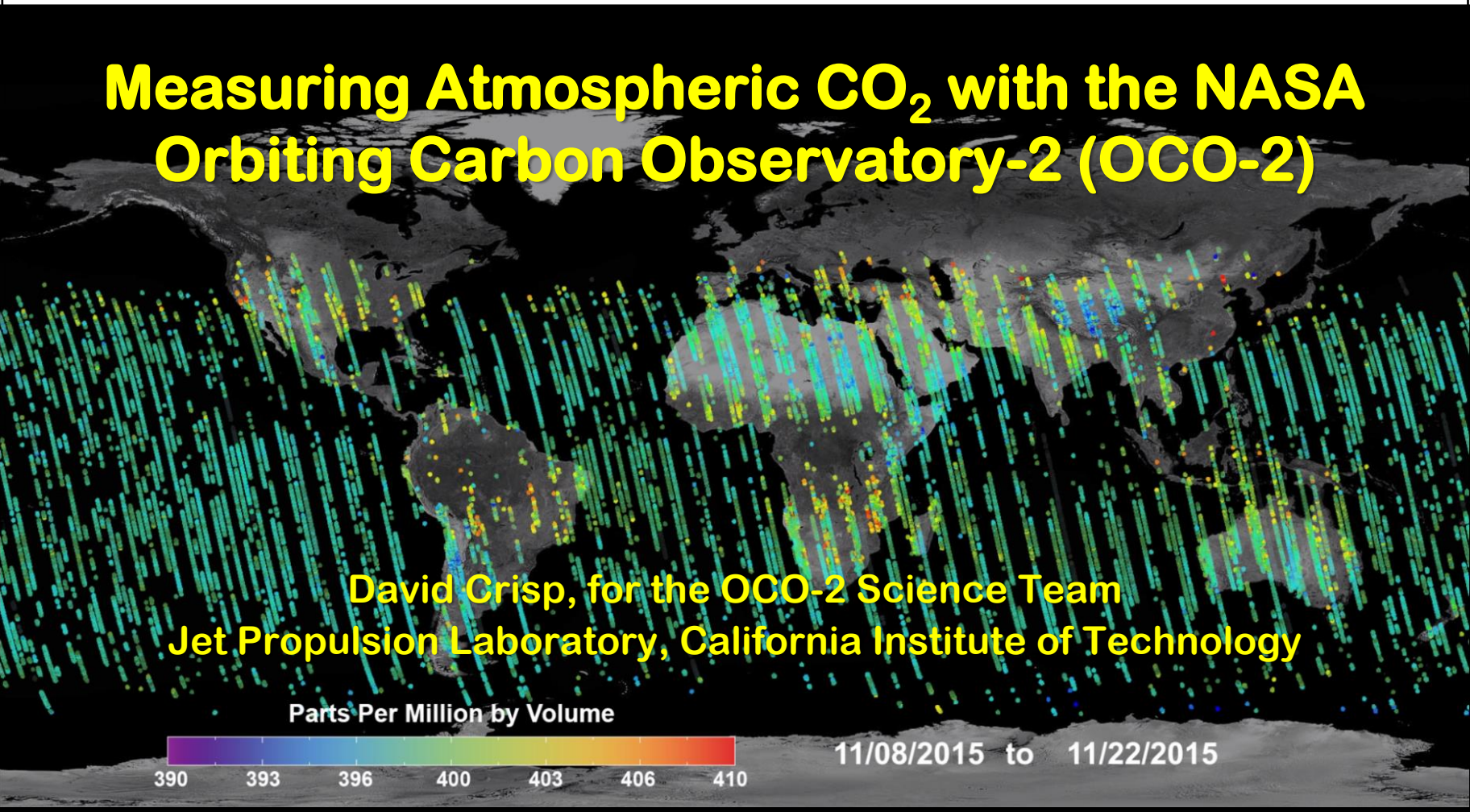
Measuring Atmospheric CO_2 with the NASA Orbiting Carbon Observatory-2 (OCO-2)

David Crisp, for the OCO-2 Science Team
Jet Propulsion Laboratory, California Institute of Technology



8 November 2016

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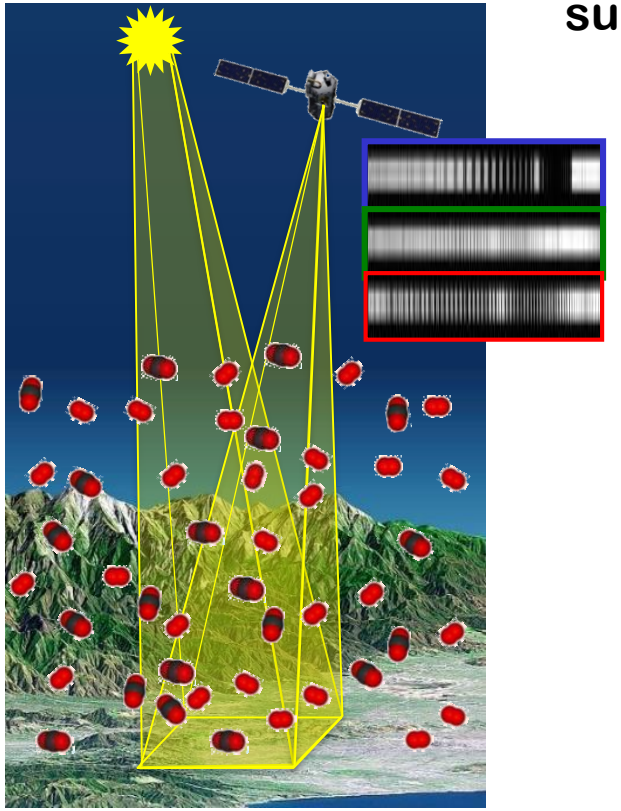
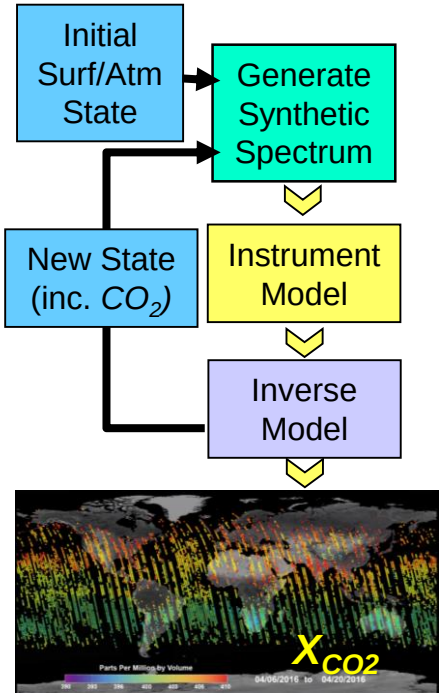
Government sponsorship acknowledged.

Measuring CO_2 from Space

- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight

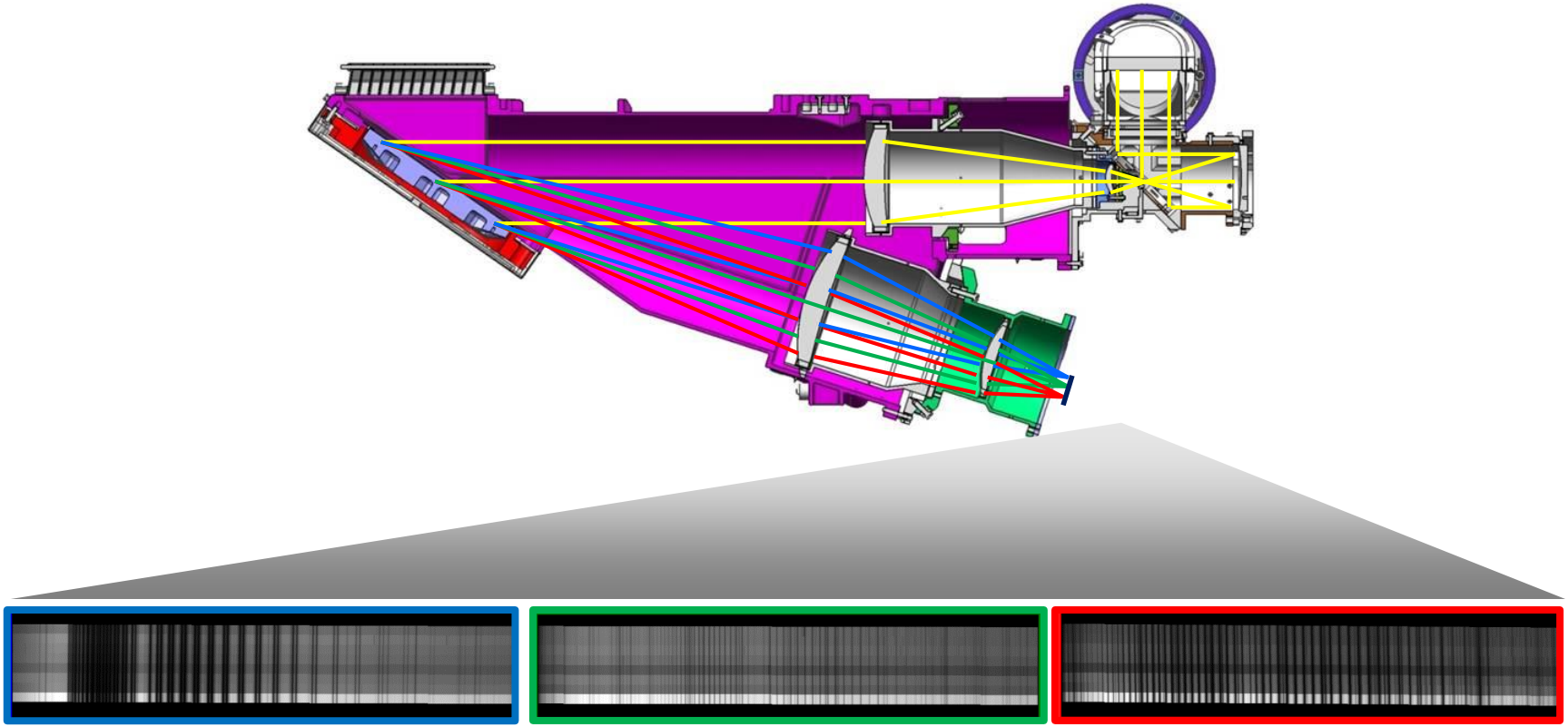


Retrieve variations in the column averaged CO_2 dry air mole fraction, X_{CO2} over the sunlit hemisphere



Validate measurements to ensure X_{CO2} accuracy of 1 ppm (0.25%)

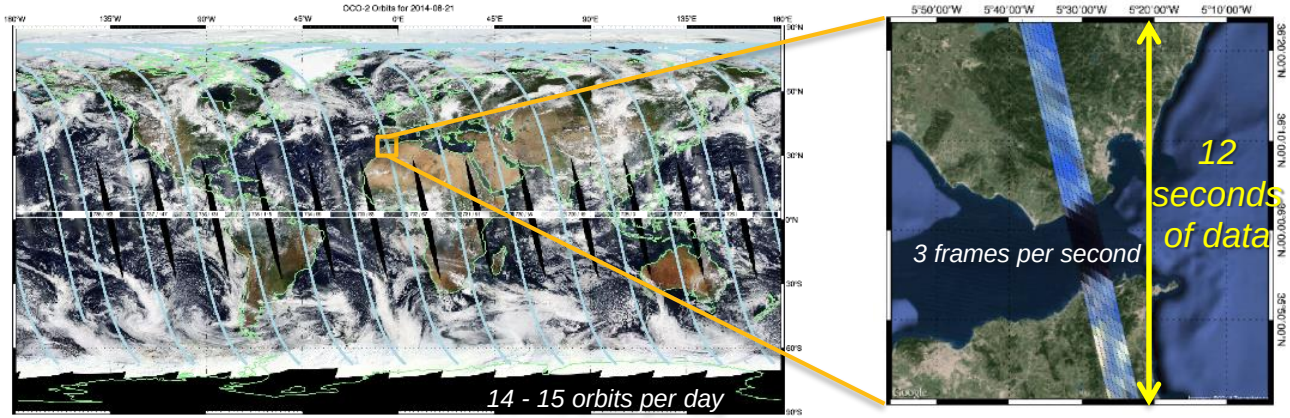
The OCO Instrument – Optimized for Sensitivity

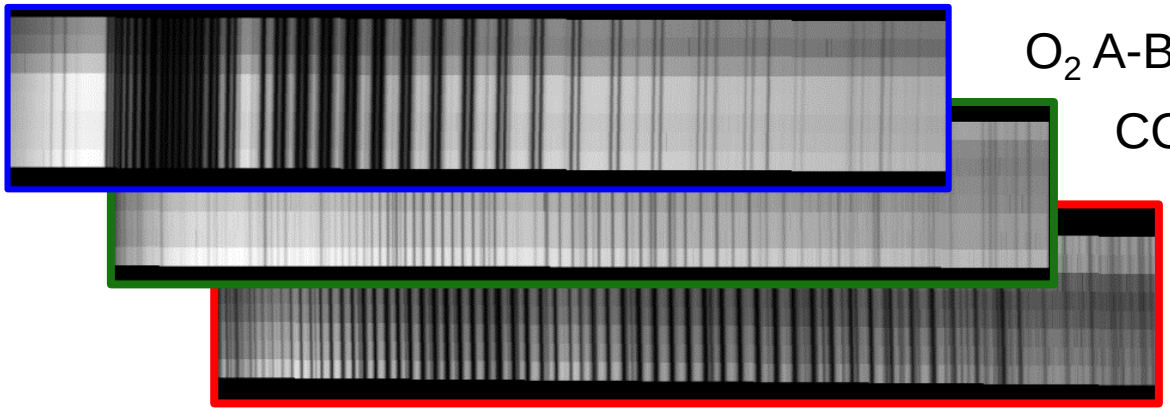


0.765µm O_2 A-Band | CO_2 1.61µm Band | CO_2 2.06 µm Band

Each 1/3 sec frame includes 8 spatial footprints with 1,016 wavelengths in 3 spectral channels.

OCO-2 Sampling Approach





O_2 A-Band

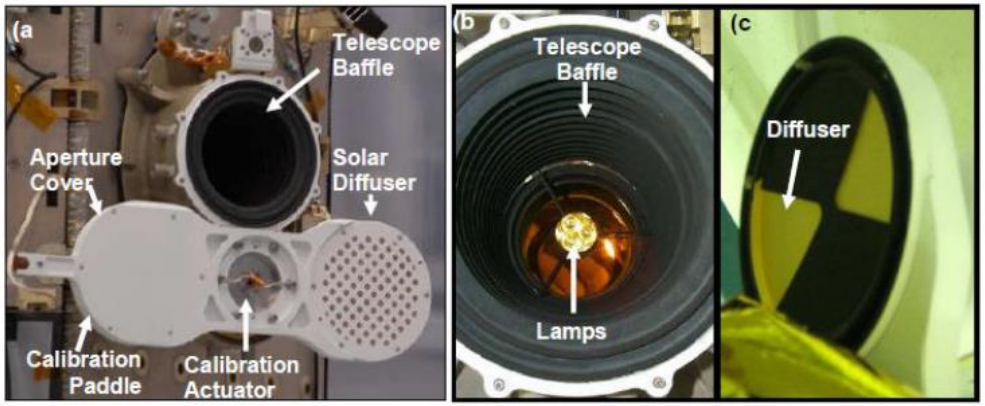
CO_2 1.61 μm Band

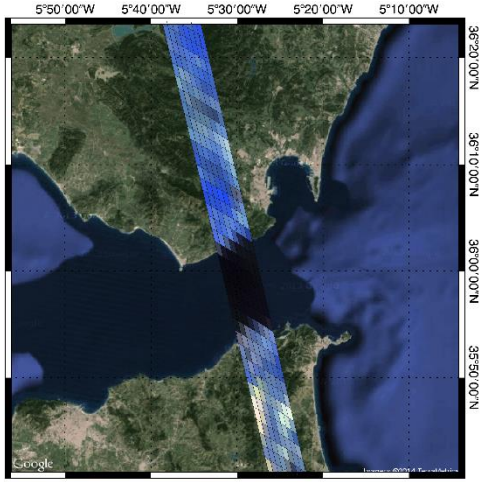
CO_2 2.06 μm Band

The OCO-2 instrument collects 24 soundings each second as it flies over the sunlit hemisphere of the Earth, yielding almost 1 million soundings each day

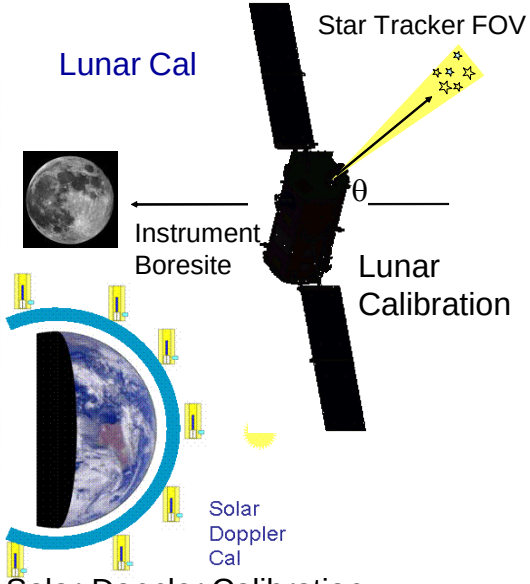
The OCO-2 On-Board Calibration System

- The OCO-2 on-board calibration system includes
  - An on-board calibration assembly (OBC), with a solar diffuser, a lamp diffuser and lamps
  - The spacecraft's ability to point the instrument boresight at the sun, the moon, or stationary surface targets
- This system facilitates routine (every orbit) and "special" calibration activities to verify the radiometric, spectroscopic and geometric calibration





Geometric calibration over the strait of Gibraltar



Solar-Doppler Calibration

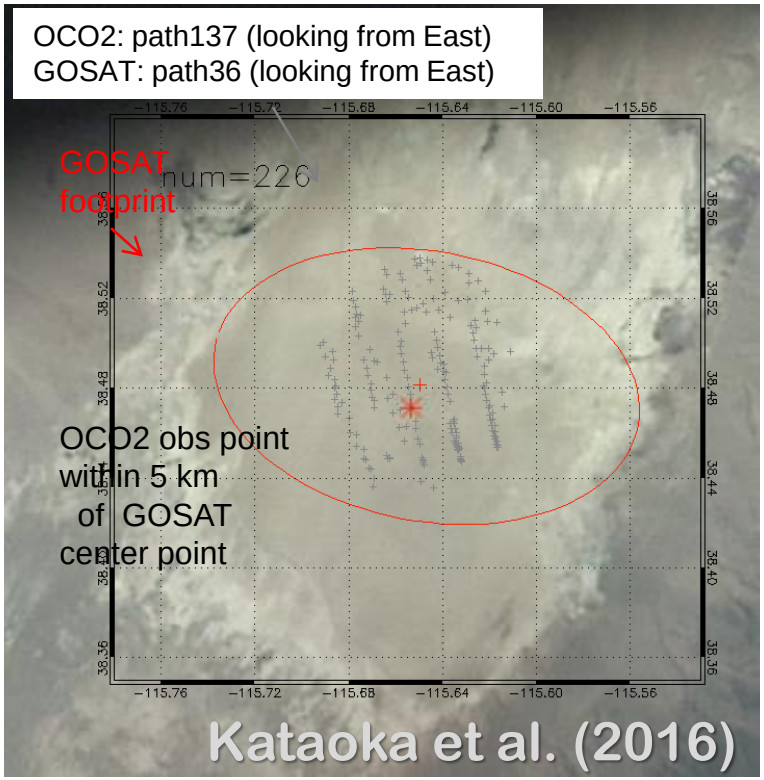
OCO2- GOSAT Radiometric Comparisons over Railroad Valley

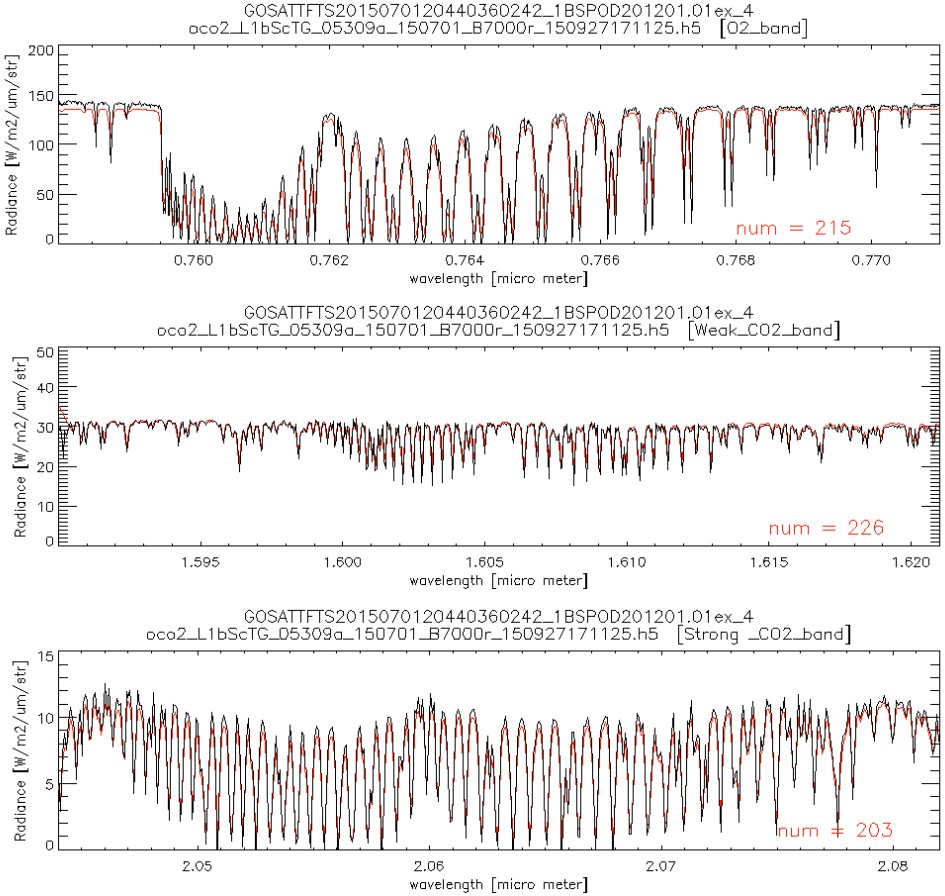
Comparisons between OCO-2 and GOSAT also indicate very good agreement

Jul01,2015 [1]

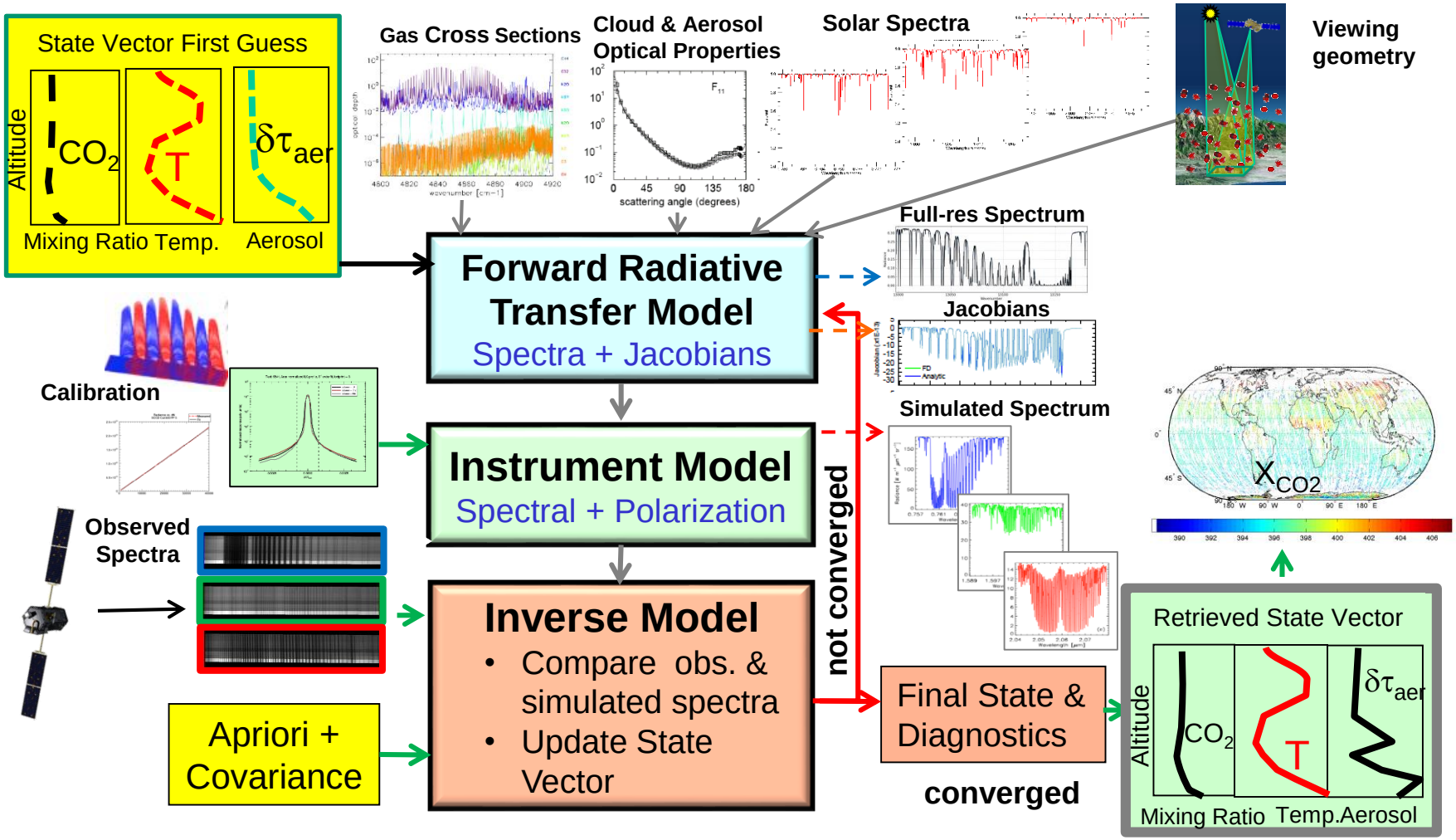
oco2_L1bScTG_05309a_150701_B7000r_150927171125.h5
GOSATTFTS2015070120440360242_1BSPOD201201.01

GOSAT Rad
OCO2 average Rad within 5km of GOSAT cnt point X 2
ratio1 = OCO2/GOSAT



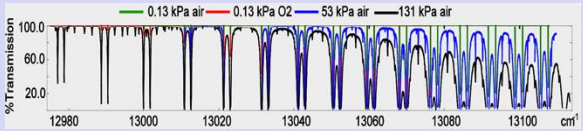


The OCO-2 XCO2 Retrieval Algorithm

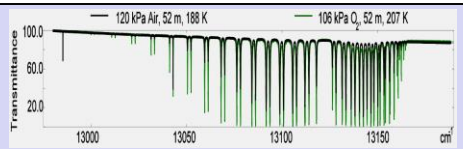


Recent updates to spectroscopy for OCO-2

Updates to the O_2 A-band (Drouin et al. [2016])



Cavity Ringdown Spectroscopy
(Lab meas from NIST, ca 2008)
- High optical depth
- Range of pressures
- Stable frequency axis

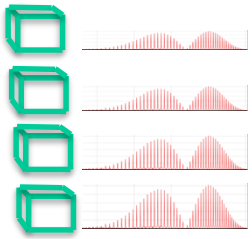


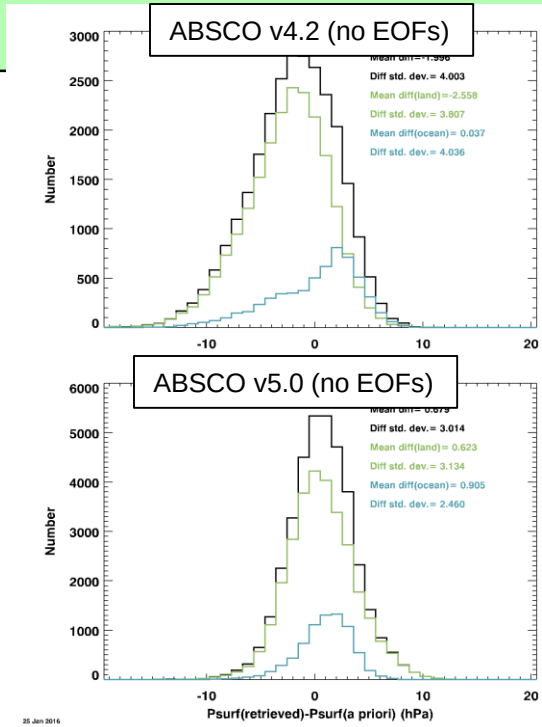
Fourier Transform Spectrometer
(Lab meas from JPL, 2012, 2015)
- Range of pressures and temp.
- Measures entire band for consistency

TCCON spectra
(Lamont TCCON site)
Long path length: constraints on line mixing and collision-induced absorption

Multispectrum fitting analysis
Simultaneous fitting of different p, T and measurement techniques capitalizes on strengths of all the different measurements

New ABSCO tables

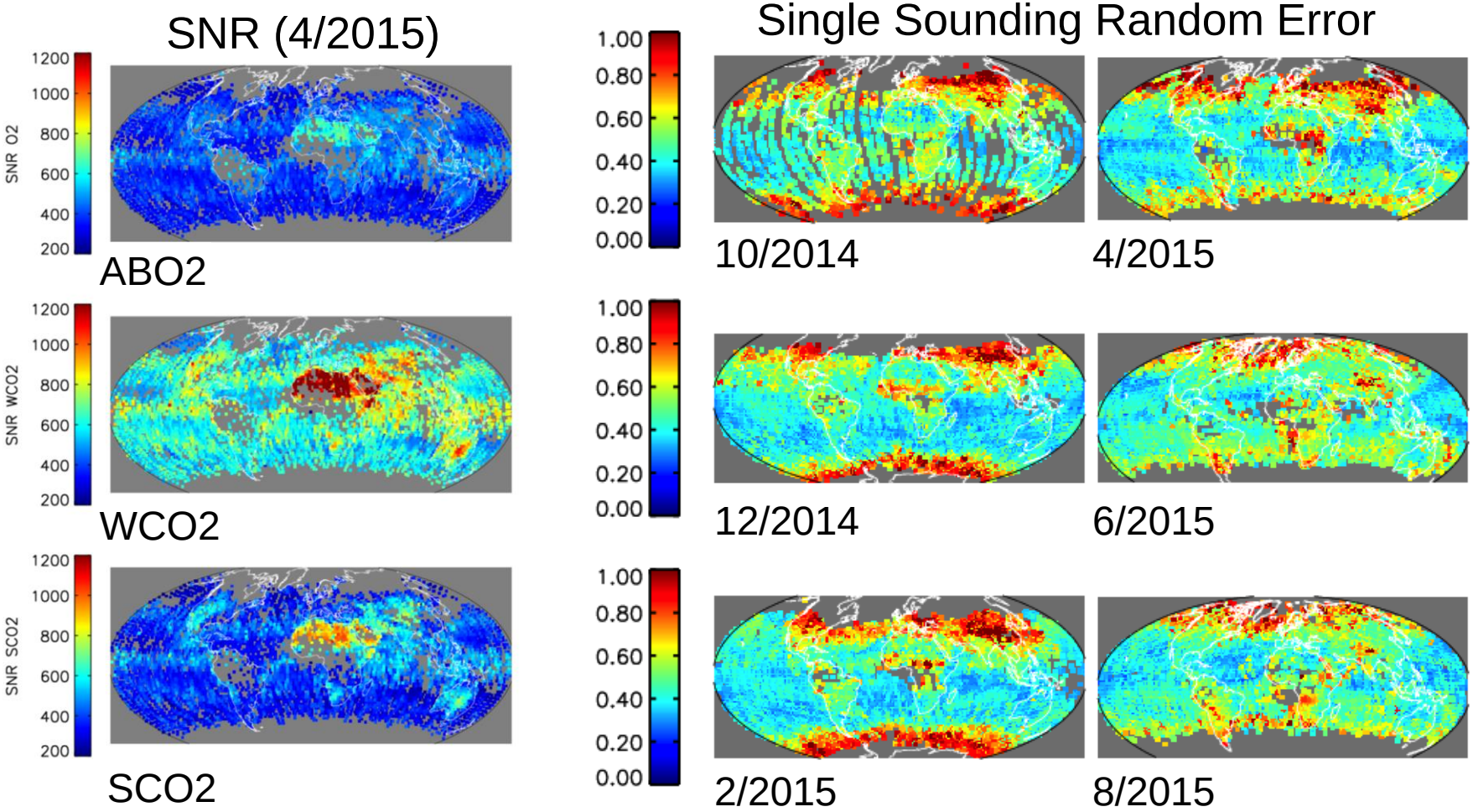




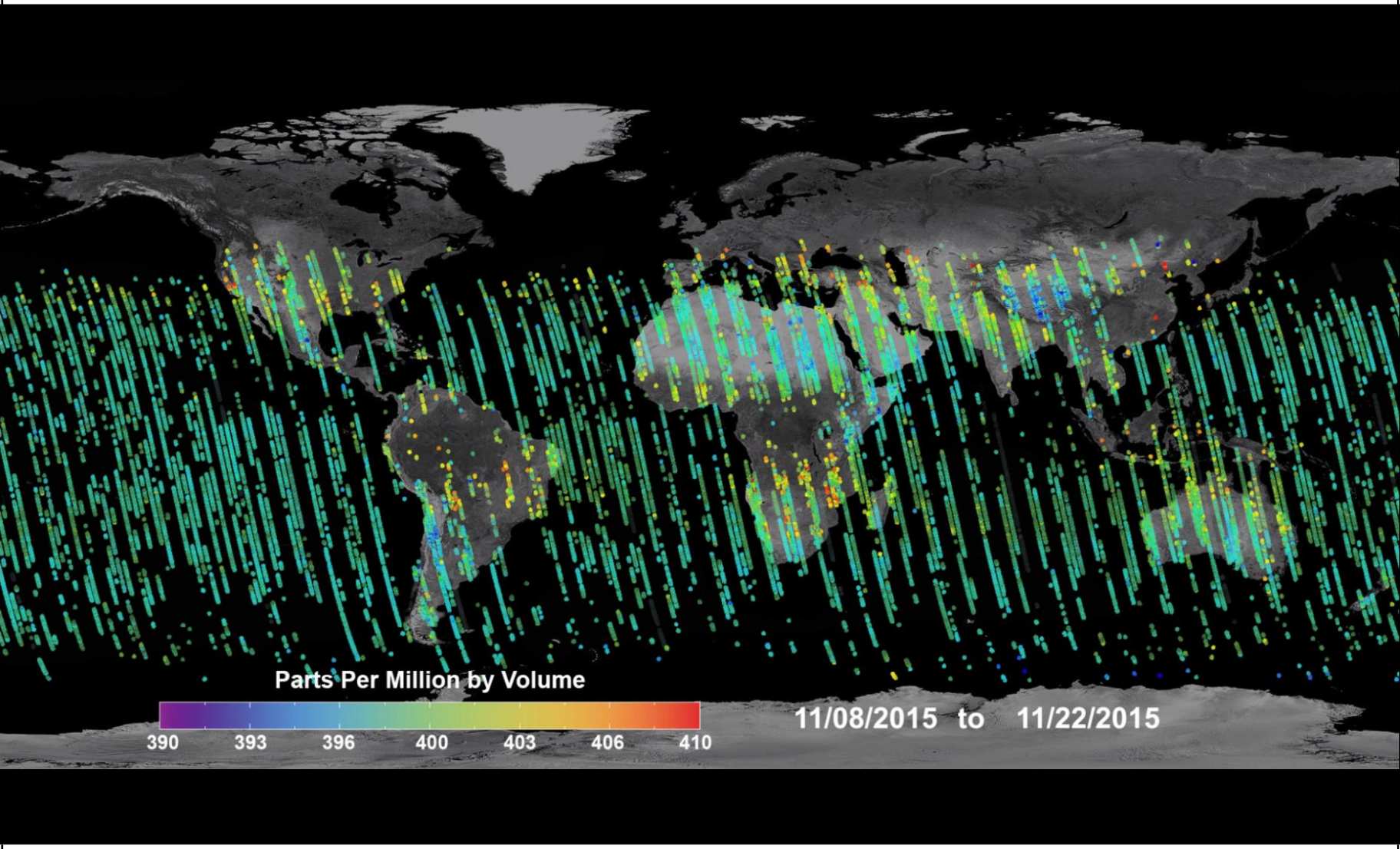
Impact of ABSCO O_2 update on surface pressure retrievals
- **Improved consistency** between land and ocean retrievals
- **Reduced bias & std. dev**. w.r.t. ECMWF
- Distributions of bias more **symmetric**

New spectra and T-dependent analysis in the 1.6 and 2.06 μm CO_2 bands: Devi et al. [2016], Benner et al. [2016]

High Signal-to-Noise Ratio (SNR) yields low Single Sounding Random Errors

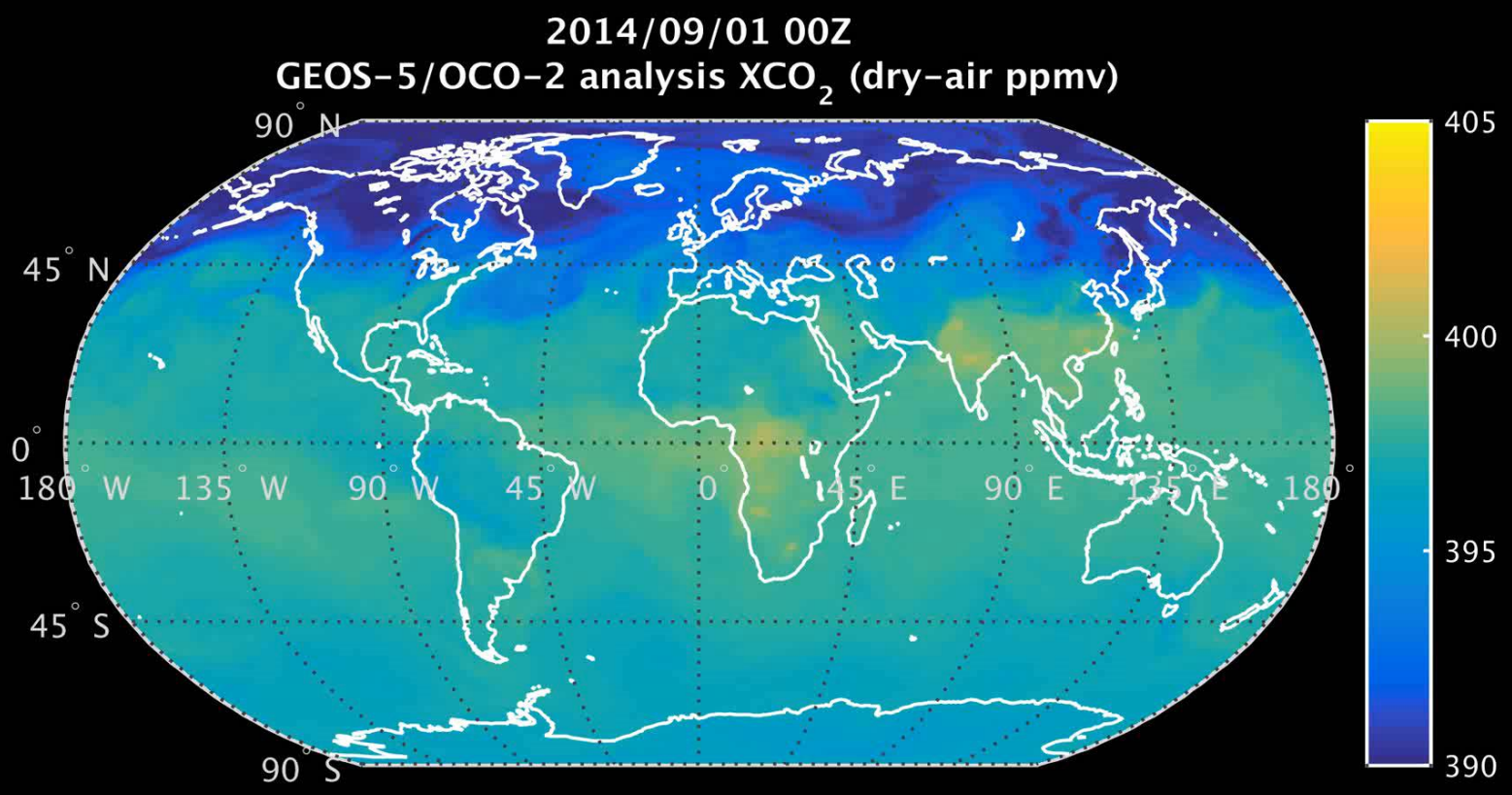


A Quick Look at the OCO-2 Prime Mission

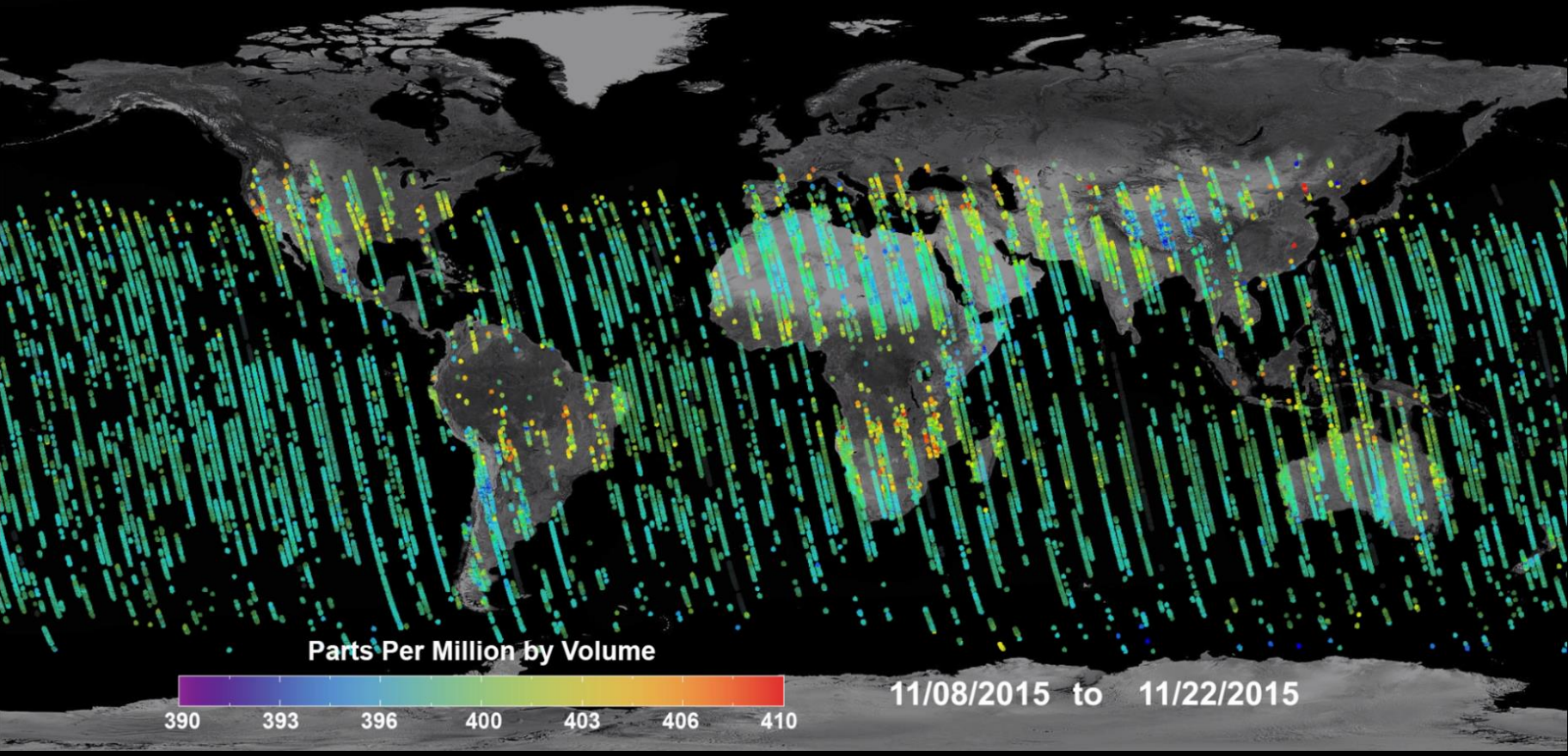


OCO-2 X_{CO2} Assimilated into GEOS-5

Brad Weir, GSFC GMAO

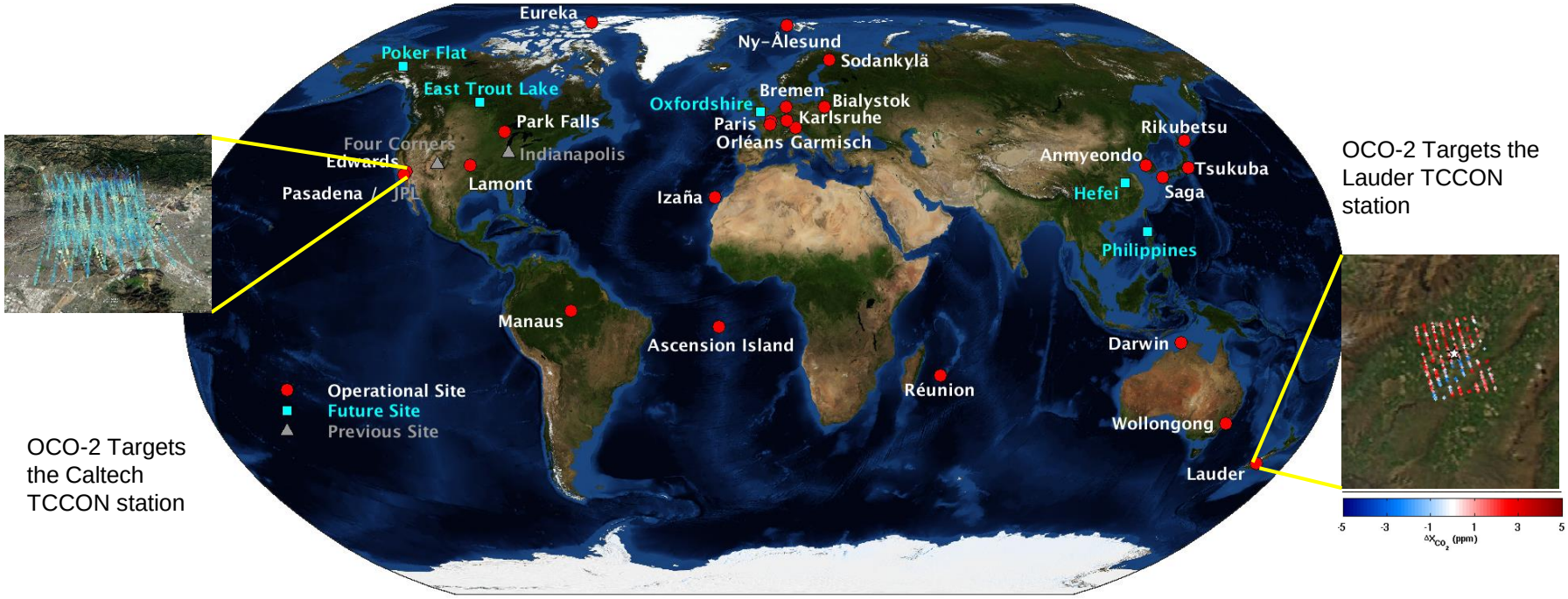


Validating the OCO-2 Products



Validation: The TCCON Network

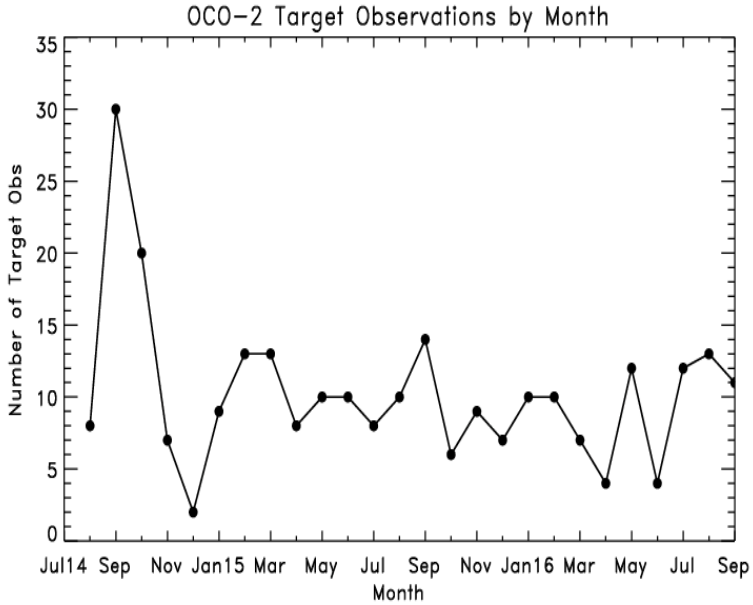
- Members of the OCO-2 team designed the Total Carbon Column Observing Network (TCCON) specifically to:
  - Serve as a transfer standard between OCO-2 and the World Meteorological Organization (WMO) in situ atmospheric CO_2 standard
  - Measure CO_2 to the precision and accuracy required to validate OCO-2.
  - Cover a wide range of latitudes and surface conditions.



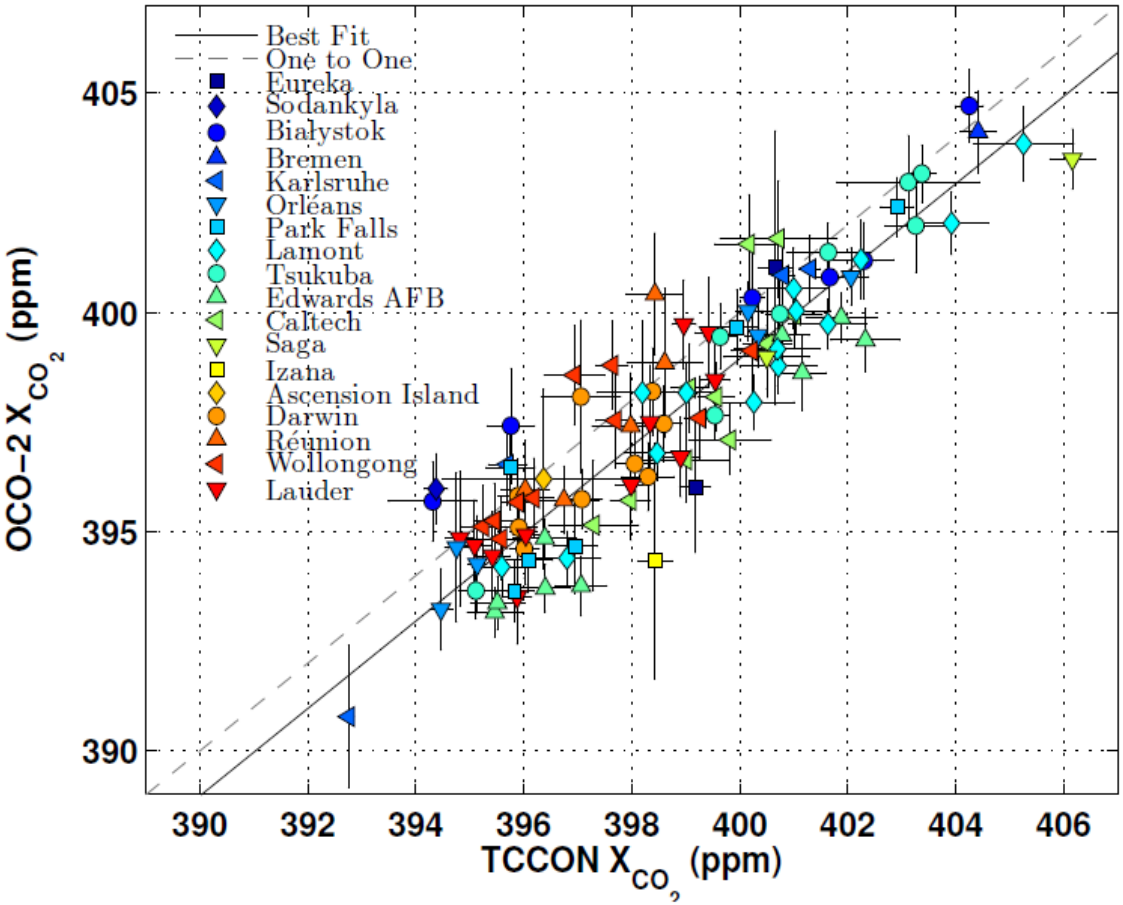
OCO-2 Regularly Targets TCCON Stations

Target Location	Date/Time	MODIS Image
Wollongong	2016-09-28 04:01:26	-
Sodankyla	2016-09-18 10:28:27	
Park Falls	2016-09-14 19:01:32	
Libya	2016-09-13 11:38:00	
Sodankyla	2016-09-13 10:10:12	
Karlsruhe	2016-09-12 12:39:13	
Poker Flat	2016-09-09 22:06:19	
Reunion Island	2016-09-09 10:10:03	
Orleans	2016-09-08 13:03:39	
Railroad Valley	2016-09-05 20:46:42	
Caltech	2016-09-01 21:08:07	

- OCO-2 has executed 267 target observations since August 8, 2014
- There were 11 target observations made in September 2016
- Targets are selected on a daily basis, depending on weather, time since last measurement, and TCCON operational status



Comparison of TCCON and OCO-2 X_{CO2}
(Wunch et al., ATMD, 2016)

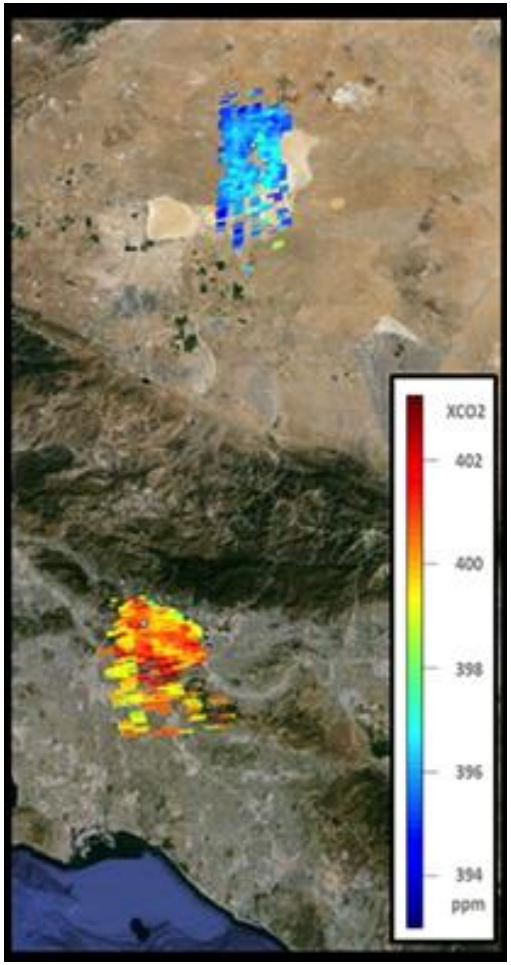


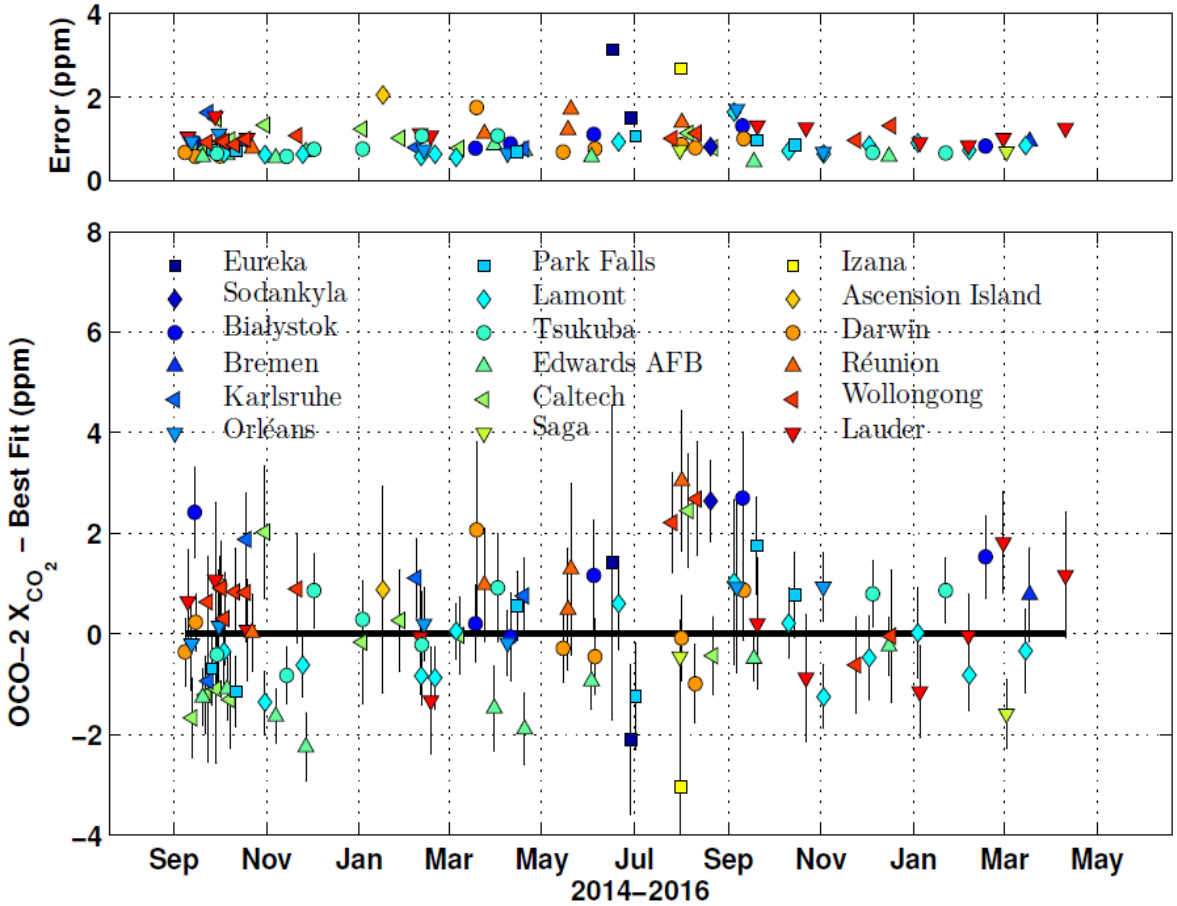
Comparisons with Total Carbon Column Observing Network (TCCON) stations are being used to identify and correct biases in target observations.

After applying a bias correction

- Global bias is reduced to < 1 ppm
- Station-to-station biases reduced to ~1.5 ppm

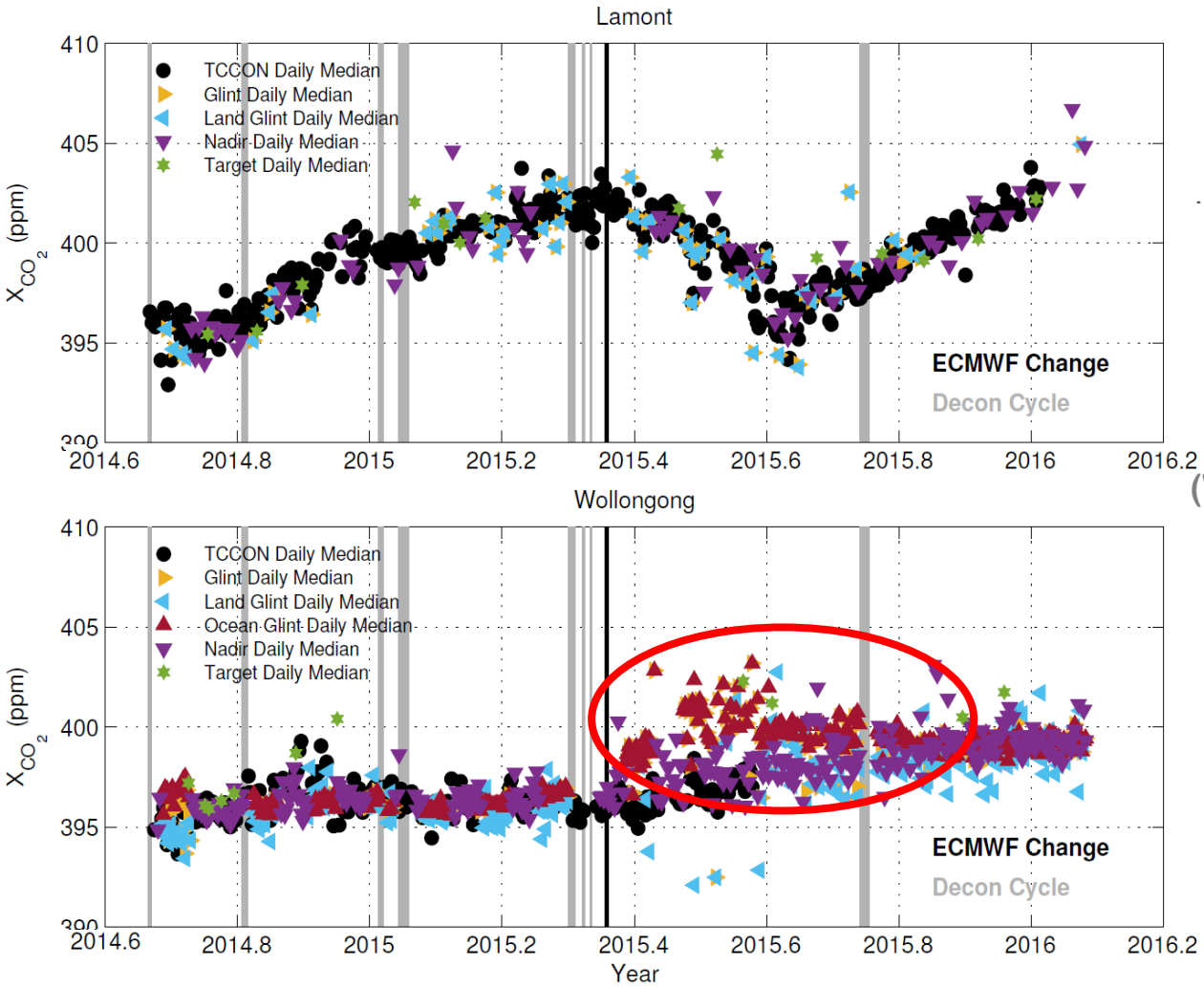
OCO-2/TCCON Time Series – Target Data (Wunch et al., ATMD, 2016)

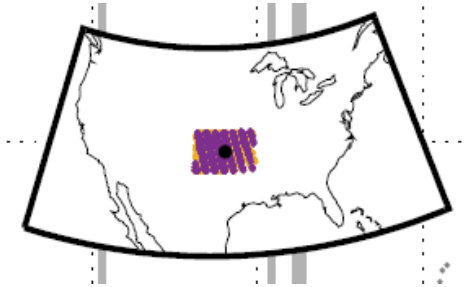




OCO-2 provides the most accurate X_{CO2} observations ever collected from space

Temporal Changes in X_{CO2}: Comparisons with TCCON and other Standards

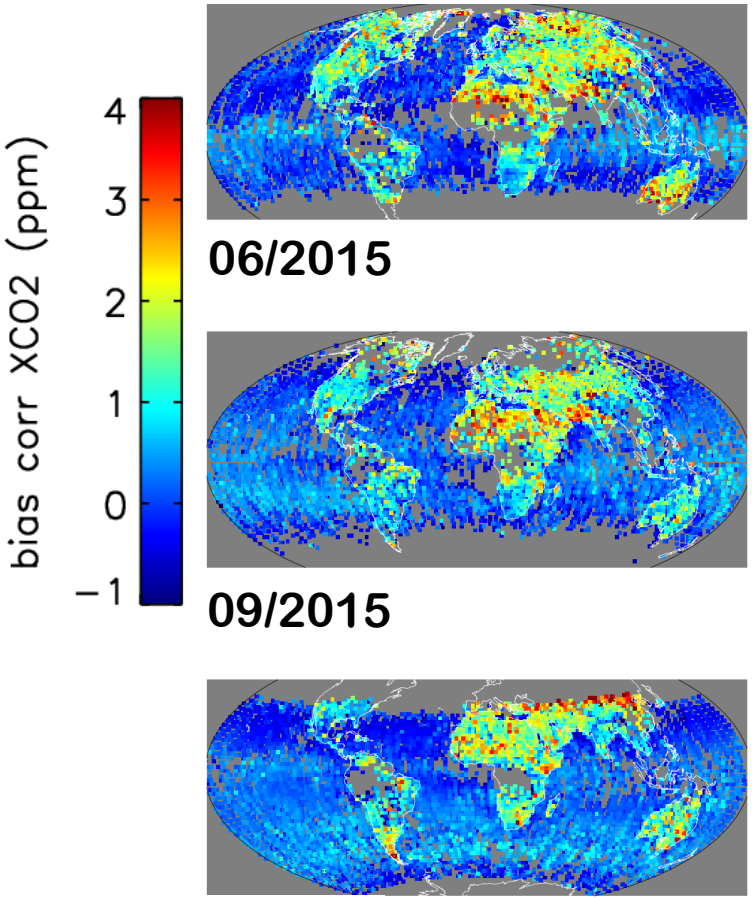




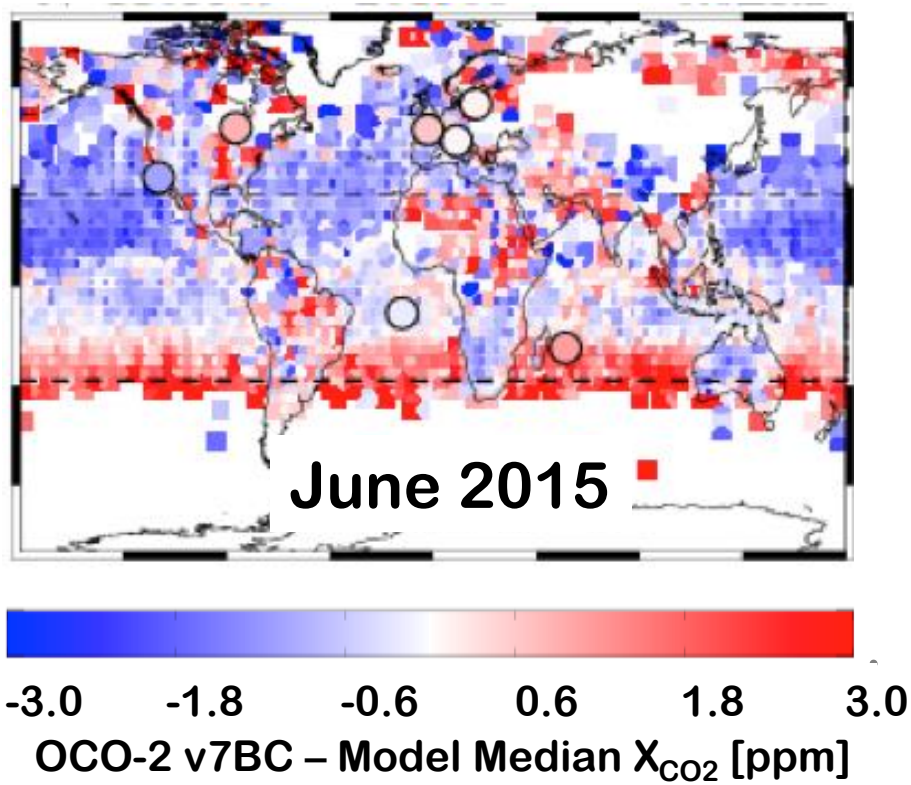
(Wunch et al., ATMD, 2016)

Bias Corrections in the V7 Lite Products

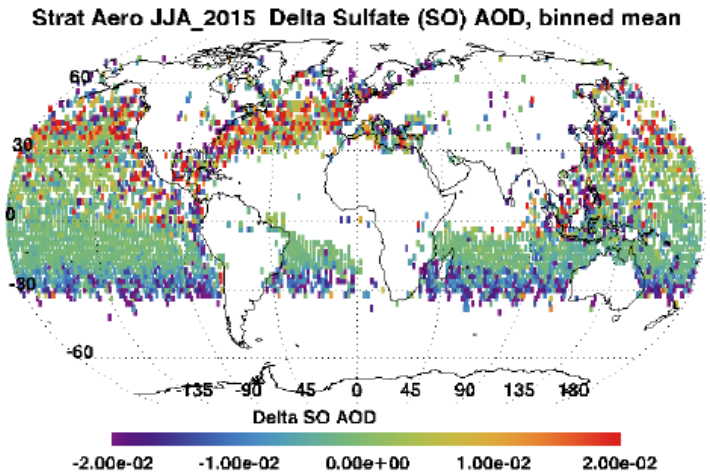
Amplitude of V7 Lite bias correction in 2°x2° bins

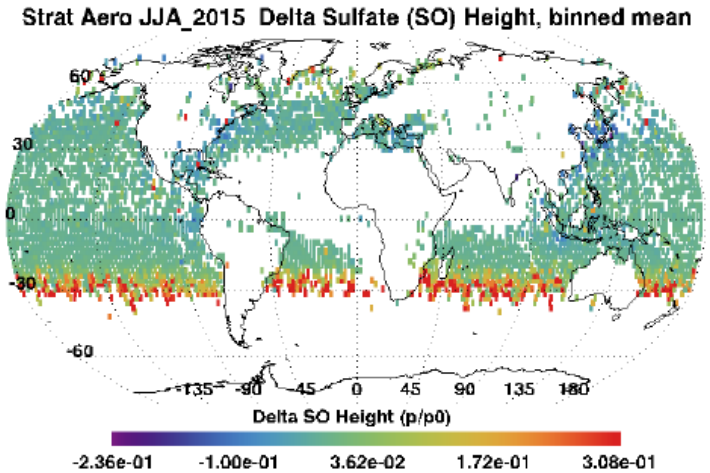


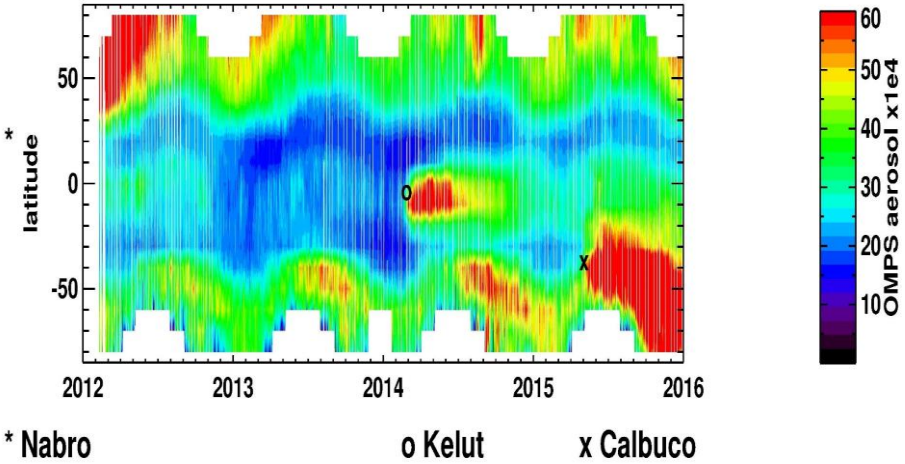
Residual bias vs Multi-Model Means



The 2015 Data affected by the Chilean Calbuco volcano eruption

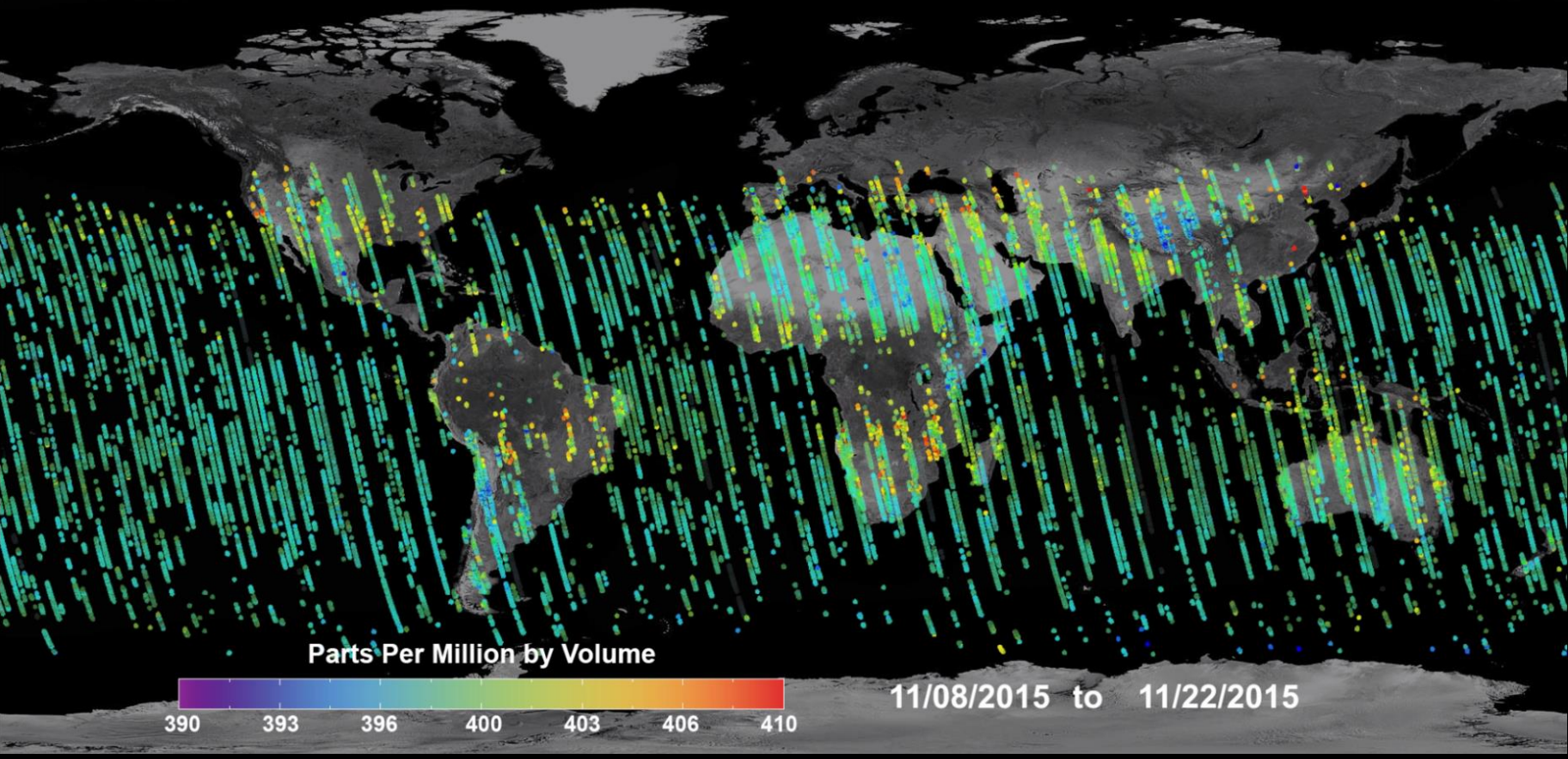




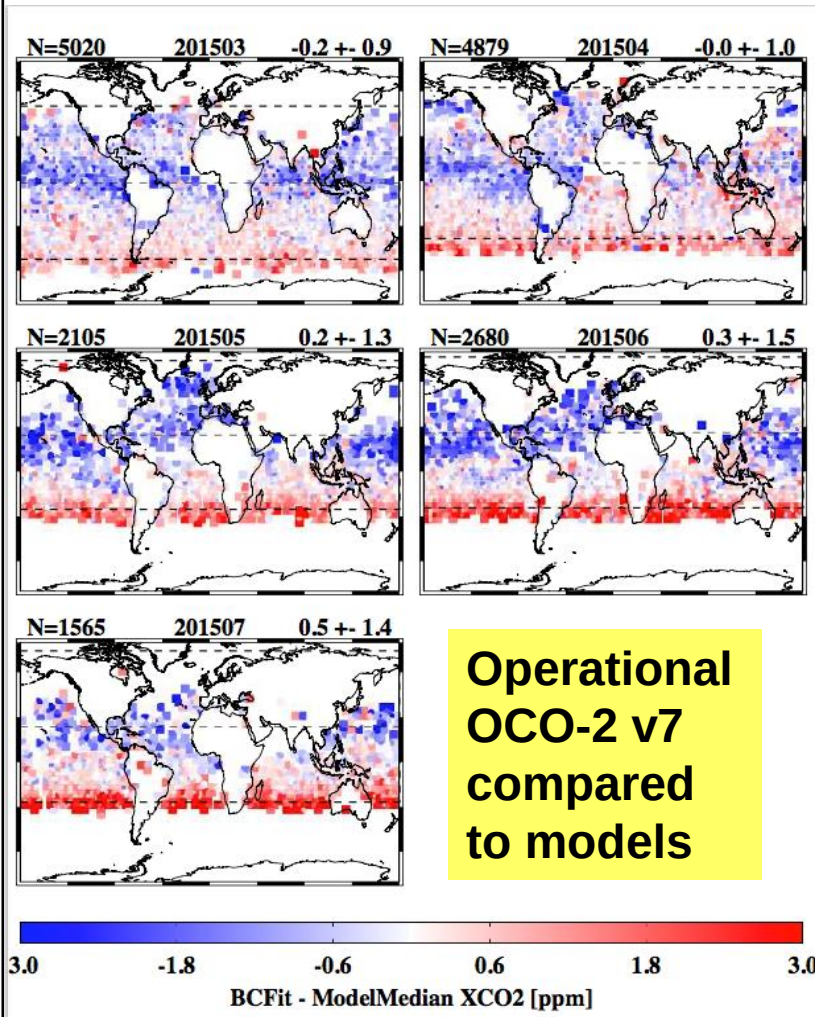


OMPS detected a significant enhancement in stratospheric H_2SO_4 aerosols in mid 2015

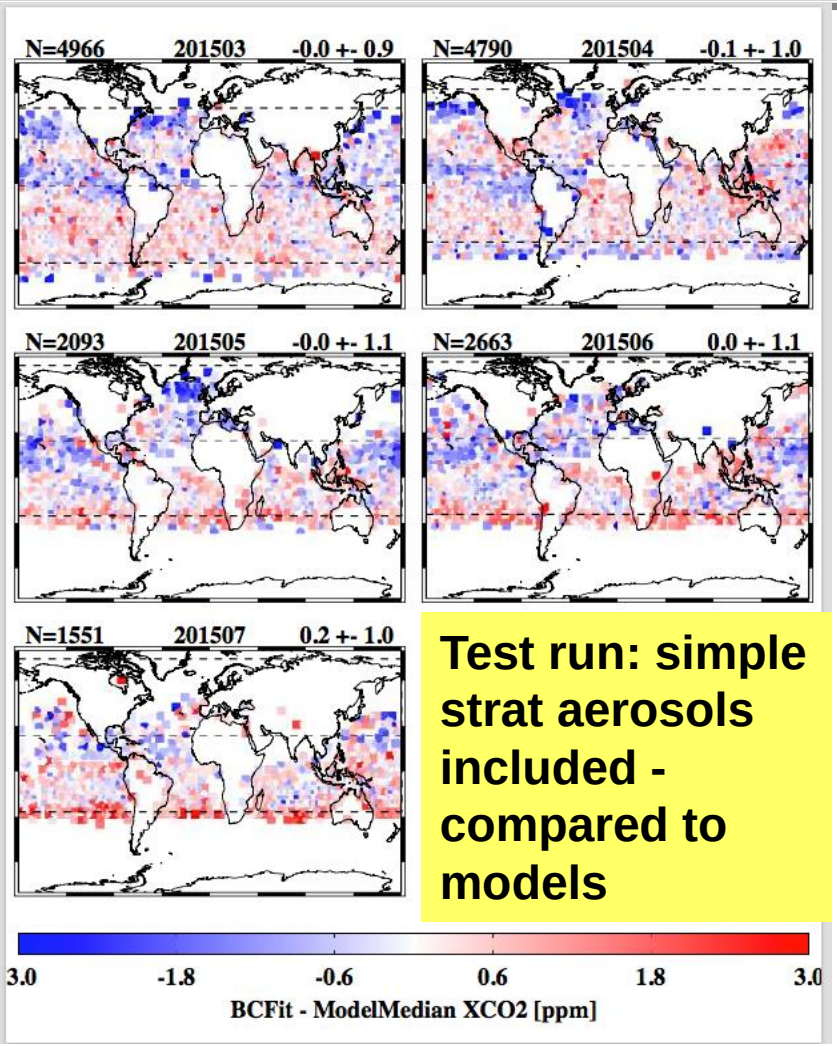
OCO-2 Science Results



A simple test that includes stratospheric aerosols reduces bias



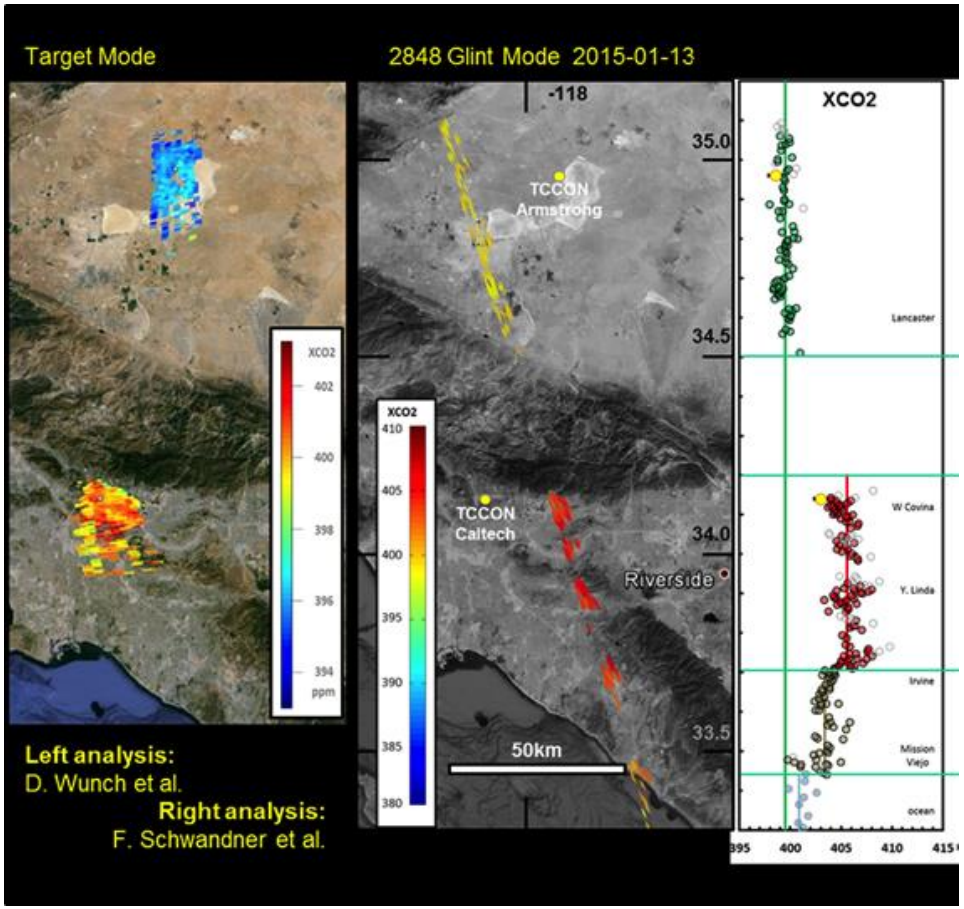
Operational OCO-2 v7 compared to models



Test run: simple strat aerosols included - compared to models

Local enhancements in CO_2 quantified
(Schwandner et al., in prep)

- **Problem**: How well can OCO-2 X_{CO2} measurements quantify the increase in X_{CO2} from fossil fuel burning?
- **Results**: In the Los Angeles region, differences of ~3 ppm were seen, and the statistics show that difference of 1 ppm can be quantified from the data.
- **Significance**: The OCO-2 data enable the next step in quantifying fossil fuel CO_2 emissions impacts with space based data.



Both target observations (left panel) and glint observations (right panel) show enhanced XCO2 of the LA basin relative to the Antelope Valley and AFRC.

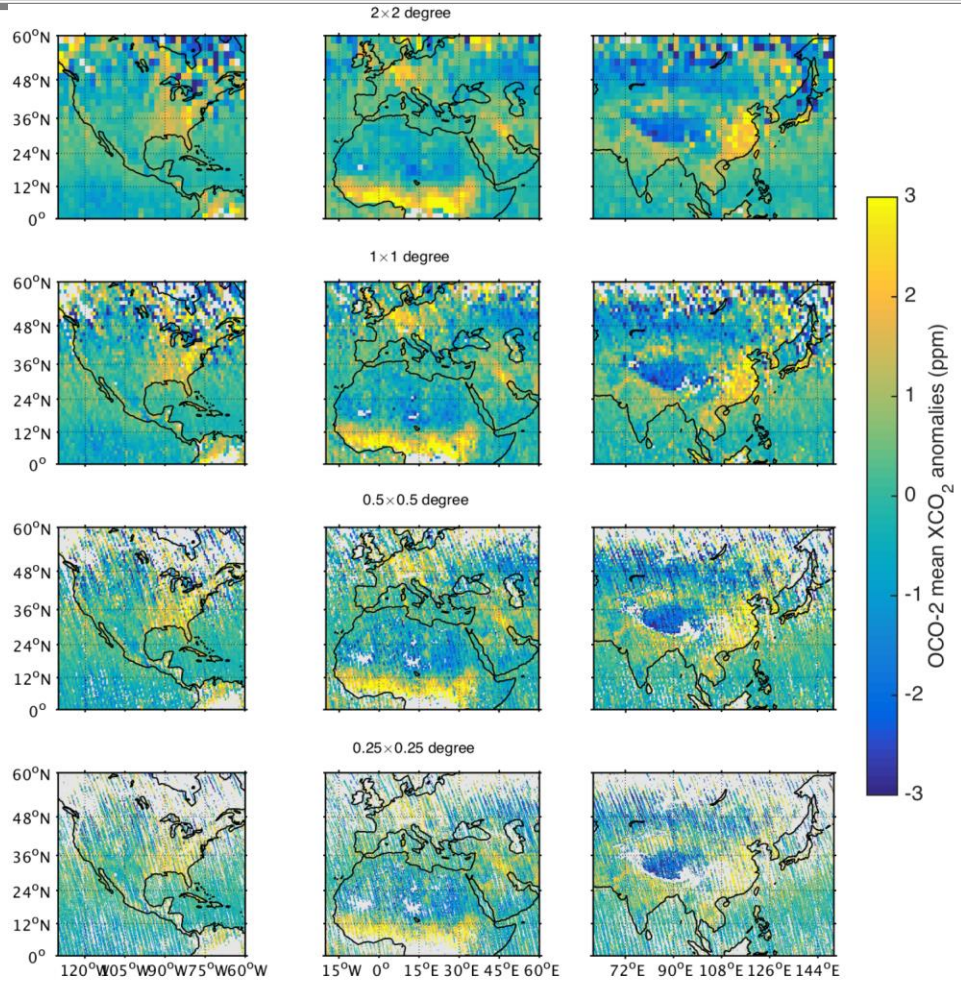
Impact of Spatial Averaging on Anomaly Detection and Characterization

Issue: What is the optimal spatial sampling and averaging for detecting and characterizing X_{CO2} anomalies?

Results: For a mission like OCO-2, with a narrow swath:

- Small scale features become harder to detect as the spatial resolution decreases
- Large scale features become easier to detect and quantify as the spatial resolution decreases

Significance: High spatial resolution is essential for characterizing emission anomalies from small scale sources.



Hakkarainen et al., GRL, 2016

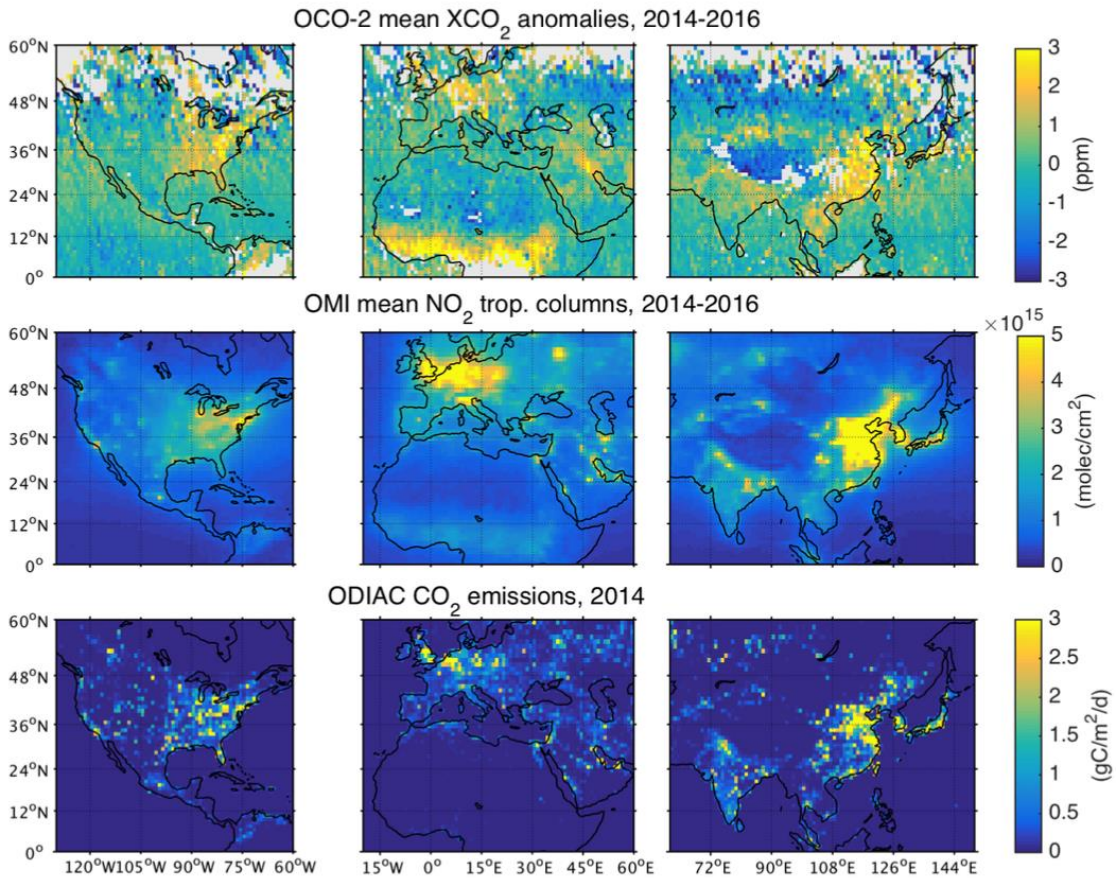
OCO-2 Observations of Anthropogenic CO_2 Emissions (Hakkarainen et al., GRL)

Issue: Can space based observations discriminate anthropogenic CO2 emissions?

Results: OCO-2 X_{CO2} & OMI NO_2 combined to produce global maps of anthropogenic CO_2 emissions

- High CO_2 over eastern USA, central Europe, and China consistent with fossil fuel use inferred from OMI NO_2 and fossil fuel emission inventories.
- CO_2 emissions from fossil fuel extraction activities in the Middle East clearly seen in OCO-2 maps, but not tracked in inventories.
- High CO_2 emissions over central Africa and Southeast Asia are due to intense biomass burning rather than fossil fuel combustion.

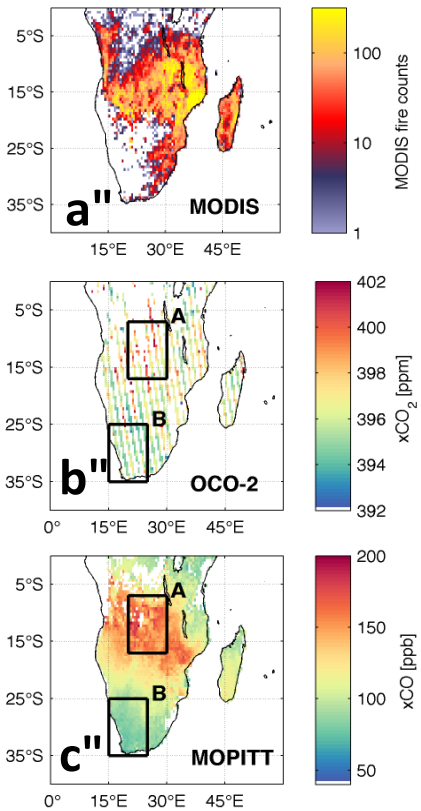
Significance: These results demonstrate the power of spaceborne data for monitoring anthropogenic CO_2 emissions.

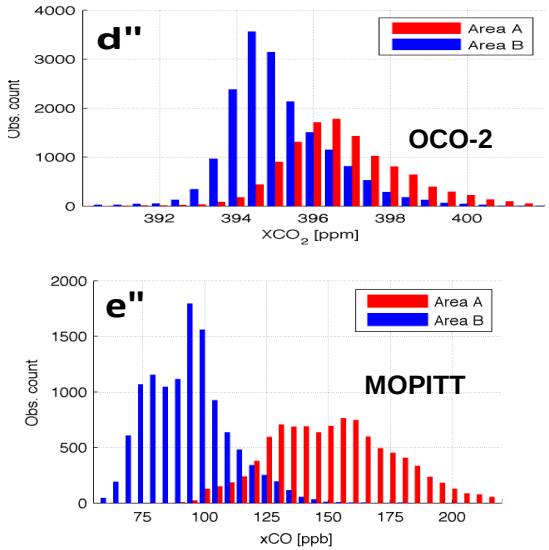


OCO-2 CO_2 anomaly data (top row), OMI NO_2 data (middle row) and an emission inventory (bottom row) were used in a cluster analysis to discriminate CO_2 emissions from fossil fuel use (northeast USA, Europe, China) fossil fuel extraction (Middle East), and biomass burning (Africa)

African fire emissions as seen by OCO-2
(Bloom et al., in prep)

- **Problem**: Do fires explain the elevated X_{CO2} that OCO-2 observes over Africa?
- **Results**: *September-October 2014 fire season:* OCO-2 L2 data revealed elevated CO_2 over southern Africa. CO (from MOPITT; dominated by fires in the tropics) is also elevated over the southern Africa fire region.
- **Significance**: Correlation between atmospheric CO_2 and CO anomalies (r=0.41) and atmospheric CO2:CO (16:1; consistent with bottom-up inventories, in-situ observations and CO_2 and CO model simulations) indicate enhanced CO_2 is largely due to fires.





Figures a-c: September-October 2014 0.5° × 0.5° MODIS fire counts (**a**) mean OCO-2 dry column CO_2 (**b**) and mean MOPITT dry column CO (**c**).

Figures d-e: Histograms of CO (**d**) and CO_2 (e) within fire region (area A) and background region (area B).

El Niño Impacts in Pacific seen by OCO-2
(Chatterjee et al., in prep)

- **Problem**: Quantify the effects of El Niño on carbon flows from the Pacific Ocean
- **Results**: OCO-2 X_{CO2} estimates shows the impact of reduced ocean outgassing caused by warmer waters, and later increased atmospheric CO_2 caused by increased respiration and biomass burning in South America
- **Significance**: OCO-2 provides the first direct regional observations of the impacts of El Niño on the carbon cycle

Figure courtesy of Abhishek Chatterjee.

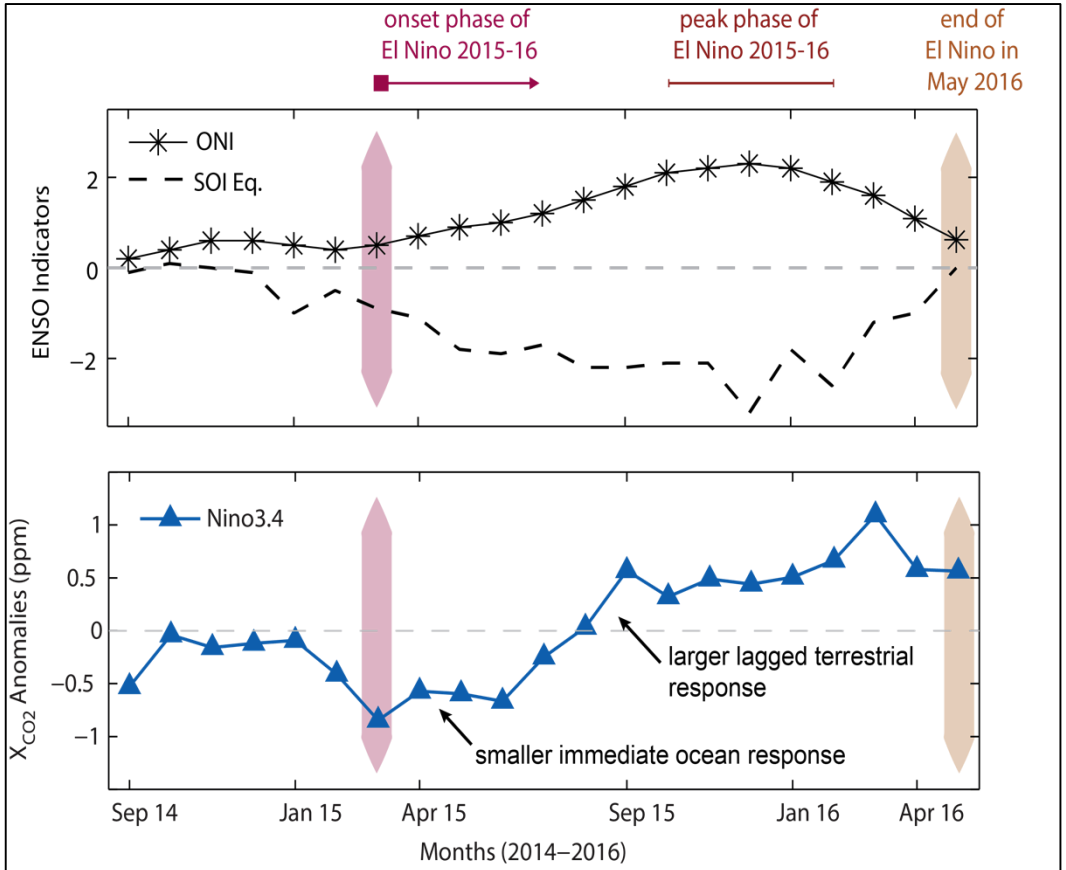
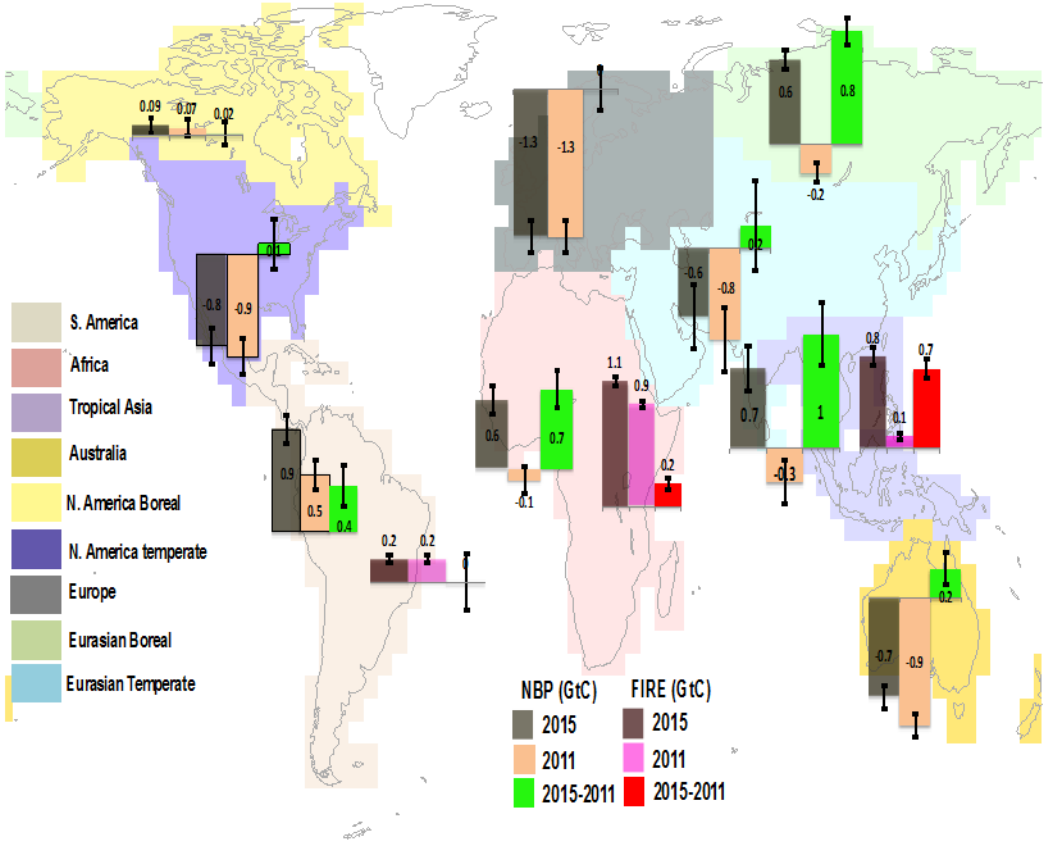


Figure 2: OCO-2 observes the response of the carbon cycle for an entire El Nino event

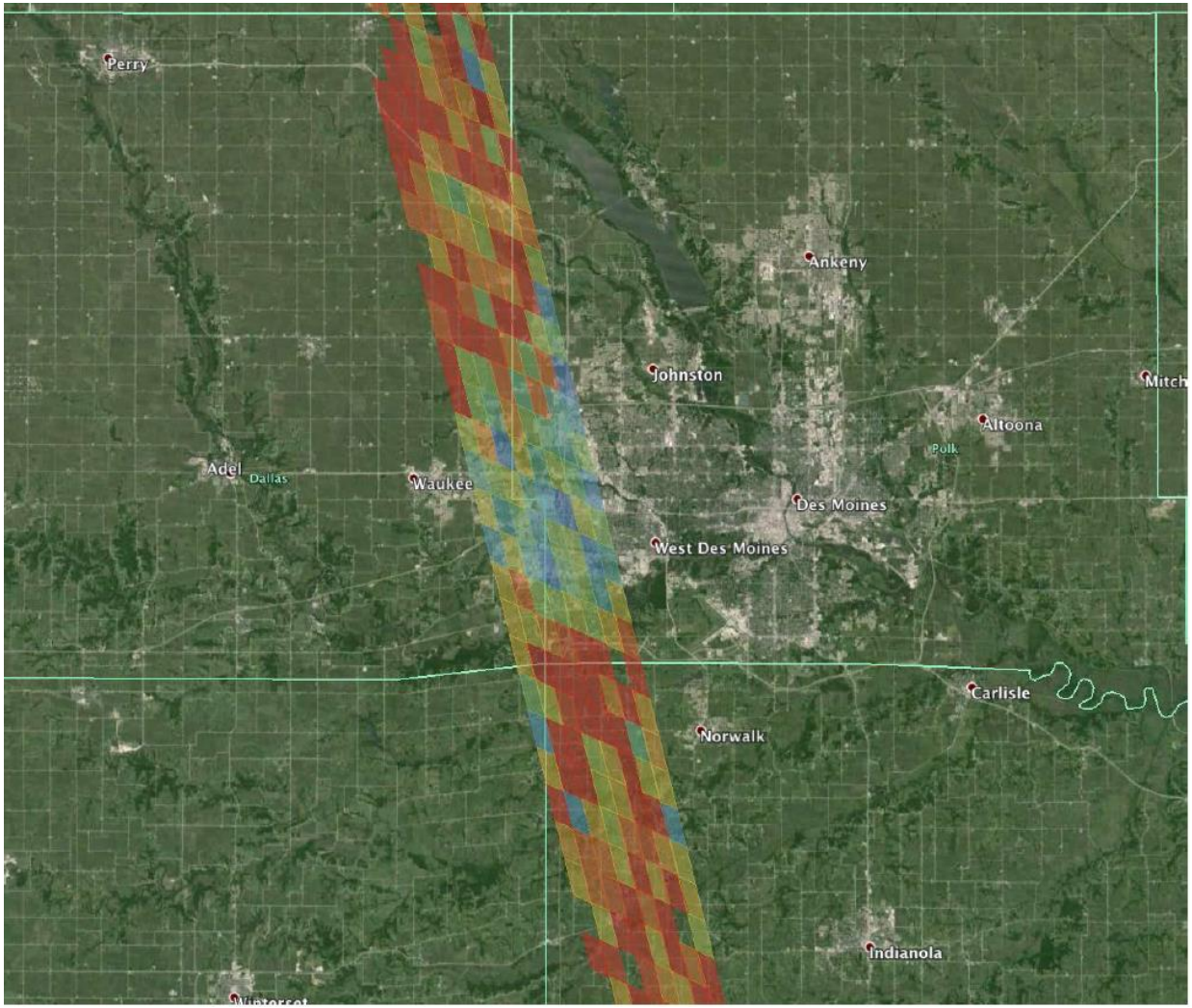
Temperature effects more important than fire in 2015 El Niño (Liu et al. , in prep)

- **Problem**: Are fires or droughts the cause of changes in carbon release during El Niños?
- **Results**: OCO-2 and GOSAT carbon dioxide and SIF show that in 2015, fire was a relatively minor contributor to the loss of carbon, indicating that larger fluxes were associated with reduced plant growth and increased plant mortality. The Northern extra-tropics continue to be a sink of CO2 during the El Niño year.
- **Significance**: OCO-2 data suggests that the sensitivity of tropical net biome exchange to temperature is 3.5 Pg/°K/yr, a key model benchmark, at the low end of the literature



Regional scale CO_2 fluxes (excluding fossil fuel) inferred from OCO-2 and GOSAT X_{CO2} estimates Positive bars indicate net sources while negative values indicate net sinks.

Solar Induced Chlorophyll Fluorescence (SIF)



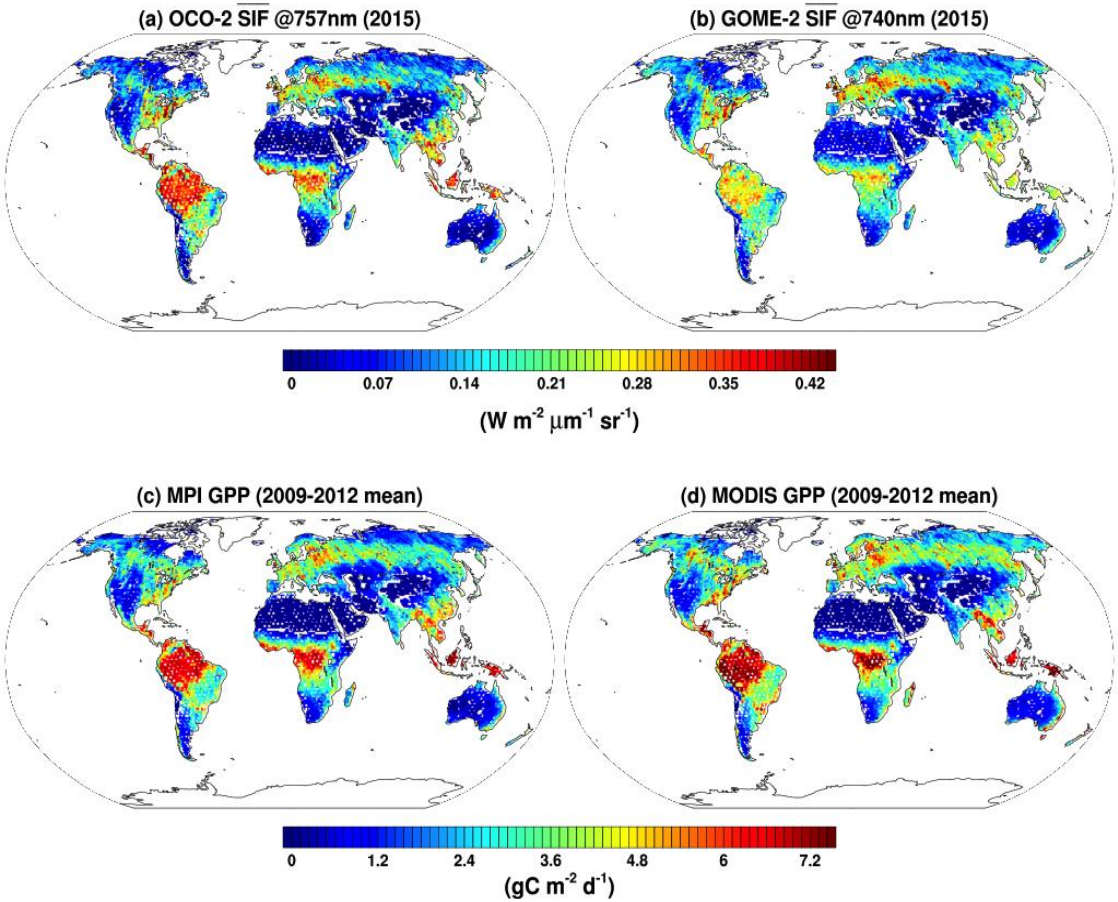
OCO-2 Flies over Des Moines, Iowa.

If not removed from the O_2 A-Band radiances, SIF will introduce biases in the dry air mole fraction and other A-band products

SIF measurements also provide a constraint on the spatial distribution of CO_2 uptake by photosynthesis

OCO-2 Solar-Induced Fluorescence has high precision (Sun et al., in prep)

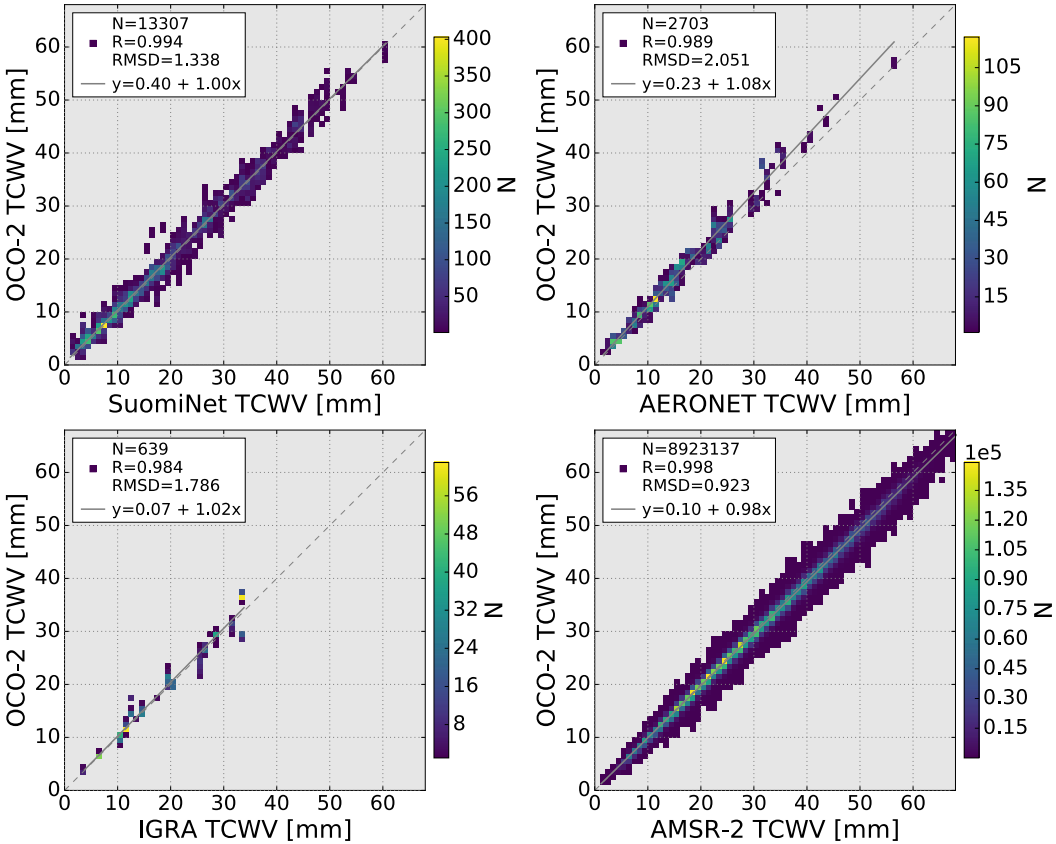
- **Problem**: Are the OCO-2 global SIF products valuable for monitoring the terrestrial carbon cycle?
- **Results**: OCO-2 SIF data were compared to GOME-2 and GOSAT SIF, model-driven gross primary productivity (GPP) including FLUXCOM and MODIS products.
  - OCO-2 SIF closely resembles the spatial pattern of GPP from the equator to extra-tropics in both hemispheres.
  - The OCO-2 SIF has an improved precision compared to existing spaceborne SIF products.
- **Significance**: This study demonstrated that the OCO-2 SIF products are robust and valuable for monitoring global terrestrial carbon cycle and for constraining the carbon source/sink of the Earth system.



OCO-2 SIF (upper right) compared to GOME SIF (upper right) and model-driven primary production estimates using FLUXCOM and MODIS products.

Total Column Water Vapor from OCO-2 is as good as existing estimates (Nelson et al., submitted)

- **Problem**: How accurate are OCO-2 total column water vapor (TCWV) measurements?
- **Results**: Water vapor must be retrieved, or it introduces a bias OCO-2 X_{CO2} retrievals.
  - OCO-2 TCWV measurements are highly accurate and nearly unbiased over land and ocean, with root mean square differences of 1.3 mm vs. SuomiNet
  - These results also agree well with other standards including AERONET (2.1 mm), IGRA (1.8 mm), and AMSR-2 (0.9 mm)
- **Significance**: The OCO-2 sampling limits operational use of our data, but this demonstrates a accurate new approach for remote sensing of TCWV.



Comparisons of OCO-2 Total Column Water Vapor (TCWV) retrievals with those from other standards including SuomiNet, AERONET, radiosondes (IGRA) and microwave instrument (AMSR-2)

Figure courtesy of Robert Nelson..

The Evolving Near-Infrared Atmospheric Carbon Measurement Capabilities

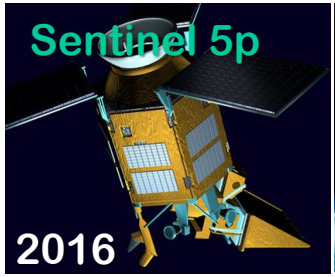
PAST

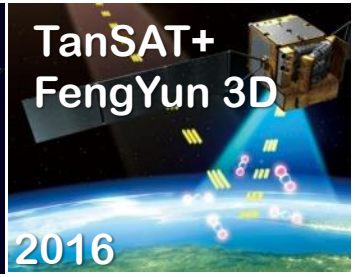
If carefully coordinated, these missions can be integrated into an ad hoc constellation and their measurements can be combined to produce a continuous data record.

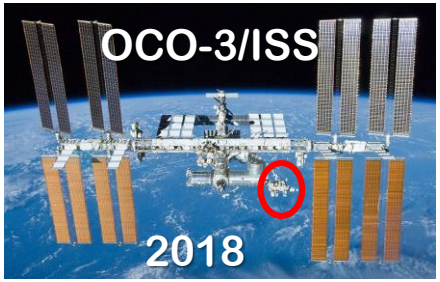
PRESENT

However, none of these missions provides the capabilities needed to quantify fossil fuel emissions and other human activities. For that, we need a constellation.

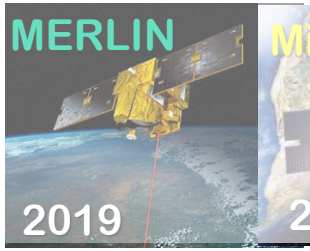
NEAR FUTURE

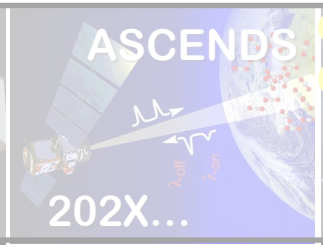


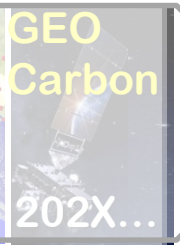




LATER







Summary

- OCO-2 was successfully launched on 2 July 2014, and began routine operations on 6 September 2014
  - Now returning about 100,000 full-column measurements of X_{CO2} each day over the sunlit hemisphere
  - These products are being validated against TCCON and other standards to assess their accuracy
- Over 24 months of data have been delivered to the Goddard Earth Sciences Data and Information Services Center (GES-DISC) for distribution to the science community

  http://disc.sci.gsfc.nasa.gov/OCO-2
- This product is now being used by the carbon cycle science community to identify and quantify the CO_2 sources and sinks on regional scales over the globe

Thank You for Your Attention

Questions?