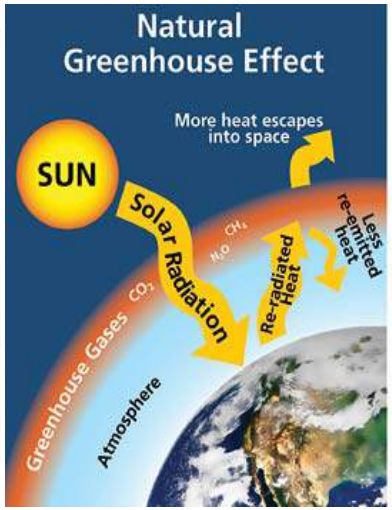
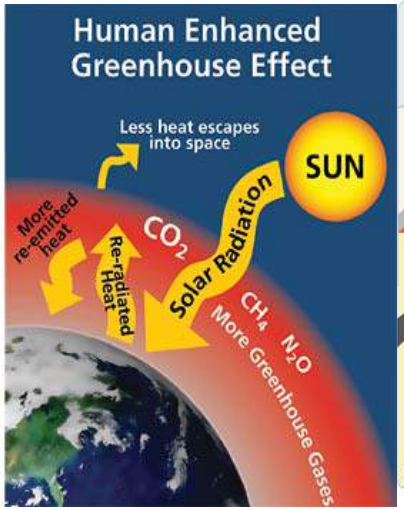
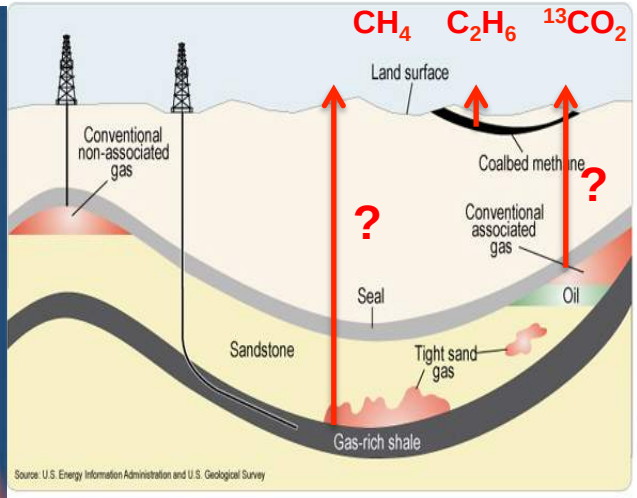
CO_2 & CH_4 Emission Verification by High Frequency Mesoscale Atmospheric Observations







Manvendra K. Dubey
EES-14 & IGPPS, LANL

dubey@lanl.gov

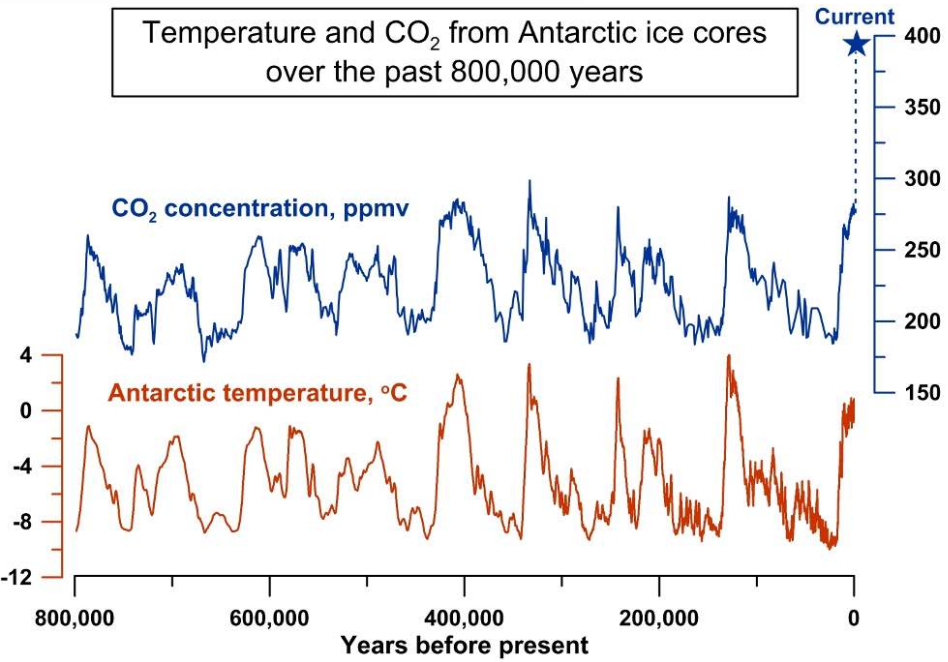
NASA CMS Atmospheric Verification Working Group, 4 Feb 2015

Outline: Tackle the Emission Verification Challenge

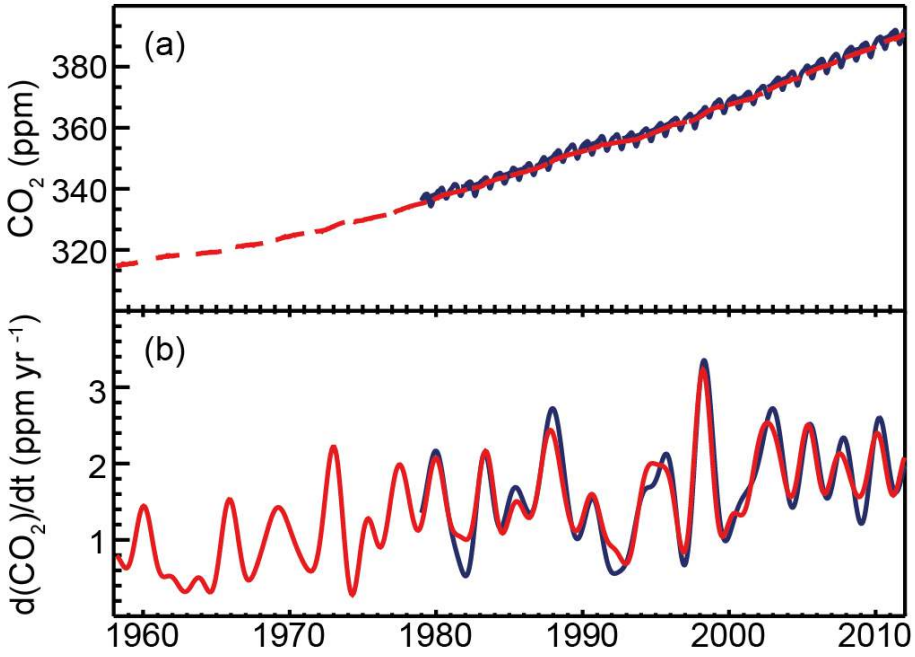
- Can we verify CO_2 emissions for trading or a treaty?
  - Four Corners power plant emission attribution & verification.
- Can we quantify CH_4 leaks from fossil fuel infrastructure
- Fugitive CH_4 leaks from hydraulic fracturing are a hot issue.
- Current Measurement Challenges
  - Large Meteorological variability (in situ)
  - Low frequency sampling (satellite)
- Solar absorption spectroscopy (e.g. TCCON, Pandora)
  - Mean Mesoscale (γ) 10km Column CO_2, CH_4 & NO_2 Observations
- Model and Empirical Analysis
  - High Resolution Forward Modeling with inventory (CEMS, EDGAR)
  - Emprirical tracer-trace relations for emission factor verification

Atmospheric CO_2 Paleo-climatic Variations and Rapid Growth in The Anthropocene

Ice core data from analysis of trapped bubbles

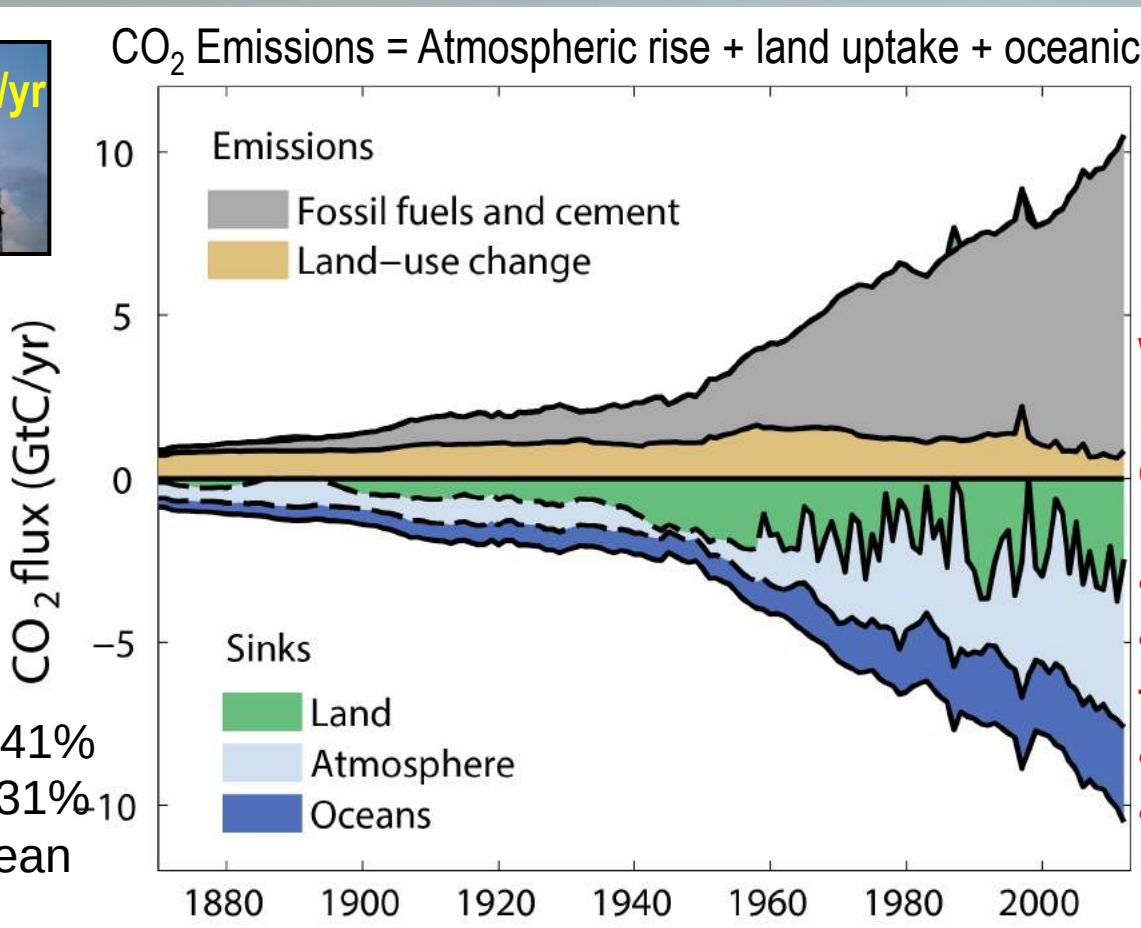


Real time *in situ* data from global networks



- CO_2 > 400ppm, 43% increase since 1750, highest in 0.8 million years
- Greenhouse gas that traps terrestrial IR to warm the earth
- Acidifies oceans and suppresses calcite precipitation (coral growth)

Global CO_2 Cycle: Currently ~55% of human emissions soaked up by the biosphere & oceans



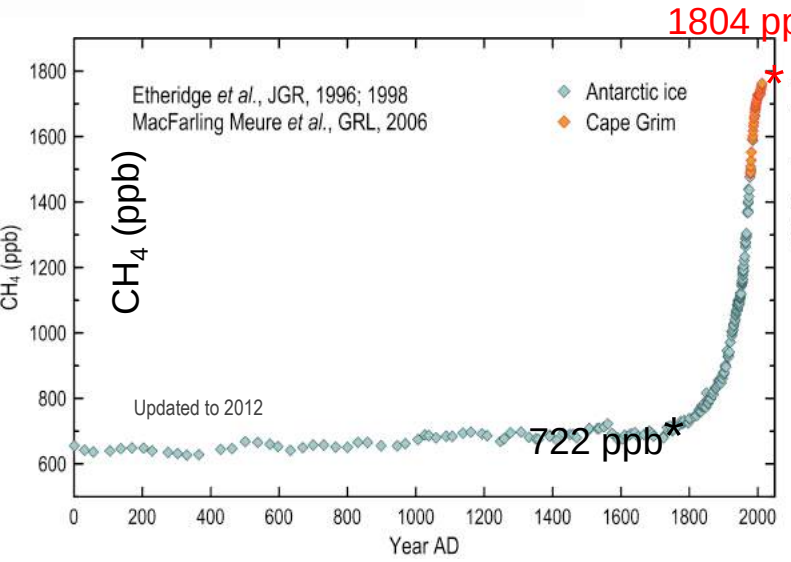
Will nature's CO_2 buffering as climate change intensifies?

- **Forest dieback!**
- **Release from thawing tundra!**
- **Ocean outgassing!**
- **Slow calcification!**

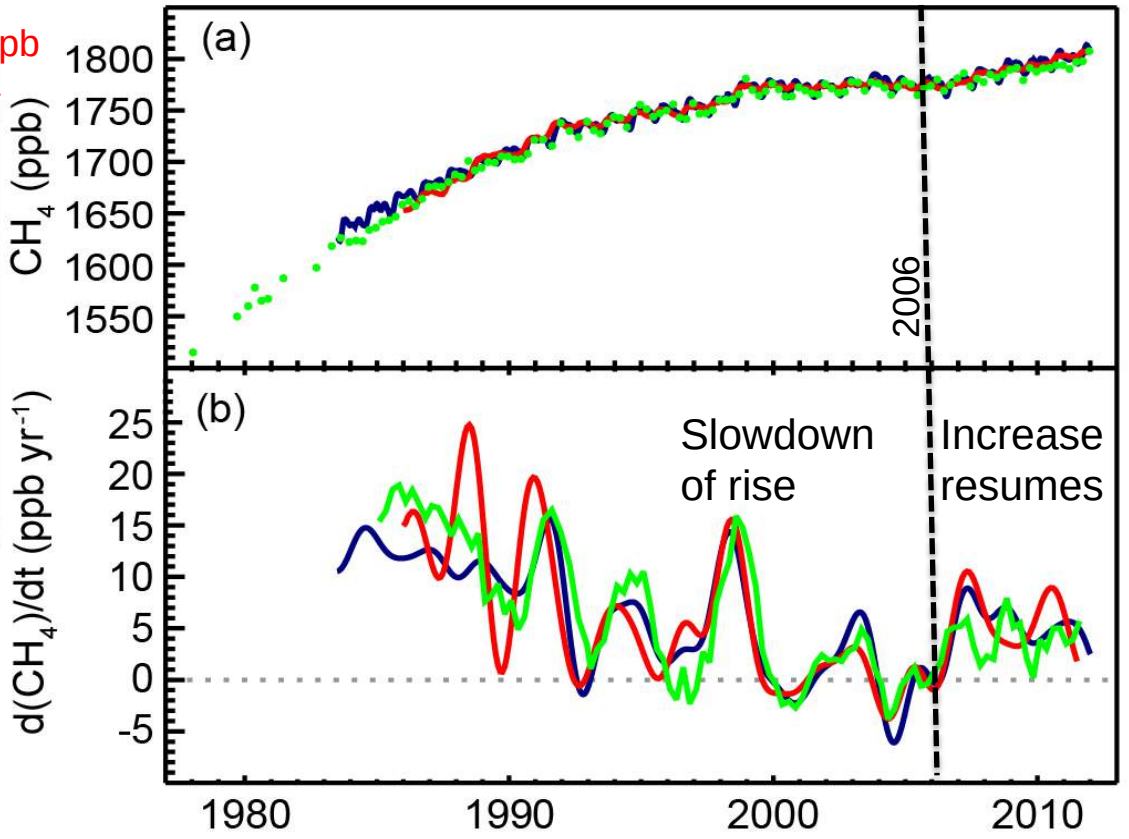
*Since 1870: 41% atmosphere, 31% land, 28% ocean

Atmospheric CH_4: Rising again

Ice core data from analysis of trapped bubbles



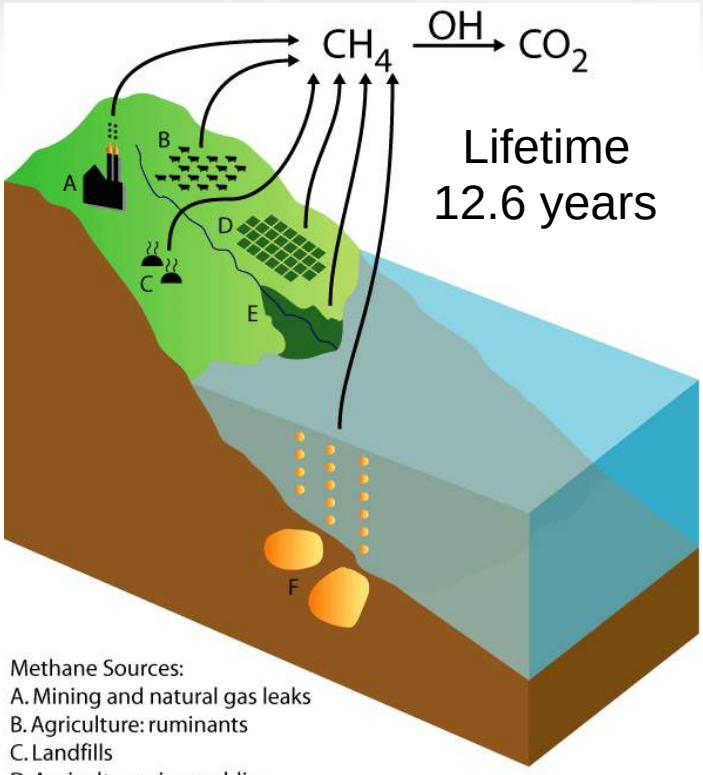
Real time in situ data from global networks



- 150% increase since 1750
- Greenhouse gas
- Source of stratospheric H_2O

*Produces tropospheric O_3

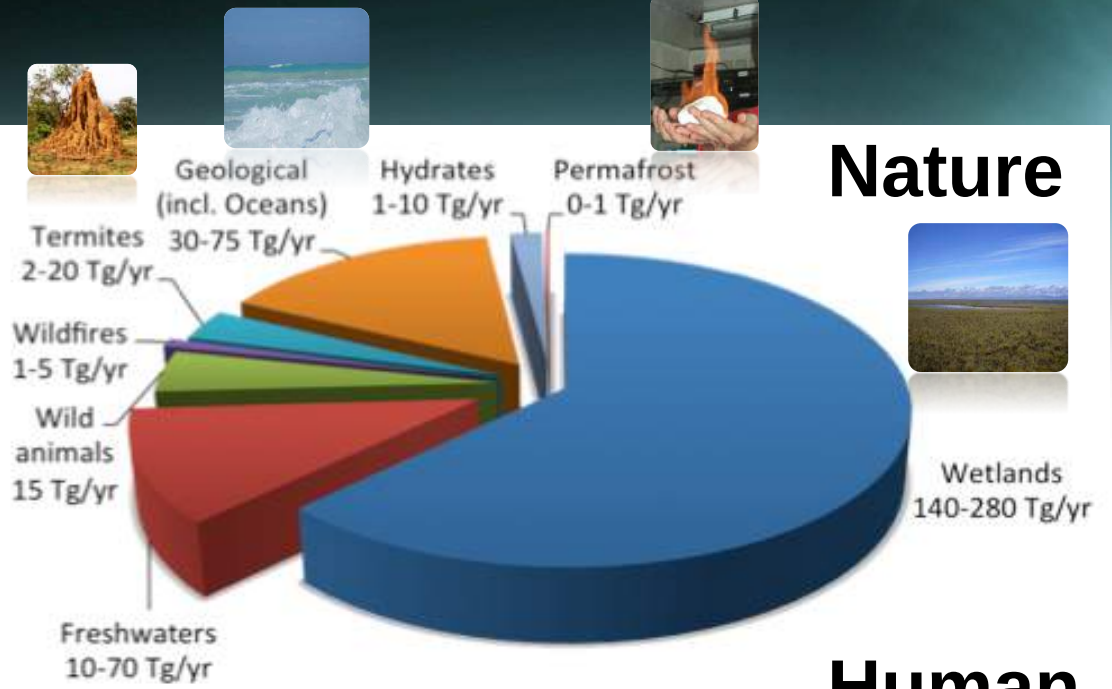
Methane: lifetime ~ 10 yrs, Complex source mix



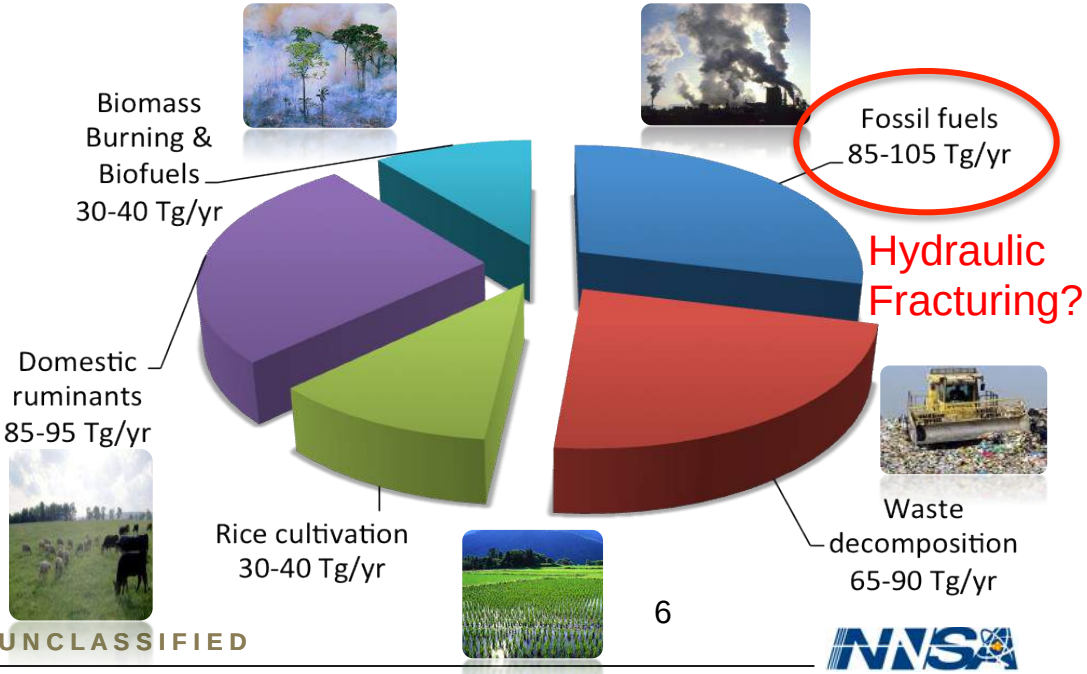
Lifetime
12.6 years

Methane Sources:
A. Mining and natural gas leaks
B. Agriculture: ruminants
C. Landfills
D. Agriculture: rice paddies
E. Natural wetlands
F. Hydrates

Nature



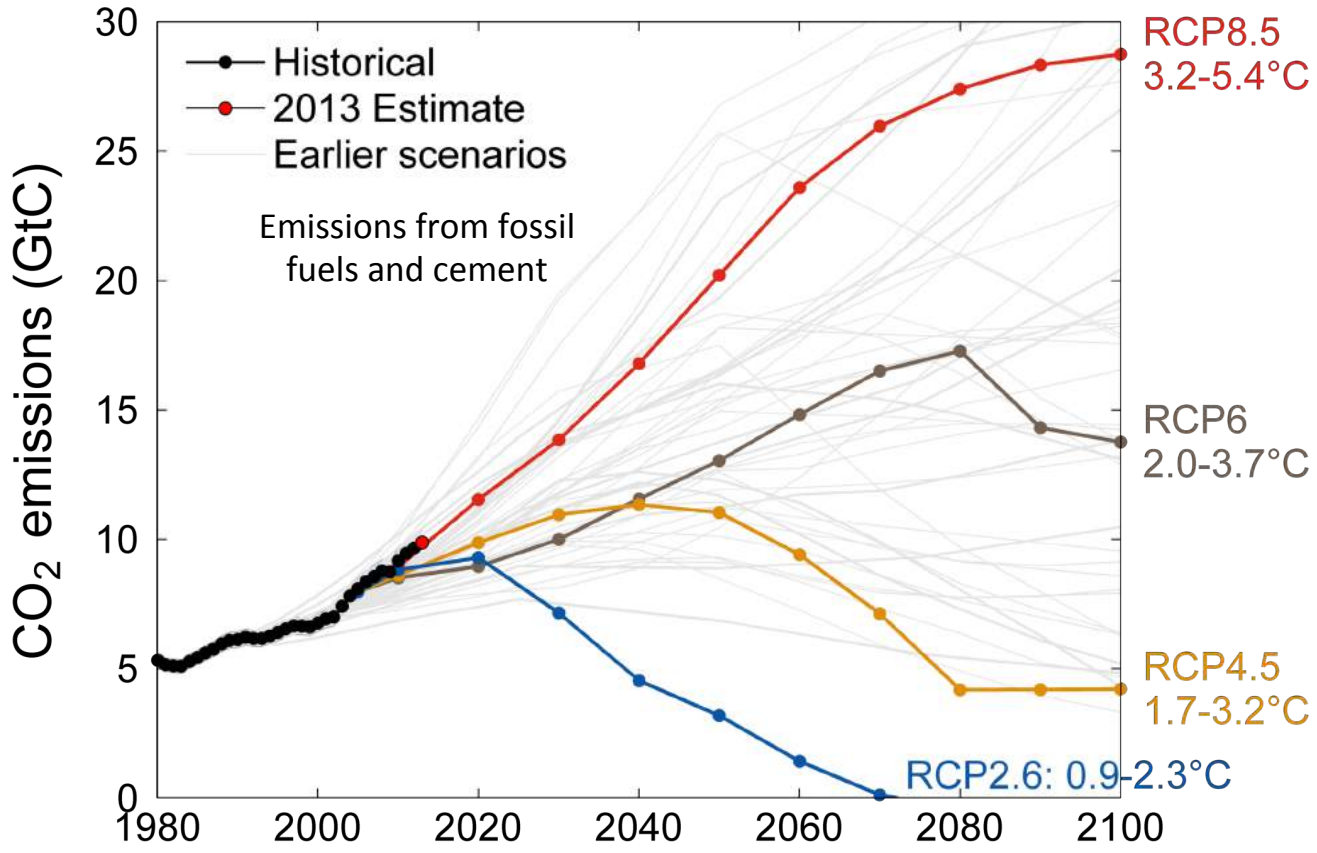
Human



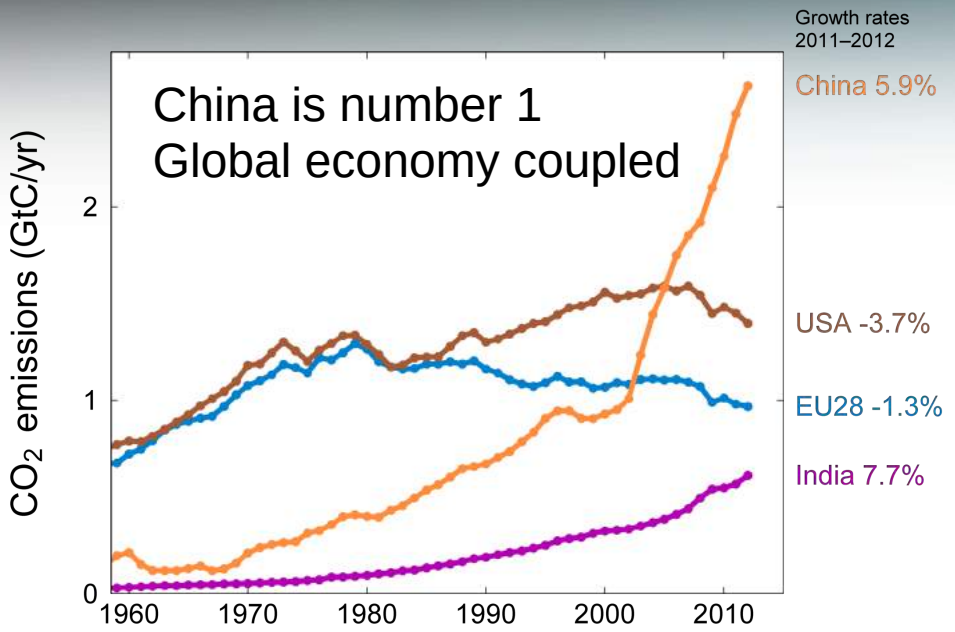
The need for a climate treaty or trading: Observed emissions at high end heded to 3-5C

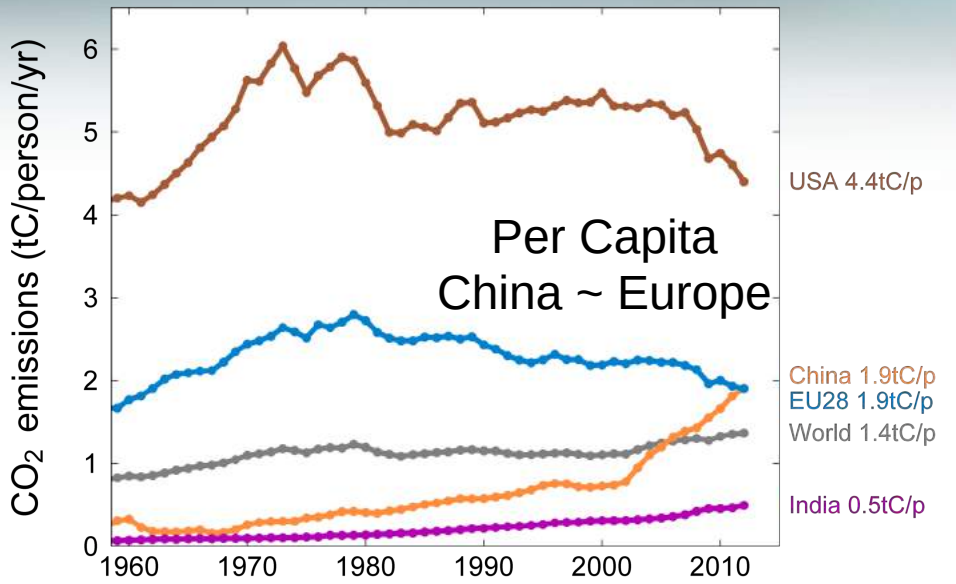
Emissions on high end of past projections and are on track for 3.2–5.4ºC "likely" increase in temperature above pre-industrial

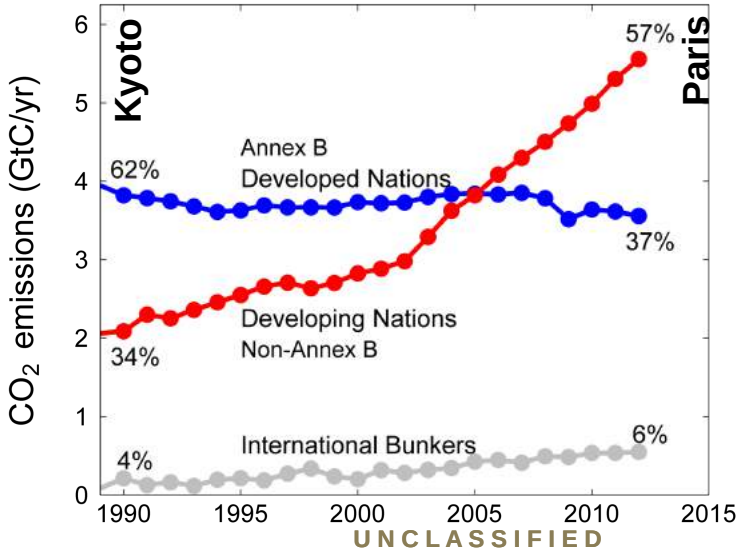
Large and sustained mitigation is required to keep below 2ºC



Changed Emission Patterns: Need to update treaty framework (verify both sinks to sources)

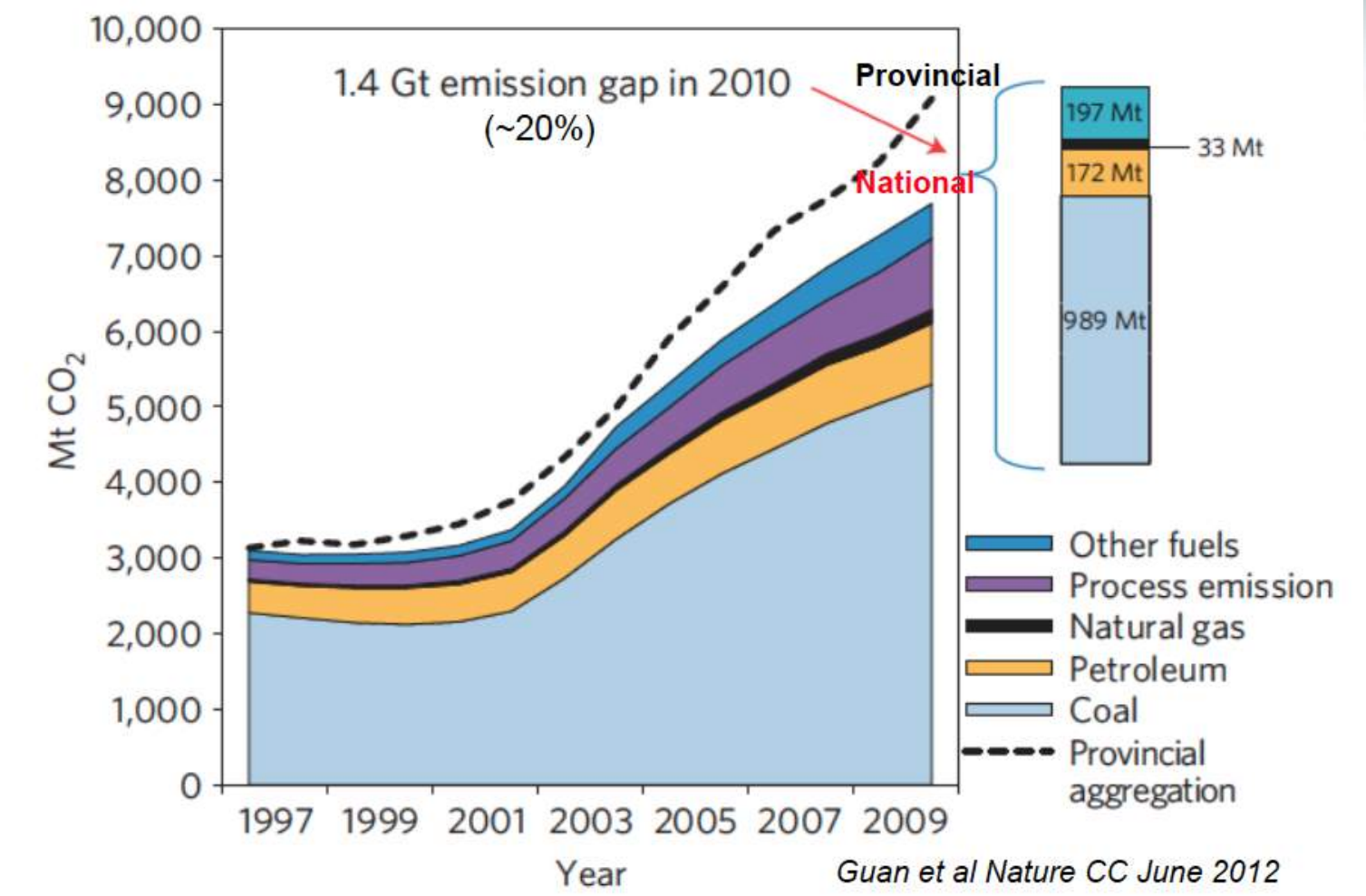






- Kyoto targeted forestation
- Copenhagen grappled with verification, unsuccessfully
- Paris needs to develop an effective framework

The need for verification: China's CO_2 Provincial & National Inventories Diverge by 1.4Gt



The US Verification Science Challenge: Need and Opportunity

Detect and infer emissions from small human CO_2 signal (<1ppm) over large and variable natural background (390 ppm) in complex flows from afar without spatio-temporally resolved inventories.

National Academies Report
March 19, 2010

VERIFYING GREENHOUSE GAS EMISSIONS: METHODS TO SUPPORT INTERNATIONAL CLIMATE AGREEMENTS

Global Greenhouse Gas Information System, 201

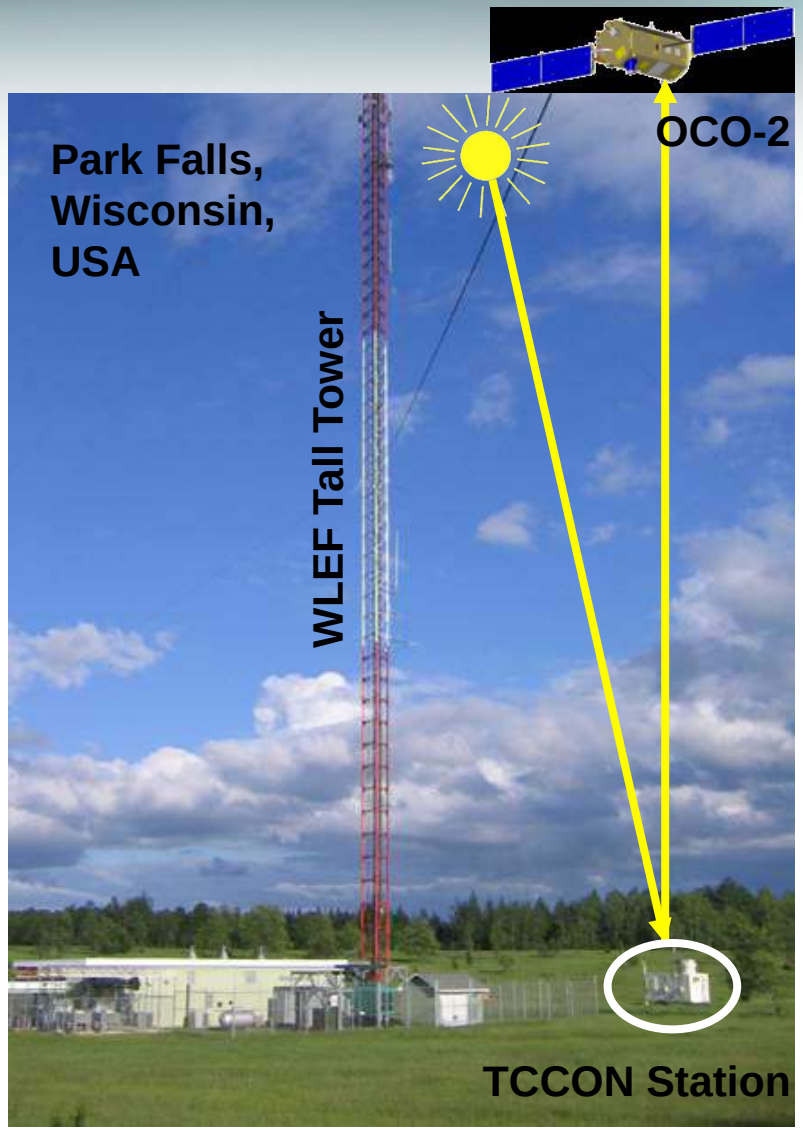
MULTILAB NNSA-JPL STUDY
January 2012

JAPAN's GOSAT & NASA's OCO2 satellites

LANL (DOE-OBER) sole validation target from ground in Amazon (<0.3ppm)

TCCON Science Objectives

- Constrain global fluxes of carbon and improve our understanding of the carbon cycle
- Provide the primary validation (ground-truth) dataset for satellite instruments
  - GOSAT
  - OCO-2
  - SCIAMACHY
  - ASCENDS
  - AIRS
  - TES
  - CARBONSAT
- Provide a transfer standard between the satellite measurements and the ground-based *in situ* network

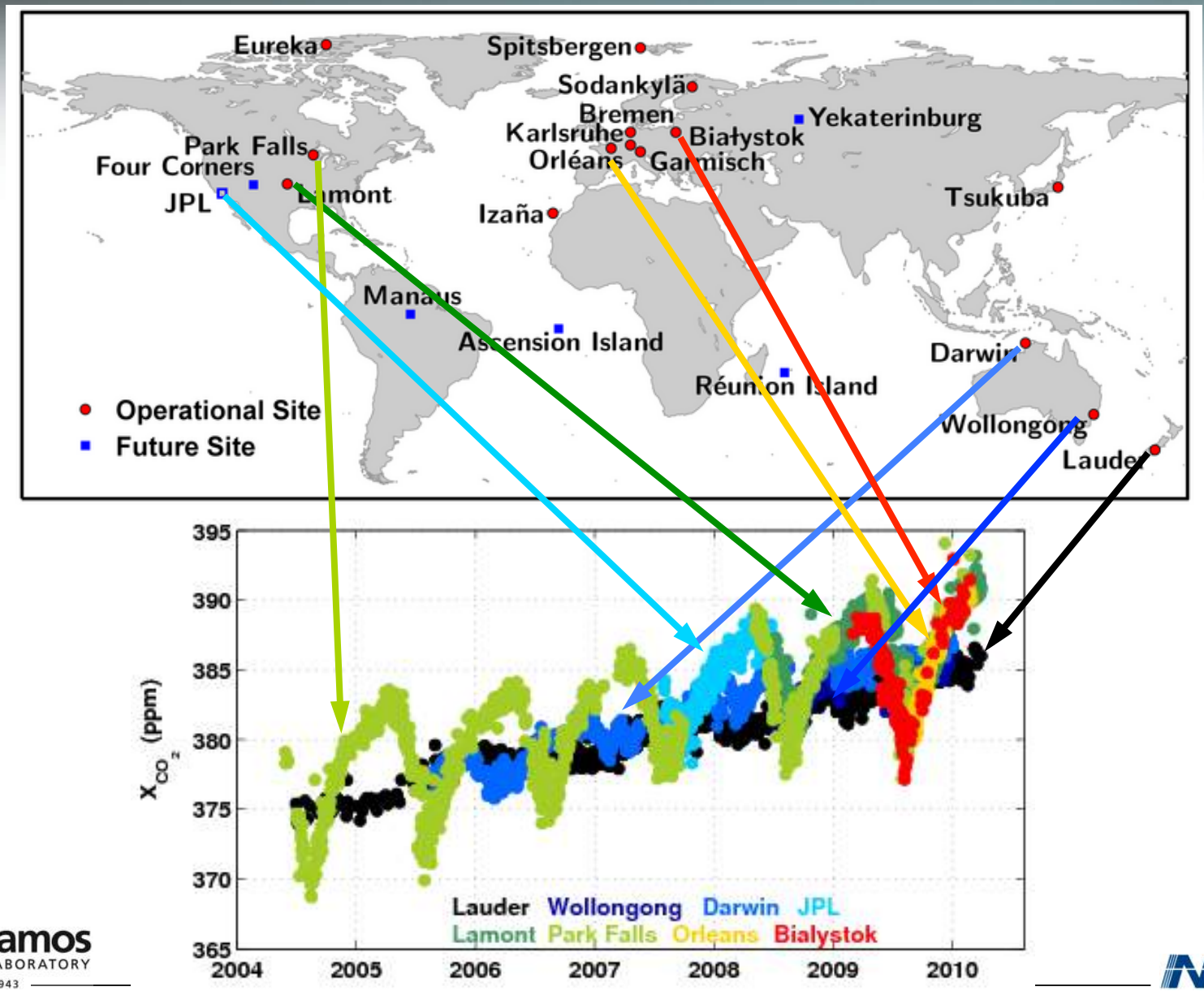


TCCON Instruments

- Ground-based Fourier transform spectrometers
- Remote sensing of total columns of CO_2, CH_4, N_2O, CO, H_2O, HDO, O_2 via solar absorption
- Divide trace gas columns by O_2 column to get dry-air mole fractions: X_{CO_2}, X_{CH_4}, X_{N_2O}, X_{CO}, X_{H_2O}, X_{HDO}

Molecule	Precision	Accuracy
CO_2	~0.8 ppm	~0.8 ppm
CH_4	~5 ppb	~7 ppb
N_2O	~1.5 ppb	~3 ppb
CO	~0.5 ppb	~4 ppb

TCCON Measurements



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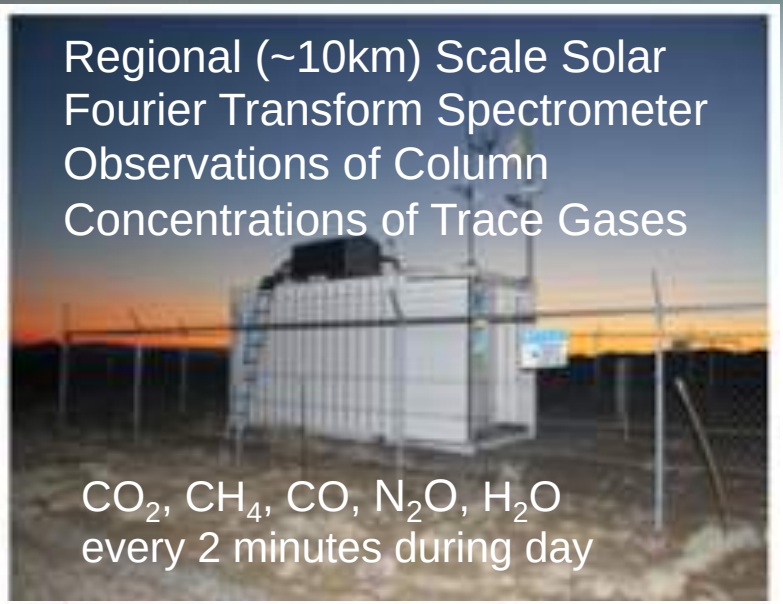
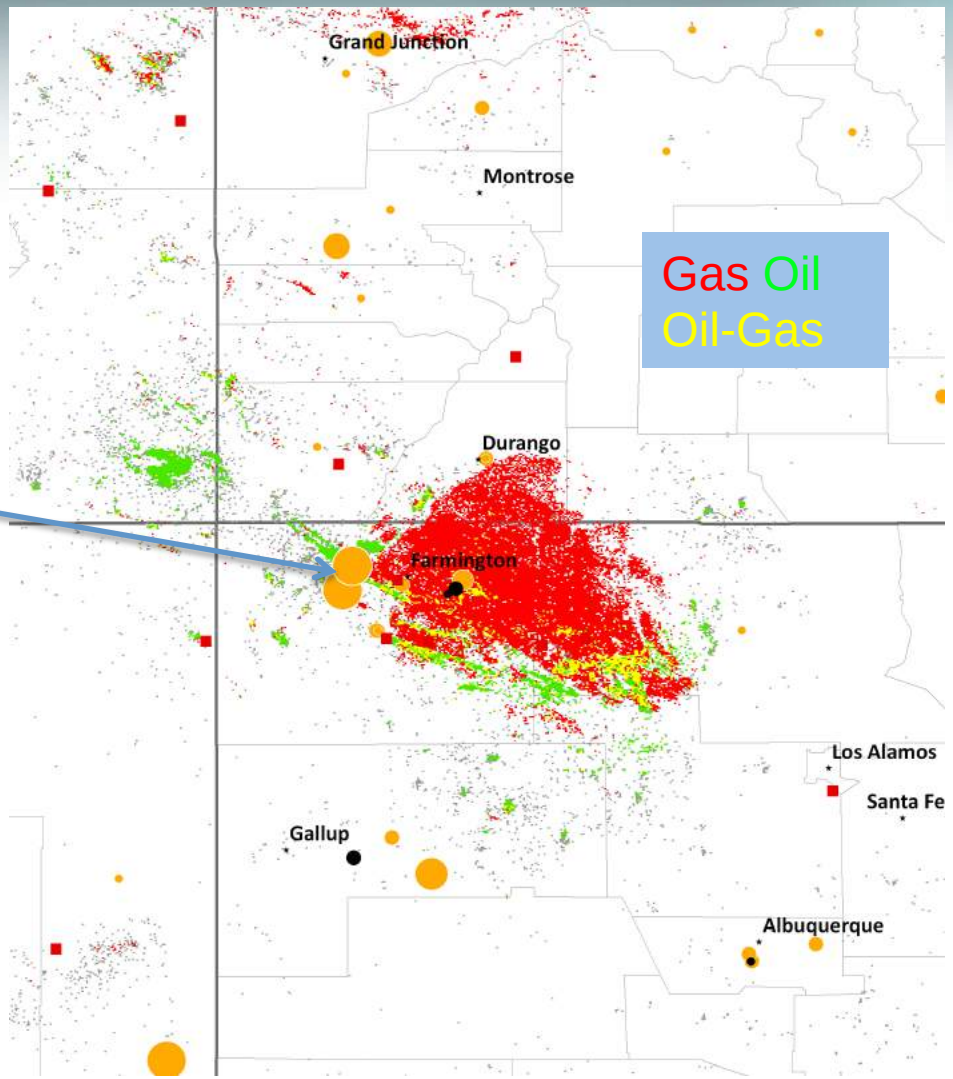
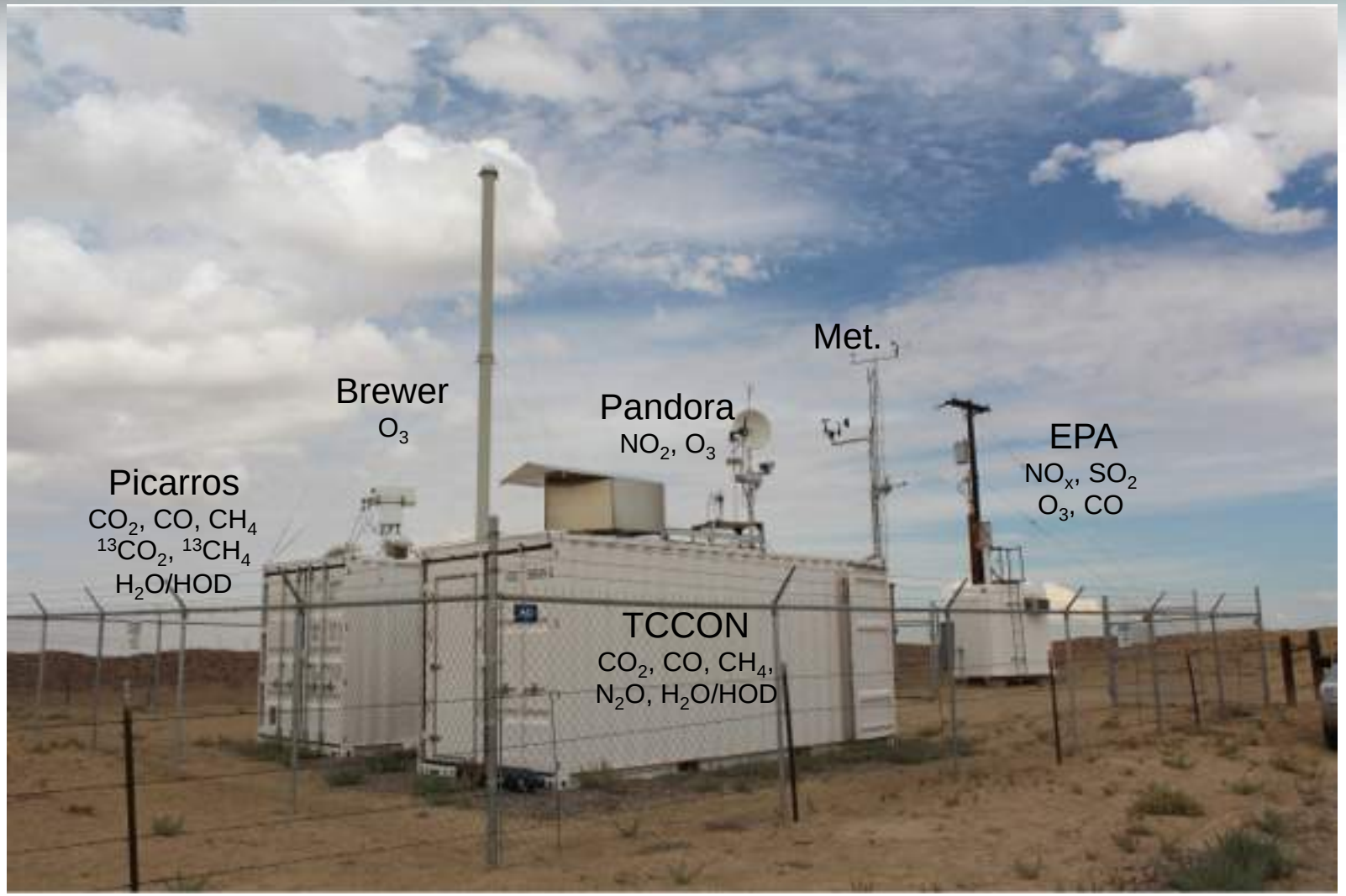
NNSA

4-Corners Site: In between San Juan & 4Corners Power Plants E/SE of Coal, Gas & Oil Mining Region

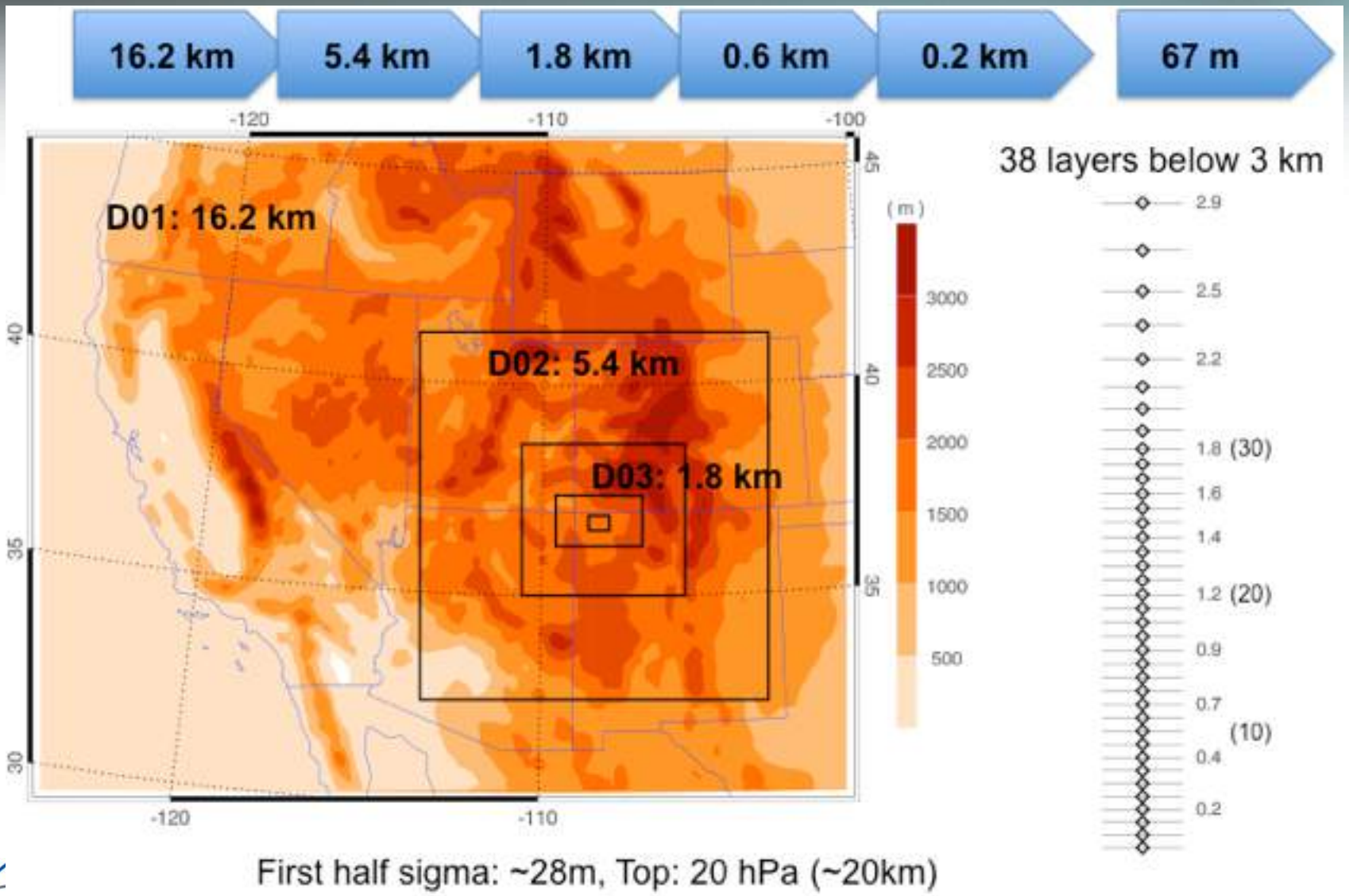




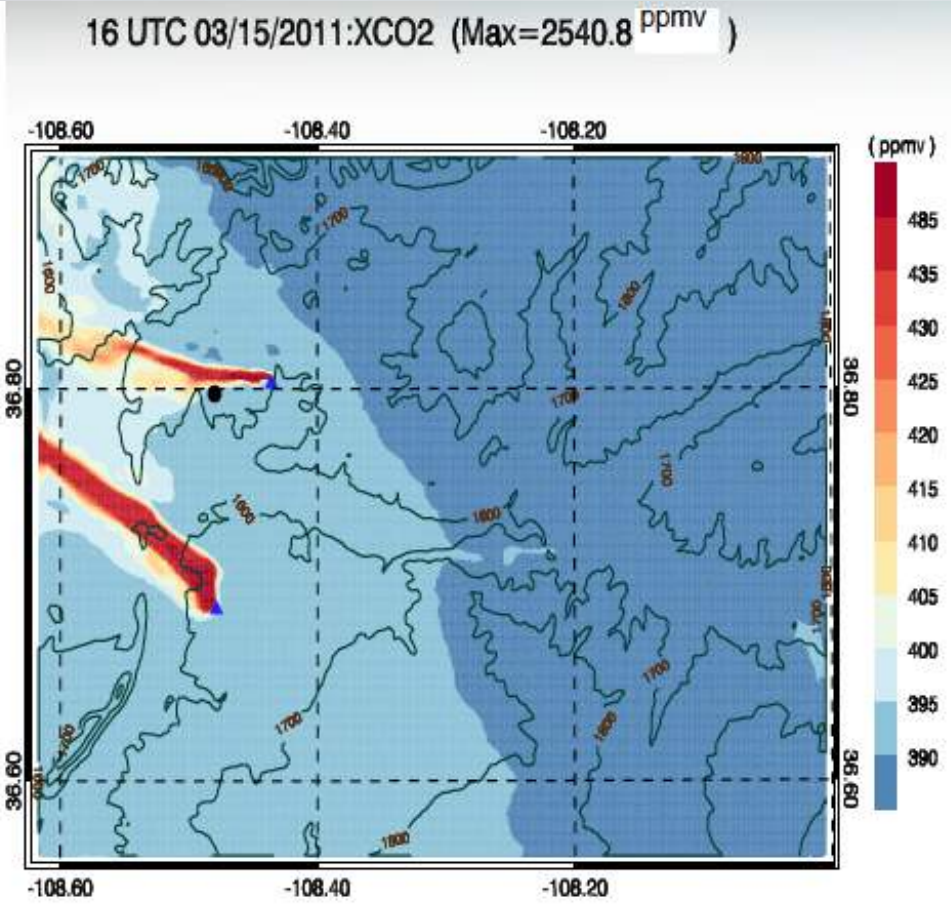
Four Corners GHG and Pollution Monitoring

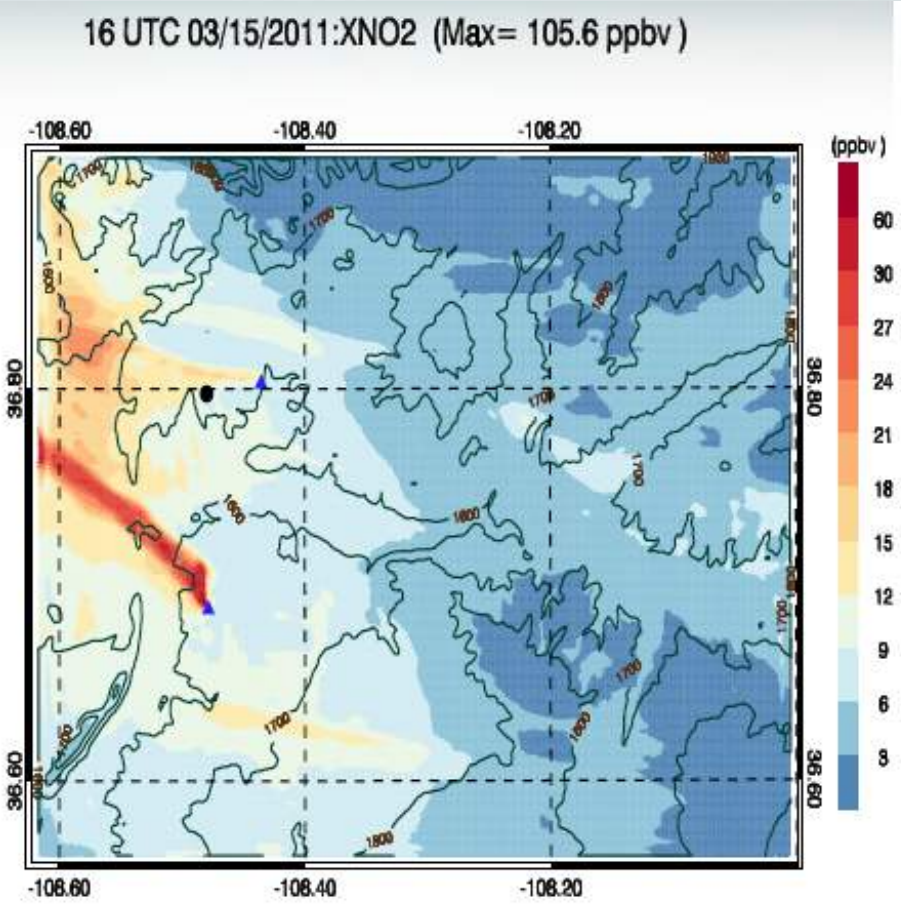


Nested WRF Chem Model of 4Corners (NCEP) with real time CEMS power plant emissions + NEI urban inventory



WRF Chem Plume Simulation (200m res.)



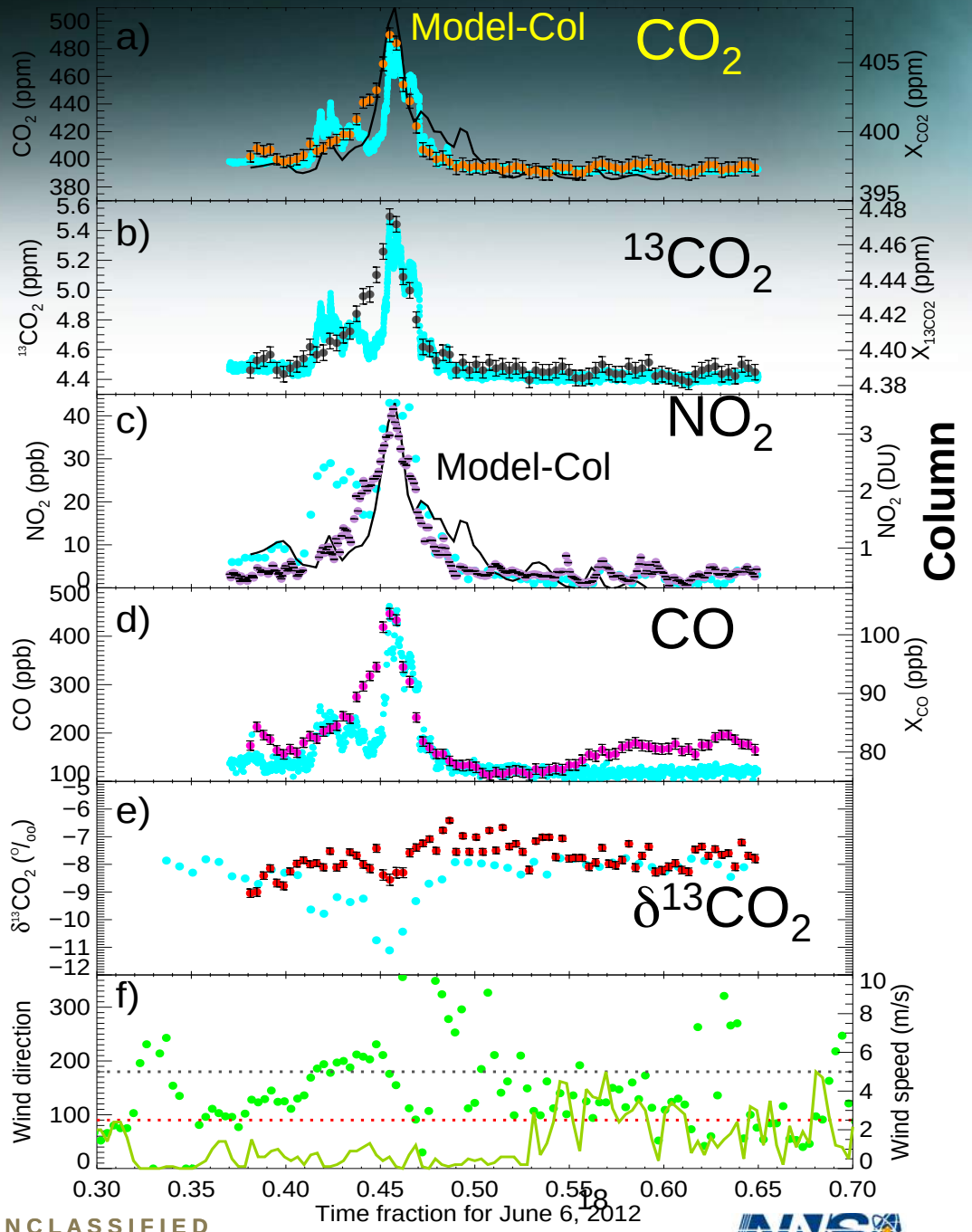


Power Plant Plume Composition

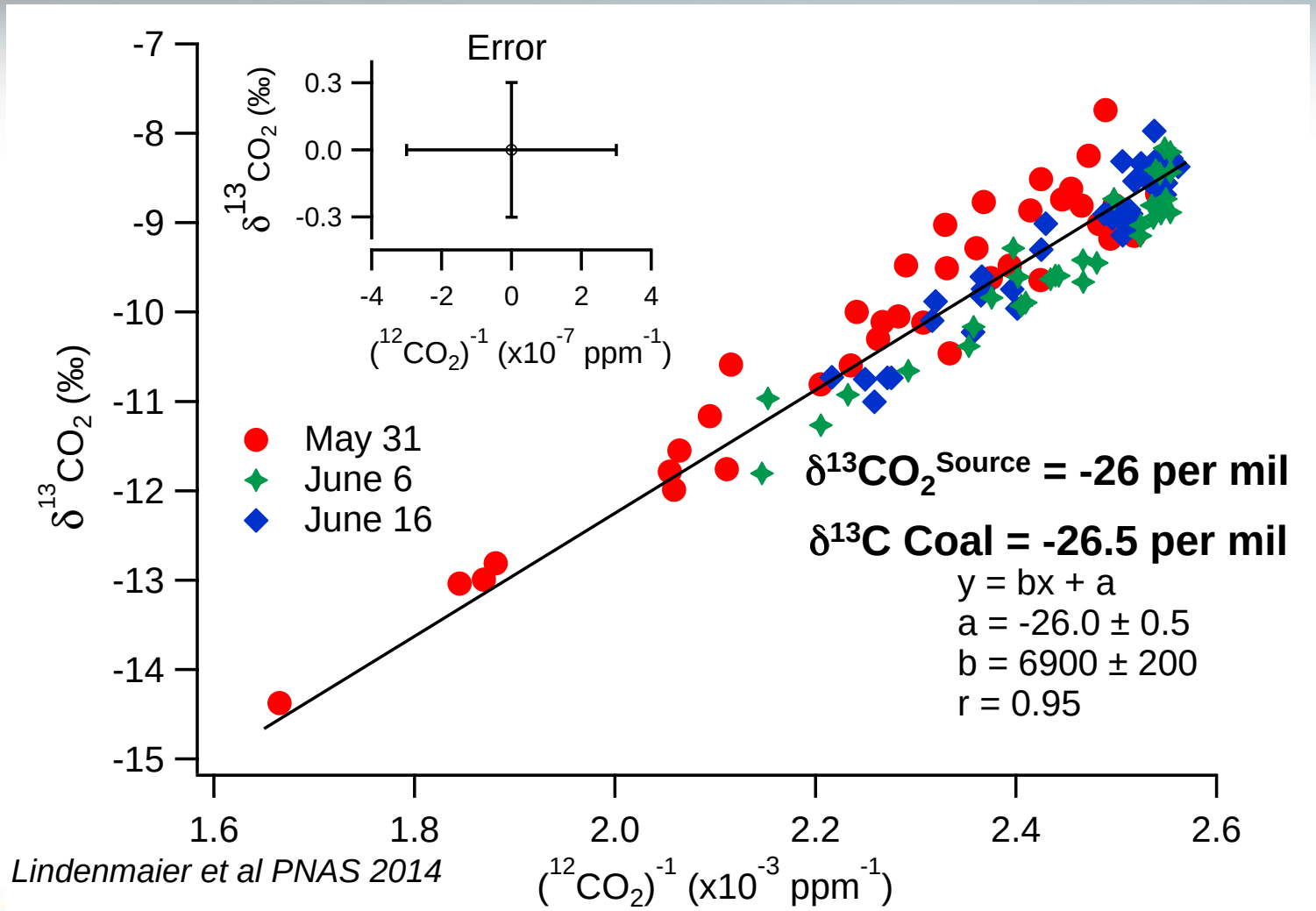
Traced in exquisite detail at multiple scales by remote (column) and *in situ* (point) surface sensors.

Forward WRF-Chem simulations with CEMS reproduce the column CO_2 and NO_2 plume signals.

Lindenmaier et al PNAS 2014



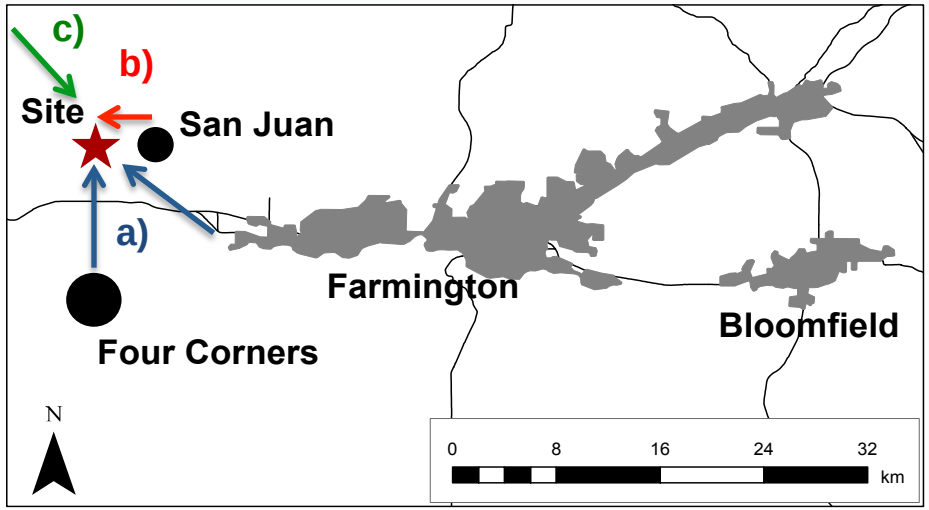
Source Attribution with *in situ* ^{13}C Keeling Plot



Lindenmaier et al PNAS 2014

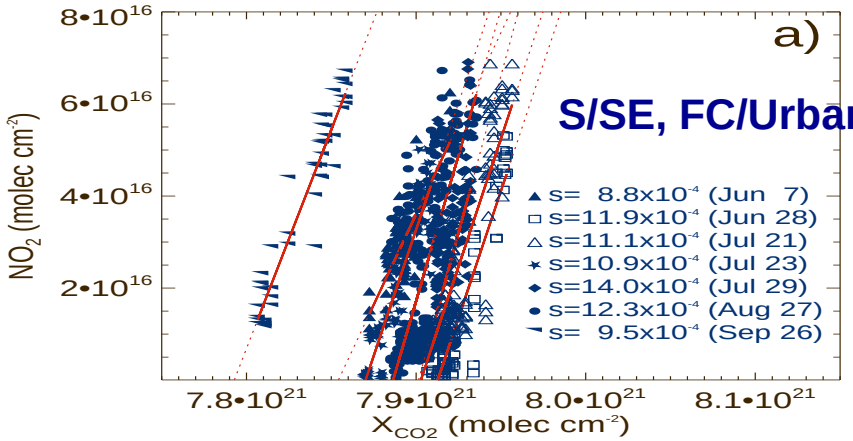
Column NO_2/CO_2: Source Attribution (123 plumes)

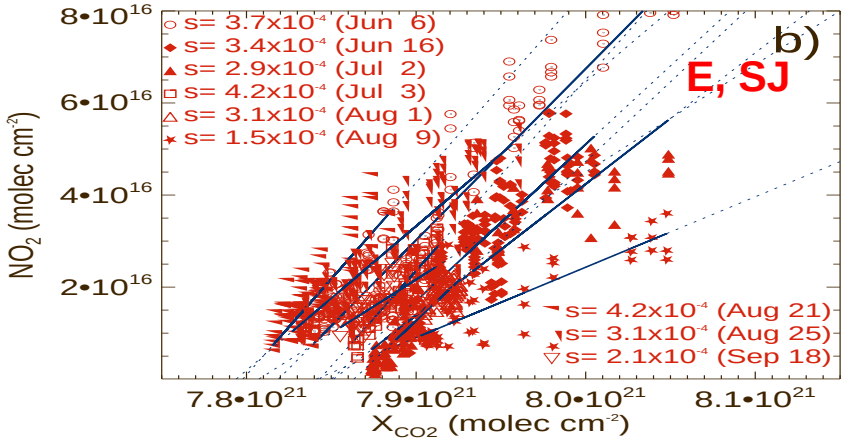
Fire

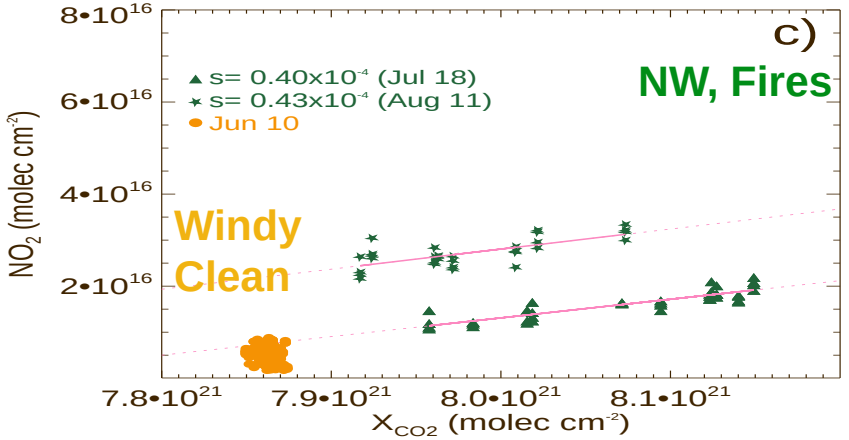


75% of atmosphere sampled by FTS is polluted Discriminate Sources

Lindenmaier et al PNAS 2014







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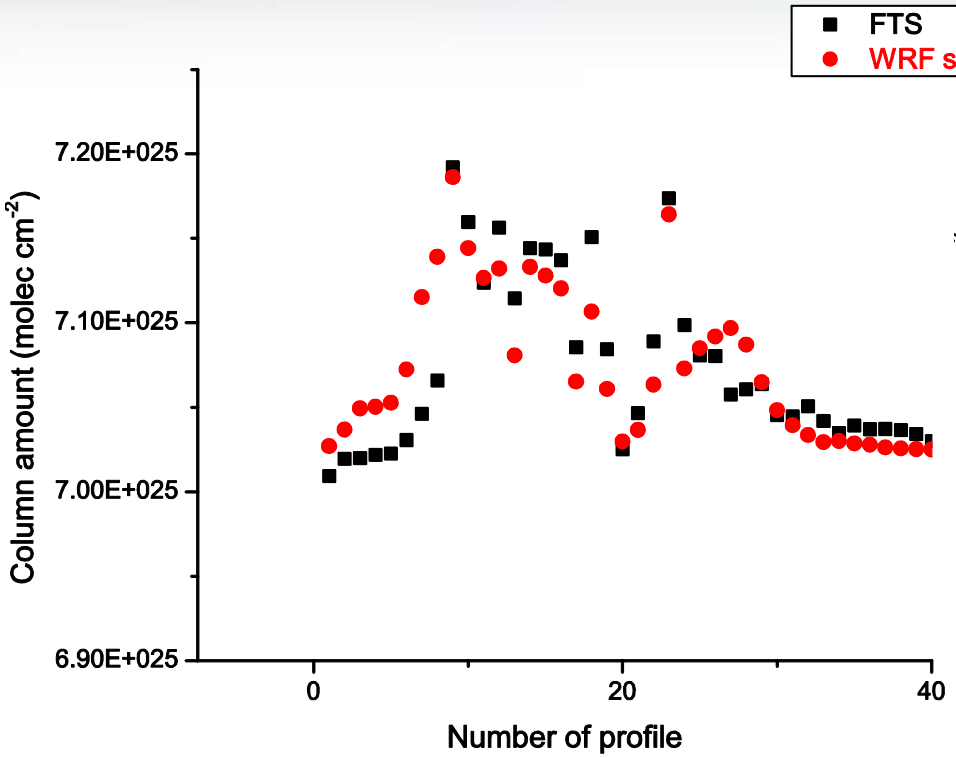
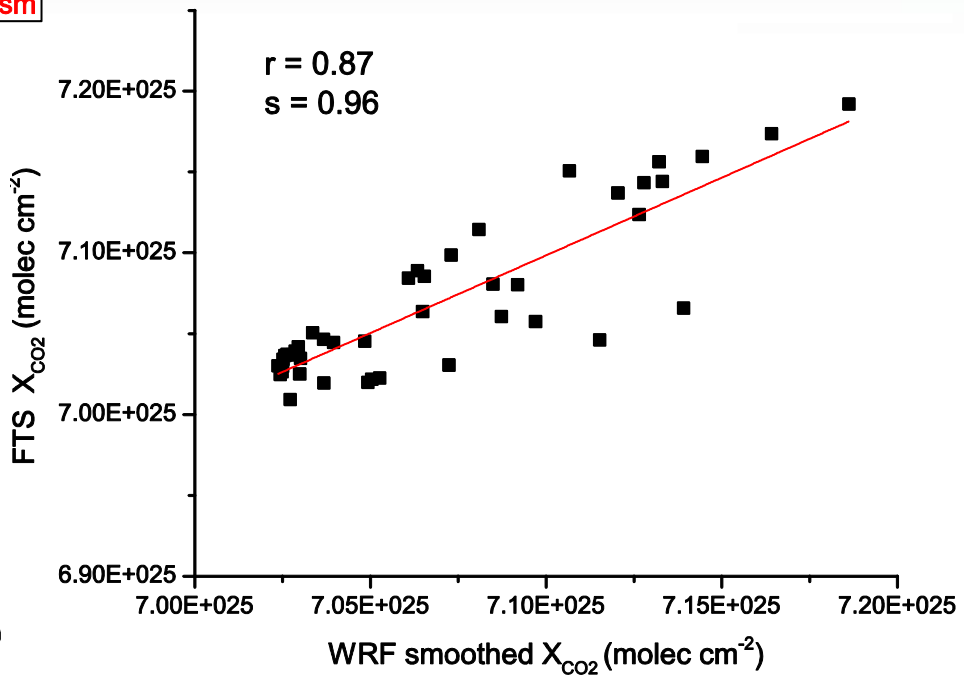
WRF columns vs. FTS columns March 15 2011



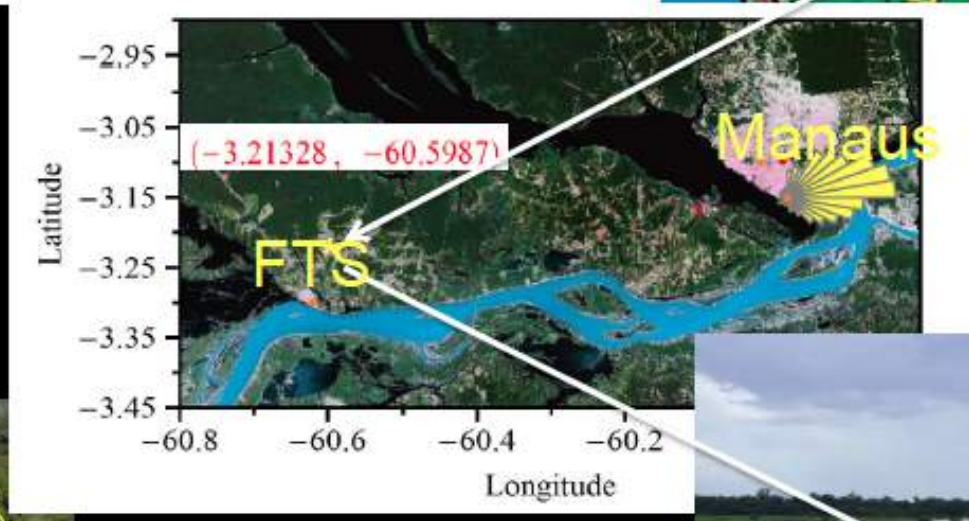


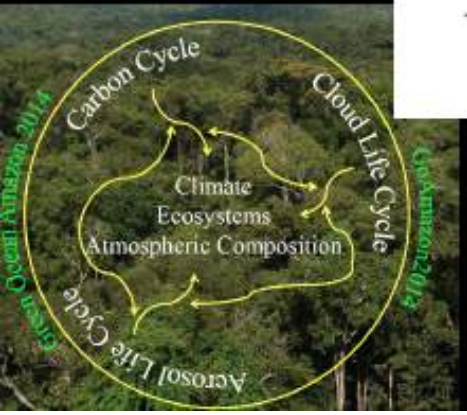
CEMS verified to 4% accuracy by FTS column data in SJPP plume

DOE-OBER GoAmazon Manaus, Brazil 2014 (TES, ARM)

Carbon Cycle - improve Community Earth System Model (CESM) for land-atmosphere processes in the Amazon Basin, including aerosol-cloud-precipitation connections

- Objective - Reduce uncertainties in our knowledge of feedbacks between vegetation-hydrology that underlie the Amazon forest dieback hypothesis. The uncertain range of feedbacks at present leads to large differences in ESM predictions.
- Objective - Response of photosynthesis and transpiration, including BVOC emissions, to changes in the direct and diffuse components of incoming solar radiation, i.e., in the context of current and future scenarios of aerosols and clouds in the Amazon Basin.



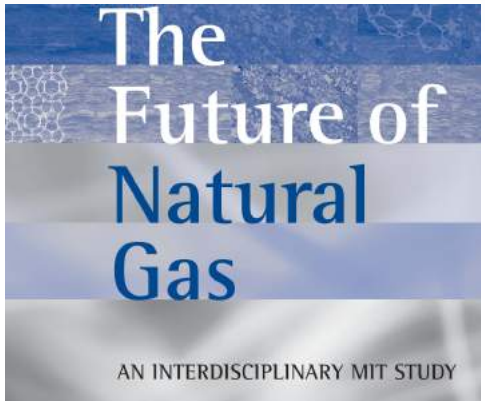


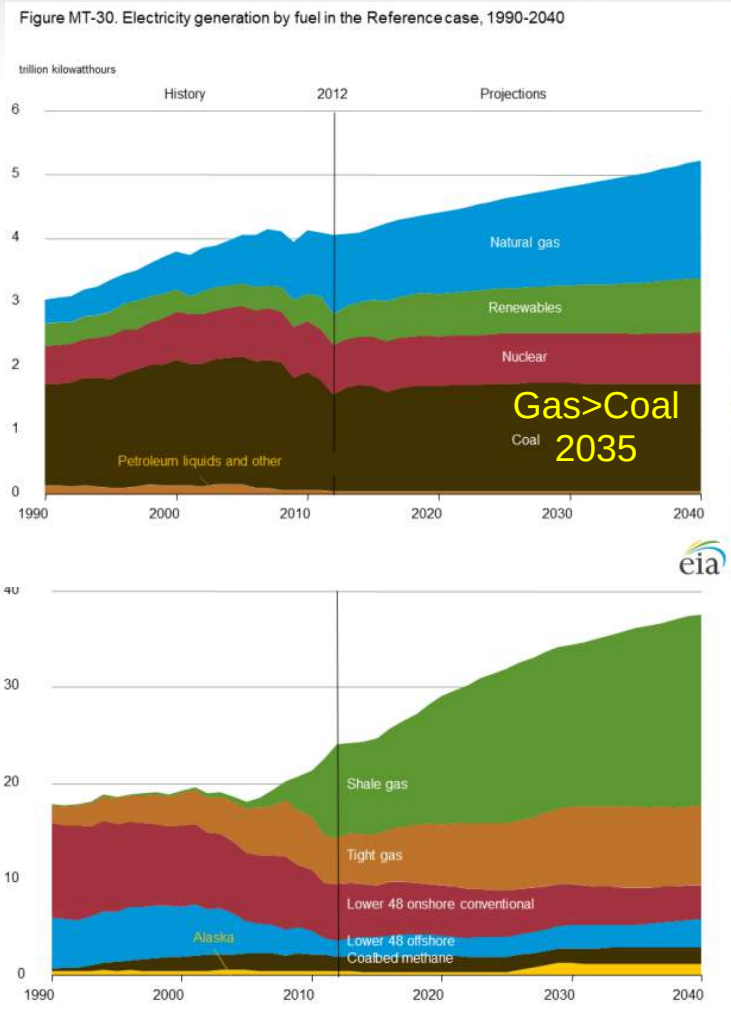
UNCLASSIFIED

Natural Gas Opportunities & Challenges for Climate

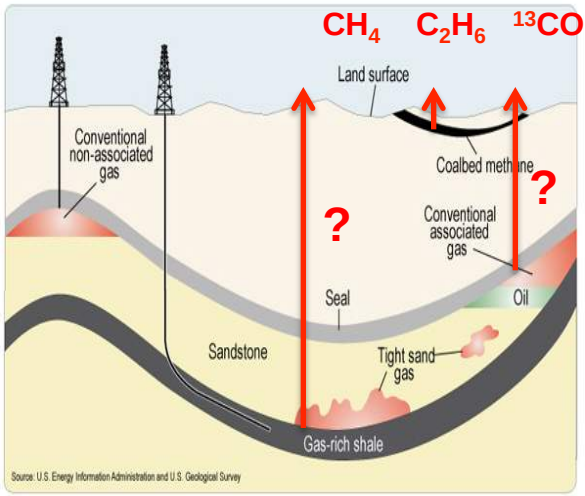
Growing Methane Supply from Hydraulic Fracturing

Moniz Report





Fugitive Leaks?



EPA & DOE should review & update CH_4 emissions from gas production and distribution. CH_4 leaks at the levels indicated by the new EPA estimates, could prompt efforts to capture them for environmental & business…

Need to baseline leaks from conventional mining as we quantify those from unconventional methods.

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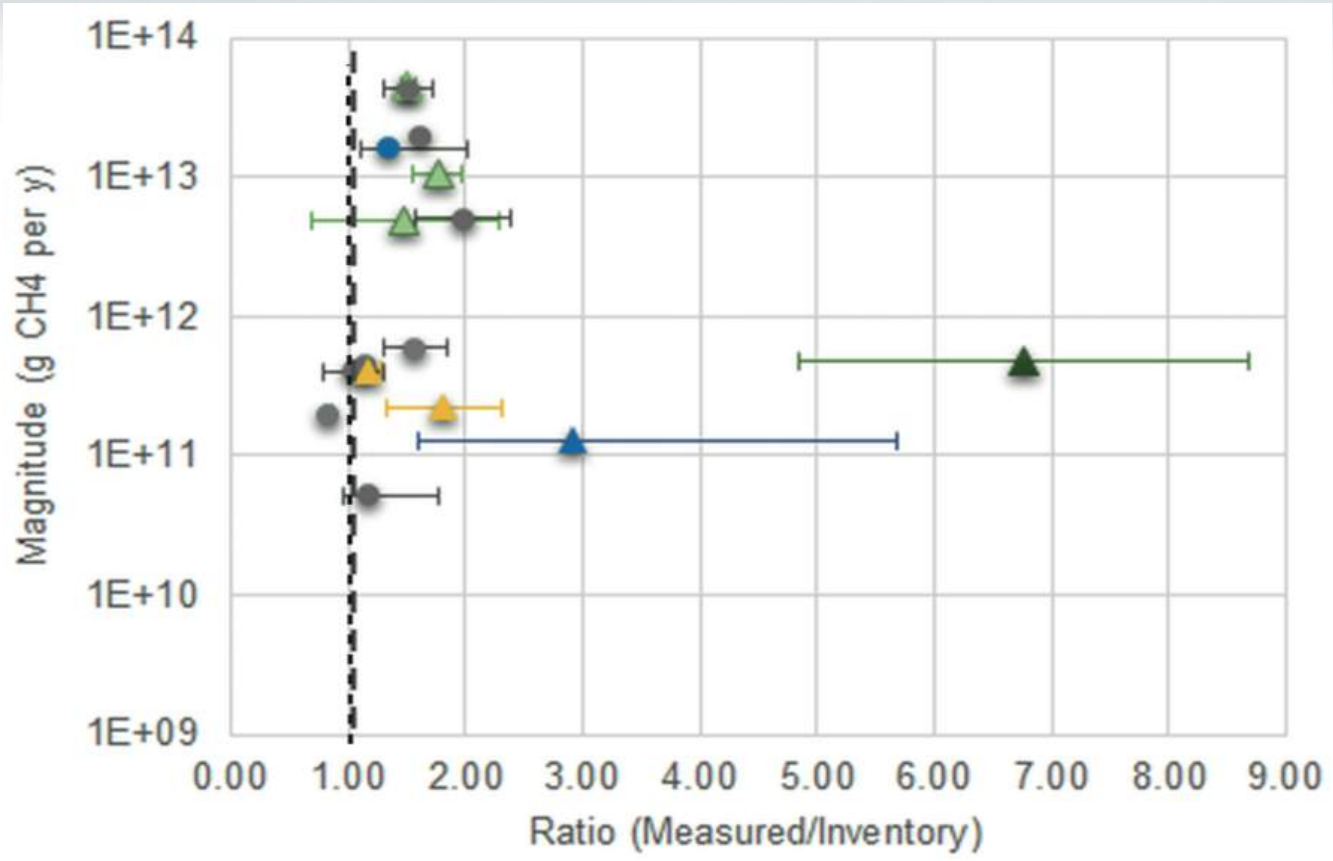
NNSA

Shale Gas is Clean and Abundant Domestic Fuel that is being Mined Profitably by Hydraulic Fracturing to Supplant Coal and Oil to help US achieve Energy Independence

- *Clean Air*: No particulates or SOx and less NOx making a desirable transportation and energy fuel*
- *Climate Friendlier*: CH_4 produces half as much CO_2 per unit energy produced as coal?
- **Fugitive CH_4 leaks highly uncertain and a sensitive issue!**
- CH_4 25 times more potent a GHG than CO_2 (100yr)*
- CH_4 leaks < 3% needed for smaller climate impact than coal?
- HC leaks and Rig & Infrastucture emissions pollute local air*
- 6-11% leaks from top-down data > x 3 EPA inventories
- *Moniz Study: "the environmental impacts of shale development are challenging but manageable"*

Inventories & emissions factors (bottom up) underestimate actual measured CH_4 emissions (top down) across scales



Brandt, Science 2014

Ensure CH_4 leaks <3% keep it climate friendlier than coal & make it a bridge to carbon neutrality

Area of national need that DOE has prioritized & LANL is harnessing its SoS capability to assess

Satellite: SCIAMACHY 2003-2009 CH_4 Hotspots

25-50 ppb excess over background above O&G regions

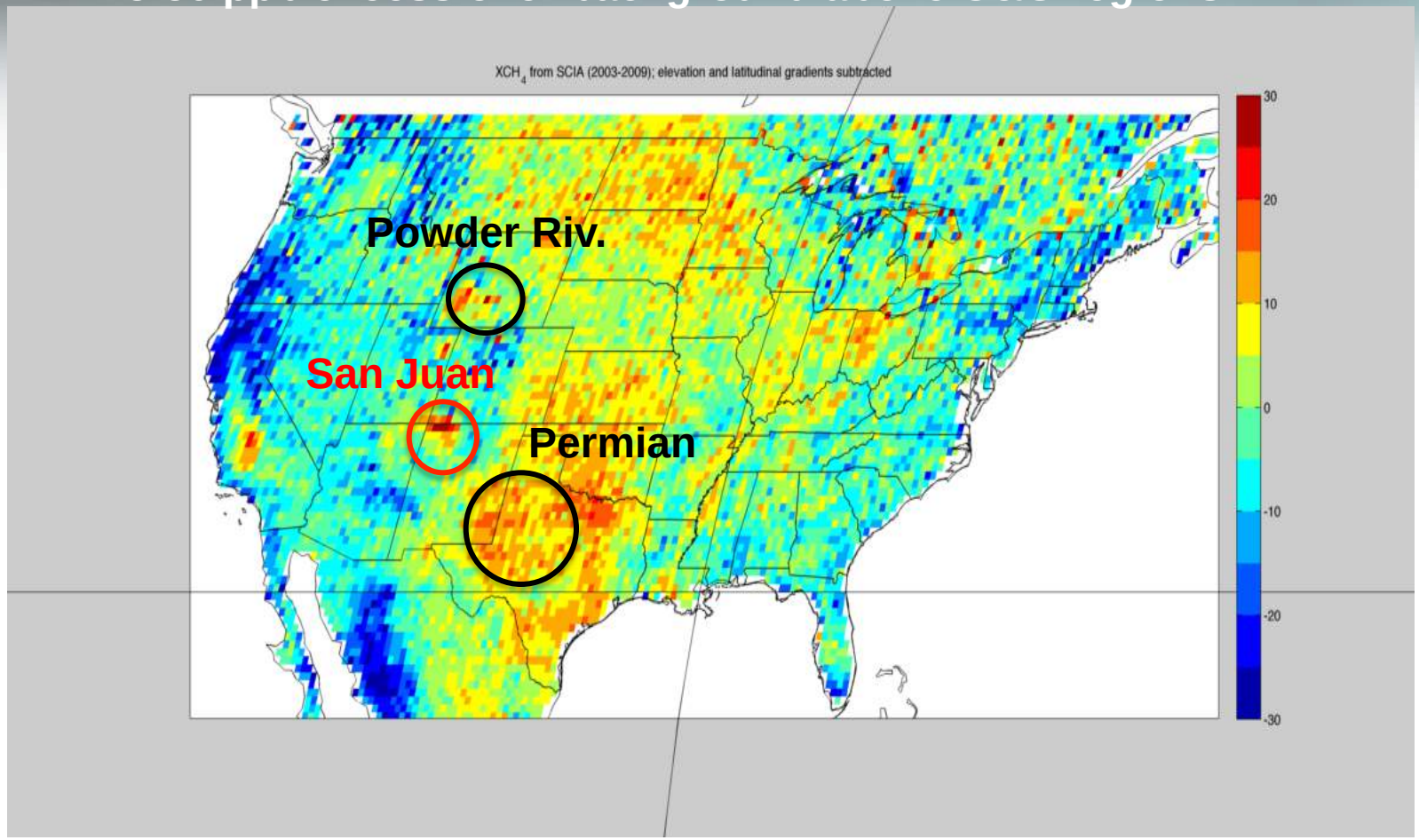


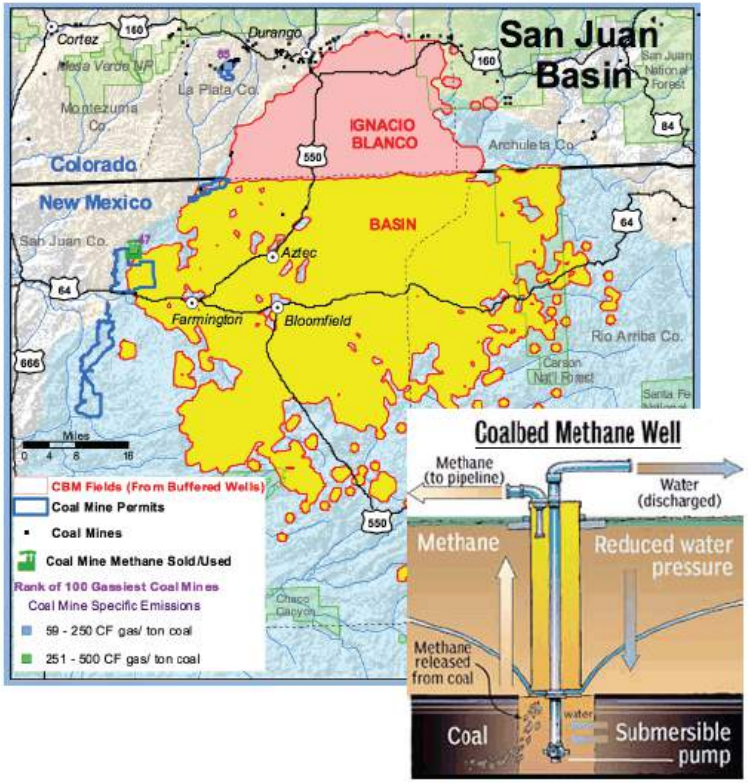
Figure 1: Average methane anomaly as seen by SCIAMACHY from 2003-2009. The four-corners region exhibits the largest regional enhancement in the conterminous US.

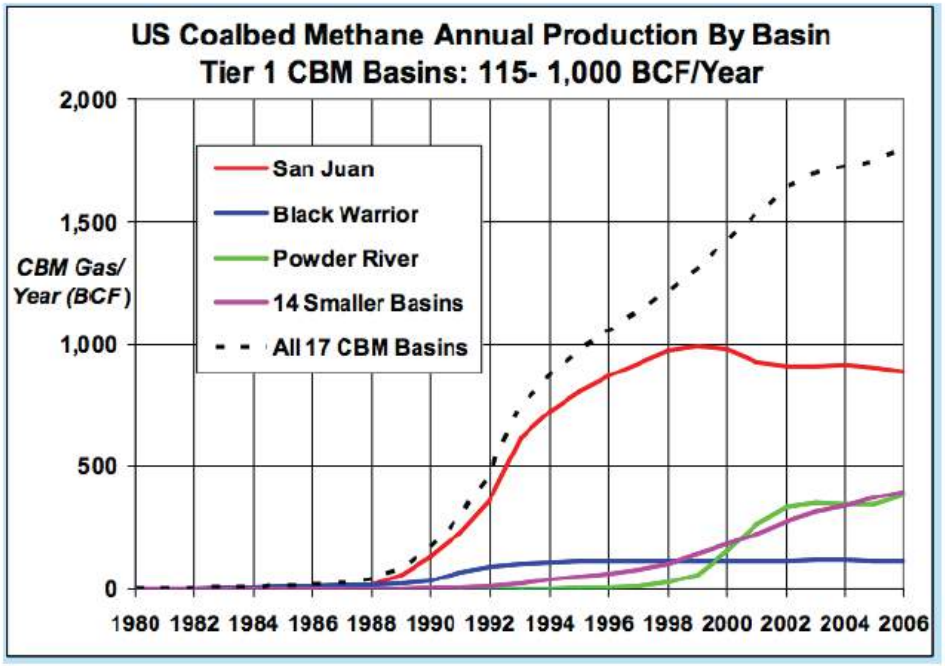
Also a gas hub!

4-Corners: What is going on?

Largest Coalbed methane production area in the US

Production of 1.32 trillion cubic feet per year in 2007
corresponds to about 27 Tg/yr
What part of the emissions is related to production vs. natural seepage? Hard to say...





Satellite see CH_4 hot spot at 4-Corners: Edgar inventory has sources at right locale

Satellite *Kort et al GRL 2014* **Edgar-Inventory**

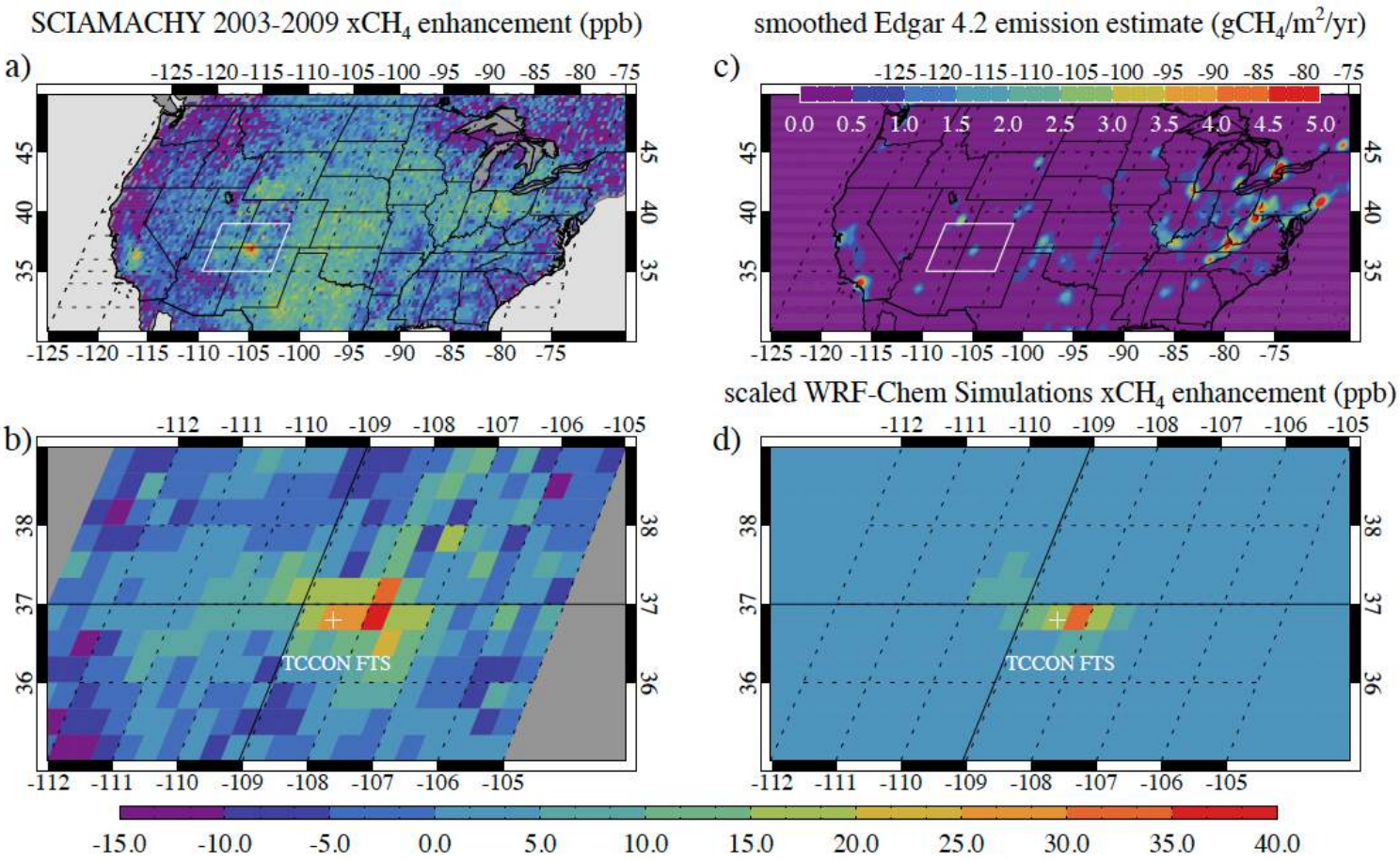
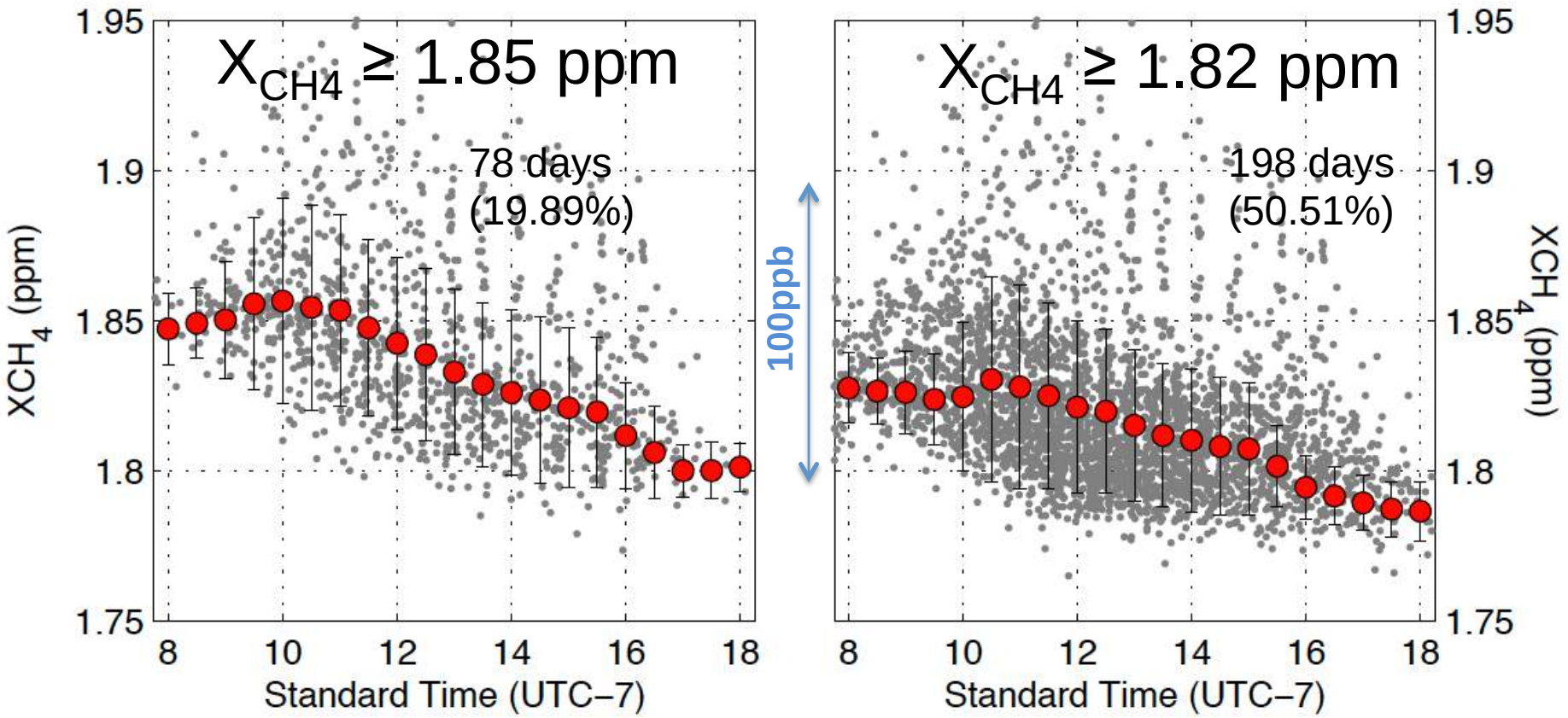


Figure 1: Column methane anomalies and emissions over the conterminous US

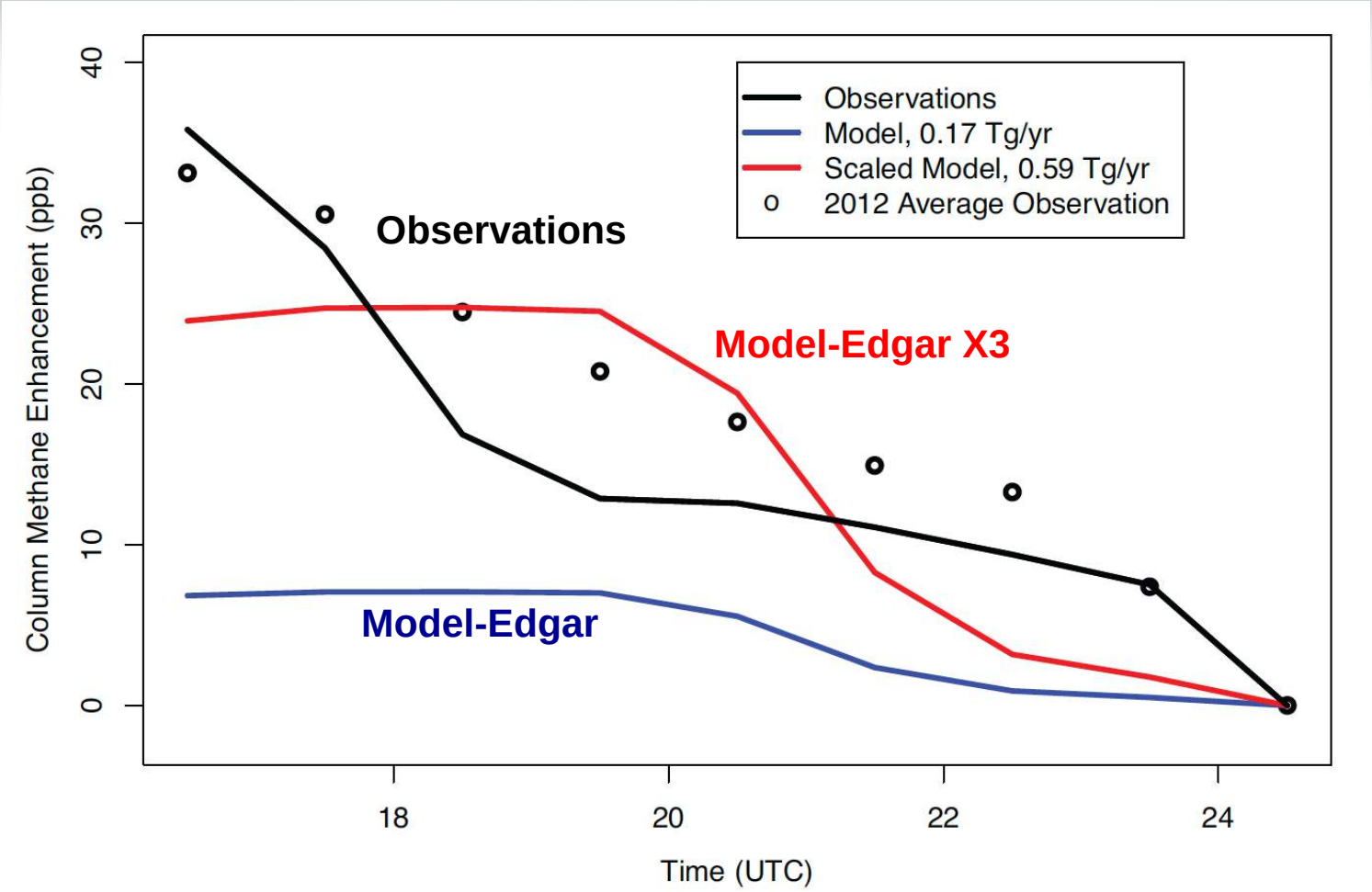
High regional CH_4 plumes observed routinely with when winds are low and from SE

Total measurement days 2011+2012 =392



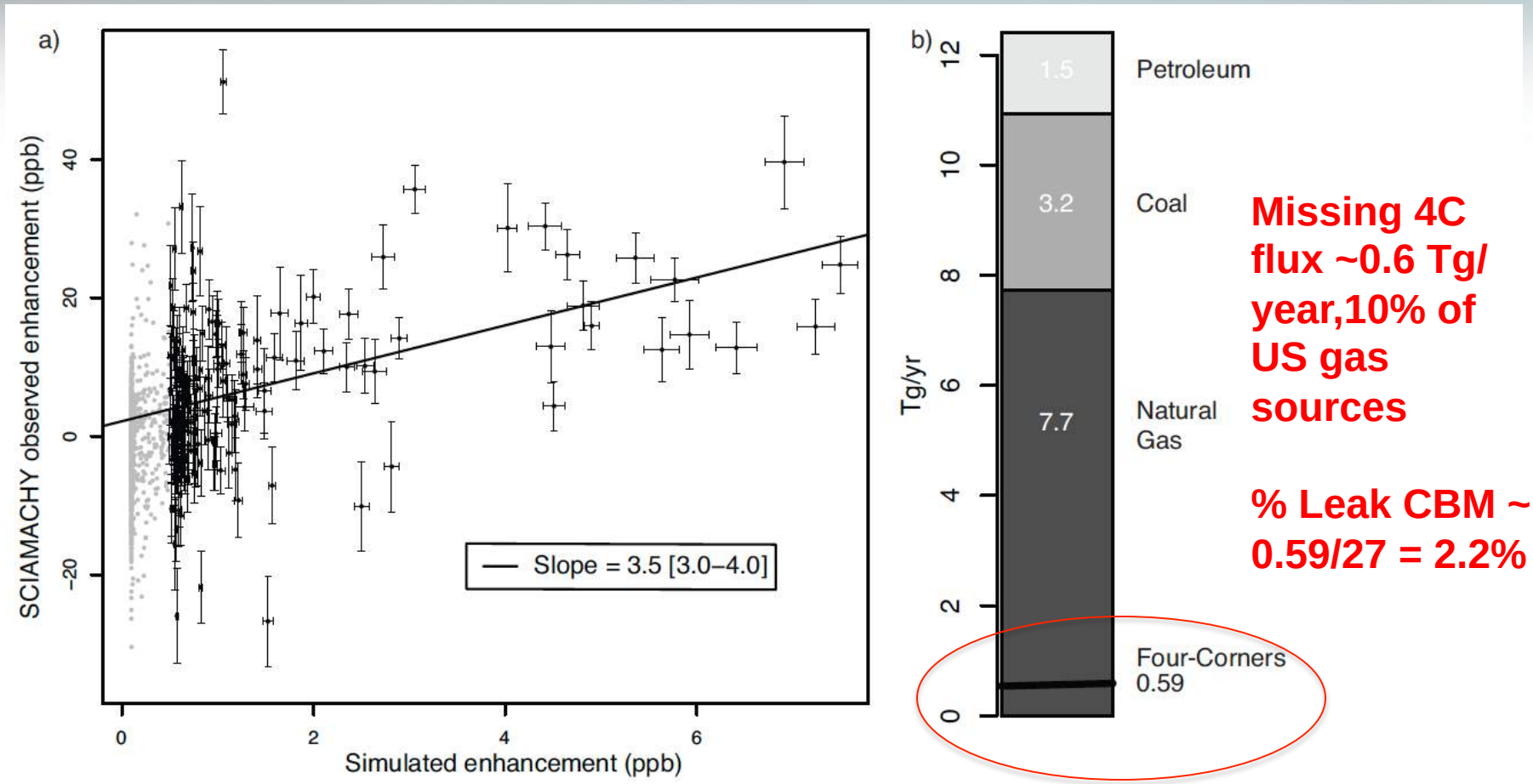
(X_{CH4} ≥ 1.85 ppm means that at least one value that day reached 1.85 ppm)

Edgar emissions have to be scaled by x 3 in WRF model to match 4-Corners FTS data



Kort et al in review Nature Geosciences 2014

Satellite data confirm 4-Corners "missing" emission in inventory is double of value in current Edgar inventory



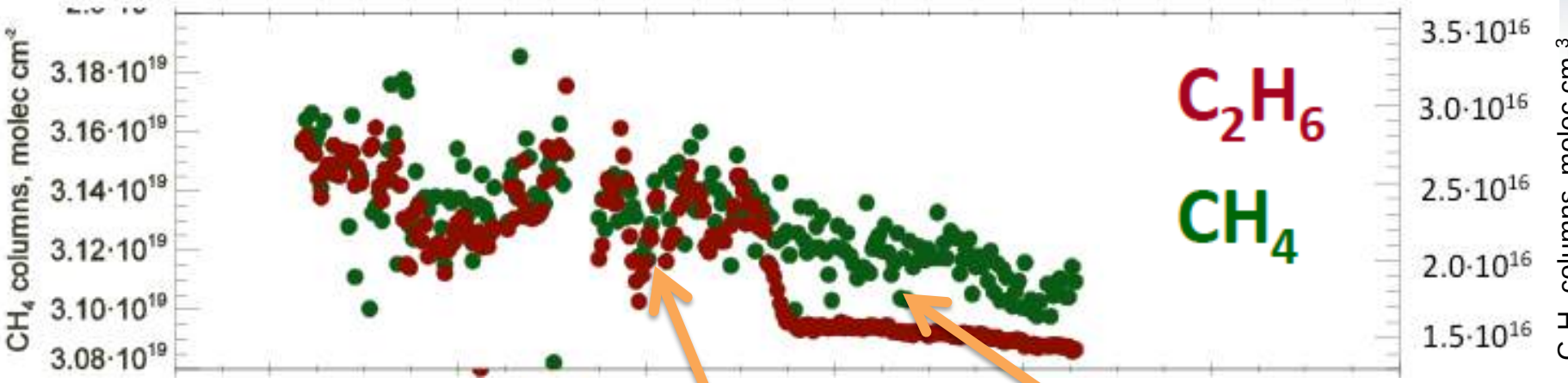
Missing 4C flux ~0.6 Tg/ year,10% of US gas sources

% Leak CBM ~ 0.59/27 = 2.2%

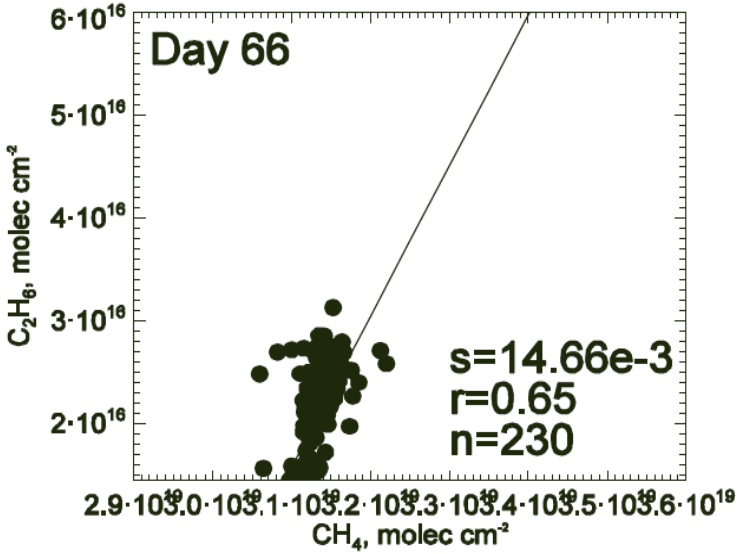
Figure 2: Methane enhancement for Four Corners region & US EPA inventory estimates.

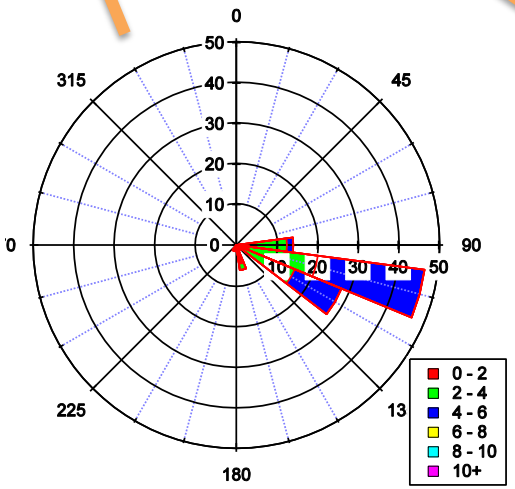
Consistent with US wide study *Miller PNAS '13. But had* no data for 4Corners and showed Edgar emissions were too high. Turner et al 2015 inversions correct for this with our data.

Attribution of Fugitive Sources: Regional solar FTS (Mid-IR, InSb) retrievals of column C_2H_6 & CH_4

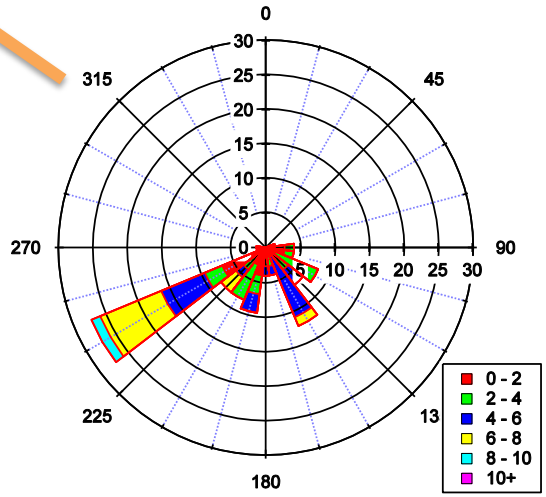


C_2H_6/CH_4 = 1.5%



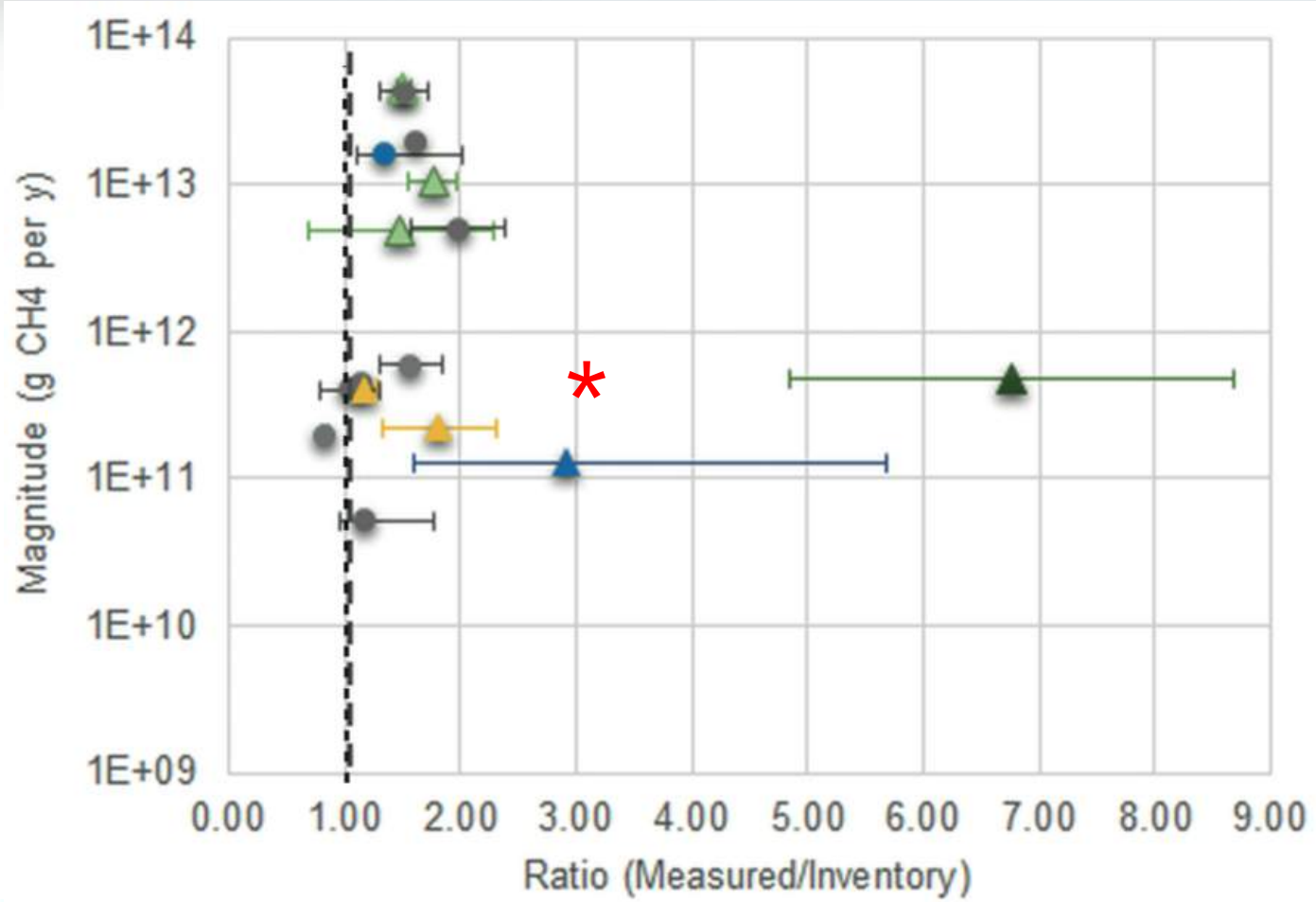


8 AM – 1 PM



1 PM – 6 PM

Inventories & emissions factors (bottom up) underestimate actual measured CH_4 emissions (top down) across scales



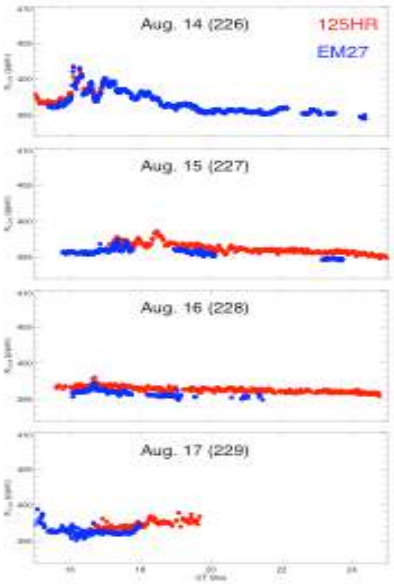
Brandt, Science 2014

***4Corners Attributed to conventional coal bed methane production (pre hydraulic fracturing)**

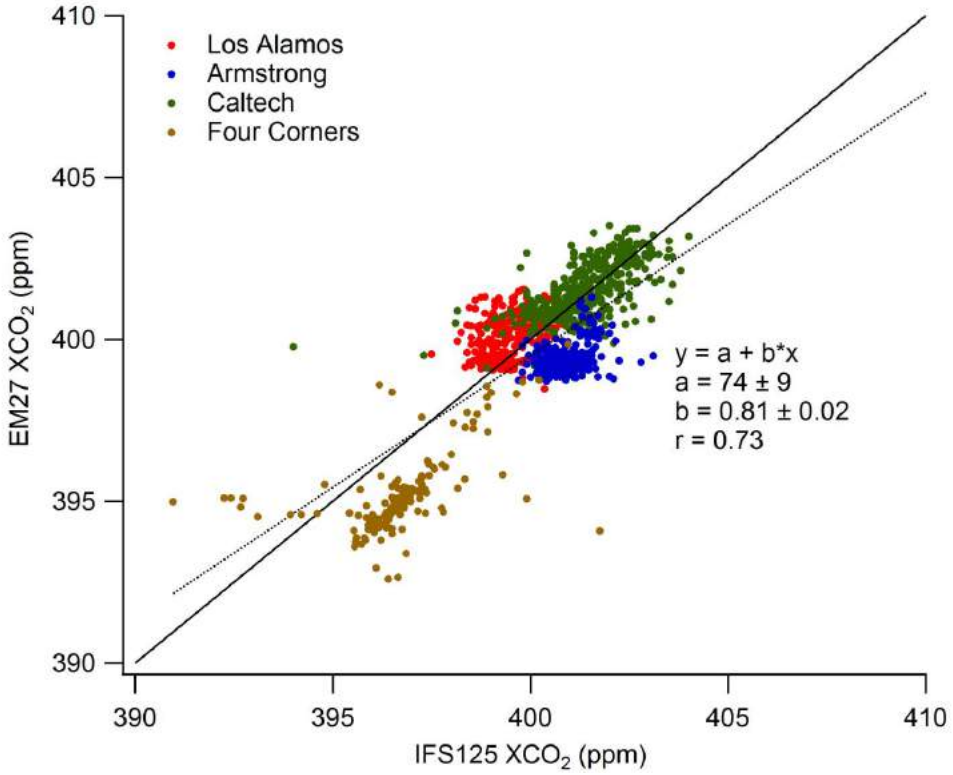
**4Corners*

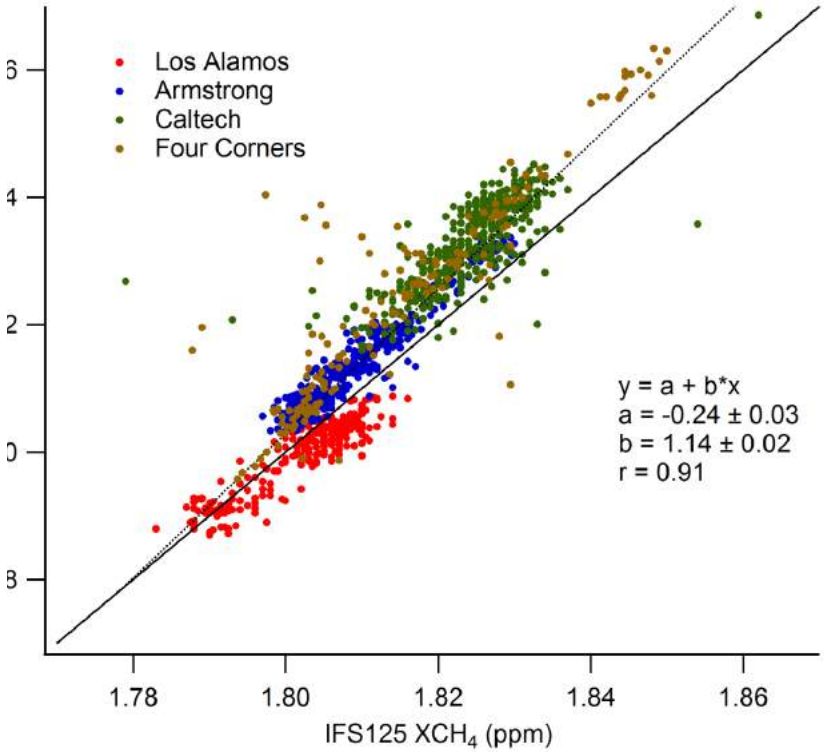
Portable mini-mobile FTS compared with TCCON at 4-Corners, Los Alamos, Armstrong & Caltech

Developing a **portable** and **robust** instrument Without compromising **Accuracy** and **long term** stability! EM27/SUN validated with TCCON: Promising results.

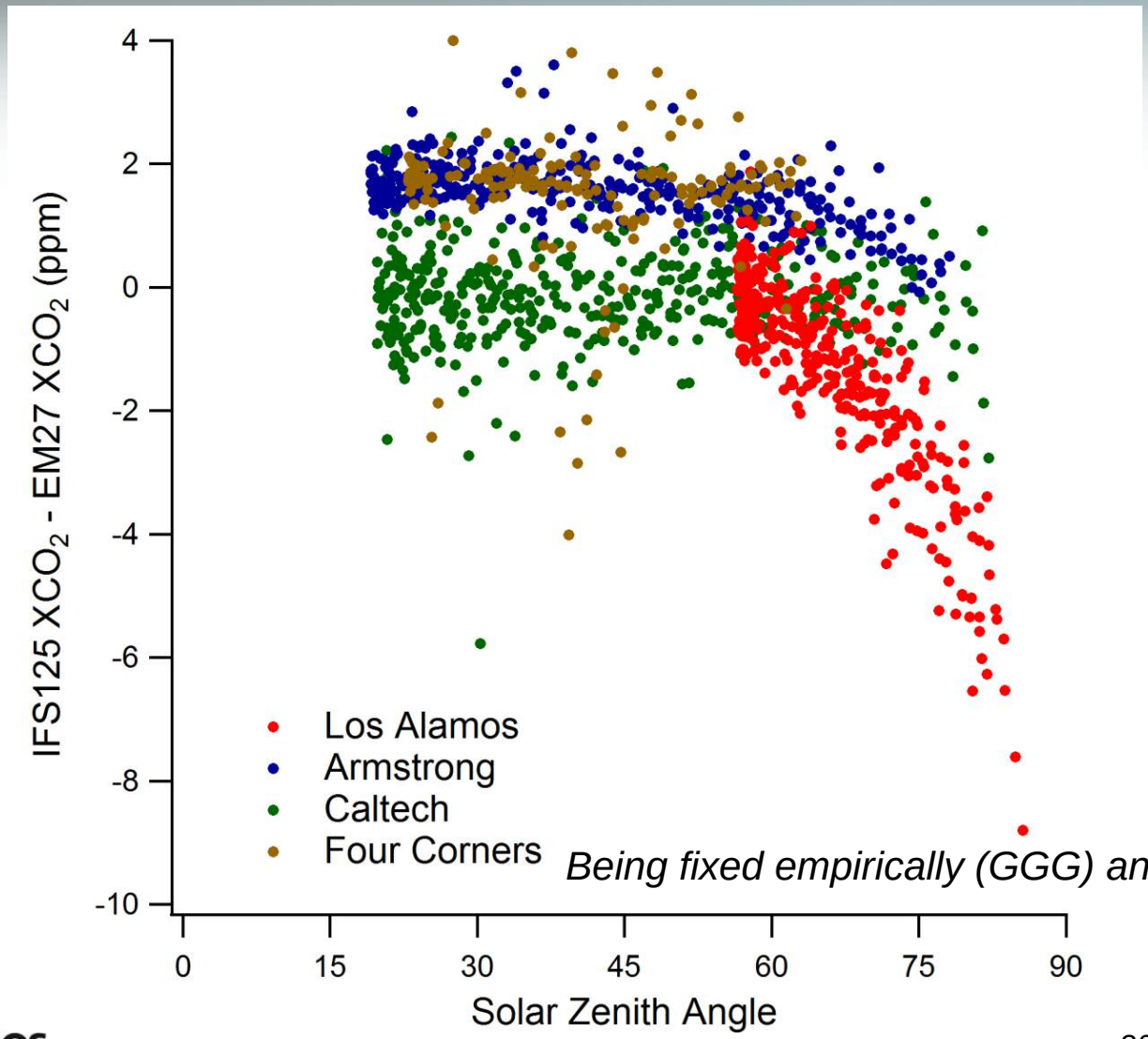


TCCON-EM27SUN Comparisons





Low CO_2 Bias at High Solar Zenith



Being fixed empirically (GGG) and apriori (PROFFIT)

Mesoscale Atmopsheric Emission Verification

- Remote NO_2 and CO_2 verification of power plant emissions.
- WRF simulations with CEMS agree well with FTS column, with less scatter from met. variability than *in situ* network (McKain 12)
- Satellite CH_4 hot spots at 4-Cormers attributed to coal bed CH_4
- Modeling of data shows current CH_4 inventory low by factor of 3.
- Remote C_2H_6 signatures used to attribute CH_4 sources
- Compact mobile FTS expands observational opportunities
- Amazon rainforest monitoring in Brazil with OCO2 validation
- Mini FTS-TCCON comparisons are promising