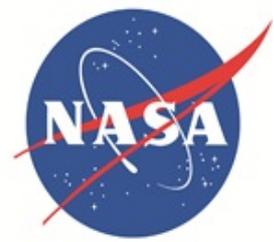




NASA Air Quality Applied Sciences Team

Earth Science Serving Air Quality Management Needs

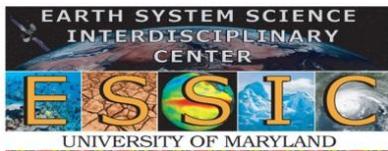


Satellite Signatures of Trace Gases Associated with US Oil and Gas Extraction FY 14 AQAST Project

Debra Kollonige (UMD/ESSIC) & Brad Pierce (NOAA)

Lead PI: Anne M. Thompson (GSFC)

Other AQAST participants: D. Kollonige (UMD/ESSIC), B. Pierce (NOAA), R. Dickerson (UMD), D. Jacob (Harvard), D. Edwards /G. Pfister(NCAR), D. Henze /J. Milford (CU-B) , T. Holloway (UW)



HARVARD
UNIVERSITY



University
of Colorado
Boulder



2014 Midwest and Central States Air Quality Workshop
April 22 – 24, 2014, St. Louis, MO



NASA Air Quality Applied Science Team (AQAAT) FY14 Tiger Team Activity

Project Description:

Air Quality Managers (AQM) in regions affected by rapidly ONG extraction are working to address these questions:

- (1) What is the burden of CH₄, NO_x, non-methane hydrocarbons [NMHC], and byproducts (eg, HCHO, CO) being released by new mines and wells?
- (2) Can we verify modified emissions inventories that AQM are developing based on increased ONG sources?

Collaborator	Stakeholder Roles
Julie McDill (MARAMA)	New emission inventories using oil & gas well & production data
Tad Aburn (MDE)	Support Marcellus aircraft flights
Theresa Pella (CenSARA) / Margaret Robertson (OK DEQ)	Liaison for CenSARA: Assessment of Oil and Gas (O&G) emissions inventory based on satellite NO ₂ , CH ₄ and HCHO distributions / Liaison to OK DEQ
Gail Tonnesen (US EPA Region 8)	Liaison for EPA Region 8: Comparison of satellite HCHO/NO ₂ ratios to EPA model results
Patrick Reddy / Gordon Pierce (CDPHE)	Liaisons to CDPHE (Colorado Dept Public Health & Environment)
John Lyon (BLM)	Liaison to BLM (Bureau of Land Management)

NASA Air Quality Applied Science Team (AQAAT)

FY14 Tiger Team Activity

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- (2) Can we verify modified emissions inventories that AQM are developing based on increased ONG sources?

Approach:

- For Question #1: (1) Satellite maps and trends will be derived for regions affected by newer ONG activity: Marcellus (OH, WV, PA, MD), Bakkan (ND), Barnett/Woodford (TX-OK), and Utah-Colorado-Wyoming region (UT-CO). Products and trends from different sensors will be compared as each satellite product has inherent limitations. (2) We will compare satellite products with available ground and aircraft CH₄, NMHC, NO_x data in each region.
- For Question #2: (1) AQM are using emissions inventories with models to predict impacts of ONG emissions. We will partner with these activities to support model validation using our combined satellite and in-situ datasets.

Tiger Team Member	Products / Deliverables
A Thompson / D Kollonige	<ul style="list-style-type: none"> (1) Identification of ONG leaks (if possible) with satellite measurements and comparison to ground and aircraft instrumentation (Extreme events). (2) TES CH₄ trend analysis with comparisons to other methane sensors (eg. SCIAMACHY and GOSAT). (3) Correlations of CH₄ to CO for the focus regions (MOPITT).
B Pierce / T Holloway	<ul style="list-style-type: none"> (1) Develop a high res(4km) Level 3 (L3, gridded) tropospheric NO₂ column data set over US using cloud cleared VIIRS Day/Night visible band reflectances to re-distribute BEHR NO₂ retrieval within OMI footprint. (2) Compare the high res L3 OMI NO₂ column to NEI 2011 and WRAP Phase III Oil & Gas NO₂ emission inventories. (3) Conduct regional OMI NO₂ assimilation studies using nested RAQMS/CMAQ/GSI framework.
D Jacob	<ul style="list-style-type: none"> 1) Identification and if possible quantification of methane emissions for the focus regions using GOSAT satellite data. 2) Identification and if possible quantification of highly reactive VOC emissions for the focus regions using OMI and GOME-2 satellite data.
R Dickerson	<ul style="list-style-type: none"> (1) Aircraft validation flights with in situ & remote sensing of CH₄ and other trace gases near Marcellus Shale Mid-Atlantic (2) CMAQ modeling of DISCOVER-AQ CH₄ (3) SCIAMACHY CH₄ trend analysis.
D Edwards / G Pfister	<ul style="list-style-type: none"> 1) Analyze multi-year retrievals of CO from MOPITT (and IASI) and OMI HCHO. 2) Use data collected during the D-AQ and FRAPPE campaigns in Colorado in summer 2014 to relate emissions and concs measured by aircraft and ground instrumentation in areas of strong Oil & Gas activities (e.g. Weld County) to satellite data.
D Henze / J Milford	<ul style="list-style-type: none"> (1) Liaison to On-going NSF sustainability network (interpret western ONG emissions)

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B Pierce / T	<div data-bbox="241 382 1806 492" style="border: 2px solid red; padding: 5px; text-align: center; color: red; font-weight: bold; font-size: 1.2em;"> Progress on these two activities discussed today </div> <ul style="list-style-type: none"> (1) Use cloud cleared Time Day/Night Visible band reflectances to retrieve OMI NO₂ retrieval within OMI footprint. (2) Compare the high res L3 OMI NO₂ column to NEI 2011 and WRAP Phase III Oil & Gas NO₂ emission inventories. (3) Conduct regional OMI NO₂ assimilation studies using nested RAQMS/CMAQ/GSI framework.
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Satellite carbon gas burdens for comparison to O&NG emissions inventory

Objectives:

- (1) Determine regional changes in CH₄ and related carbon gases near O&NG activities in Eastern and Western US based on satellite and in situ measurements.
- (2) Work with AQ stakeholders, such as MARAMA and CenSARA, to compare satellite observations with emissions inventories and air quality modeling.

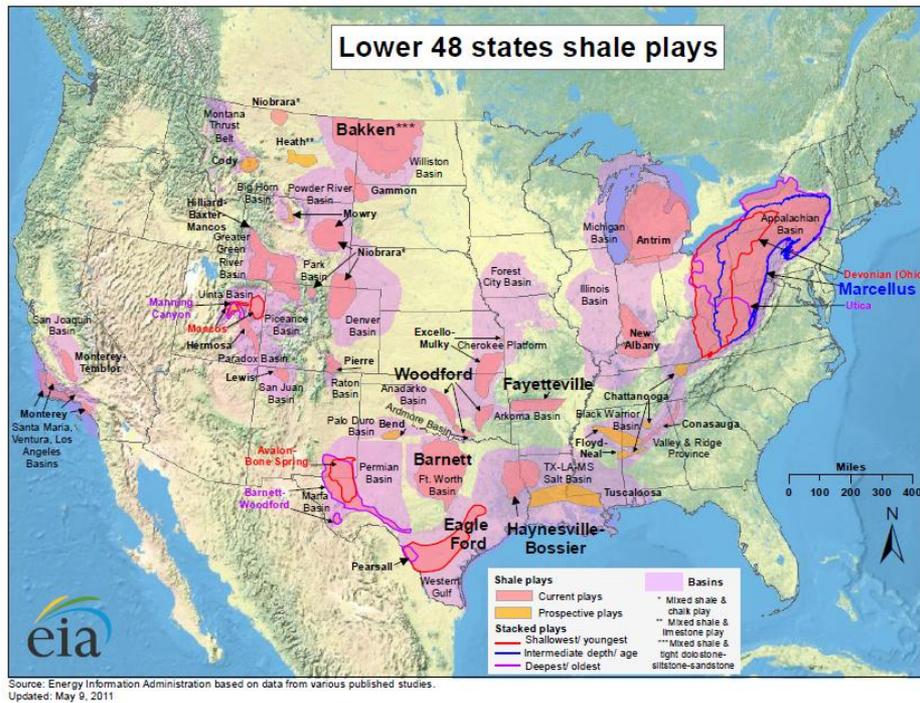


Figure from <http://www.eia.gov>.

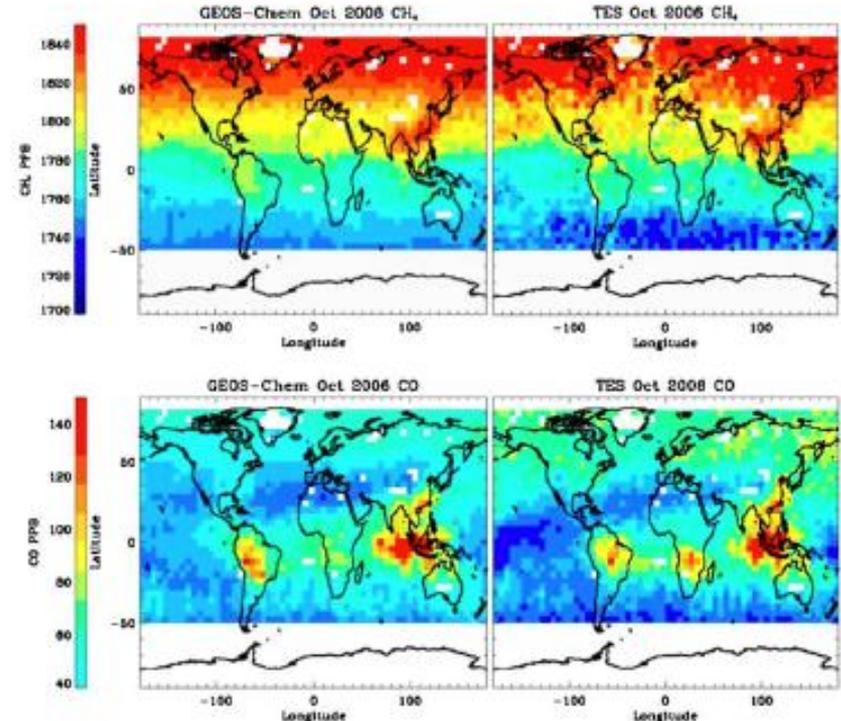
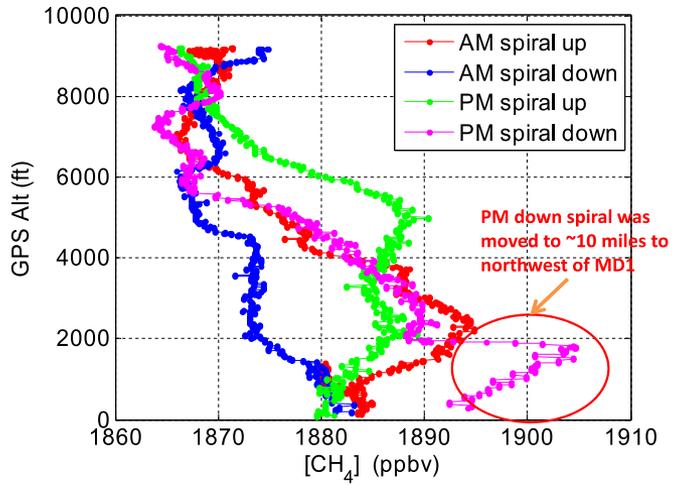


Figure 1 from Worden et al., GRL, 2013.

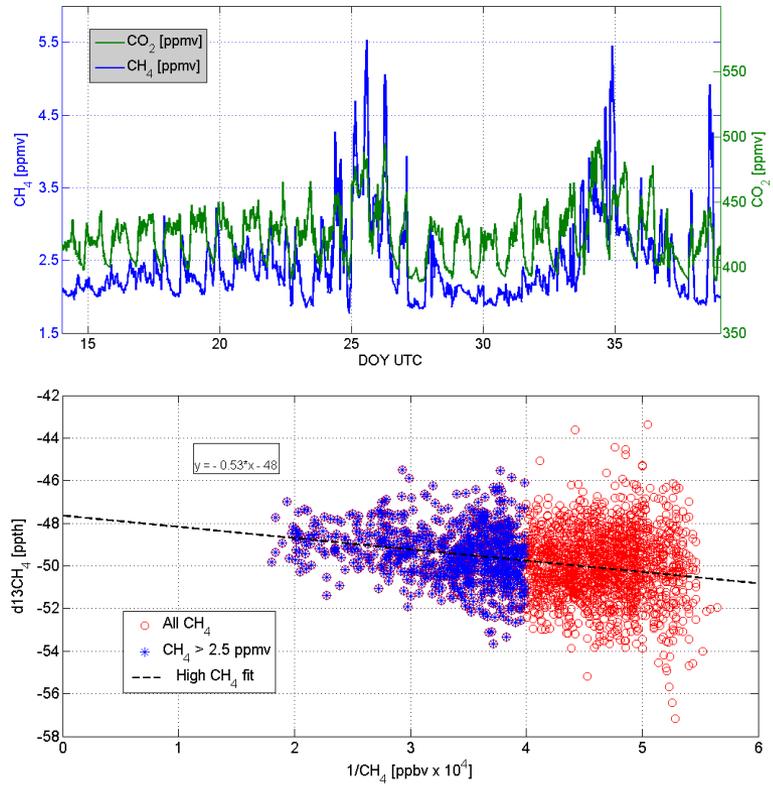
First step: Validate satellite observations with ground/aircraft measurements

- Regional campaigns, like NASA DISCOVER-AQ (2011-MD, 2013-CA/TX, and 2014-CO), provide in situ ground and aircraft measurements perfect for validation.
- With these datasets, we:
 - Compare collocated aircraft and satellite profiles to find biases (dependent on region).
 - Interpret satellite instrument horizontal and vertical sensitivities.
 - Identify local sources of CH₄ and carbon gases other than O&NG operations.

CH₄ vertical profiles over MD1 (Millington, MD) on 8/15/2013



Ground CH₄ (& its isotope) and CO₂ from PSU NATIVE trailer at Porterville, CA Jan-Feb 2013.



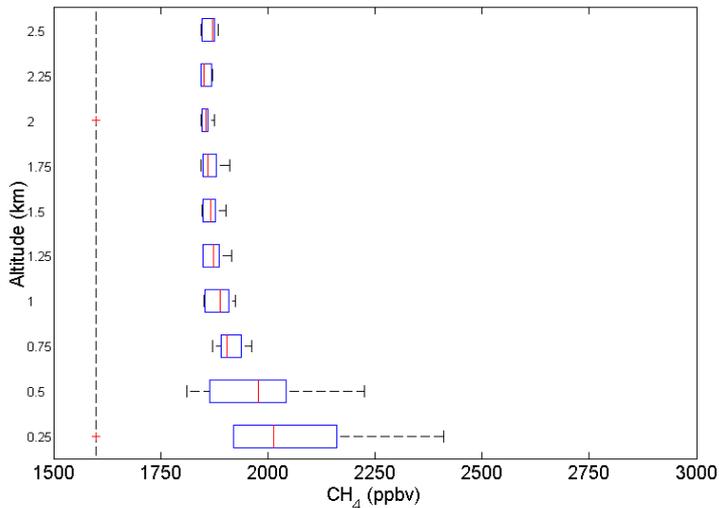
In Situ CH₄ taken Aug 2013 from Cessna 402B courtesy of R. Dickerson et al.

Possible satellite observations for use in this study

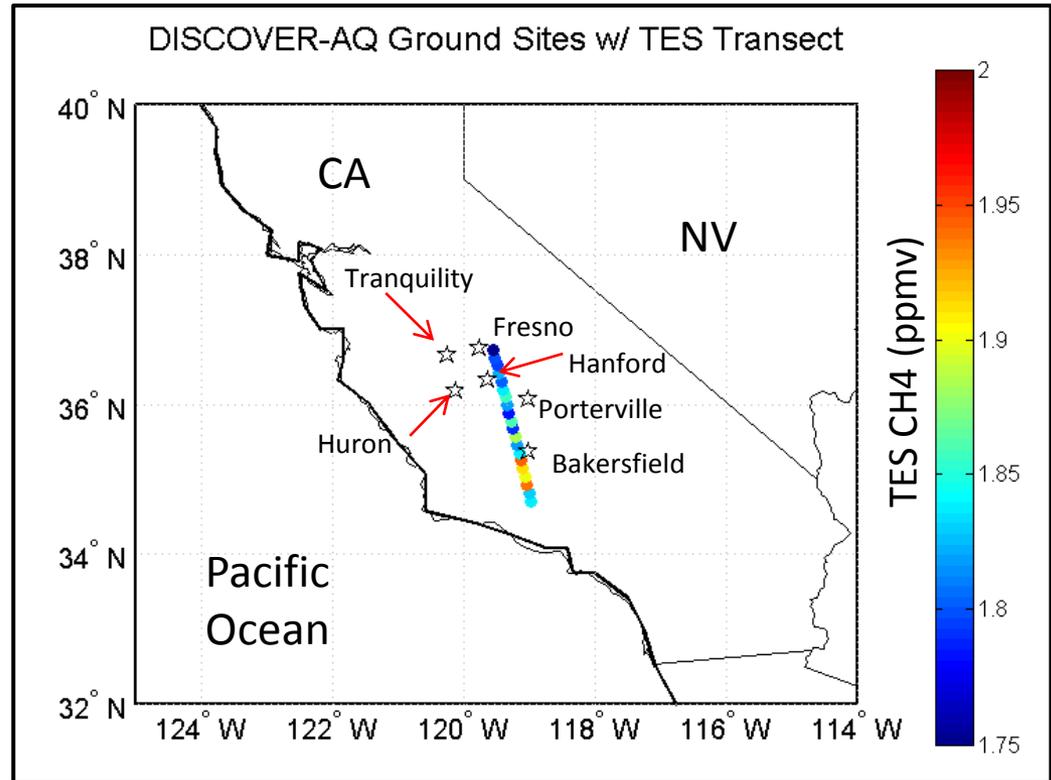
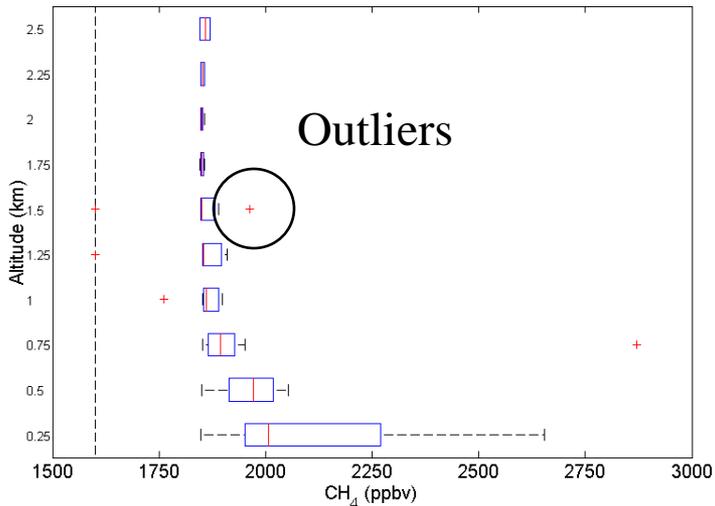
- **TES**
 - New **Tropospheric Emission Spectrometer (TES) CH₄ product** (V005) offers sensitivity lower in the troposphere than other TIR sensors, increasing its value for identifying CH₄ sources (*Worden et al., AMT, 2012; Worden et al., ACP, 2013*).
- **GOSAT** - Greenhouse gases Observing SATellite
- **MOPITT** - Measurements Of Pollution In The Troposphere

2013 DISCOVER-AQ CA Campaign: P3B Profiles

Distribution of CH₄ for P3B Profiles over Bakersfield, CA



Distribution of CH₄ for P3B Profiles over Porterville, CA



- Bakersfield and Porterville vertical profile distributions were expected, with highest concentrations near the surface.
- Although TES cannot see the surface, it consistently retrieved elevated CH₄ concentrations in the mid-troposphere near Bakersfield, CA with values ~2 ppmv at times (See Figure above).

Second Step: Analyze satellite carbon gas time series to characterize regional trends and compare to emissions inventories and AQ modeling

- Taking advantage of the lifespan of most available satellites, at least a decade of carbon gas measurements can be explored regionally.
- TES will provide mid-tropospheric trends in CH_4 near and downwind of O&NG operations (background) and locate regional hotspots in CH_4 .
- Similar methods analysis will be completed using GOSAT, too.

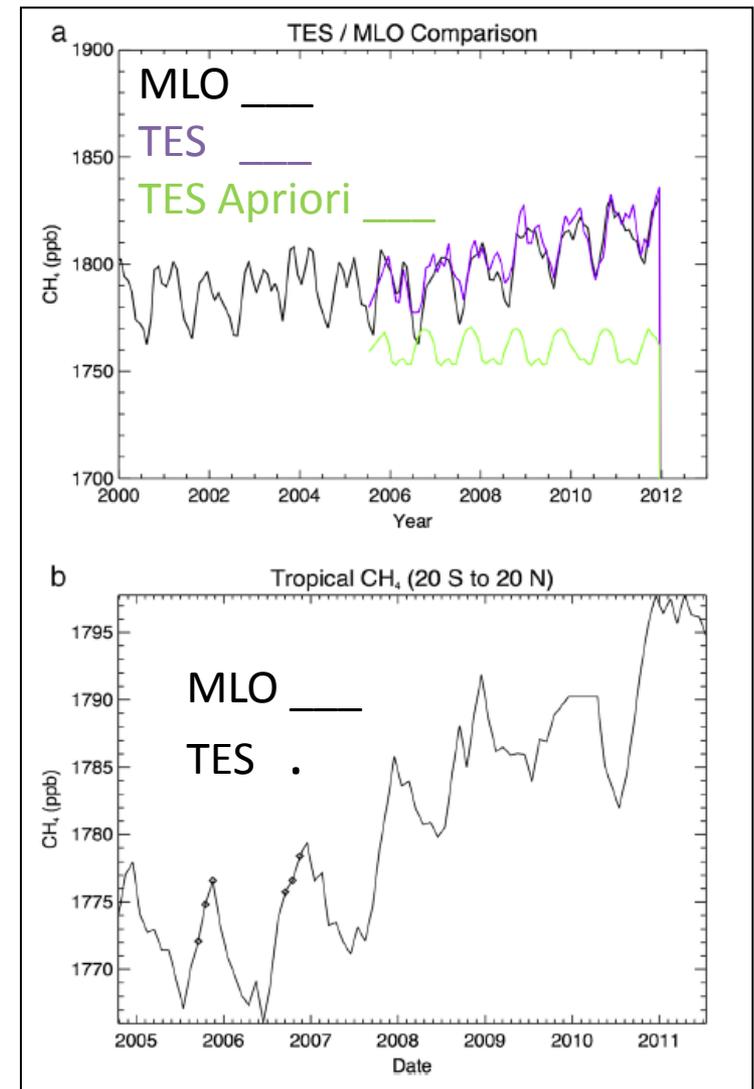
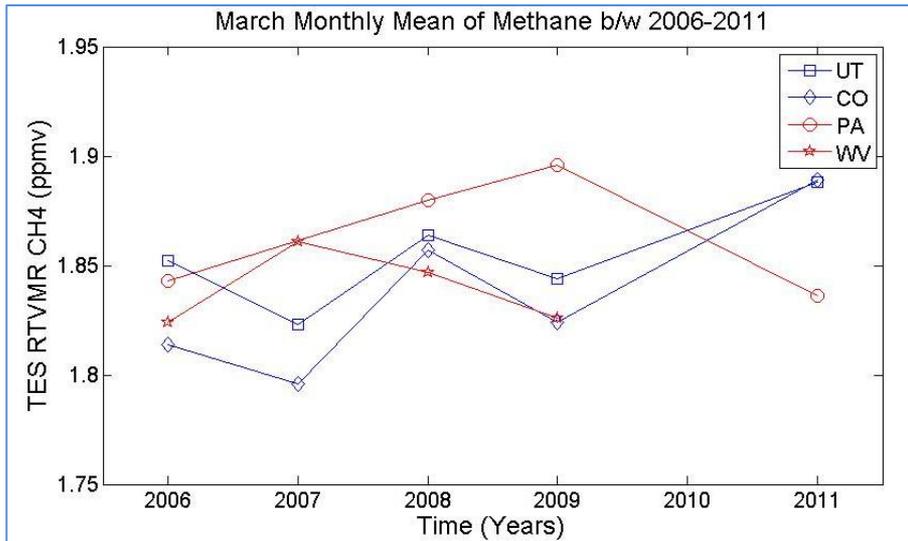


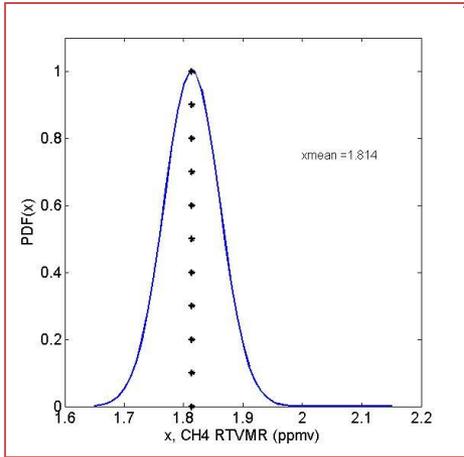
Figure 4 from Worden et al. ,GRL, 2013.

TES annual CH₄ time series for individual states

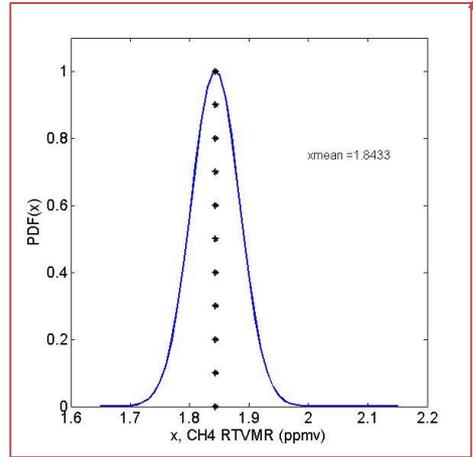
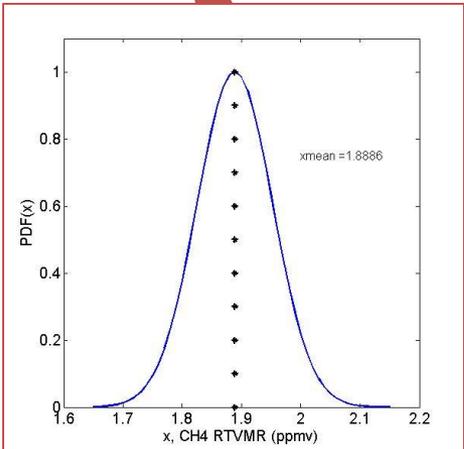
- During late winter/early spring, Colorado (CO) and Utah (UT) CH₄ increases gradually by ~ 4% from 2006 to 2011.
- CH₄ in Pennsylvania (PA) does not show a gradual increase in concentrations although large variability is evident.



2006 CO Methane RTVMR

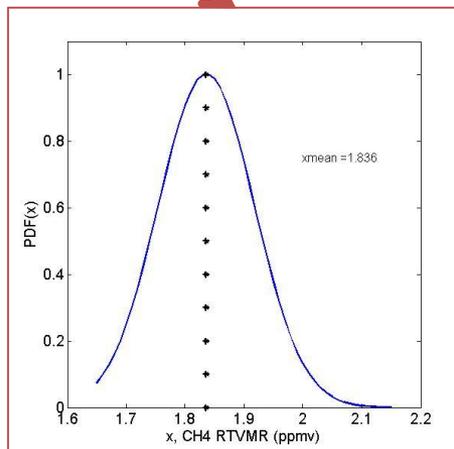


2011

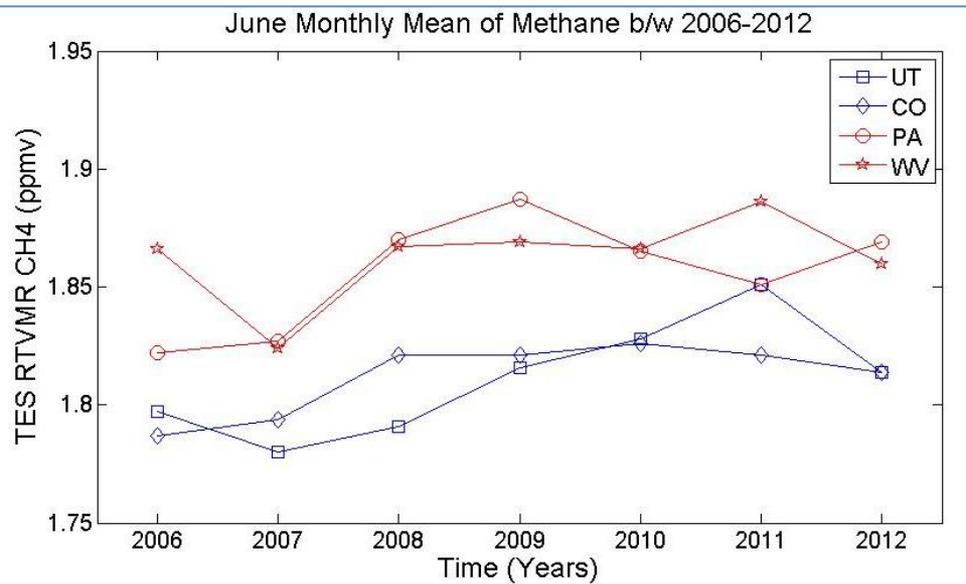


2011

2006 PA Methane



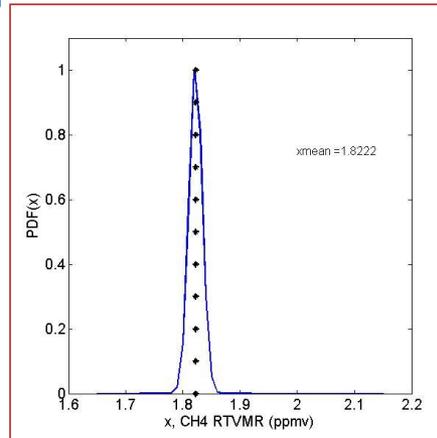
TES annual CH₄ time series for individual states



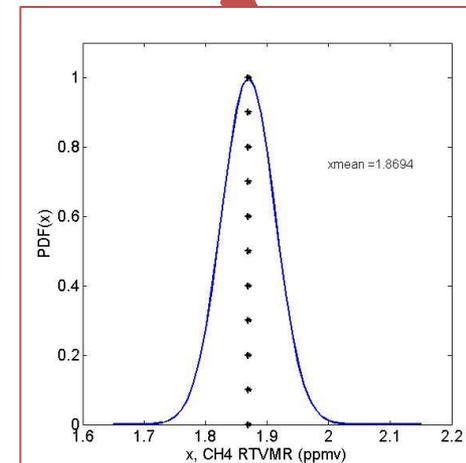
- Mean June RTVMR of CH₄ shows ~2% increase over PA between 2006-2012.
- Distributions show larger variability in 2012 compared to 2006 for PA too.

- Preliminary time series show seasonal differences between two regions of interest.
- Continuance of this work will include main regions discussed.

2006 PA Methane RTVMR

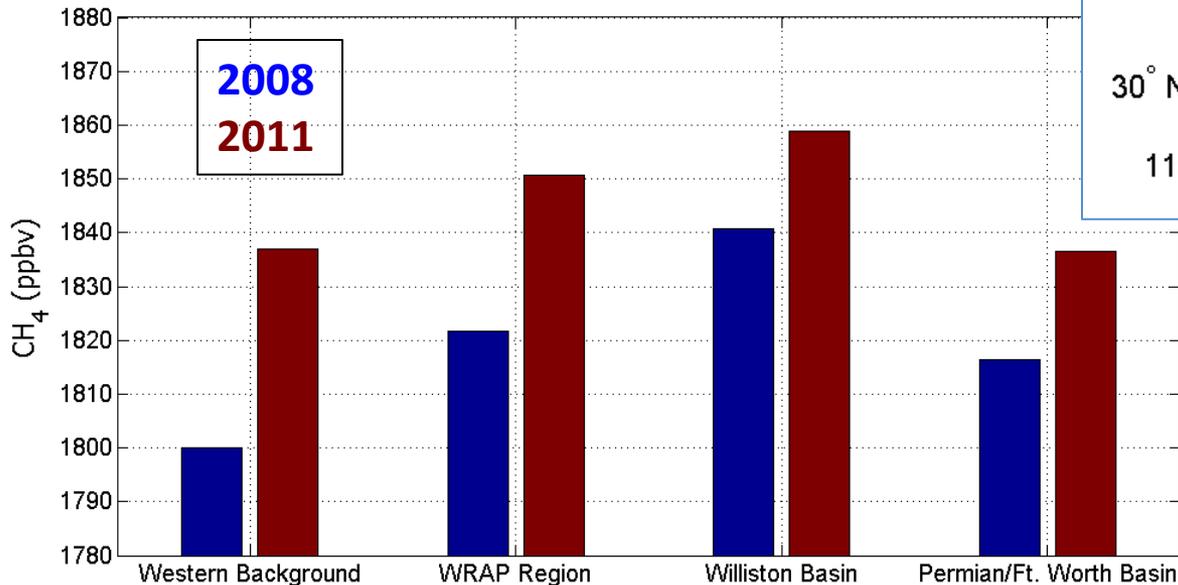
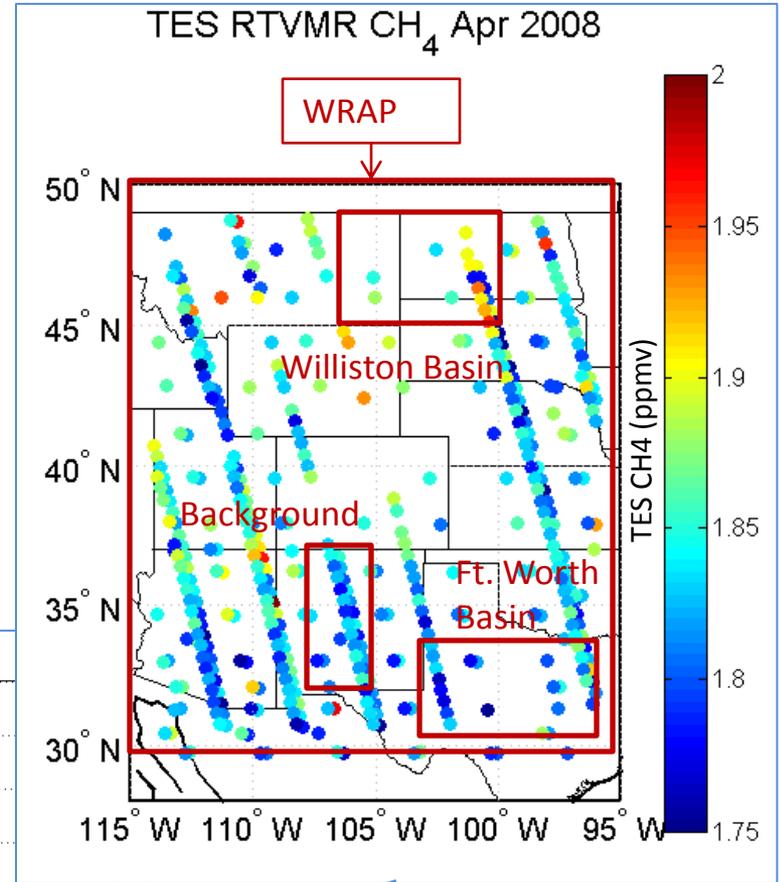


2012



Comparisons of 2008 and 2011 TES CH₄ RTVMR

- Preliminary comparisons of 2008 vs 2011 from TES demonstrate increasing CH₄ burdens.
- Our background region sees the largest change in concentration from 2008 to 2011, ~ 40 ppbv.
- Both Basins averaged ~ 20 ppbv increase in CH₄ from 2008 to 2011.



Development of spatially enhanced NO₂ column for evaluation of O&G emissions

Objective: Work with the WRAP, CenSARA, CDPHE, BLM and EPA Region 8 to use satellite data to evaluate the Oil and Gas (O&G) modeled emission inventories within the major O&G basins in the Western US and high resolution air quality modeling. Starting point is to evaluate emissions modeling data fields from 2008 [WestJumpAQMS](#) for all NO₂ area sources and Phase III O&G NO₂ sources (area + point)

Outcome: Improved constrains on Oil and Gas emissions used by States and EPA

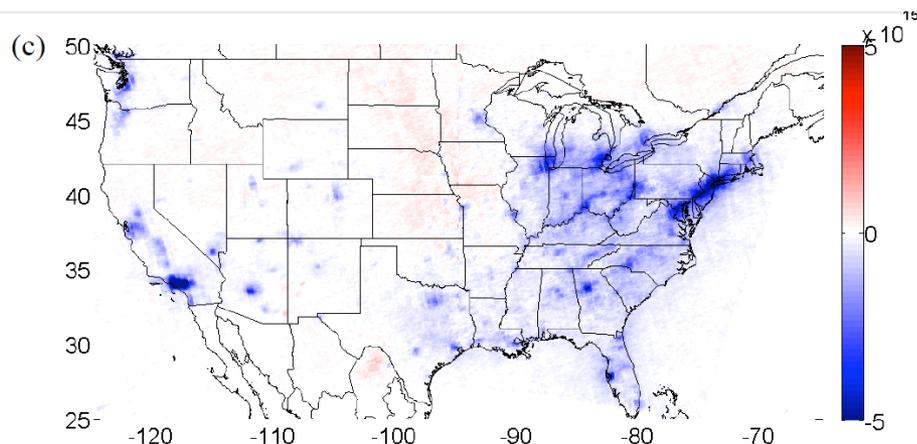
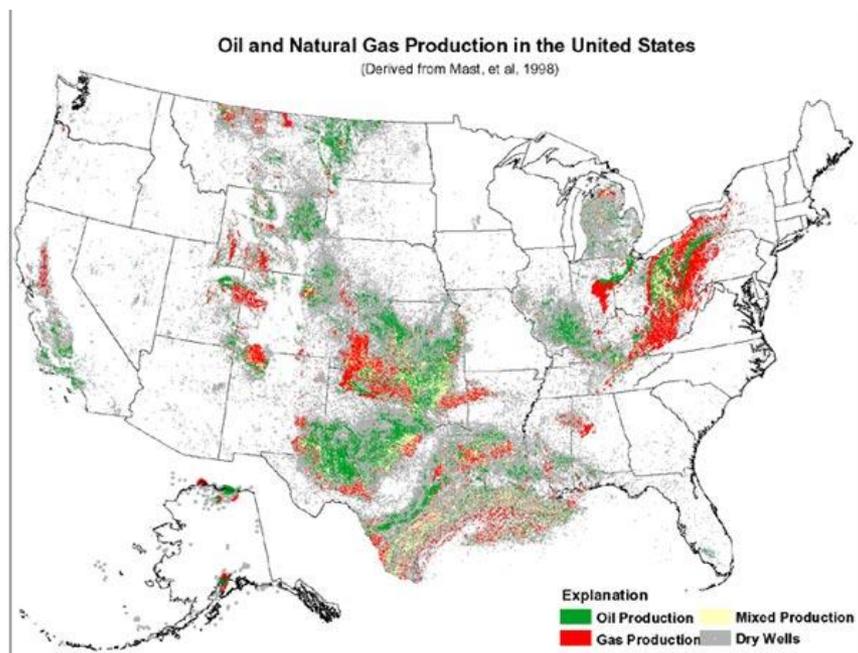


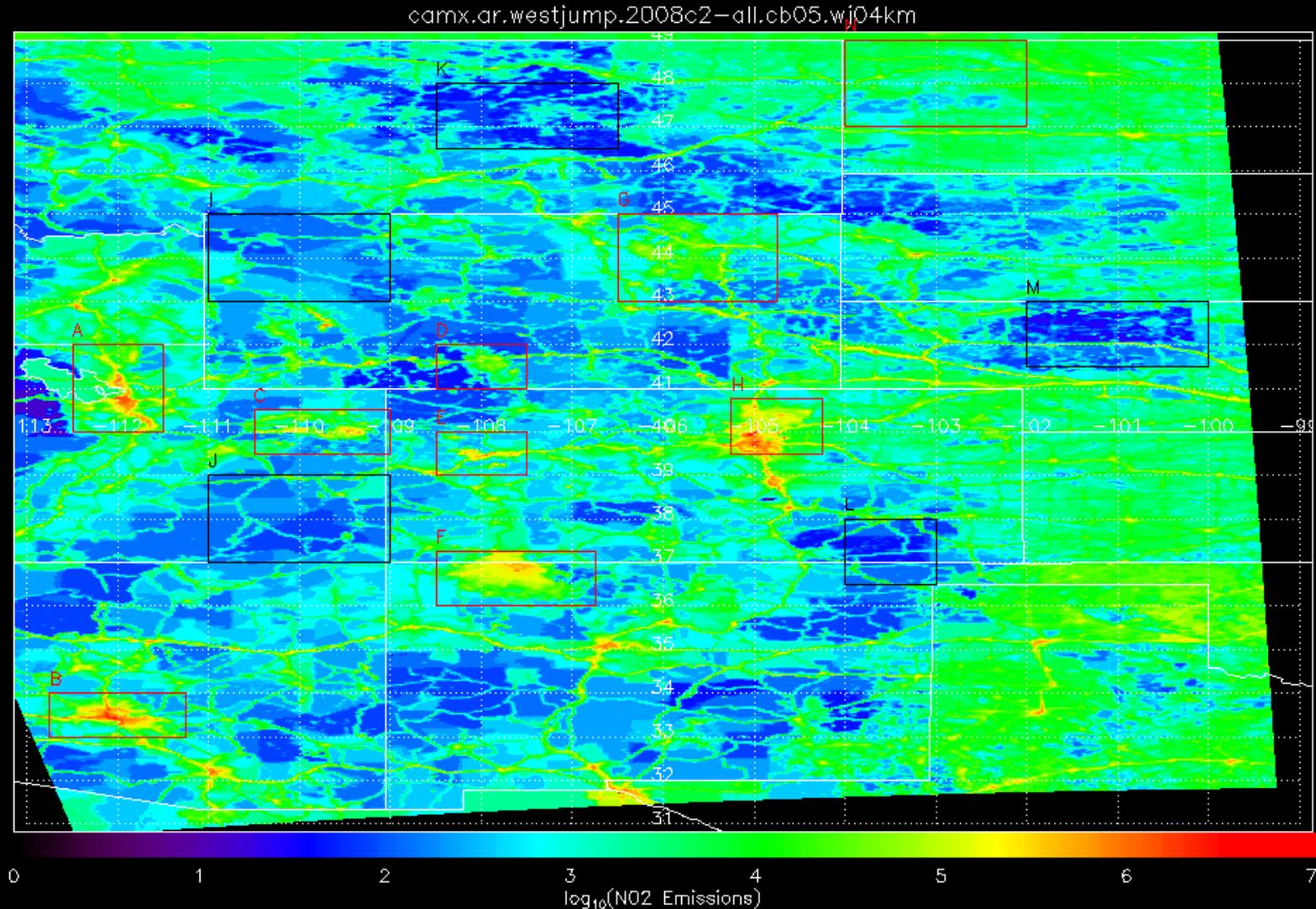
Fig. 1. Average summertime (April–September) OMI BEHR NO₂ column densities (molecules cm⁻²) for (a) 2005, (b) 2011, and (c) the difference, 2011–2005.

First Step: Investigate statistical relationship between WRAP Phase III NO₂ emissions used in WestJumpAQMS and OMI BEHR* NO₂ retrieval at native OMI pixel resolution (13 km 24 km at nadir)

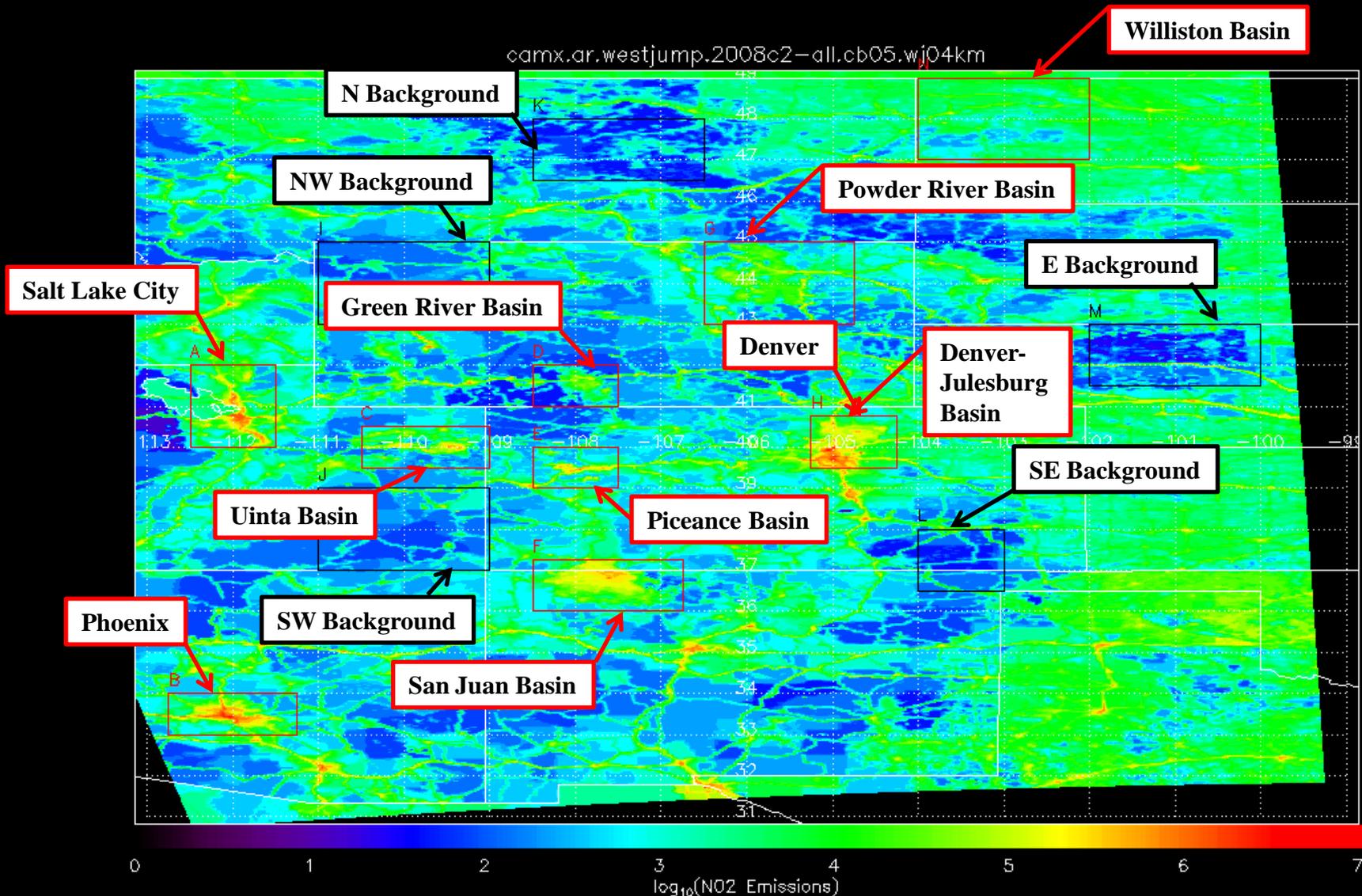
- Identify regions of interest (urban areas with well constrained emissions, O&G areas, and background areas for null cases)
- Aggregate WRAP Phase III 4km modeled emissions within individual OMI BEHR NO₂ pixels (filter by cloud radiance <30%)
- Conduct statistical analysis to determine sensitivity of OMI NO₂ column to modeled NO₂ emissions
- Compare 2008 and 2011 OMI NO₂ columns to characterize regional trends

*Berkeley High Resolution OMI NO₂ (BEHR, <http://behr.cchem.berkeley.edu/TheBEHRProduct.aspx>)

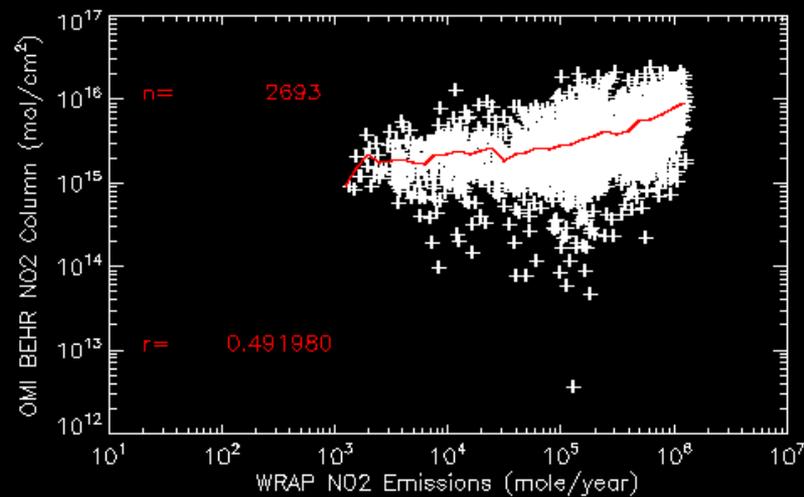
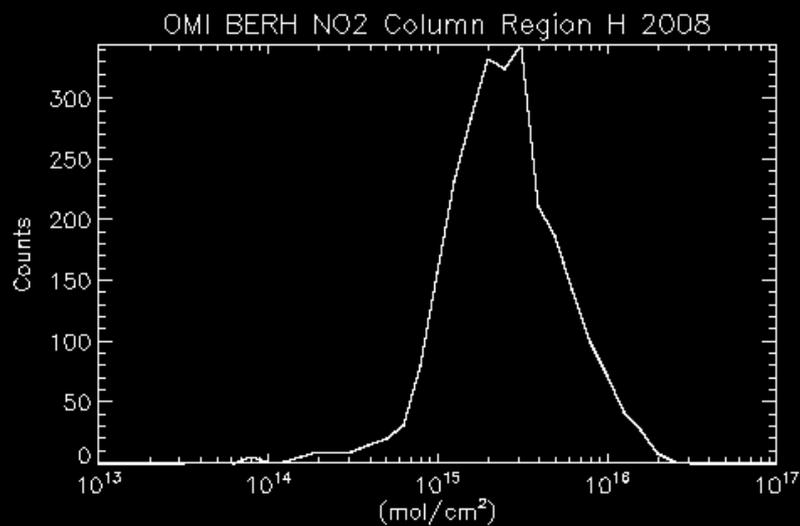
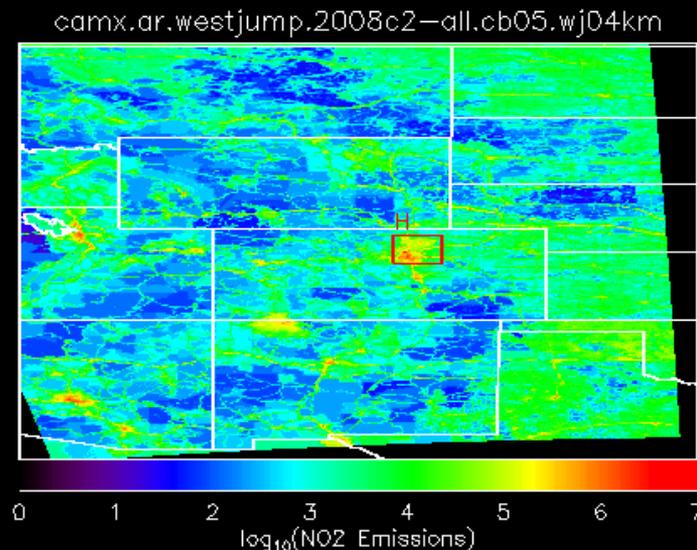
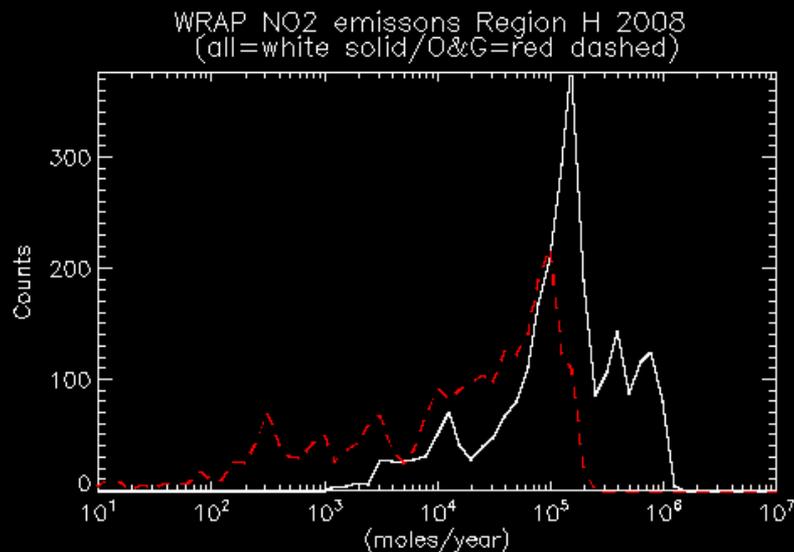
WRAP WestJumpAQMS Phase III O&G NO2 modeled/gridded emissions-(all area sources)



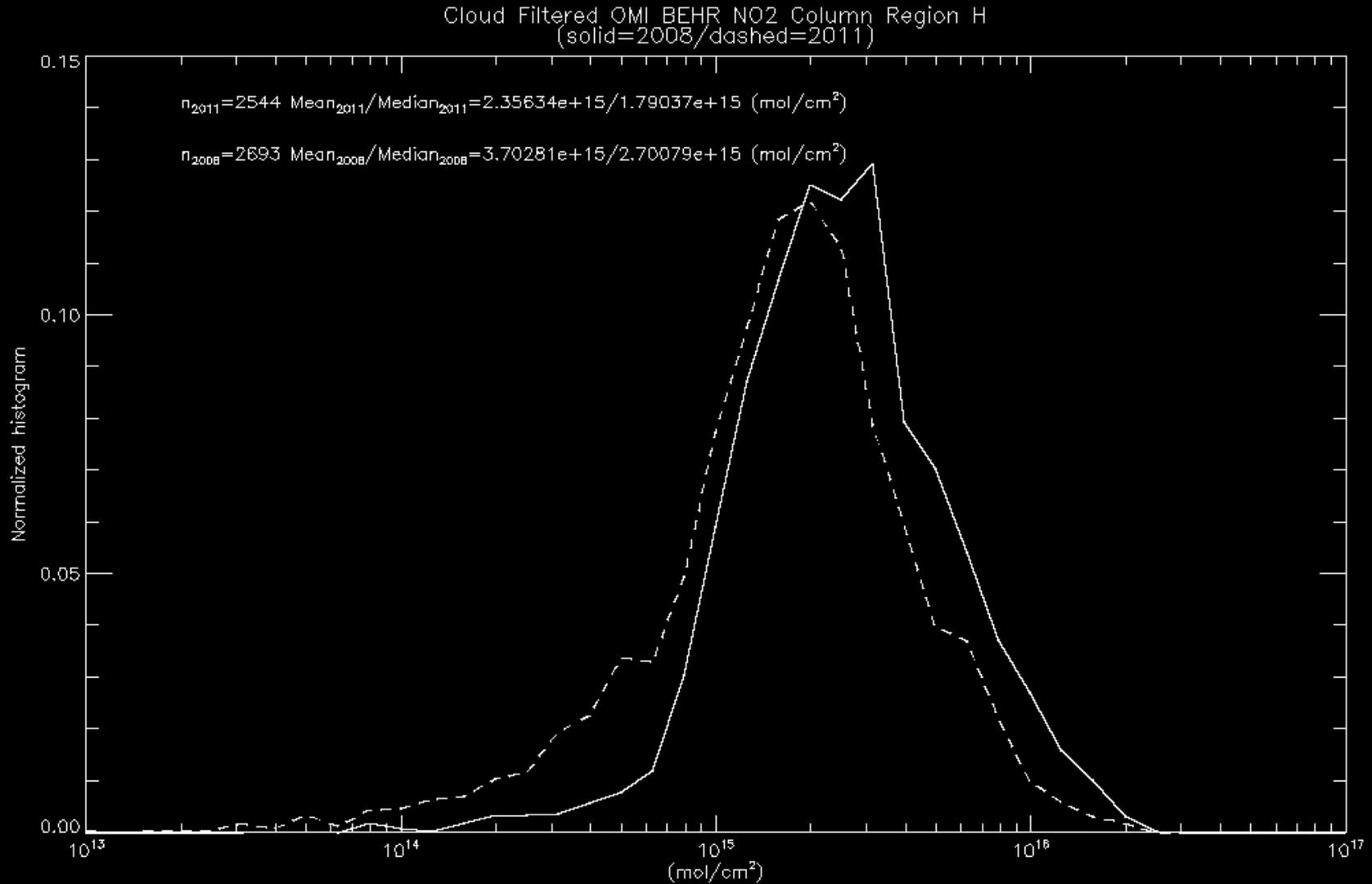
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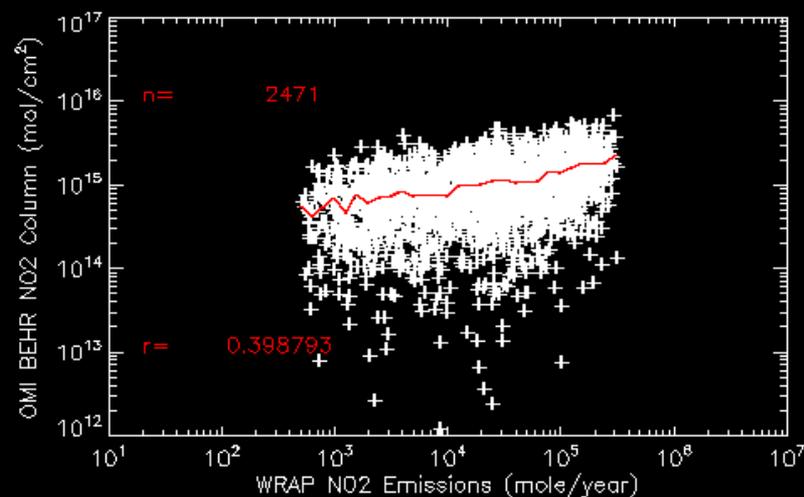
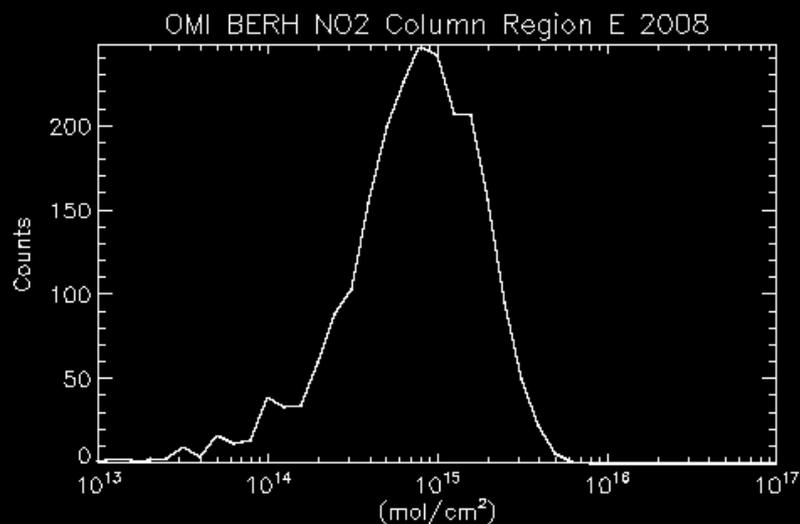
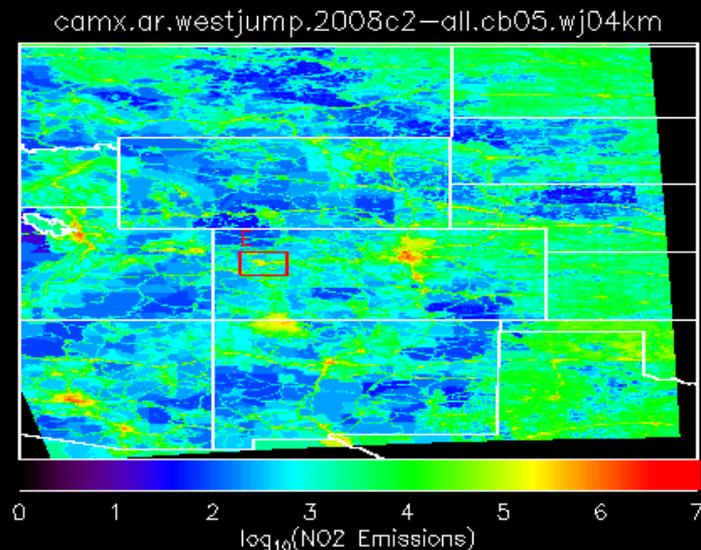
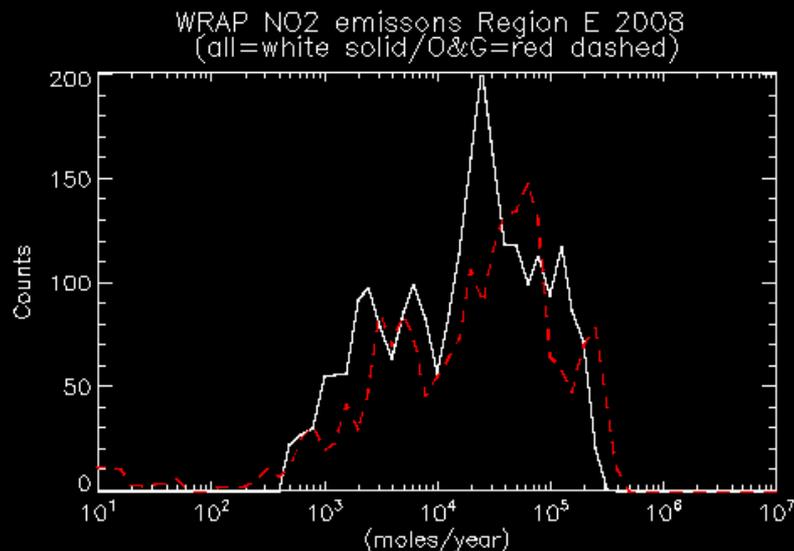
Aggregated WRAP WestJumpAQMS Area Source 2008 NO2 modeled/gridded emissions vs OMI BEHR NO2 column Region H: Denver/Denver-Julesburg Basin



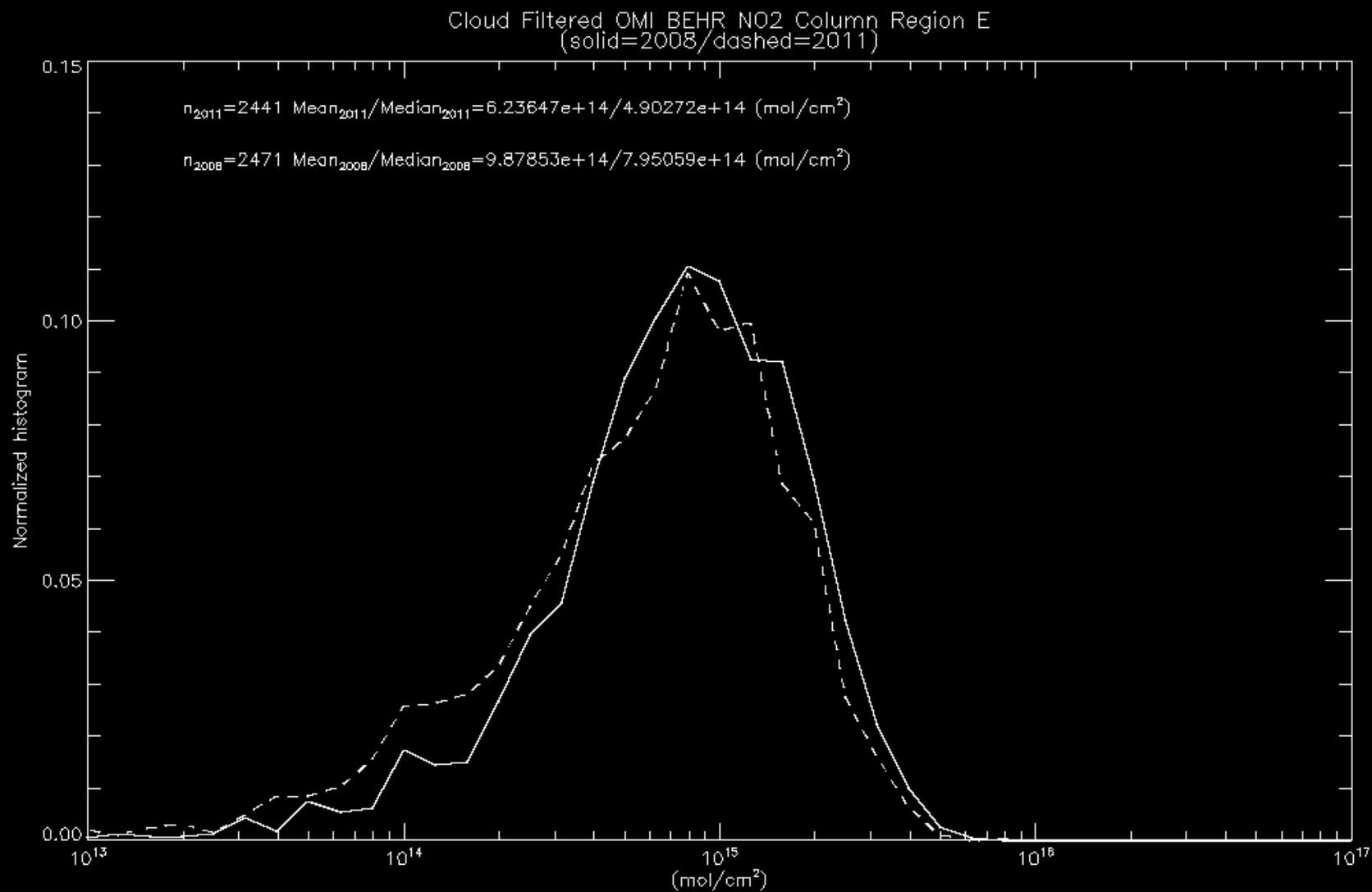
2008 vs 2011 OMI BEHR NO2 column Region H: Denver/Denver-Julesburg Basin



Aggregated WRAP WestJumpAQMS Area Source 2008 NO2 modeled/gridded emissions vs OMI BEHR NO2 column Region E: Piceance Basin

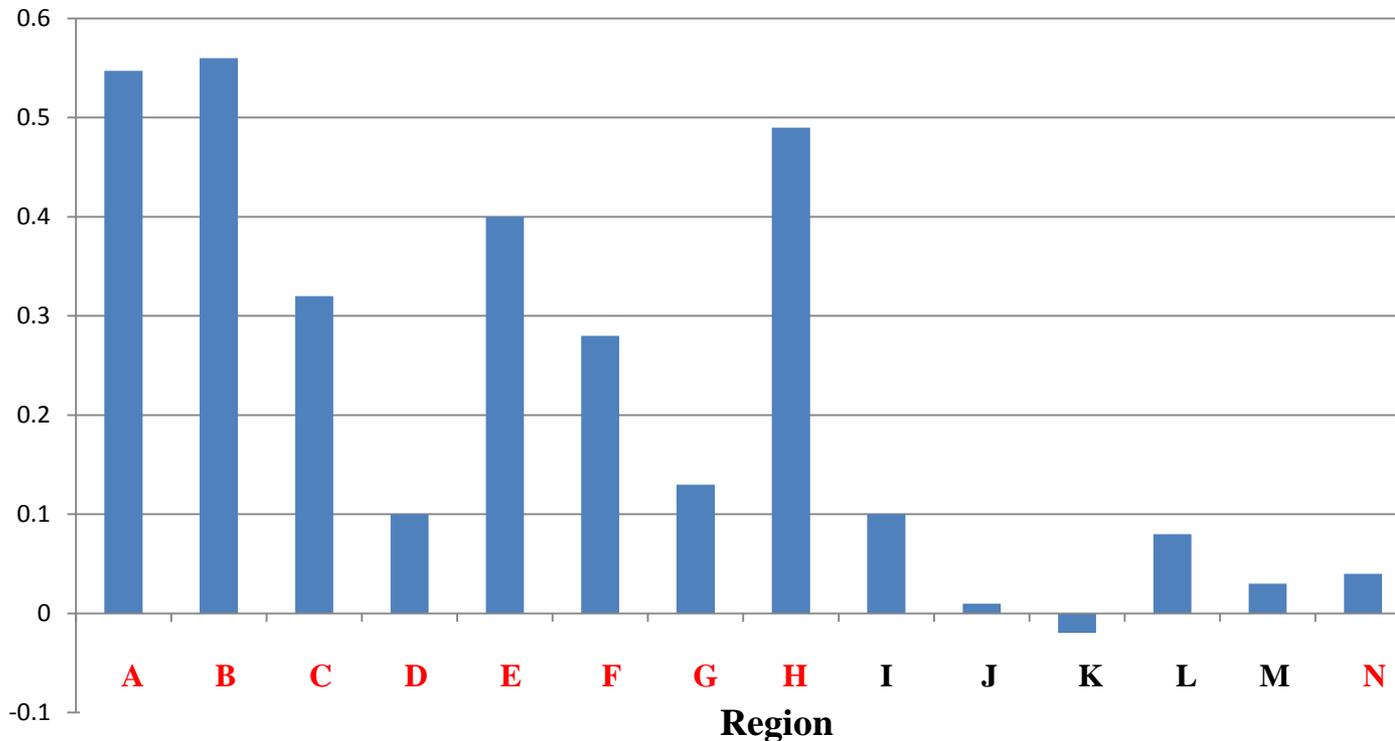


2008 vs 2011 OMI BEHR NO2 column Region E: Piceance Basin



Summary of Regional Correlations 2008

2008 WRAP Phase III NO₂ emissions and OMI BEHR NO₂
Correlation



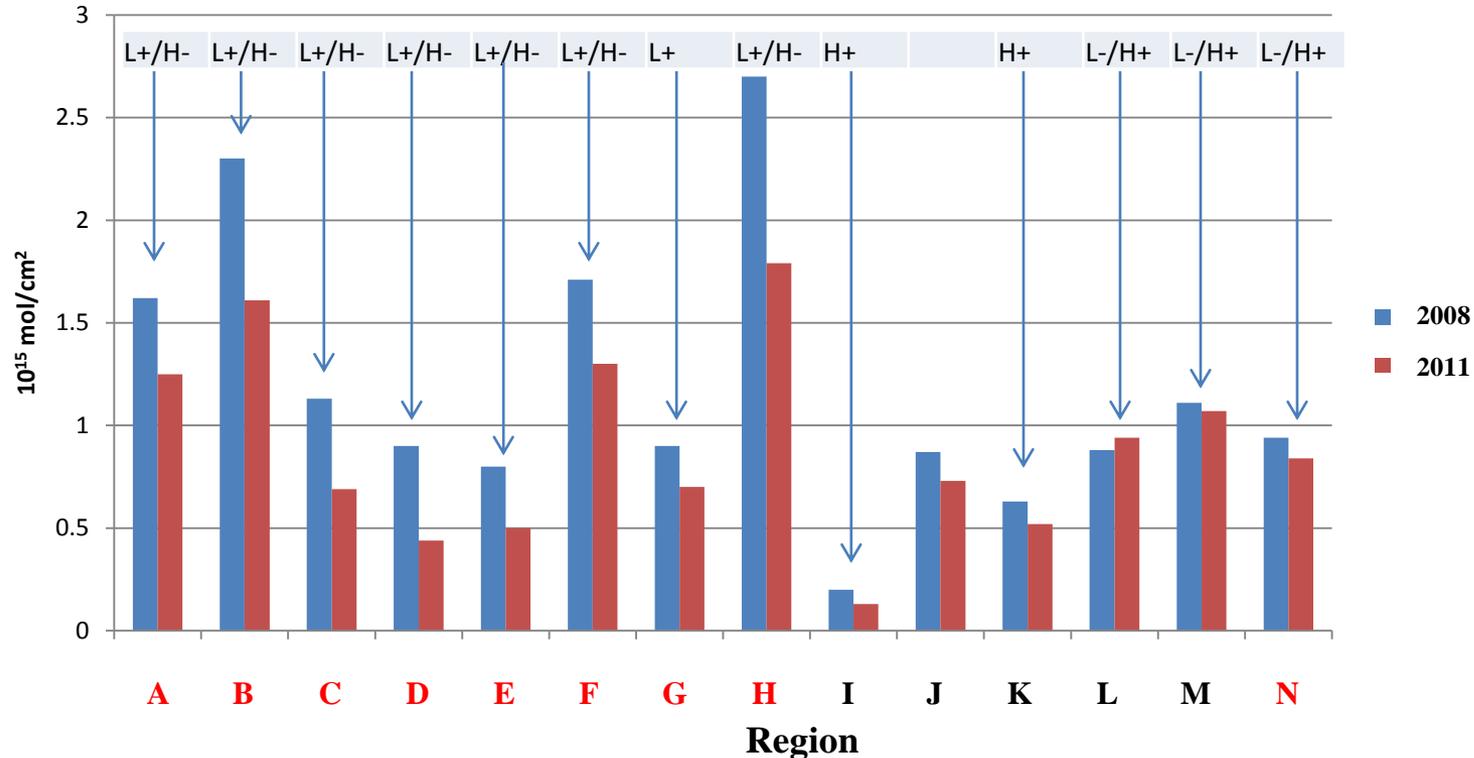
A= Salt Lake City
B=Phoenix
C=Uinta Basin
D=Green River Basin
E=Piceance Basin
F=San Juan Basin
G=Powder River Basin
**H=Denver/Denver-
Julesburg Basin**
I=NW Background
J=SW Background
K=Northern Background
L=SE Background
M=Eastern Background
N=Williston Basin

- Reasonable (~ 0.5 or above) spatial correlations with 2008 [WestJumpAQMS](#) urban NO₂ area emissions (A, B, H)

- Some skill ($r \sim 0.3$) in capturing the spatial variability in Uinta, Piceance and San Juan Basin NO₂ O&G area+point emissions (C, E, F)

Summary of Regional Trends 2008 vs 2011

Median OMI BEHR Column NO2 2008 vs 2011



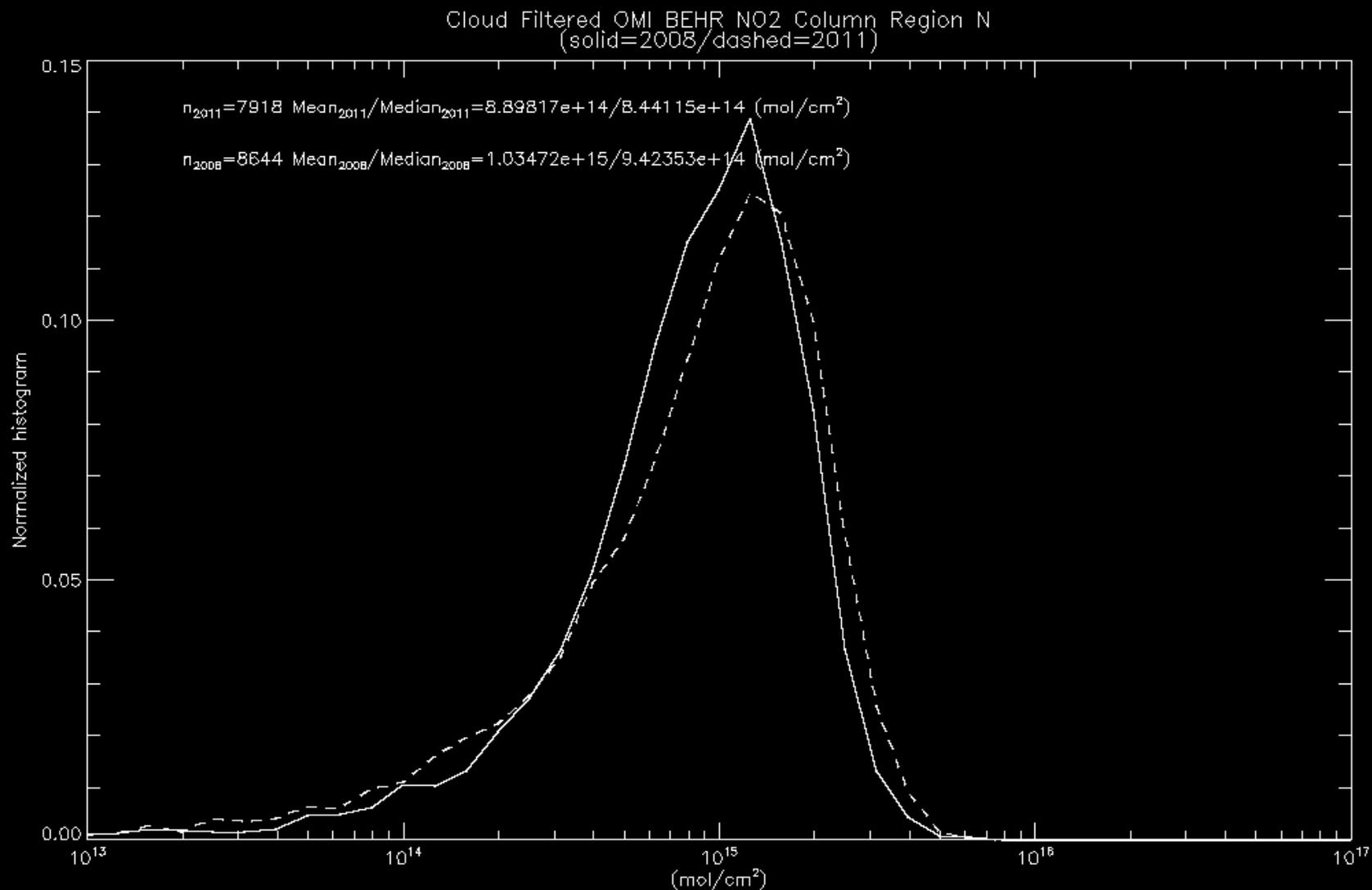
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- M=Eastern Background**
- N=Williston Basin**

- General declines in mean and median NO2 columns within the WestJumpAQMS domain between 2008 and 2011.

- Eastern and SE background and Williston Basin show (decrease/increase) in the frequency of (low/high) NO2 columns, respectively

L+=low end of distribution increases
L-= low end of distribution decreases
H+=high end of distribution increases
H-= low end of distribution decrease

2008 vs 2011 OMI BEHR NO2 column Region E: Williston Basin



Second Step: Investigate relationship O&G emissions and SNPP VIIRS Day Night Band (DNB) radiances (2012 cloud free composite, 15 arc second resolution)

- Conduct spatial analysis to determine if VIIRS DNB can be used as a Spatial Allocation Surrogate for O&G emission inventories
- Identify locations of potential missing O&G sources

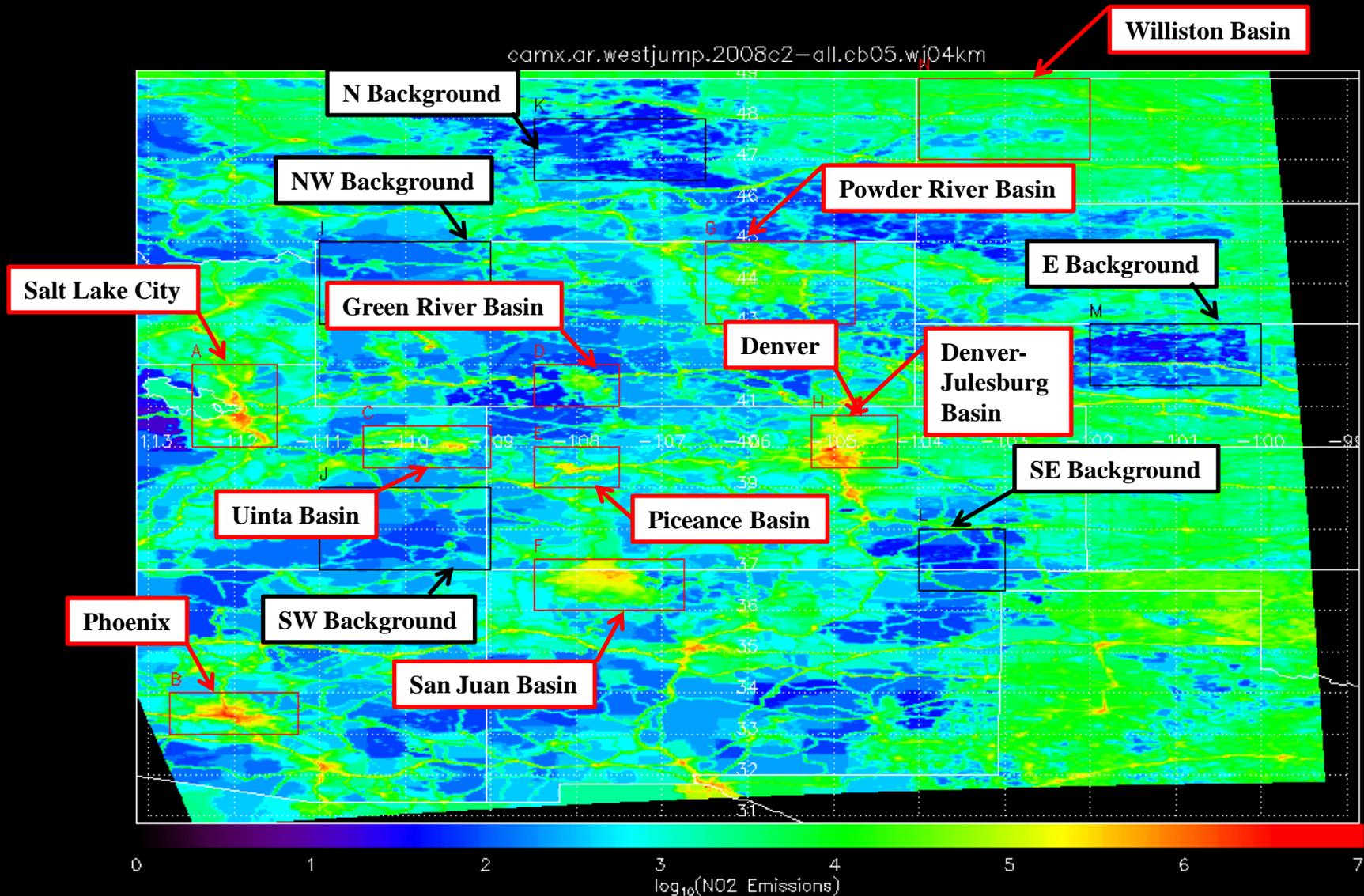
VIIRS DNB

SNPP VIIRS cloud-free composite (2012/4/18-26 and 2012/10/11-23) DNB data on 15 arc sec grid from Earth Observation Group, NOAA National Geophysical Data Center in GEOTIFF format

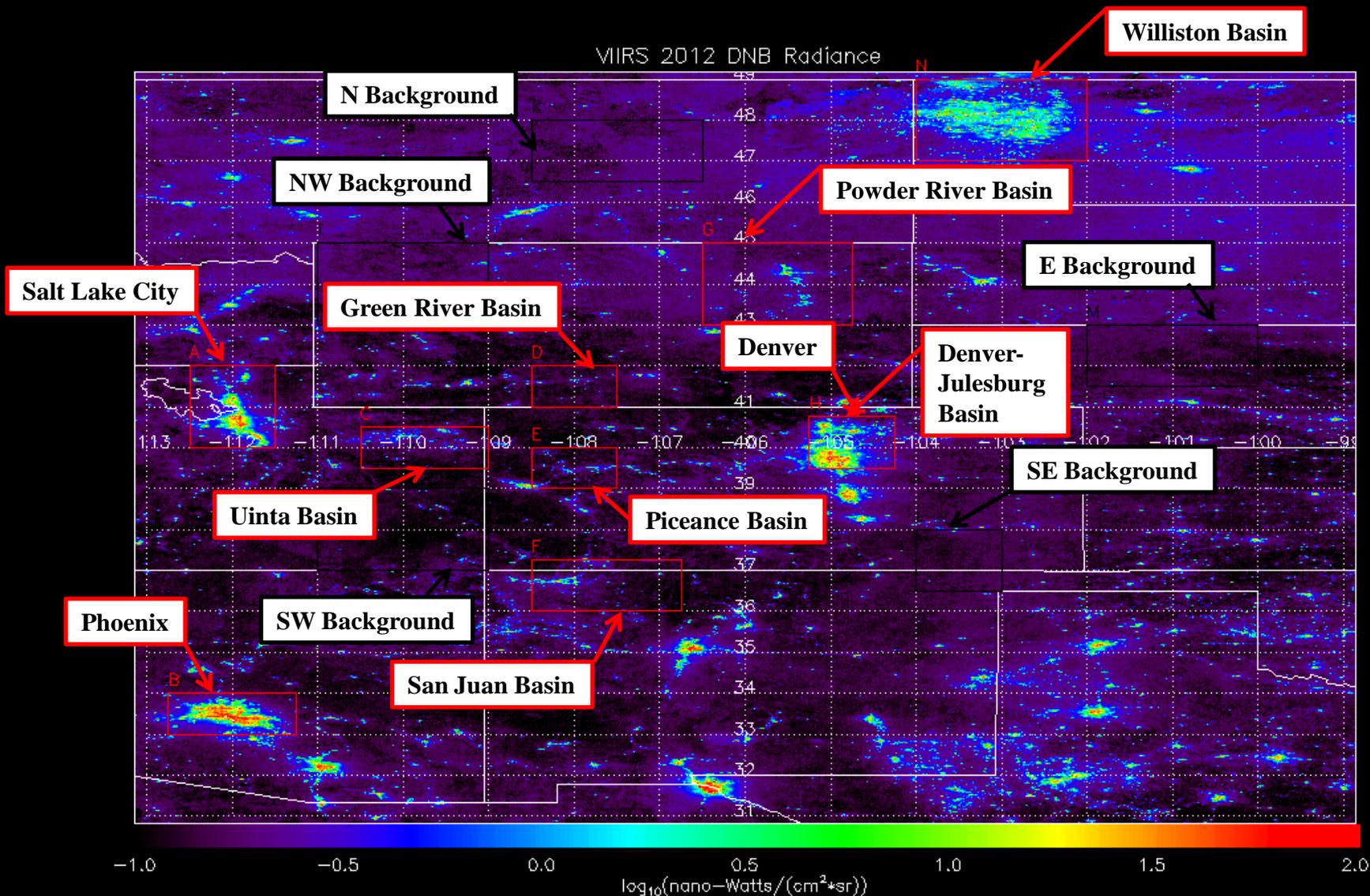
WRAP Phase II total NO2 emissions inventory

(4km all area sources)

Provided by Tom Moore (WRAP)

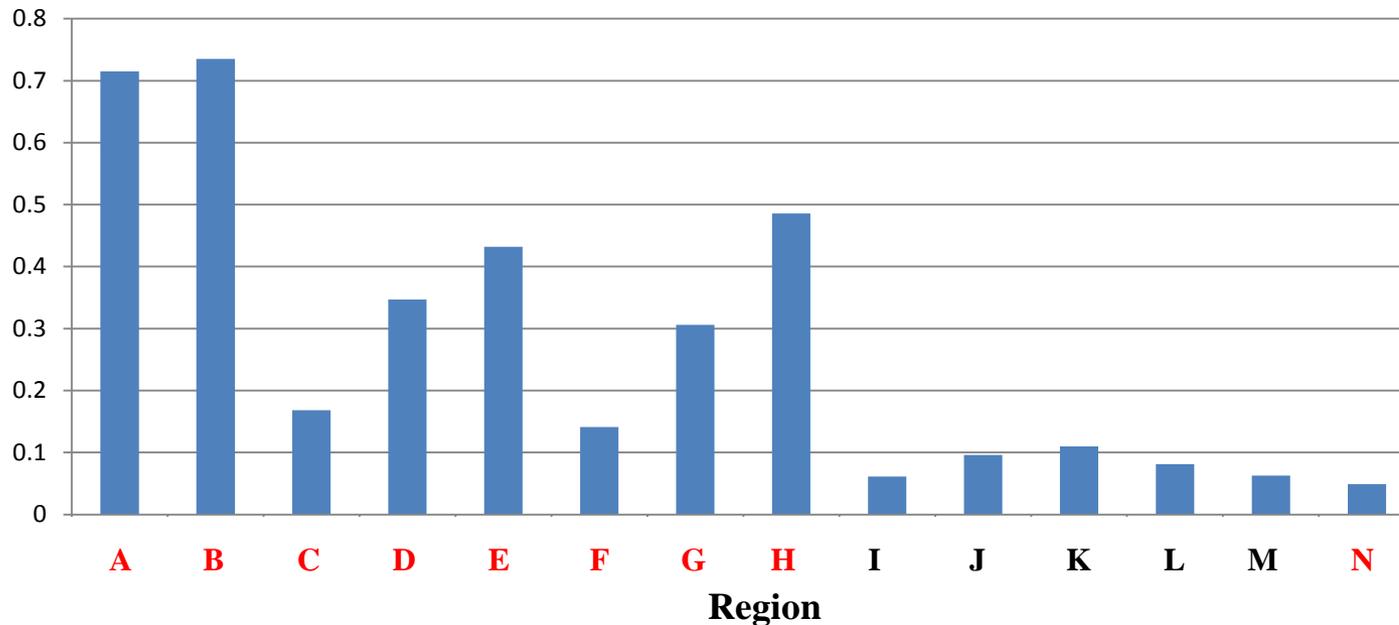


VIIRS DNB cloud cleared radiance composite (2012/4/18-26 and 2012/10/11-23) (15 arc second) Provided by NOAA NGDC



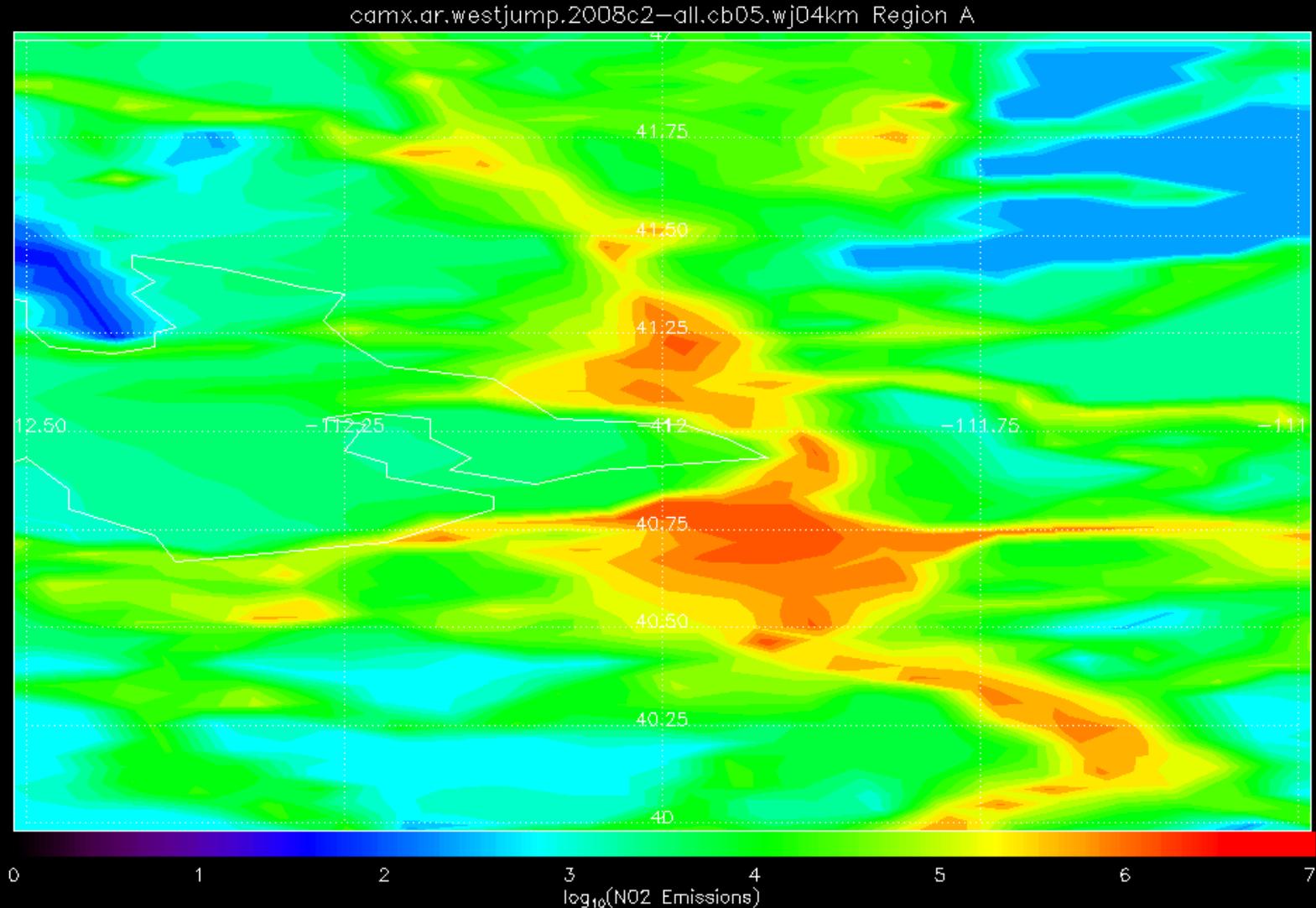
Summary of Regional Correlations 2008 and 2012

Correlation between 2008 WRAP Phase III NO₂ emissions and VIIRS 2012 DNB Radiance



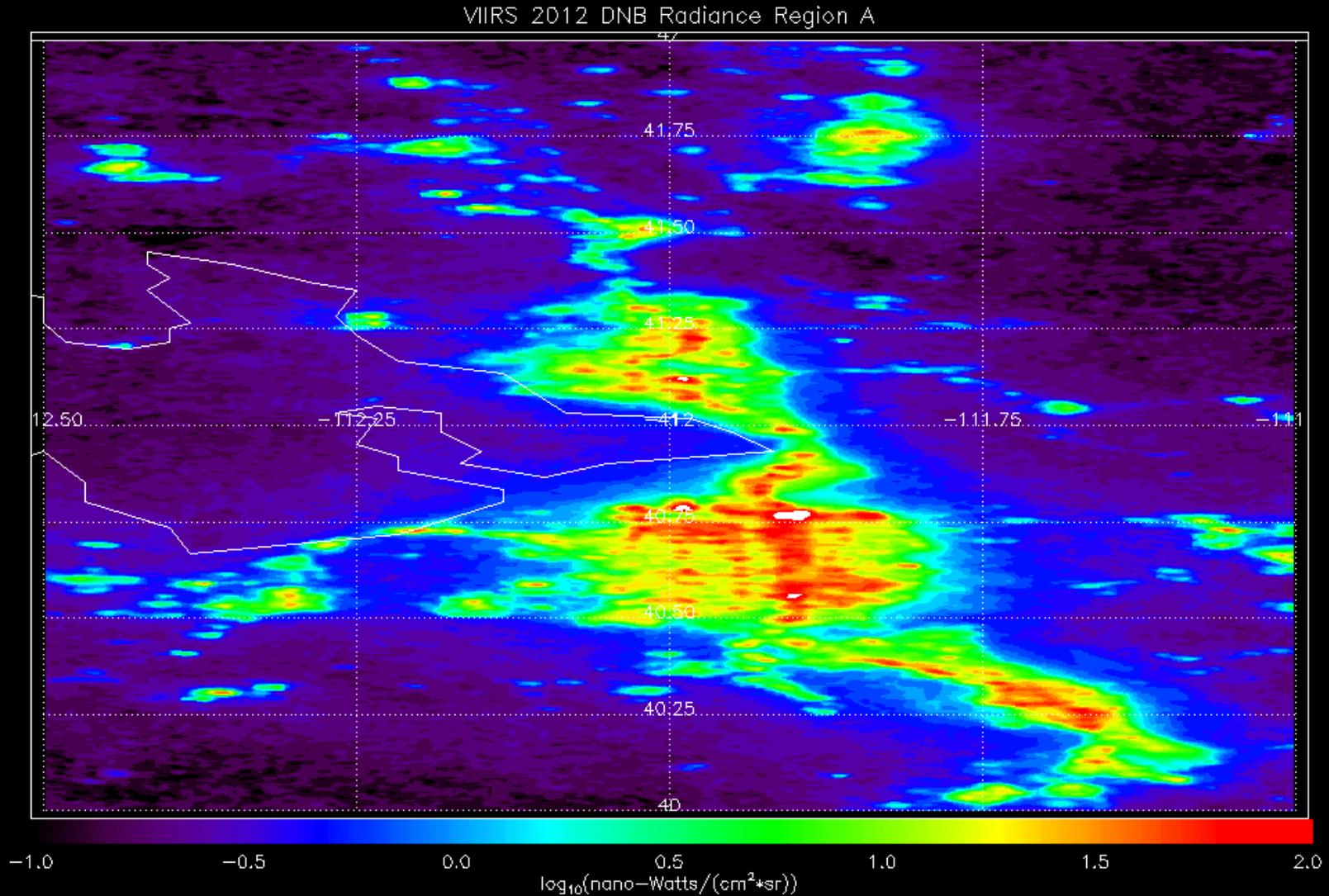
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N=Williston Basin

WRAP WestJumpAQMS Phase III O&G NO2 modeled/gridded emissions-(all area sources) Region A: Salt Lake City

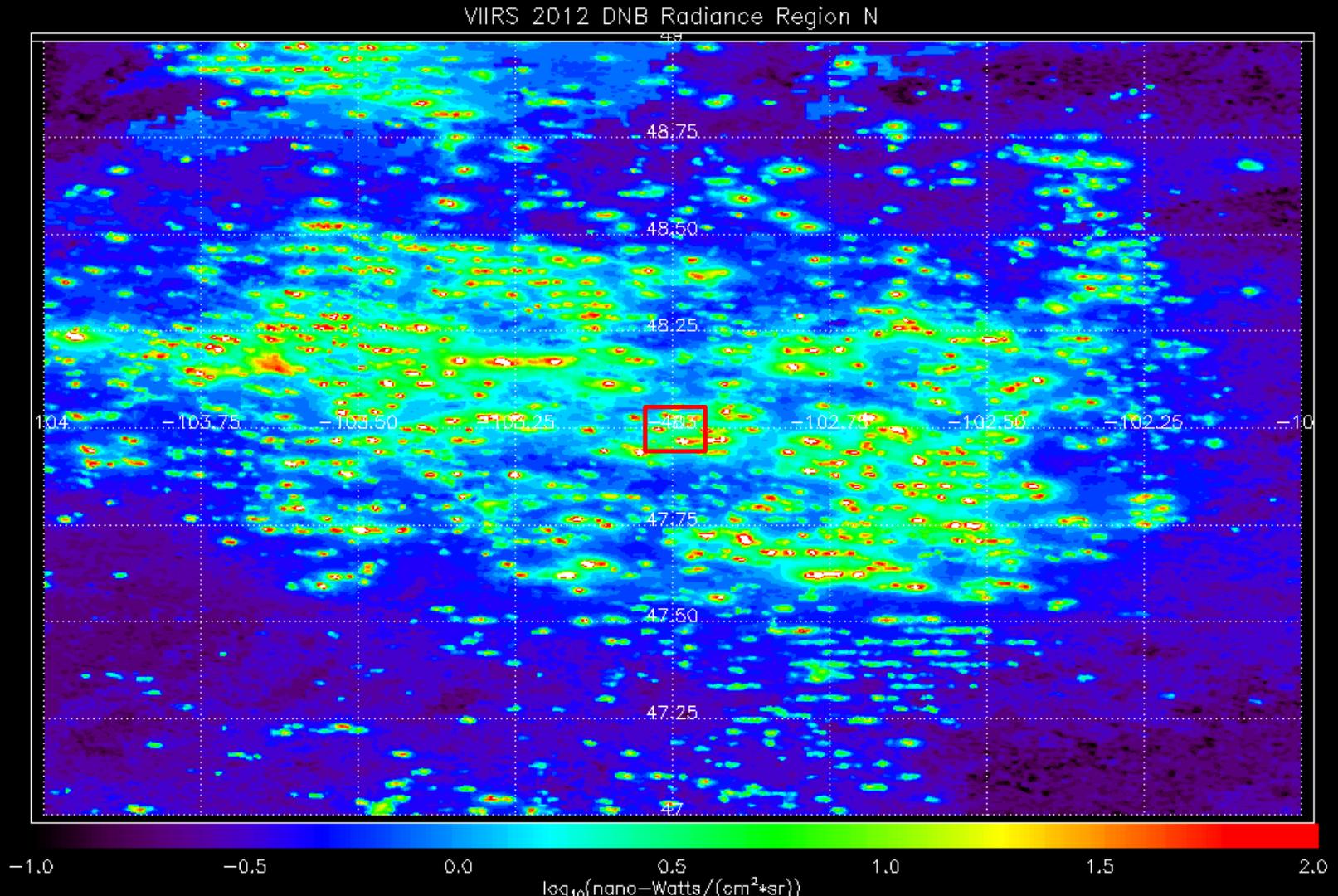


Composite 2012 VIIRS Day-Night-Band Radiances

Region A: Salt Lake City



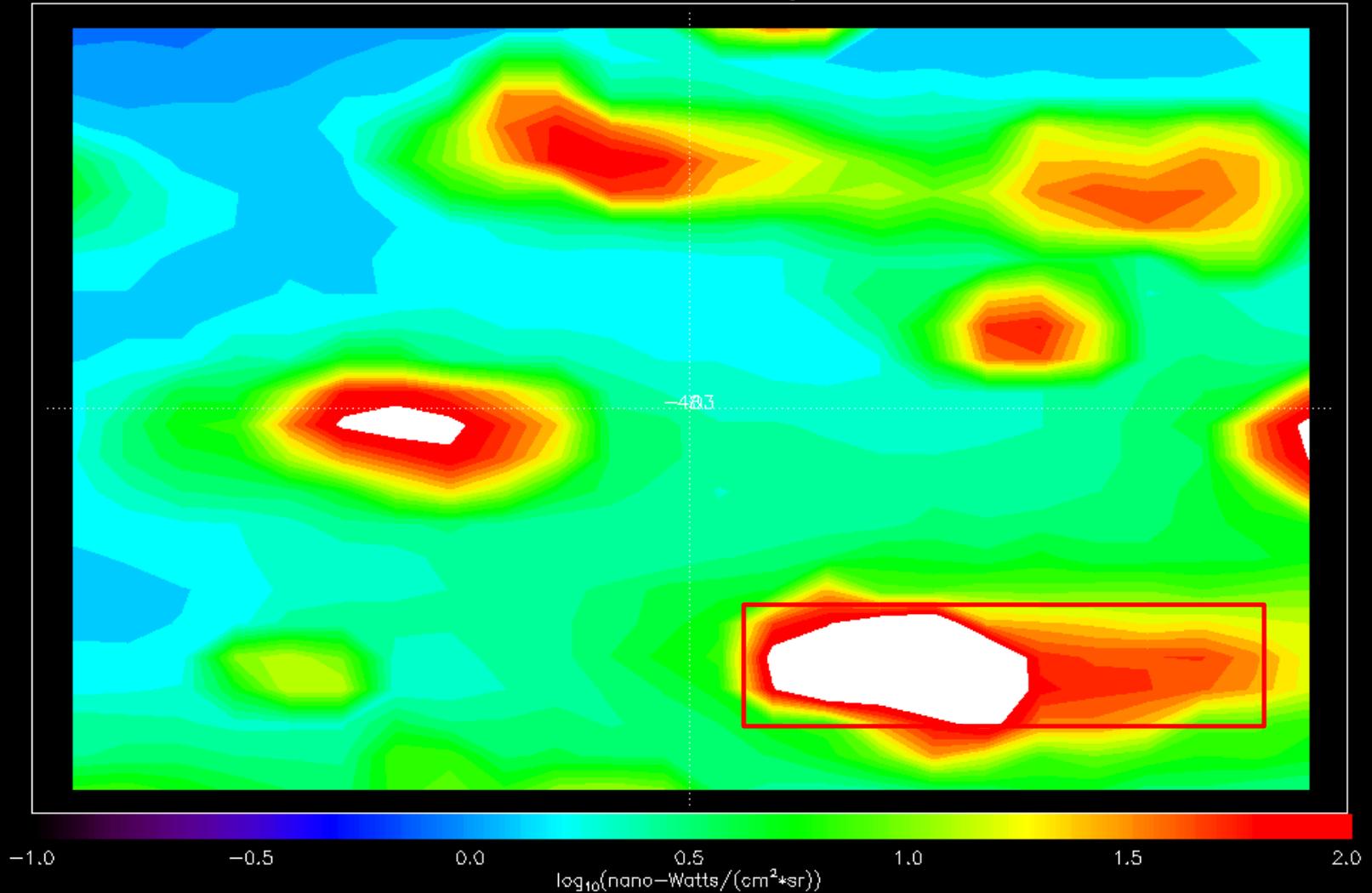
2012 VIIRS DNB Radiance Region N: Williston Basin



2012 VIIRS DNB Radiances

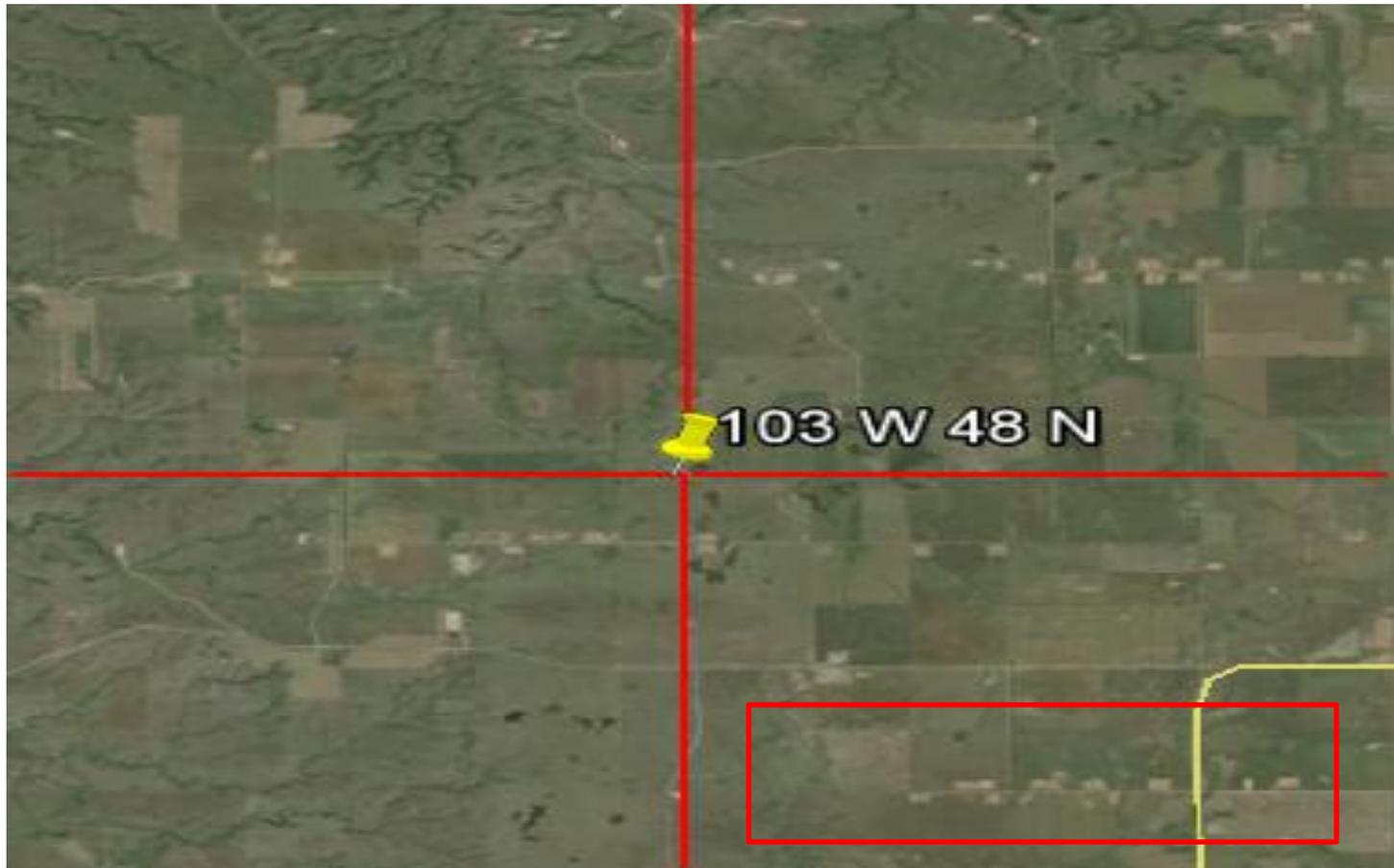
Region N: Williston Basin (103W 48N 0.1° Zoom)

VIIRS 2012 DNB Radiance Region N_zoom



Google Earth

Region N: Williston Basin (103W 48N 0.1° Zoom)



Google Earth Zoom

Region N: Williston Basin



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Google Earth Zoom Region N: Williston Basin



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Summary

- **TES Carbon Gas Studies**
 - Past DISCOVER-AQ campaigns in MD (2011), TX (2013), and CA (2013) serve as validation for carbon gas products from the Tropospheric Emission Spectrometer (TES) and others like GOSAT. So far, there is reasonable correlation between aircraft measurements and satellites.
 - Preliminary comparisons of 2008 vs 2011 from TES demonstrate increasing CH₄ burdens overall with percent change varying between regions. Carbon gas correlations will assist with source attribution in these regions.
- **OMI BEHR NO₂ Studies**
 - Ozone Monitoring Instrument (OMI) Berkley High Resolution (BEHR) NO₂ column retrievals show reasonable (~0.5 or above) spatial correlations with 2008 [WestJumpAQMS](#) urban NO₂ area emissions and some skill (r~0.3) in capturing the spatial variability in Uinta, Piceance and San Juan Basin (NO₂ O&G area+point emissions).
 - Regional comparisons between the 2008 and 2011 OMI BEHR NO₂ retrievals shows general declines in mean and median NO₂ columns within the WestJumpAQMS domain. However, Eastern and SE background and Williston Basin shows a decrease in the frequency of low NO₂ columns and an increase in the frequency of high NO₂ columns.
- **VIIRS DNB Studies**
 - 2012 VIIRS Day-Night Band shows high (>0.7) spatial correlations with 2008 WestJump AQMS urban NO₂ area emissions for Salt Lake City and Phoenix and signatures of increased O&G activity within the Williston Basin that is most likely due to flaring activity due to the high radiances associated with well pads.
- **July-August FRAPPE/DISCOVER-AQ mission in Denver/Front Range will target O&G emissions and Air Quality impacts using extensive airborne, ground based, and mobile van measurements**
 - PSU NATIVE trailer and PI Anne Thompson will be at Platteville, CO conducting insitu trace gas/hydrocarbon measurements and launching ozonesondes.
 - UW-Madison SPARC trailer will be at NOAA BAO tower (Erie, CO) conducting remote trace gas and aerosol measurements and launching radiosondes.
- **Update at Upcoming June AQA Meeting in Boston at Harvard U.**