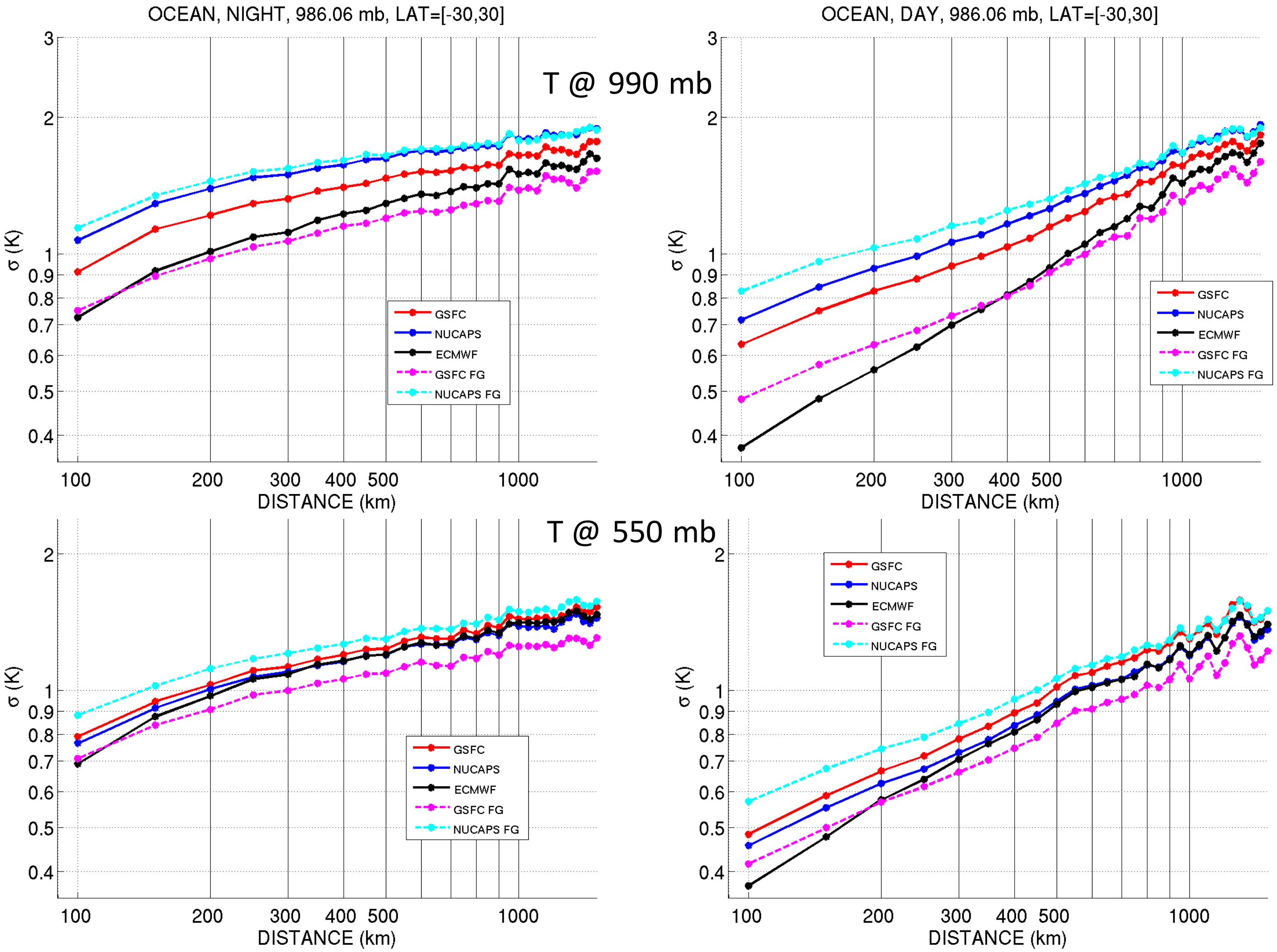
Figures by Stuart McKeen

Spatial Variability in Satellite Data

Night Time
AM orbit
(~01h30)

Standard deviation of NUCAPS T at different spatial scales

"Variance scaling" methods allow the characterization of nonlinear atmospheric processes and cross-scale energy transfer.



Day Time
PM orbit
(~13h30)

Satellite data have sampling challenges different to any other data source.

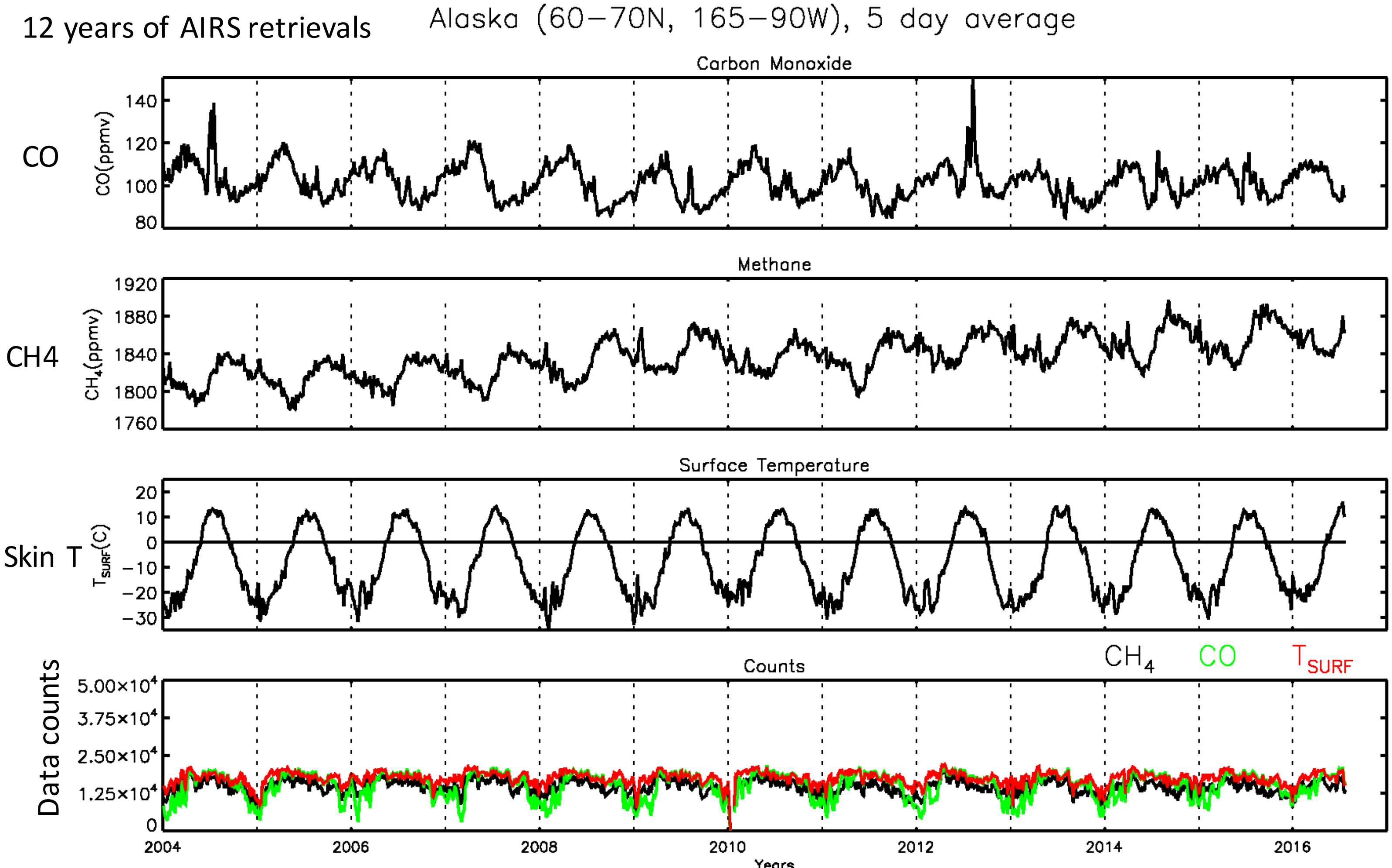
We need to find methods that aggregate spatially non-uniform data in objective manner and do not introduce systematic effects in end result.

Collaboration with Stuart McKeen (ESRL, CIRES)
Brian Kahn and Van Dang (NASA/JPL)

Figures by Van Dang
NASA/JPL

Temporal Variability in Satellite Data

12 years of AIRS retrievals



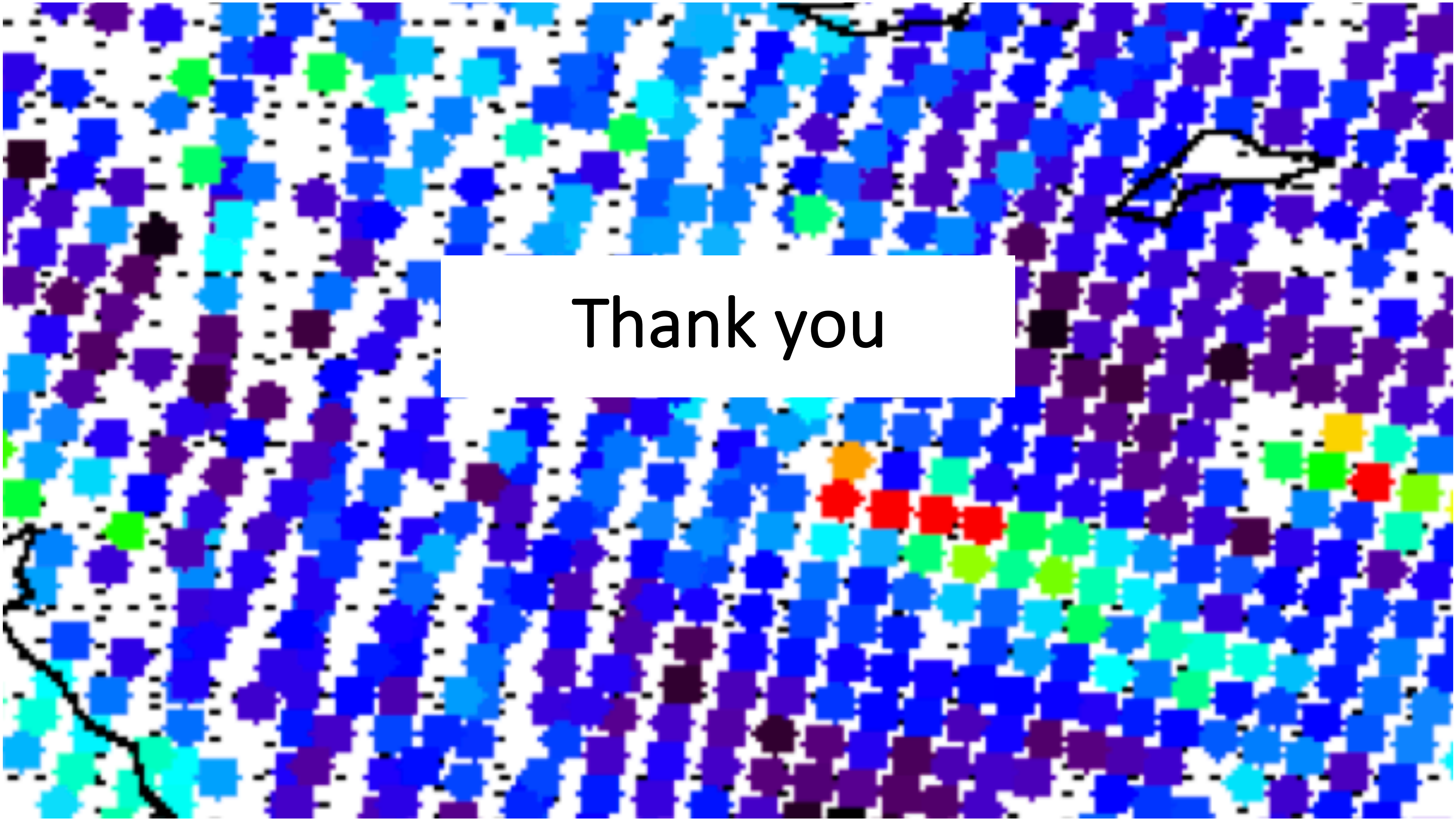
Experiments in temporal averaging.

Aqua and SNPP have repeat cycles of 16 days. How does the long term temporal pattern change when we average different sets of days together?

Figure by Colby Francoeur, STC

Lessons Learned

- The NOAA Sounding Initiative allows Users and Developers to collaborate and more effectively work towards solutions – we are all learning in the process
- There is a user need to not only improve the retrieval quality, but also the data product design, i.e., to to tailor the type of information made available in the data product files
- Given that QC removes data, we need to understand how the systematic patterns in data sampling affect analyses and propagate into applications, especially those that are concerned with dynamic, complex processes
- Our efforts will lead to products tailored to user needs AND applications tailored to satellite data



Thank you

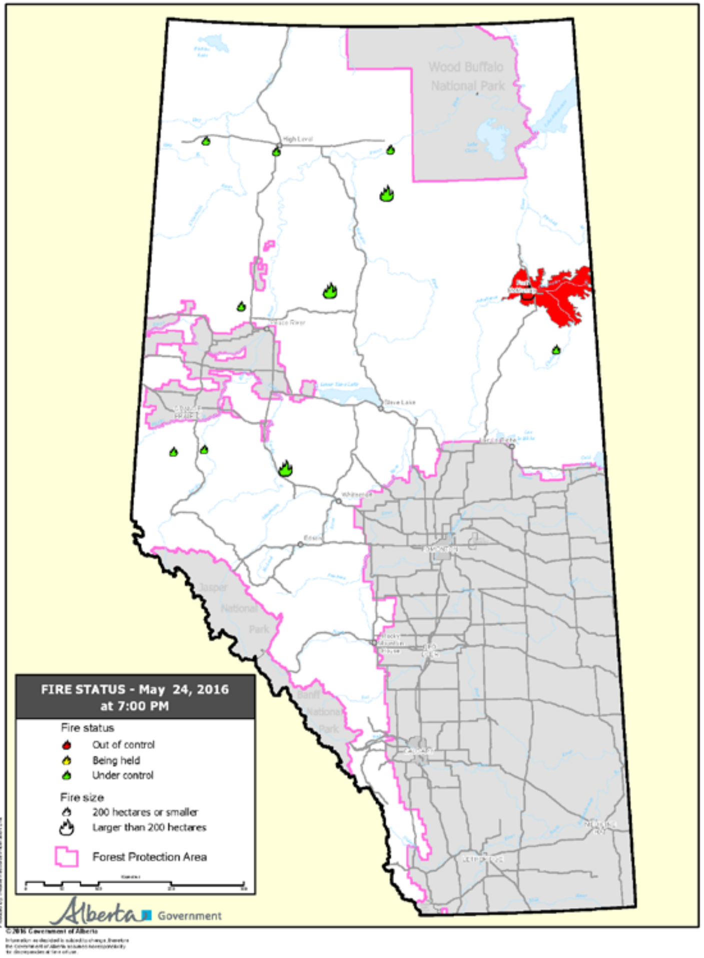
Evaluation of NUCAPS CO Retrieval and High Resolution Smoke Trajectory Forecasting

Brad Pierce (NOAA/NESDIS/STAR)

Collaborators:

Nadia Smith, Antonia Gambacorta and Chris Barnet (STC)
Jim Davies and Kathy Strabala (CIMSS)
Greg Frost and John Holloway (NOAA/ESRL)
Shobha Kondragunta (NESDIS/STAR)

Fort McMurray wildfire Case study

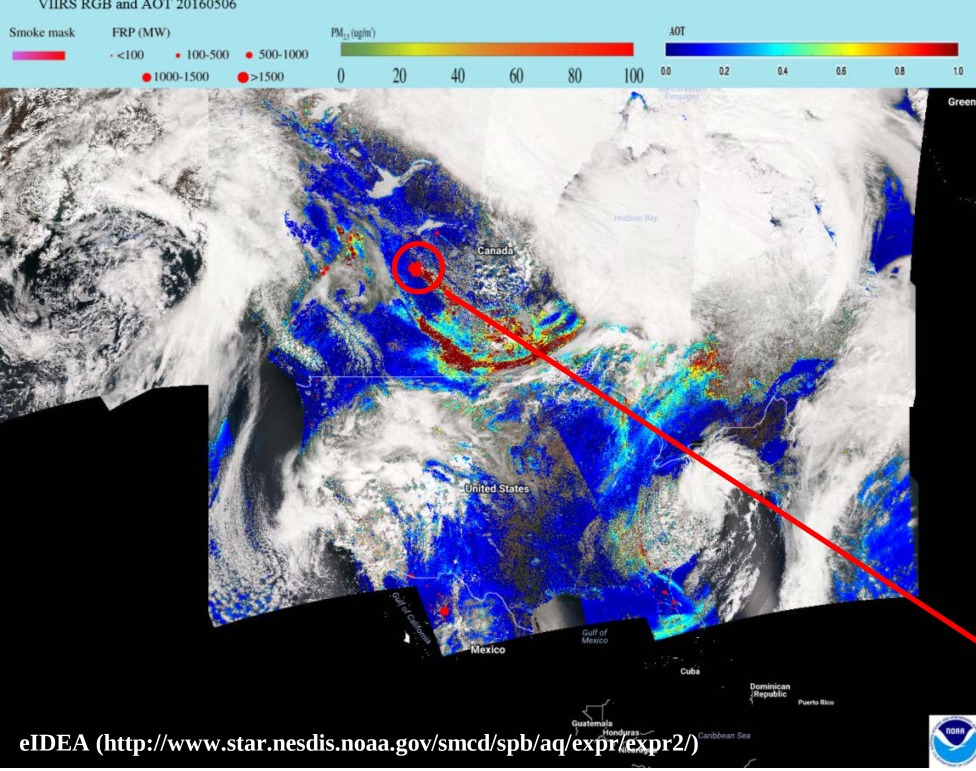


(May 1, 2016) – 9:57 p.m., Mayor Blake has declared a State of Local Emergency in Fort McMurray localized to Gregoire.

(May 4, 2016) –Mandatory evacuation of Anzac, Gregoire Lake Estates and Fort McMurray First Nation.

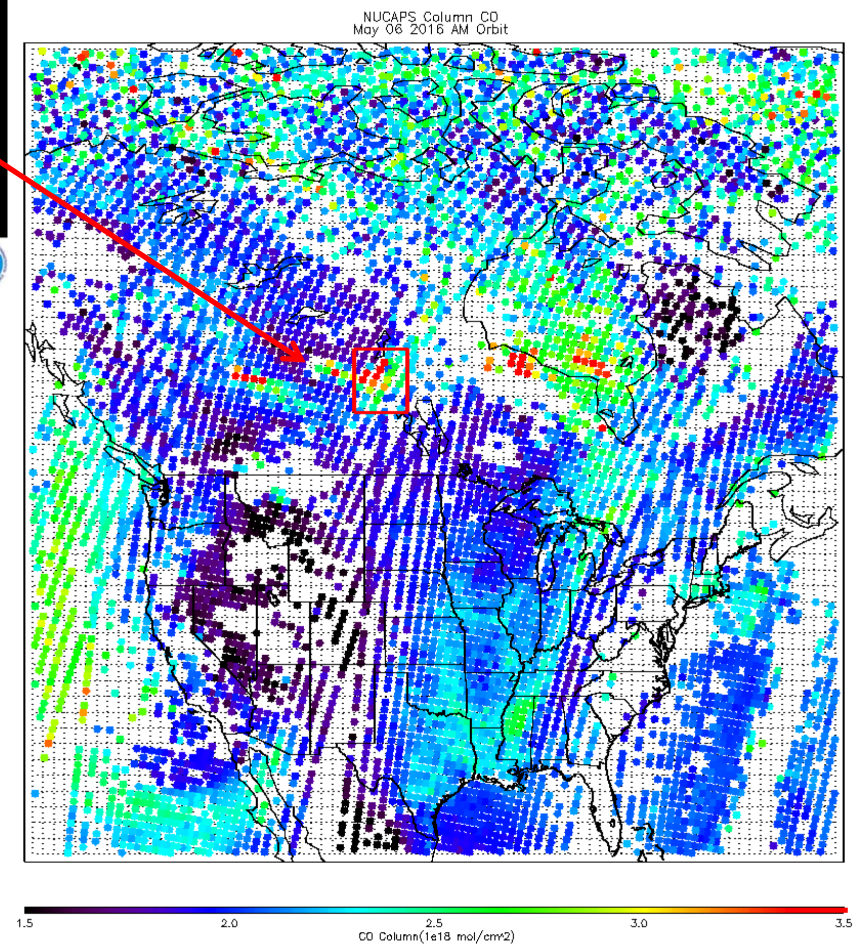
(May 16, 2016) The evacuation zone has increased north of the city of Fort McMurray.

(May 18, 2016) A voluntary, phased re-entry for the safe return of Fort McMurray residents will begin June 1 if future wildfire conditions do not delay restoration efforts.



CSPP NUCAPS trace gas EDR

- Include averaging kernel, apriori, interpolation and inverse matrices for applying to model (or insitu) profiles for data assimilation (or validation) activities.

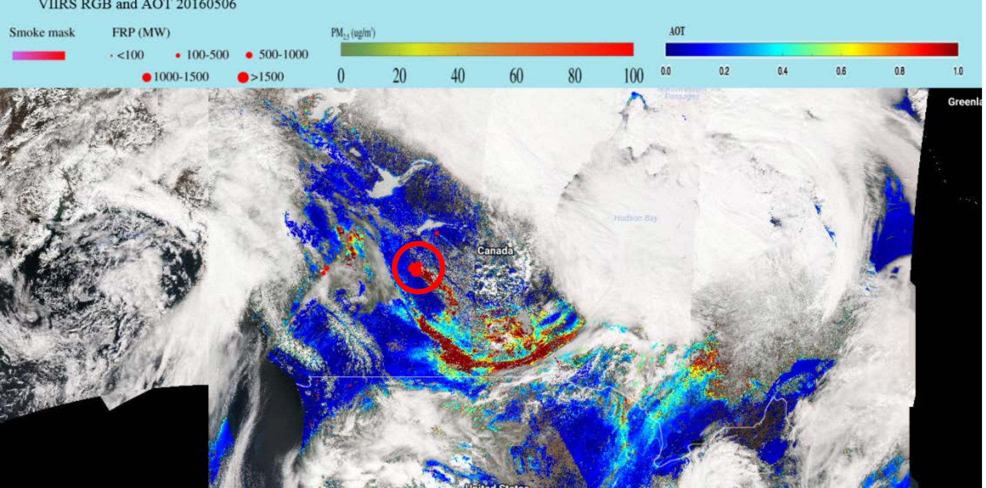


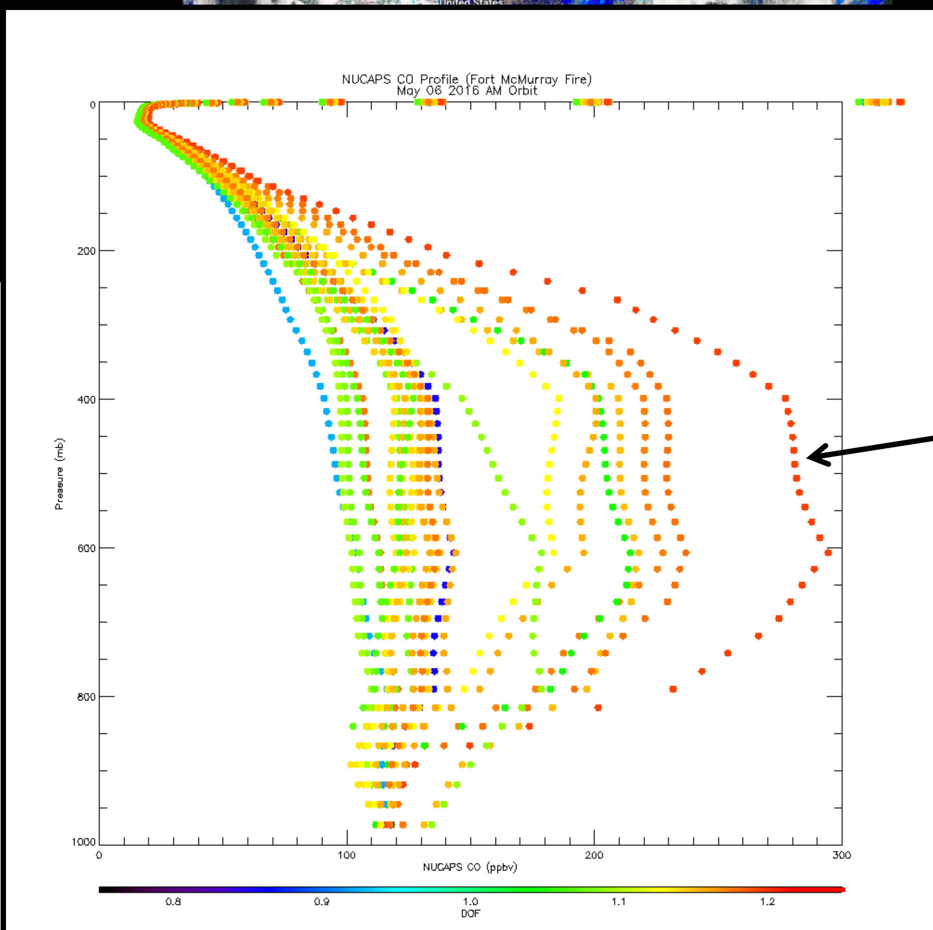
- Files also include surface parameters, degrees of freedom, and combined microwave and infrared quality flags.

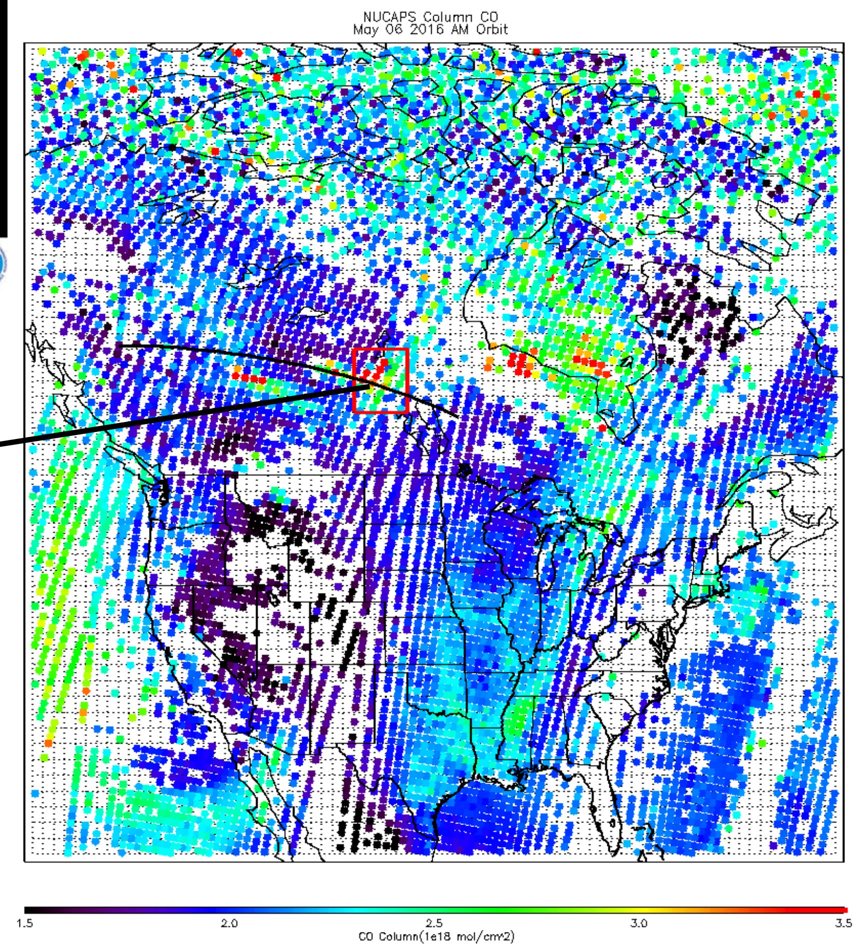
- Will be used within CSPP for IDEA-I NUCAPS smoke forecasts and also in collaboration with colleagues at NOAA/ESRL for NUCAPS CH4 and CO retrieval validation activities.

CSPP NUCAPS trace gas EDR

- ❑ Include averaging kernel, apriori, interpolation and inverse matrixes for applying to model (or insitu) profiles for data assimilation (or validation) activities.



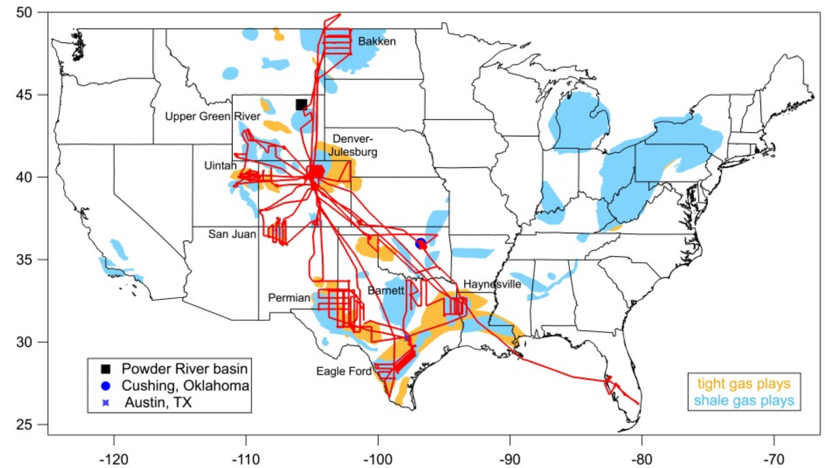




Satellite Retrievals → Global Assimilation → Regional Prediction → Validation

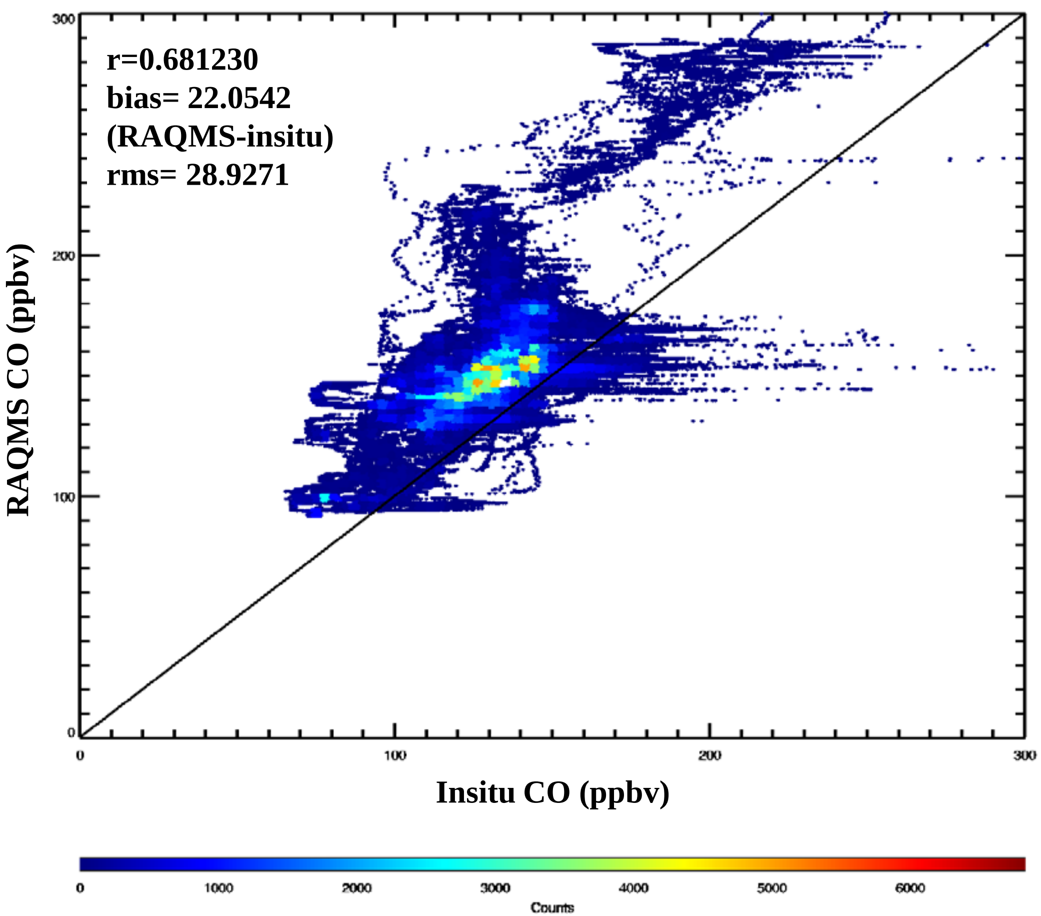
RAQMS Realtime Air Quality Modeling System

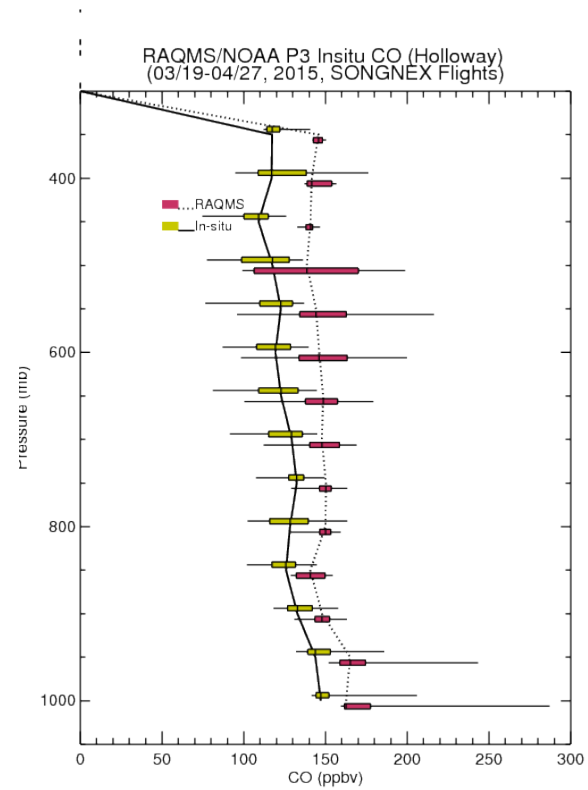
SONGNEX 2015
Shale Oil and Natural Gas Nexus



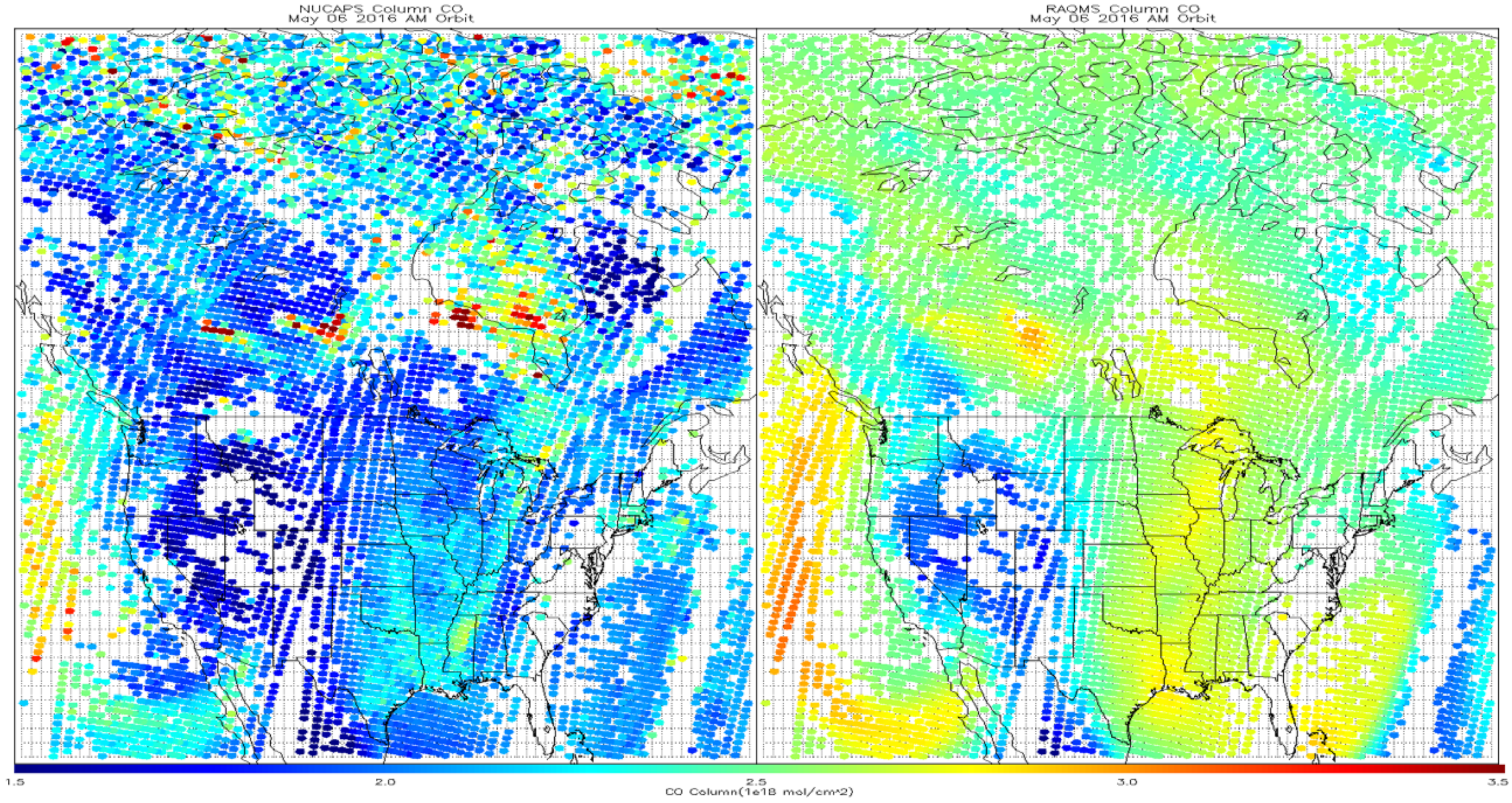
Evaluate RAQMS vs insitu CO during NOAA/ESRL SONGNEX 2015 for indirect NUCAPS CO validation

RAQMS vs Insitu SONGNEX 2015
(March 19-April 27, 2015)

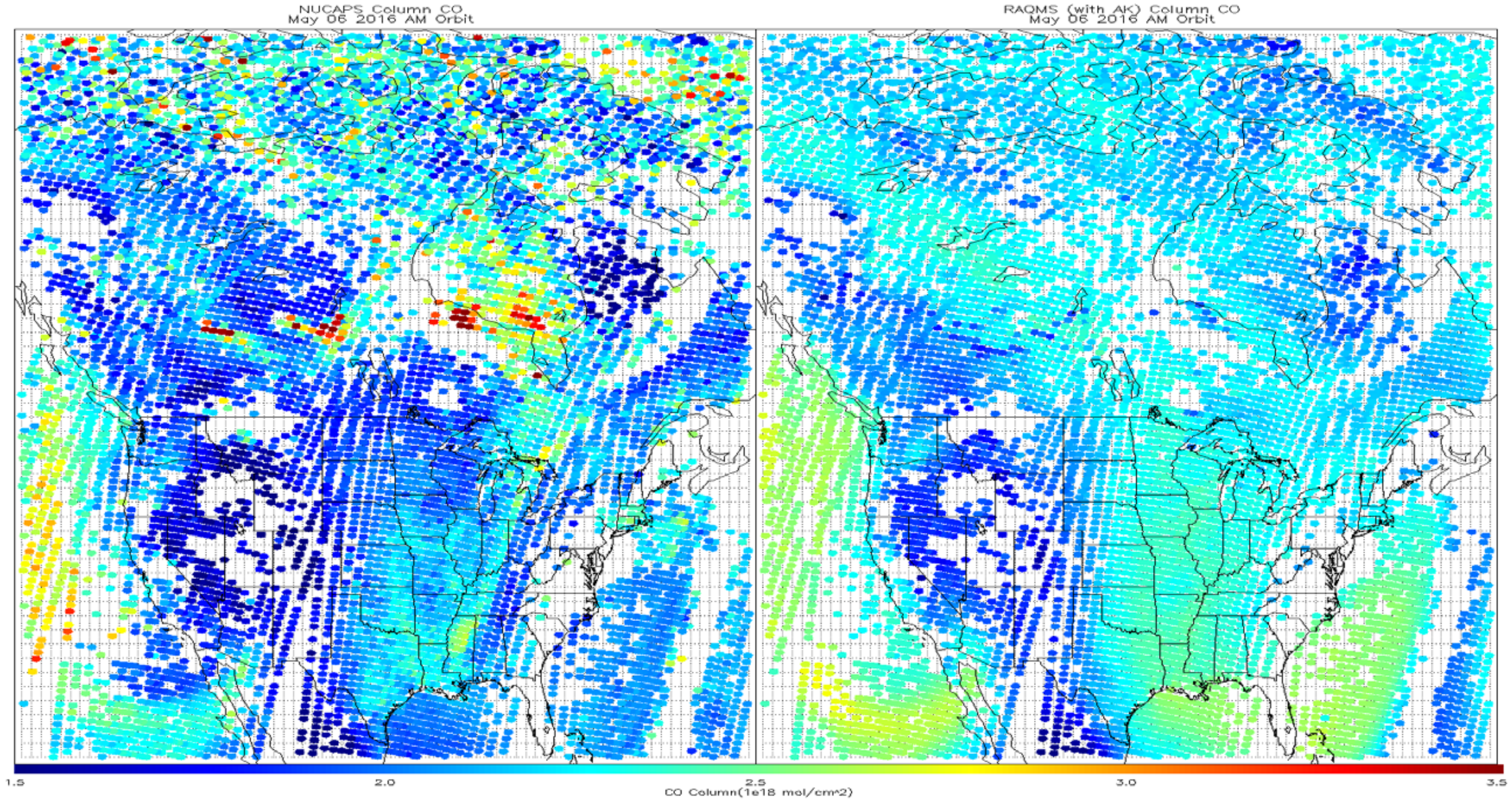




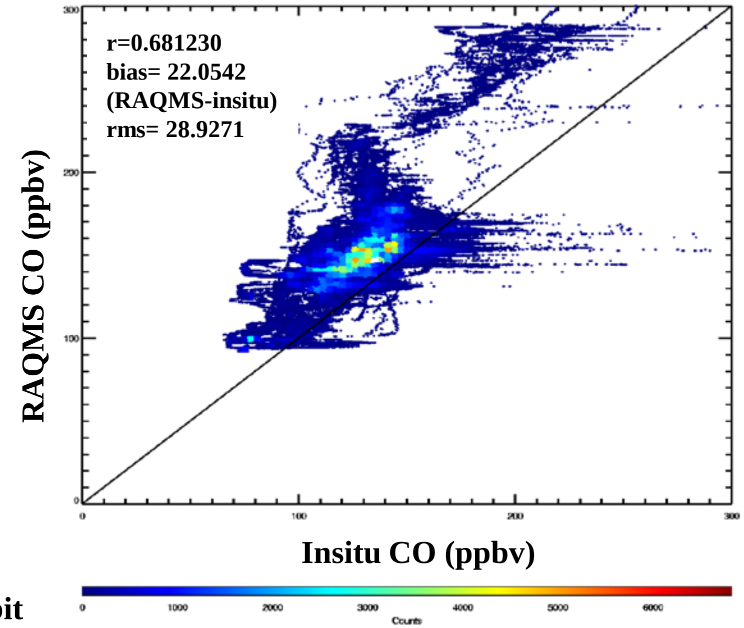
NUCAPS verses RAQMS Column CO May 06, 2016 AM Orbit



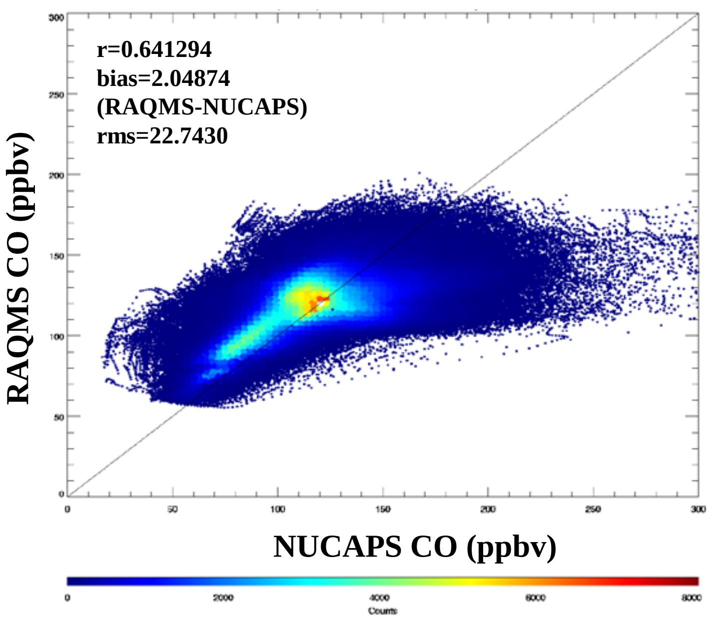
NUCAPS verses RAQMS (AK) Column CO May 06, 2016 AM Orbit



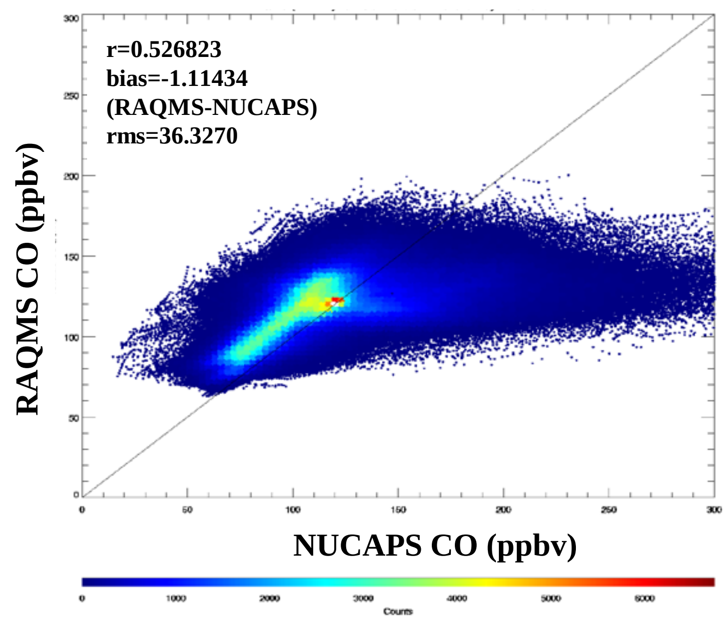
RAQMS vs Insitu SONGNEX 2015
(March 19-April 27, 2015)



RAQMS vs NUCAPS AM Orbit
(May 1-16, 2016)



RAQMS vs NUCAPS PM Orbit
(May 1-16, 2016)



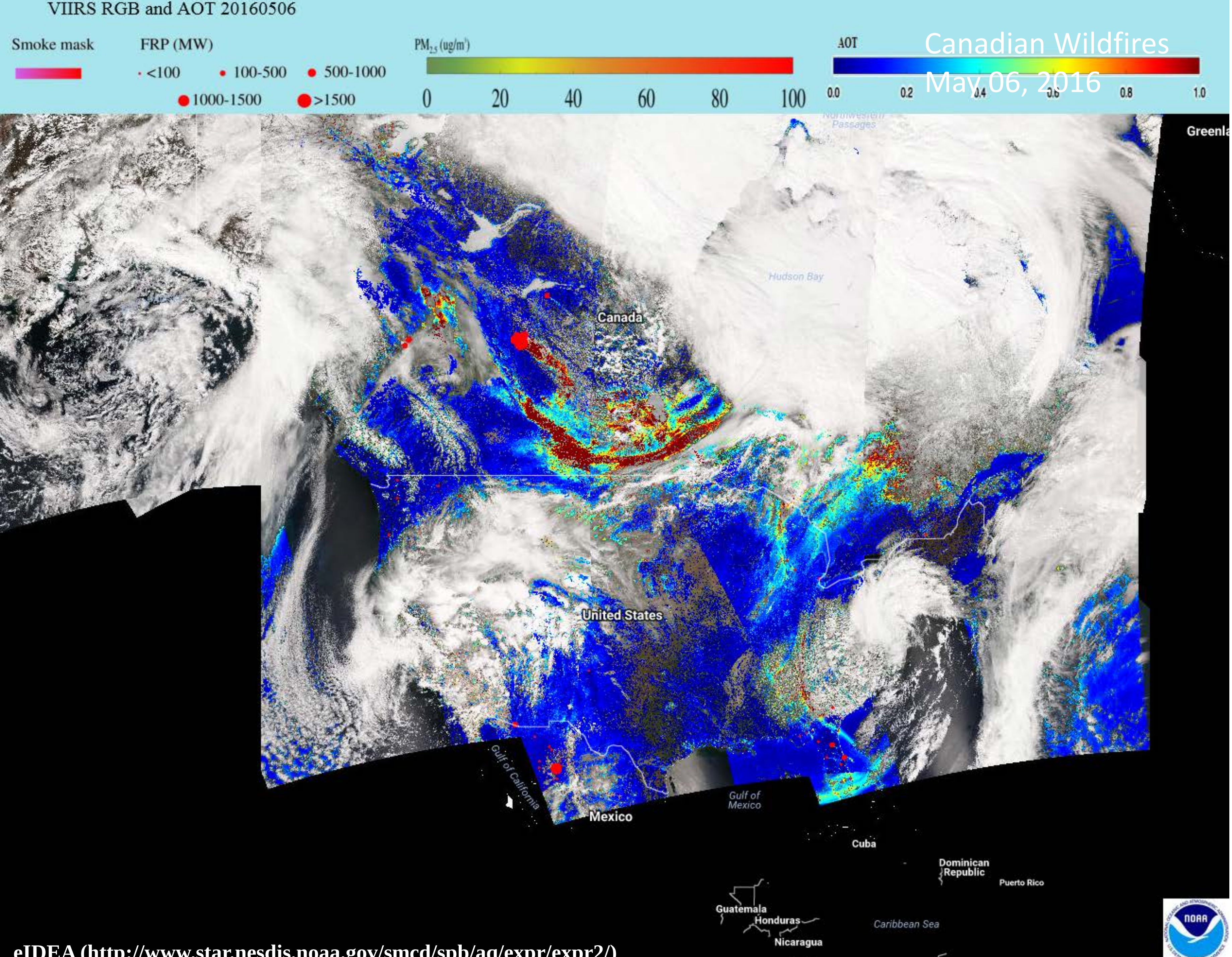
High Resolution Trajectory-Based Smoke Forecasts

- **Goal:** Provide low latency, web-based, high resolution forecasts of smoke dispersion for use by NWS Incident Meteorologists (IMET) to support on-site decision support services for fire incident management teams.

  - Project utilizes VIIRS AOD and NUCAPS CO retrievals to initialize trajectory-based, high spatial resolution smoke dispersion forecasts.

  - Project is an extension of Infusion of satellite Data into Environmental Applications-International (IDEA-I) trajectory based aerosol forecast capabilities and will be tested and released within CSPP prior to transition to Operations at NESDIS.

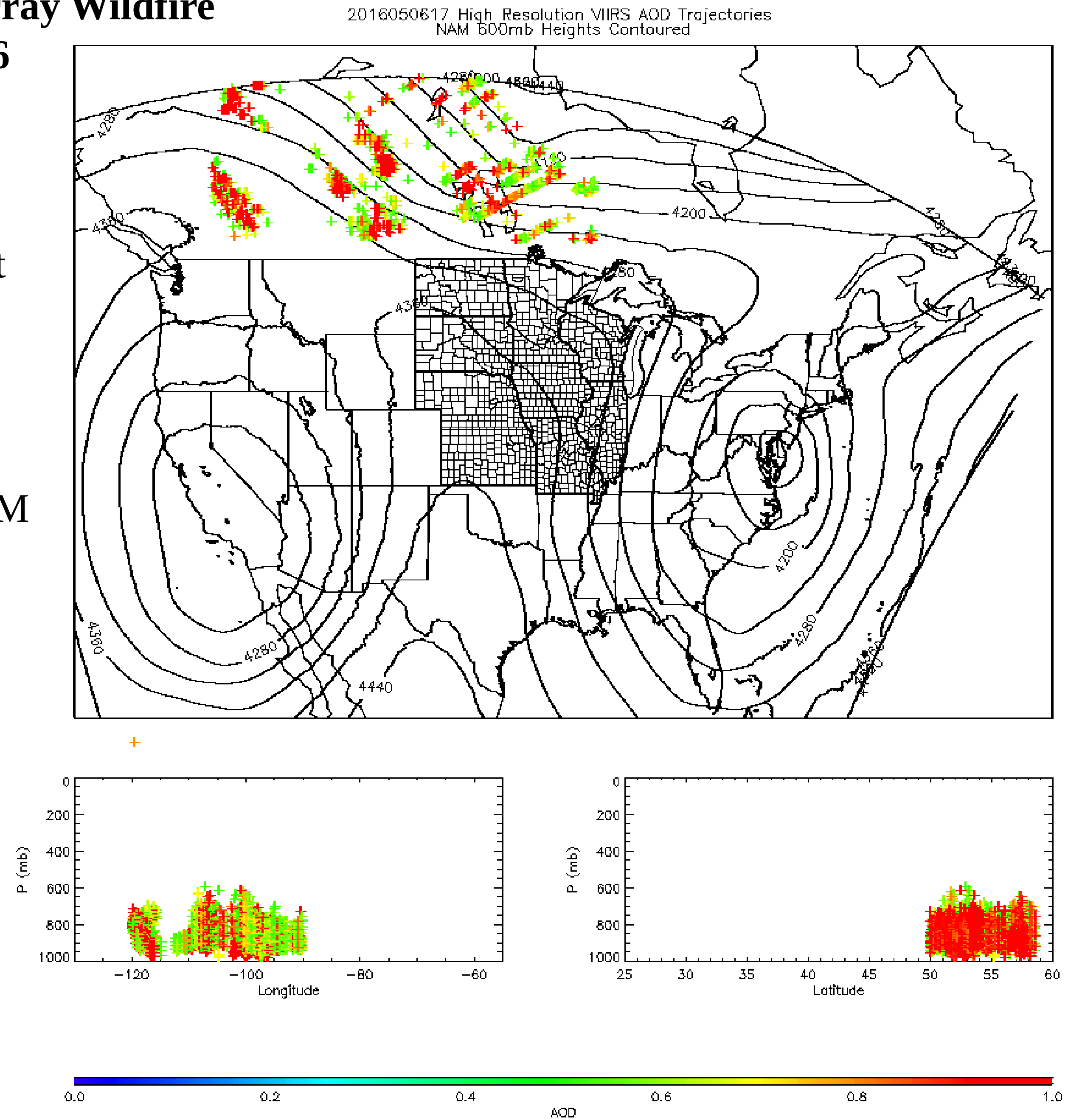
Canadian Wildfires
May 06, 2016



eIDEA (http://www.star.nesdis.noaa.gov/smcd/spb/aq/expr/expr2/)

IDEA-I High resolution (NAM 4km) trajectory forecast
Fort McMurray Wildfire
May 06, 2016

- IDEA-I high resolution trajectories initialized at each 6km VIIRS pixel (only AOD>0.5 initialized)
- Upper panel shows NAM 600mb heights
- Lower panels show longitude and latitude cross sections
- IDEA-I high resolution trajectory forecast colored by initial AOD



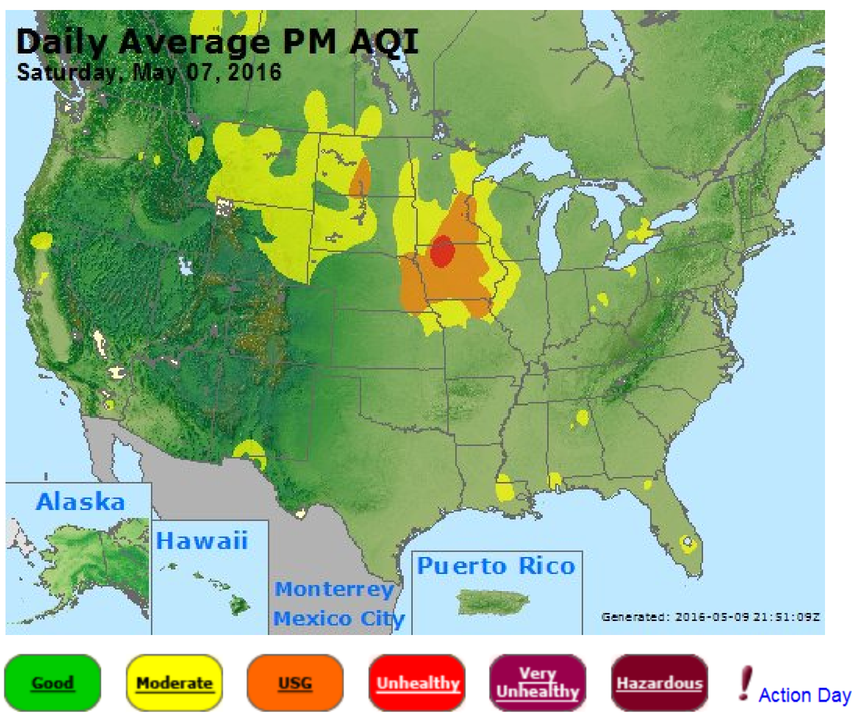
652
WWUS83 KMPX 070627
SPSMPX

From Andy Edman/NWS

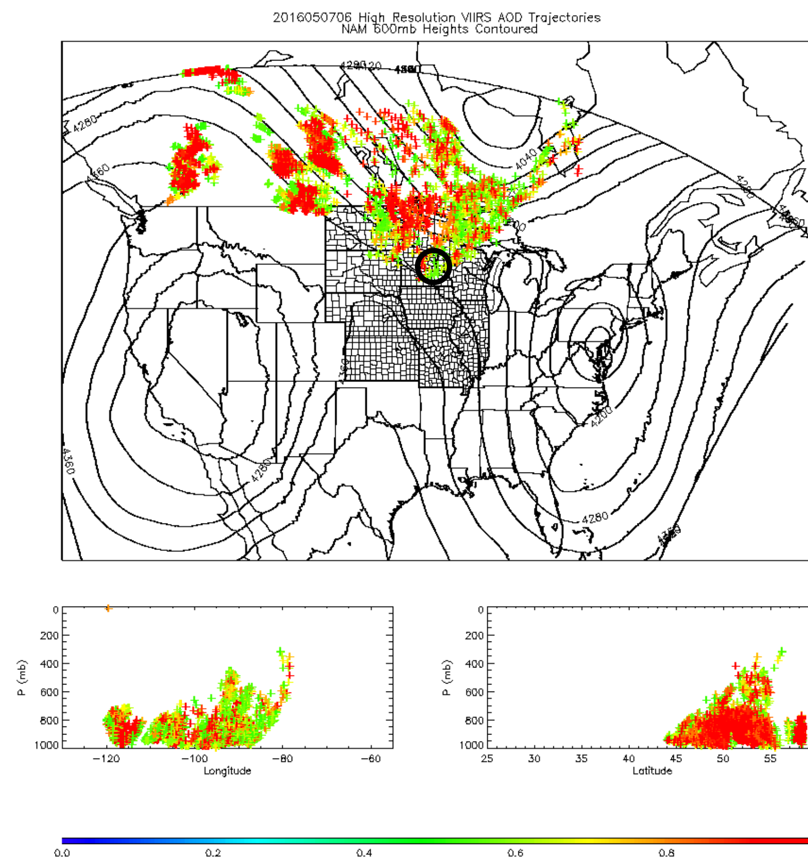
SPECIAL WEATHER STATEMENT
NATIONAL WEATHER SERVICE TWIN CITIES/CHANHASSEN MN
127 AM CDT SAT MAY 7 2016

...SMOKY CONDITIONS TO PERSIST THROUGH THE OVERNIGHT HOURS...

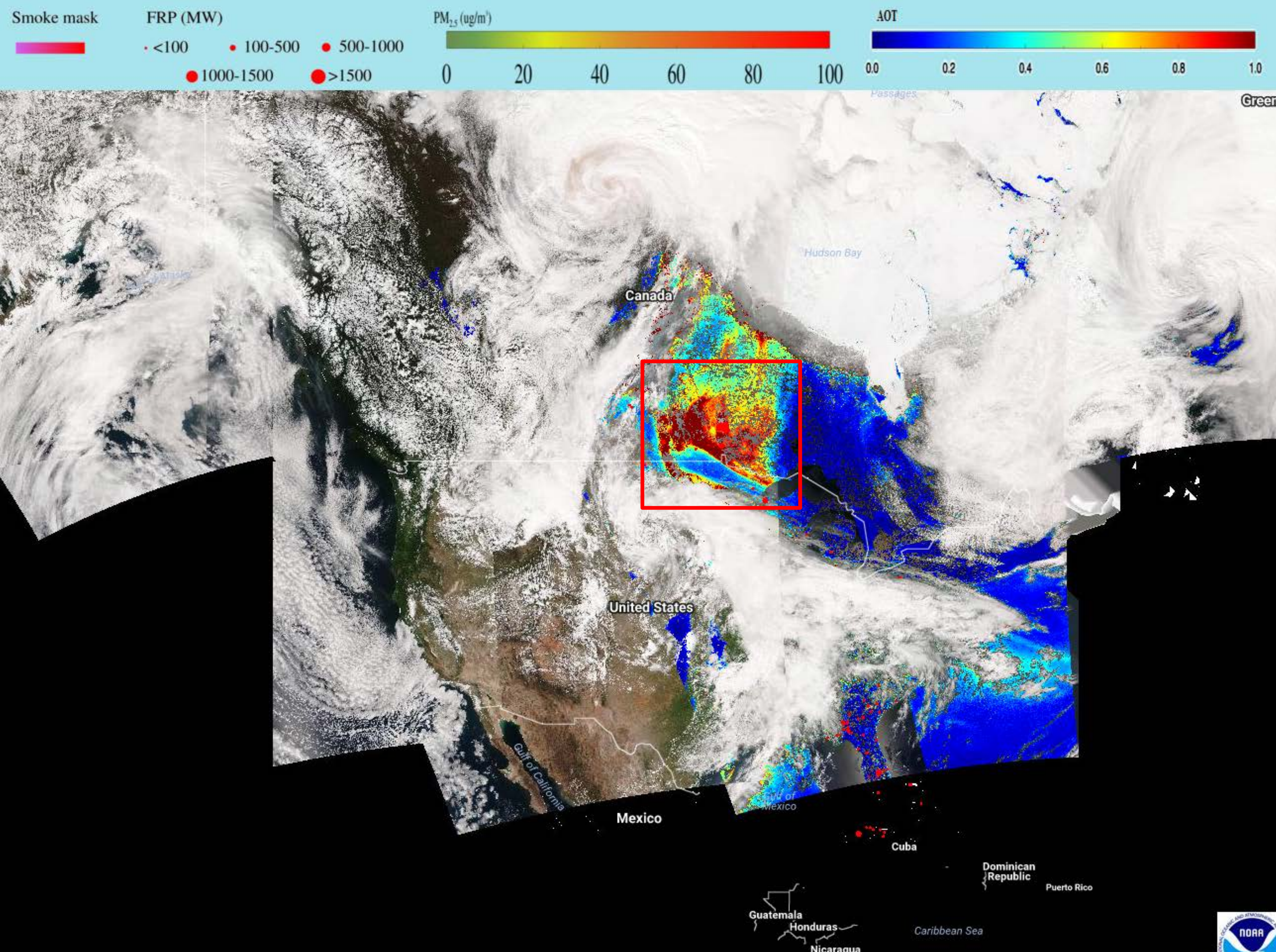
WIDESPREAD SMOKE FROM BOTH THE LARGE CANADIAN WILDFIRES AND A SMALLER WILDFIRE NEAR LAKE HATTIE IN HUBBARD COUNTY MINNESOTA HAS BLOWN INTO CENTRAL MINNESOTA...PARTICULARLY WITHIN AND NEAR THE TWIN CITIES METROPOLITAN AREA...DUE TO STRONG WINDS FROM THE NORTHWEST. VISIBILITIES HAVE BEEN REDUCED TO BETWEEN 1 AND 3 MILES...AND AIR QUALITY HAS BEEN SIGNIFICANTLY IMPACTED.



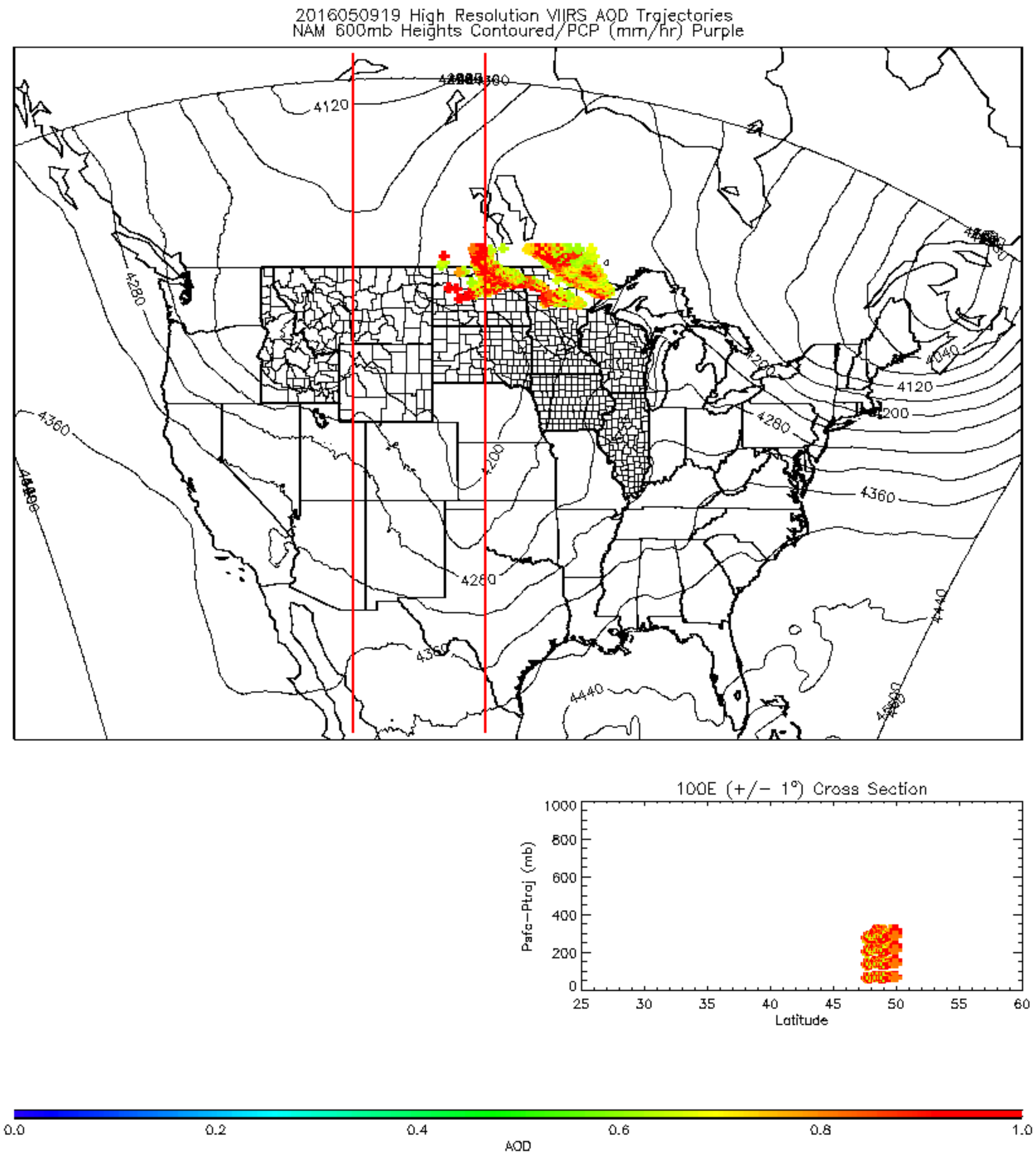
https://www.airnow.gov/



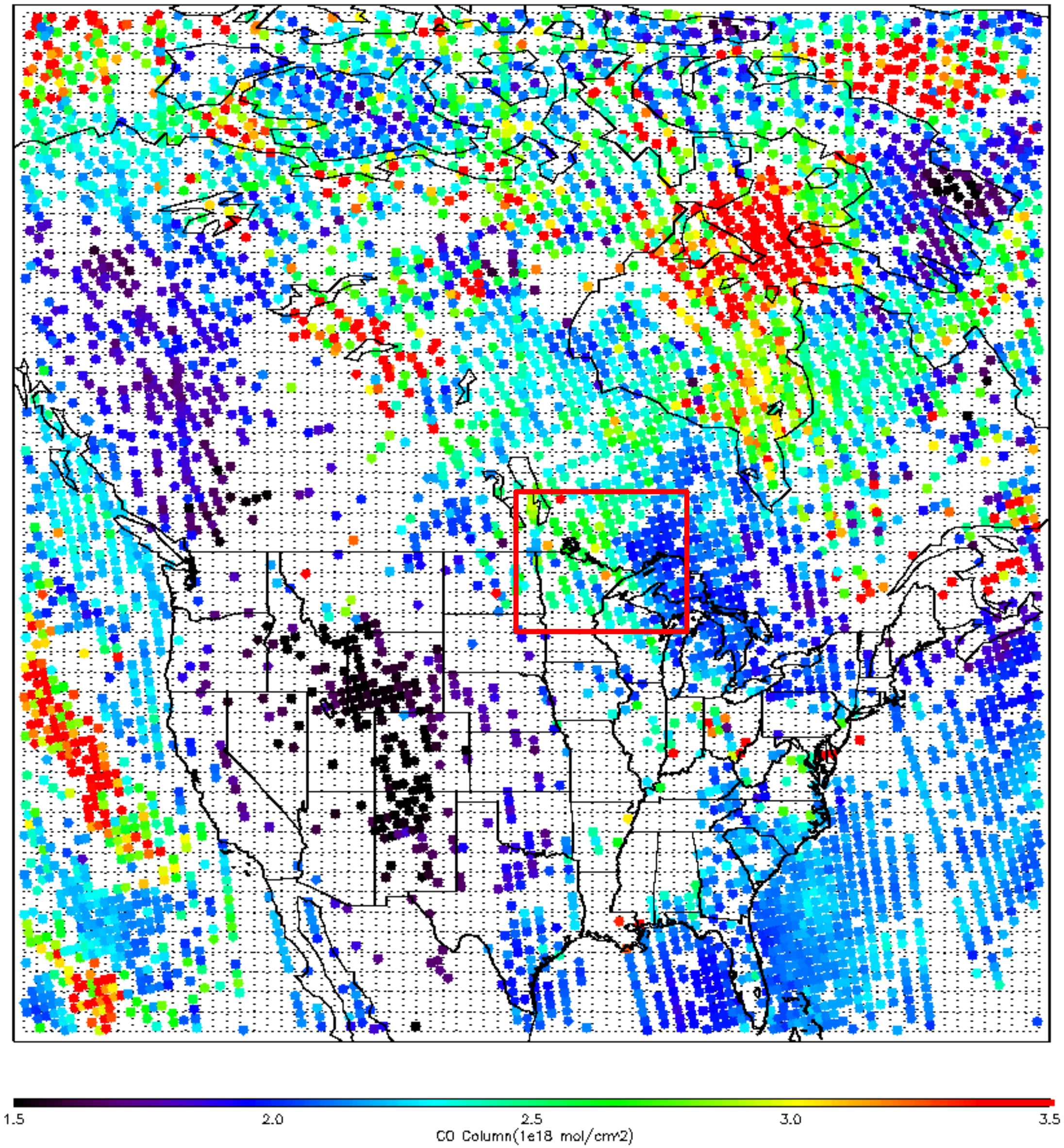
VIIRS RGB and AOT 20160509

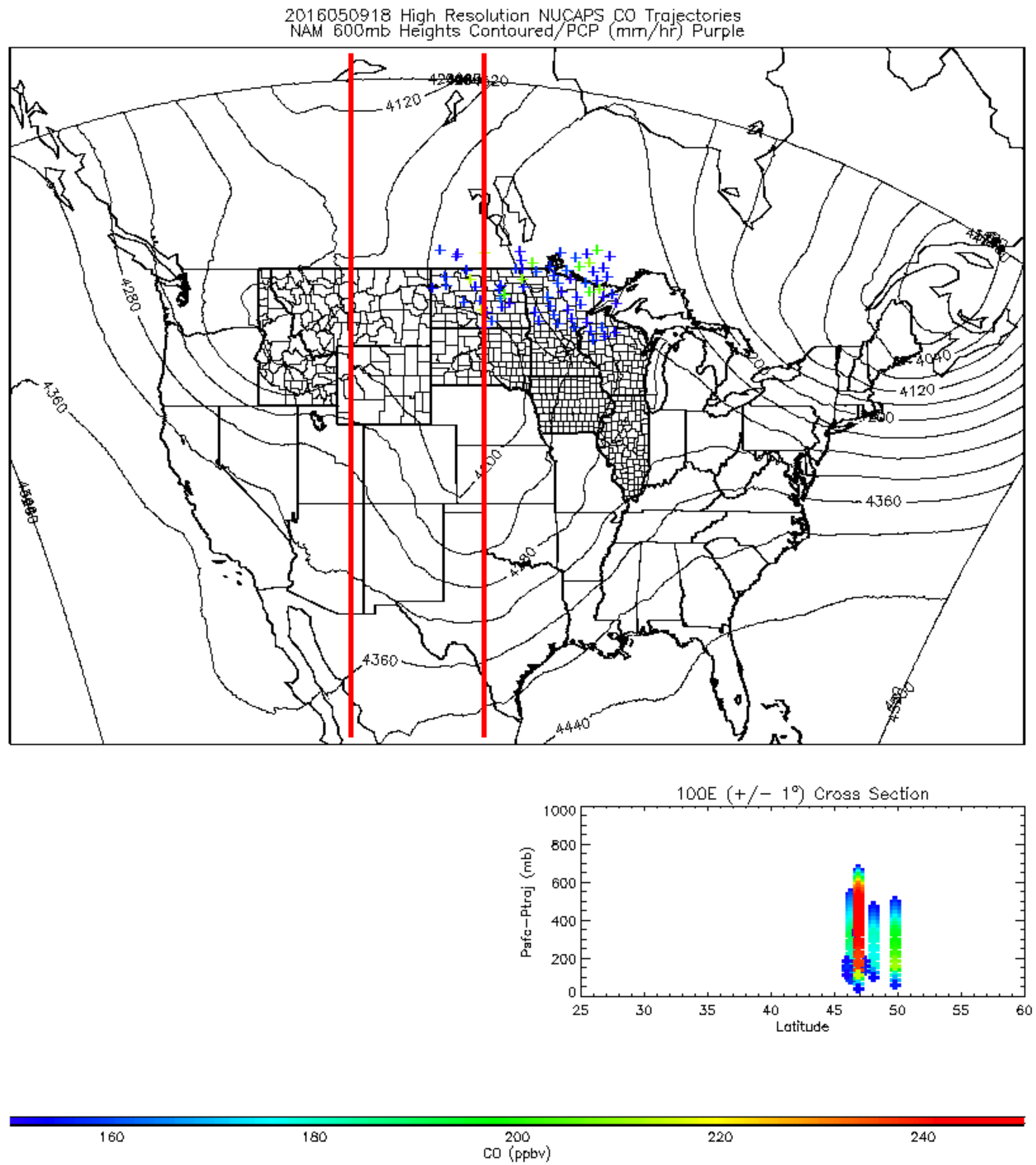


eIDEA (http://www.star.nesdis.noaa.gov/smcd/spb/aq/expr/expr2/)


2016050919 High Resolution VIIRS AOD Trajectories
NAM 600mb Heights Contoured/PCP (mm/hr) Purple
4120
4280
4360
4200
4040
4440
100E (+/- 1°) Cross Section
Psfc-Ptraj (mb)
1000
800
600
400
200
0
25
30
35
40
45
50
55
60
Latitude
0.0
0.2
0.4
0.6
0.8
1.0
AOD

NUCAPS Column CO
May 09 2016 PM Orbit




2016050918 High Resolution NUCAPS CO Trajectories
NAM 600mb Heights Contoured/PCP (mm/hr) Purple
4120
4280
4360
4040
4120
4200
4360
4400
4480
4360
4440
100E (+/- 1°) Cross Section
Psfc-Ptraj (mb)
1000
800
600
400
200
0
25
30
35
40
45
50
55
60
Latitude
160
180
200
220
240
CO (ppbv)

VIIRS True Color Image May 9, 2016 20:15 UTC

Smoke from Fort McMurray fire imbedded with low pressure system over northern Canada

(From NOAA Environmental Visualization Laboratory)

NOAA • NESDIS JPSS Joint Polar Satellite System

Understanding Emissions and Tropospheric Chemistry using NUCAPS and VIIRS

A JPSS Proving Ground/Risk Reduction Project

NOAA OAR ESRL: *G. Frost, S. McKeen, S.-W. Kim, R. Ahmadov, M. Trainer, Y. Cui, W. Angevine, T. Ryerson, J. Roberts, C. Warneke, C. Granier, K. Rosenlof, J. Brioude*

STC: *C. Barnet, N. Smith, A. Gambacorta*

NOAA NESDIS STAR: *R. B. Pierce*

NOAA NESDIS NCEI: *C. Elvidge*

Project Overview

Goal: Use aircraft data and atmospheric models to characterize NUCAPS CH_4 and CO retrievals

Objectives:

- Validate atmospheric chemical-transport models with aircraft observations
- Simulate spatial and temporal variability of CH_4 and CO
- Evaluate NUCAPS CH_4 and CO retrievals with validated model
- Assess ability of JPSS datasets to constrain modeled CH_4 and CO

End Users: Researchers and forecasters at NOAA and elsewhere

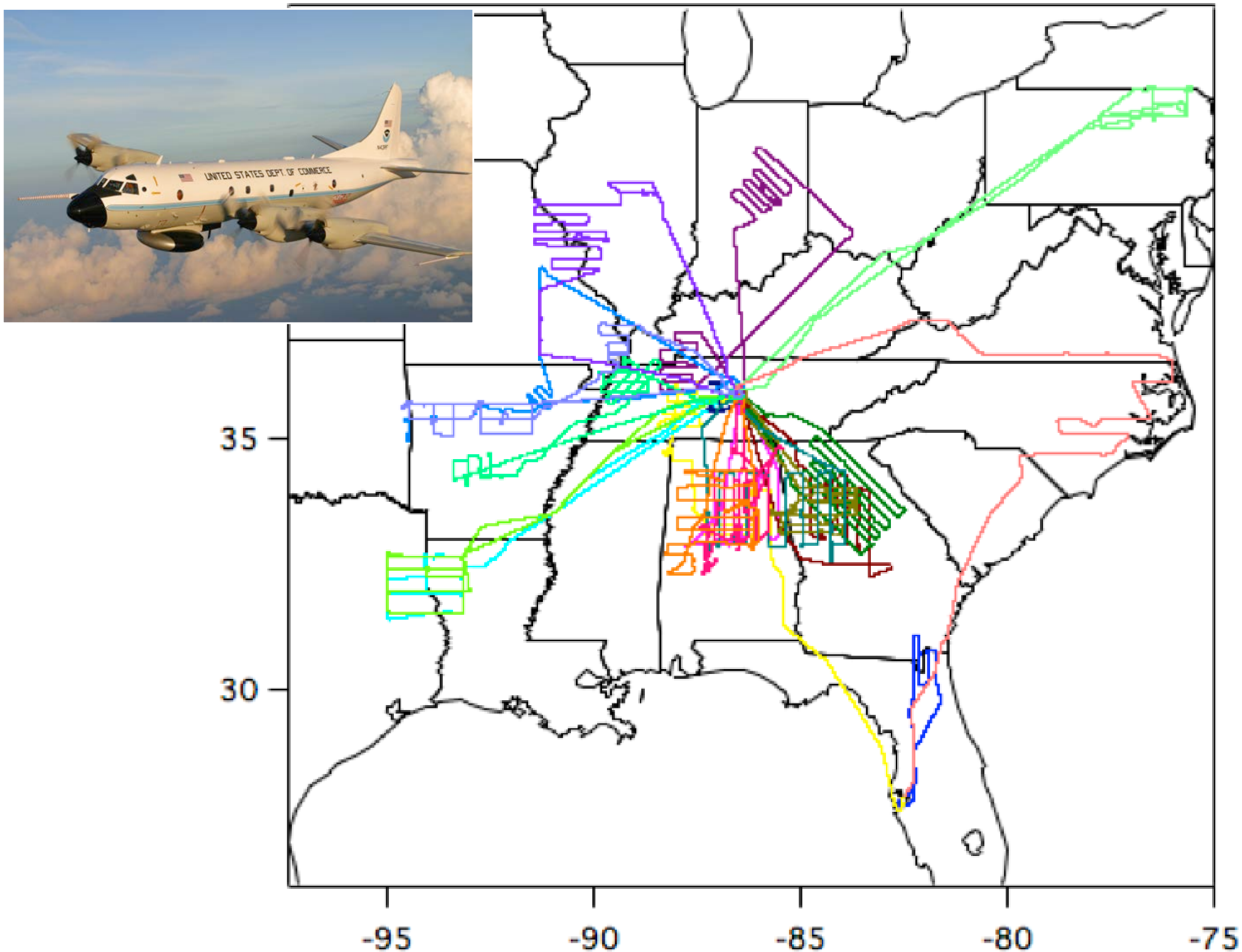
Close collaboration of NOAA ESRL team with STC NUCAPS retrieval team and NESDIS STAR analysis team is absolutely critical to this project's success and adds value to PGRR investment

ESRL Research Assets

ESRL employs unique combination of observational platforms, analysis approaches, and human expertise

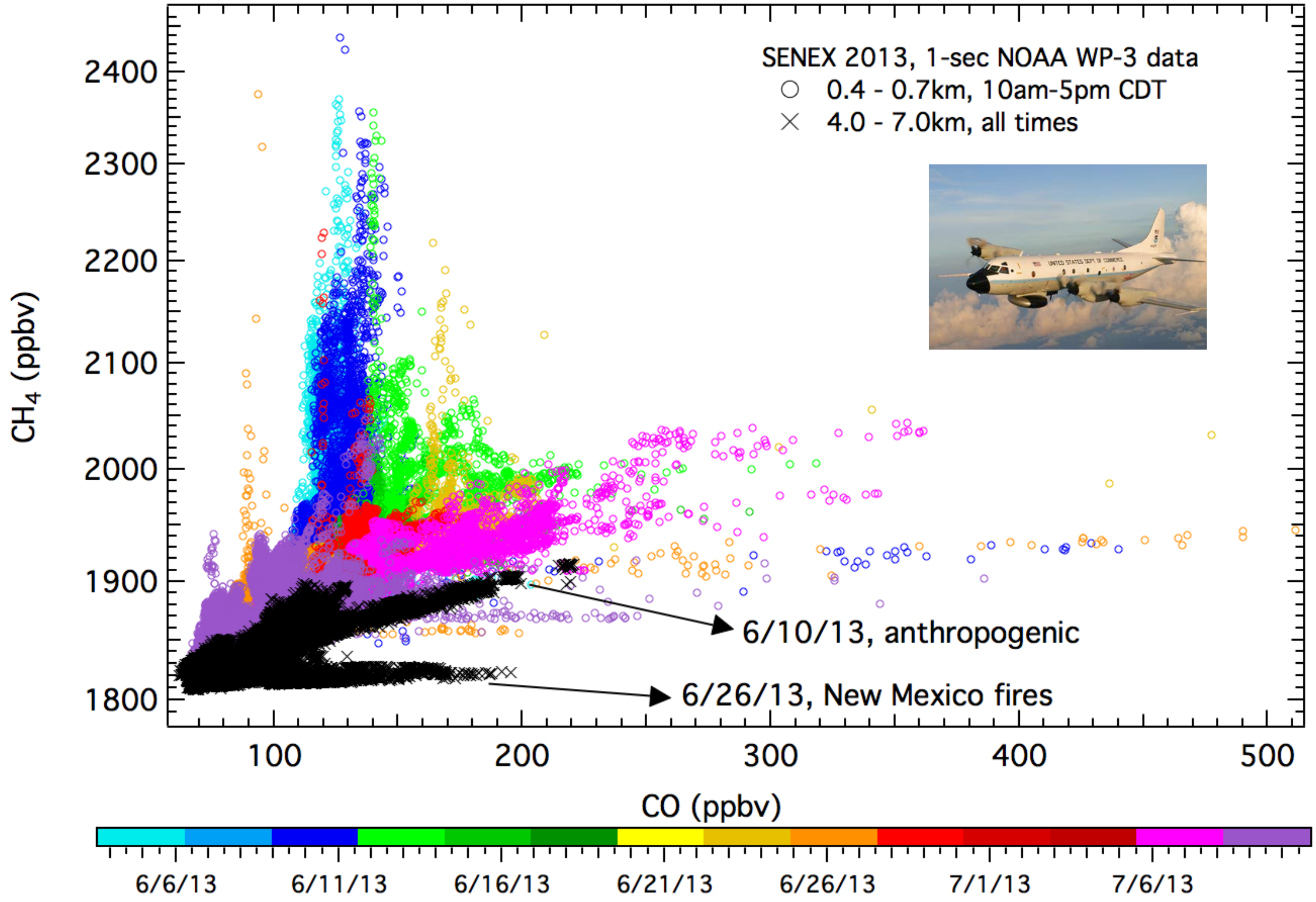
http://www.esrl.noaa.gov

SENEX 2013 NOAA WP-3 Flights



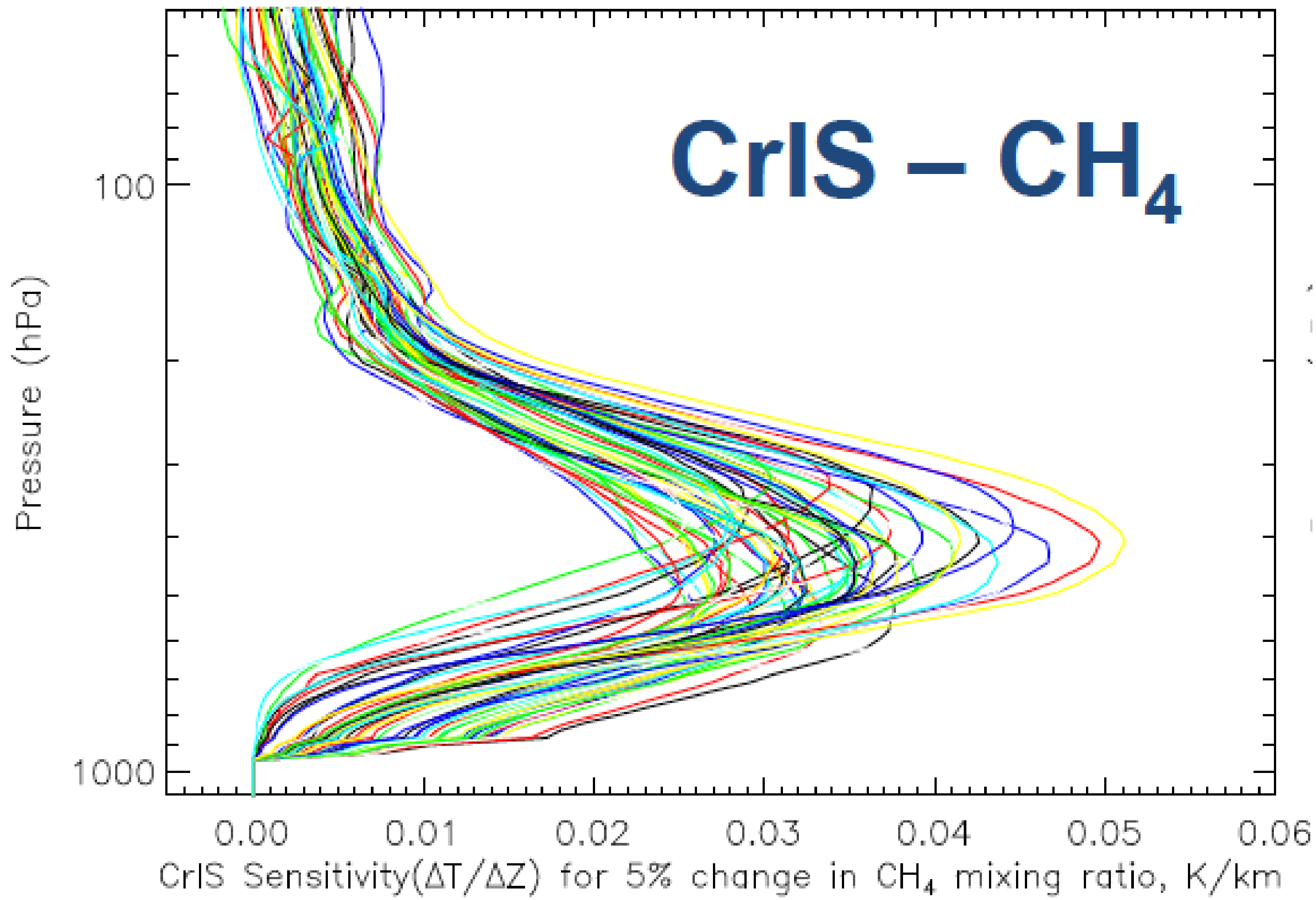
http://www.esrl.noaa.gov/csd/projects/senex/

Detecting Source Signatures with Aircraft Data



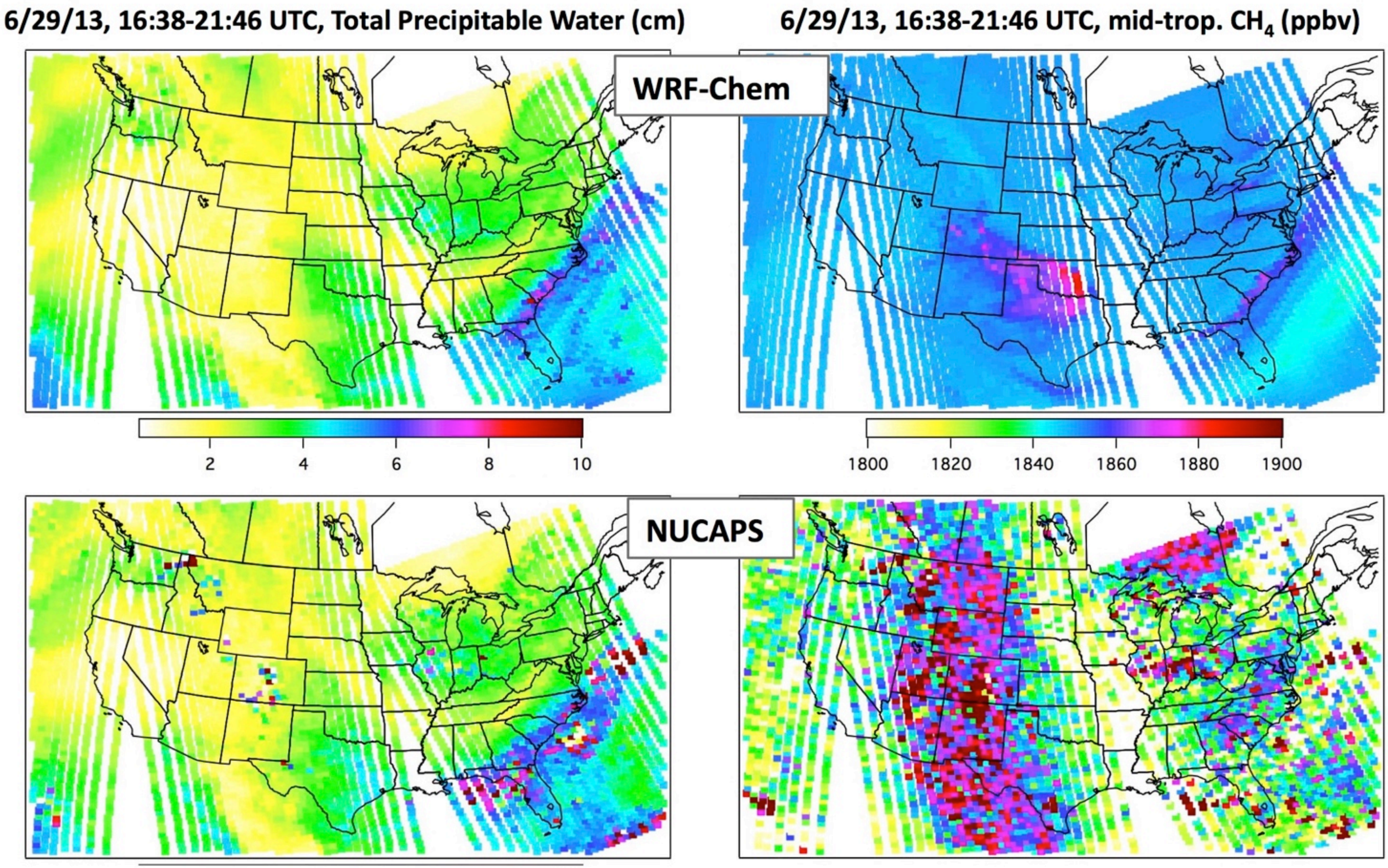
Stuart McKeen

CrIS CH_4 Vertical Sensitivity



Xiaozhen Xiong et al., CrIS Trace Gas Data Users Workshop, 18 Sept 2014

NUCAPS vs. WRF-Chem Model Comparison



Brad Pierce, Stuart McKeen

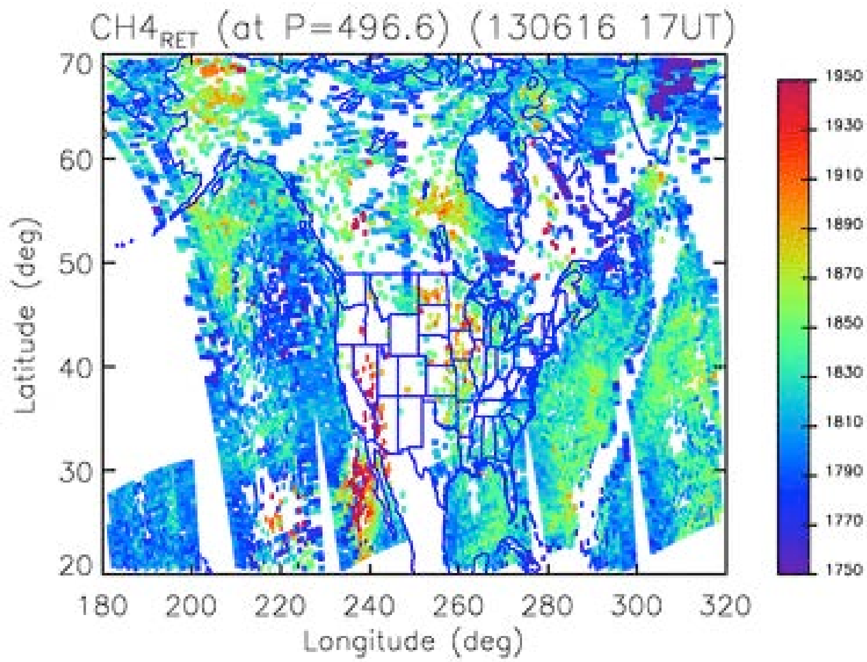
NUCAPS CH_4 Science Retrievals: Initial Data Processing Issues

- Many granules not processed due to failures in pre-processor code, possibly from too stringent ATMS QC threshold
- “Acceptable” QC (QC = 0): Daytime data rejection >> nighttime over land, likely from too stringent CrIS QC threshold
- Very noisy CH_4 signal. Noise filter or averaging may be needed.
- CrIS averaging kernels not initially available

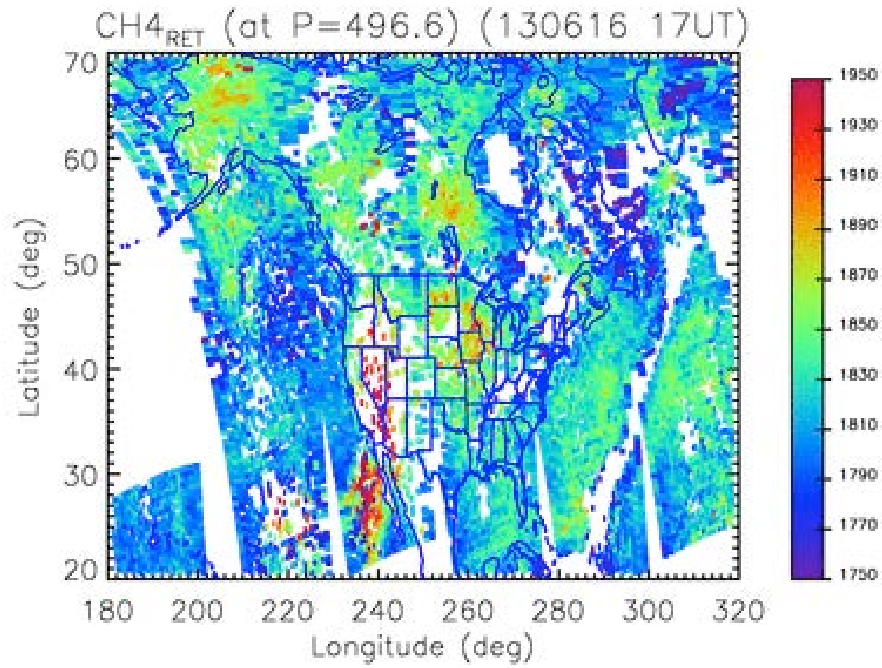
Chris Barnet

Improved NUCAPS Science Code Quality Control Thresholds

Before QC Changes

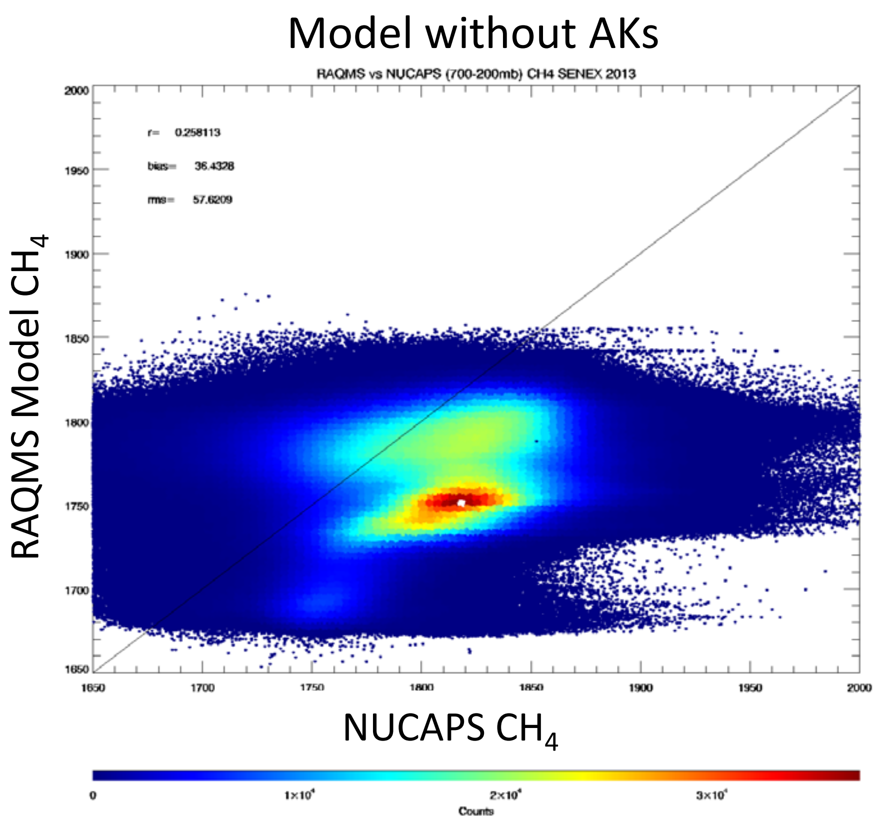


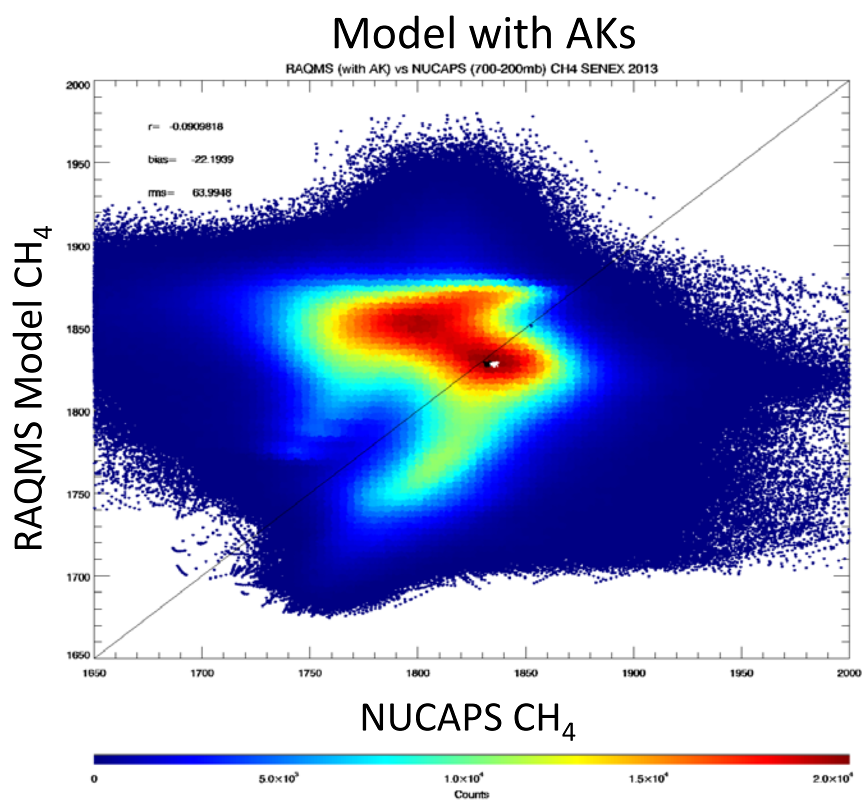
After QC Changes



Nadia Smith

CrIS Averaging Kernels Now Available in Science Code Output



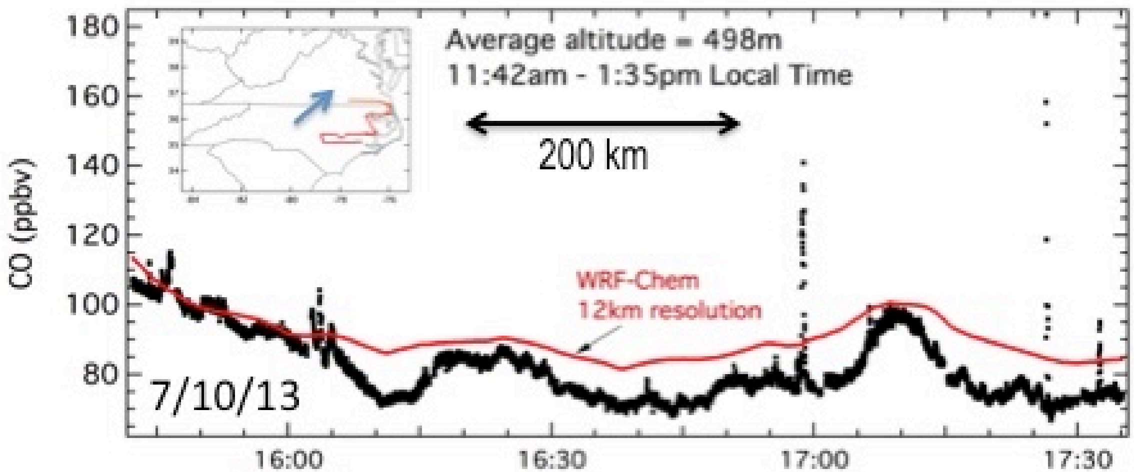


Brad Pierce

Analyzing Scale Dependence of Variance

Compare SENEX-2013 aircraft and WRF-Chem model CO

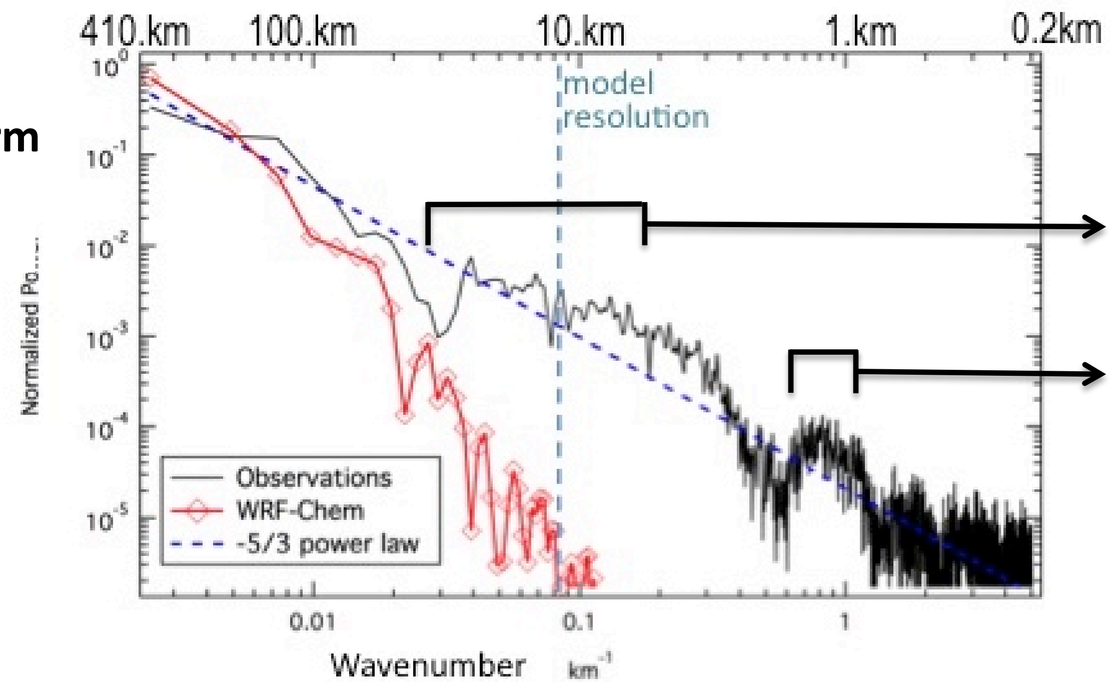
Time Series



Urban Plumes:
15:50 Raleigh/Durham
16:20 Greenville
17:10 Fayetteville

Burning Plumes:
Throughout transect

Fourier Transform Power Spectra



Length Scale

5–30 km scale:
combustion source areas (cities and towns)

1-2km scale:
Agricultural burn plumes

Power Spectra of CO depends on both emissions and transport

Model spectra somewhat similar to observations for length scales > 4ΔX

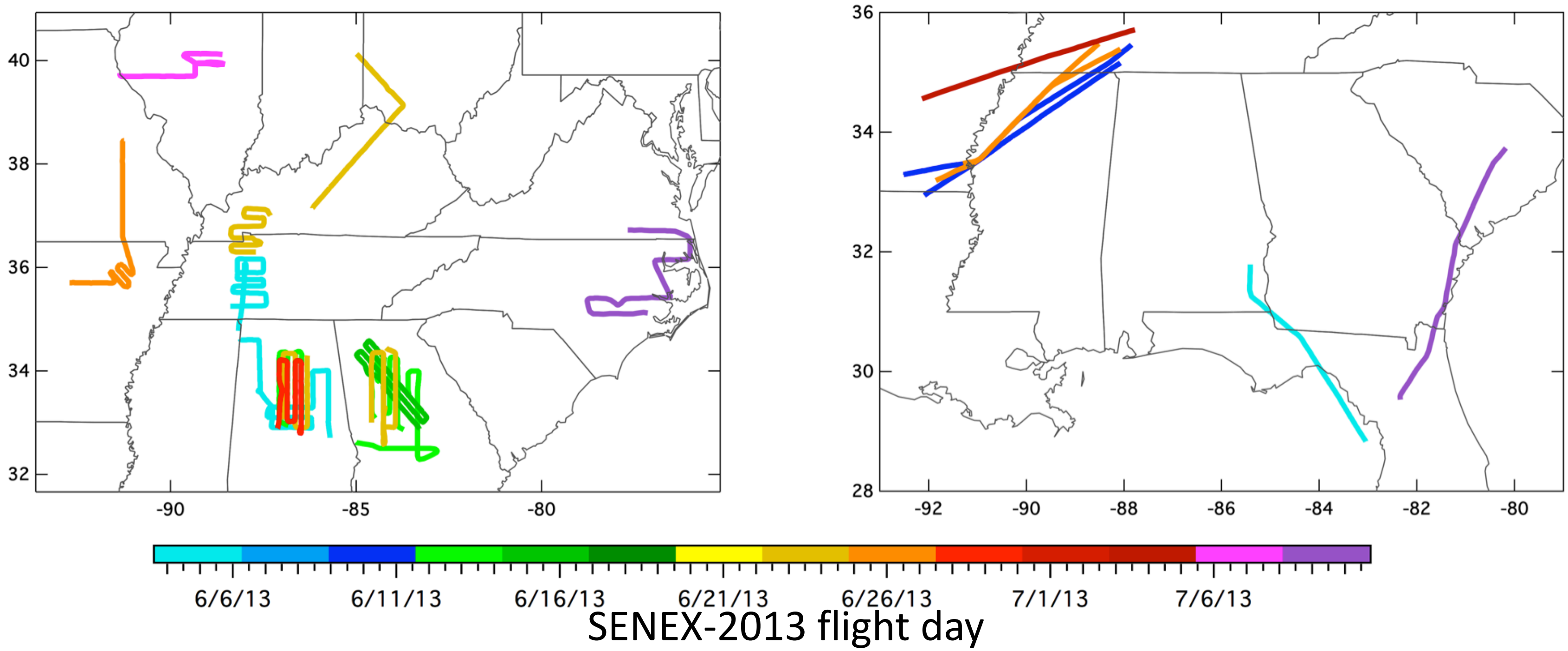
Stuart McKeen

Comparing Average Power Spectra: Aircraft and Model

SENEX 2013 flights within the boundary layer and at high altitude (~500mb)

14 Daytime PBL transects (300-700 m AGL)

7 Hi Altitude transects (480-530 mb)



14 transects, 10:00am-6:00pm EDT,
with N > 4096 for 1-Hz data

21.6 Hours of flight time

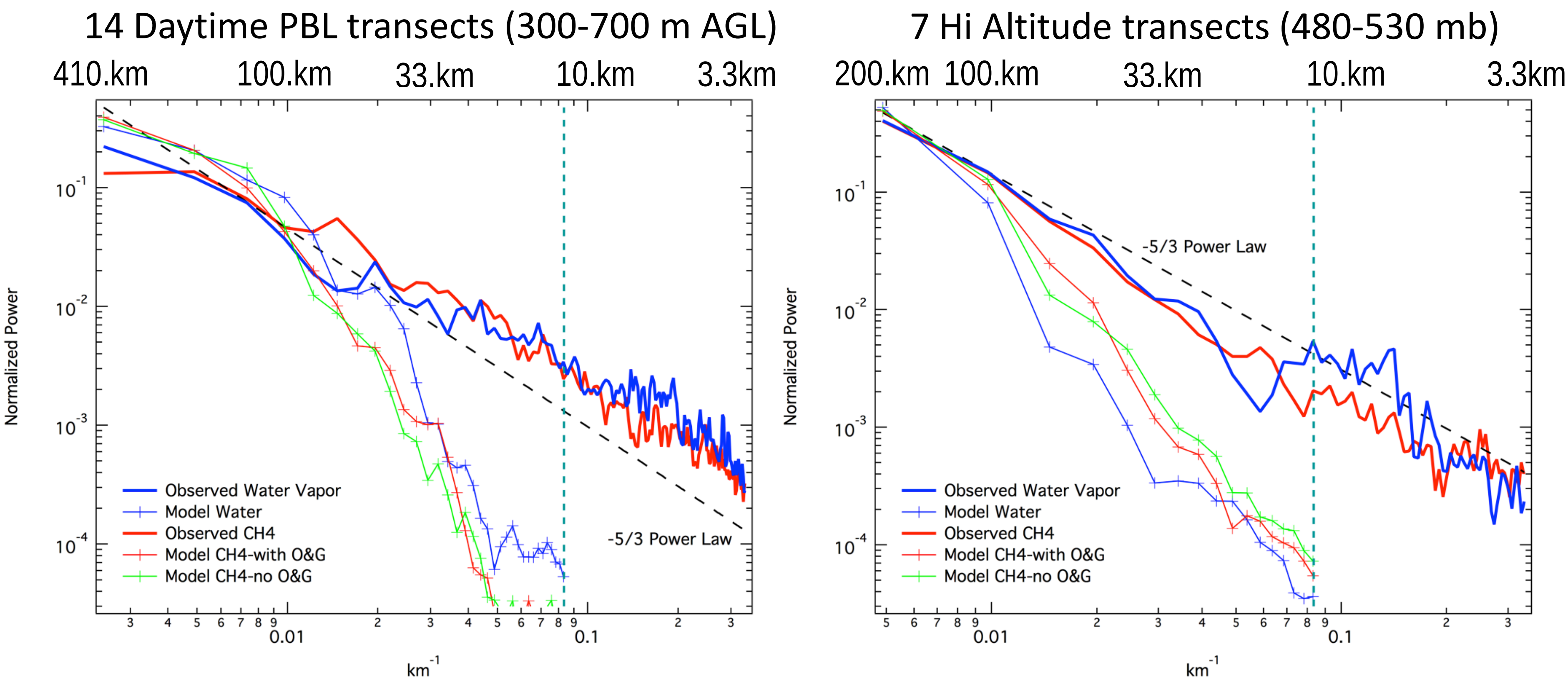
7 transects, day and night,
with N > 2048 for 1-Hz data

5.4 Hours of flight time

Stuart McKeen

Comparing Average Power Spectra: Aircraft and Model

CH_4 and H_2O mixing ratios within the boundary layer and at high altitude (~500mb)



Power spectra for CH_4 and H_2O show similar slopes and tendencies.
At high altitude the slope is about -5/3 for longer (>50 km) length scales.

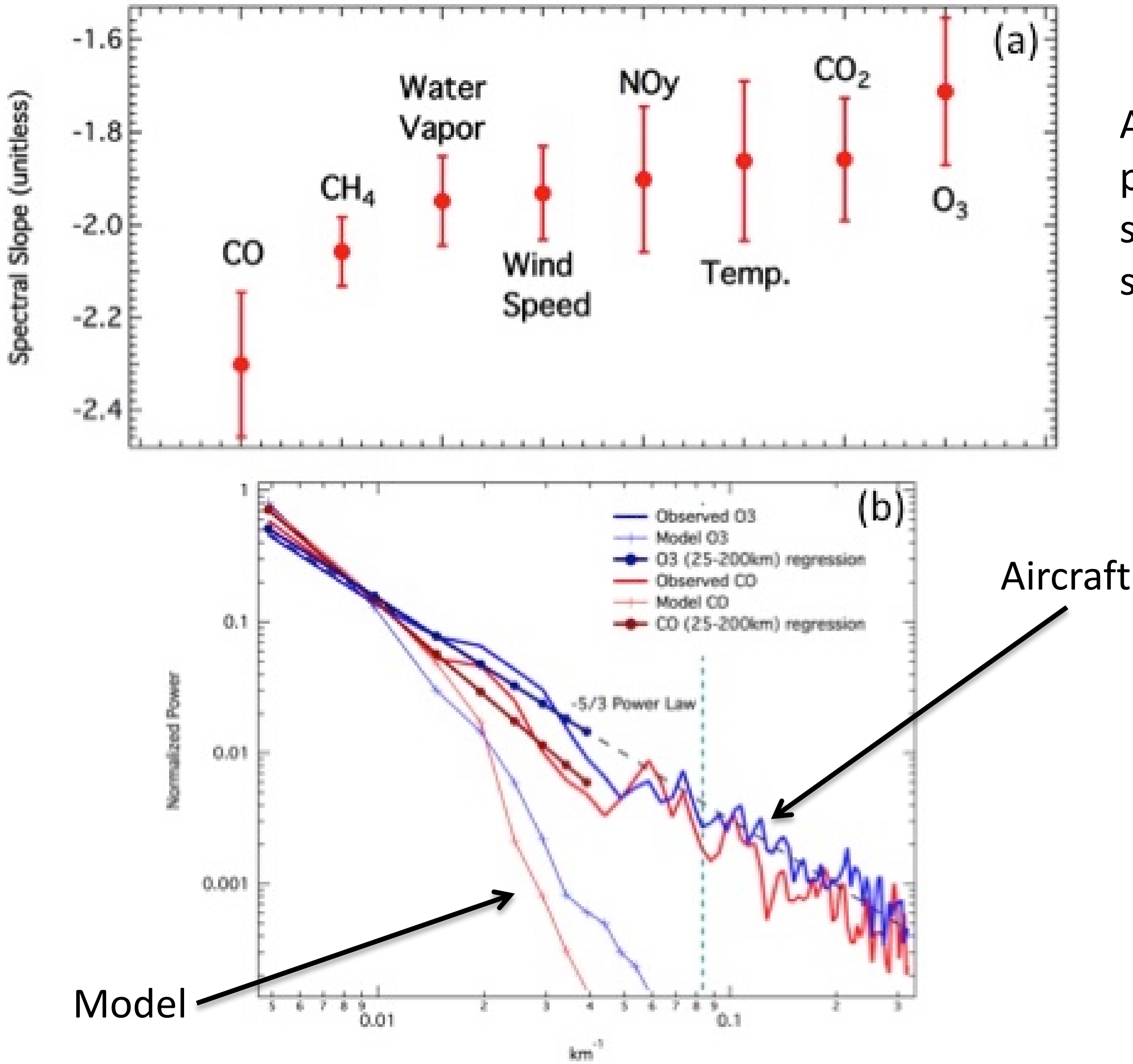
Model H_2O vapor captures variability for length scales > 3ΔX in the PBL, > 7ΔX at 500mb.

Adding/Removing model Oil/Gas emissions impacts CH_4 power spectra for both the PBL and high altitude transects.

Stuart McKeen

Comparing Average Power Spectra: Aircraft and Model

Data at high altitude (~500mb)

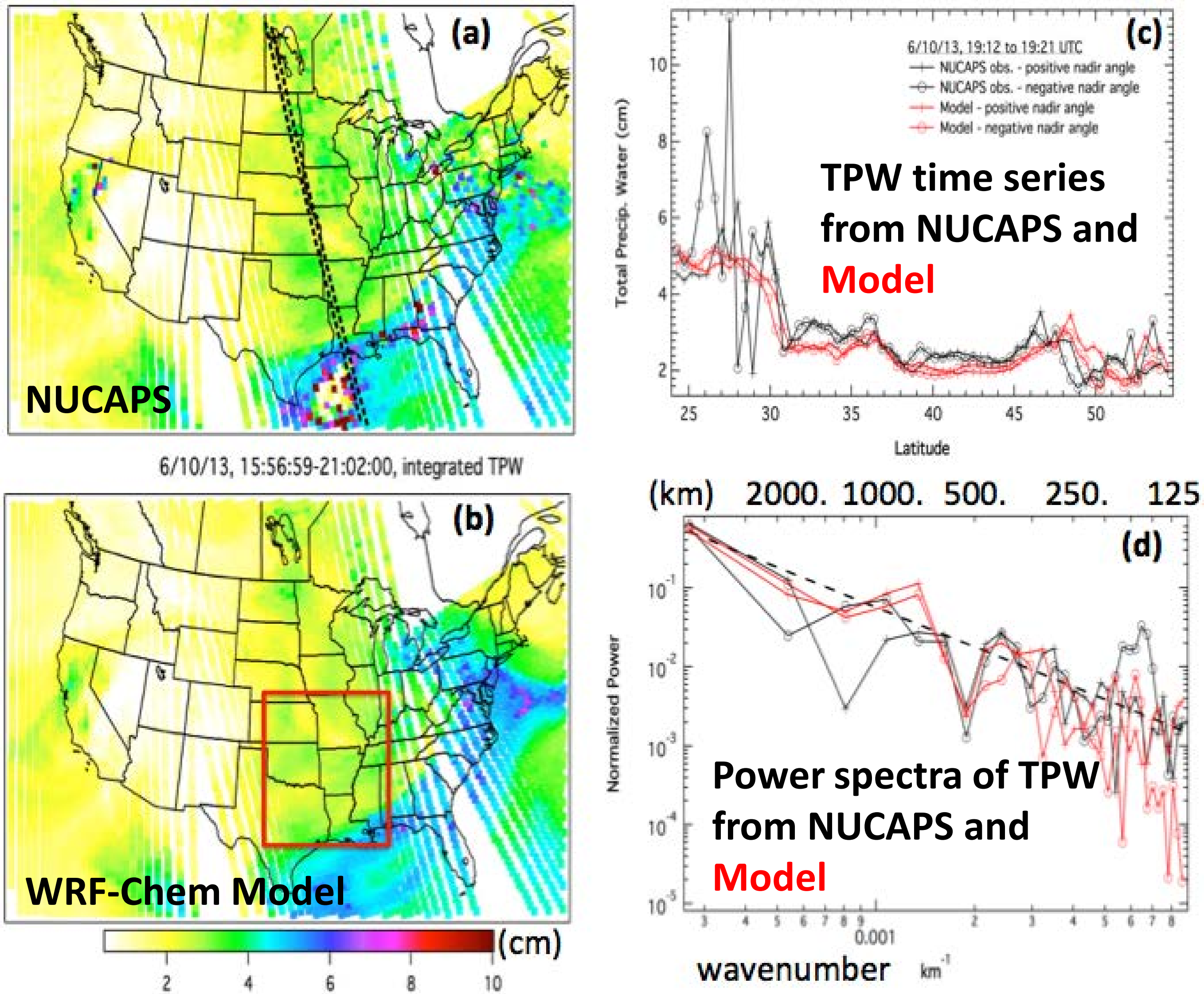


Aircraft power spectral slopes

Stuart McKeen

Comparing Average Power Spectra: NUCAPS and Model

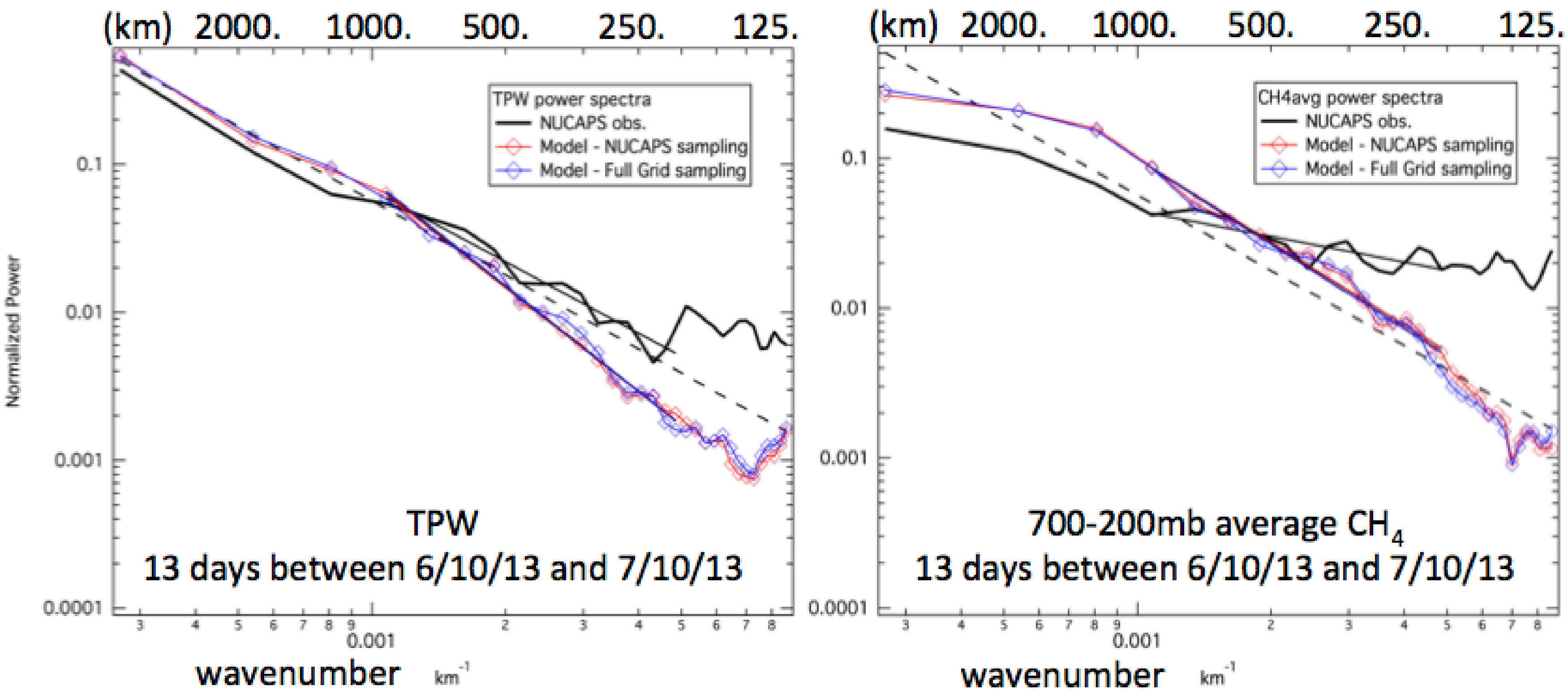
Total precipitable water (TPW) data, 6/10/13



Stuart McKeen

Comparing Average Power Spectra: NUCAPS and Model

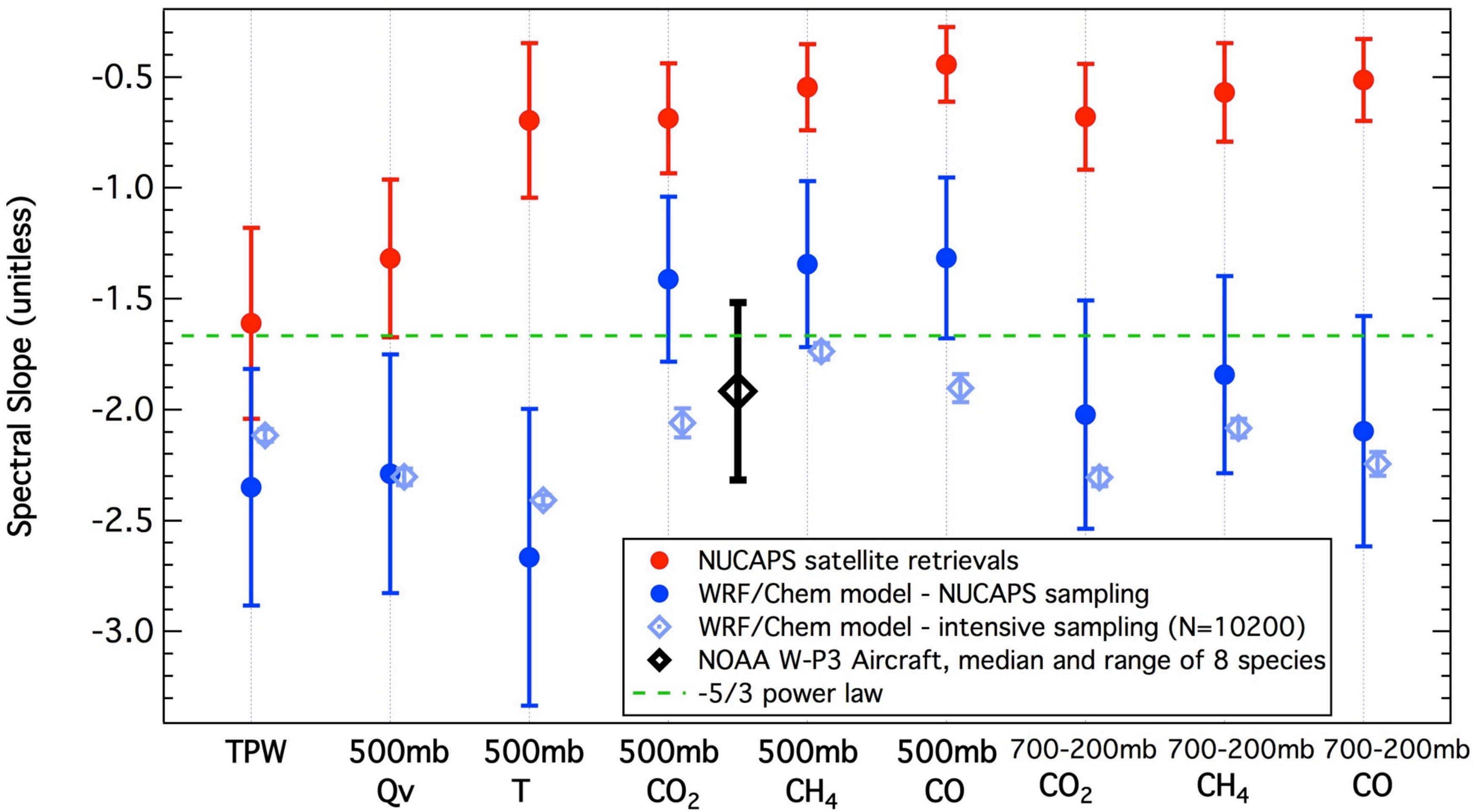
TPW and CH_4 data, 13 days between 6/10/13-7/10/13



Stuart McKeen

Comparing Average Power Spectra: NUCAPS and Model

6/10/13-7/10/13



Stuart McKeen

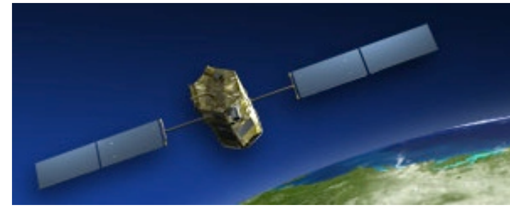
Some Next Steps

- Use averaging kernels to scale model vertical sensitivity to match CrIS
- Incorporate updated NUCAPS data from science code processing and filter with revised quality control flags
- Examine alternative scale variance approaches beyond Fourier analysis to evaluate NUCAPS data
- Examine NUCAPS CH_4 and CO during other recent aircraft field experiments (2015 and beyond)

A Surface-to-Space Atmospheric Carbon Observing System for Decision Support

Arlyn Andrews

NOAA Earth System Research Laboratory



STAR JPSS 2016 Annual Science Team Meeting

8-12 August 2016

Outline

- Current and planned surface, aircraft, and satellite measurements of atmospheric CO_2 and CH_4
- Magnitude of important carbon emissions and sink signatures
- A vision for a future observing system to provide decision support services

Focus here is on CO_2, but story for CH_4 is similar.

There is broad and growing consensus that rising atmospheric CO_2 is a planetary emergency:

- The Paris Agreement at the 21st Conference of the Parties of the UNFCCC was negotiated by representatives of 195 countries.
- The agreement opens for signature on Earth Day, 22 April 2016. Some 120 countries, including the US and China, are expected to sign.

PARIS2015
CONFÉRENCE DES NATIONS UNIES SUR LES CHANGEMENTS CLIMATIQUES
COP21·CMP11

United Nations
Framework Convention on Climate Change

Data Transparency: New Dynamic at COP-21 in Paris

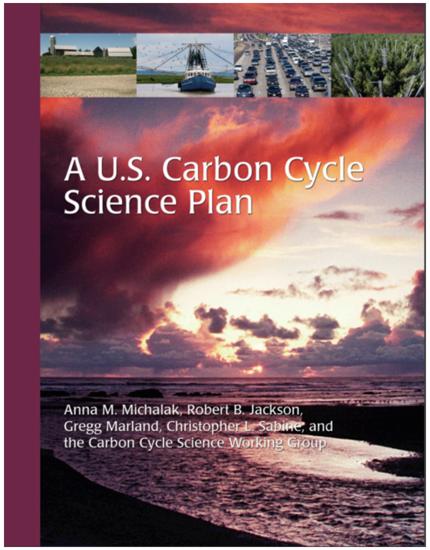
Posted by Angel Hsu, Andrew Moffat and Kaiyang Xu on Dec 22, 2015

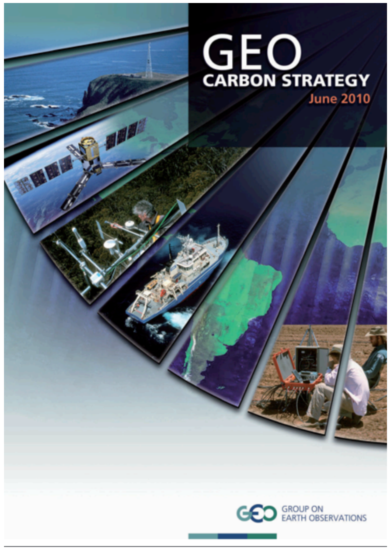
From the Paris Climate Negotiations

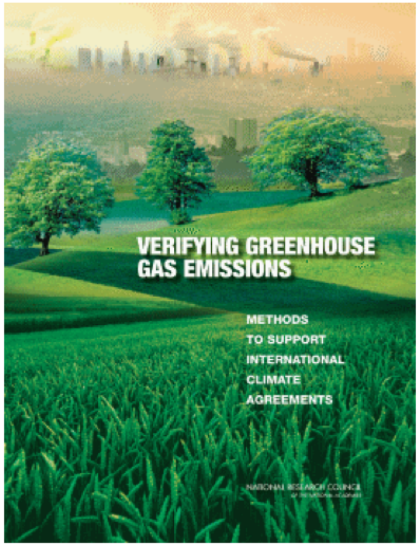
The **Paris Agreement and decision** together mention "transparency" 30 times. Language is often open to interpretation, yet **the Agreement's mandate is clear**: each country is to regularly provide standardized national GHG emissions inventories and "information necessary to track progress made in implementing and achieving its nationally determined contribution" (Article 13). This provision, part of an agreement signed by all Parties including the U.S. and China, marks a step forward toward gaining clarity on what the world is doing to address climate change.

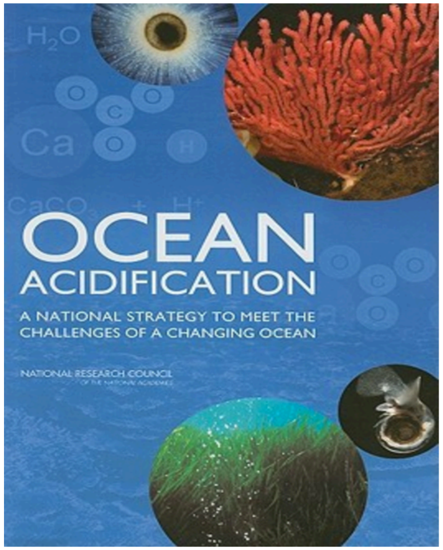
There is an urgent need to transition carbon research efforts into a state-of-the science greenhouse gas information system for decision support. Long-term monitoring of atmospheric CO_2 and CH_4 will be an essential component of this system.

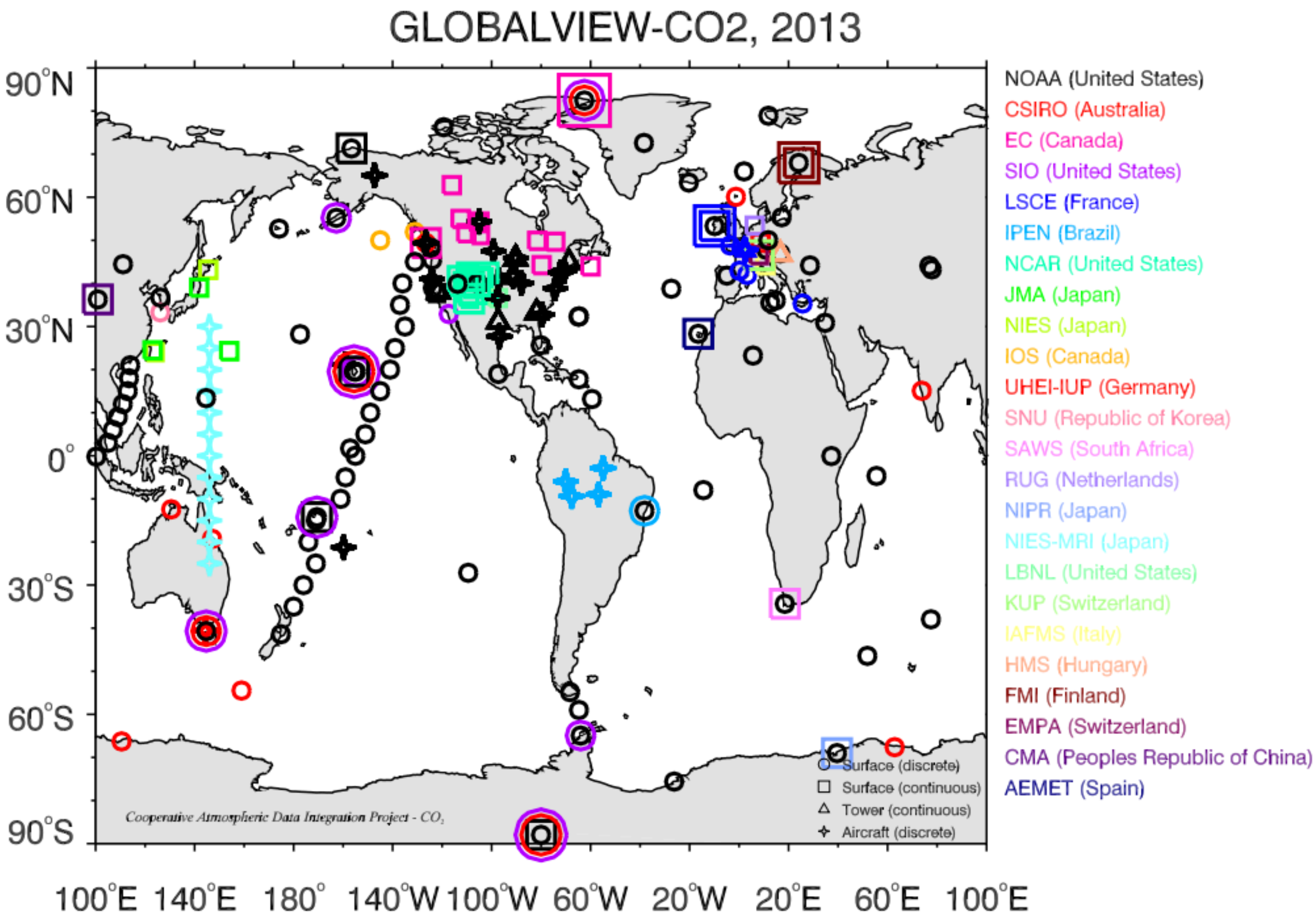
Several recent reports describe measurement requirements for carbon observations to advance science and to support policy:











- Current knowledge of global CO_2 and CH_4 budgets is based primarily on in situ measurements, with satellite data products becoming available during the past decade.

The Evolving Near-Infrared Atmospheric Carbon Measurement Capabilities

If carefully coordinated, these missions can be integrated into an ad hoc constellation and their measurements can be combined to produce a continuous data record.

However, none of these missions provides the capabilities needed to identify carbon/climate tipping points

Slide courtesy of Dave Crisp, NASA JPL

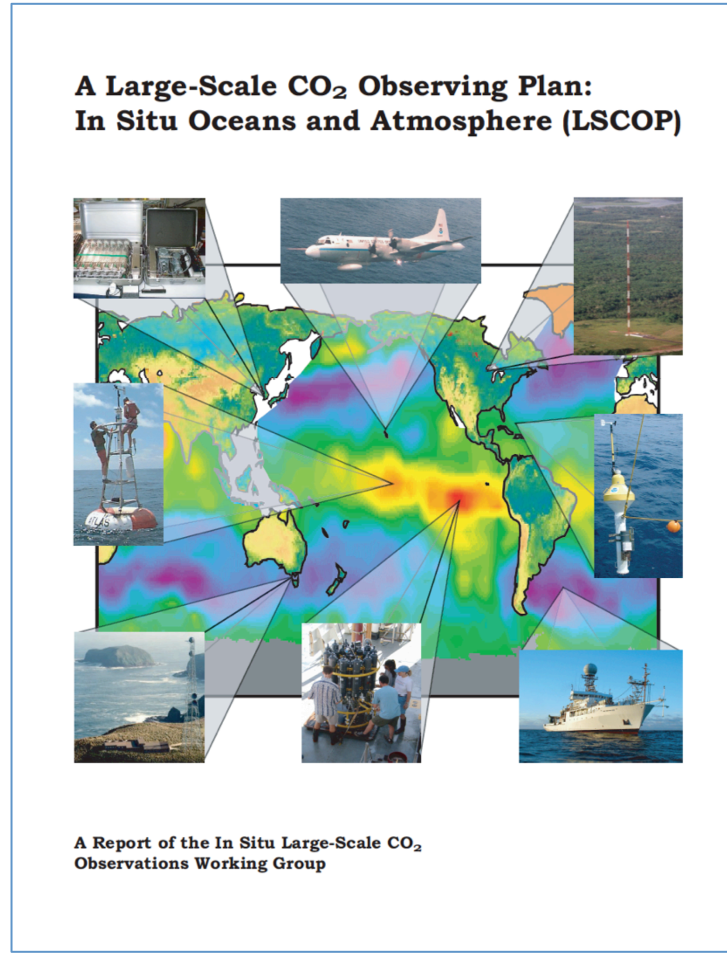
Tracking emissions and sink changes with atmospheric data: A very hard problem

Tracking emissions and sink changes with atmospheric data: A very hard problem

In Situ Large-Scale CO_2 Observations Working Group:

Bender, M., S. Doney, R.A. Feely, I. Fung, N. Gruber, D.E. Harrison, R. Keeling, J.K. Moore, J. Sarmiento, E. Sarachik, B. Stephens, T. Takahashi, P. Tans, and R. Wanninkhof

Note: the report covers oceanic and atmospheric observations, but for this talk focus is on atmospheric measurements.



A contribution to the implementation of the U.S. Carbon Cycle Science Plan, April 2002

Our future observing system should have the following characteristics:

- Regional spatial resolution, down to 10^6 km^2 on the continents and 10^7 km^2 over the oceans, with an accuracy of 0.1 Gt C/yr. This resolution will enable meaningful quantification of processes regulating surface carbon exchange. An ability to see the effects on atmospheric CO_2 of specific processes and mechanisms on these spatial scales will allow a marked increase of confidence in our understanding and predictive capability.
- Integration of satellite observations. The in situ measurements should be able to stand on their own, but will be merged with satellite CO_2 data if and when these become available, providing crucial accuracy to the latter. Space-based observations of the CO_2 mole fraction in the atmospheric column are expected to have nearly complete spatial coverage, but lower chemical resolution and accuracy.
- Assimilation of all available data. Data assimilation models must be an integral part of the observing system. The models should assimilate weather and CO_2 observations, and remotely sensed indicators of primary productivity. They should be high resolution in time and space, dynamically consistent, and include carbon processes.

Large Scale CO_2 Observing Plan, April 2002

Magnitude of atmospheric signature of various carbon fluxes:

Table 2-1: Rate of change in integrated vertical column abundance for specific CO_2 sources and sinks.

Source	Assumptions	ppm/day
Los Angeles Basin	12×10^6 people, 4,000 km^2, 1100 mol C/person/day	+10
Netherlands	16×10^6 people, 40,000 km^2, 500 mol C/person/day	+0.6
Germany	83×10^6 people, 350,000 km^2, 580 mol C/person/day	+0.4
Photosynthetic Uptake	Harvard Forest, July	–1.2
U.S. Carbon Sink	1 Gt C/yr, constant in time, uniform over the lower 48 states	–0.08
Southern Oceans	$\Delta pCO_2 = -30\ \mu atm$, wind 15 m/s	–0.06
Eastern Equatorial Pacific	$\Delta pCO_2 = 100\ \mu atm$, wind 7 m/s	+0.04

If residence time of air over Los Angeles Basin is ~3 hours, then column signal downwind would be 1.25ppm.

Signal comparisons and measurement requirements for continental-scale fluxes

Source or Sink	Emission Rate (GT C / year)	Column CO_2 signal downwind of continent (ppm)
US fossil fuel emissions	1.4	0.7
20% emissions reduction	0.28	0.14
Biological Uptake during July	5.8	2.9
Climate Induced terrestrial anomalies	0.2	0.1

Detection of subtle signals resulting from changes in emissions and from climate-induced biological flux anomalies will require sensitivity of ~0.1 ppm in X_{CO2} maintained over many years.

Space-based observations of megacity carbon dioxide

Eric A. Kort,[1,2] Christian Frankenberg,[2] Charles E. Miller,[2] and Tom Oda[3,4]

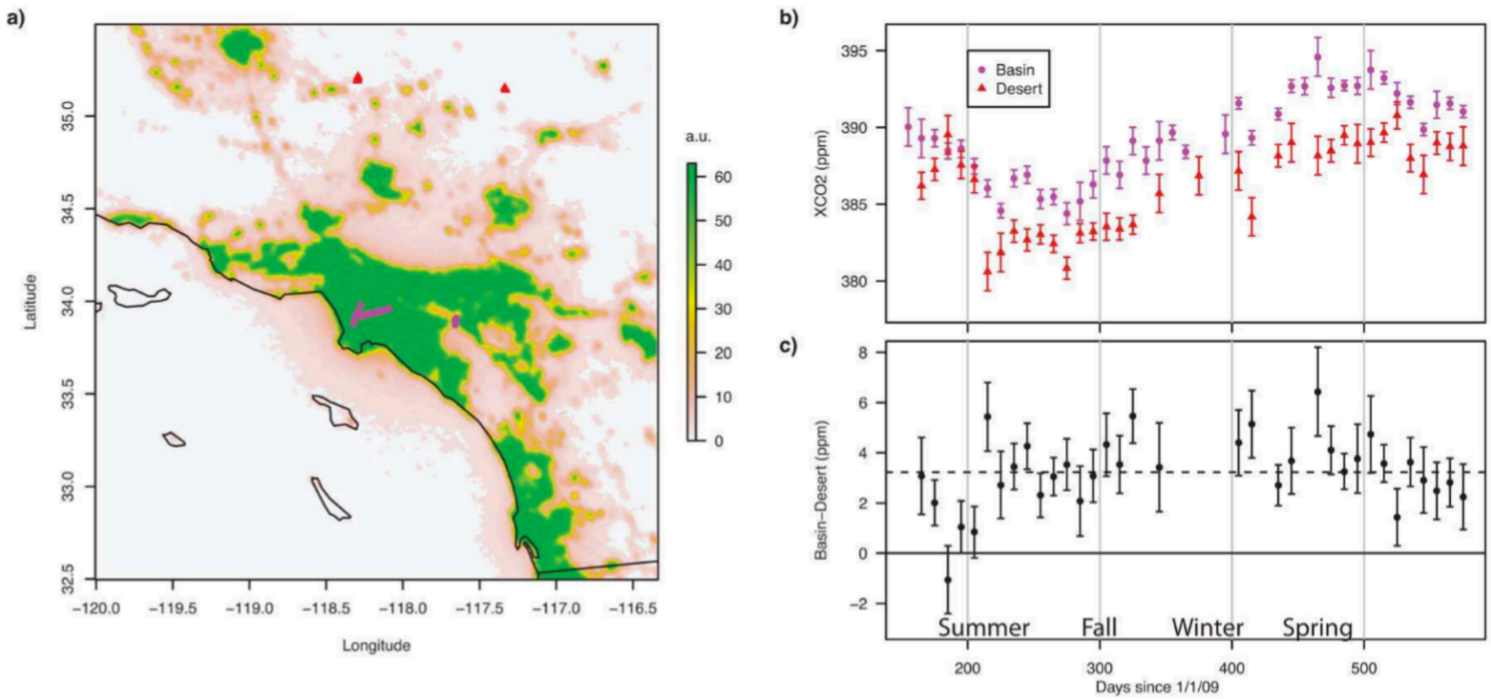
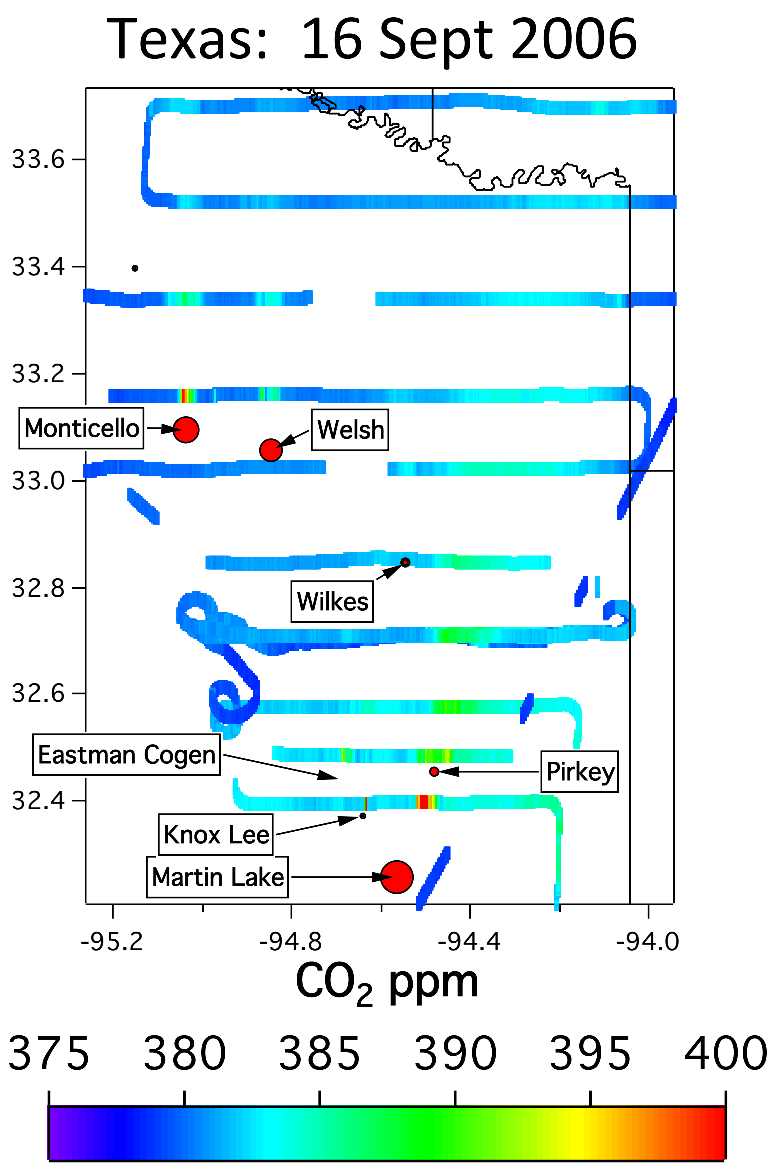
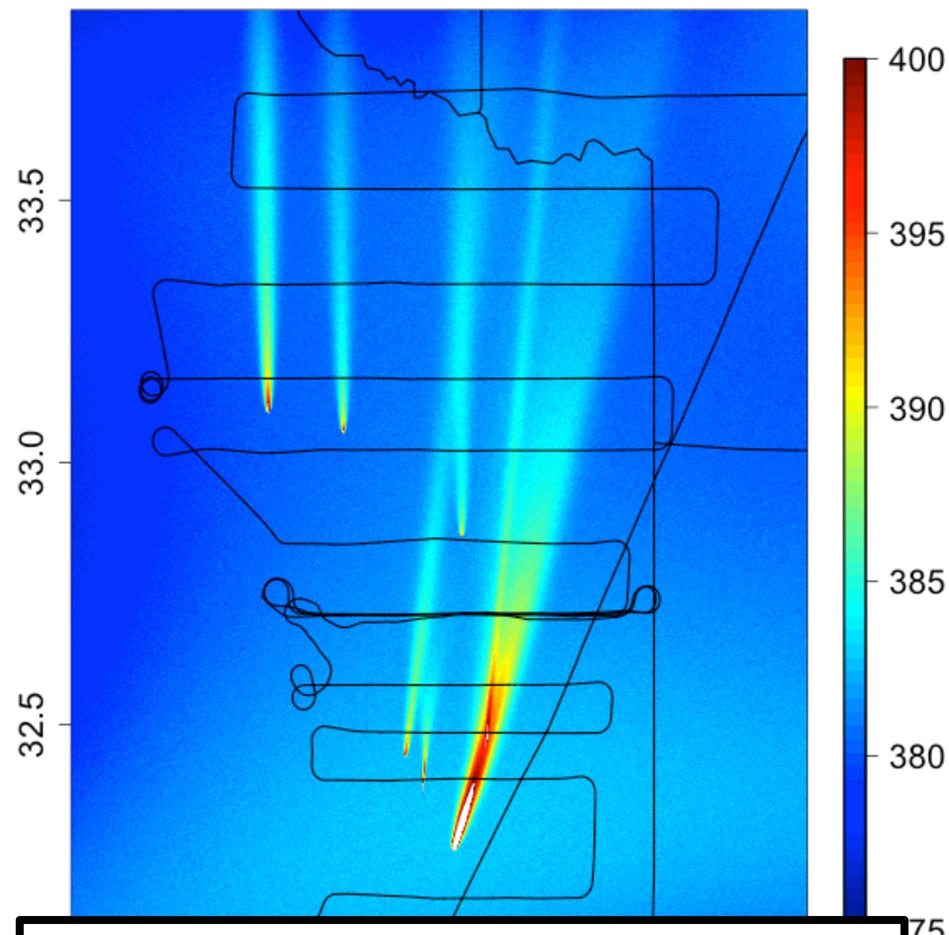


Figure 1. Observed X_{CO2} urban dome of Los Angeles from June 2009 to August 2010. (a) Nightlights map of the Los Angeles megacity and surroundings. Selected GOSAT observations within the basin (pink circles near 34°N, 118°W) and in the desert (red triangles near 35°N, 117–118°W). (b) Time-series for basin and desert observations averaged in 10-day bins. (c) The difference between 10-day block averages of basin and desert observations. The dashed black line shows the average difference (3.2 ± 1.5 ppm). All error bars plotted are one-sigma. Note Bakersfield is located near 35.4°N, 119.0°W.

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L17806, doi:10.1029/2012GL052738, 2012

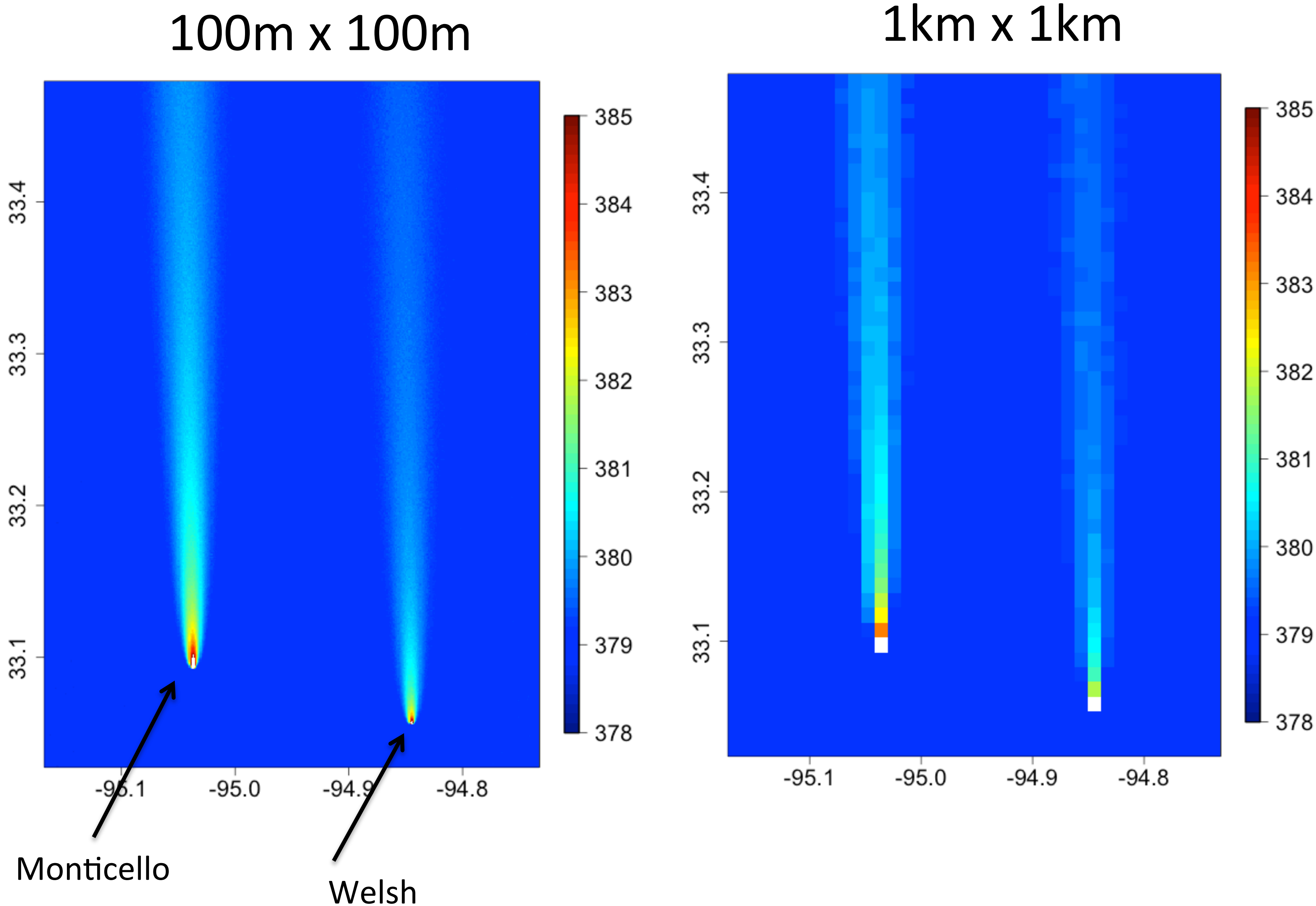
Power Plant Plume Sampling by the NOAA WP-3D Aircraft



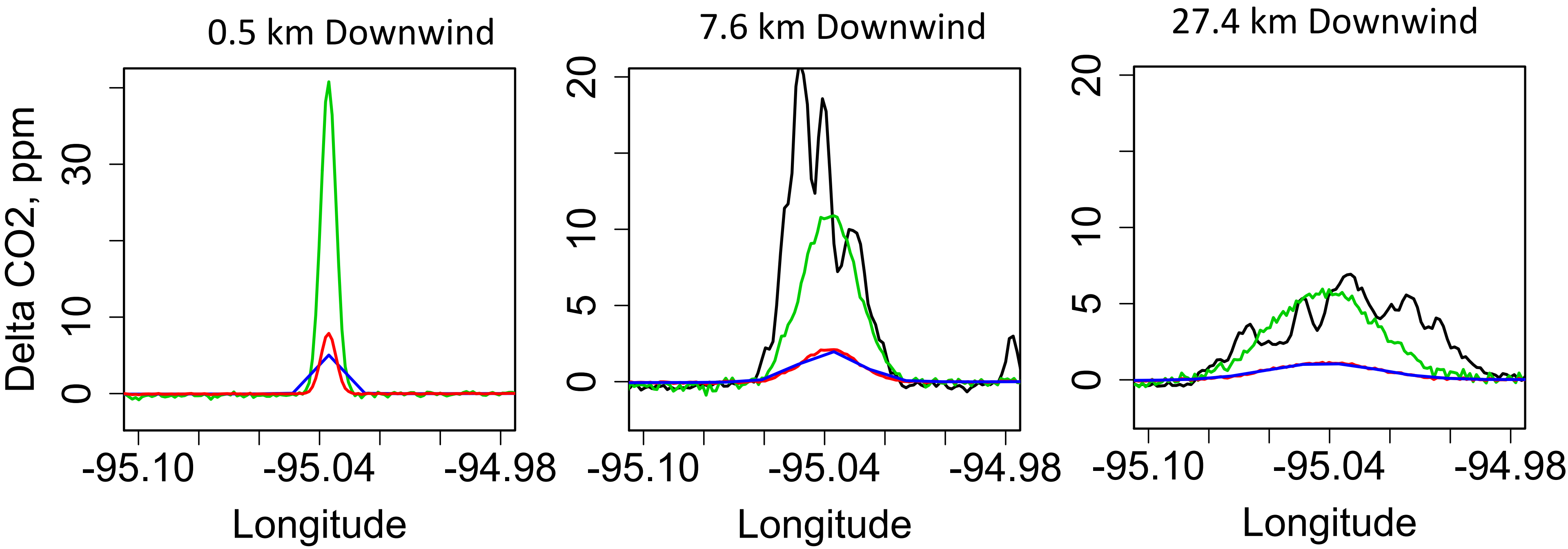


Use a simple plume model to create a 2D field representing the PBL integrated CO_2.

Total Column: XCO_2

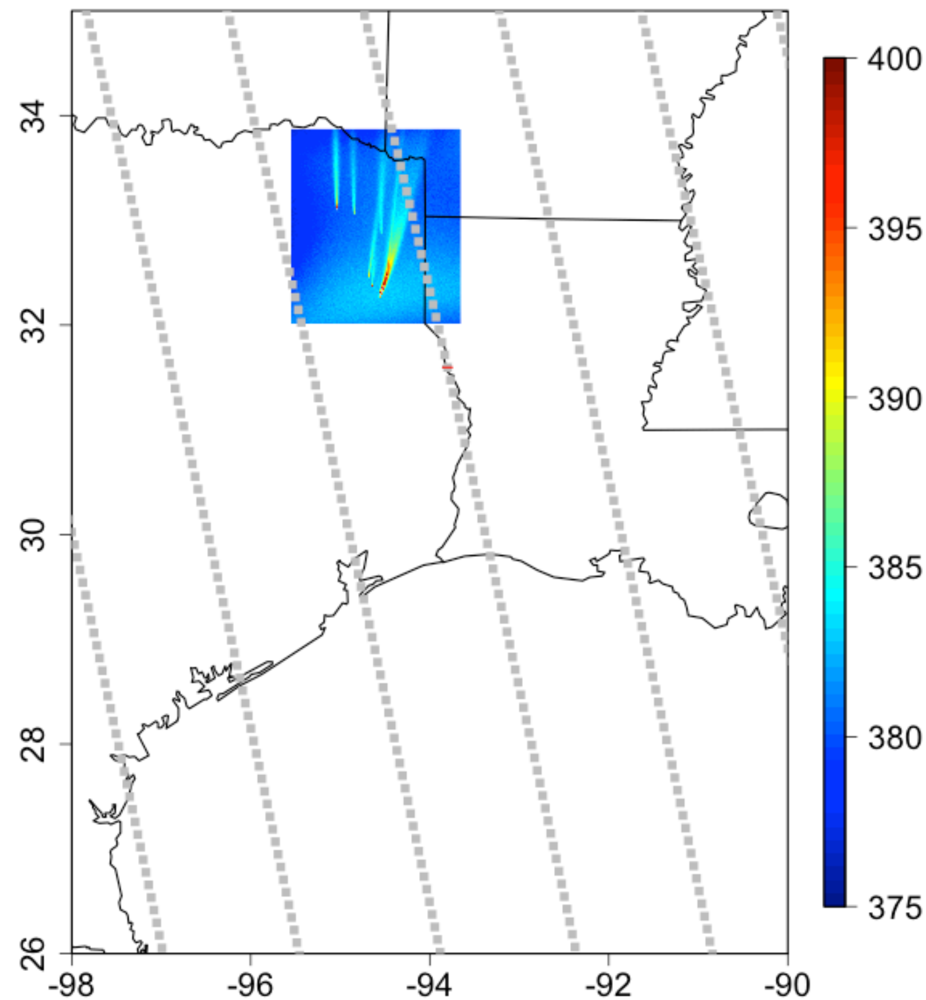


Monticello (18.3 MTon CO_2/yr, 1.98 GW)



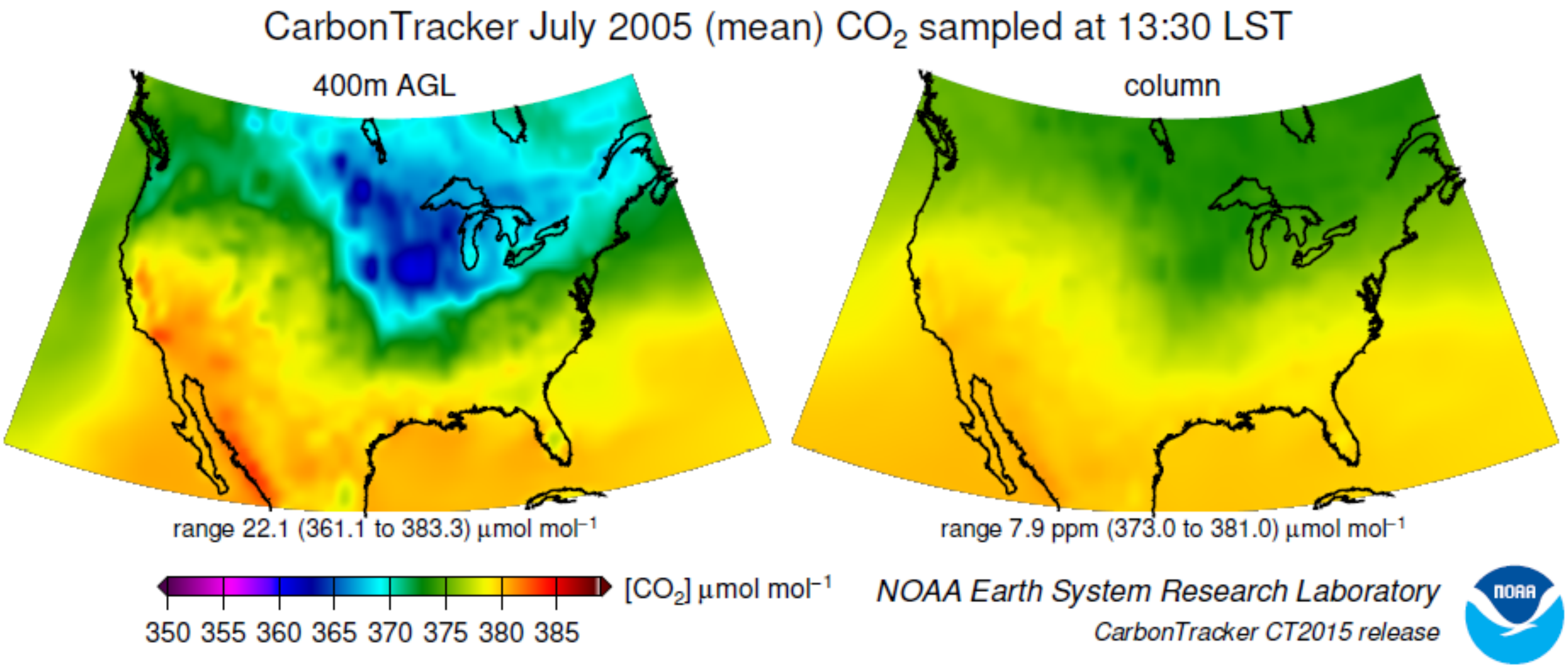
PBL: 40.8 ppm	PBL: 10.9 ppm	PBL: 6.0 ppm
XCO_2 100m: 7.9 ppm	XCO_2 100m: 2.1 ppm	XCO_2 100m: 1.1 ppm
XCO_2 1km: 5.0 ppm	XCO_2 1km: 1.97ppm	XCO_2 1km: 1.0ppm
No Obs	Obs: 600 magl	Obs: 600 magl

- Current and planned satellite CO_2 sensors do not have large enough field of view for emissions monitoring.
- Geostationary or Low Earth Orbiting mapping satellites have been proposed to monitor emissions from large point sources and urban areas.



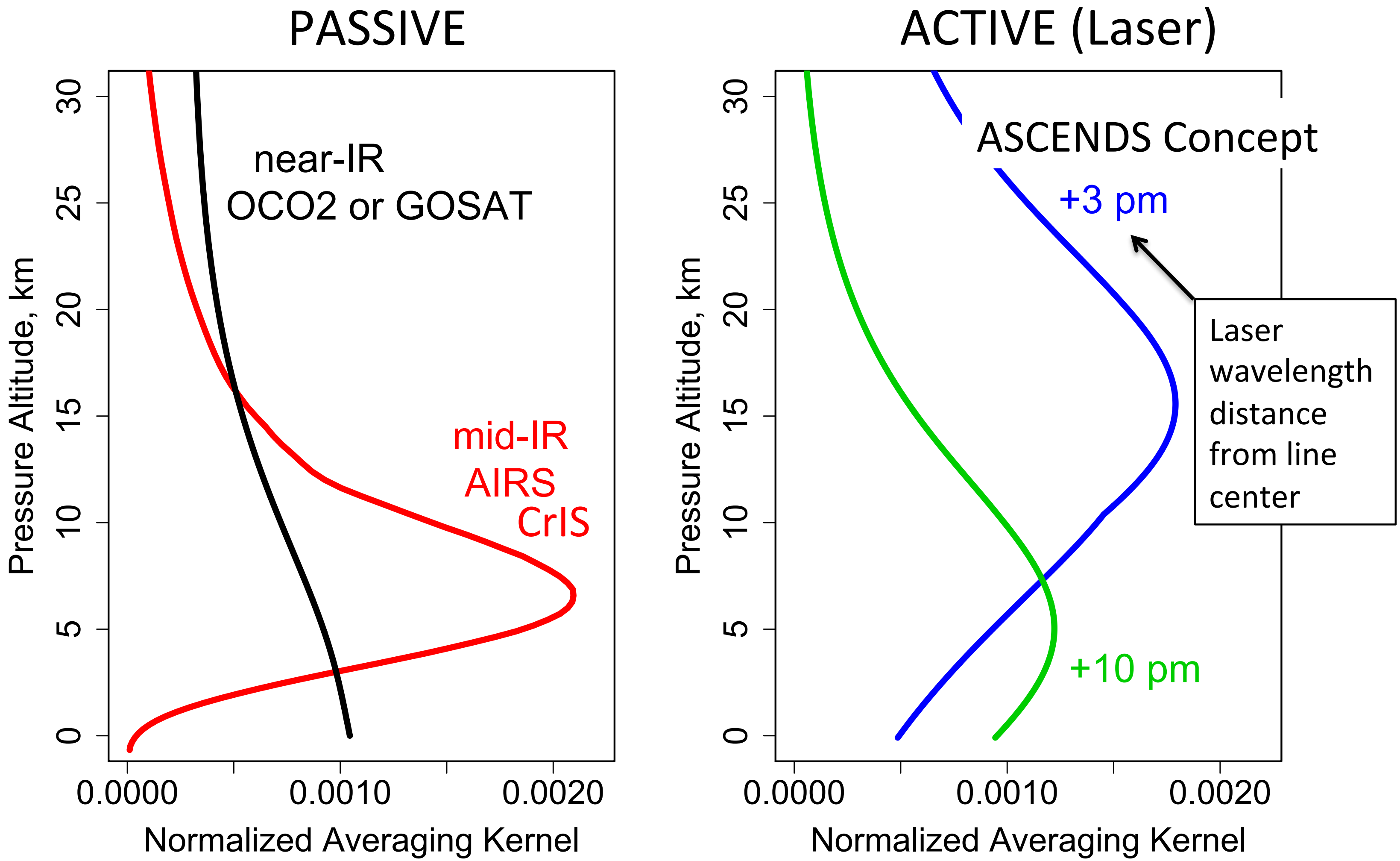
OCO-2 swath width is ~10km. Figure shows A-train afternoon orbit with 10x10 km pixel size.

Boundary Layer versus Column CO_2:



- Relevant signatures of CO_2 and CH_4 emissions are very small in the column -- detection with satellites will be extremely challenging.
- In situ measurements can be made very precisely, but measurements are sparse and variability in proximity to sources is large.

Satellite Sensor Averaging Kernels

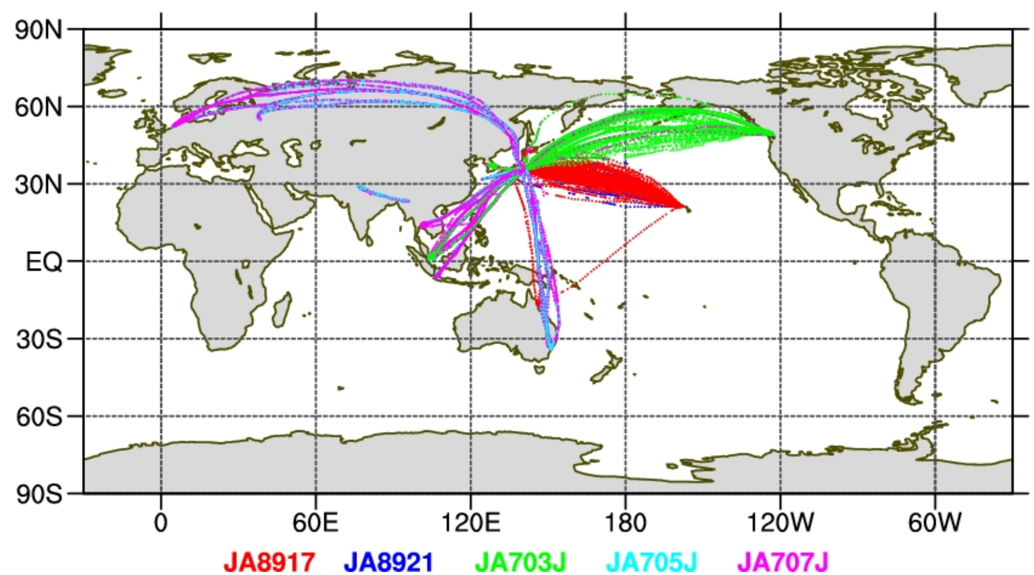


Combination of thermal-IR and near-IR satellite measurements should enable separation of boundary layer versus free-troposphere signals with rigorous data assimilation techniques.

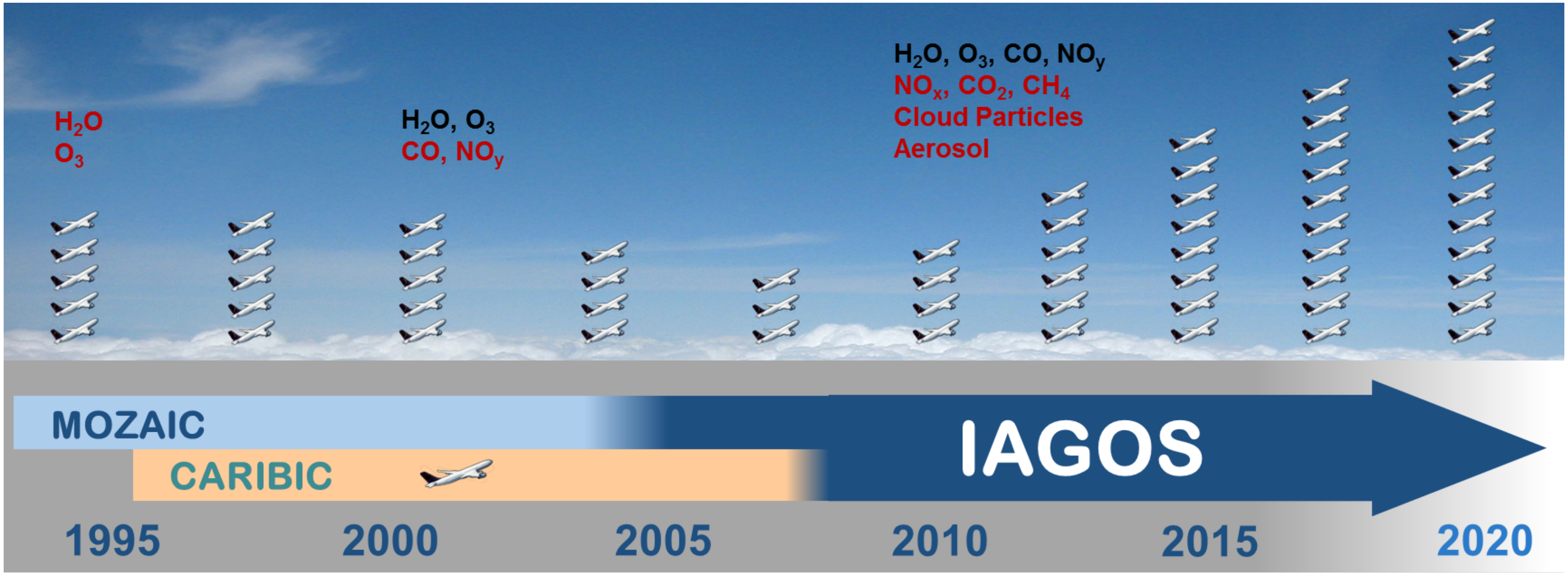
Commercial aircraft are an underutilized platform for atmospheric sampling and could provide critical data for evaluating satellite retrievals and for flux estimation:

Japanese CONTRAIL program has been making continuous CO2 measurements on Japan Airlines flights since 2005:

- Five aircraft
- 20 Airports
- >2000 vertical profiles



European In-service Aircraft for a Global Observing System (IAGOS)

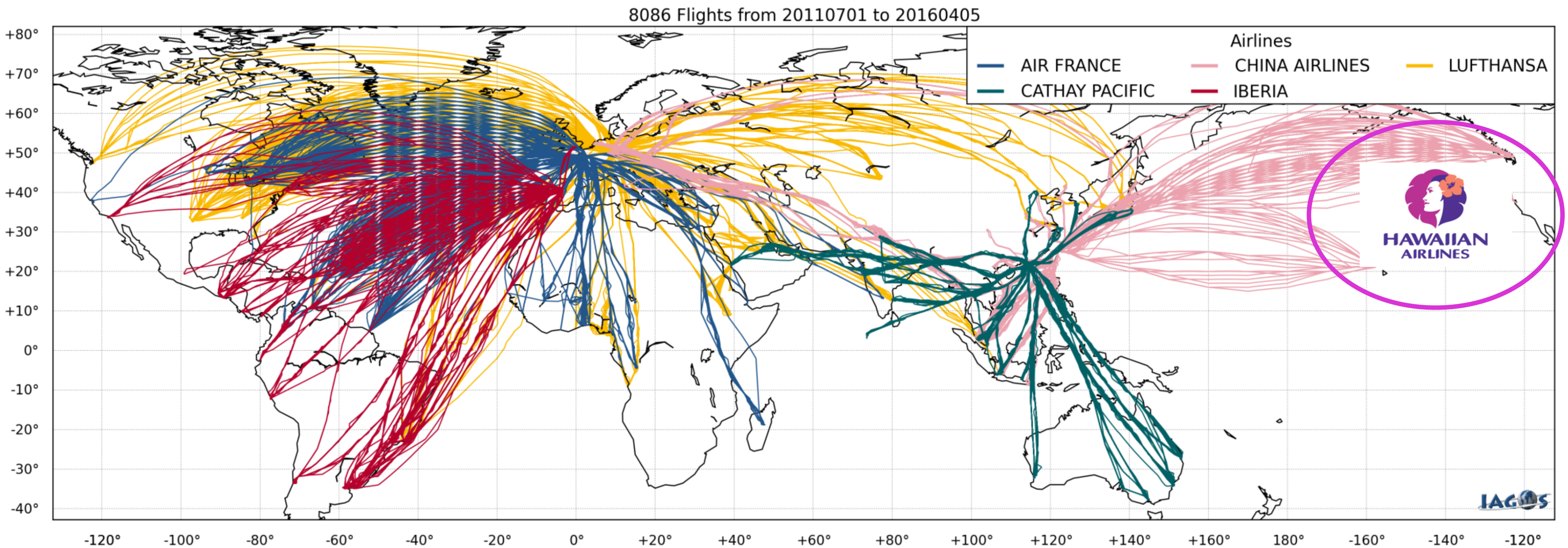


Plans to add CO_2 and CH_4 as soon as certification is finalized.

Figure courtesy of Andreas Volz-Thomas

IAGOS-CORE Flight Routes

> 8300 flights July 2011 - May 2016



Slide courtesy of Andreas Volz-Thomas

NOAA already has the WVSS-2 commercial aircraft program for measuring water vapor from more than 100 commercial aircraft:

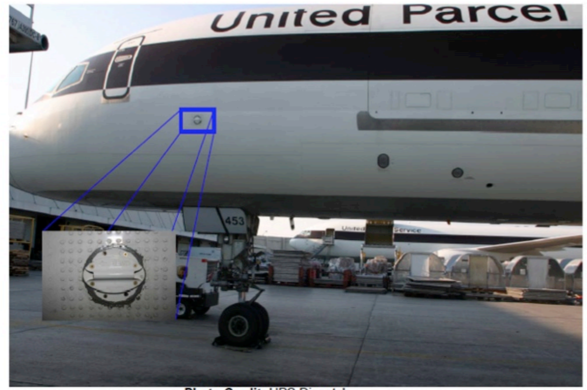
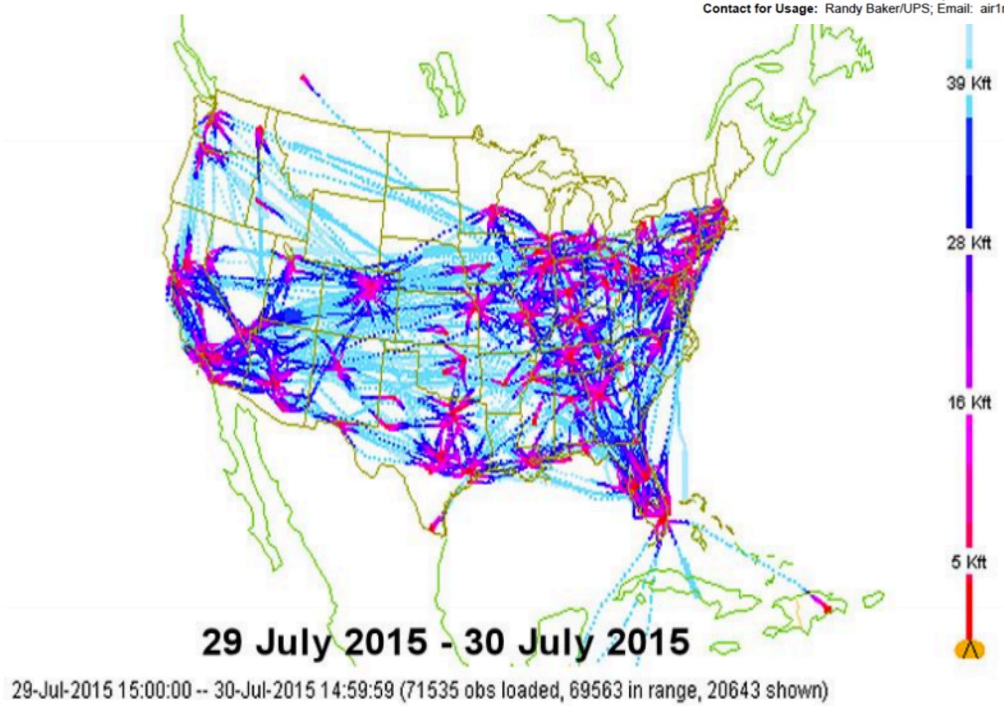


Photo Credit: UPS Dispatch
Contact for Usage: Randy Baker/UPS; Email: air1rtb@ups.com



Final Points

New investment and coordination of existing resources will be required to realize a global greenhouse gas information system for decision support.

- Sophisticated data assimilation systems are needed that can utilize in situ, near-IR and thermal-IR measurements.
- A thorough and coordinated approach is needed to evaluate retrievals from current and future greenhouse gas missions and to establish continuity across missions.
- Careful observing system design experiments are needed to evaluate cost, risk, and information content of proposed new measurements.

Quantifying Lower Tropospheric Methane Using Total Column (NIR) and Tropospheric (TIR) measurements

Authors

John R. Worden[1], Alex J. Turner[2], Anthony Bloom[1], Susan S. Kulawik[3], Robert Parker[4], and Vivienne H. Payne[1]

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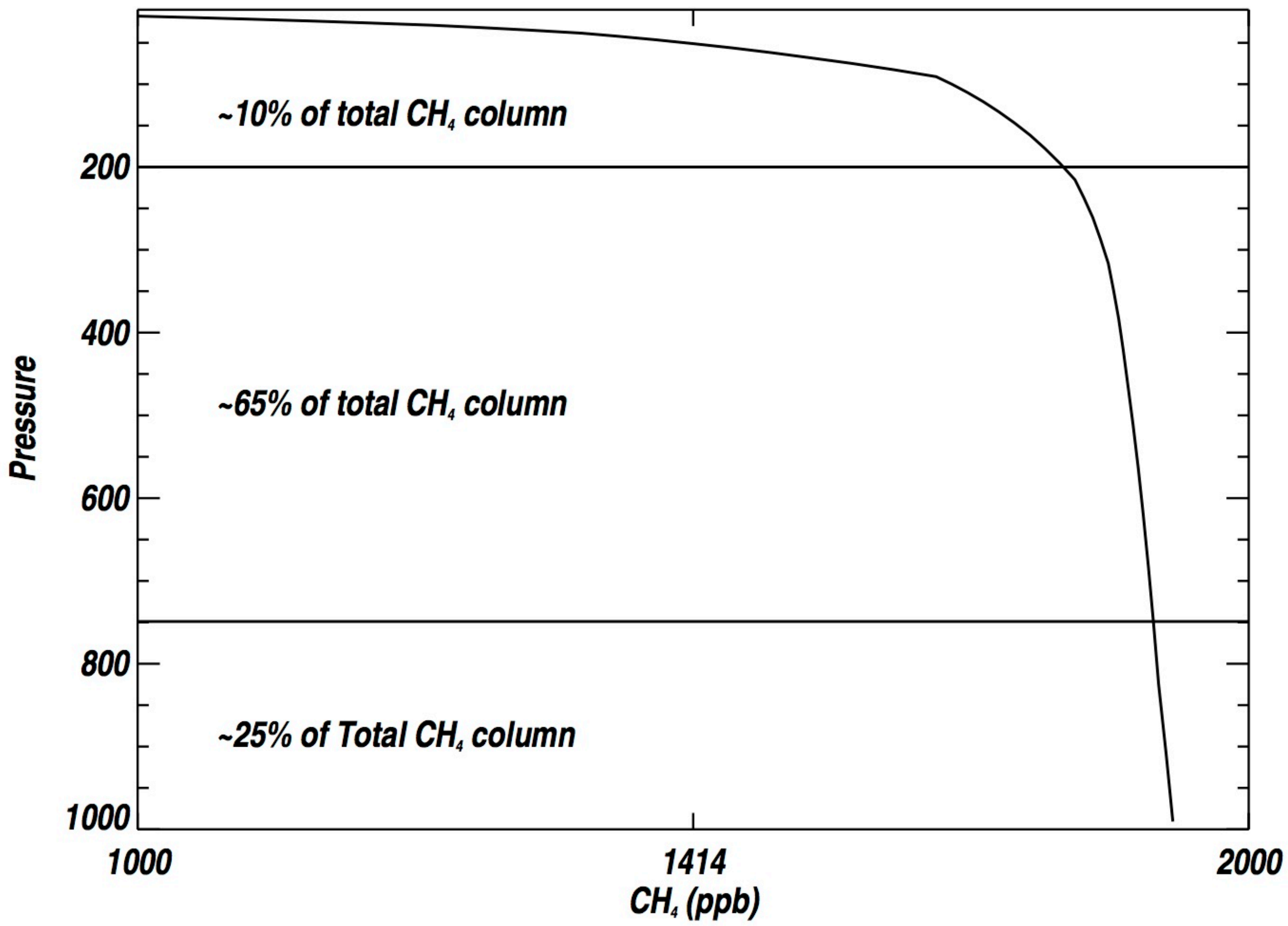
3. Bay Area Environmental Research Institute, Mountain View CA, USA

4. Dept. of Physics and Astronomy, University of Leicester, Leicester, UK

Methane profile at ~55 N in July 2006

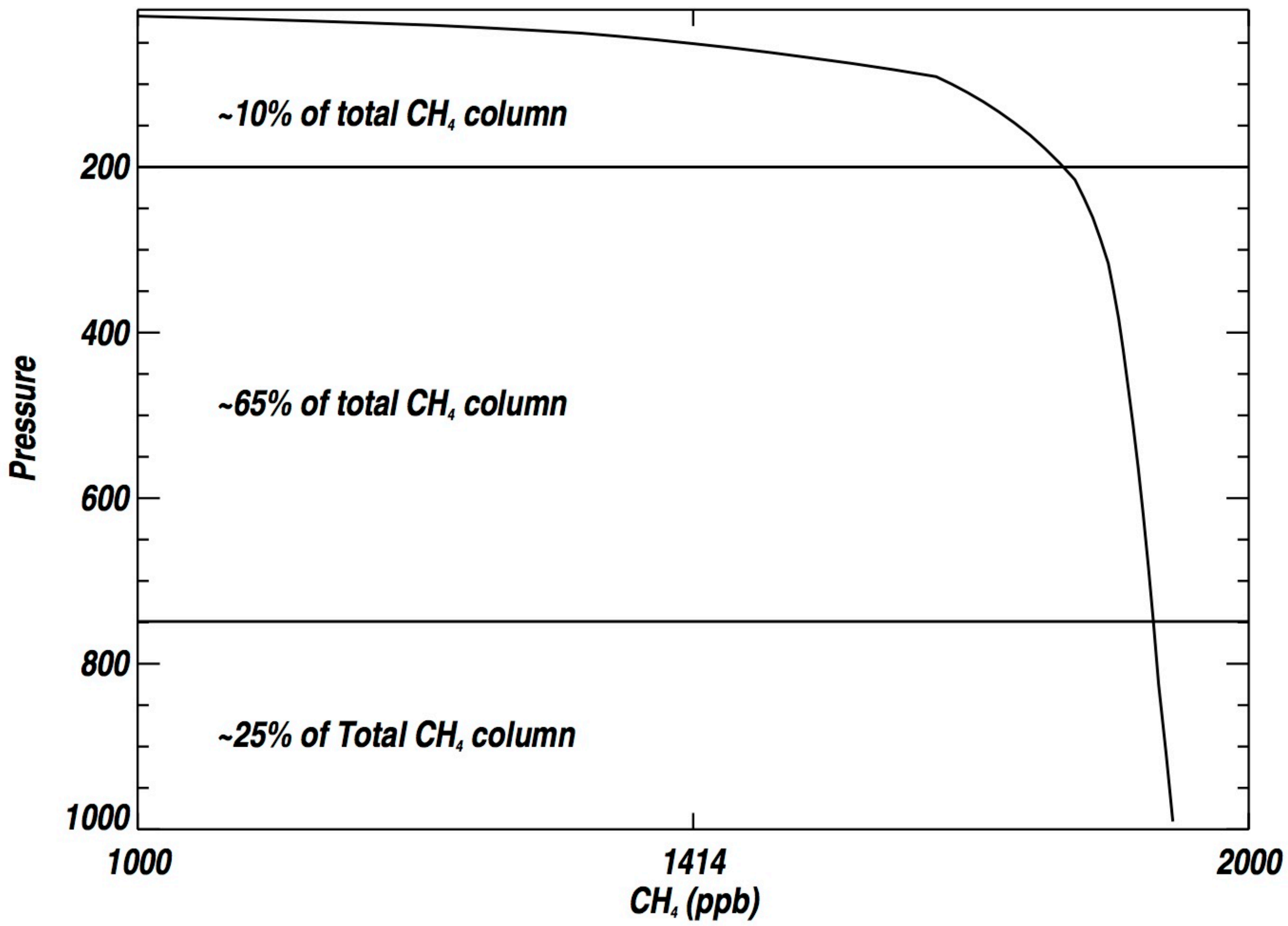


Primarily sensitive to sources really really far away from measurement

Primarily sensitive to sources ~1000's of km away

Primarily sensitive to sources ~100's of km away from measurement

Methane profile at ~55 N in July 2006

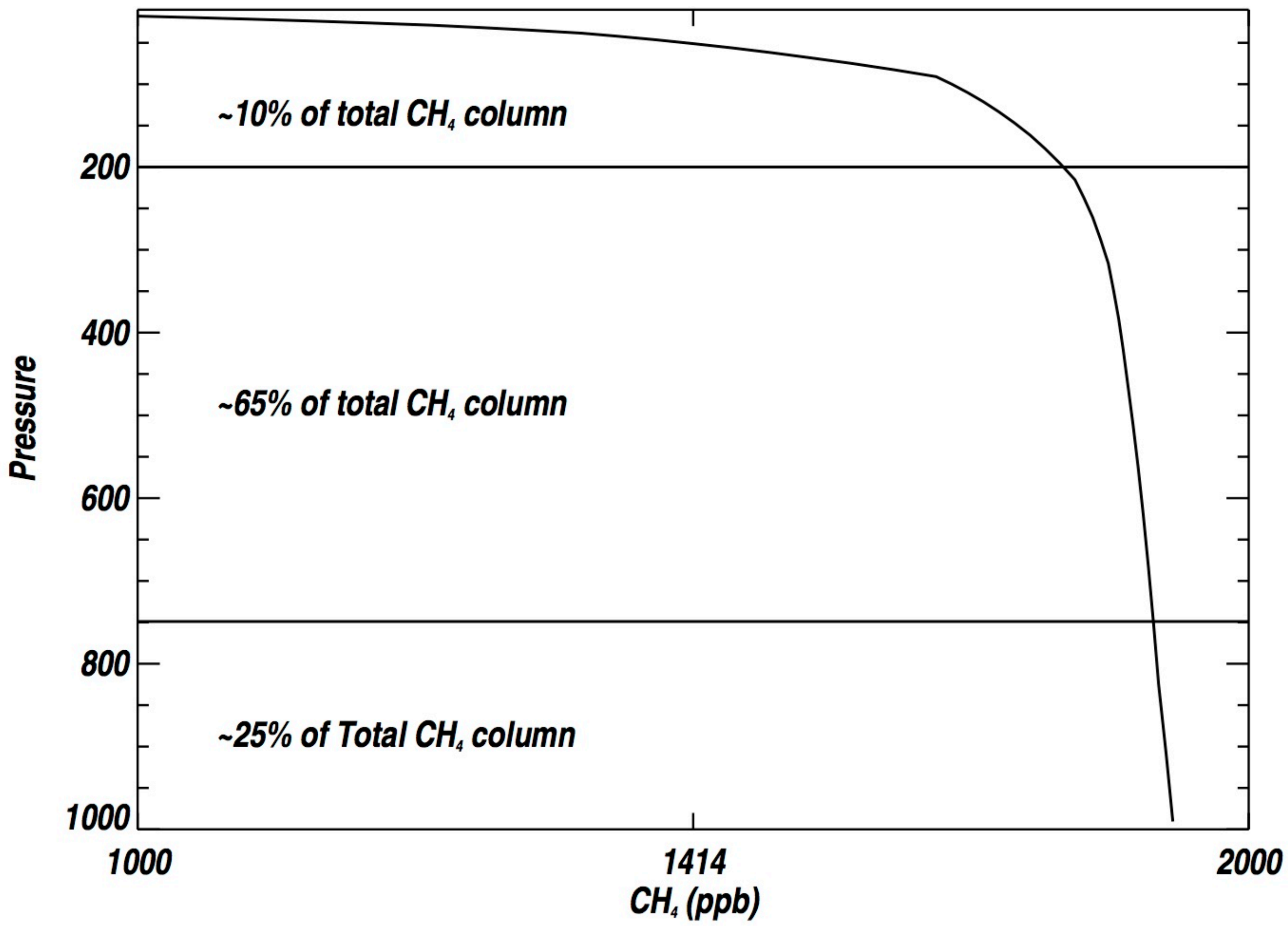


Chemistry, transport, and tropopause height

Transport and Chemistry

Boundary layer height, transport, and chemistry

Estimating Fluxes Using Surface Network

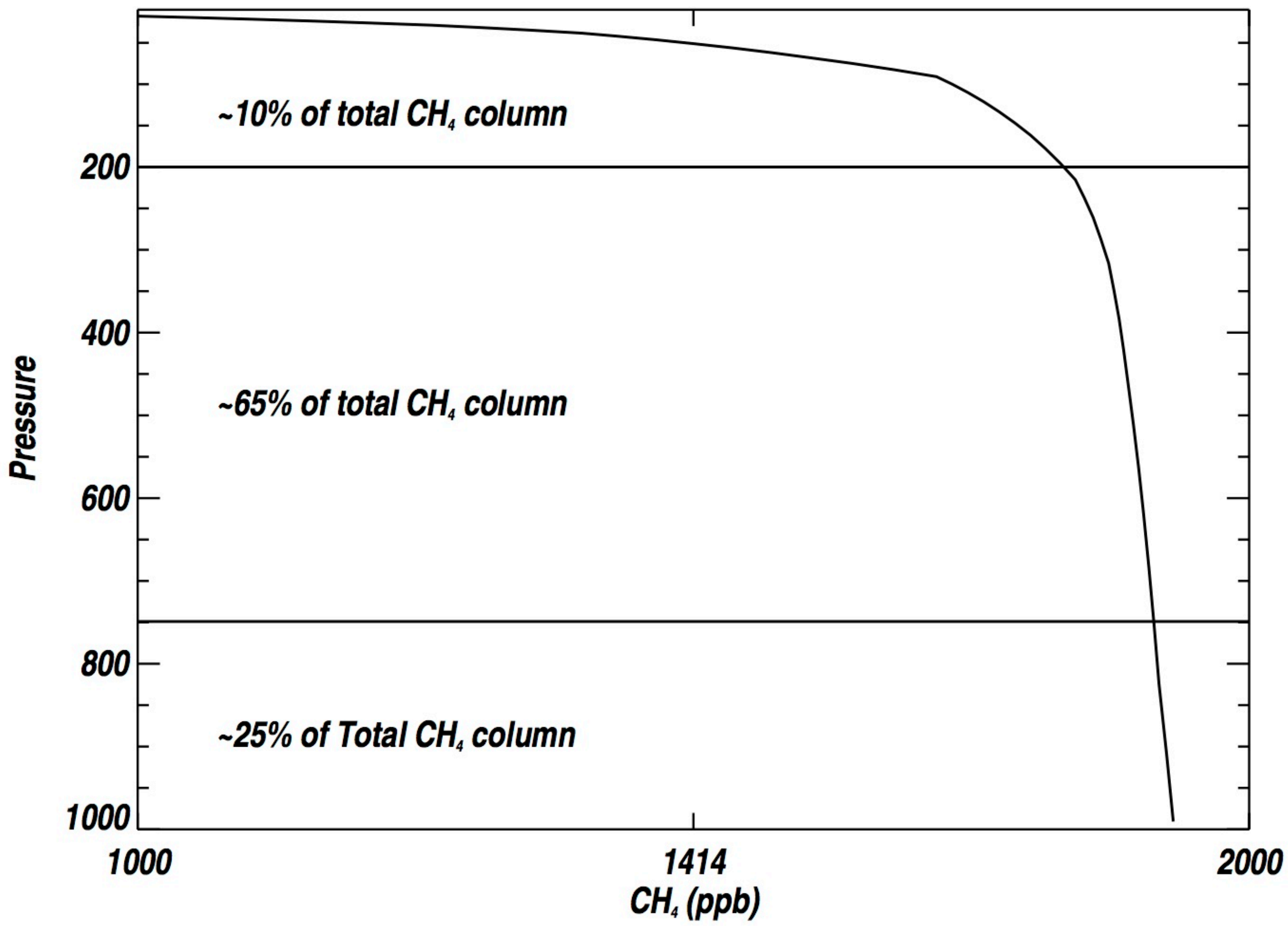


Transport and Chemistry

Boundary layer height,

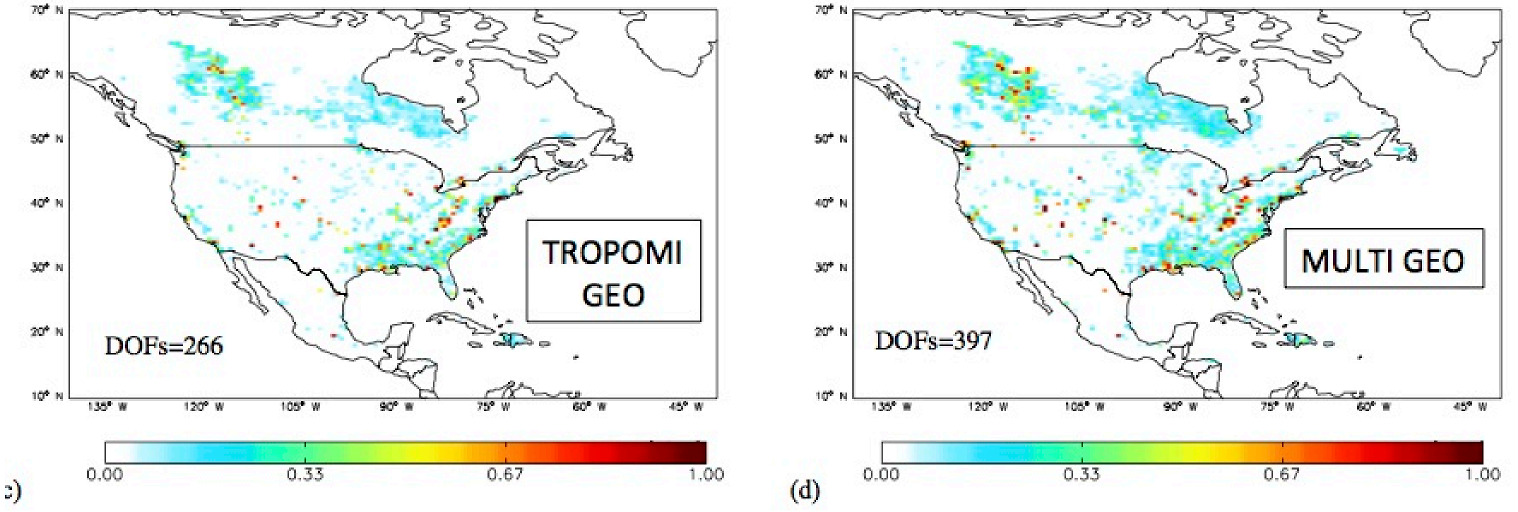
Transport, and chemistry

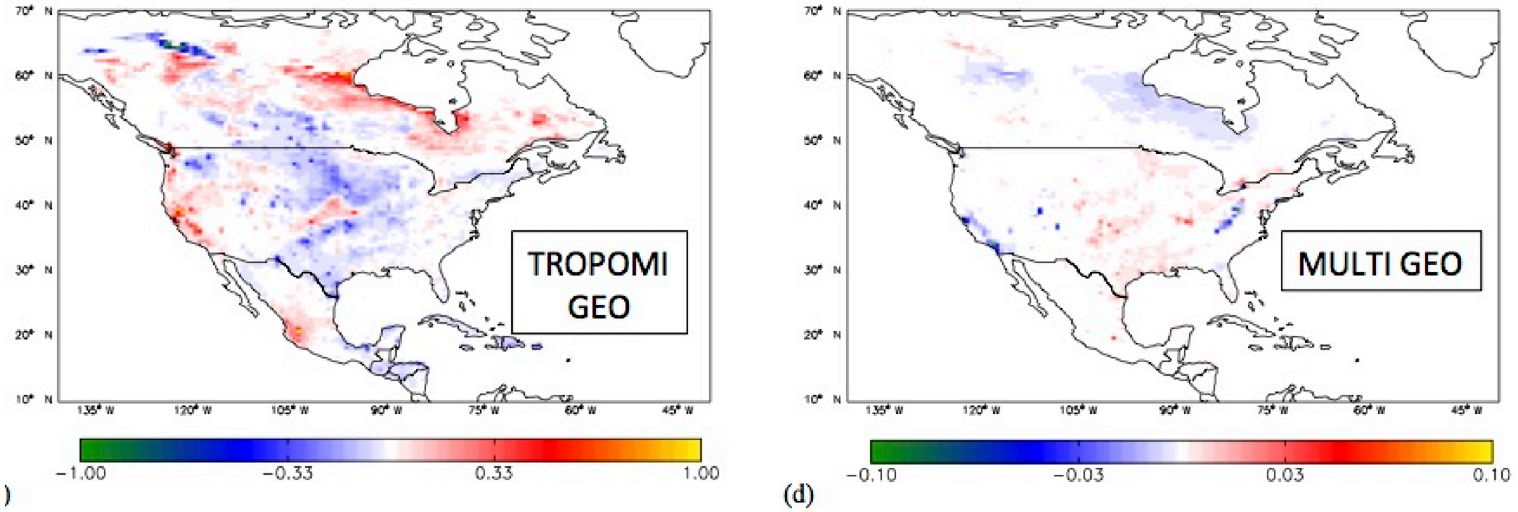
Estimating Fluxes Using Total Column Data



Need accurate model calculations of transport and chemistry over very long length scales (~1000's of km)

Estimating Fluxes Using Methane Total Column and Profiles from a GEO Orbit
Bousserez et al., ACP 2016



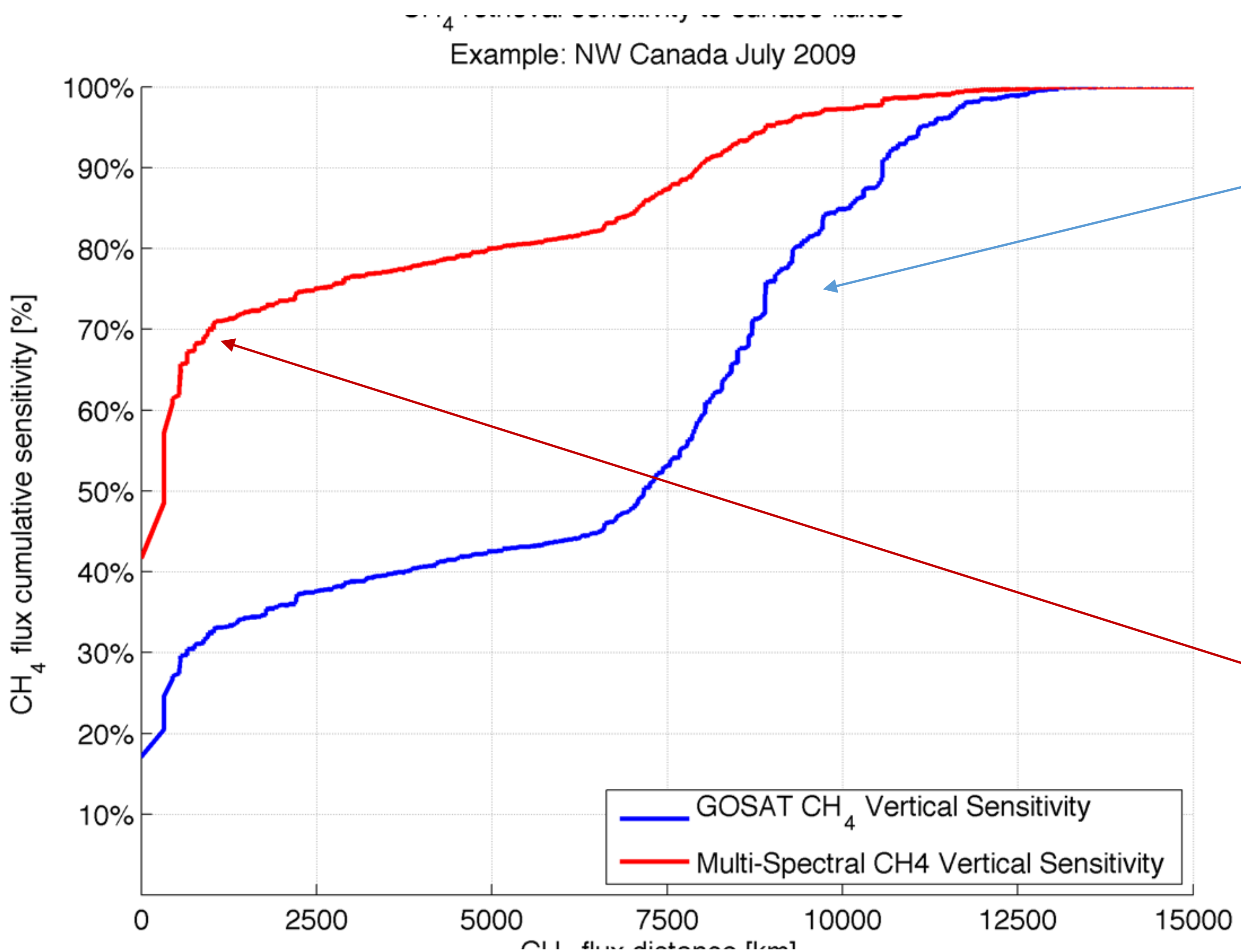


Use of Thermal IR and Near IR radiances allows for profiling of methane that can resolve the boundary layer.

Use of profiles (instead of columns) to quantify fluxes results in a:
~50% increase in sensitivity to surface fluxes

Substantial reduction in sensitivity to background errors (e.g. transport and chemistry)

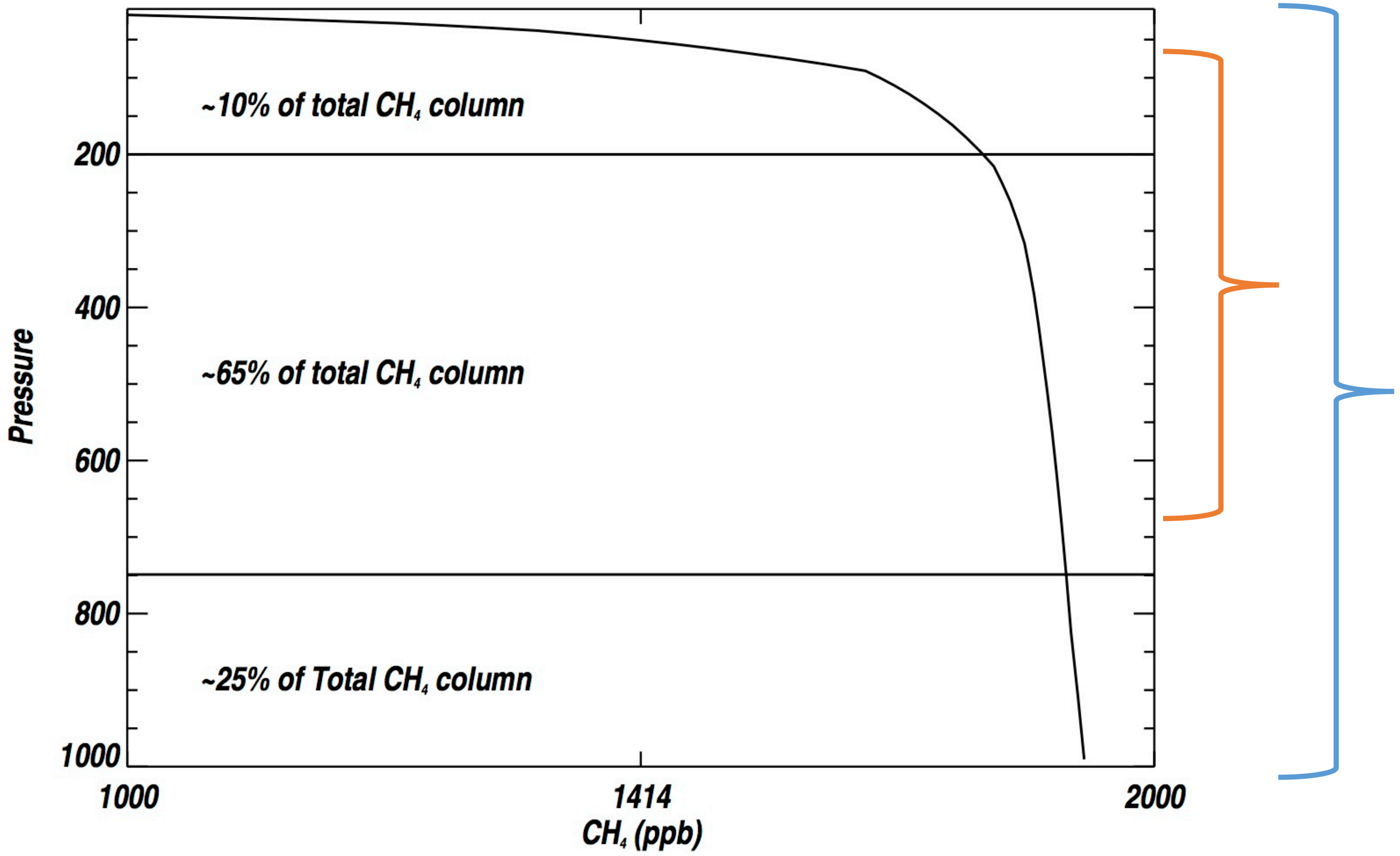
Sensitivity of Total Column and Lower-Tropospheric Methane (at high latitudes) to Methane Fluxes Using the Adjoint of the GEOS-Chem Model



Total Column Methane primarily sensitive to fluxes ~8000 km away

Lower-Tropospheric Methane primarily sensitive to fluxes ~1000 km away

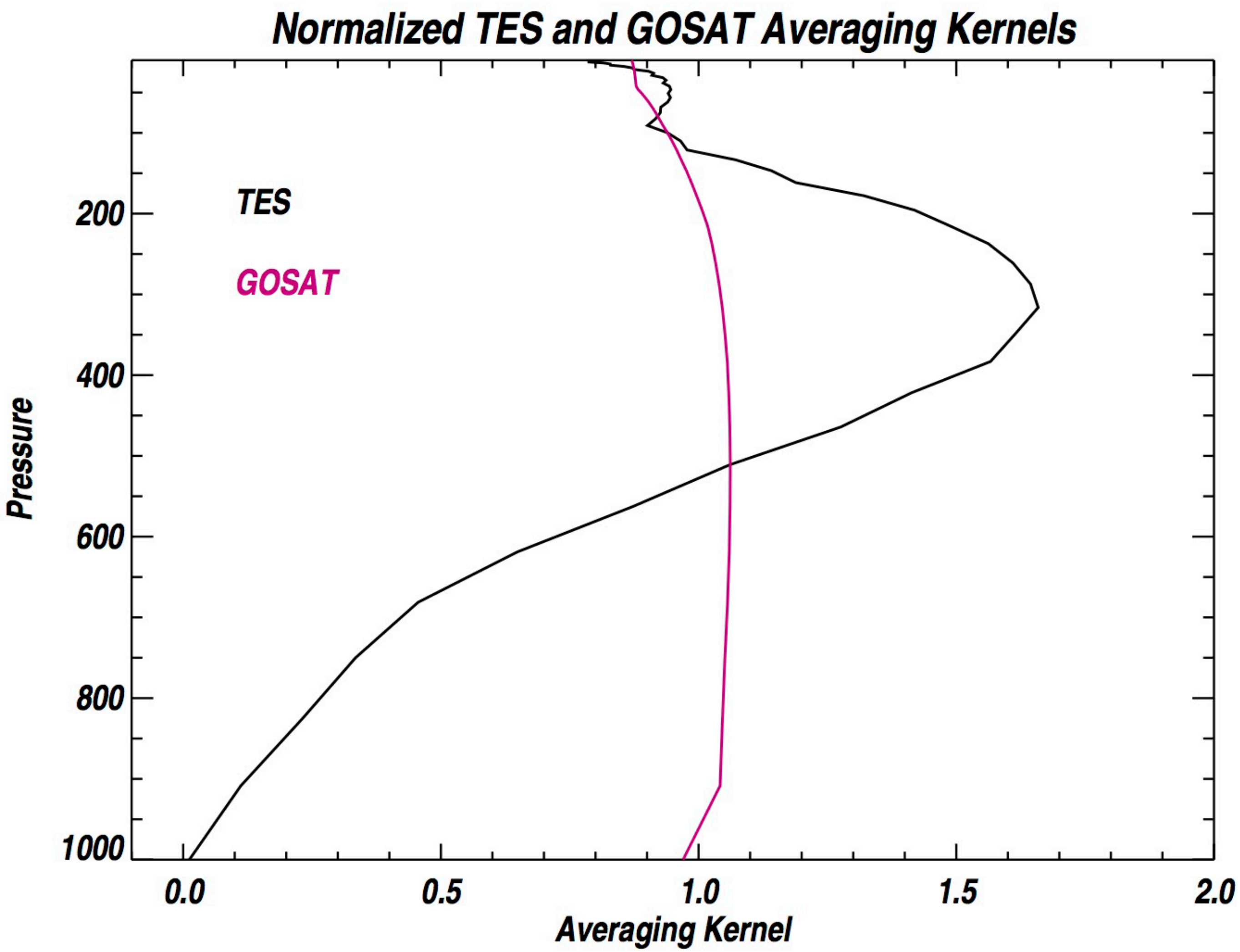
Estimating Fluxes Using Profile (or Lower Tropospheric Methane Measurements)



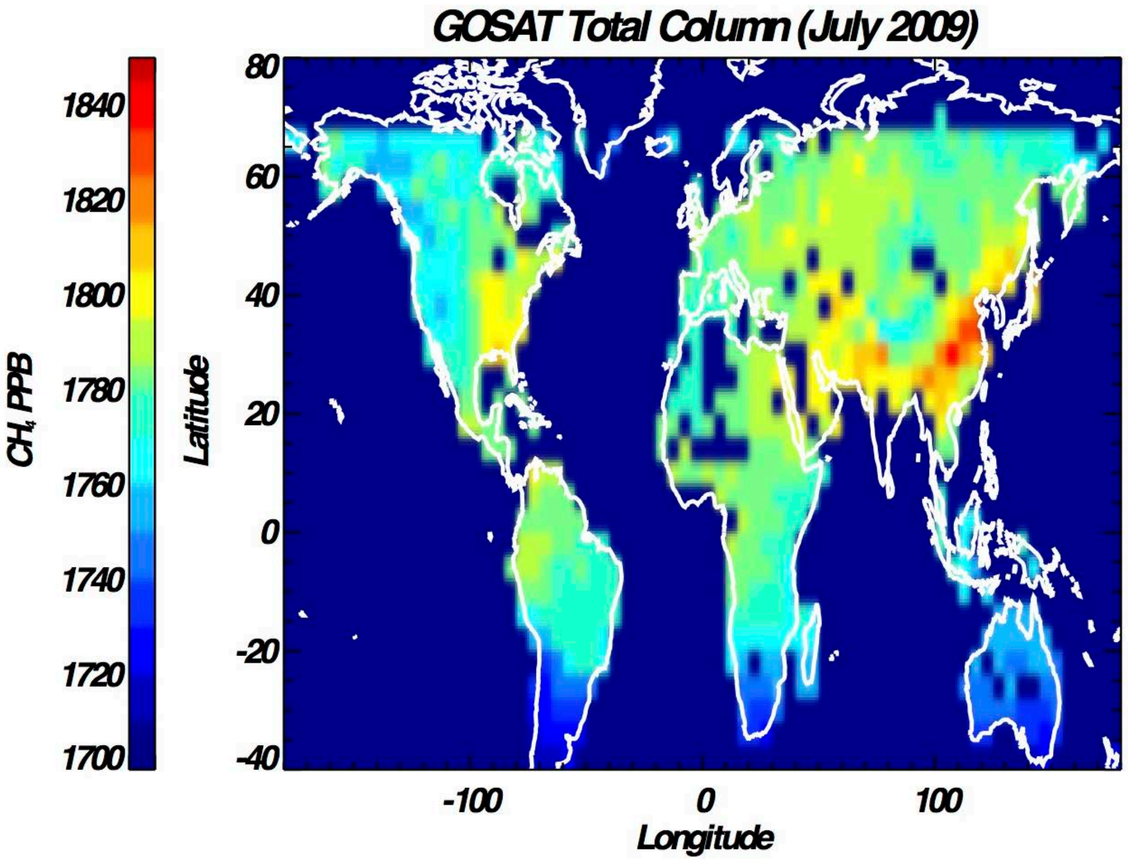
CH_4 from Thermal IR
(e.g. CRIS, TES, AIRS, IASI)

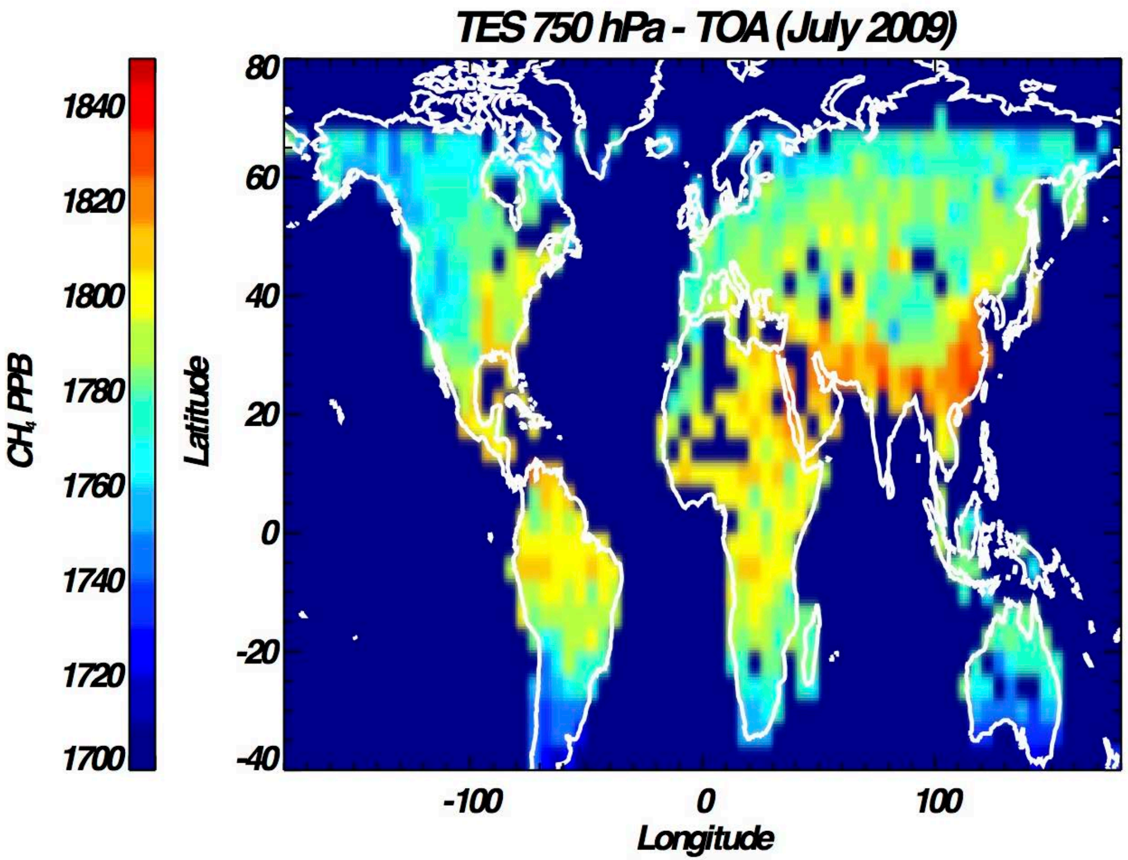
Total column CH_4 from Near IR
(e.g. TROPOMI, GOSAT, SCIAMACHY, GOME)

Example of Lower-Tropospheric Methane from GOSAT and TES: GOSAT and TES Total Column Averaging Kernels



Comparison of GOSAT Total Column and Aura TES FT/Strat Column (~850 hPa to TOA)





Precision ~15 ppb
Bias ~-17 to 2ppb
Parker et al., GRL 2011

Precision ~15 ppb
Bias ~26 ppb
Worden et al., AMT 2012; Alvarado et al., 2015

Both data sets use optimal estimation → a priori, vertical sensitivity (averaging kernels), and aposteriori uncertainties for noise and interferences are provide in the product files

Some Math: Derivation of Averaging Kernel and Uncertainties

$$\hat{C} = C^a + C_{air} h^T \mathrm{A}(x - x^a) + C_{air} \sum_{\mathrm{i}} h^T \delta_i$$

$$\hat{C}_L = \hat{C}_{tot} - \hat{C}_U$$

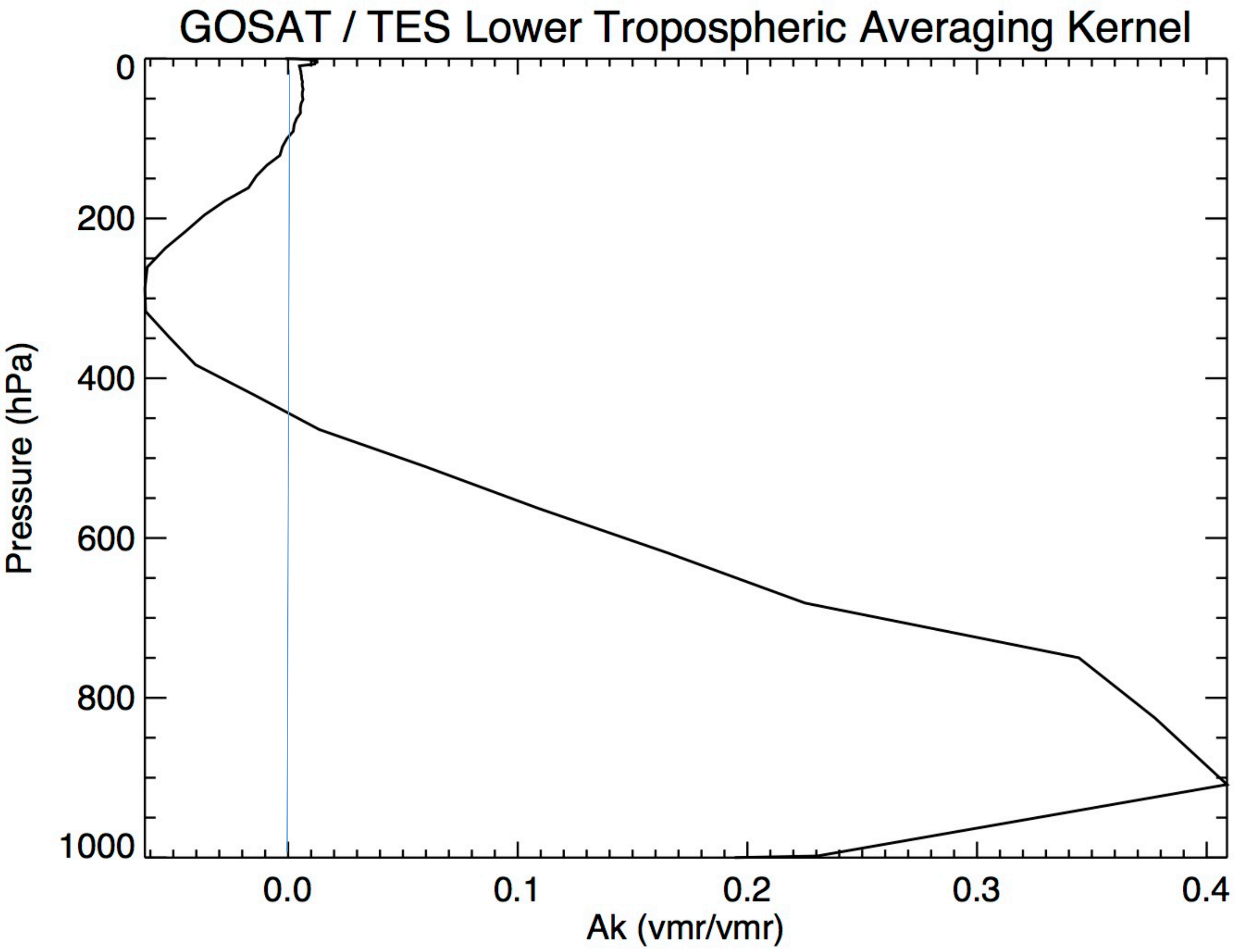
$$\hat{C}_L = C_L^a + C_{air}\, b_L(x_L - x_L^a) + C_{air}\left(b_u - h_u \mathrm{A}_{\mathrm{UU}}^{\mathrm{TES}}\right)(x_u - x_u^a) + C_{air} \sum_i h\delta_i$$

Divide above equation by the column of dry air in the lower troposphere and re-arrange and combine terms and we get:

$$\hat{X}_L = X_L^a + a^T(x - x^a) + C_{air}/C_L^{air} \sum_i h\delta_i$$

Now we have an equation that is similar to that described in Rodgers (2000).
Note amplification of uncertainties by about a factor of 4 due to C_{air}/C_L^{air} term

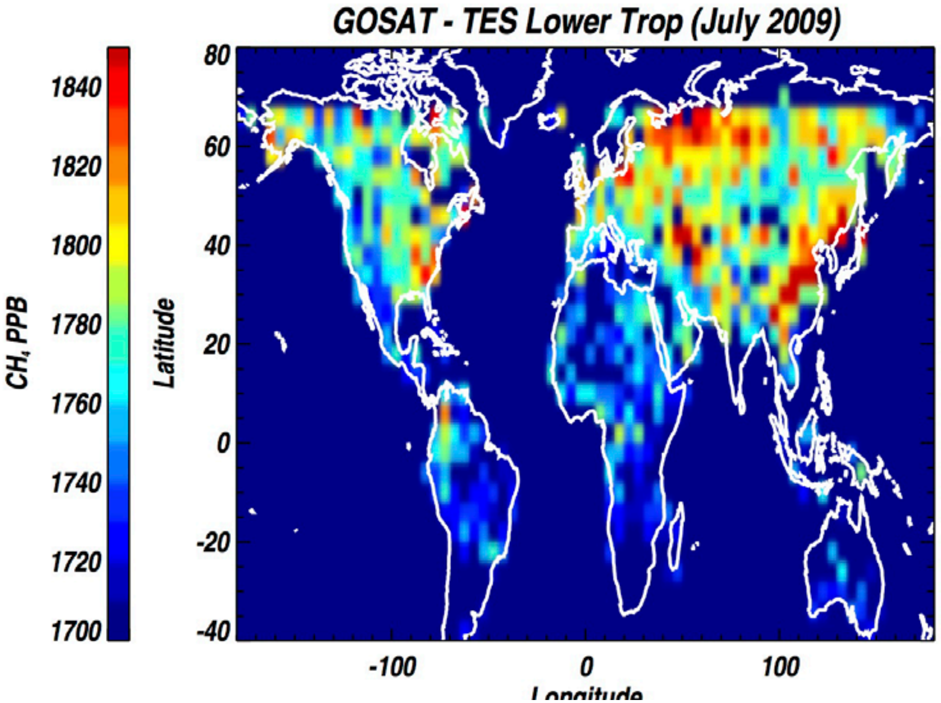
Worden et al., AMT 2015



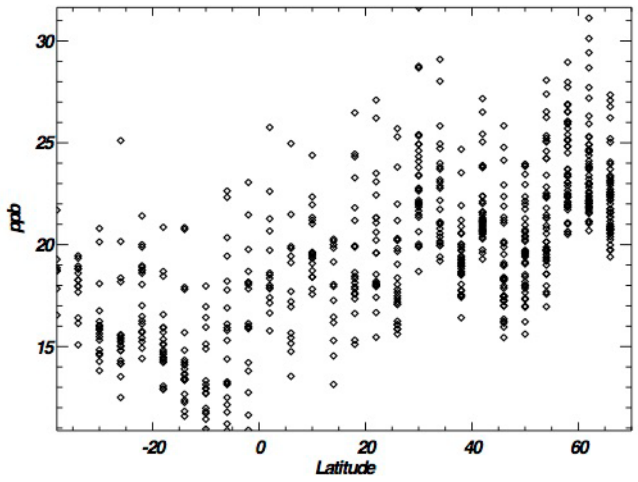
Reduced sensitivity of lower tropospheric estimate to stratosphere and upper tropospere → Reduced uncertainties due to transport and chemistry

Typical Averaging Lower Trop "column" averaging kernel peaks at 900 hPa → Greater sensitivity to nearby methane sources

Lower Tropospheric CH_4 Estimates are for a Monthly Average on a 4x5 degree bin

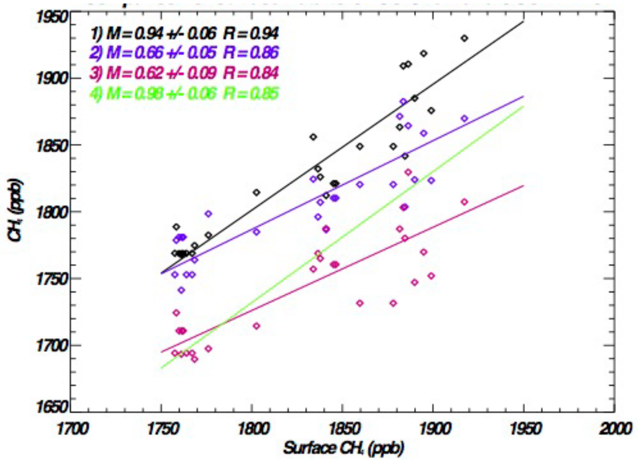


Precision



Precision depends on (1) noise, (2)sampling differences between GOSAT and TES, (3) cross-state error in TES free-tropospheric methane

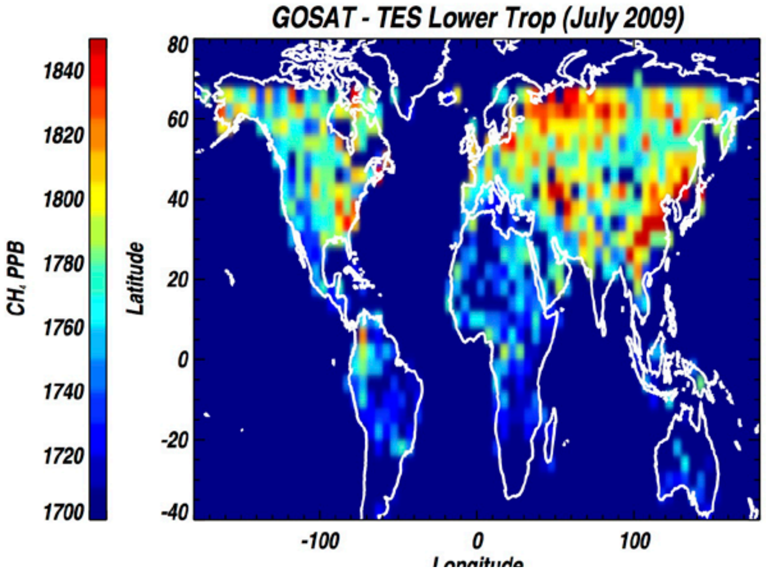
Comparison to Surface Network

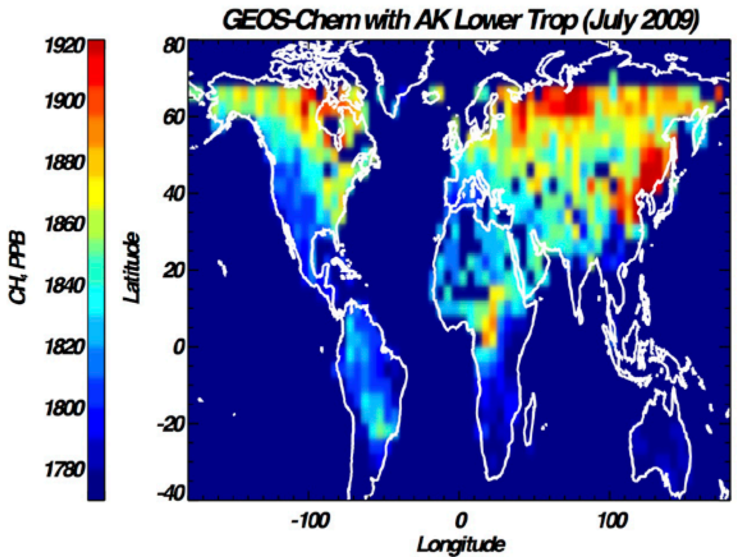


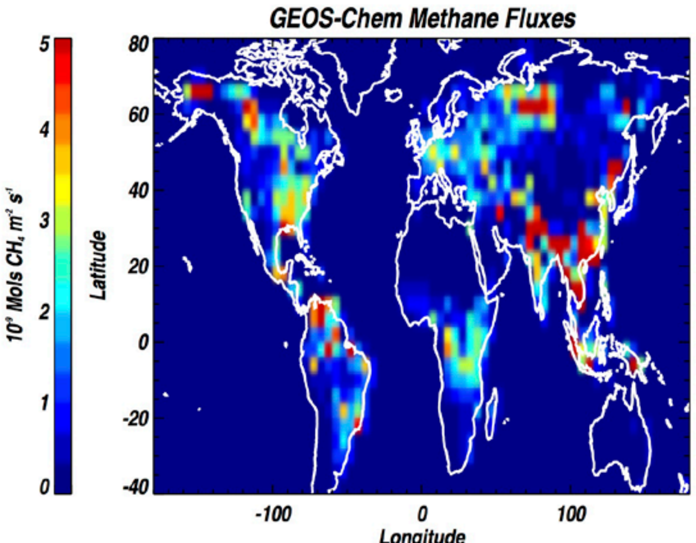
Comparison to surface data (via GEOS-Chem model) suggests that data are biased low by ~65 ppb)

Comparison between data and model (using averaging kernel and a priori constraints)reveal regional enhancements over methane sources

$$\hat{X}_L = X_L^a + a^T(\boldsymbol{x} \quad - \boldsymbol{x}^{\boldsymbol{a}})$$



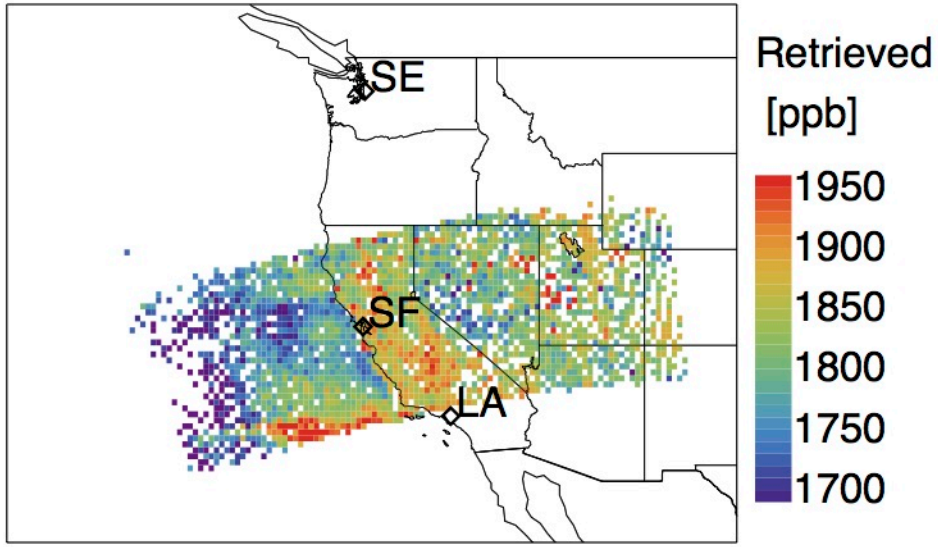




Lower Tropospheric Estimates from CRIS and TROPOMI

- TROPOMI ~1000X soundings relative to GOSAT ~same precision and accuracy as GOSAT
- CRIS ~ 10000X soundings relative to TES ~same accuracy and better precistion than TES
- Precision of GOSAT/TES estimate ~30 ppb so precision of TROPOMI/CRIS estimate ~< 1 ppb
- Greatly increased precision and sampling allows us to better diagnose accuracy using surface network and aircraft data

CRIS Methane Retrievals Based on Aura TES Optimal Estimation Composition Retrieval Algorithm



Summary

Lower tropospheric estimates based on CRIS/TROPOMI measurements can quantify boundary layer methane with ~1ppb precision or better at 100 km length scales

These data could potentially provide fluxes with greatly reduced uncertainty (~10x reduction) due to transport and chemistry error, one of the limiting errors for using satellite-derived estimates of methane fluxes to evaluate the processes controlling the global methane cycle.

Key to this effort is an optimal estimation based methane retrieval algorithm in order to quantify and characterize lower-tropospheric methane → subtraction approach depends on knowledge of vertical resolution, a priori constraints, and a posteriori uncertainties of both TIR and NIR based methane estimates.

A New Global HCHO Retrieval Technique based on Principal Component Analysis of Satellite Radiance Data: Implementation with OMPS and Preliminary Results

Can Li
NASA GSFC Code 614 & ESSIC, UMD
Email: can.li@nasa.gov

Joanna Joiner, Nick Krotkov, Laura Dunlap
Trace Gas Session
3rd Annual JPSS Meeting
August 11, 2016
College Park, MD

Why Formaldehyde (HCHO)?

- Intermediate oxidation product of volatile organic compounds (VOCs)
  - Small global background from oxidation of methane
  - Relatively large regional sources (NMVOCs emitted from biogenic, anthropogenic, and biomass burning sources)
- Short-lived (lifetime: hours) - used to provide constraints on NMVOCs [*e.g.*, *Barkley et al.*, 2008; *Fu et al.*, 2007; *Palmer et al.*, 2003; *Zhu et al.*, 2014]
- Why NMVOCs? – precursors of tropospheric ozone and organic aerosols (*e.g.*, isoprene)

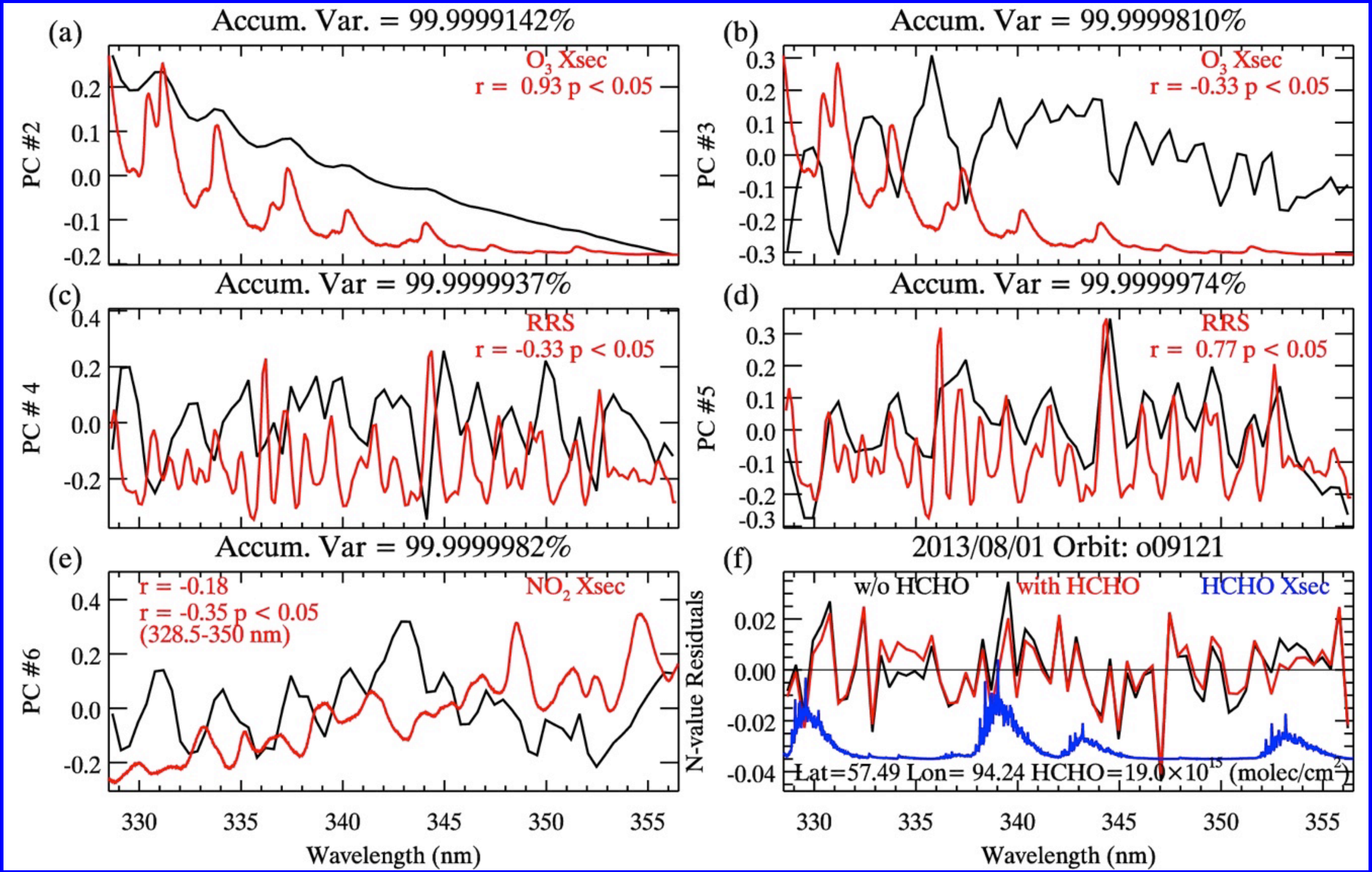
Space-based Detection of HCHO

- Absorption of UV in ~325-360 nm
- Weak signals, various interferences (BrO, O_3, NO_2, rotational Raman scattering or RRS, *aka* the Ring effect)
- DOAS-type algorithms using hyperspectral measurements to separate HCHO signals from interferences
- First demonstrated for GOME [*Chance et al.*, 2000]
- Products available from OMI [*e.g., De Smedt et al.*, 2015; *González Abad et al.*, 2015], GOME-2 [*e.g., De Smedt et al.*, 2012], SCIAMACHY [*e.g., Wittrock et al.*, 2006]
- Still fairly large differences between satellites and/or algorithms [*e.g., Zhu et al.*, 2016]

PCA-based Approach

- Based on successful PCA SO_2 algorithms
- Extract spectral features directly from satellite radiance data
- Use these features in spectral fitting to minimize interferences
- Preliminary implementation with OMPS :
  - PCs from each row, each orbit
  - Window: 328.5-356.5 nm
  - 8 PCs in fitting (no strong dependence on # of PCs)
  - Additional reference spectrum: BrO cross section
  - *A priori* profiles from GMI simulated climatology
  - A table lookup approach for Jacobians for each pixel: O_3 and cloud from NASA OMPS products

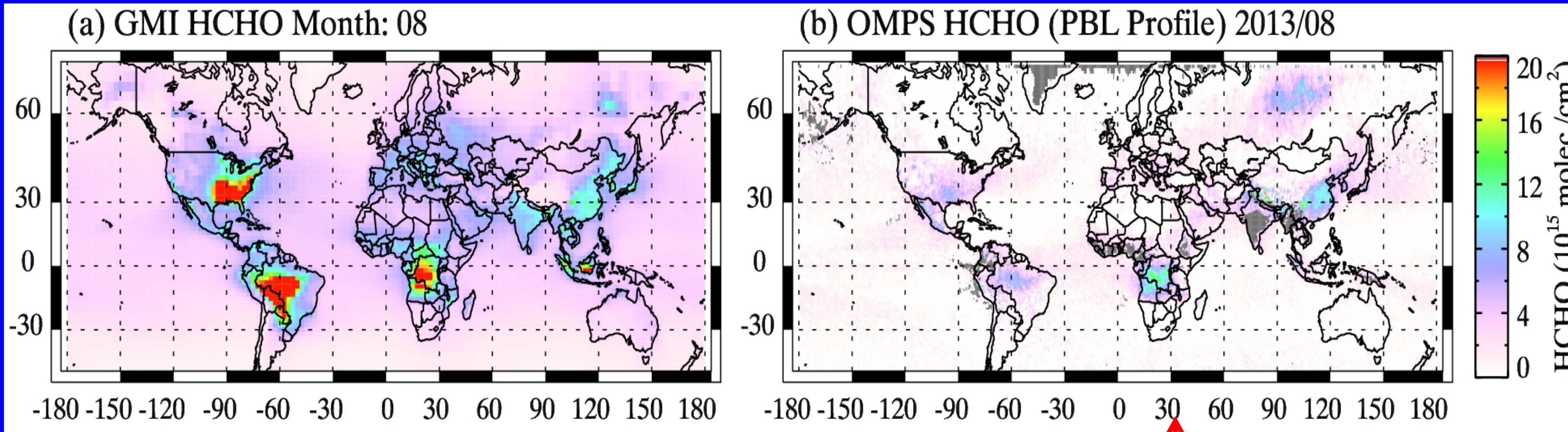
Principle Components and Residuals



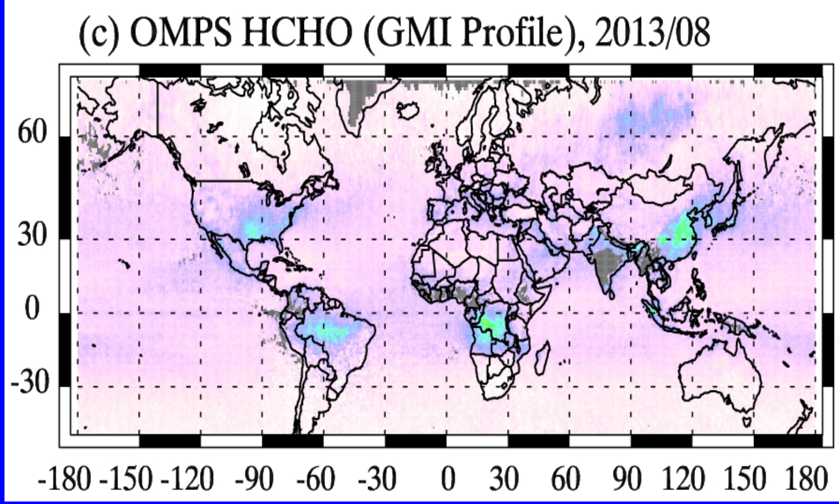
Example PCs from **entire row** # 20, Orbit 9121 reveal clear, known physical features

[*Li et al.*, GRL, 2015]

OMPS Capable of Detecting HCHO Signals



The same *a priori* profile everywhere, independent from model



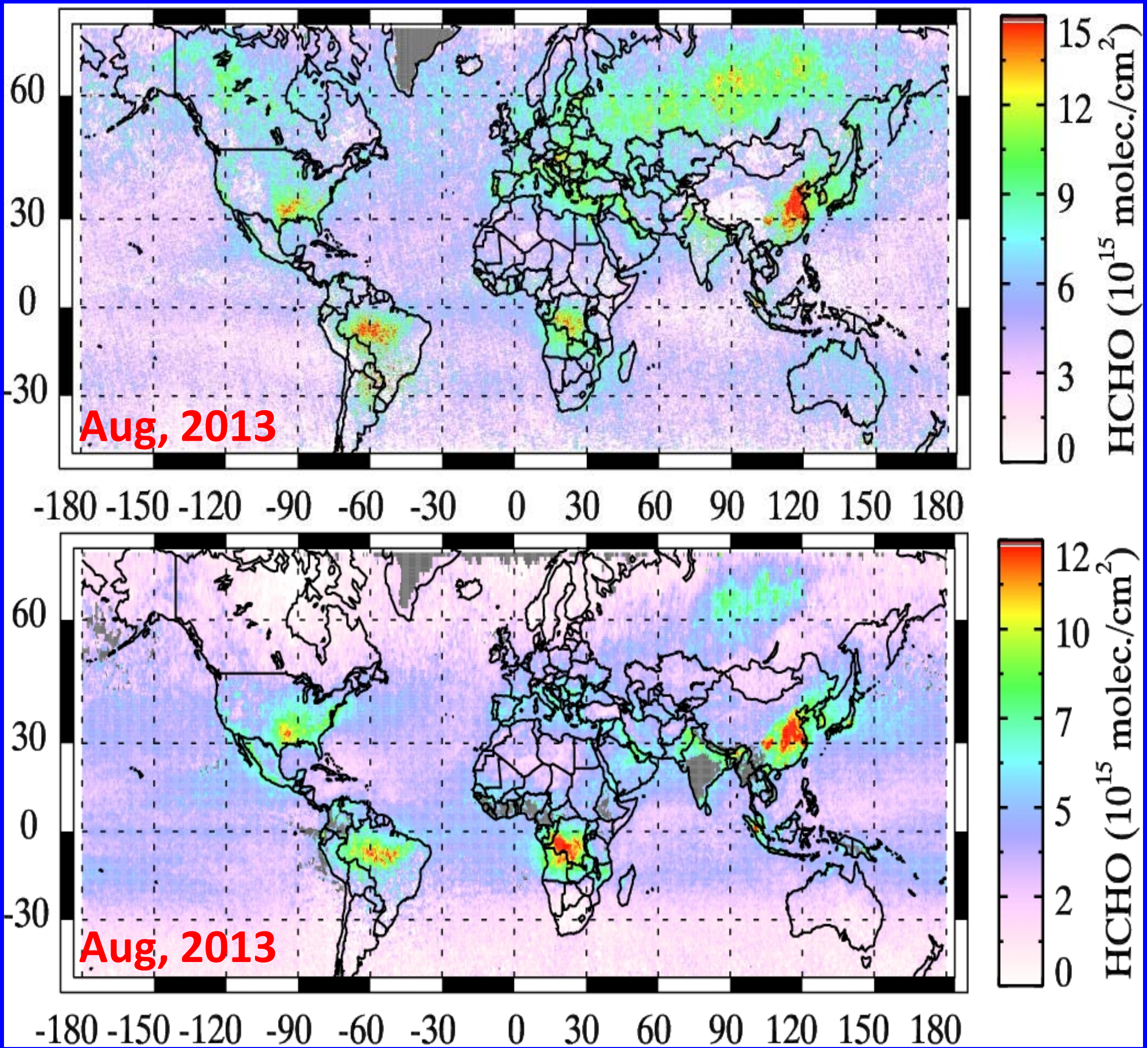
Model *a priori* profiles + adding model column amounts from Pacific to all longitudes

[*Li et al.*, GRL, 2015]

Comparison with OMI DOAS HCHO

OMI DOAS (BIRA)

OMPS PCA (GSFC)

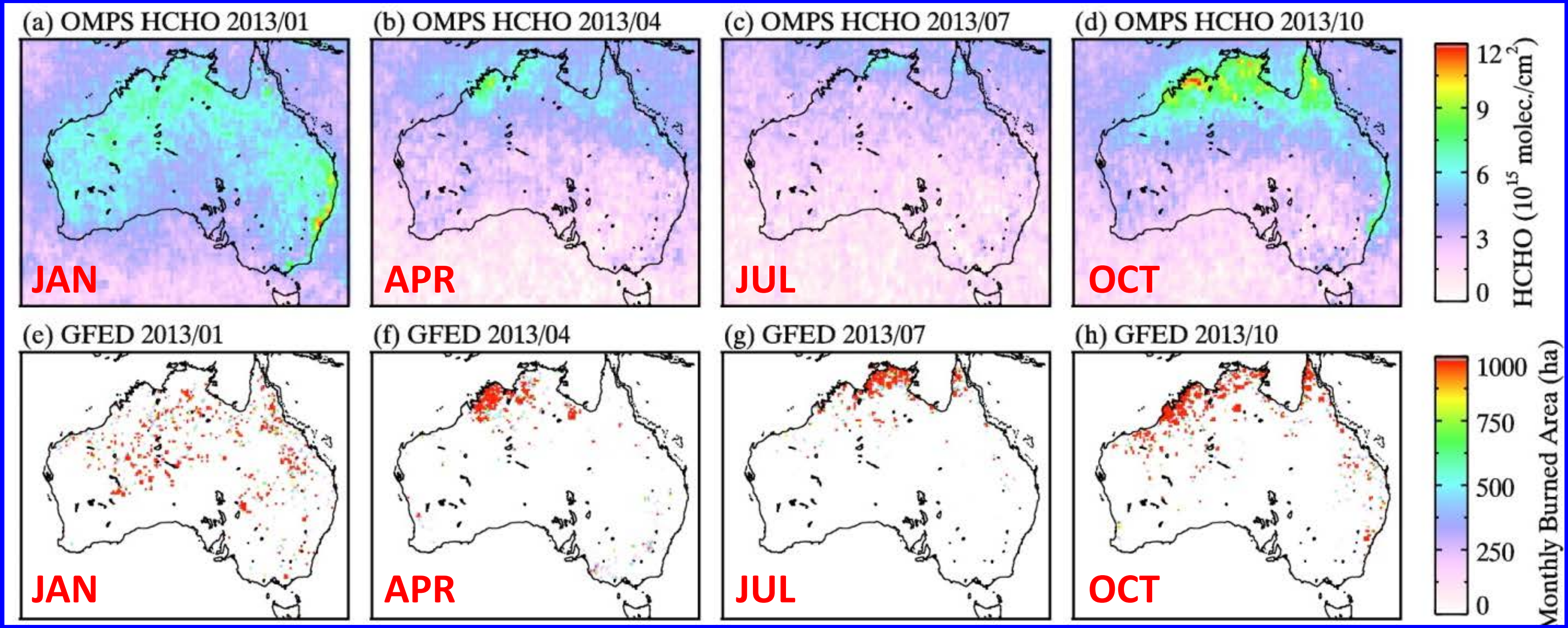


Two independent retrievals show fairly consistent spatial patterns in HCHO.
OMPS HCHO ~15-20% smaller than OMI, probably due to several instrumental and algorithmic factors (e.g., *a priori* profiles etc.).

[***Li et al.***, **GRL, 2015]**

Seasonal Pattern: OMPS HCHO *vs.* Global Fire Emission Database - Australia

OMPS PCA HCHO Retrievals for 2013

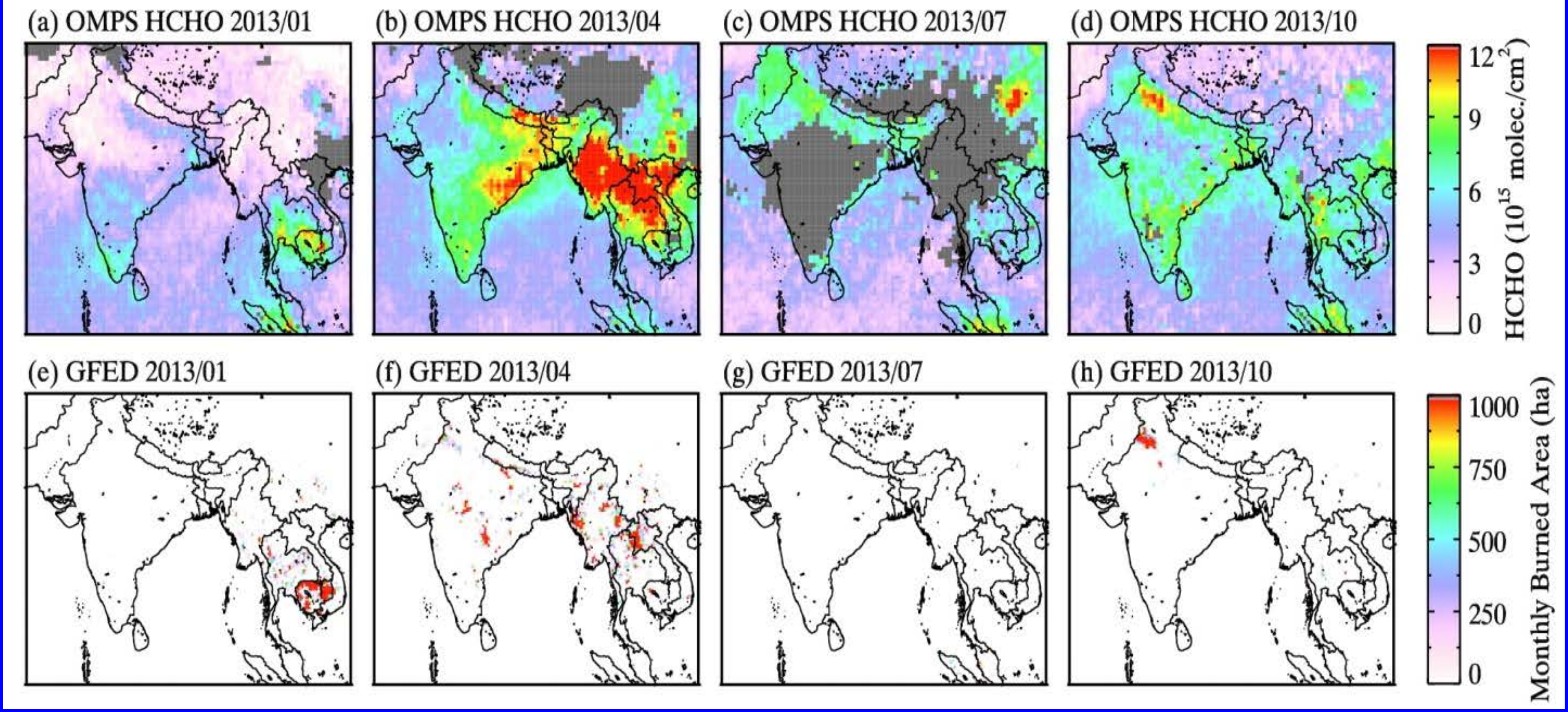


GFED Monthly Burnt Area (indicator of fires)

OMPS PCA HCHO retrievals show consistent spatial and seasonal patterns with fires in regions where seasonal biomass burning emissions dominate sources of NMVOCs (and HCHO). Biogenic emissions also contribute in the growing season (January).

Seasonal Pattern: OMPS HCHO *vs.* Global Fire Emission Database – South & Southeast Asia

OMPS PCA HCHO Retrievals for 2013



GFED Monthly Burnt Area (indicator of fires)

Work Underway

- OMPS PCA retrievals biased low – more detailed comparison has been planned in collaboration with BIRA
- Algorithm also implemented with OMI and will be implemented with TROPOMI
- Airborne HCHO measurements regularly taken over and near the San Francisco Bay Area (the Alpha Jet and COFFEE[1] payload)

[1]Compact **Formaldehyde** Fluorescence Experiment (Hanisco et al @NASA GSFC & Marrero et al @NASA Ames)

Photo from *Hamill et al.* [2016]

Conclusions

- The good news: OMPS provides an unplanned opportunity to continue the OMI HCHO data record (also demonstrated by *González Abad et al.* [2016]).
- A long-term data record will be crucial for investigating how biogenic emissions respond in a changing climate.
- More development underway.
- Inter-instrument consistency still an issue, but the PCA approach may offer a way to mitigate the issue.

Applications of satellite NO2 observations in US National Air Quality Forecasting Capability

Pius Lee[1], Daniel Tong[1,2,3*], Lok Lamsal[4,5], Li Pan[1,2], Charles Ding[1,6], Hyuncheol Kim[1,2], Tianfeng Chai[1,2], Kenneth E. Pickering[5], Shobha Kondragunta[7], and Ivanka Stajner[7], Barry Baker[1,9]

1) NOAA ARL; 2) UMD CICS; 3) GMU CSISS; 4) USRA;
5) NASA GSFC; 6) UC-Berkeley; 7) NOAA/NESDIS/STAR; 8) NOAA NWS
9) NRC

The Great Recession

- **Starting – Ending time: December 2007 – October 2009;**

- **Cause: Bursting of the housing bubble in 2007, followed by a subprime mortgage crisis in 2008;**

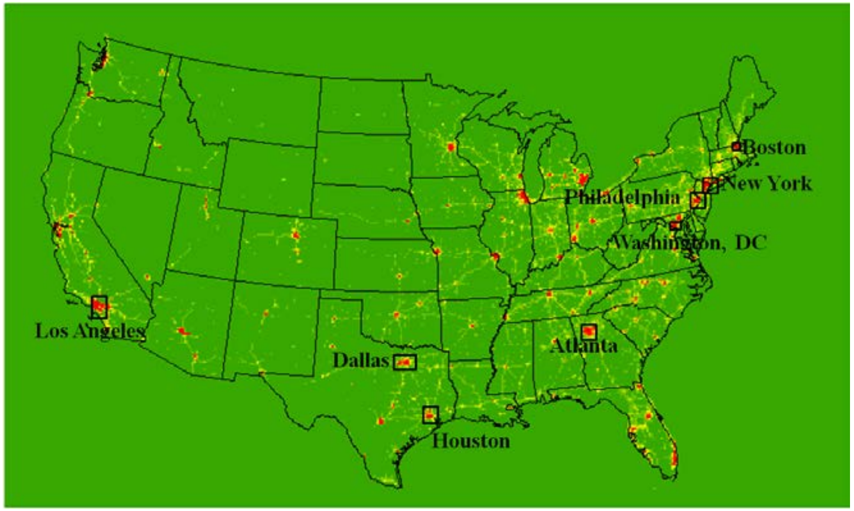
- **Impacts:**
  - **Unemployment rate: 4.7% in Nov 2007 → 10.1% in Oct 2009.**
  - **Income level: dropped to 1996 level after inflation adjustment;**
  - **Poverty rate: 12% → 16% (50 millions);**
  - **GDP: contract by 5.1%;**

- **Worst economic recession since the Great Depression**

Question: What does it mean to Air Quality (and Emissions)?

Methodology

- **Emission Indicator – Urban NOx in Summer**
  - **Short lifetime → proximity to emission sources**
  - **Urban NO2 dominated by local sources;**
  - **High emission density → low noise/signal ratio;**
- **NOx Data sources**
  - **Satellite remote sensing (OMI-Aura NO2).**
  - **Ground monitoring (EPA AQS NOx);**
  - **Emission data (NOAA National Air Quality Forecast Capability operational emissions);**
- **Deriving the trend:** (Y2–Y1)/Y1 × 100%
- **Selection of urban areas**



NO_x Regulatory Actions Since 2005

- **2003 – 2008: NO_x Budget Trading Program (SIP Call)**
  - Summer time power plant emission reductions in 20 states
  - Point sources can pay for reductions at other facilities (trading)
  - 2500 large combustion units affected.

- **2005: Clean Air Interstate Rule (CAIR)**
  - NO_x reductions of 53% by 2009 (2003 baseline). Affects 28 states
  - Thrown out by courts in 2008.

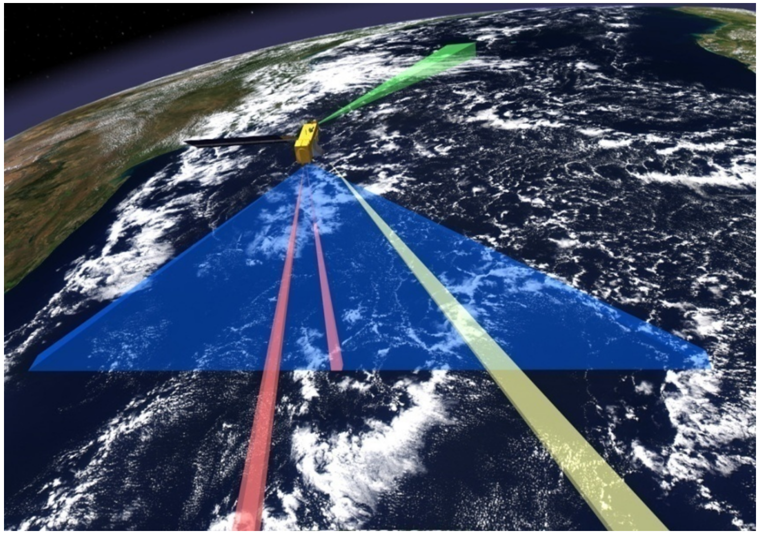
- **State-specific rules beyond Federal CAIR have led to further NO_x reductions in some states.**

- **2011: Cross-State Air Pollution Rule (CSAPR)**
  - Replacement of CAIR
  - Add five additional mid-West states to reduce NOx during ozone season.

- **Tier II Tailpipe NO_x Emission Standards – 5% reduction in fleet emissions per year over 2002 to 2010.**

Contributed by Ken Pickering

Ozone Monitoring Instrument (OMI)



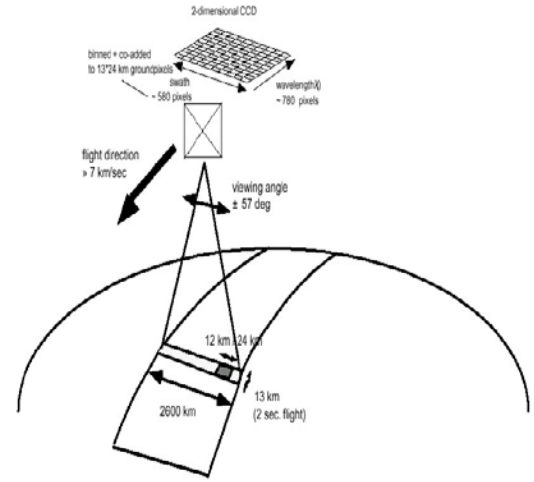


Figure 2.1 Measurement principle of OMI.

Courtesy of Fokker Space

One of four sensors on the EOS-Aura platform (OMI, MLS, TES, HIRDLS)

Courtesy of OMAR Torres

Launched on 07-15-04

Instrument Characteristics

-Nadir solar backscatter spectrometer

-Spectral range 270-500 nm (resolution~0.6 nm)

-**Spatial resolution: 13X24 km footprint**

-**Swath width: 2600 km (global daily coverage)**

-**13:45 (+/- 15 min) Local equator crossing time (ascending node)**

Data Quality Control

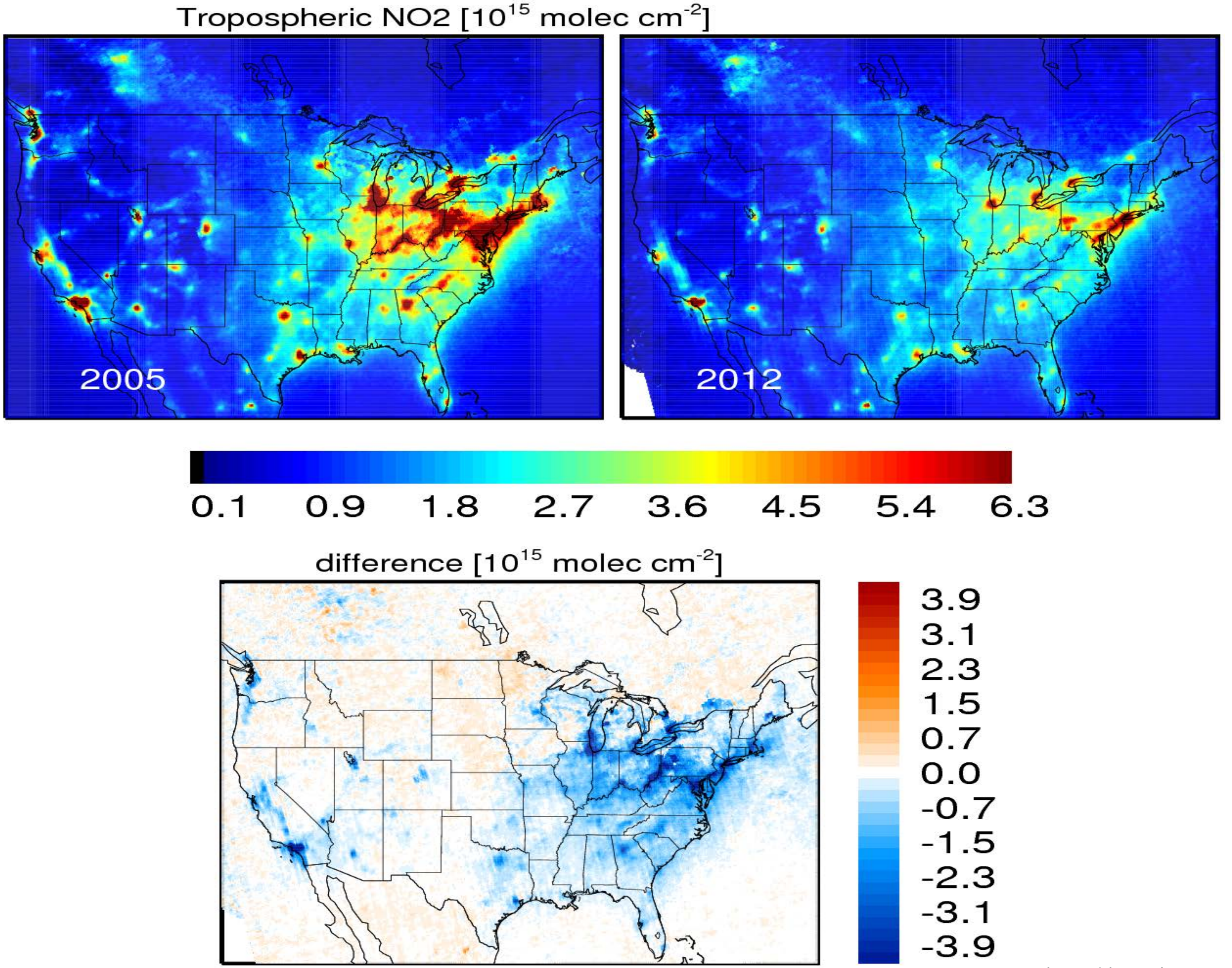
- VCD quality flag;

- Cloud fraction;

- **Row Anomaly;**

- **Outliners (5% at each end)**

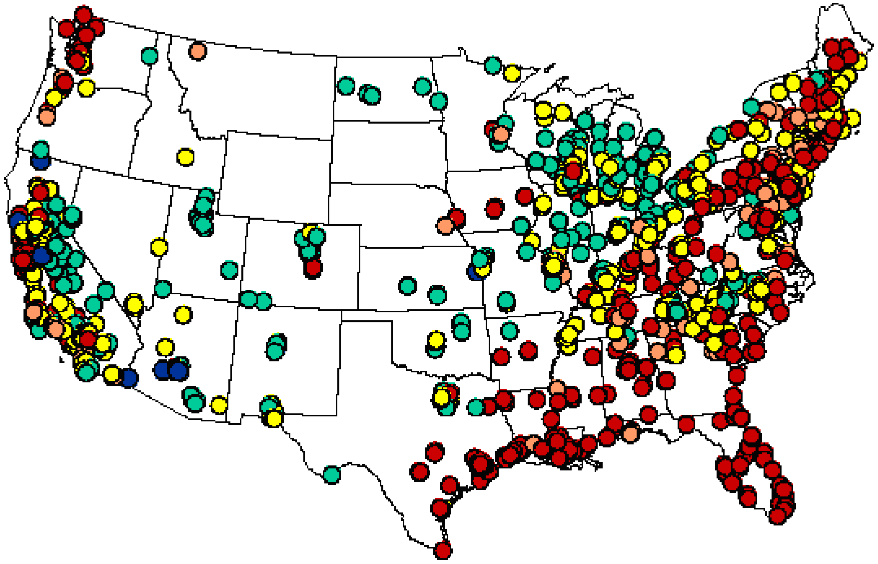
OMI Observed NOx Change (July)



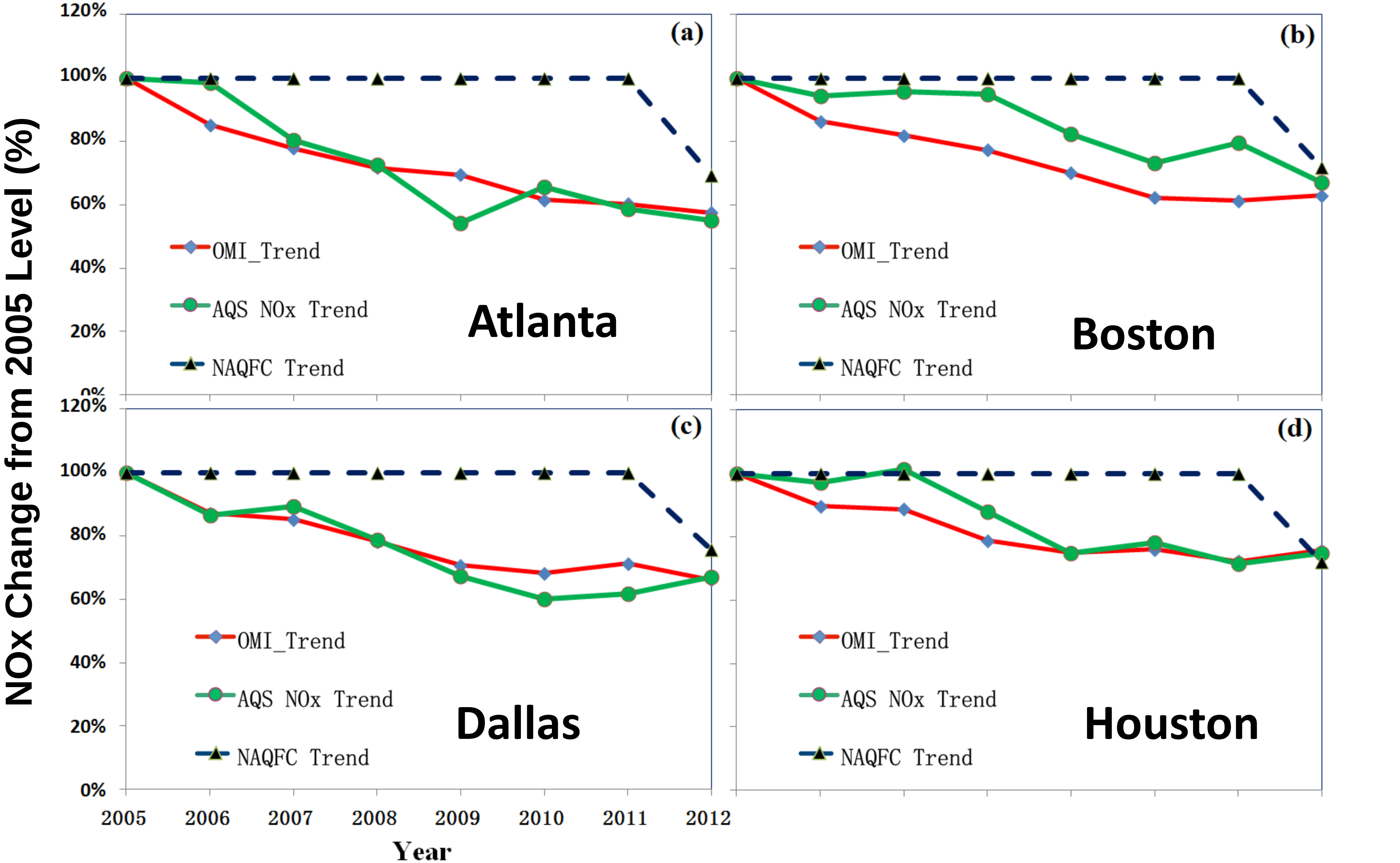
Contributed by Lok Lamsal

AQS: EPA Ambient NO2 Monitoring

- **Method: Chemiluminescence**
  - **Interferences with PAN, O3 and alkyl nitrates**
  - **Uncertainty higher at lower end**
- **Select early morning rush hours (6-9AM): higher values and less photochemistry**

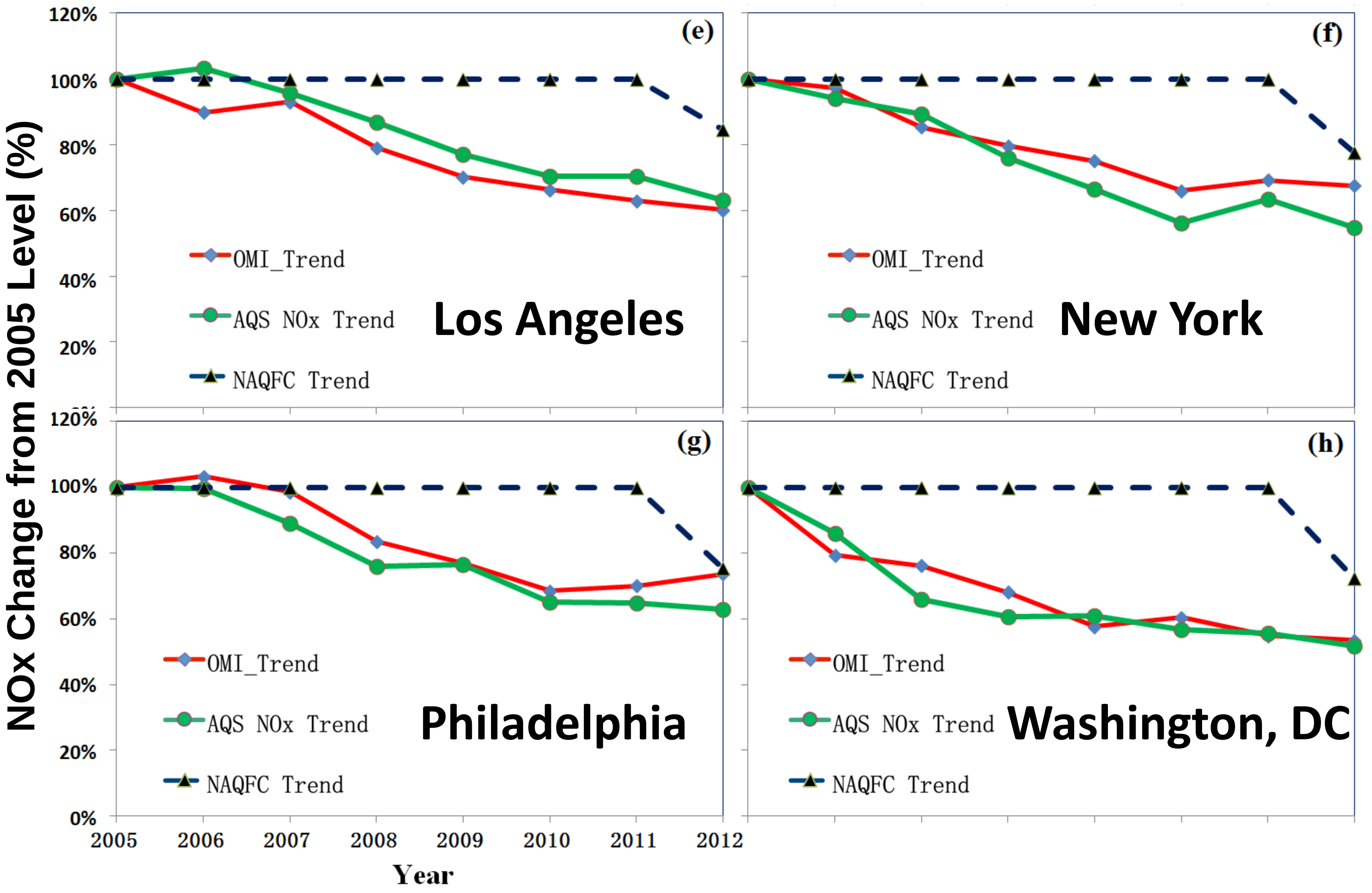


Inter-Comparison of OMI, AQS and NAQFC



(Source: Tong et al., 2015)

Inter-Comparison of OMI, AQS and NAQFC (Continued)



(Source: Tong et al., 2015)

Morning Rush Hours vs Early Afternoon

Atlanta

Boston

Dallas

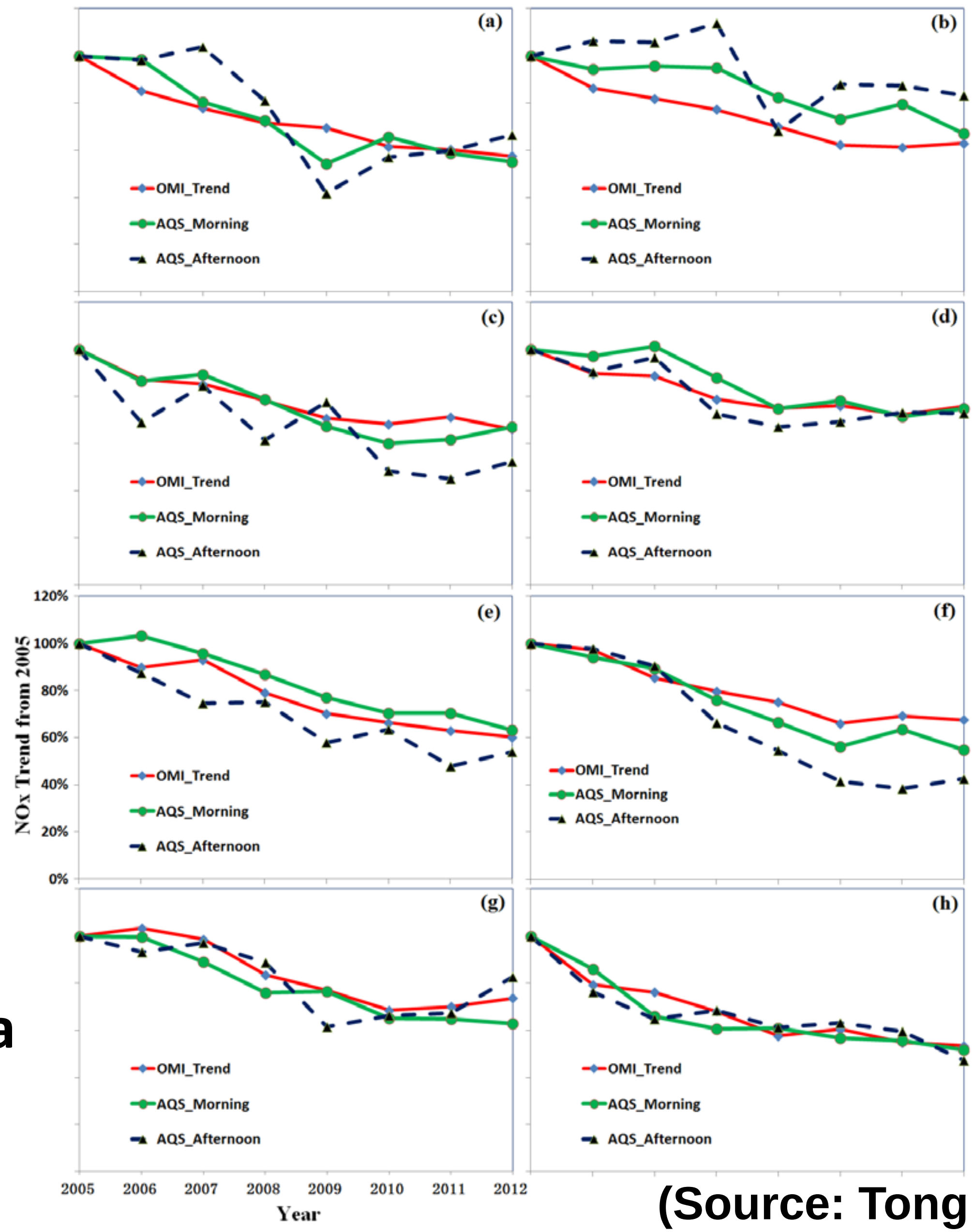
Houston

Los Angeles

New York

Philadelphia

Washington, DC



(Source: Tong et al., 2015)

Seven-year NOx Changes

City	Atlanta	Boston	Dallas	Houston	Los Angeles	New York	Philadel-phia	Washing-ton, DC	Mean
OMI	-42%	-37%	-34%	-24%	-40%	-32%	-26%	-47%	-35%
AQS	-45%	-33%	-33%	-25%	-37%	-45%	-37%	-48%	-38%
NAQFC	-31%	-28%	-24%	-28%	-15%	-22%	-25%	-28%	-25%

- **Both observations (OMI and AQS) revealed -5%/yr reduction rate;**
- **NAQFC adopted change corresponds to -3.5%/yr;**

NOx Changes
Prior to, during and after the Recession

Stage	Sources	Atlanta	Boston	Dallas	Houston	Los Angeles	New York	Philadel-phia	Washing-ton, DC	Mean
Before	OMI SP	-11.7	-9.4	-7.5	-5.7	-3.3	-7.5	-0.6	-12.3	-7.3
	AQS	-9.9	-2.1	-5.2	0.7	-2.0	-5.5	-5.5	-18.7	-6.0
During	OMI SP	-5.5	-7.5	-8.9	-7.9	-13.1	-6.2	-11.7	-13.0	-9.2
	AQS	-17.5	-7.0	-13.0	-14.0	-10.3	-13.6	-7.0	-3.7	-10.8
After	OMI SP	-6.0	-3.3	-2.1	0.4	-5.0	-3.2	-1.2	-2.3	-2.8
	AQS	1.4	-6.1	0.1	0.2	-6.4	-5.4	-6.1	-5.3	-3.4

- **Distinct regional difference;**
- **Average NOx changes are consistent for OMI and AQS data;**
- **-6%/yr - -7%/yr prior to Recession;**
- **-9%/yr - -11%/yr during Recession;**
- **-3%/yr after Recession (Recovery?).**

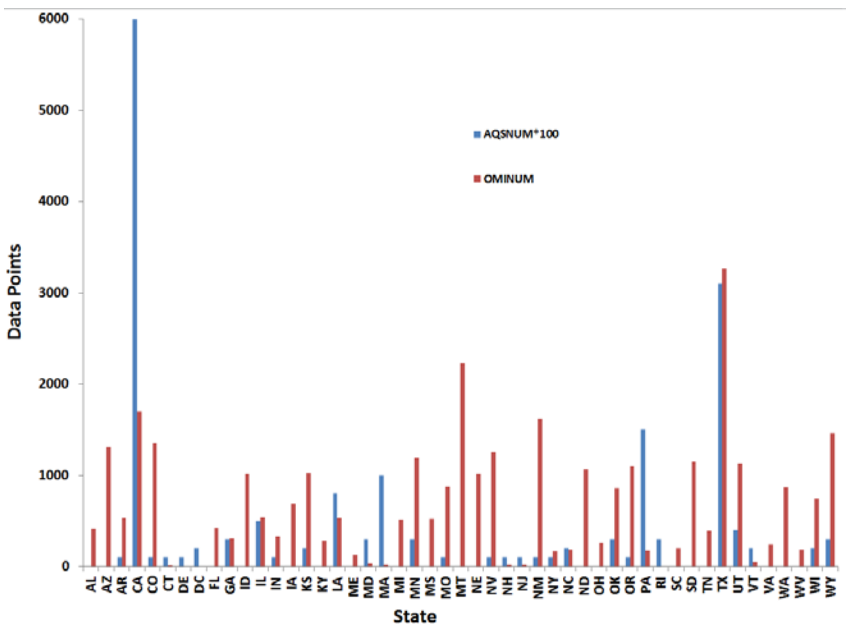
(Source: Tong et al., 2015)

Rapid Refresh of NO_x Emissions

Question: Can satellite and ground data be used to rapidly refresh NOx emissions?

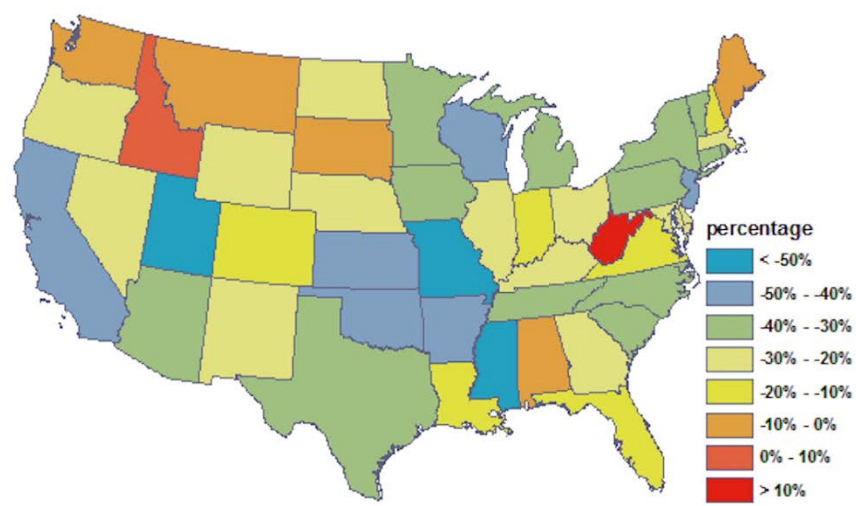
Fusing AQS & OMI

$$AF = \frac{\Delta S \times N_S \times f_S + \Delta G \times N_G \times f_G}{N_S \times f_S + N_G \times f_G}$$



Comparison of OMI and AQS (x100) Samples

State-level Projection

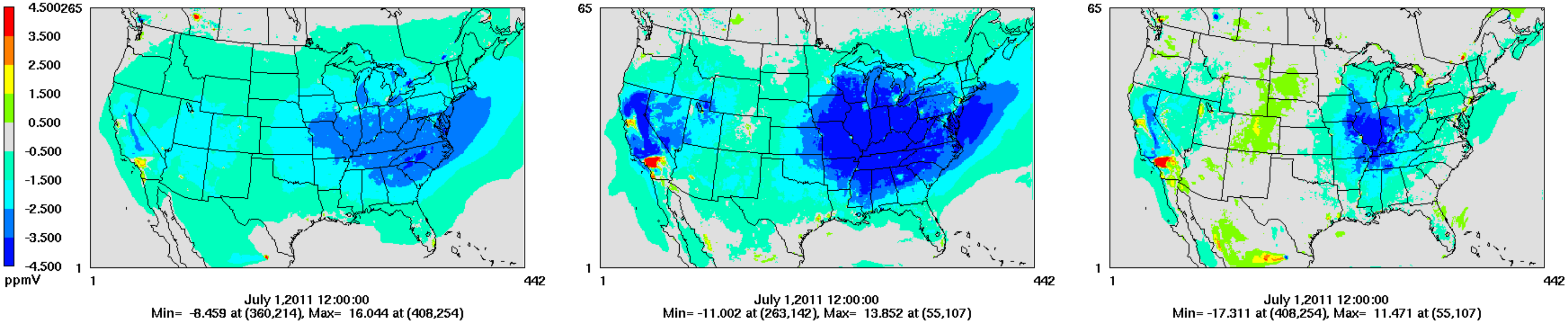


(2005 to 2012)

(Source: Tong et al., GRL, 2016)

Effect on O_3 Forecast

Effect of Using EPA Projection | **Effect of Using Fused Obs.** | **Difference**



Performance Metrics (July 2011 over CONUS)

	MB (ppbv)		NMB (%)		RMSE (ppbv)	
	Hourly	Max8	Hourly	Max8	Hourly	Max8
Op. NAQFC	11.9	9.9	29.7	20.3	23.1	21.5
Fused Obs	11.5	9.7	28.7	20.1	22.7	21.4

(Source: Tong et al., GRL, 2016)

Summary

- **Revealed consistent NOx responses to the 2008 Economic Recession by OMI and AQS (-6%, -10%, and -3% reduction per year before, during and after the Recession);**
- **Demonstrated how to use space and ground observations to 1) evaluate emission updates; and 2) rapidly update NOx emissions to support national air quality forecasting.**

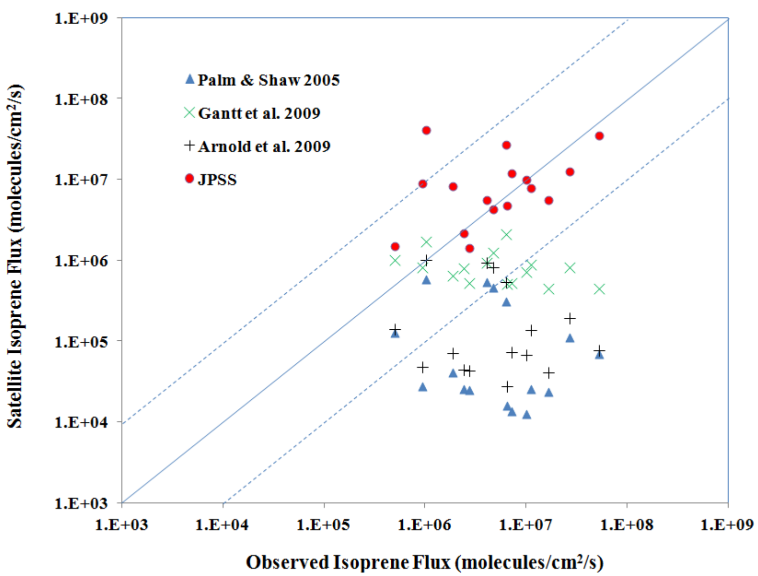
References:

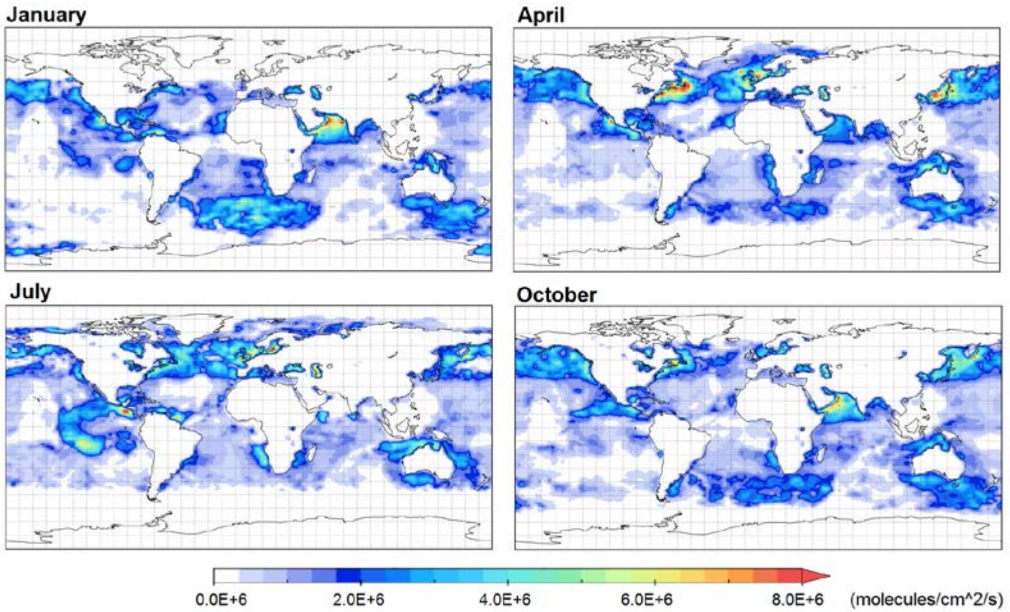
Tong, D.Q., L. Pan, W. Chen, L. Lamsal, P. Lee, Y. Tang, H. Kim, S. Kondragunta, I. Stajner, 2016. Impact of the 2008 Global Recession on air quality over the United States: Implications for surface ozone levels from changes in NO_x emissions. Geophysical Research Letter, Accepted.

Tong, D.Q., L. Lamsal, L. Pan, C. Ding, H. Kim, P. Lee, T. Chai, and K.E. Pickering, and I. Stajner, 2014. Long-term NO_x trends over large cities in the United States during the 2008 Recession: Intercomparison of satellite retrievals, ground observations, and emission inventories, Atmospheric Environment, 107,70-84, doi:10.1016/j.atmosenv.2015.01.035.

JPSS and Marine Isoprene

- SNPP-VIIRS, MODIS and SeaWiFS was used to produce marine isoprene emissions for use in NAQFC and other NOAA models





Continuation of Global Anthropogenic and Volcanic SO_2 Monitoring from OMI to OMPS

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Can Li, Yan Zhang, Simon Carn, Joanna Joiner, Rob Spurr

Trace Gas Session
3rd Annual JPSS Meeting
August 11, 2016
College Park, MD

Outline

- Background and motivation
- PCA algorithm – data driven, straightforward to implement, small noise and artifacts
- Application to OMI – operational algorithms for new OMI PBL and volcanic SO_2 data
- Application to OMPS – implementation of OMI PCA algorithms with OMPS shows good consistency between two instruments

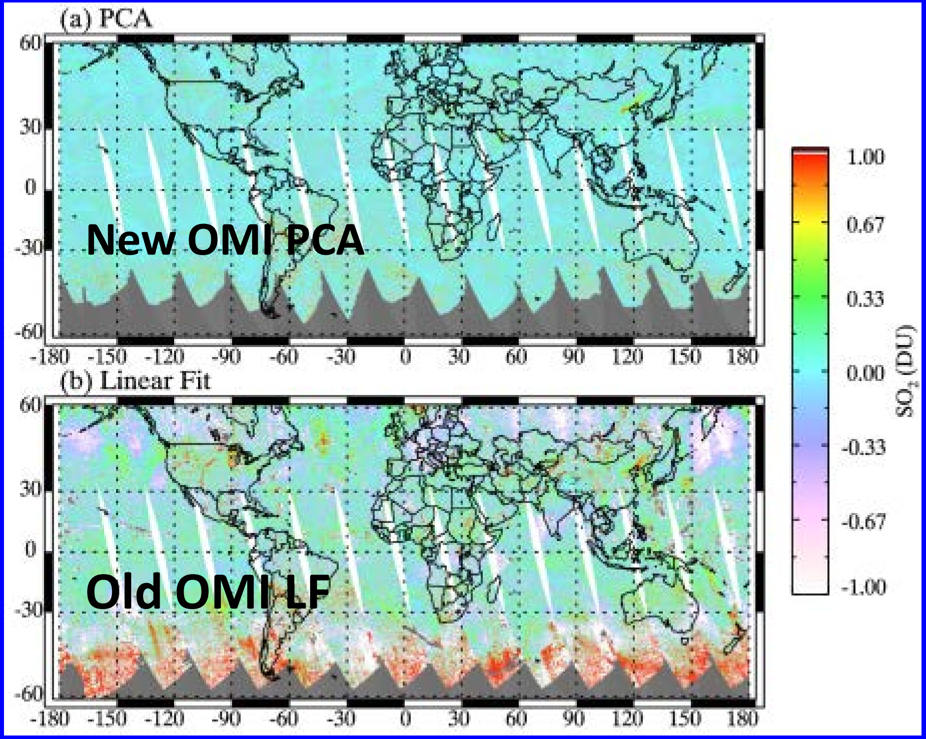
NASA SO_2 processing

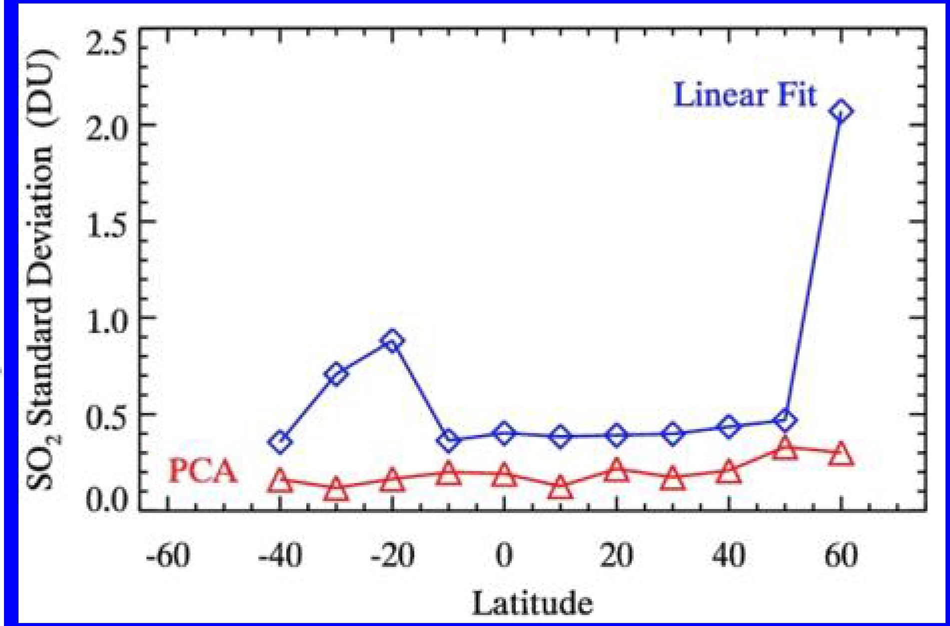
- Developed new PCA algorithm [Li et al., 2013]
  - data driven,
  - efficient,
  - smallest noise and artifacts
  - Does not require soft calibration => good consistency
- Application to OMI – operational algorithms for new OMI PBL and volcanic SO_2 data
- Application to OMPS – implementation of OMI PCA algorithms with OMPS shows good consistency between two instruments
- Data are available on our web site: http://so2.gsfc.nasa.gov

Execution Speed of the PCA SO_2 Algorithm

- ~4 min per OMI orbit (~70,000 pixels) using simplified SO_2 Jacobians LUT ;
- 5 days used for reprocessing 10-year OMI data for the current operational PBL product;
- ~65 min per OMI orbit using full LUT - can be reduced to ~10 min if cross-section is used in fitting for SCD and then converted to VCD using AMF;
- ~20 s per OMPS orbit (~10,000 pixels) using simplified SO_2 Jacobians LUT

OMI: New Operational OMI Volcanic SO_2 Product Greatly Reduces Bias and Noise over Background Areas

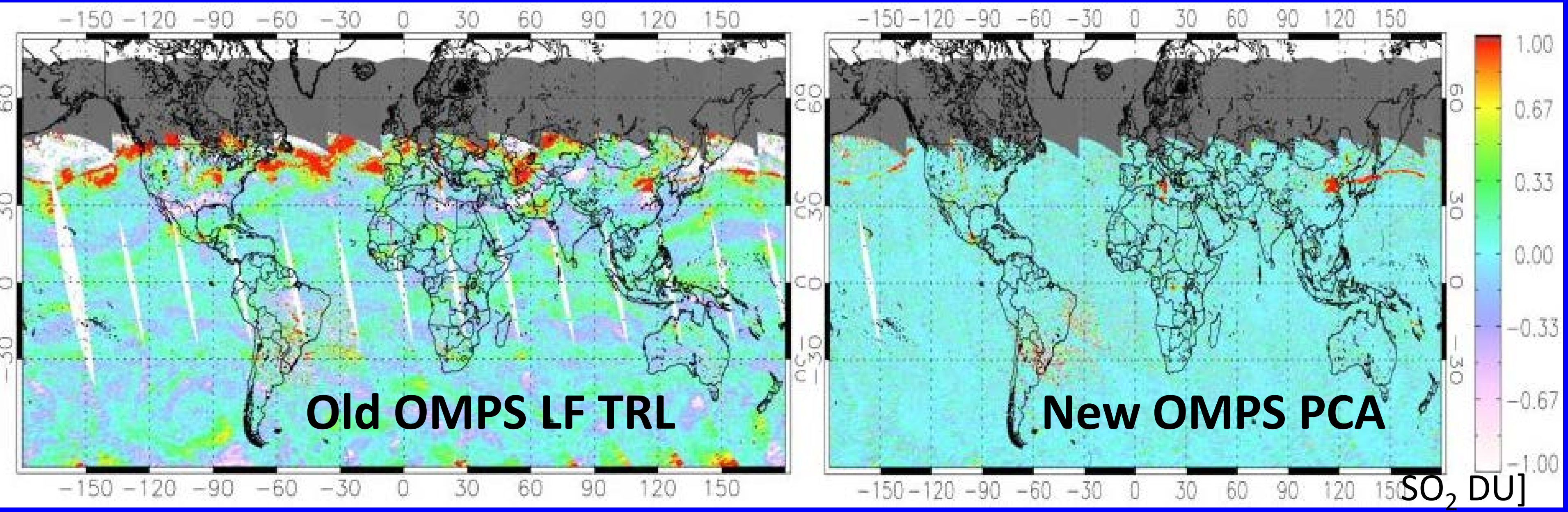




Retrieval noise reduced by a factor of two

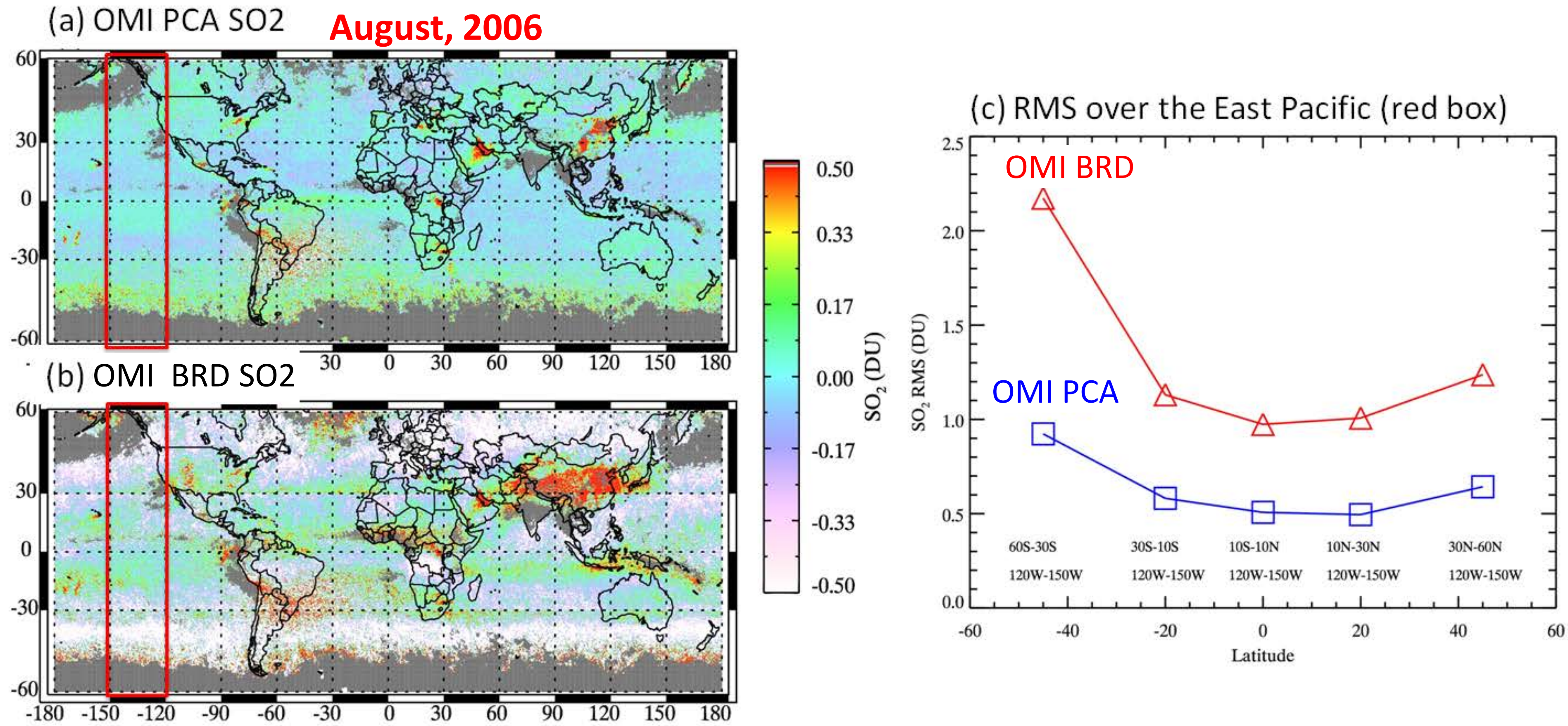
OMI TRL Retrievals, August 5, 2006 [Li et al., AMTD 2016]

OMPS: Reduced Background noise and artifacts: volcanic SO_2



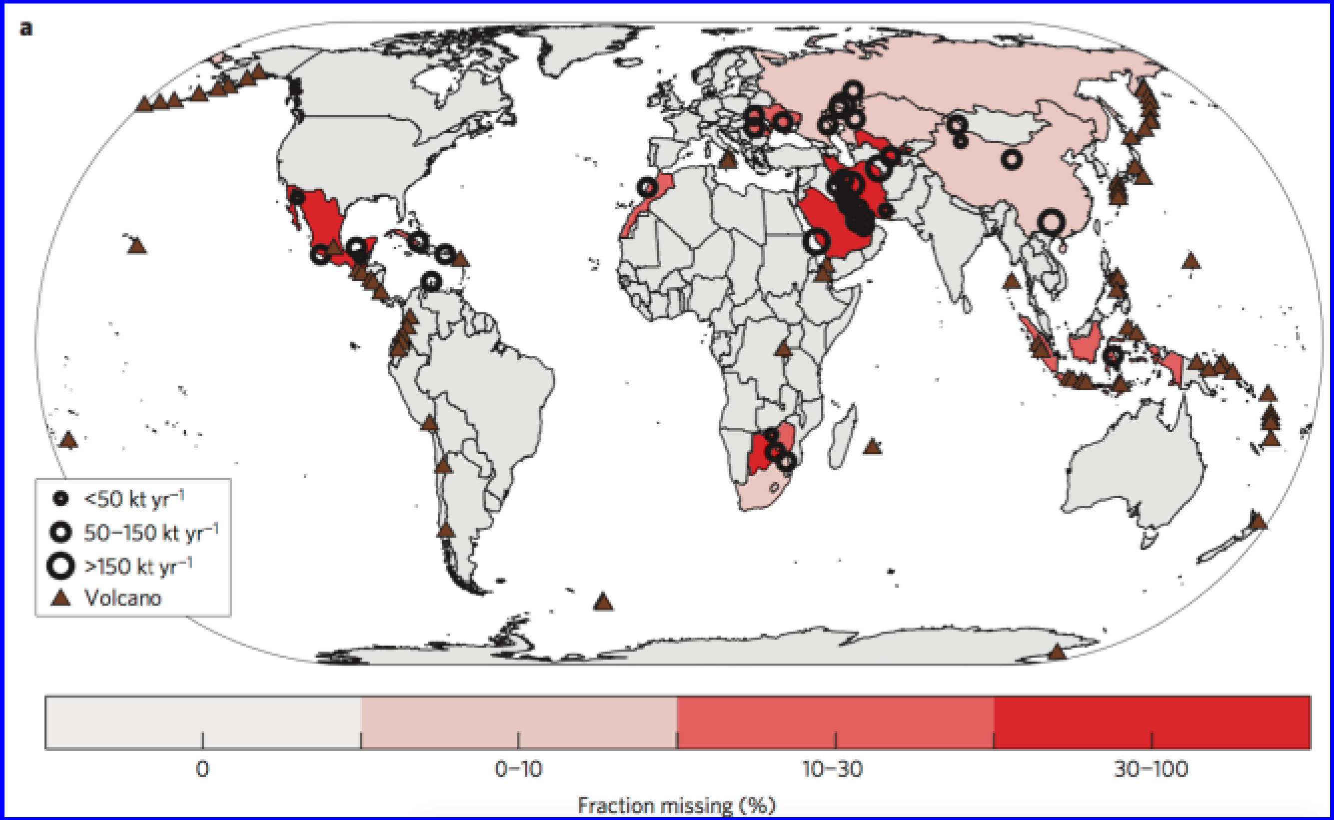
OMPS NRT LF TRL retrievals for 12/08/2015, a few days after the December 3 2015 Mt. Etna eruption.

Reduced Background noise and artifacts: PBL SO_2



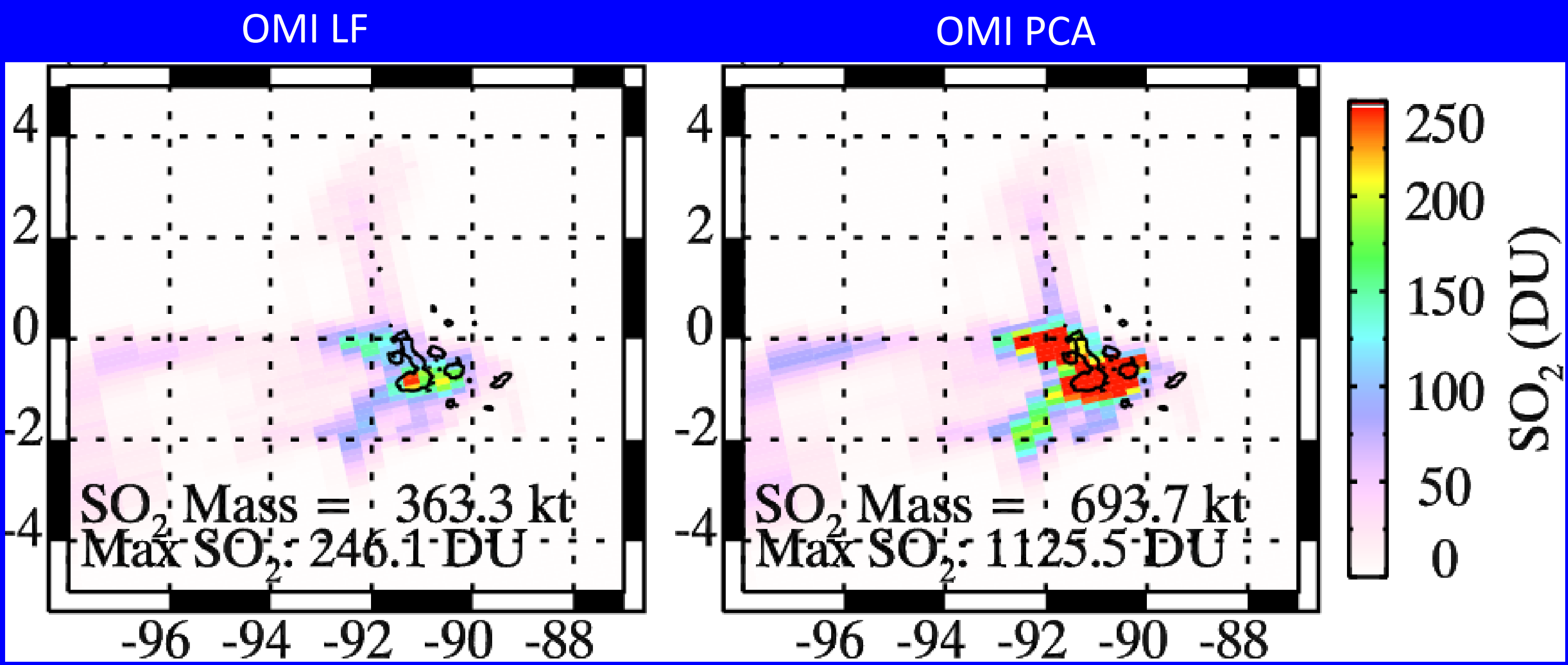
- PCA algorithm reduces retrieval noise by a factor of two as compared with the BRD algorithm
- SO_2 Jacobians for PCA algorithm calculated with the same assumptions as in the BRD algorithm

When combined with wind data and careful, innovative data analysis …



- An independent "top-down" global SO_2 emission inventory [*McLinden et al.*, NG 2016];
- Annual emissions quantified for ~500 large sources, ~40 missing or unreported in "bottom-up" inventories, or ~6-12% of the total anthropogenic sources;
- Emissions quantified for 75 volcanoes – large differences between OMI measurements and the Aerocom database.

New OMI Operational PCA Volcanic SO_2 Greatly Reduces Low Bias in the old LF SO_2 for Large Eruptions

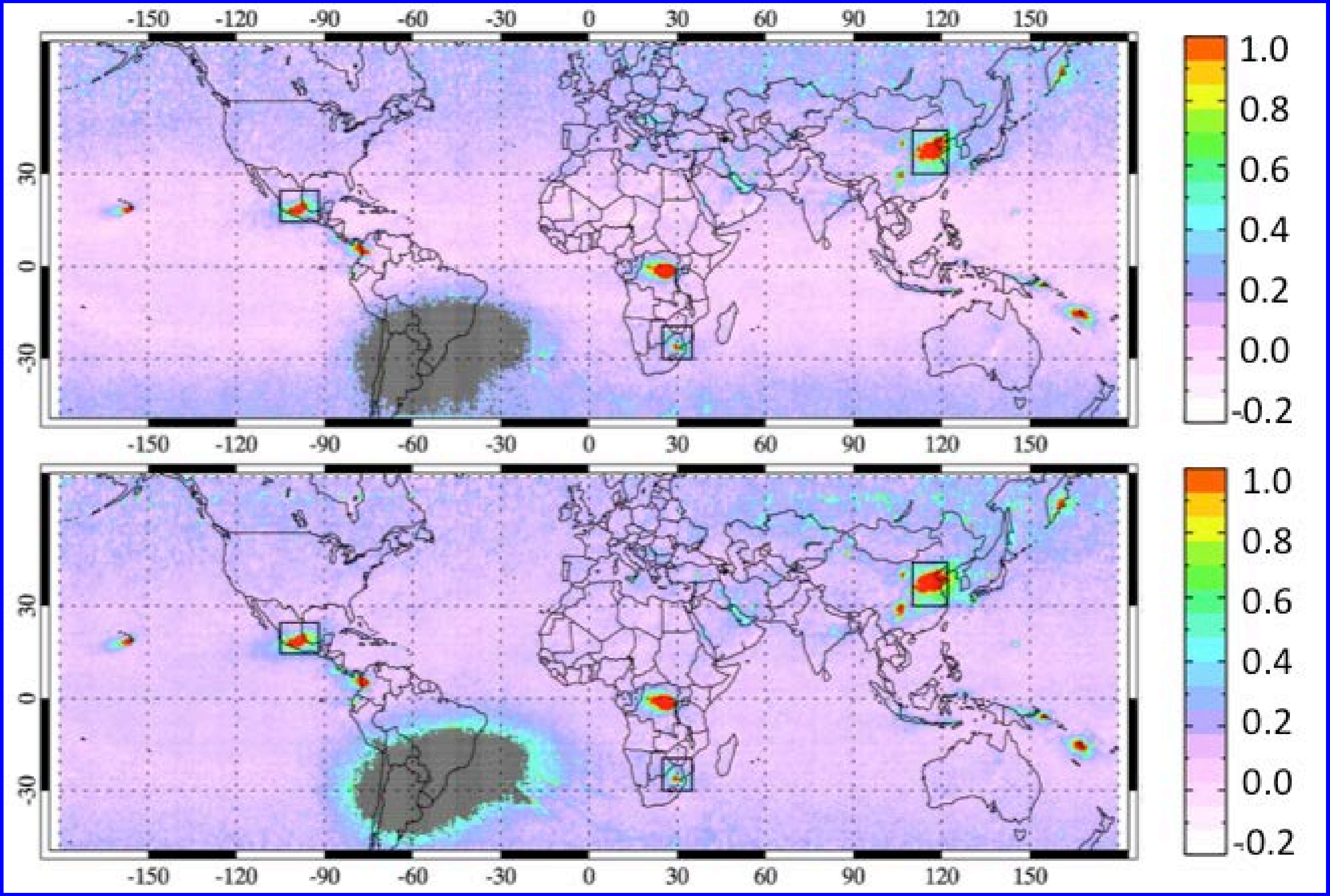


- Sierra Negra eruption in 2005, <u>max SO_2 from new operational PCA algorithm ~1100 DU</u>, in agreement with the offline ISF algorithm [*Li et al.*, 2016]
- Kasatochi eruption in 2008: PCA total SO_2 ~1700 kt, consistent with ISF and OE algorithms for OMI and GOME-2, <u>a factor of two more than LF with known low bias</u> [*Krotkov et al.*, 2010].

Good consistency between OMI and OMPS Annual Mean PBL SO_2 Retrievals for 2012

OMI

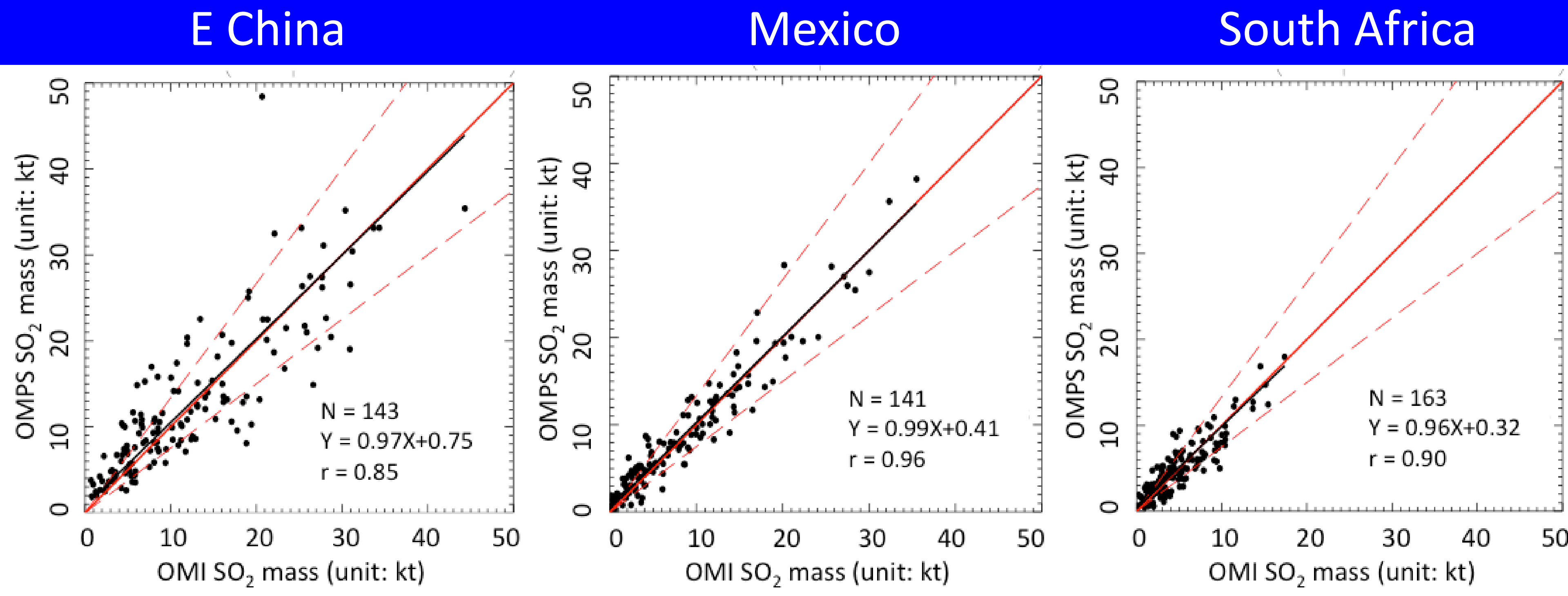
OMPS



No soft calibration or L2 correction

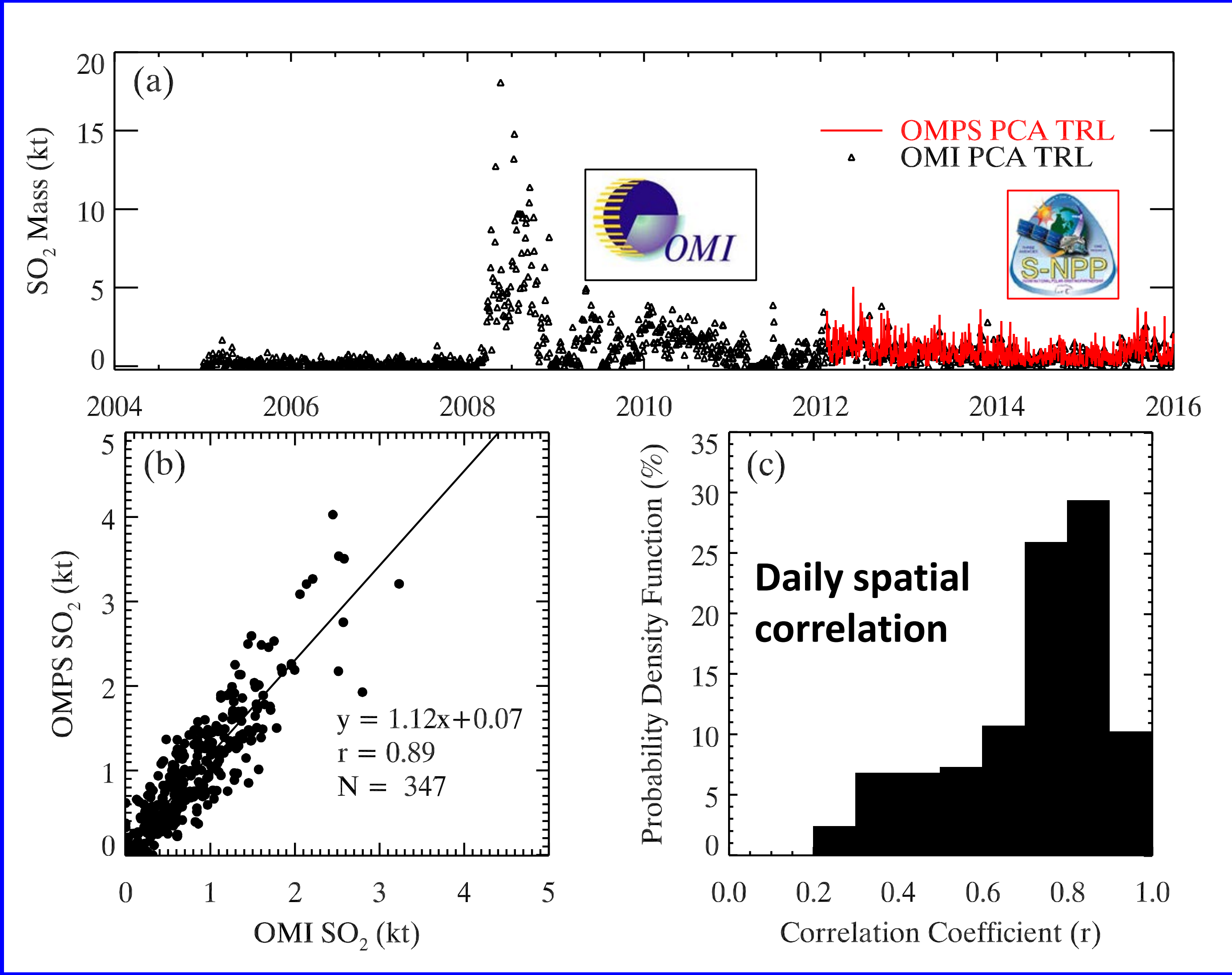
[*Zhang et al.*, 2016]

Daily regional SO_2 loading over the selected areas in 2012 (PBL retrievals)



[*Zhang et al.*, AMTD 2016]

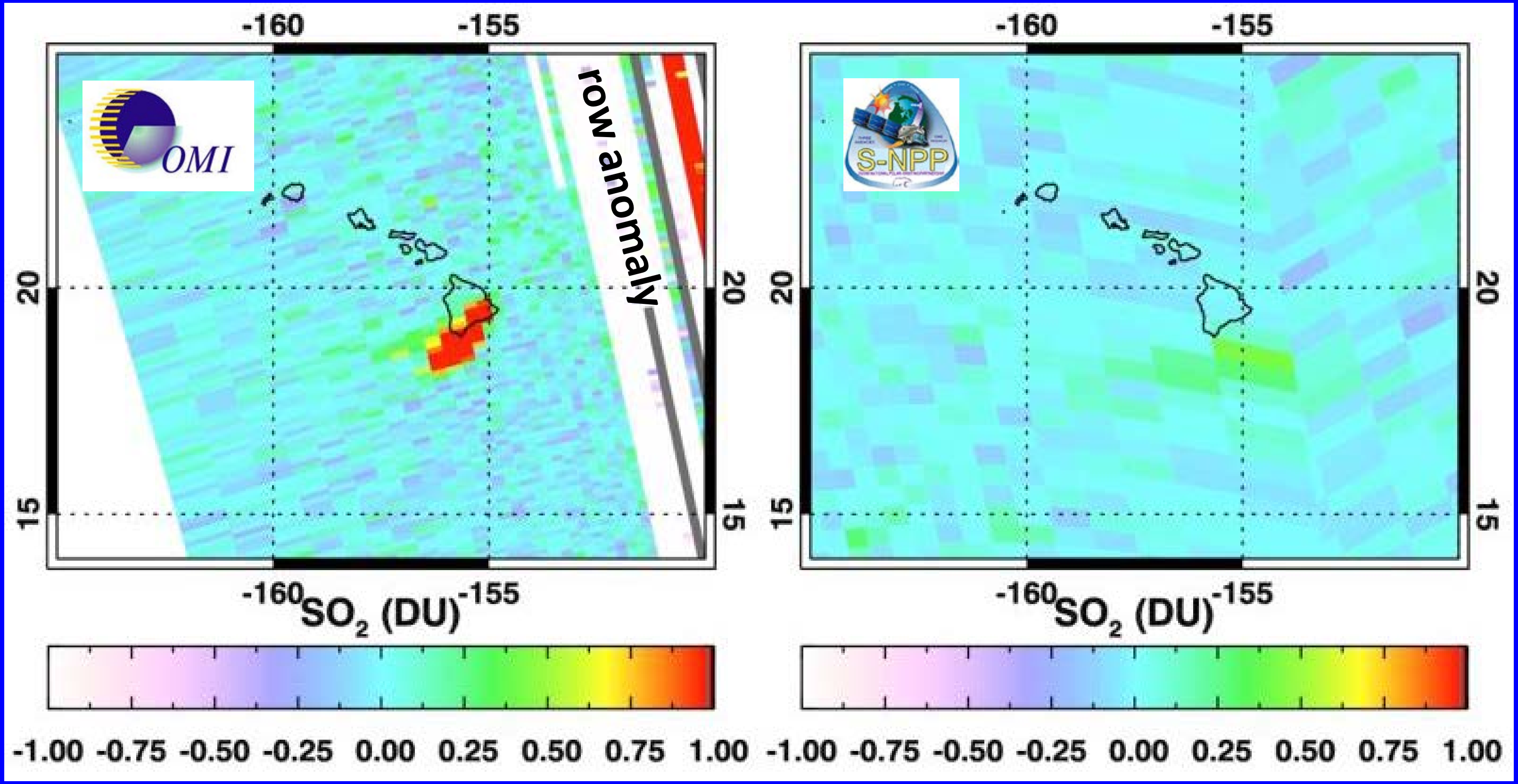
Daily OMI/OMPS regional volcanic SO_2 loading Hawaii (PCA 3-km/TRL retrievals)



[*Li et al.*, 2016]

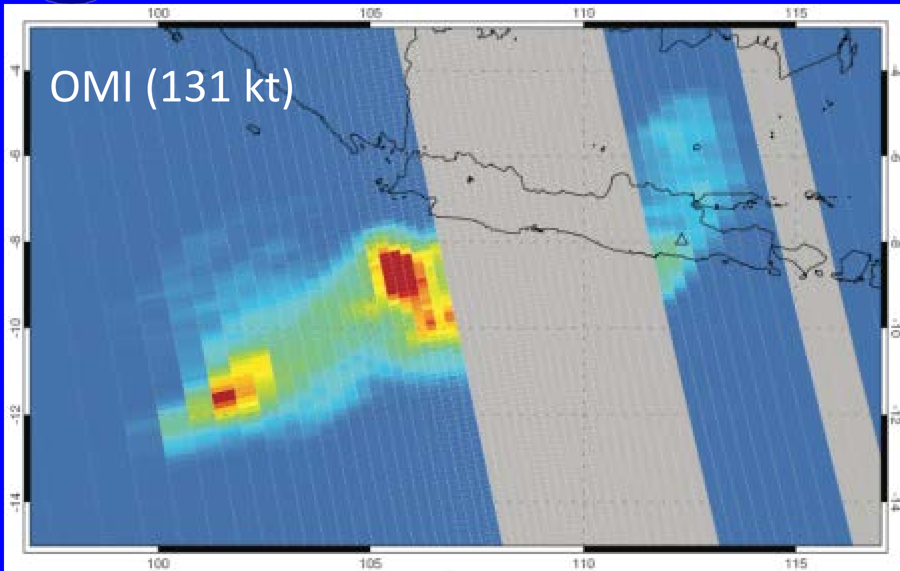
Five days with *r* < 0.3, why?

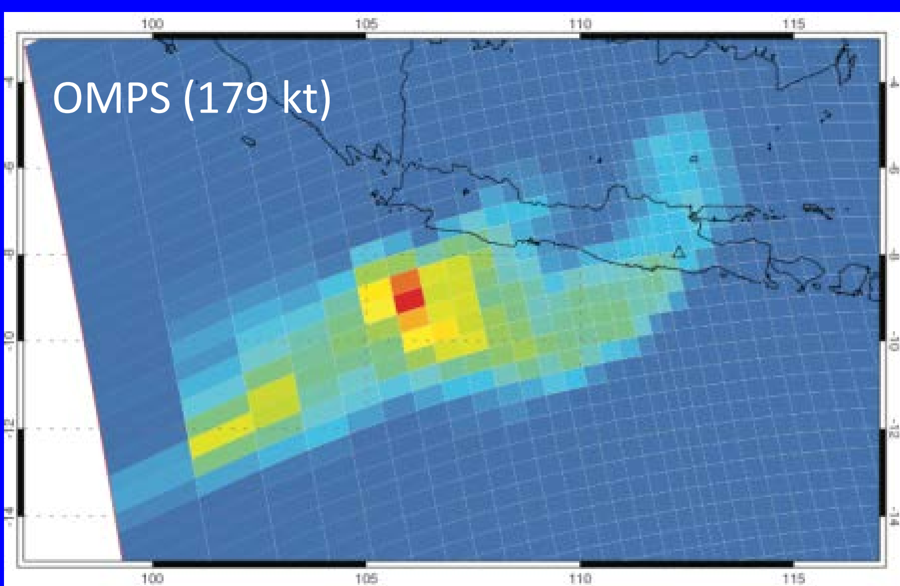
- ✓ Five days with *r* < 0.3: 02/05/2012, 10/02/2012, 05/14/2013, 11/06/2013, and 11/09/2014.
- ✓ For all five days, the plume was covered by OMI pixels near the nadir but by OMPS pixels near the edge of the swath.

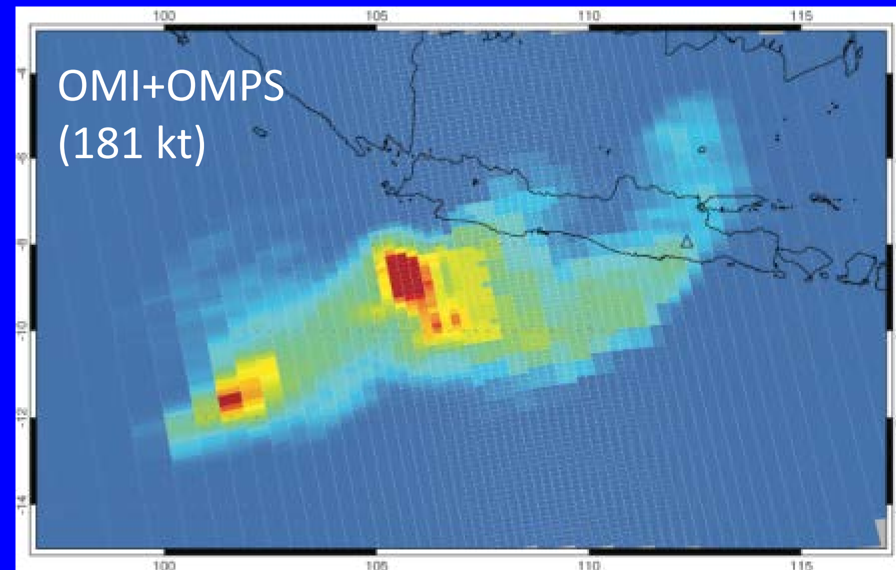


11/06/2013

Large Eruption: Kelut in 2014





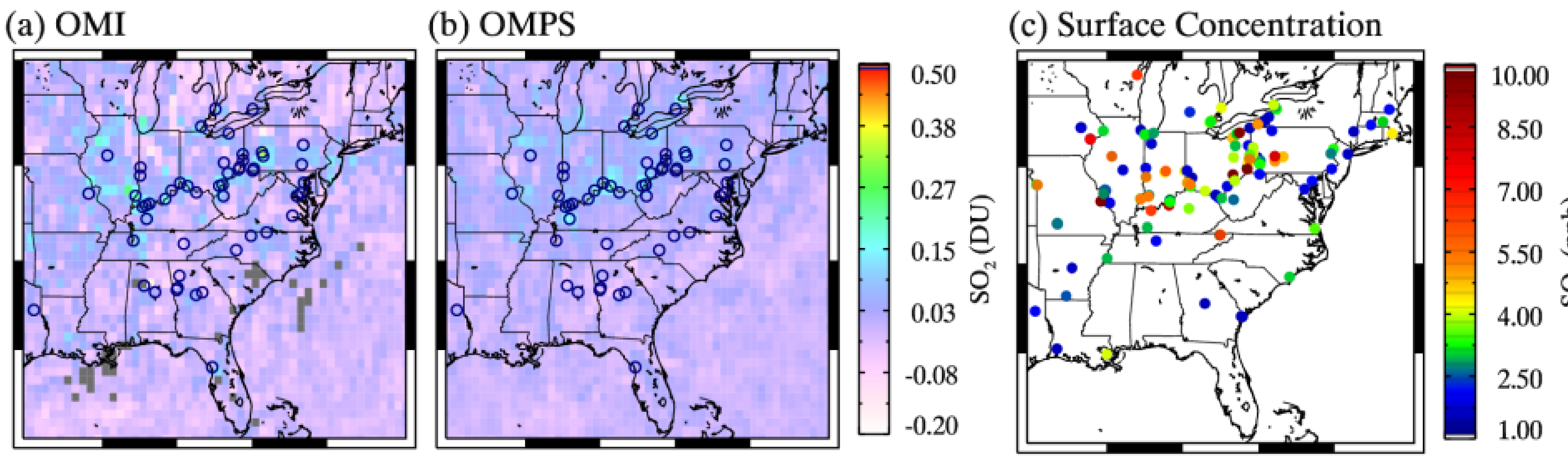


- ✓ **Merged OMI+OMPS provides full coverage and fine spatial detail**
- ✓ **Agrees with OMPS only SO_2 mass to within 3%**

[*Li et al.*, 2016]

New OMI and OMPS anthropogenic SO_2 retrievals with comprehensive LUT for Jacobians

Monthly Mean, August 2012 **Monthly Mean at 2 pm Local Time**



- ✓ Preliminary new OMI and OMPS pollution SO_2 retrievals both reveal emission sources over the Ohio River valley (circles are sources with > 50 kt emissions in 2006).
- ✓ Surface monitoring stations show qualitatively consistent pattern.
- ✓ If assuming the same mixing ratio for the lowest 100 hPa (~1000 m) of the atmosphere and no SO_2 above, 4 ppb translates into ~0.3 DU in column loading.

4+ Years of OMPS PBL SO_2 Research Product Now Available on NASA's SO_2 Website: http://so2.gsfc.nasa.gov

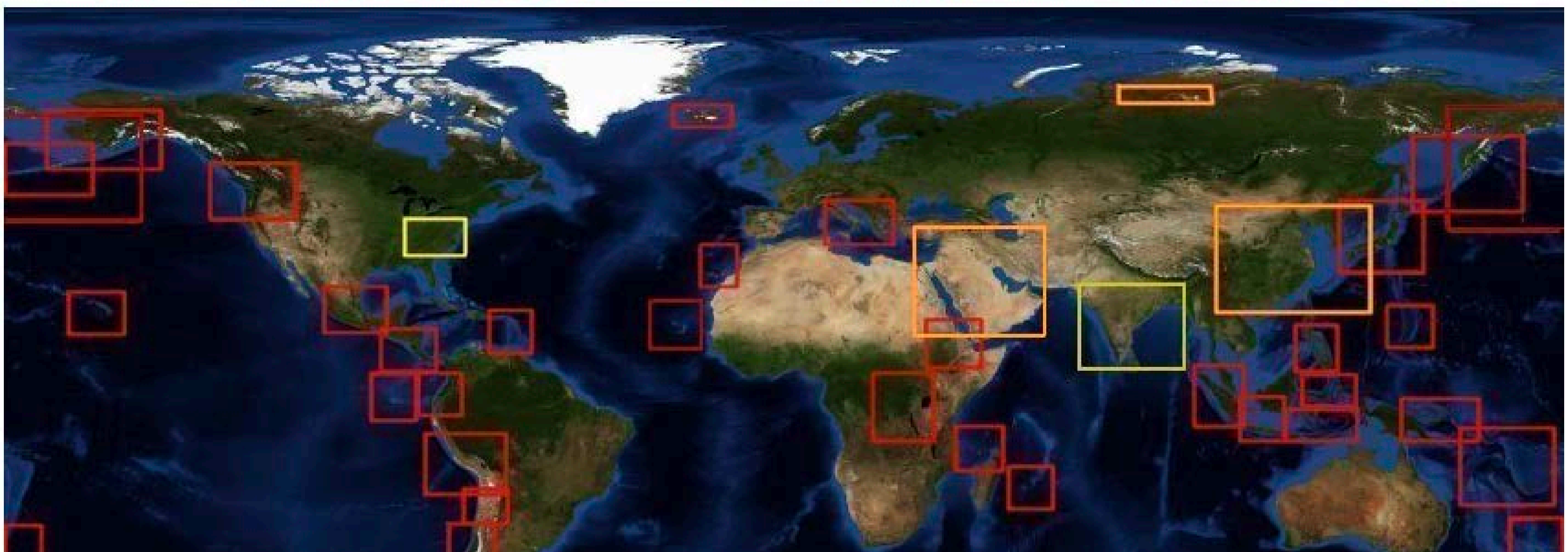
TOMS images (1979-2005) | AIRS images (2003-present) | OMI images (2004-present) | OMPS images (May 2012-present)

Global monthly OMI Boundary Layer SO_2 maps

Global monthly OMPS Boundary Layer SO_2 maps

Latest Daily (OMI/OMPS) Images of SO_2 (click on a highlighted rectangle)

Red = daily volcanic regions, orange = daily pollution regions, yellow = long-term pollution images



Conclusions

- The PCA SO_2 retrieval approach – data-driven, good quality, straightforward to implement.
- Operational OMI PCA PBL and volcanic SO_2 data show significant improvement over previous OMI data, also compare well with OMI DOAS SO_2 data using TROPOMI prototype algorithm [*Theys et al.*, 2015].
- Research OMPS PBL and volcanic SO_2 data based on PCA algorithms show good consistency with OMI data.

The capability of the OMPS Linear Fit SO_2 (LFSO2) algorithm for implementation at NDE

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C. Trevor Beck, Lawrence E. Flynn
NOAA/NESDIS/STAR

Kai Yang
University of Maryland

Goal for LFSO2 implementation at NOAA

1. Provide near real time ***alerts*** of volcanic SO_2 clouds.

2. Provide O_3 ***corrections*** when large amounts of SO_2 are present.

3. Provide ***accurate*** $\boldsymbol{SO_2}$ ***total column amounts*** to address the shortfall of the existing products in the Version-8 ozone algorithm.

Residuals and Linearization

The algorithm starts from N-values: $$N_m(\Omega, \Xi, R, \lambda_i) = N(\Omega, \Xi, R, \lambda_i) + \varepsilon_r \qquad (1)$$

We linearize the problem with differentials at $\Omega = \Omega_0$, $\Xi = \Xi_0$, $R = R_0$:

$$N_m(\lambda_2) - N_0(\lambda_2) = \Delta\Omega \left.\frac{dN(\lambda_2)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_2)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_2 - \lambda_0)^j\right) \left.\frac{dN(\lambda_2)}{dR}\right|_{R=R_0} + \varepsilon_r$$

$$N_m(\lambda_3) - N_0(\lambda_3) = \Delta\Omega \left.\frac{dN(\lambda_3)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_3)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_3 - \lambda_0)^j\right) \left.\frac{dN(\lambda_3)}{dR}\right|_{R=R_0} + \varepsilon_r$$

$$N_m(\lambda_4) - N_0(\lambda_4) = \Delta\Omega \left.\frac{dN(\lambda_4)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_4)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_4 - \lambda_0)^j\right) \left.\frac{dN(\lambda_4)}{dR}\right|_{R=R_0} + \varepsilon_r \qquad (2)$$

$\ldots$

$\ldots$

$$N_m(\lambda_i) - N_0(\lambda_i) = \Delta\Omega \left.\frac{dN(\lambda_i)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_i)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_i - \lambda_0)^j\right) \left.\frac{dN(\lambda_i)}{dR}\right|_{R=R_0} + \varepsilon_r$$

$N_0(\lambda)$: radiative transfer model computed at $N_0(\Omega_0, \Xi_0, R_0, \lambda)$.

$N_m(\lambda)$: measured N-value.

$N_m(\lambda) - N_0(\lambda)$: V8TOZ Algorithm output residuals.

15-Granule Bias Estimates

The ozone retrieval provided residual includes biases along-orbit. To eliminate these residual biases, A 15-granule implementation technique is designed. Residual averages <ψ(λ)> over three five-granule intervals (corresponding to ~10° latitude) are calculated at the 12 wavelength bands and 35 cross tracks. Each individual average residual within these three averaged intervals are calculated by interpolation. The corrected residual,

$\psi(\lambda) = N_m(\lambda) - N_0(\lambda) - \langle\psi(\lambda)\rangle$ is called the "adjust residual", then:

$$
\begin{aligned}
\psi(\lambda_2) &= \Delta\Omega \left.\frac{dN(\lambda_2)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_2)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_2 - \lambda_0)^j\right) \left.\frac{dN(\lambda_2)}{dR}\right|_{R=R_0} + \varepsilon_r \\
\psi(\lambda_3) &= \Delta\Omega \left.\frac{dN(\lambda_3)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_3)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_3 - \lambda_0)^j\right) \left.\frac{dN(\lambda_3)}{dR}\right|_{R=R_0} + \varepsilon_r \\
\psi(\lambda_4) &= \Delta\Omega \left.\frac{dN(\lambda_4)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_4)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_4 - \lambda_0)^j\right) \left.\frac{dN(\lambda_4)}{dR}\right|_{R=R_0} + \varepsilon_r \\
&\dots \\
&\dots \\
\psi(\lambda_i) &= \Delta\Omega \left.\frac{dN(\lambda_i)}{d\Omega}\right|_{\Omega=\Omega_0} + \Delta\Xi \left.\frac{dN(\lambda_i)}{d\Xi}\right|_{\Xi=\Xi_0} + \left(\Delta R(\lambda_0) + \sum_{j=1}^{2} c_j (\lambda_i - \lambda_0)^j\right) \left.\frac{dN(\lambda_i)}{dR}\right|_{R=R_0} + \varepsilon_r
\end{aligned}
\tag{3}
$$

These linear equations can be converted into a matrix expression.

Matrix Formulation

$$\begin{pmatrix} \psi(\lambda_2) \\ \psi(\lambda_3) \\ . \\ \psi(\lambda_i) \\ . \\ \psi(\lambda_{11}) \end{pmatrix} = \begin{pmatrix} \frac{dN(\lambda_2)}{d\Omega} & \frac{dN(\lambda_2)}{d\Xi} & \frac{dN(\lambda_2)}{dR} & (\lambda_2-\lambda_0)\frac{dN(\lambda_2)}{dR} & (\lambda_2-\lambda_0)^2\frac{dN(\lambda_2)}{dR} \\ \frac{dN(\lambda_3)}{d\Omega} & \frac{dN(\lambda_3)}{d\Xi} & \frac{dN(\lambda_3)}{dR} & (\lambda_3-\lambda_0)\frac{dN(\lambda_3)}{dR} & (\lambda_3-\lambda_0)^2\frac{dN(\lambda_3)}{dR} \\ .... \\ \frac{dN(\lambda_i)}{d\Omega} & \frac{dN(\lambda_i)}{d\Xi} & \frac{dN(\lambda_i)}{dR} & (\lambda_i-\lambda_0)\frac{dN(\lambda_i)}{dR} & (\lambda_i-\lambda_0)^2\frac{dN(\lambda_i)}{dR} \\ ..... \\ \frac{dN(\lambda_{11})}{d\Omega} & \frac{dN(\lambda_{11})}{d\Xi} & \frac{dN(\lambda_{11})}{dR} & (\lambda_{11}-\lambda_0)\frac{dN(\lambda_{11})}{dR} & (\lambda_{11}-\lambda_0)^2\frac{dN(\lambda_{11})}{dR} \end{pmatrix} \begin{pmatrix} \Delta\Omega \\ \Delta\Xi \\ \Delta R \\ c_1 \\ c_2 \end{pmatrix} + \begin{pmatrix} \varepsilon(\lambda_2) \\ \varepsilon(\lambda_3) \\ . \\ \varepsilon(\lambda_i) \\ . \\ \varepsilon(\lambda_{11}) \end{pmatrix}$$

The sensitivities differ depending upon the assumed height of the SO_2 layer. Estimates of the total column SO_2 using this Matrix formula is obtained for three different heights: Lower Troposphere (TRL), Middle Troposphere (TRM) and Lower Stratosphere (STL). Other technique is used to estimate Planetary Boundary Layer (PBL) SO_2.

Retrieval Parameters

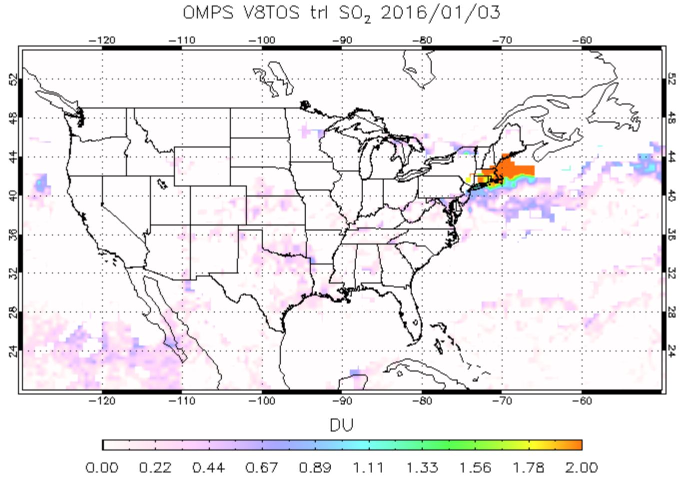
Name	Type	Description	Dimension	Units	Range
s_AlgorithmFlag_PBL	32 bit integer	PBL algorithm flag	105 x 15	Unitless	0, 1, 11
s_AlgorithmFlag_STL	32 bit integer	STL algorithm flag	105 x 15	Unitless	0, 1, 2, 11, 12
s_AlgorithmFlag_TRL	32 bit integer	TRL algorithm flag	105 x 15	Unitless	0, 1, 2, 11, 12
s_AlgorithmFlag_TRM	32 bit integer	TRM algorithm flag	105 x 15	Unitless	0, 1, 2, 11, 12
s_QualityFlags_PBL	32 bit integer	PBL quality flag	105 x 15	Unitless	0 ~ 65535
s_QualityFlags_STL	32 bit integer	STL quality flag	105 x 15	Unitless	0 ~ 65535
s_QualityFlags_TRL	32 bit integer	TRL quality flag	105 x 15	Unitless	0 ~ 65535
s_QualityFlags_TRM	32 bit integer	TRM quality flag	105 x 15	Unitless	0 ~ 65535
s_STLO3	32 bit float	STL corrected total column of O3	105 x 15	Dobson	0 ~ 1000
s_TRLO3	32 bit float	TRL corrected total column of O3	105 x 15	Dobson	0 ~ 1000
s_TRMO3	32 bit float	TRM corrected total column of O3	105 x 15	Dobson	0 ~ 1000
s_ColumnamountSO2_STL	32 bit float	STL total column of SO2	105 x 15	Dobson	-10 ~ 2000
s_ColumnamountSO2_TRL	32 bit float	TRL total column of SO2	105 x 15	Dobson	-10 ~ 2000
s_ColumnamountSO2_TRM	32 bit float	TRM total column of SO2	105 x 15	Dobson	-10 ~ 2000
s_deltaRefl331	32 bit float	Delta Reflectivity at 331 nm	105 x 15	Percent	-100 ~ 100

Retrieval Parameters

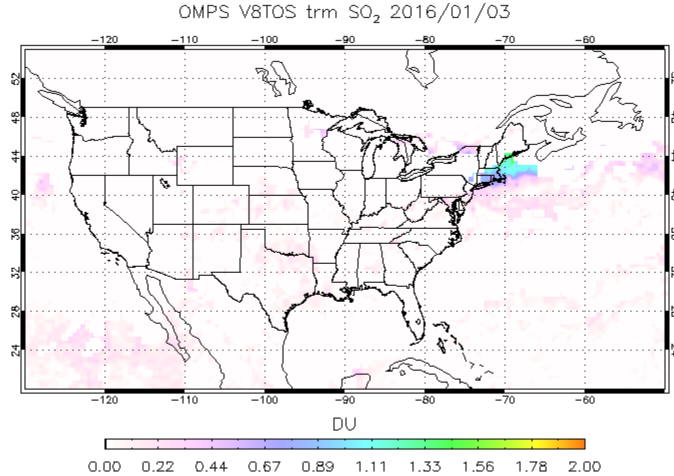
Name	Type	Description	Dimension	Units	Range
s_ChiSquareLfit	32 bit float	Chi-square of linear fit	105 x 15	Uniteless	> 0
s_dN_dSO2_STL	32 bit float	dN/dSO2(STL)	12 x 105 x 15	Per Dobson	-1 ~ 100
s_dN_dSO2_TRL	32 bit float	dN/dSO2(TRL)	12 x 105 x 15	Per Dobson	-1 ~ 1000
s_dN_dSO2_TRM	32 bit float	dN/dSO2(TRM)	12 x 105 x 15	Per Dobson	-1 ~ 100
s_Slope	32 bit float	C_1 in linear equ.	105 x 15	Uniteless	-1 ~ 1
s_Qterm	32 bit float	C_2 in linear equ.	105 x 15	Uniteless	-1 ~ 1
s_ResidualAdjustment	32 bit float	Averaged residual of nvalue	12 x 105 x 15	Uniteless	-10 ~ 10
s_ColumnamountSO2_PBL	32 bit float	Planetary Boundary Layer (PBL) SO2	105 x 15	Dobson	-300 ~ 1000
s_ColumnamountSO2_PBLbrd	32 bit float	PBL SO2 by BRD method	105 x 15	Dobson	-10 ~ 2000
s_ColumnamountSO2_STLbrd	32 bit float	STL SO2 by BRD method	105 x 15	Dobson	-10 ~ 2000
s_ColumnamountSO2_TRMbrd	32 bit float	TRM SO2 by BRD method	105 x 15	Dobson	-10 ~ 2000
s_SO2indexP1	32 bit float	Partial adjust residual for 310 and 311	105 x 15	Uniteless	-100 ~ 100
s_SO2indexP2	32 bit float	Partial adjust residual for 311 and 313	105 x 15	Uniteless	-100 ~ 100
s_SO2indexP3	32 bit float	Partial adjust residual for 313 and 314	105 x 15	Uniteless	-100 ~ 100

Products from the LFSO2 algorithm

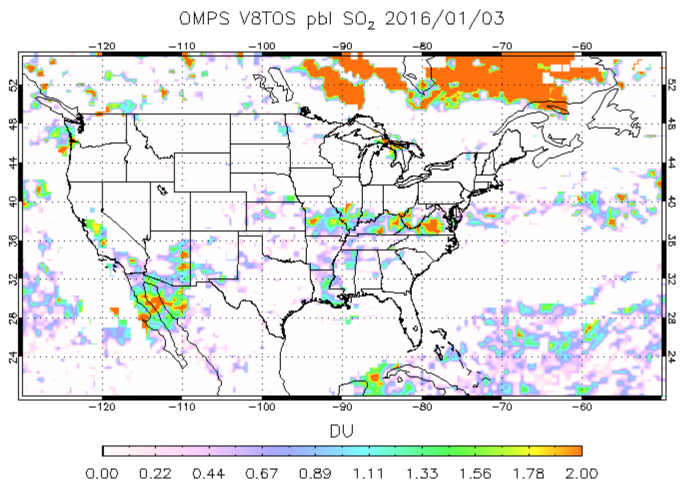
Umkhr-0: 0~5.5km



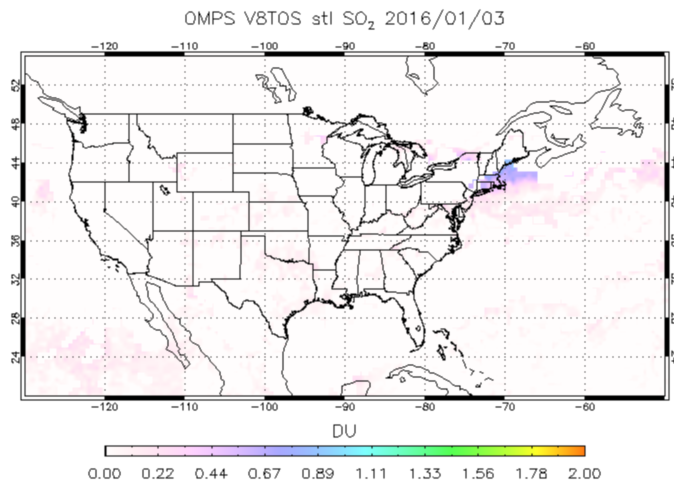
Umkhr-1: 5.5~10.3 km



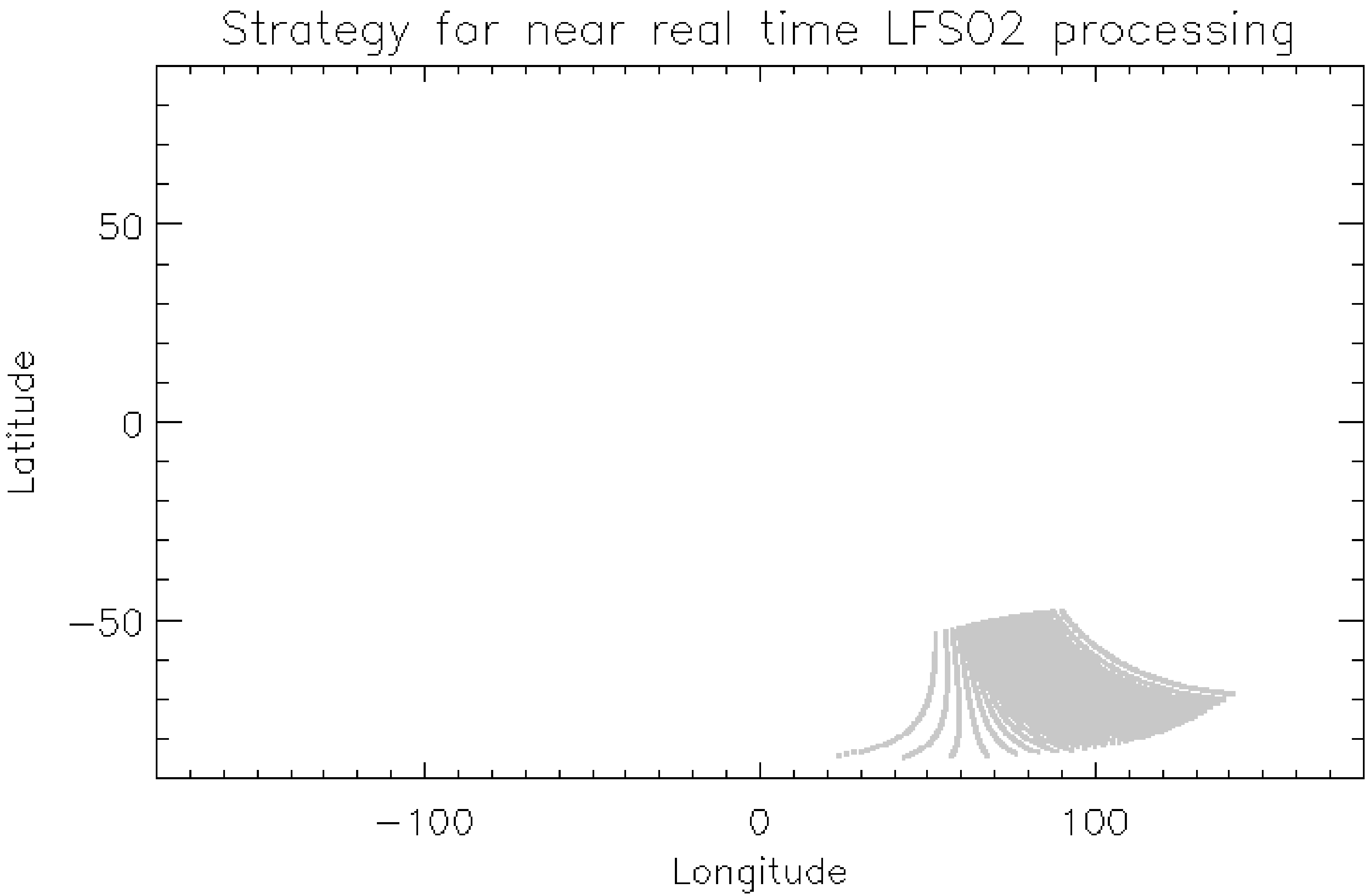
PBL: 0~2km



Umkhr-3: 14.7~19.1km

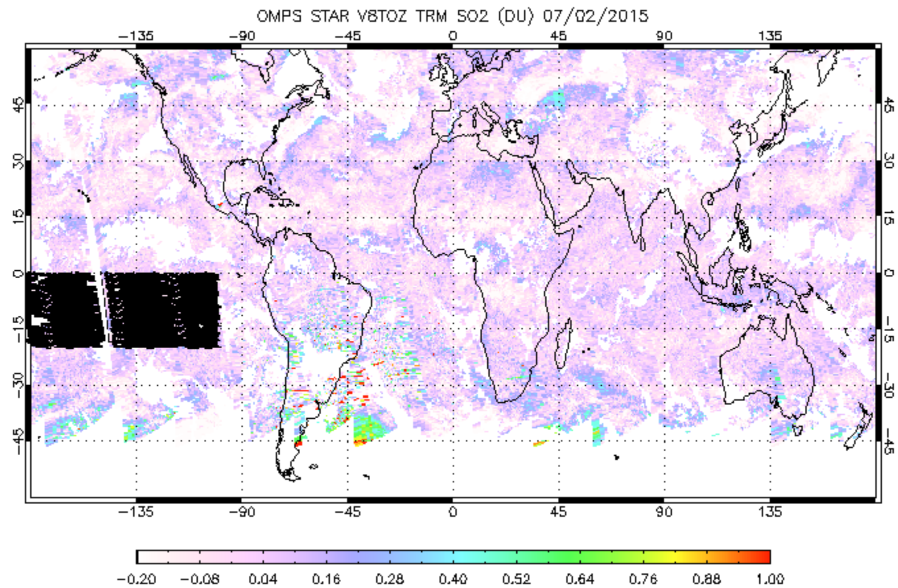


Strategy for running LFSO2



Estimates ***minimum detectable SO_2*** *for single IFOV*

	# IFOV	Average (DU)	STD (DU)
STL	5480	0.0037	0.069
TRM	5480	0.0057	0.09
TRL	5480	0.0125	0.18
PBL	5480	0.0624	0.6



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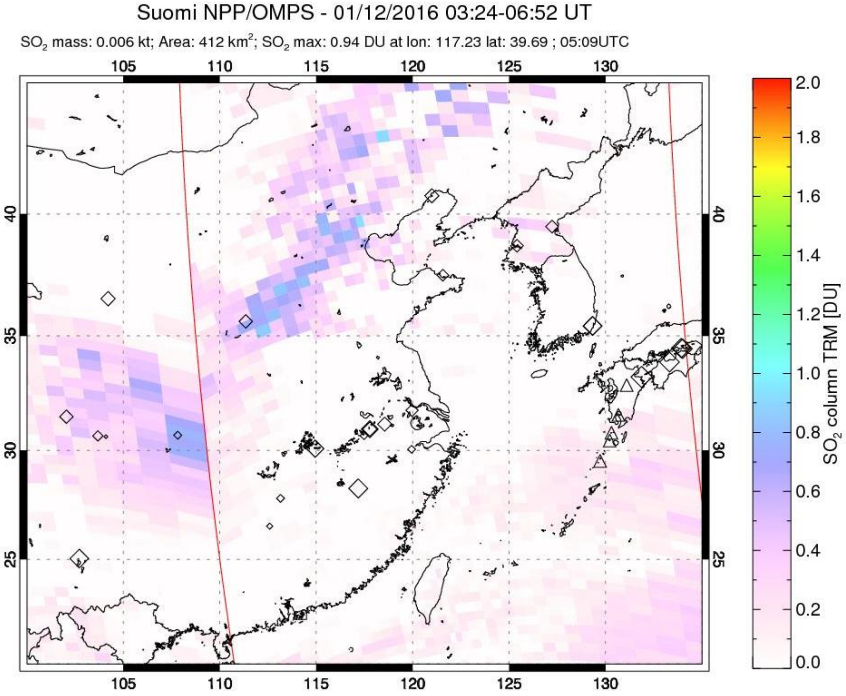
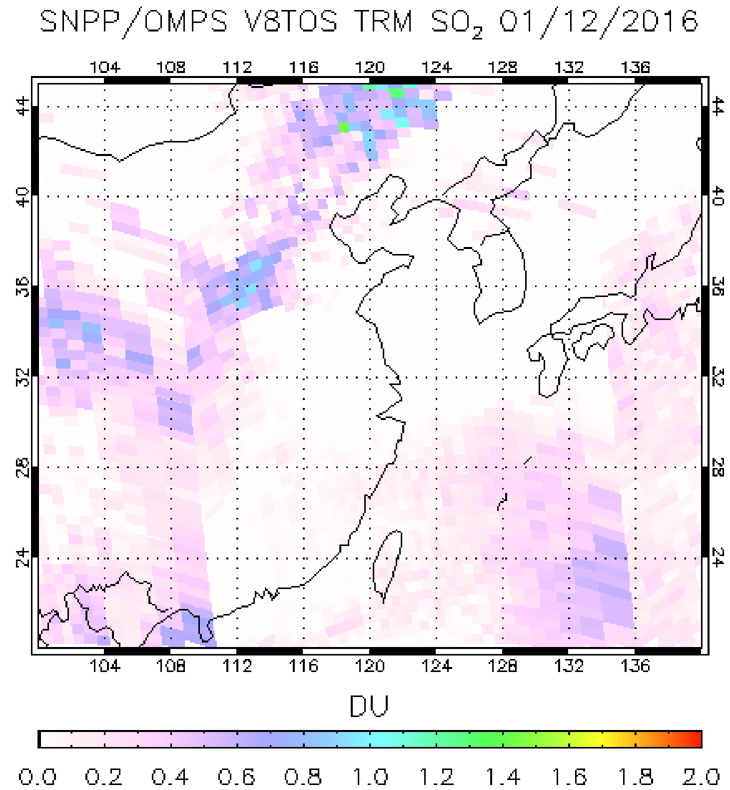
SO_2 in 5~10km (TRM) over East China

From PEATE SO_2 website

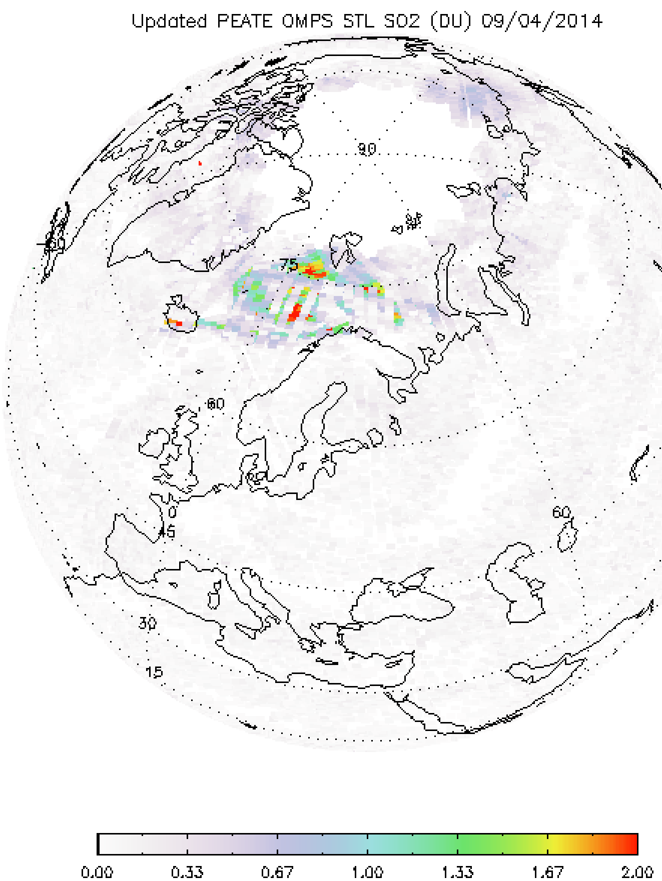


From Star LFSO2

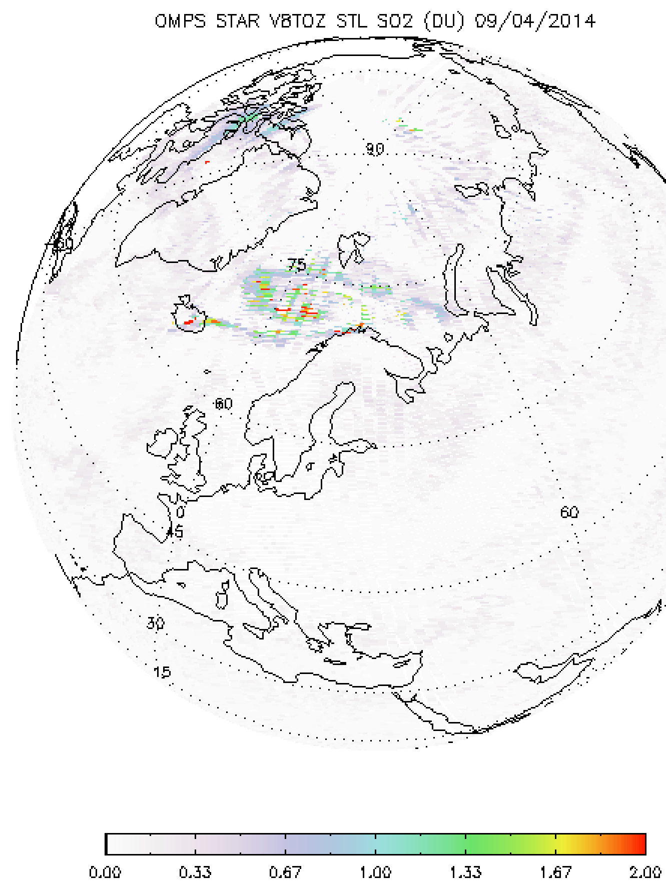


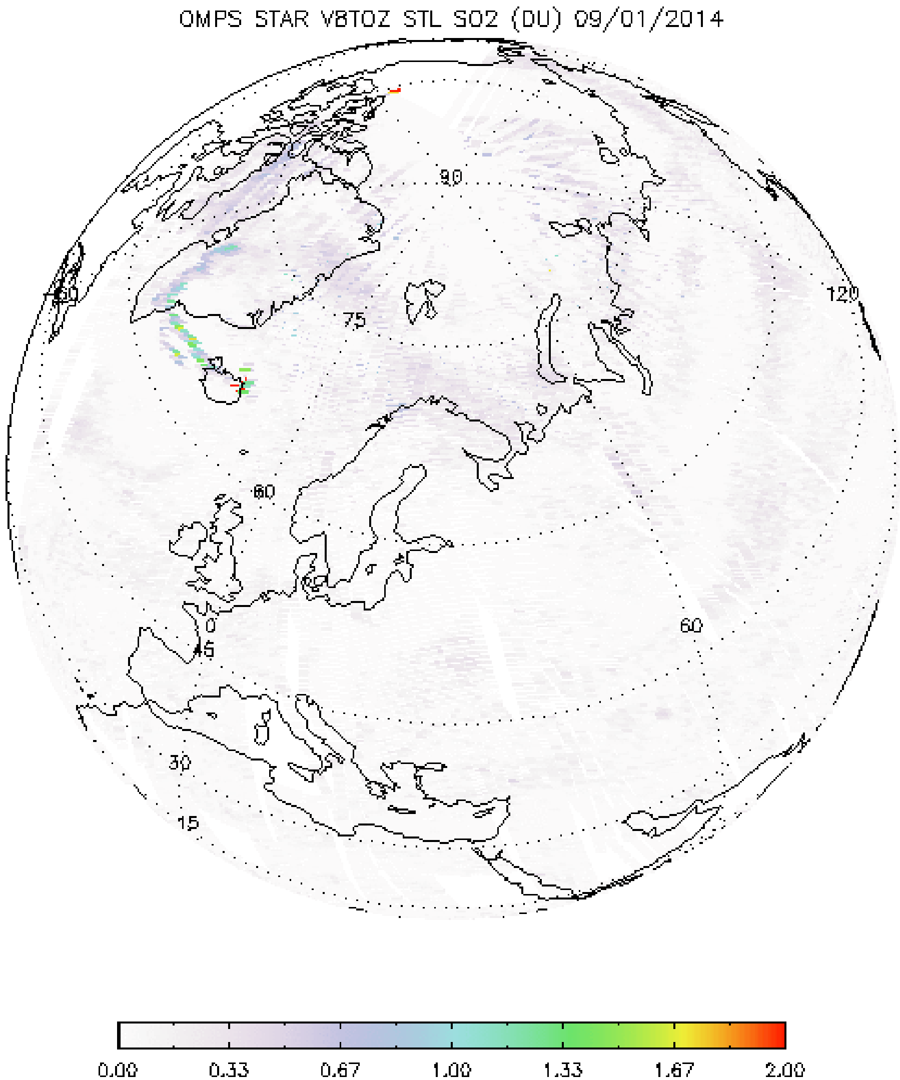
Example-1:
Iceland Bardarbunga volcano eruption

PEATE algorithm's product



STAR products

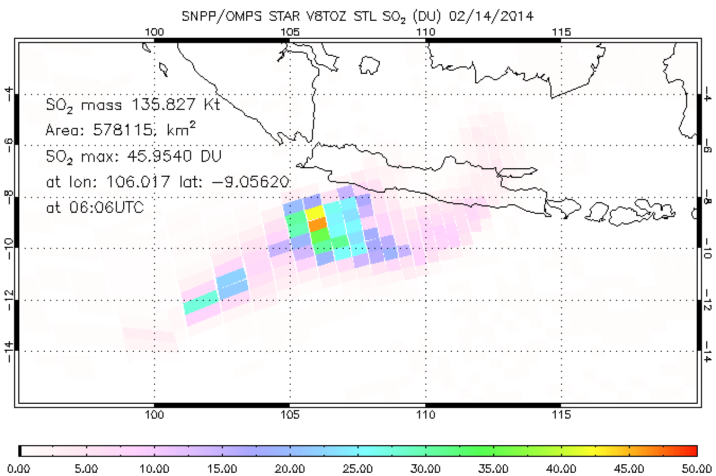




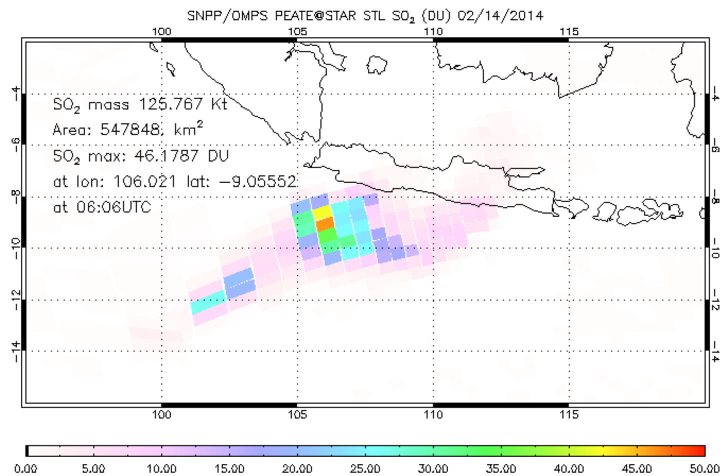
by Jianguo Niu System Research Group Inc.

Example-2: Indonesia Kelud volcano eruption February 14, 2014

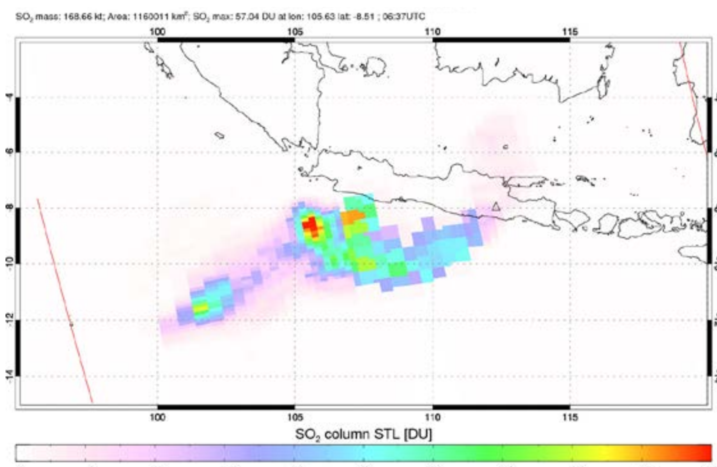
STAR V8+NMSO2



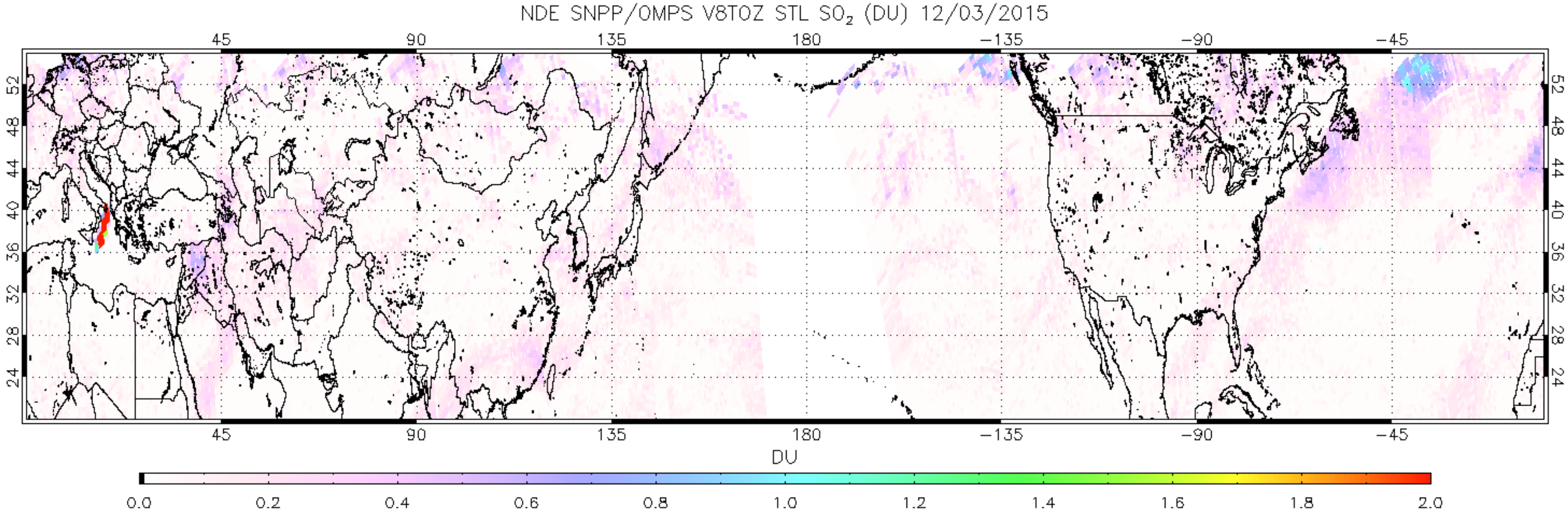
STAR/PEATE updated original



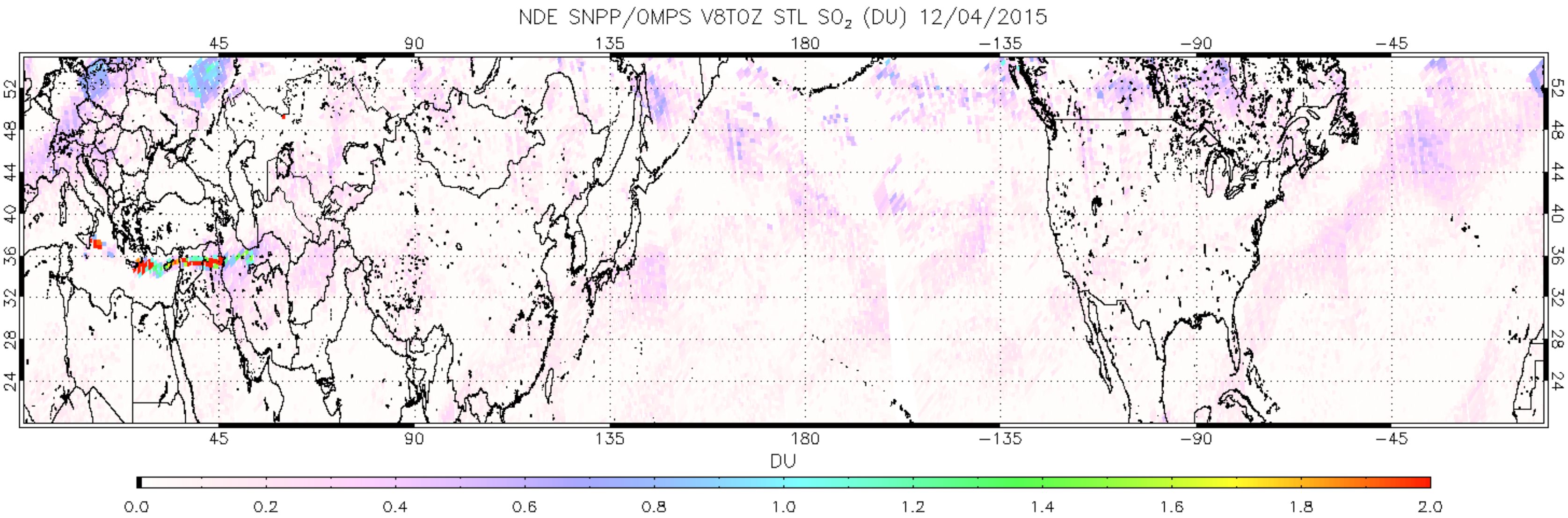
Provided by NASA PEATE →



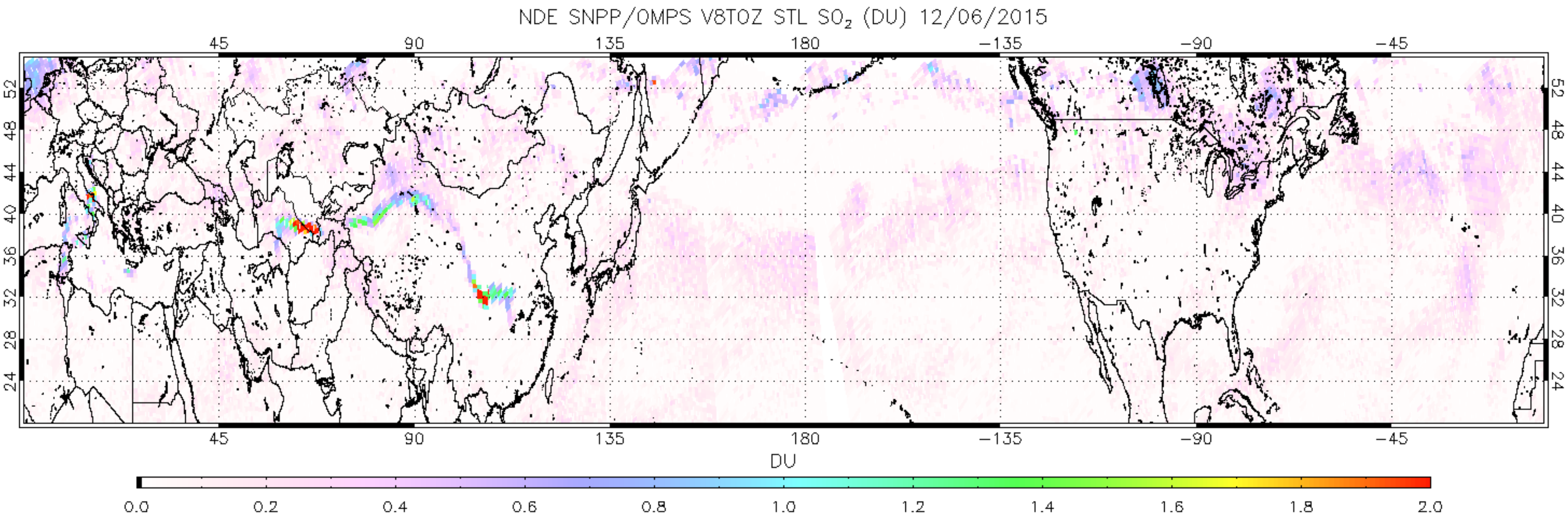
Example 3-1: Sicily Volcano eruption and transportation



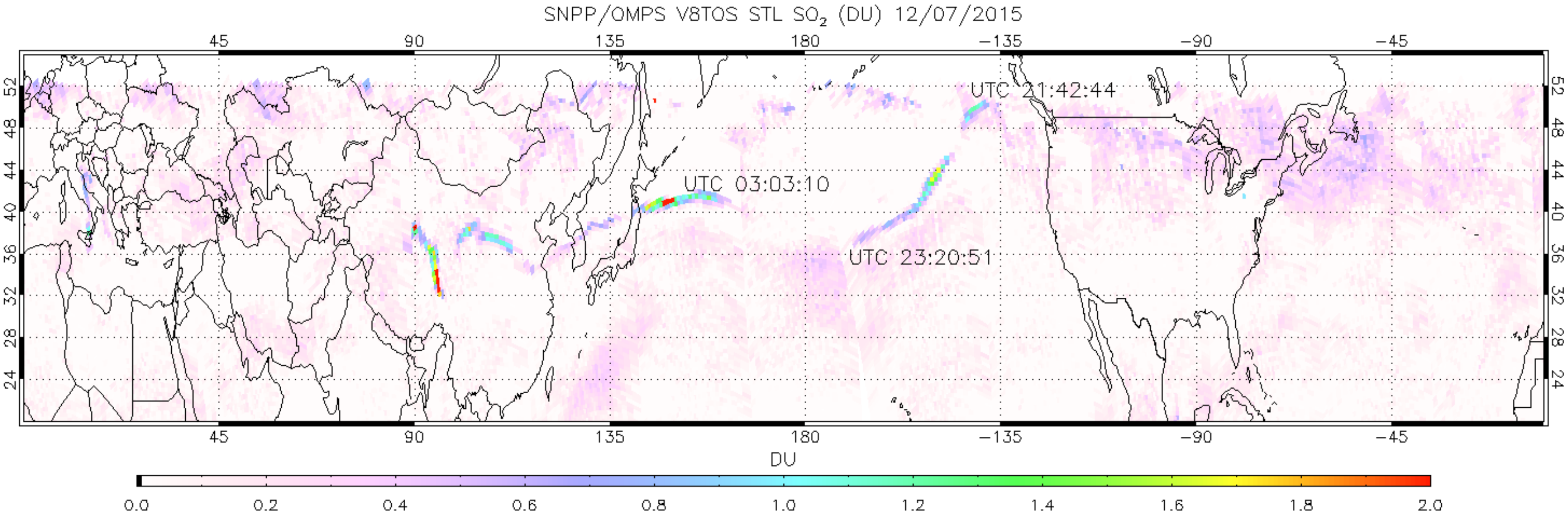
Example 3-2: Sicily Volcano eruption and transportation



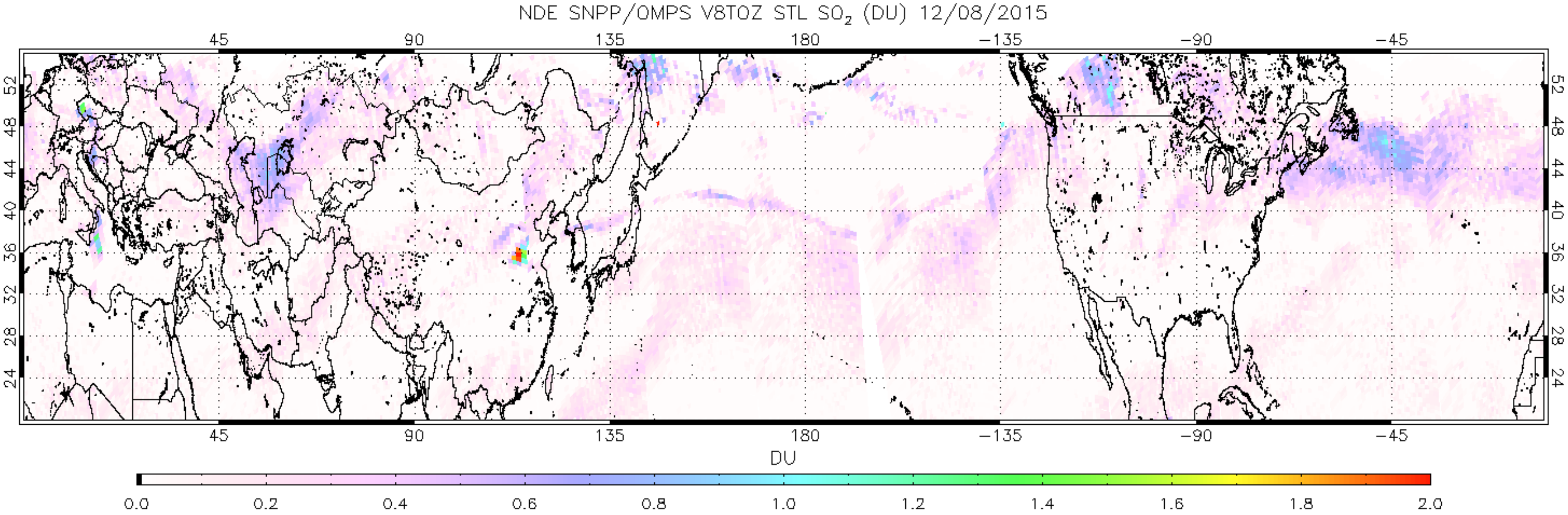
Example 3-3: Sicily Volcano eruption and transportation



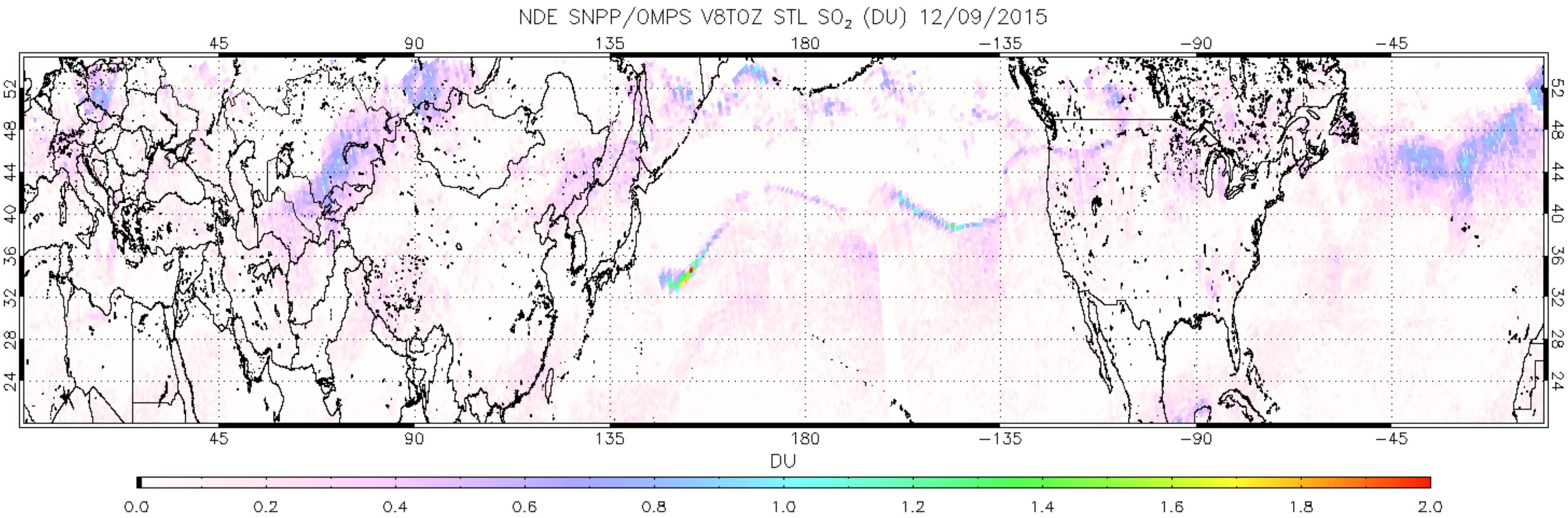
Example 3-4: Sicily Volcano eruption and transportation



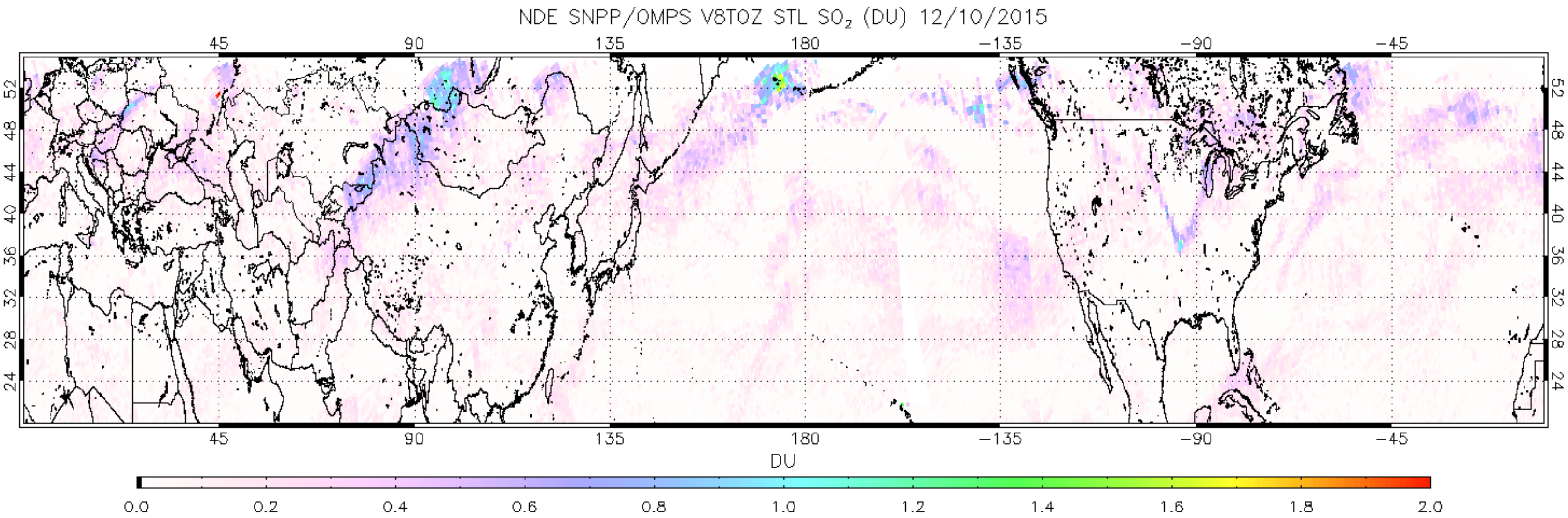
Example 3-5: Sicily Volcano eruption and transportation



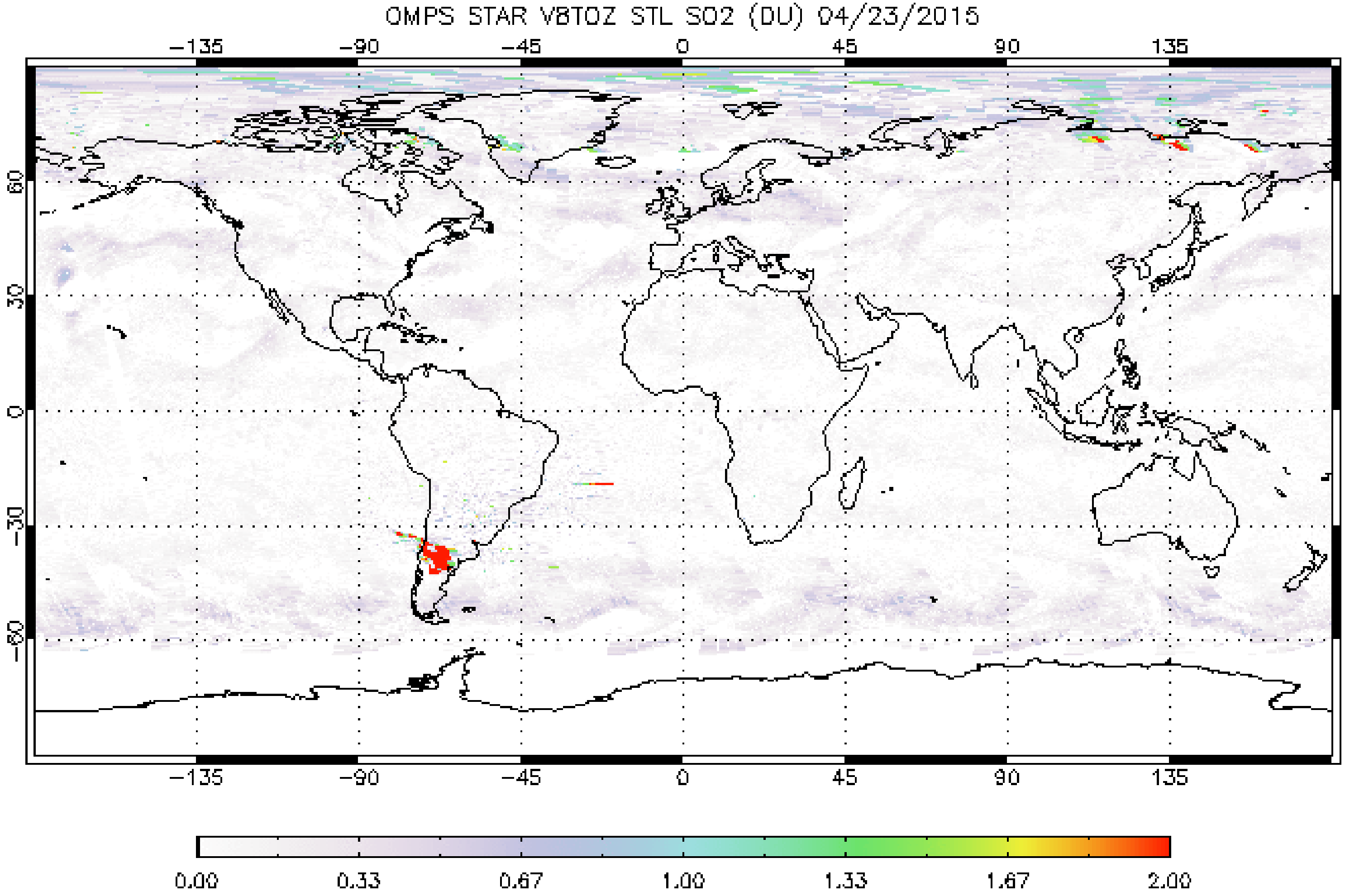
Example 3-6: Sicily Volcano eruption and transportation



Example 3-7: Sicily Volcano eruption and transportation



Example 4: Chile Calbuco volcano 4/23/2015 to 5/04/2015



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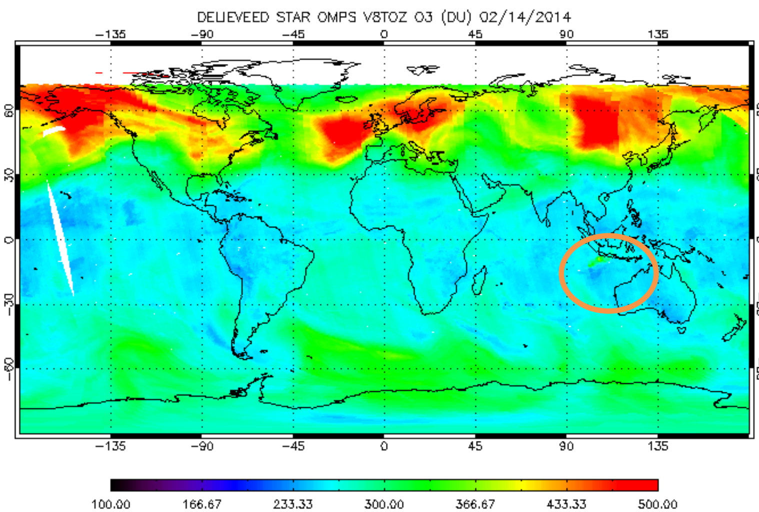
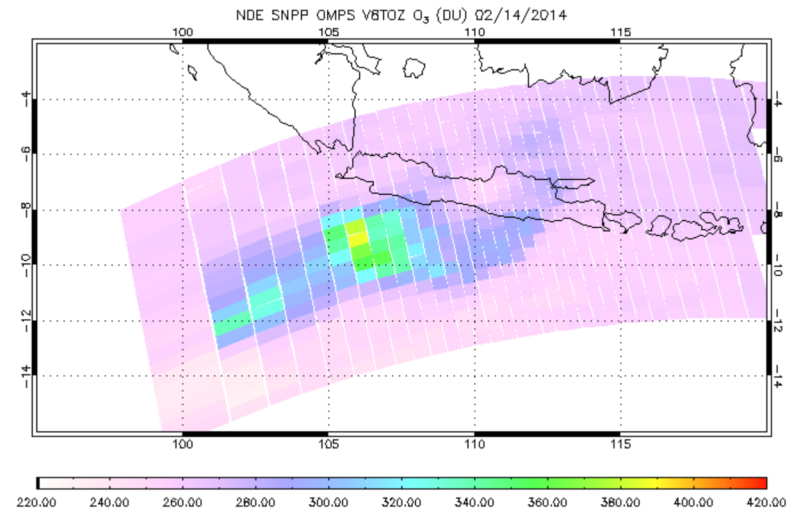
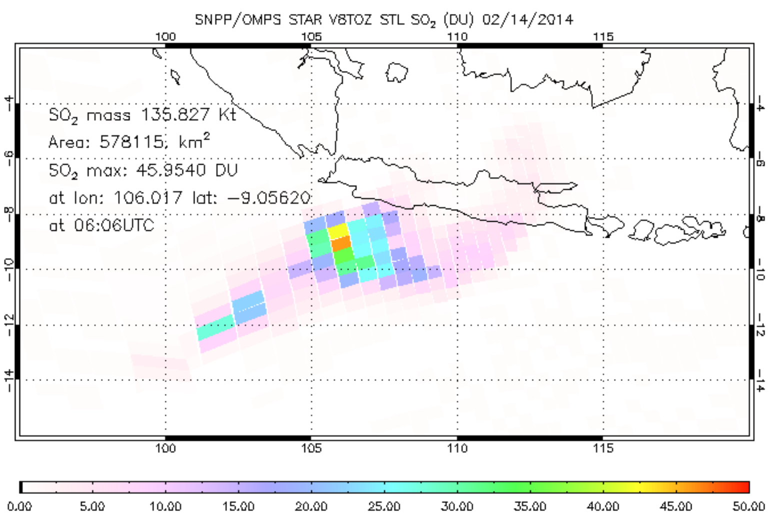
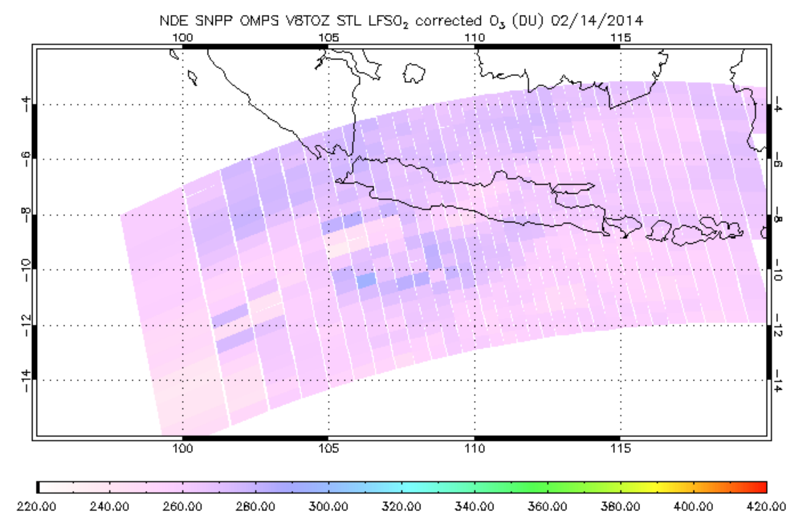
Example-5: Ozone correction by assuming SO_2 in STL for Indonesia Kelud volcano eruption case February 14, 2014









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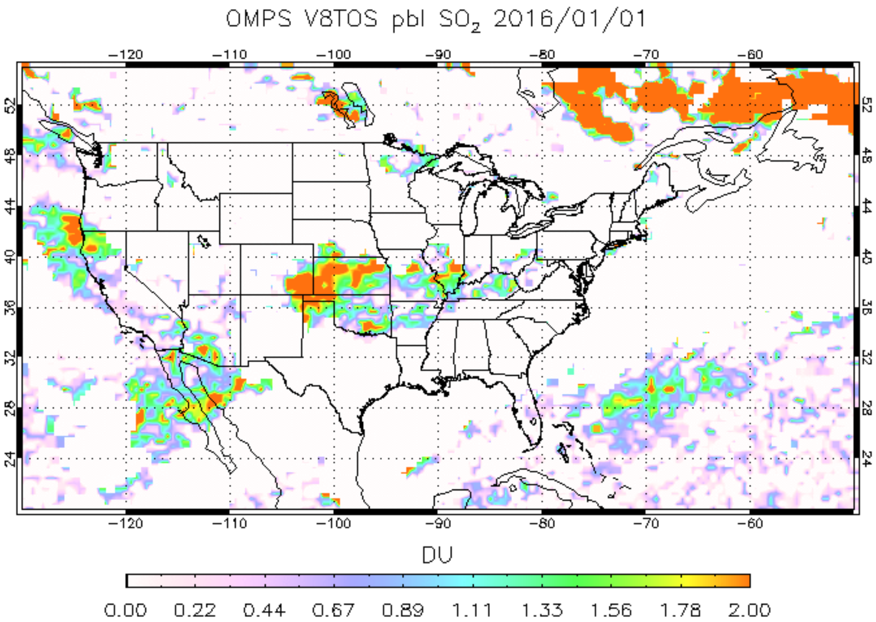
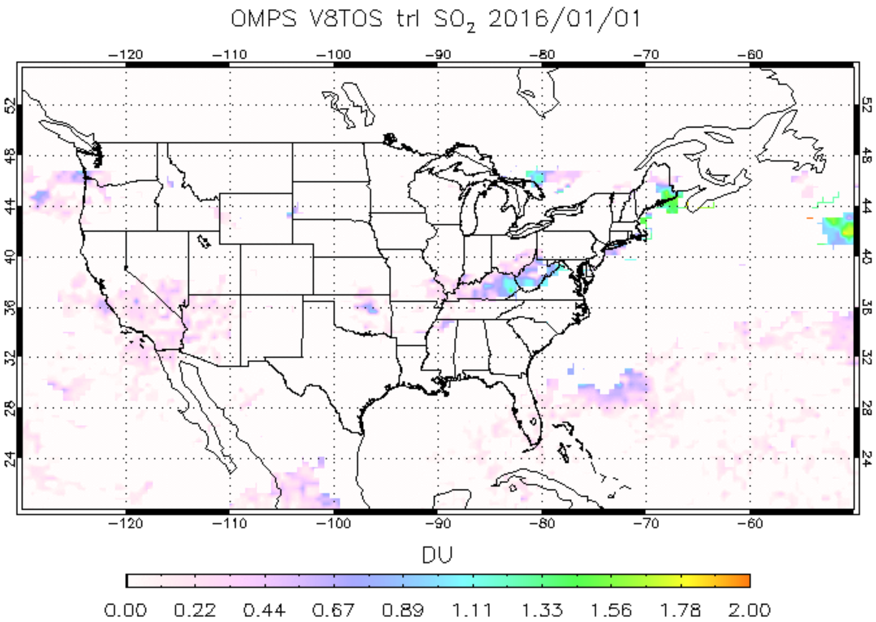
Daily PBL and TRL SO_2 maps over the US January to June 2016





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Summary

1. A 15-granule implementation provide a reliable alert to volcanic SO_2 cloud.

2. LFSO2 retrieval provides a total column O_3 correction when thick SO_2 appears in the atmosphere.

3. Provide accurate SO_2 total column amount for V8TOZ product.

4. Shown that OMPS Nadir Mapper possesses high sensitivity to monitor SO_2 as a pollutant in the atmosphere.

Marco Fulle - www.stromboli.net

Development of multi-sensor SO_2 products for JPSS

Michael J. Pavolonis

Physical Scientist

National Environmental Satellite, Data, and Information Service

Center for Satellite Applications and Research

JPSS Science Team Meeting

11 August 2016

Outline

- Importance of SO_2 monitoring
- Strengths and weaknesses of different satellite measurements
- Measurement integration plan
- Collaboration

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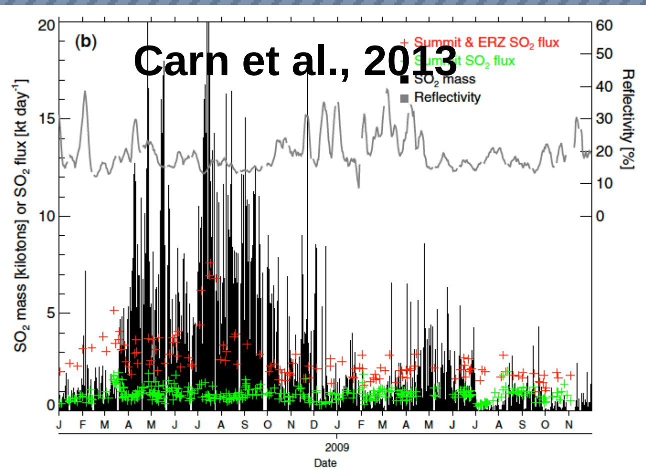
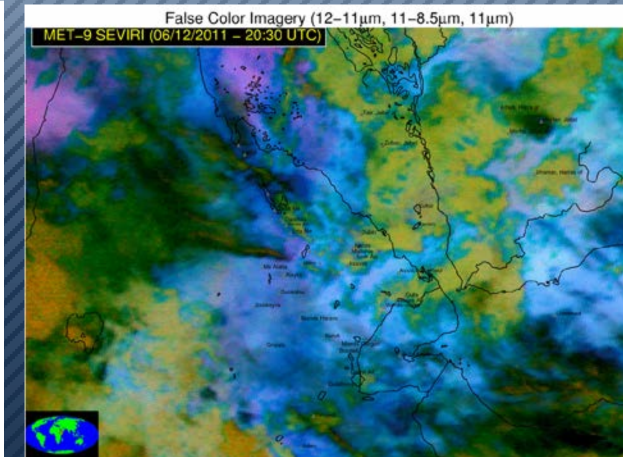
Motivation

Volcano Monitoring

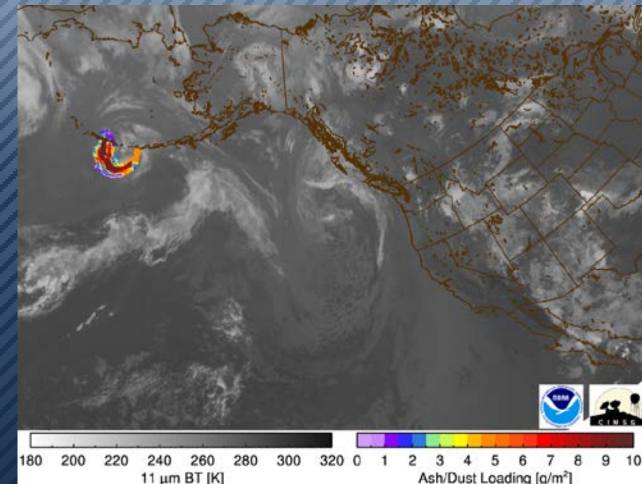


Hazard Avoidance

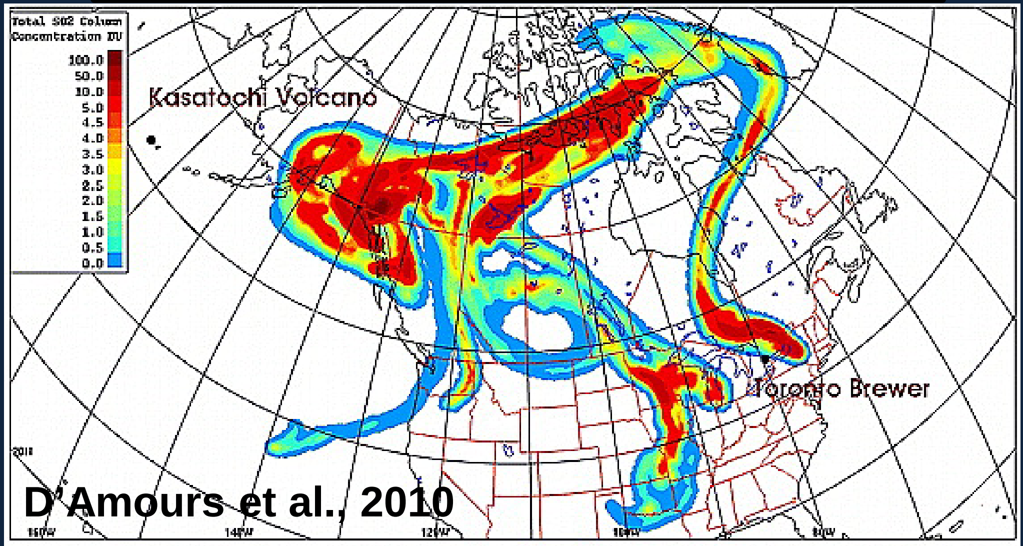


2011 Nabro Eruption

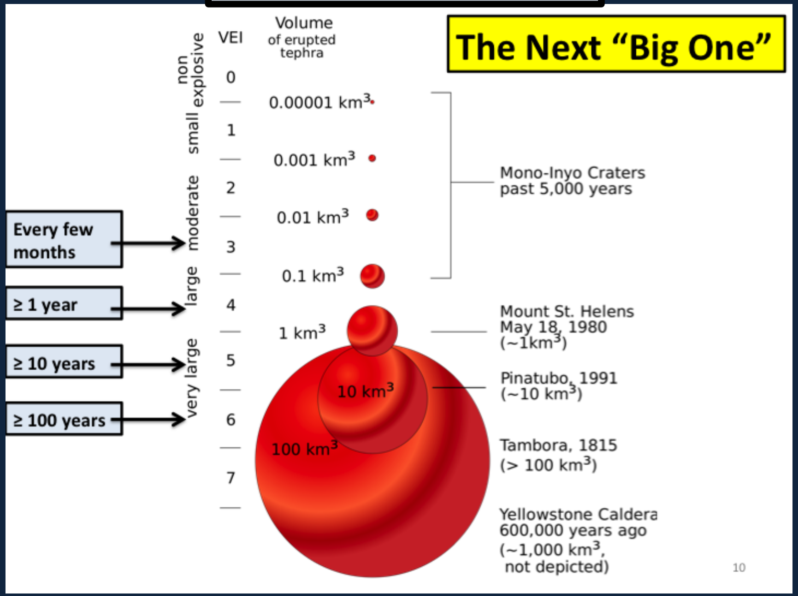
Volcanic Ash Tracking



Dispersion and Transport Modeling



Climate



End Users

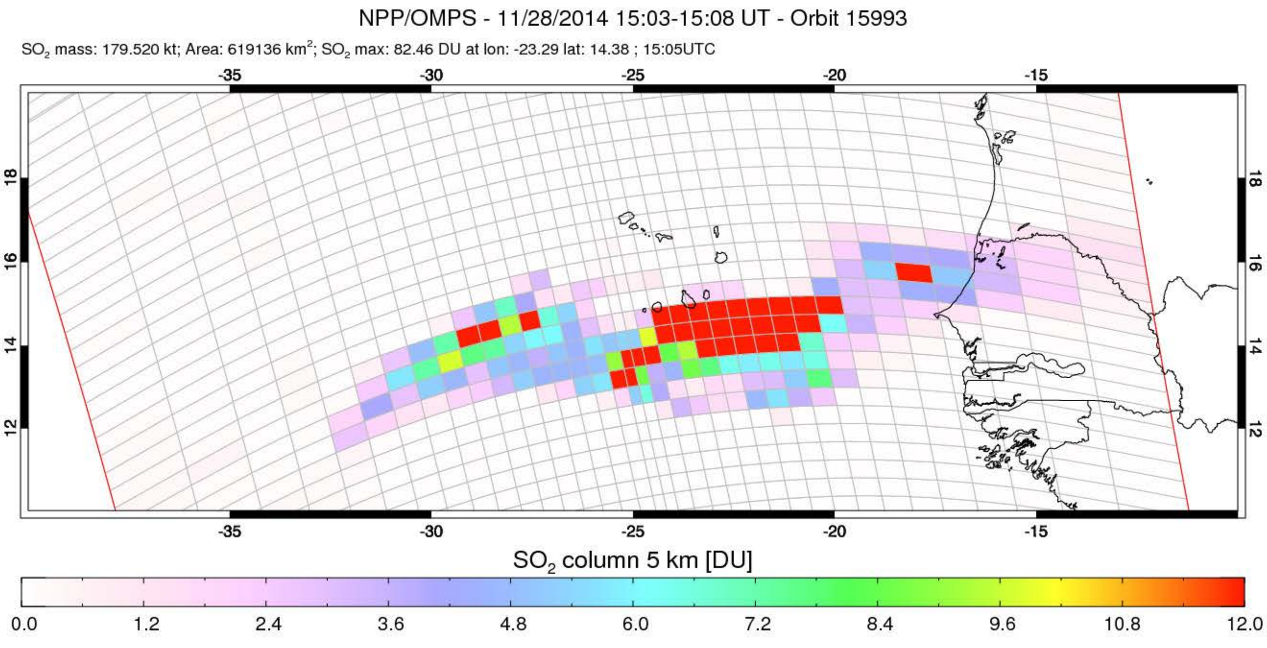
- Volcanic Ash Advisory Centers
- Meteorological Watch Offices
- Weather Forecast Offices
- Volcano Observatories (including the USGS)
- Military
- Operational modeling community (dispersion, weather, and climate)
- Research Community

Outline

- Importance of SO_2 monitoring
- Strengths and weaknesses of different satellite measurements
- Measurement integration plan
- Collaboration

Ultra-Violet (OMPS)

Source: NASA GSFC



Major Strengths:

- **Very sensitive to the presence of SO_2 under many conditions including in the presence of clouds (liquid, ice, and aerosol) and over bright surfaces**

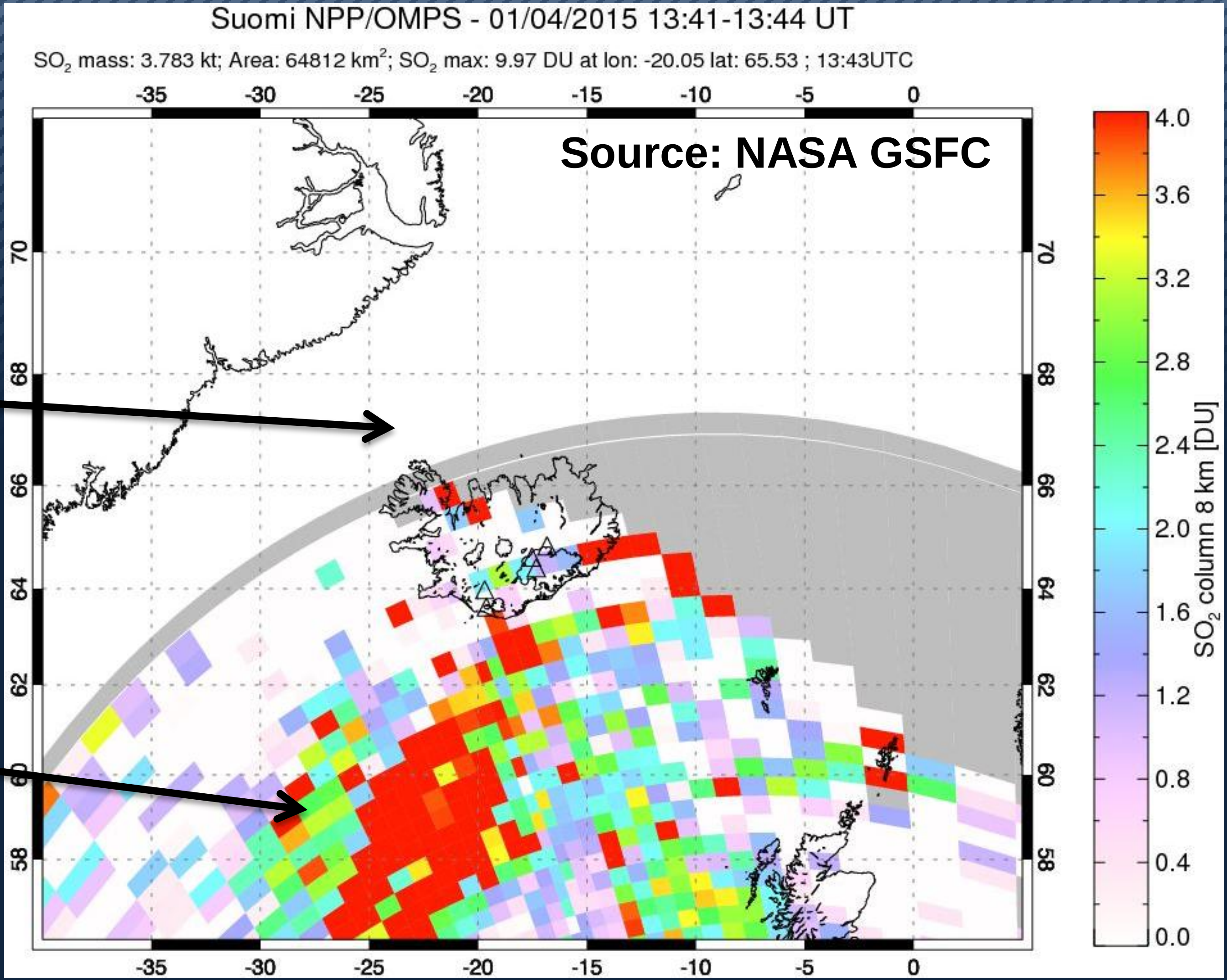
- **Sensitive to SO_2 loading, some sensitivity to SO_2 height**

Ultra-Violet (OMPS)

Weakness: Sensitive to solar zenith angle

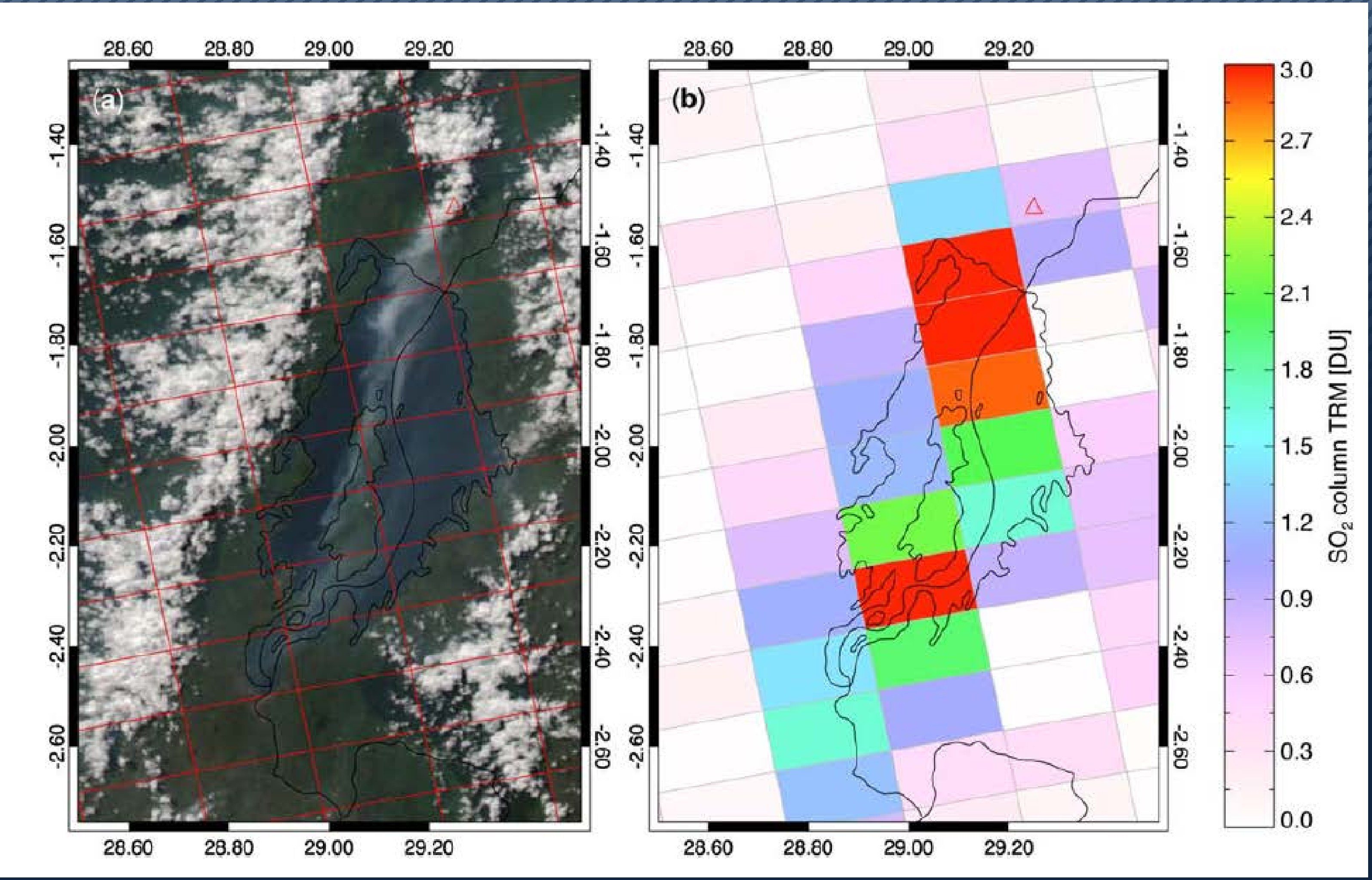
No information when SZA > 90º

Increased noise as SZA increases to 90º



Ultra-Violet (OMPS)

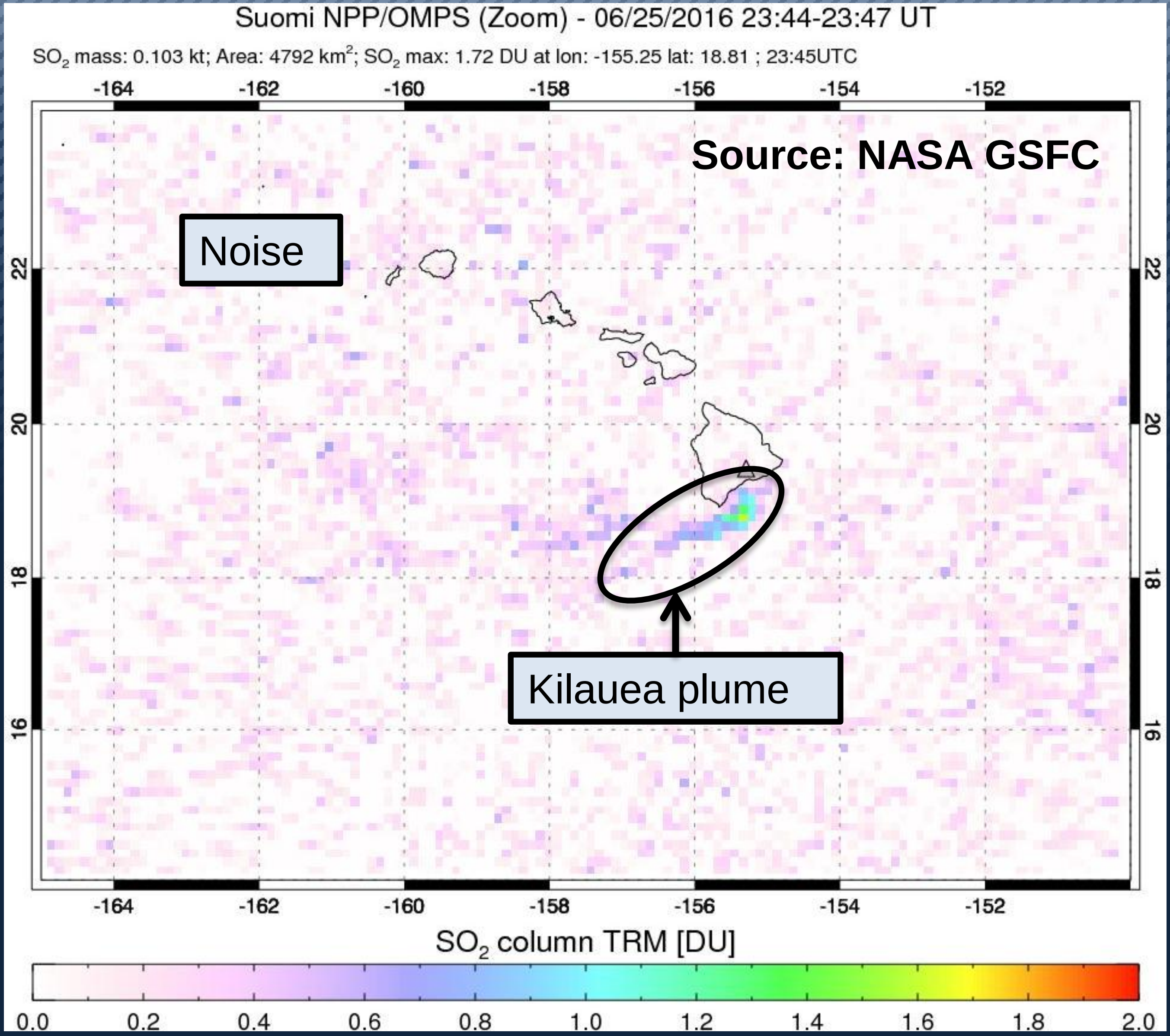
Weakness: Large footprint size relative to spatial scale of many SO_2 plumes



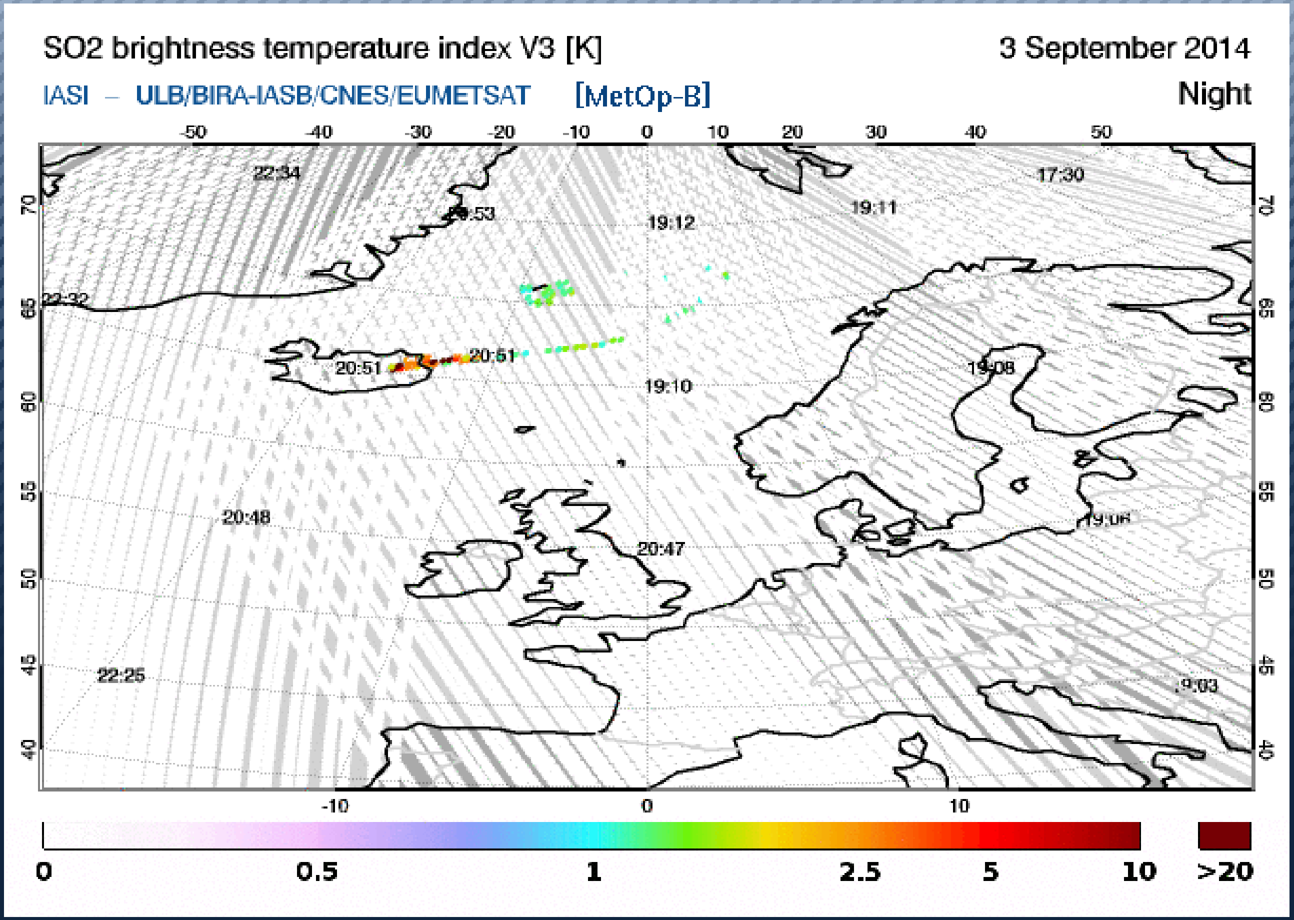
Carn et al., 2013

Ultra-Violet (OMPS)

Weakness: Noise



Hyperspectral Infrared (CrIS)

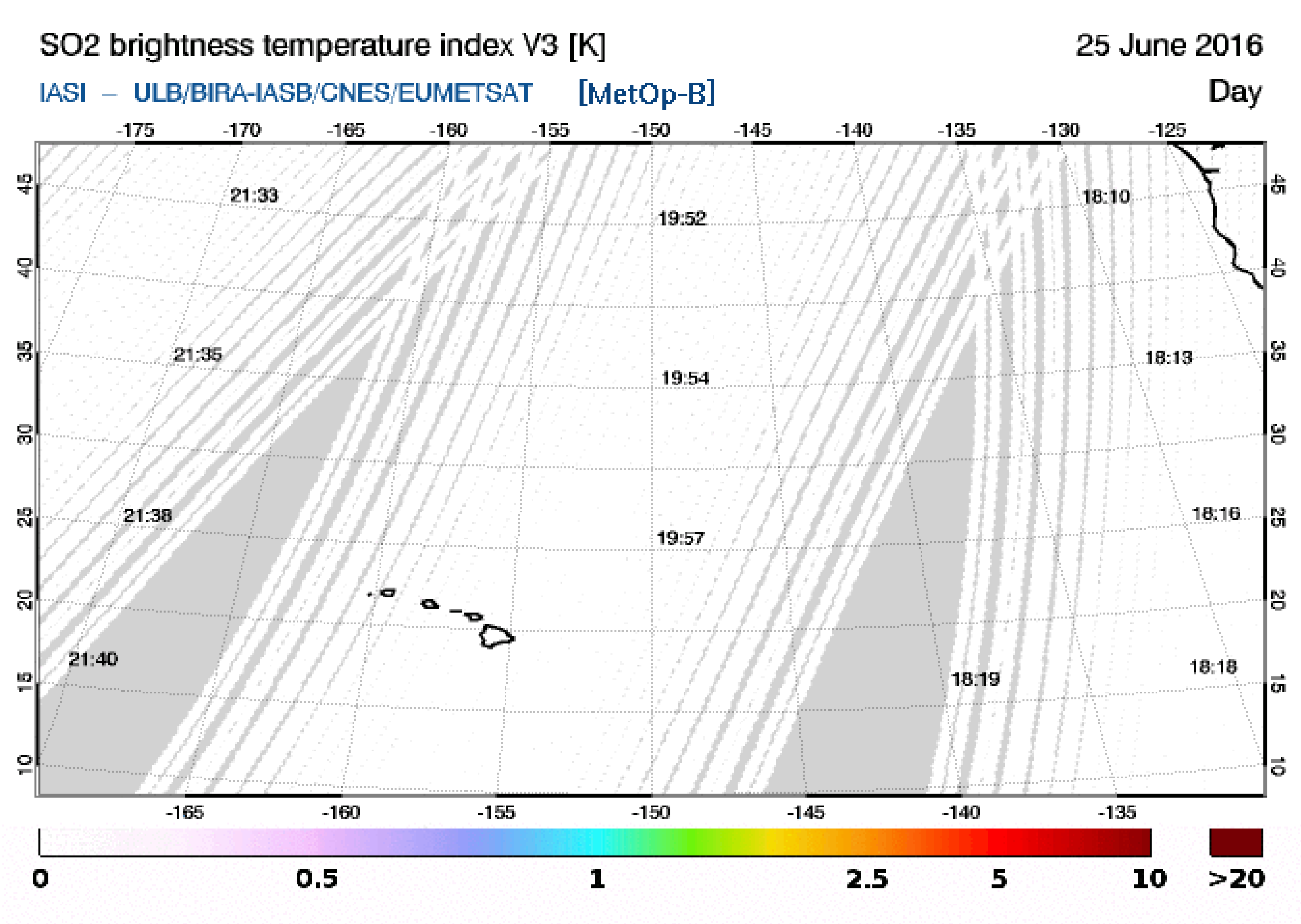


Major Strengths:

- **Provides information on SO_2 day and night**
- **Provides sensitivity to SO_2 loading and height**

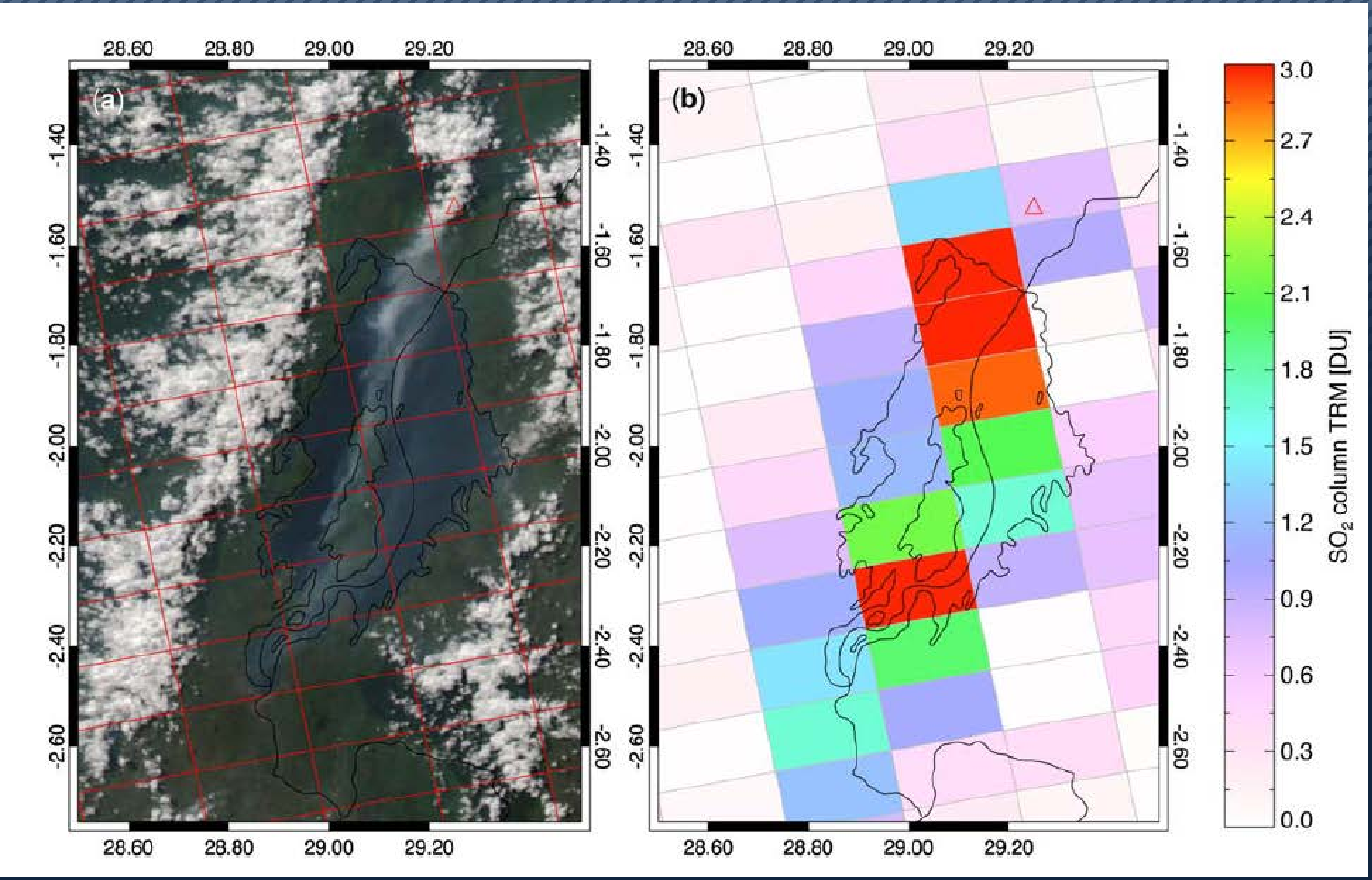
Hyperspectral Infrared (CrIS)

Weakness: Less sensitive to lower tropospheric SO_2



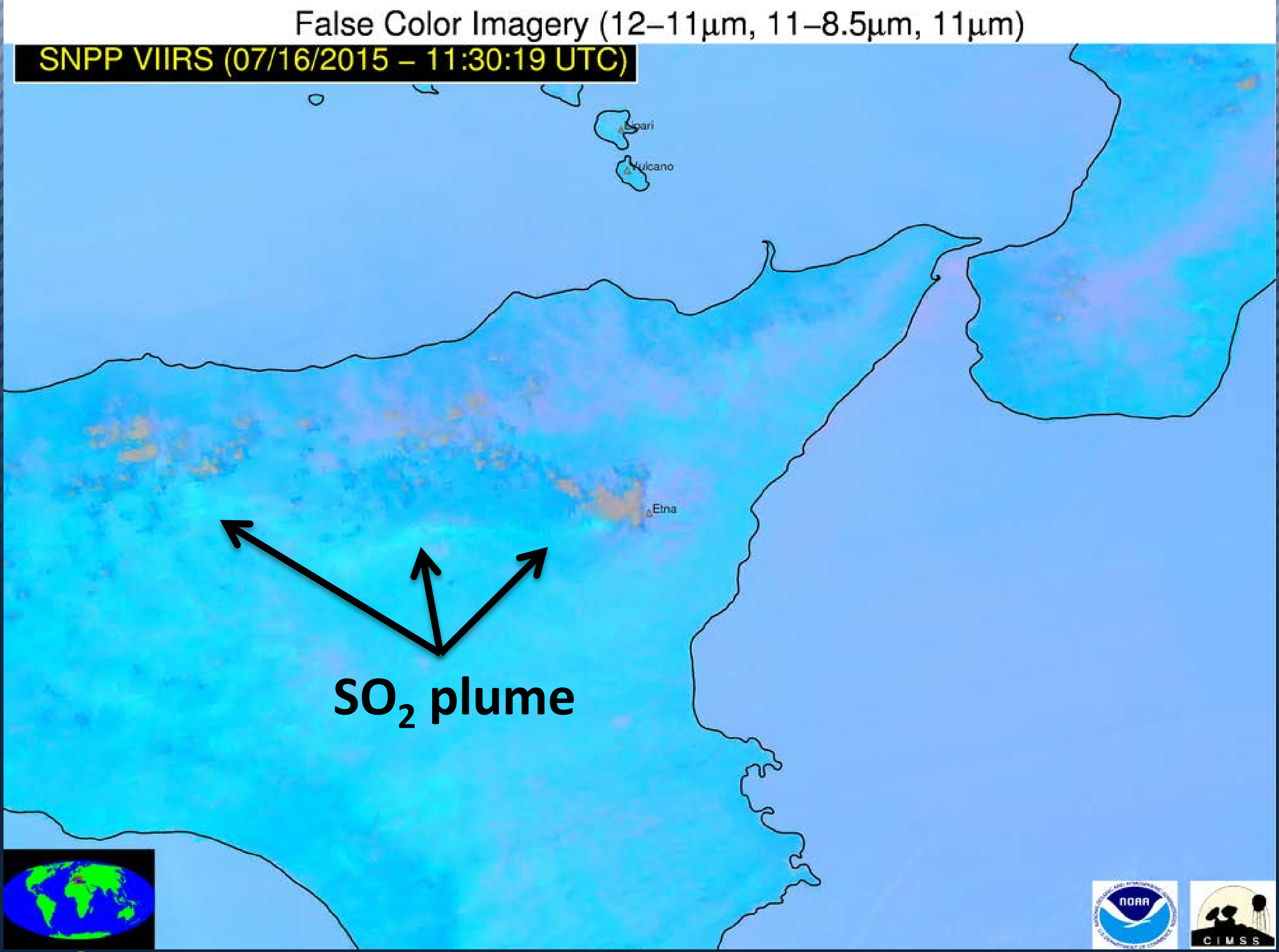
Hyperspectral Infrared (CrIS)

Weakness: Large footprint size relative to spatial scale of many SO_2 plumes



Carn et al., 2013

Narrow-band Imager (VIIRS)

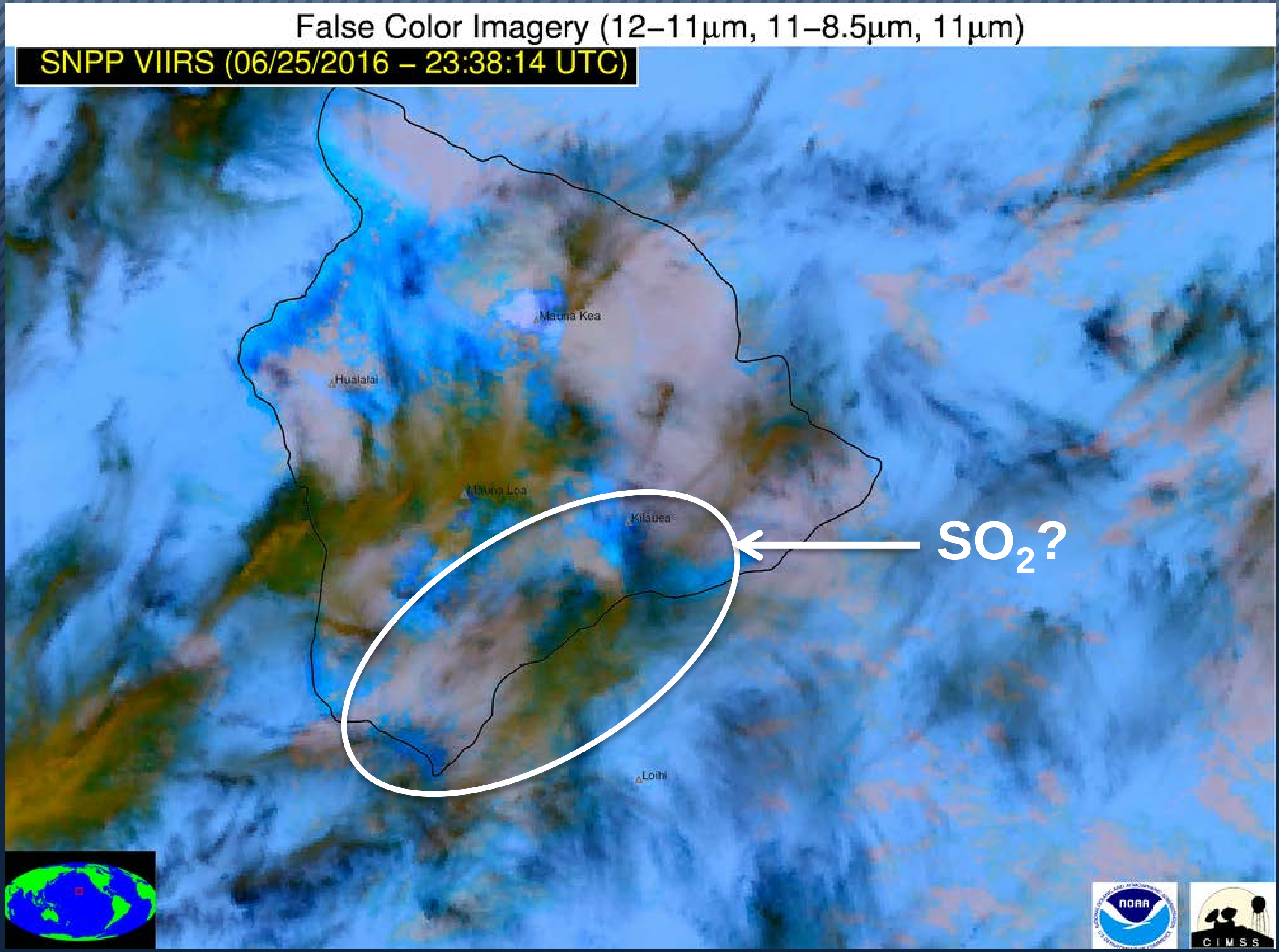


Major Strengths:

- **Provides high spatial resolution imagery of SO_2 clouds and plumes under many conditions day and night.**

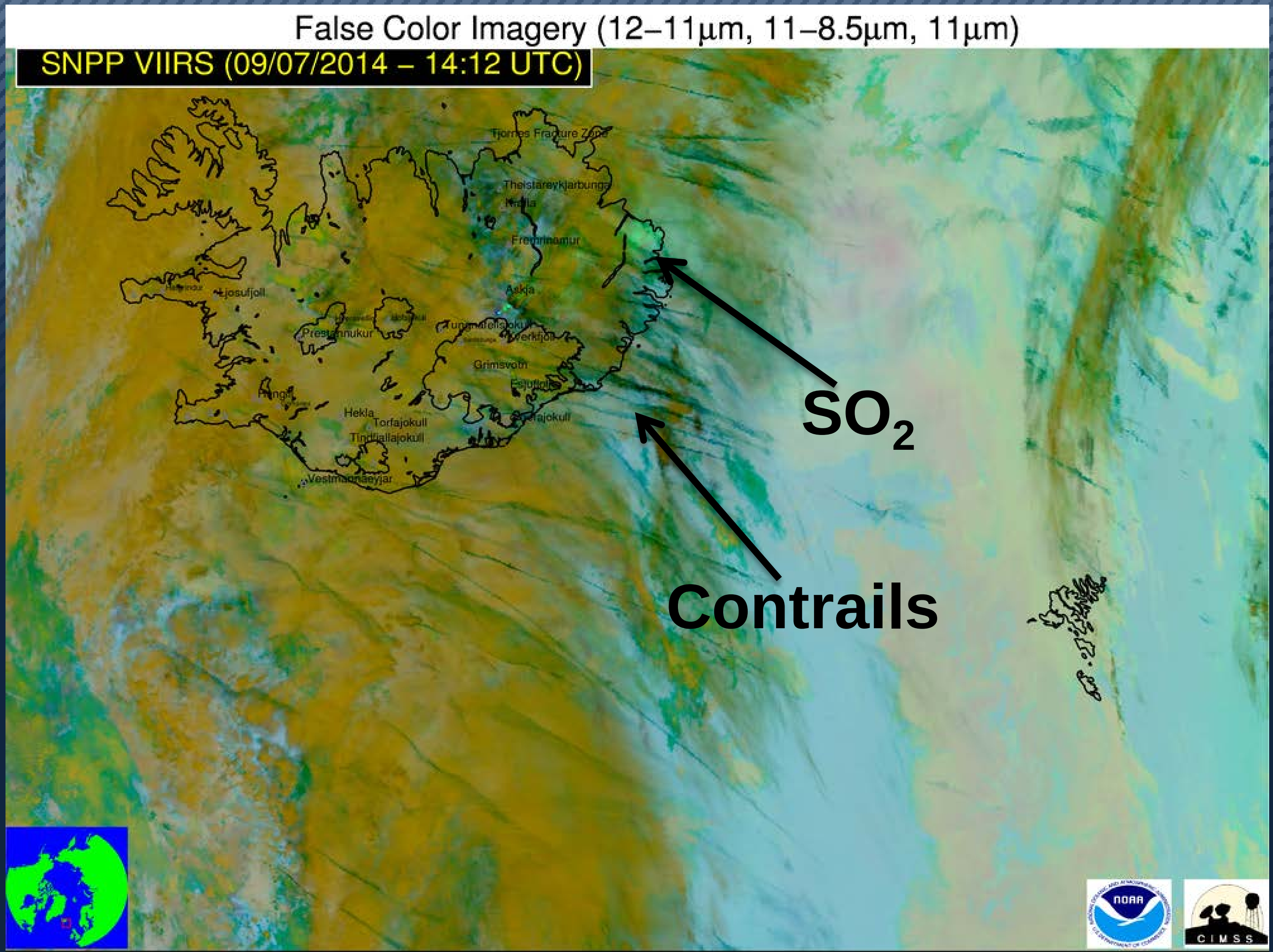
Narrow-band Imager (VIIRS)

Weakness: Larger lower limit of detection, especially in the presence of clouds

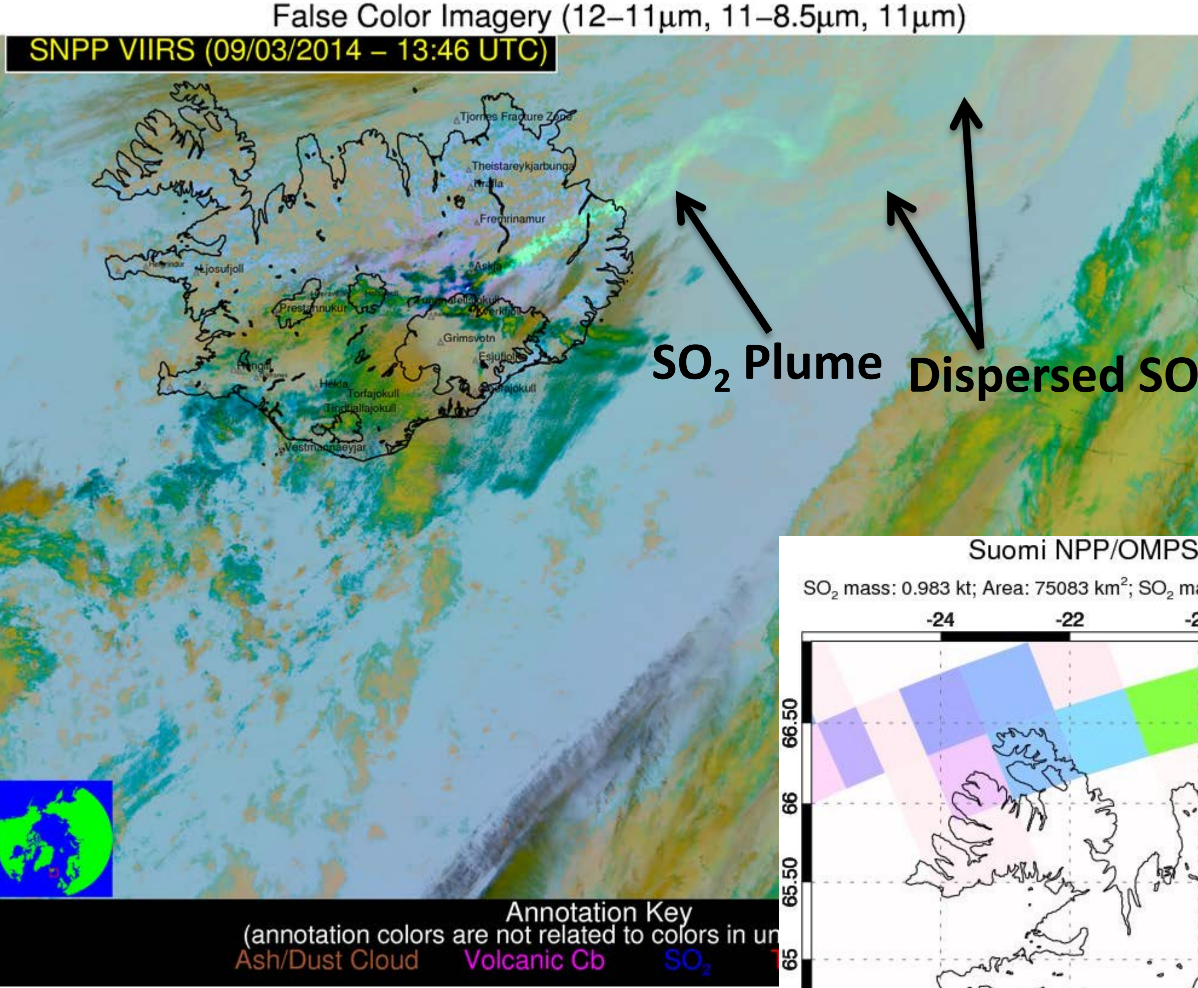


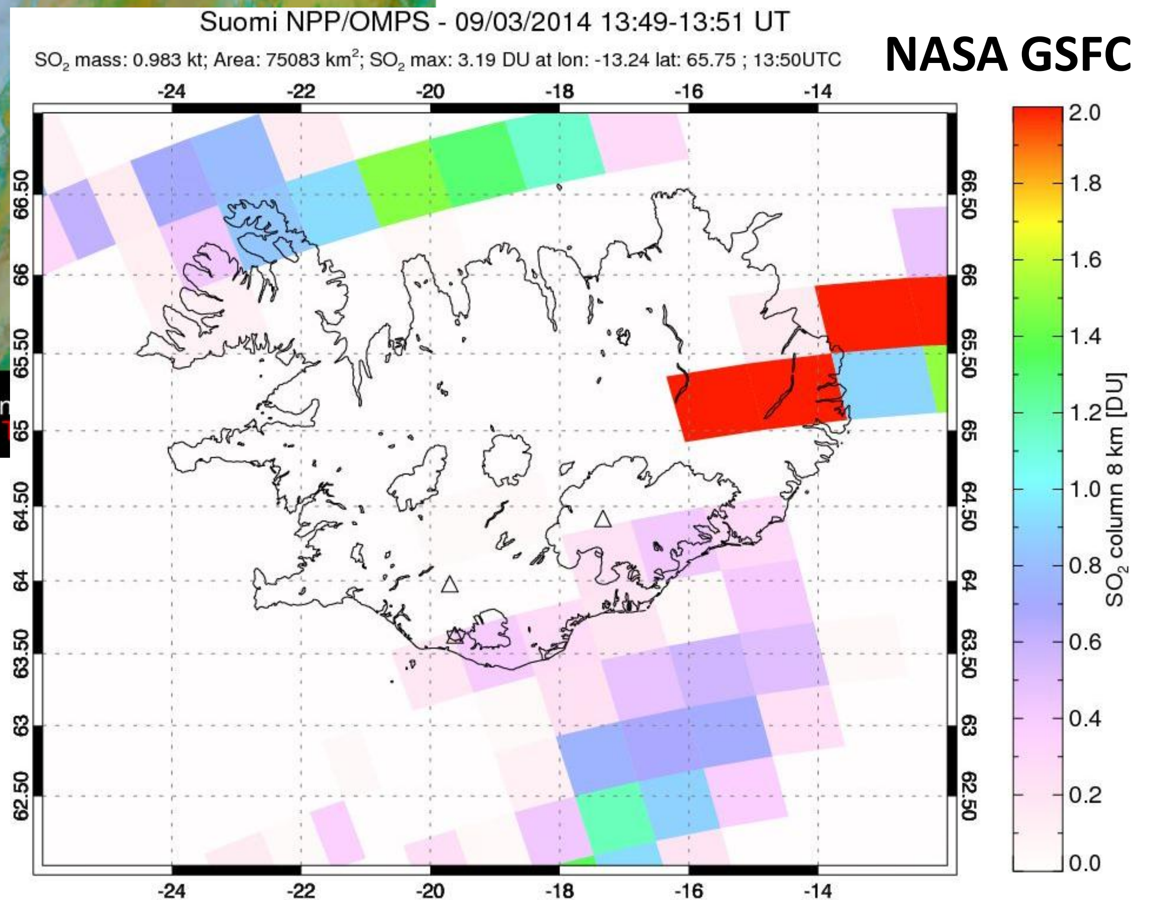
Narrow-band Imager (VIIRS)

Weakness: Challenging to extract quantitative information without additional constraints



A multi-sensor SO_2 analysis is needed





Outline

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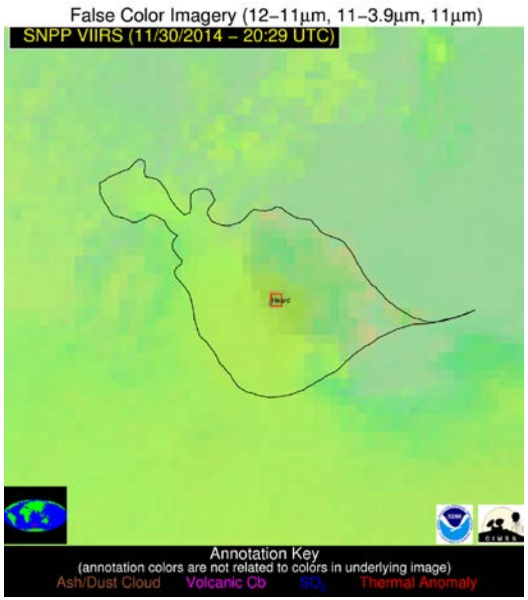
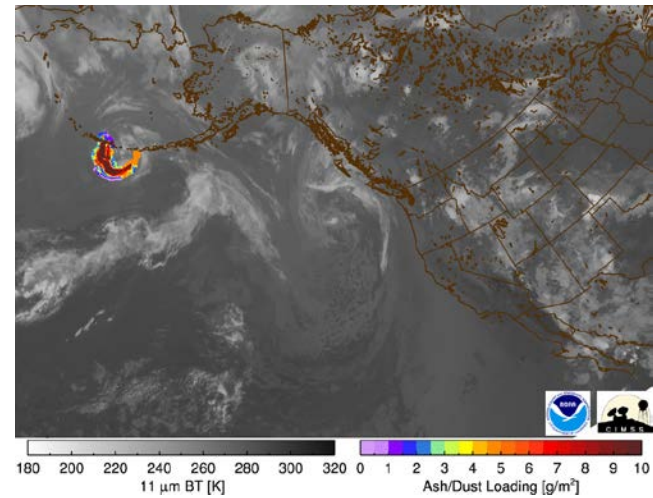
VOLcanic Cloud Analysis Toolkit (VOLCAT)

1). Unrest Alerts

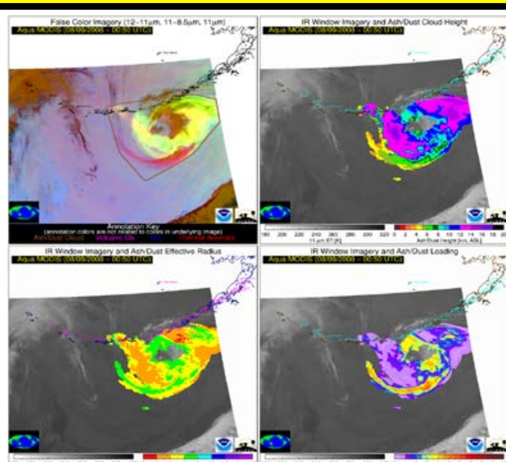


2). Eruption Alerts

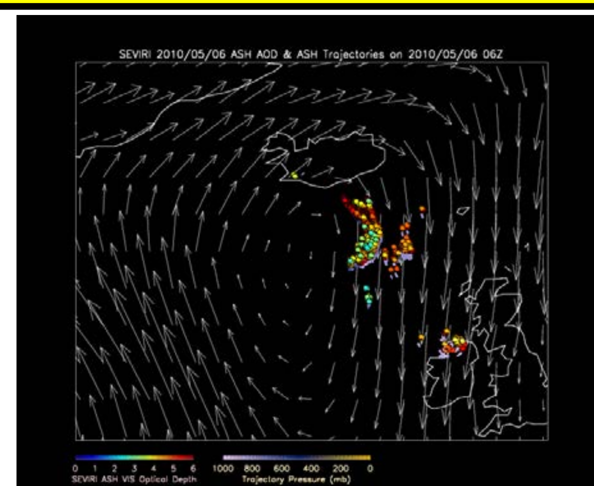
3). Volcanic Cloud Tracking



4). Volcanic Cloud Characterization



5). Dispersion Forecasting



Spectrally Enhanced Cloud Objects (SECO) Method for SO_2 Detection

- Automatically extract coherent SO_2features from OMPS and CrIS using cloud object analysis

- Construct an *a priori* probability from OMPS and CrIS and utilize it in VIIRS implementation of SECO method

- Final SO_2 detection results are at the VIIRS resolution and are overlaid on VIIRS imagery

- The fused JPSS SO_2 detection results can then be used to aid in SO_2 detection and tracking from GEO satellites

SO_2 Retrieval Options

- Utilize existing OMPS SO_2 loading products
- A variation on published methods (e.g. NUCAPS, Carboni et al. 2012; Clarisse et al., 2014) will be used to retrieve SO_2 loading and effective height from CrIS
- Optimal estimation readily allows the results from one sensor to influence another through the *a priori*. Thus, the result from OMPS or CrIS, which ever is deemed to be of higher quality, can be used to constrain the VIIRS retrieval, while allowing for small-scale spatial variability to be captured
- Many details TBD – this is R&D, not manufacturing!

References

- Pavolonis, M. J., W. F. Feltz, A. K. Heidinger, and G. M. Gallina, 2006: A daytime complement to the reverse absorption technique for improved automated detection of volcanic ash. J.Atmos.Ocean.Technol., **23**, 1422-1444.

- Pavolonis, M. J., 2010: Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances-A Robust Alternative to Brightness Temperatures. Part I: Theory. Journal of Applied Meteorology and Climatology, **49**, 1992-2012, doi:10.1175/2010JAMC2433.1 ER.

- Pavolonis, M., A. Heidinger, and J. Sieglaff, 2013: Automated retrievals of volcanic ash and dust cloud properties from upwelling infrared measurements, J. Geophysical Research, **118(3)**, 1436-1458.

- Pavolonis, M., J. Sieglaff, and J. Cintineo (2015a), Spectrally Enhanced Cloud Objects (SECO): A Generalized Framework for Automated Detection of Volcanic Ash and Dust Clouds using Passive Satellite Measurements, Part I: Multispectral Analysis, Journal Geophysical Research, **120**, 7813-7841.

- Pavolonis, M., J. Sieglaff, and J. Cintineo (2015b) Spectrally Enhanced Cloud Objects (SECO): A Generalized Framework for Automated Detection of Volcanic Ash and Dust Clouds using Passive Satellite Measurements, Part II: Cloud Object Analysis and Global Application, Journal Geophysical Research, **120**, 7842-7870.

Outline

- Importance of SO_2 monitoring
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Collaborations

- Fusing information from many sensors is challenging. Collaborations with hyperspectral UV and IR SO_2 remote sensing groups at NASA and in academia are needed.

- In addition, a collaborative effort with the USGS, academia, and international partners (e.g. IMO) is needed to validate the fused JPSS SO_2 analysis.

- International collaboration is needed to work towards best practices for combining measurements from multiple satellite sensors – connection to WMO SCOPE-Nowcasting.

- Collaboration with the dispersion, weather, and climate modeling communities are critical to ensure that the impact of the information is maximized

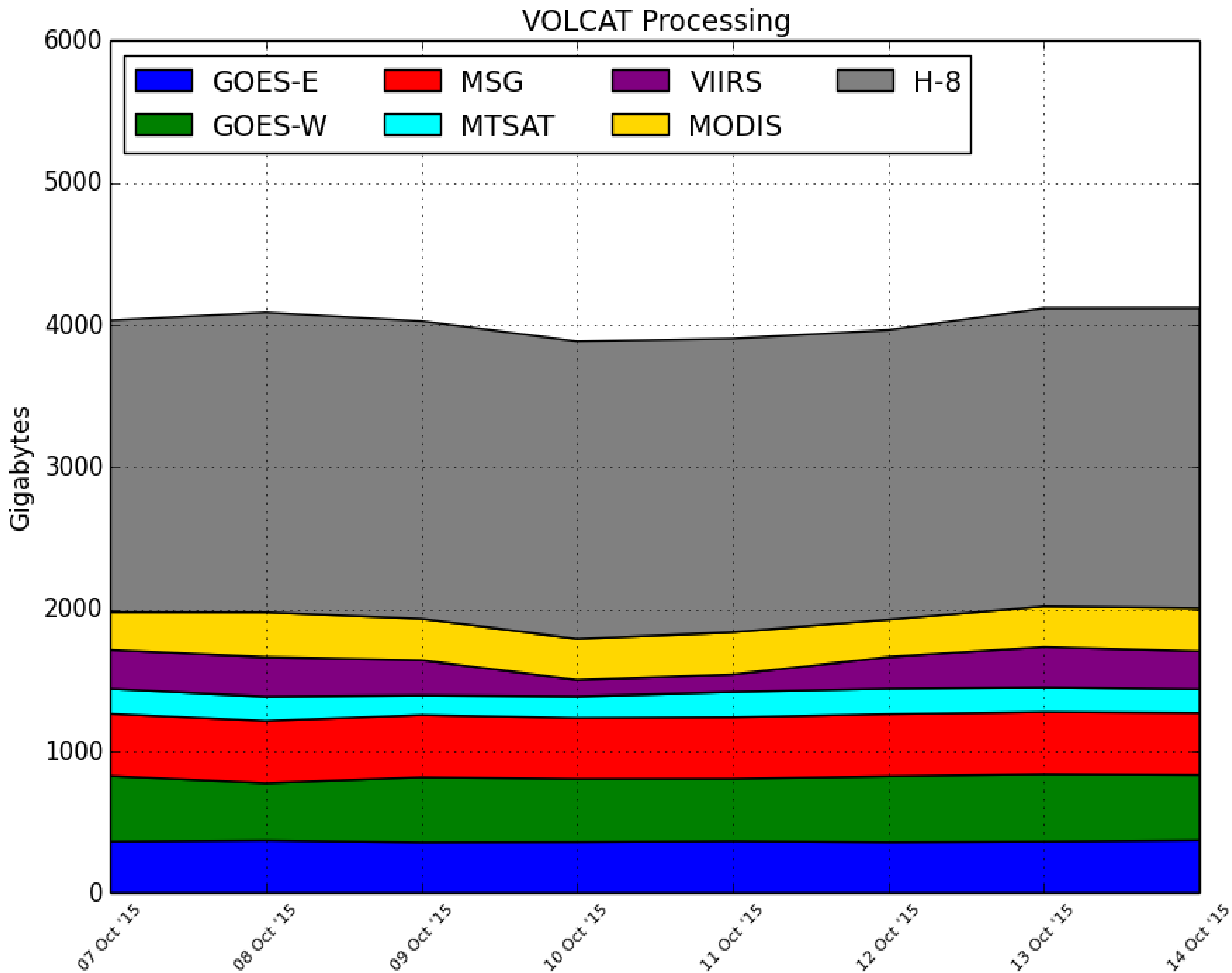
Summary

- In support of NOAA's mission, NOAA's role in generating environmental intelligence related to SO_2 needs to be expanded (and integrated with information on volcanic ash) in collaboration with NASA, USGS, and international partners.

- The JPSS satellite series is a critical component of the SO_2 observing system

- A collaborative JPSS initiative is needed to ensure that the JPSS sensors are being fully utilized for SO_2 monitoring

“Big Data”

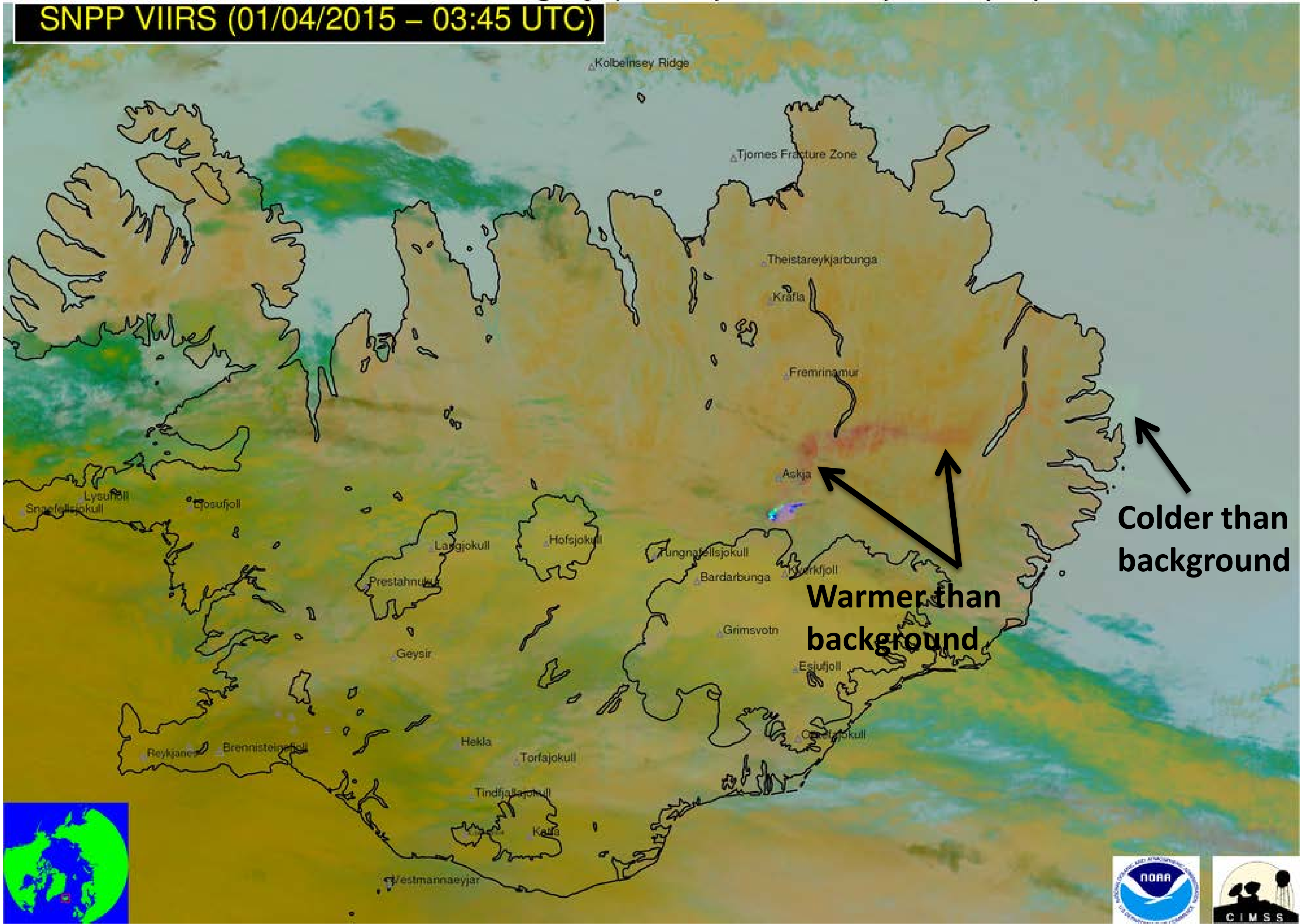


VOLCAT Processing
GOES-E
MSG
VIIRS
H-8
GOES-W
MTSAT
MODIS
Gigabytes
6000
5000
4000
3000
2000
1000
0
07 Oct '15
08 Oct '15
09 Oct '15
10 Oct '15
11 Oct '15
12 Oct '15
13 Oct '15
14 Oct '15

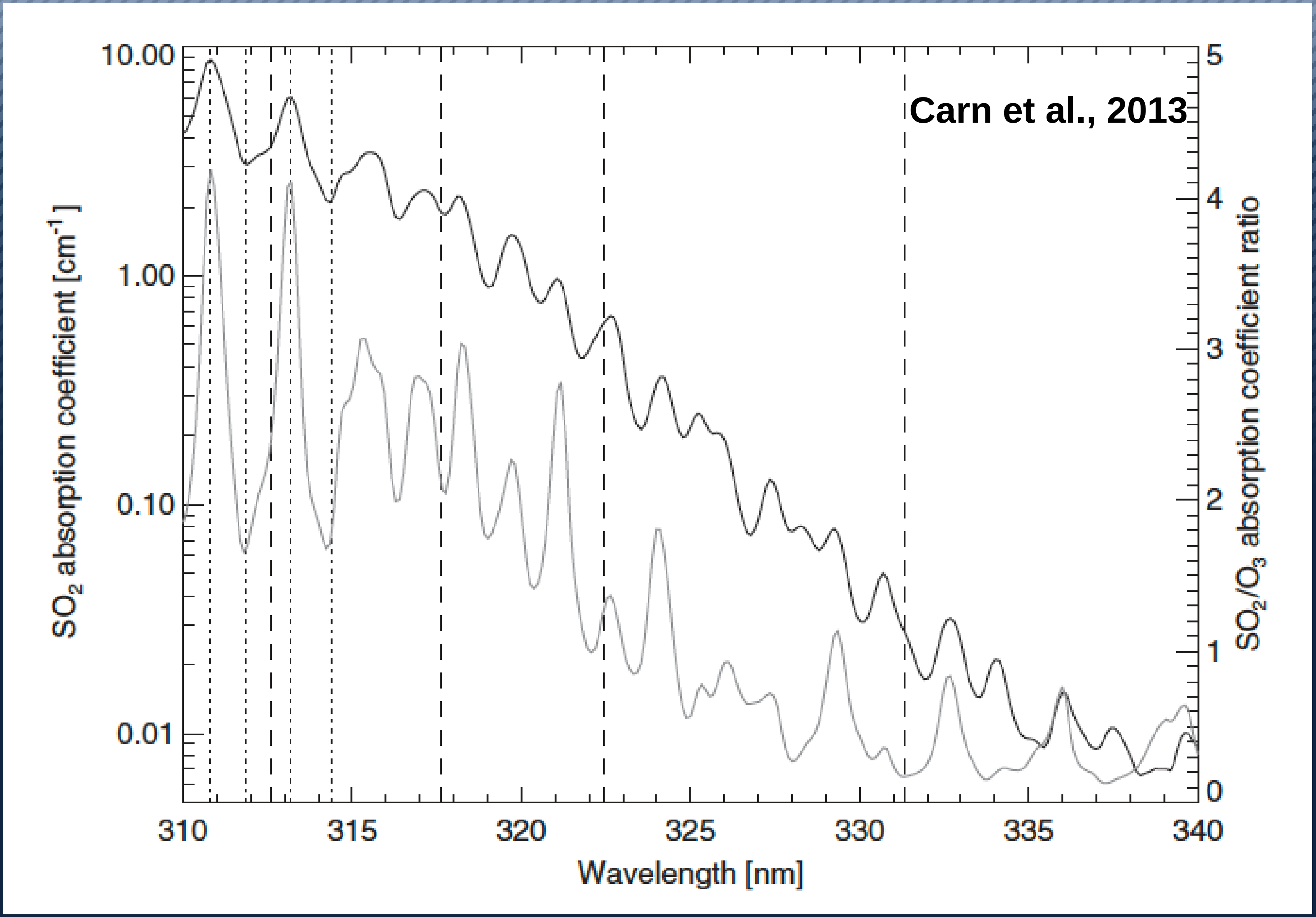
BACKUP SLIDES

Nuances/Exceptions are Prevalent

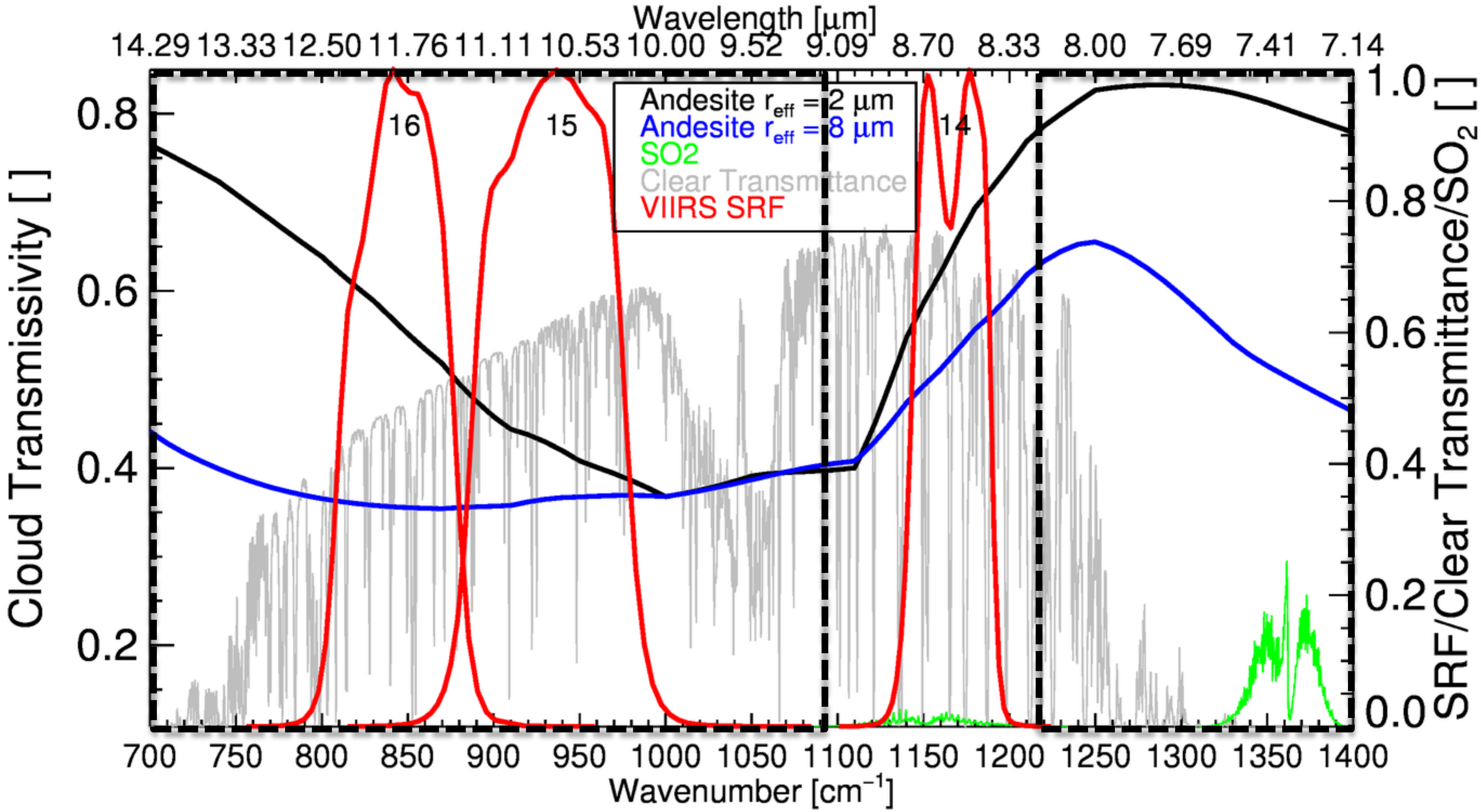
False Color Imagery (12–11µm, 11–8.5µm, 11µm)



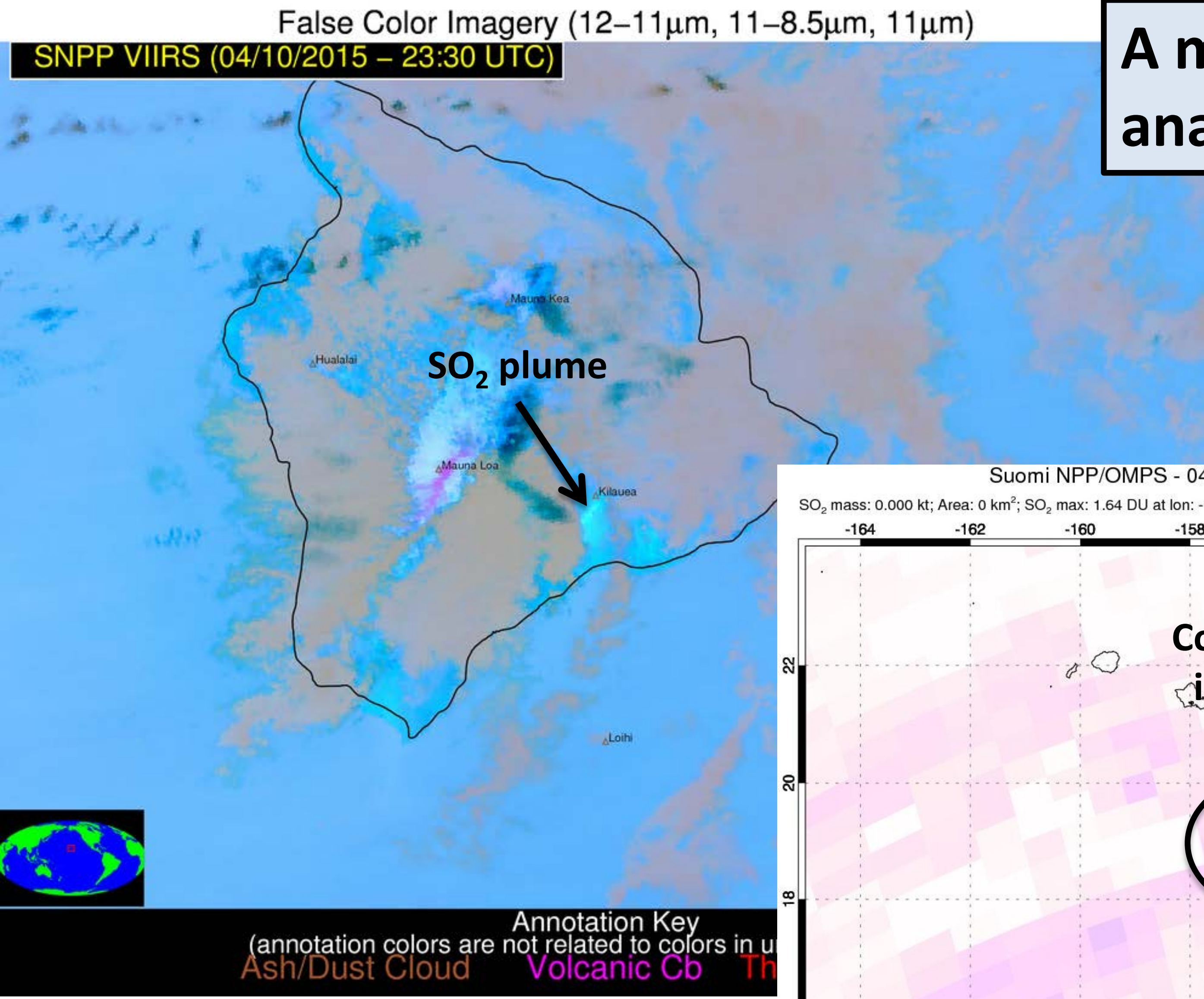
UV Sensitivity

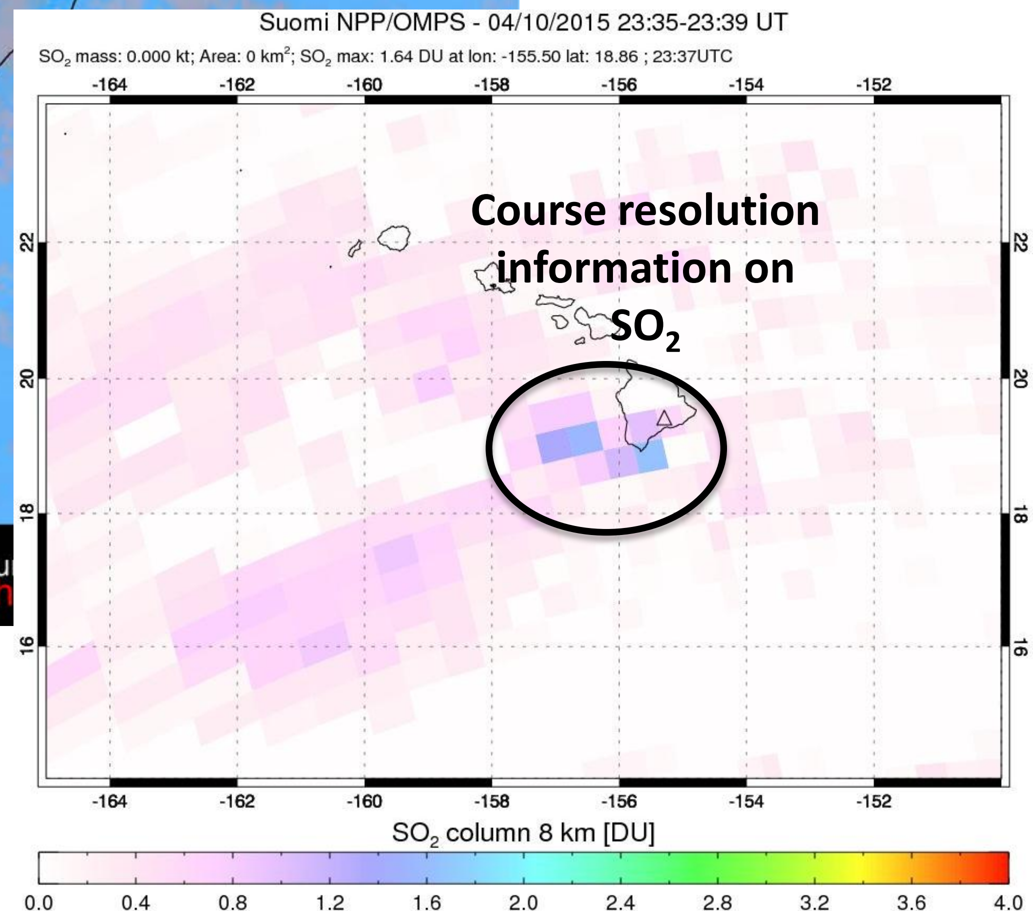


Infrared Sensitivity



A multi-sensor SO_2 analysis is needed





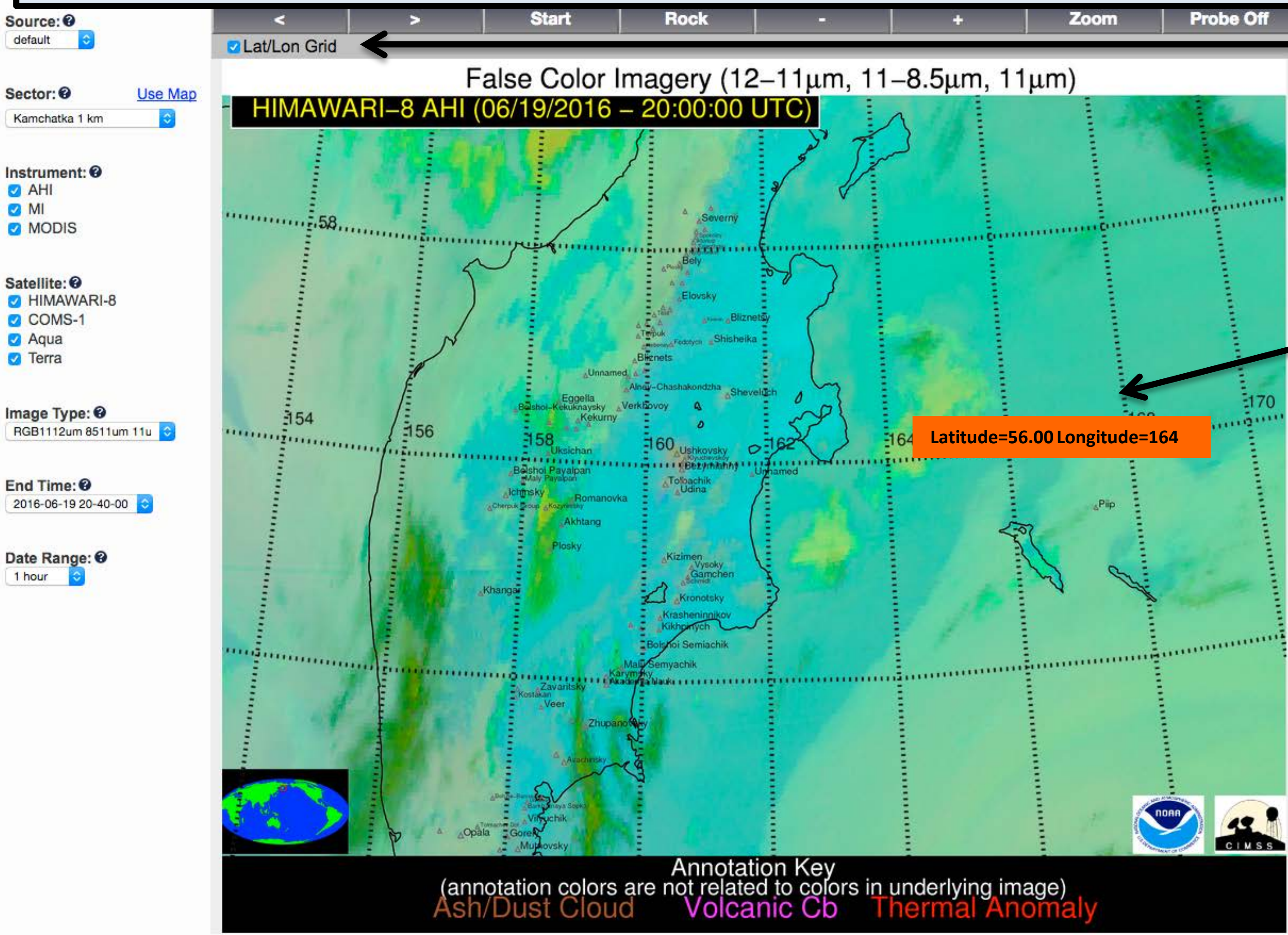
Optional Overlay Options: lat/lon grid, volcanoes, coast lines, VAAC boundaries, automated feature annotations

Image Probe: cursor readout of lat/lon and data value

Image Markup Tools: users can generate and export polygons and annotated images

SO_2: alerting, tracking, and characterization

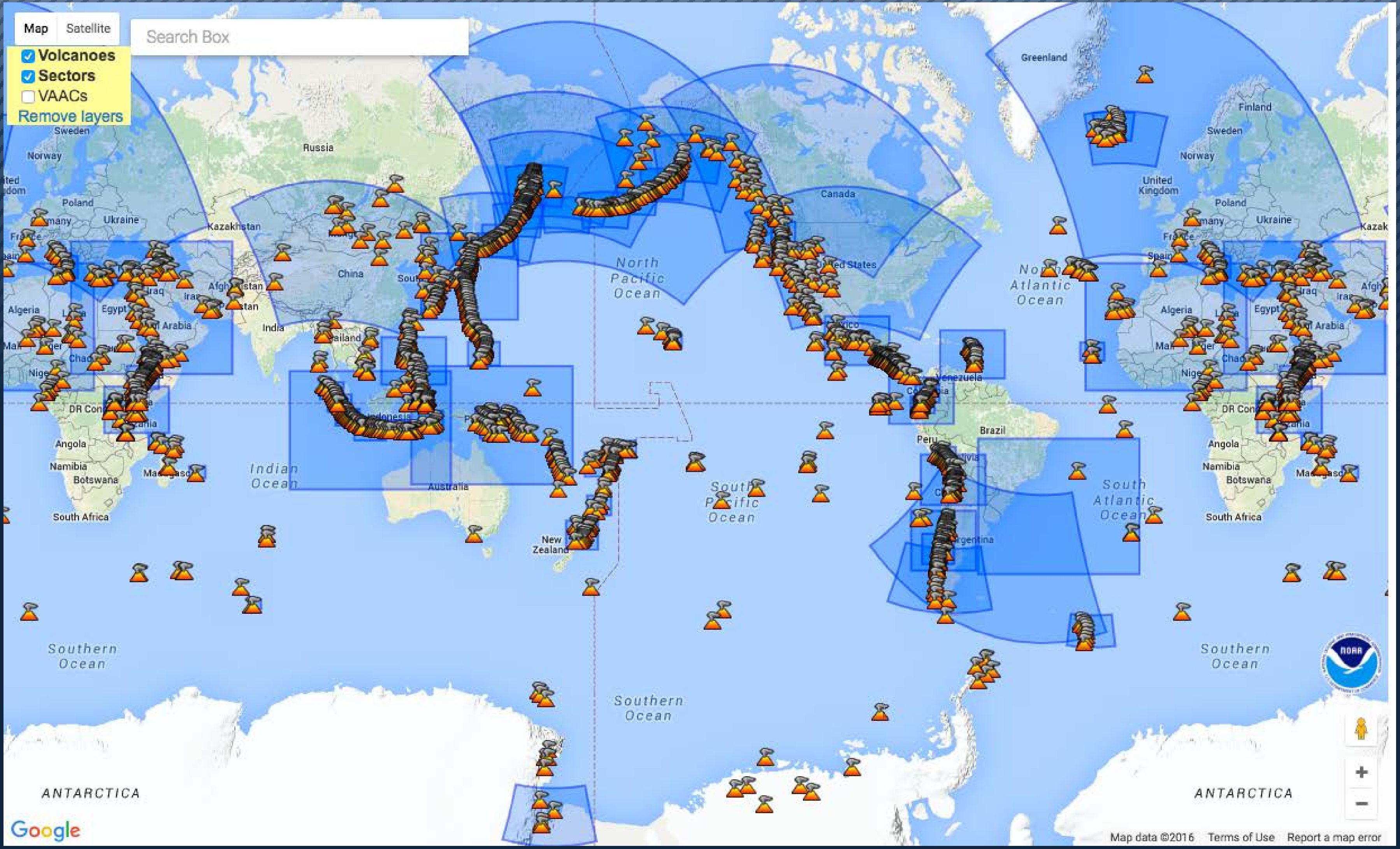
Incorporation of Non-Satellite Tools: volcano web cameras, dispersion/trajectory modeling, and infrasound



Overlay options

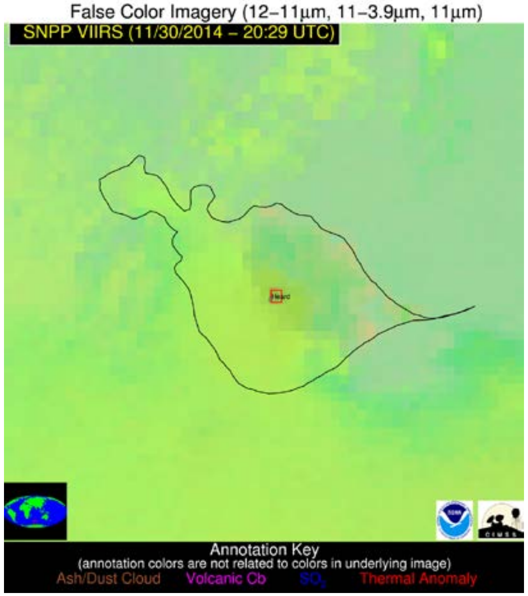
Image Probe

LEO and GEO satellite imagery are routinely generated for numerous geographic sectors that cover nearly every volcano in the world



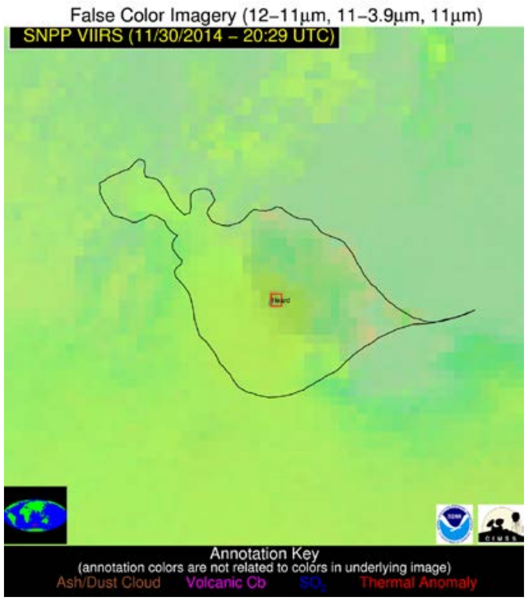
VOLCAT Goals

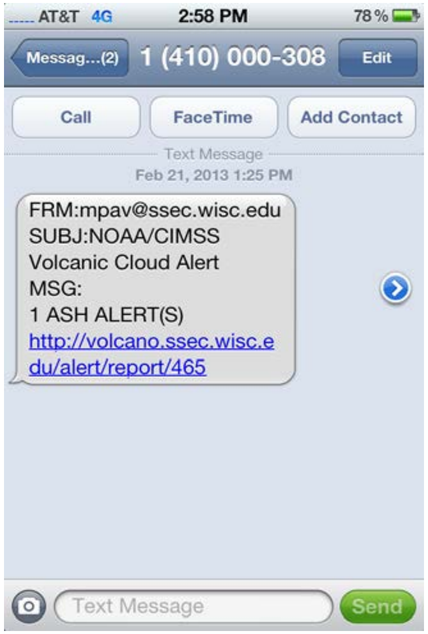
1). Unrest Alerts



VOLCAT Goals

1). Unrest Alerts	2). Eruption Alerts





VOLCAT Goals

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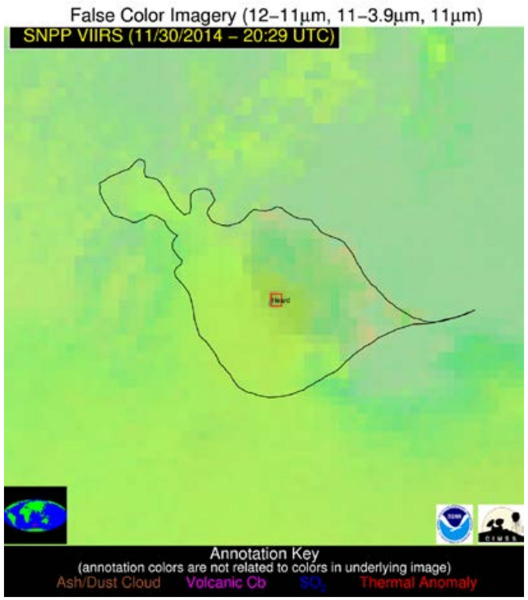
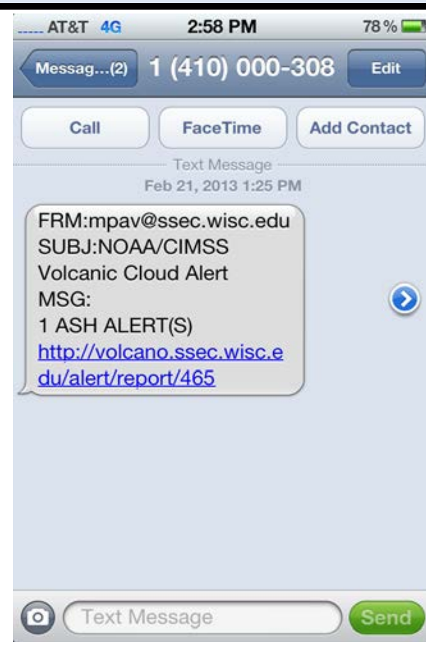
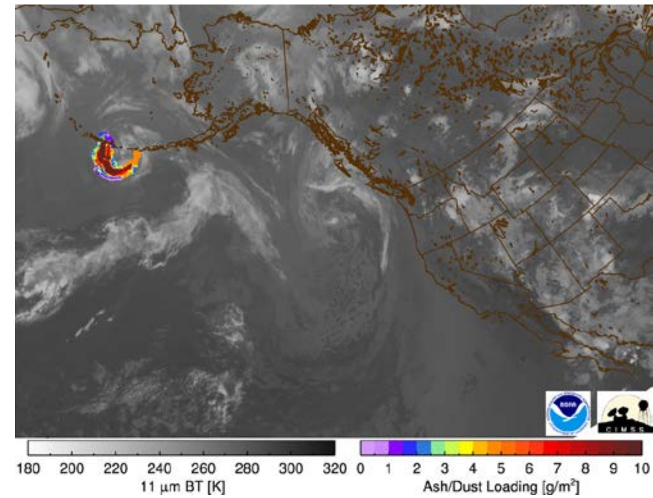


2). Eruption Alerts



3). Volcanic Cloud Tracking



VOLCAT Goals

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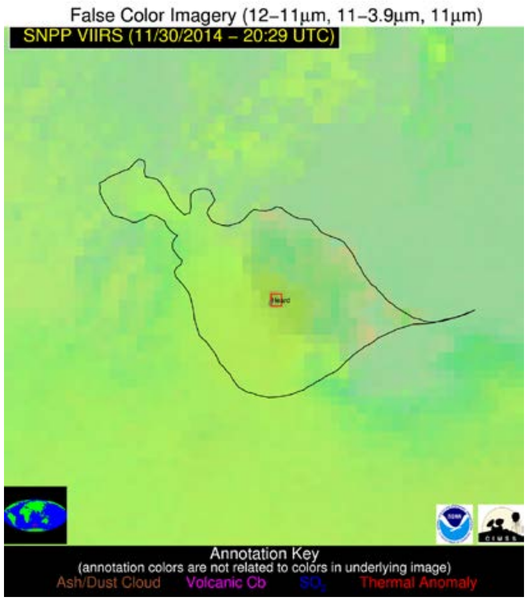

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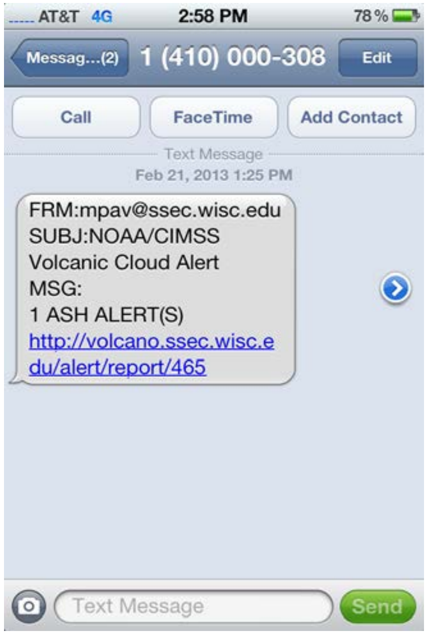

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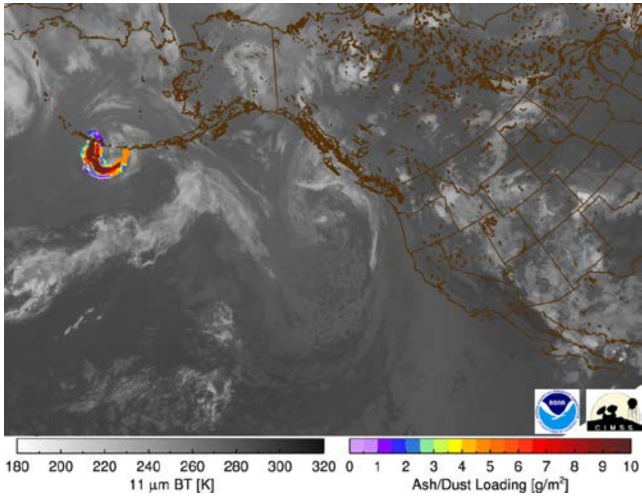
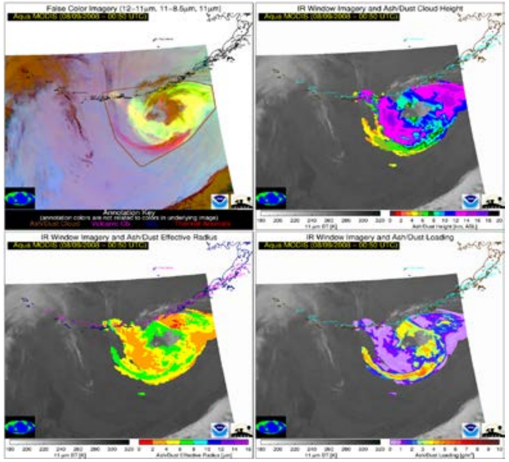


4). Volcanic Cloud Characterization



VOLCAT Goals

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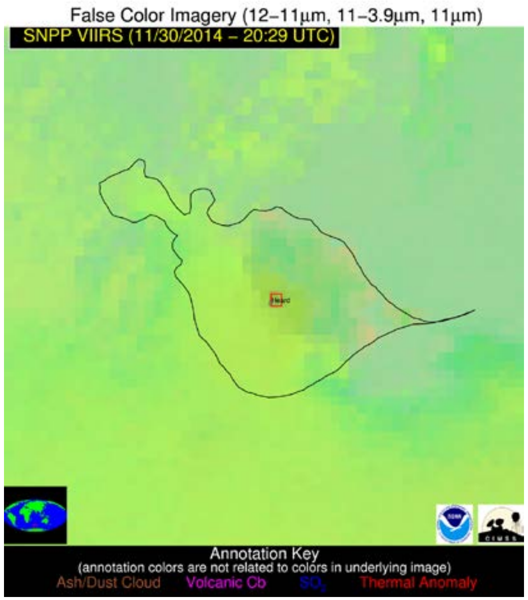

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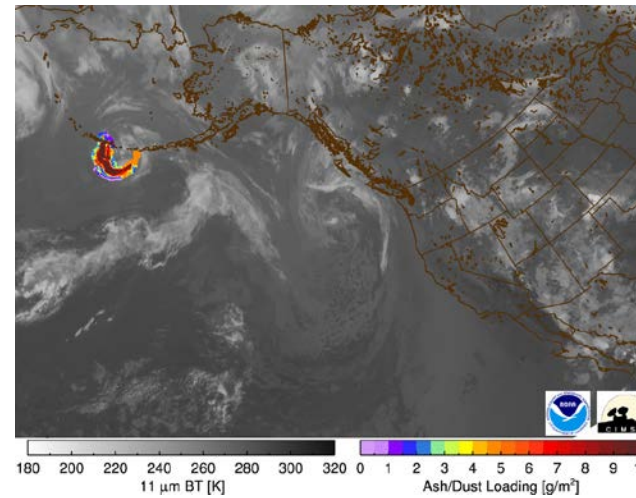

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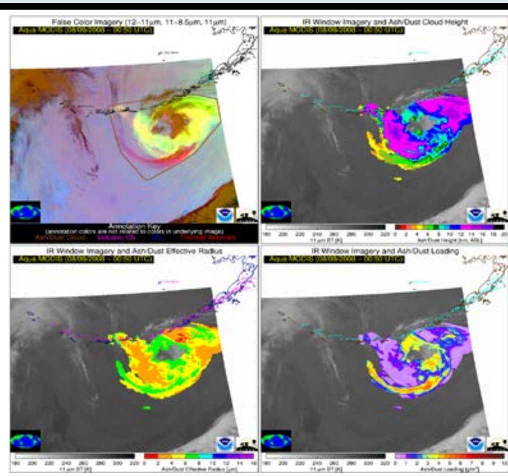
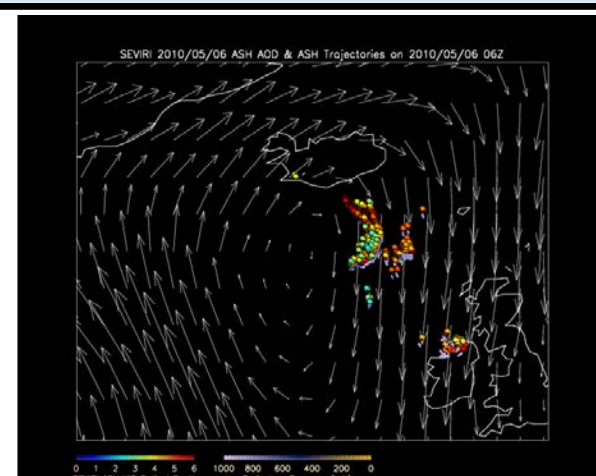


5). Dispersion Forecasting



VOLCAT Goals

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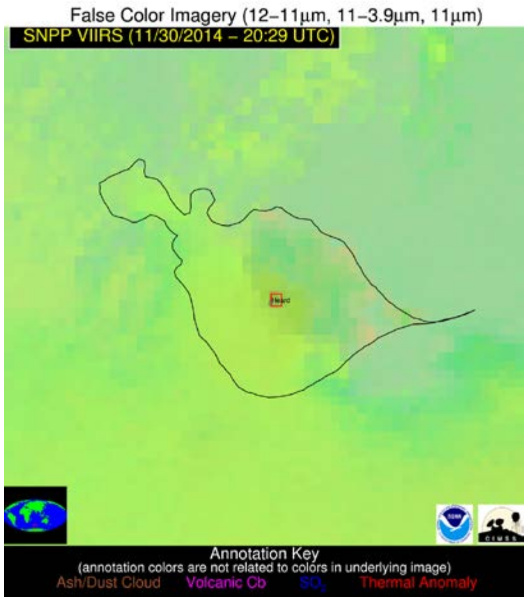

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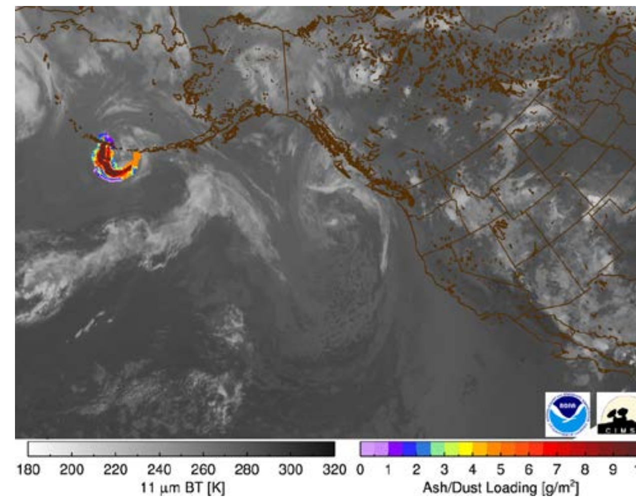

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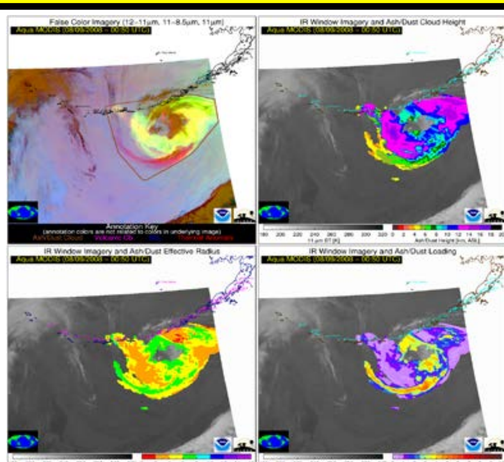

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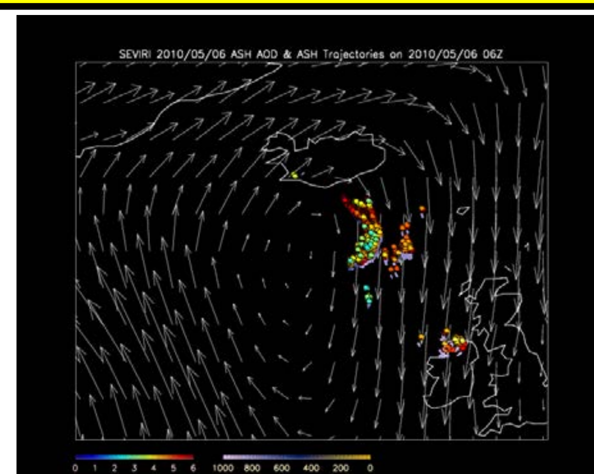
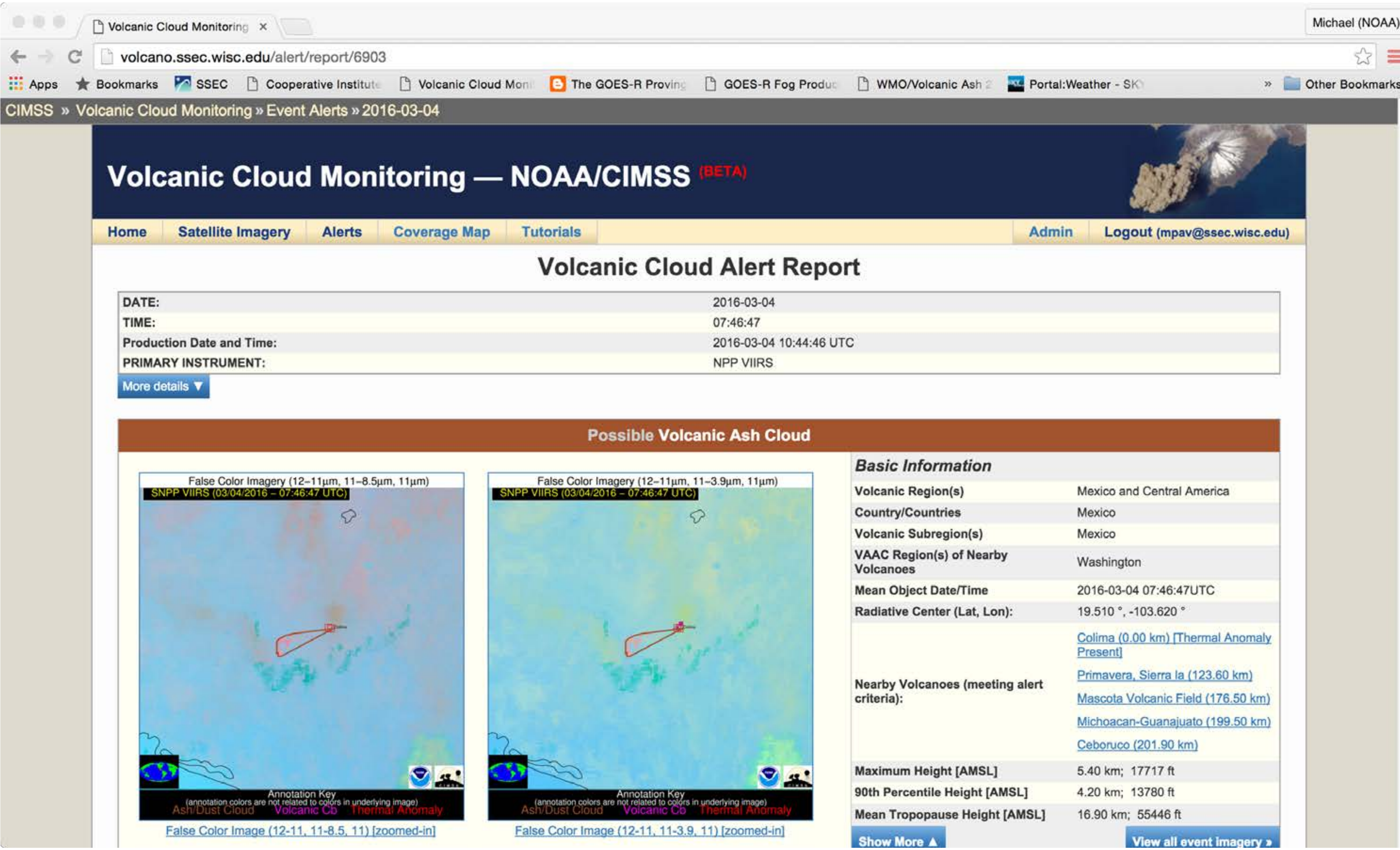


http://volcano.ssec.wisc.edu



Volcanic Cloud Detection

The VOLCAT detection approach is multi-faceted and employs several different conceptual models to identify volcanic clouds across the spectrum of eruption cloud types.

- Spectral cloud objects [spectral signature]
- Plume [spectral signature + geometric properties]
- ~~Puff [some spectral signature + cloud growth]~~
- ~~Major Explosion [cloud growth~~]
- Tracking in time [spectral signature + feature tracking]

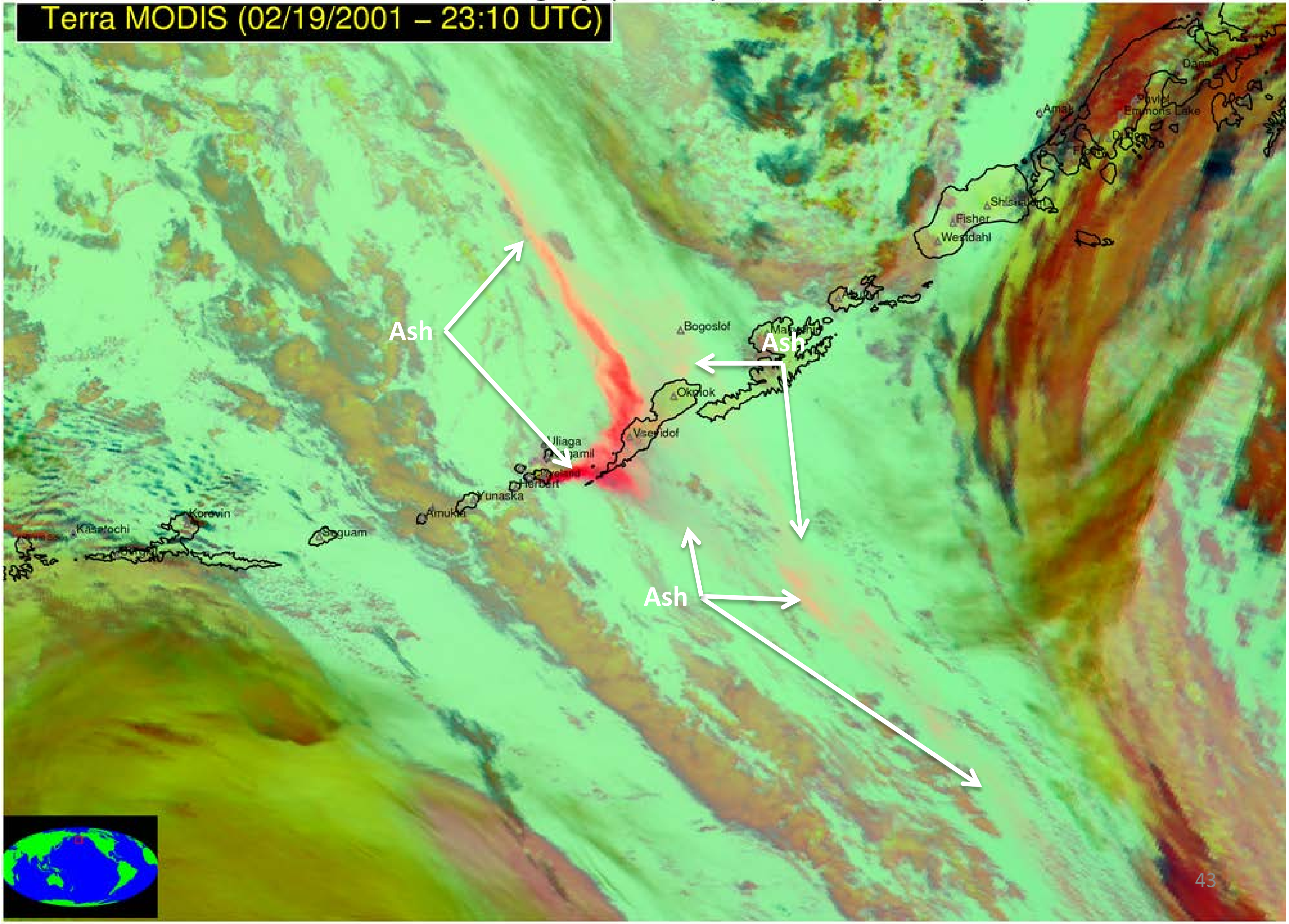
Marco Fulle - www.stromboli.net

Spectrally Enhanced Cloud Objects (SECO)

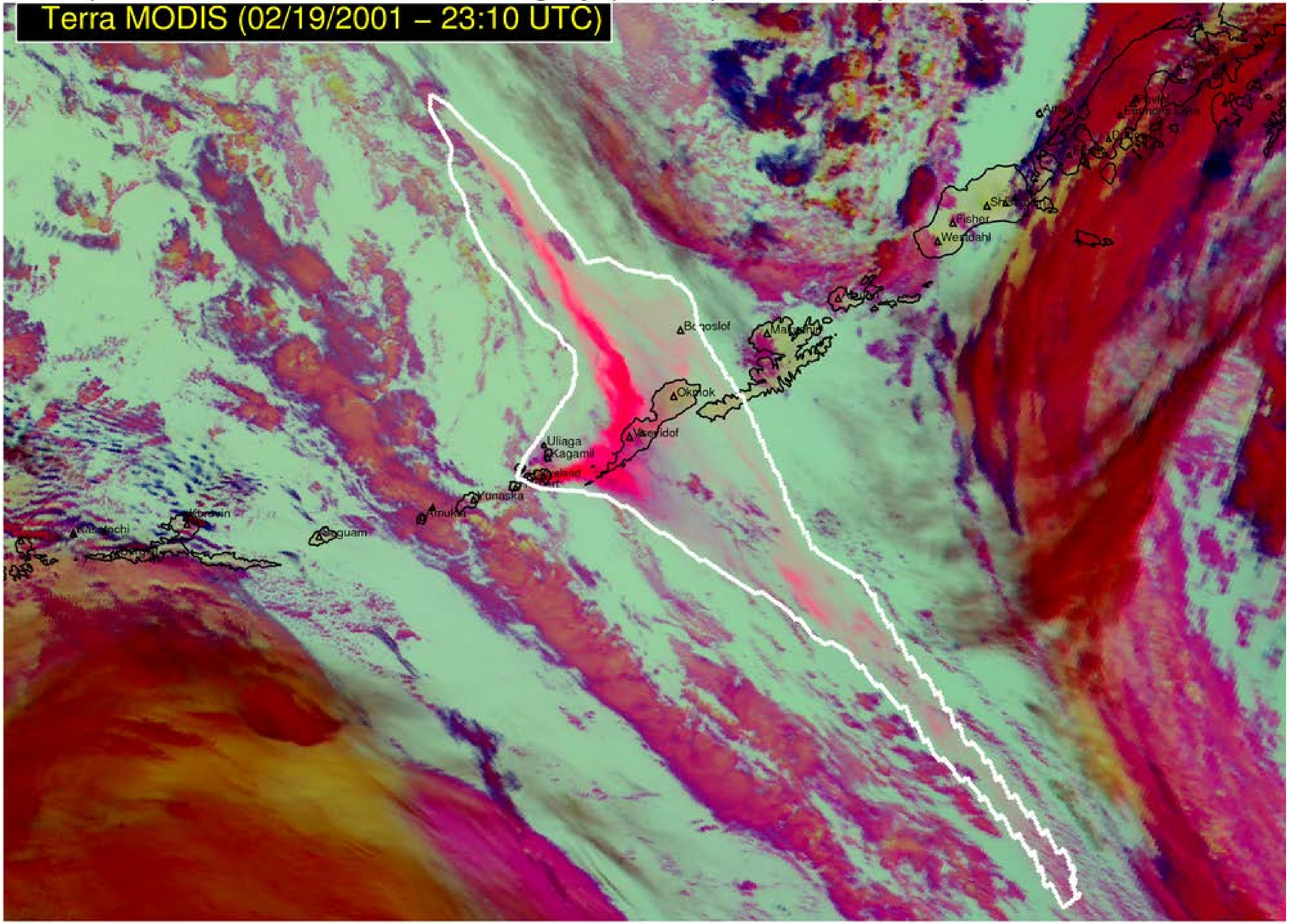
JGR - Pavolonis et al. (2015a)

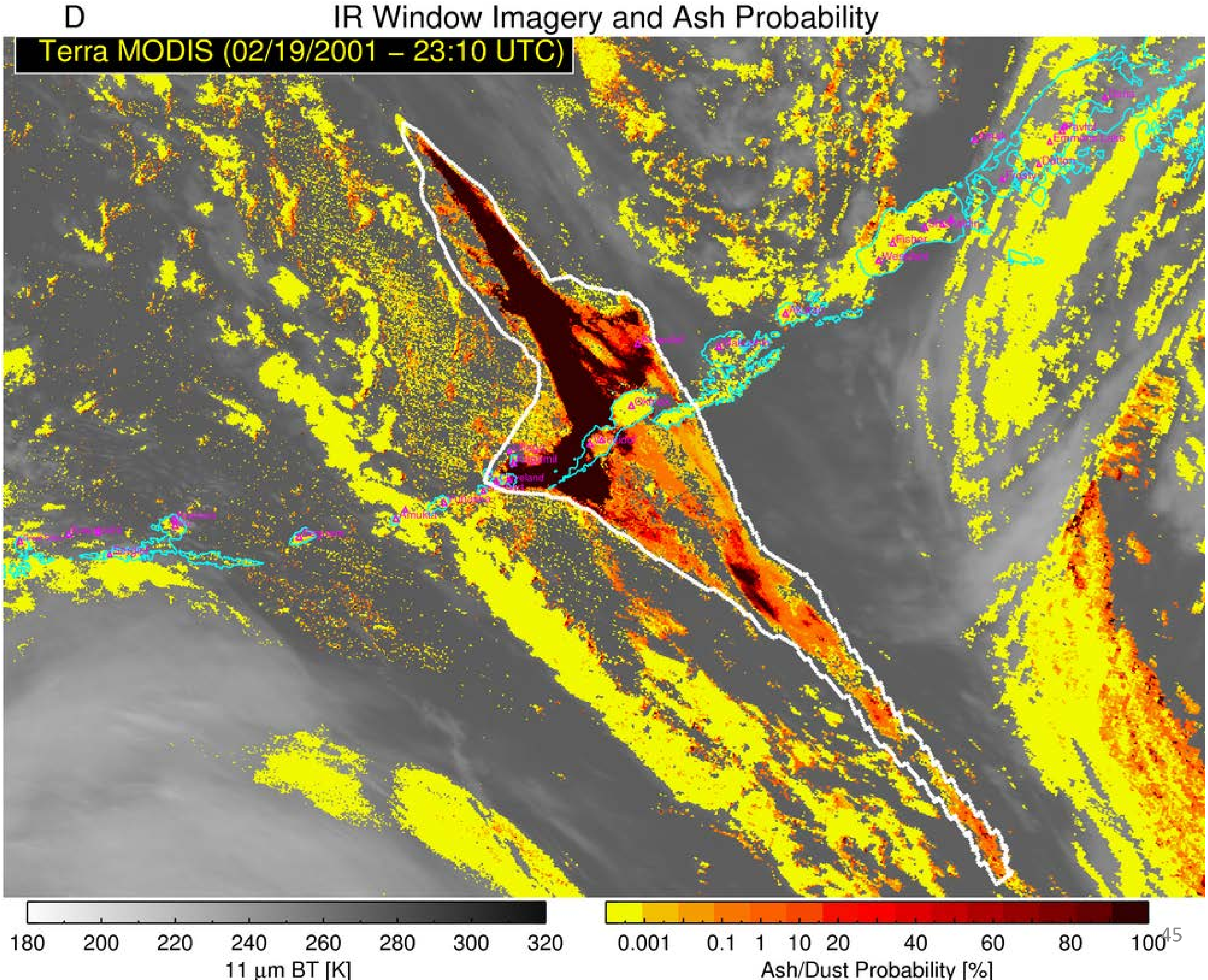
JGR – Pavolonis et al. (2015b)

False Color Imagery (12–11μm, 11–3.9μm, 11μm)



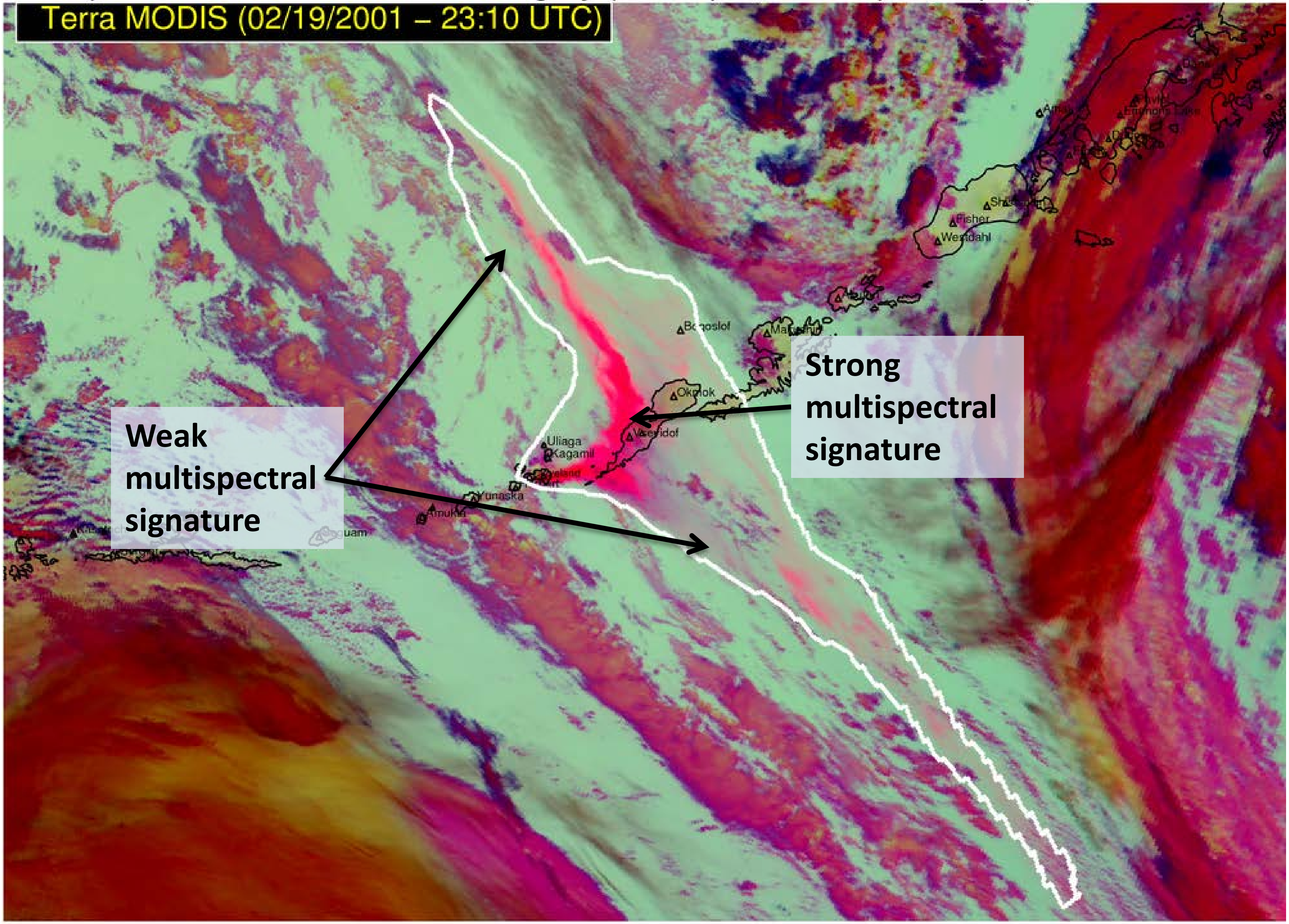
B). False Color Imagery (12–11μm, 11–3.9μm, 11μm)





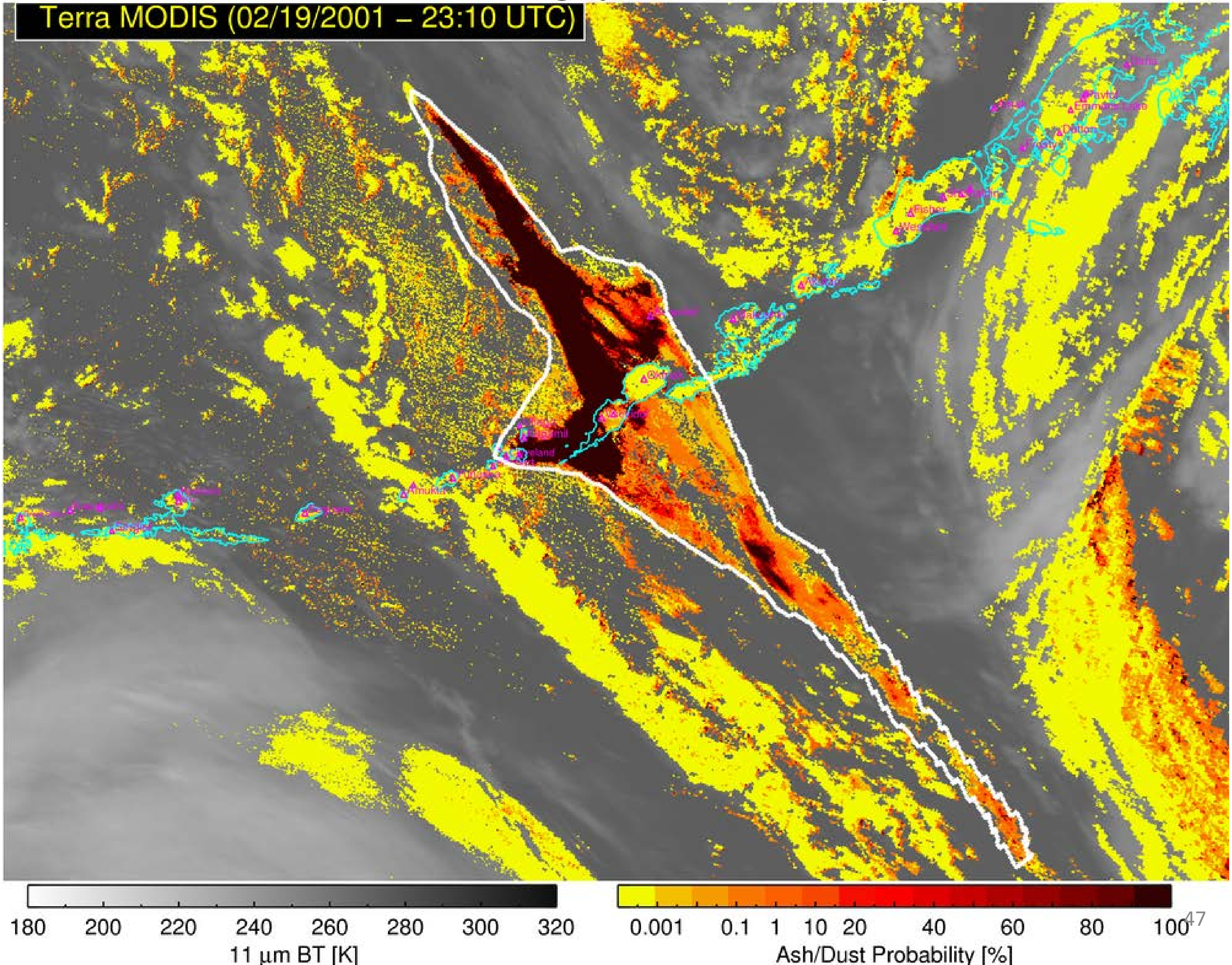
D
IR Window Imagery and Ash Probability
Terra MODIS (02/19/2001 – 23:10 UTC)
180
200
220
240
260
280
300
320
11 μm BT [K]
0.001
0.1
1
10
20
40
60
80
100
Ash/Dust Probability [%]

B). False Color Imagery (12–11μm, 11–3.9μm, 11μm)

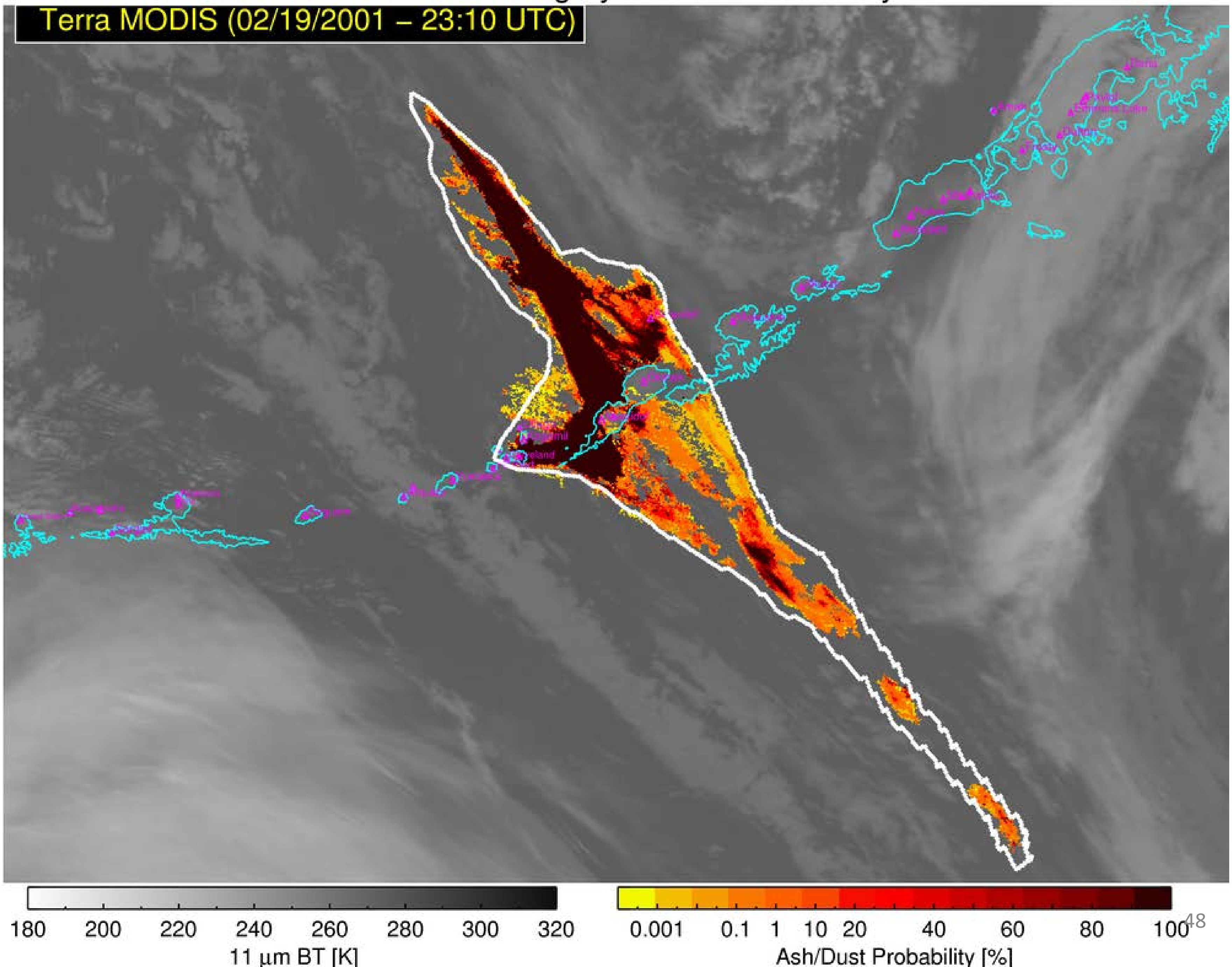


D

IR Window Imagery and Ash Probability

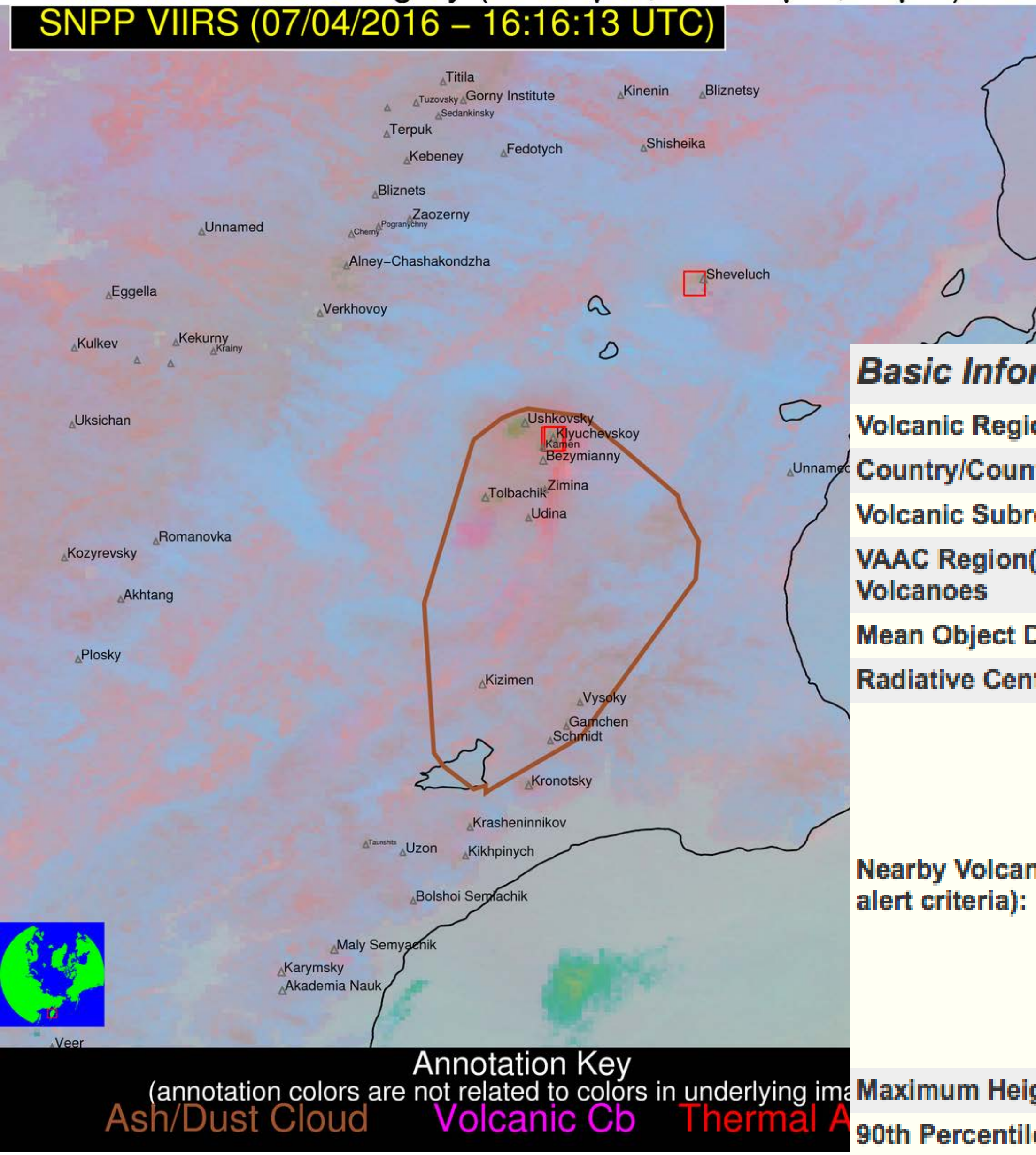


D IR Window Imagery and Ash Probability



Automated Determination of Source Volcano

False Color Imagery (12–11µm, 11–8.5µm, 11µm)

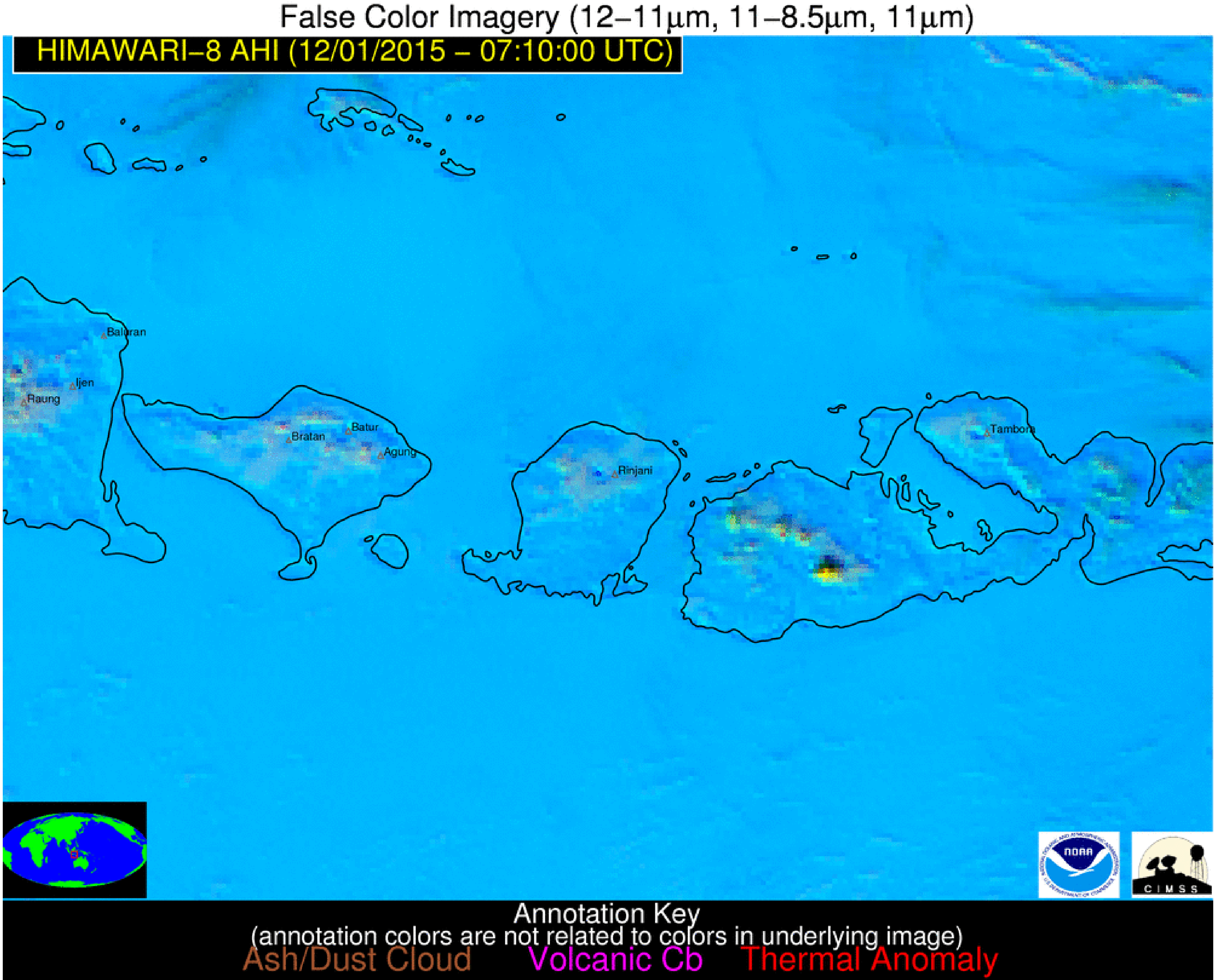


Basic Information

Volcanic Region(s)	Kamchatka and Mainland Asia
Country/Countries	Russia
Volcanic Subregion(s)	Kamchatka Peninsula
VAAC Region(s) of Nearby Volcanoes	Tokyo
Mean Object Date/Time	2016-07-04 16:16:13UTC
Radiative Center (Lat, Lon):	56.060 °, 160.640 °
Nearby Volcanoes (meeting alert criteria):	Klyuchevskoy (0.00 km) [Thermal Anomaly Present] Kamen (5.00 km) [Thermal Anomaly Present] Bezymianny (9.80 km) [Thermal Anomaly Present] Ushkovsky (10.40 km) Zimina (21.70 km)
Maximum Height [AMSL]	6.70 km; 21982 ft
90th Percentile Height [AMSL]	4.40 km; 14436 ft
Mean Tropopause Height [AMSL]	12.00 km; 39370 ft

Show More ▲

View all event imagery »


False Color Imagery (12–11µm, 11–8.5µm, 11µm)
HIMAWARI–8 AHI (12/01/2015 – 07:10:00 UTC)
Baluran
Ijen
Raung
Batur
Bratan
Agung
Rinjani
Tambora
Annotation Key
(annotation colors are not related to colors in underlying image)
Ash/Dust Cloud
Volcanic Cb
Thermal Anomaly