



# FLUXNET and Remote Sensing Workshop: Towards Upscaling Flux Information from Towers to the Globe

## Space-Based Measurements of CO<sub>2</sub> from the Japanese Greenhouse Gases Observing Satellite (GOSAT) and the NASA Orbiting Carbon Observatory-2 (OCO-2 ) Missions

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7 June 2011



# Global Measurements from Space are Essential for Monitoring Atmospheric CO<sub>2</sub>



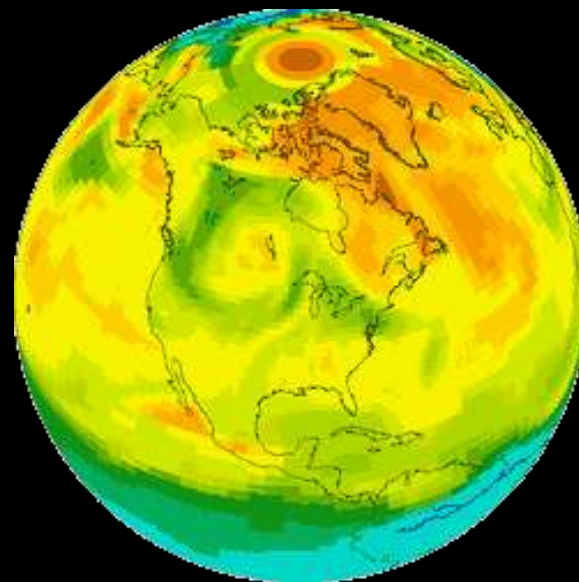
To limit the rate of atmospheric carbon dioxide buildup, we must

- Control emissions associated with human activities
- Understand & exploit natural processes that absorb carbon dioxide

**We cannot manage what we cannot measure**



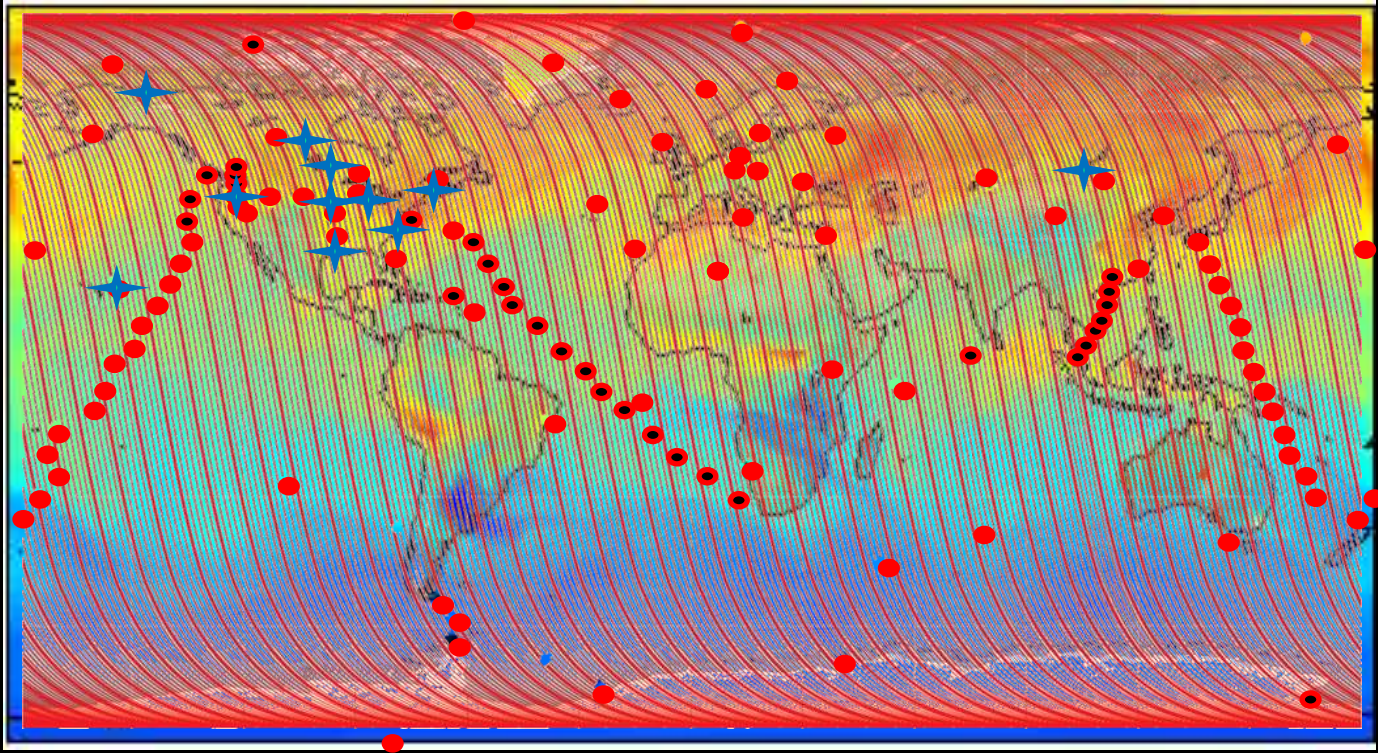
Plumes from medium-sized power plants (4 MtC/yr) elevate  $X_{\text{CO}_2}$  levels by ~2 ppm for 10's of km downwind [Yang and Fung, 2010].



These variations are superimposed on a background of “**CO<sub>2</sub> weather**”



# Primary Advantage of Space-based Data: Spatial Coverage at High Resolution



- Ground based measurements - greater precision and sensitivity to CO<sub>2</sub> near the surface, where sources and sinks are located.
- Space-based measurements – improve spatial coverage & resolution.
- Source/Sink models - assimilate space and ground-based data to provide global insight into CO<sub>2</sub> sources and sinks

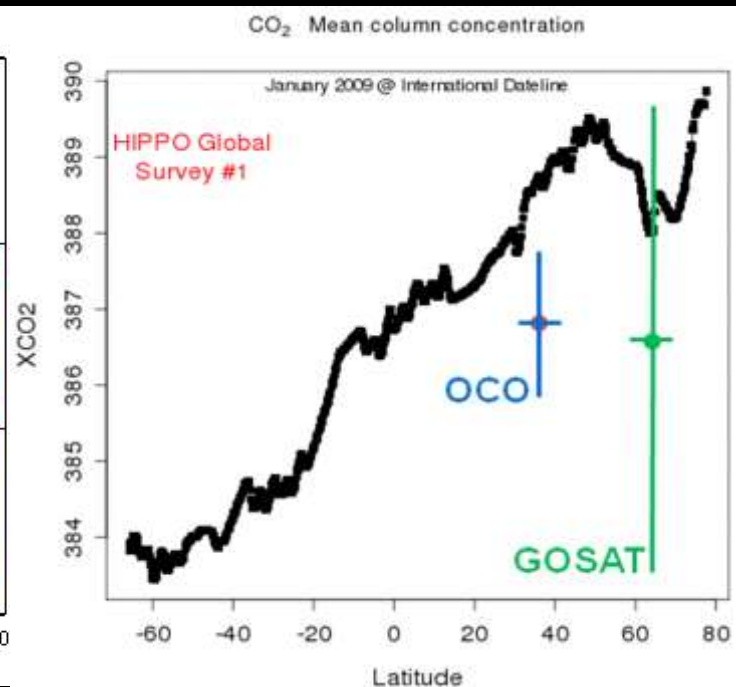
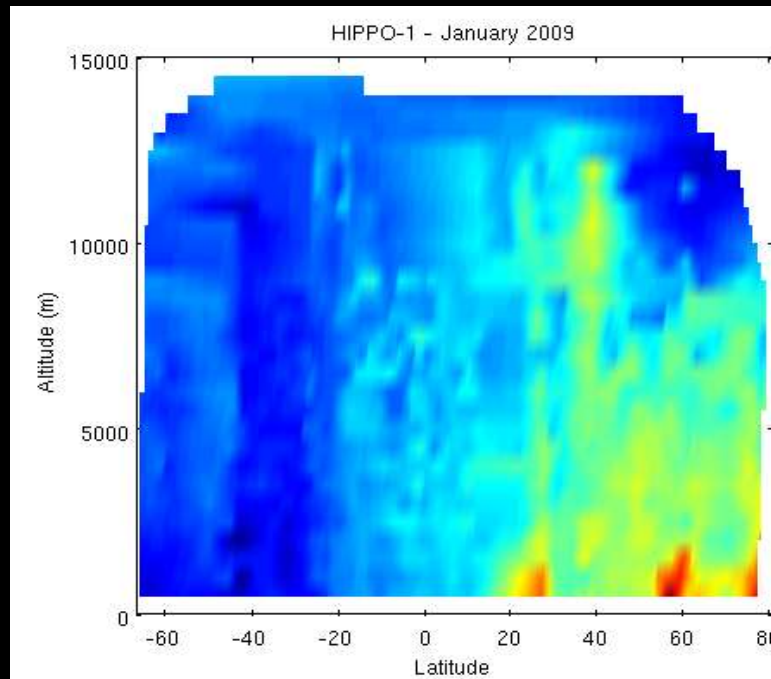


# High precision is Essential for Monitoring CO<sub>2</sub> Sources and Sinks from Space



- CO<sub>2</sub> sources and sinks must be inferred from small spatial variations in the (387 ±5 ppm) background CO<sub>2</sub> distribution
  - Largest variations near surface
  - Space based NIR observations constrain column averaged CO<sub>2</sub>,  $X_{CO_2}$

Small spatial gradients in  $X_{CO_2}$  verified by pole-to-pole aircraft data [Wofsy et al. 2010]





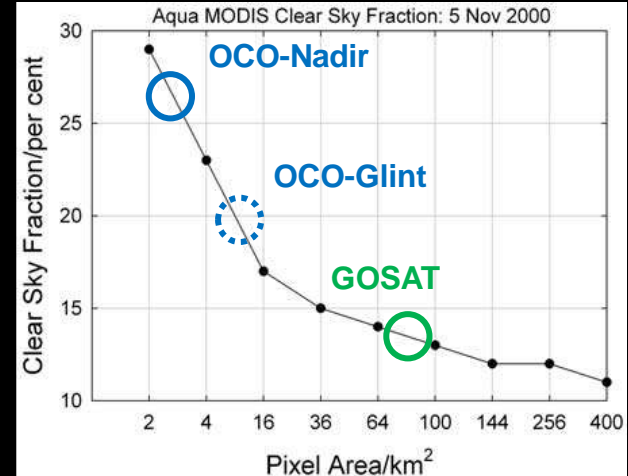
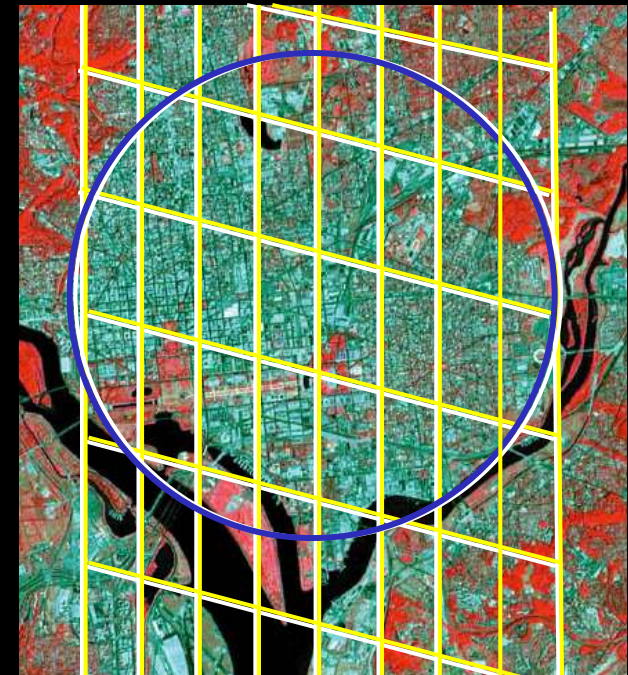
# Spatial Resolution and Sampling

## A Small Footprint:

- Increases sensitivity to CO<sub>2</sub> point sources
  - The minimum measurable CO<sub>2</sub> flux is inversely proportional to footprint size
- Increases probability of recording cloud free soundings in partially cloudy regions
- Reduces biases over rough topography

## High Sampling Rate:

- Soundings can be averaged along the track to reduce single sounding random errors





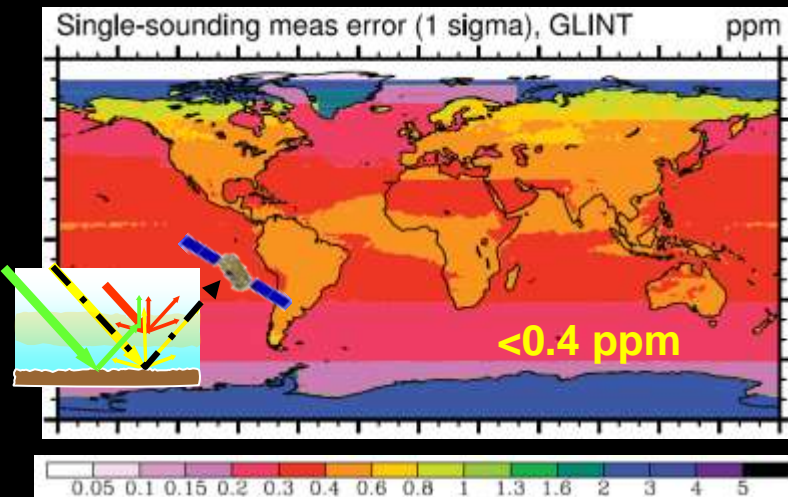
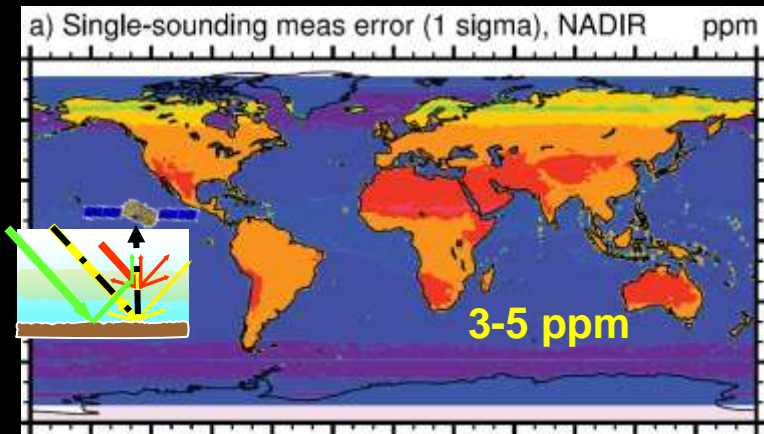
# Coverage: Obtaining Precise Measurements over Oceans as well as Continents

- The ocean covers 70% of the Earth and absorb/emit 10 times more CO<sub>2</sub> than all human activities combined
- Coverage of the oceans is essential to minimize errors from CO<sub>2</sub> transport in and out of the observed domain

Near IR solar measurements of CO<sub>2</sub> over the ocean are challenging

- Typical nadir reflectances: 0.5 to 1%
- Most of the sunlight is reflected into a narrow range of angles, producing the familiar “glint” spot

Glint and nadir measurements can be combined to optimize sensitivity over both oceans and continents

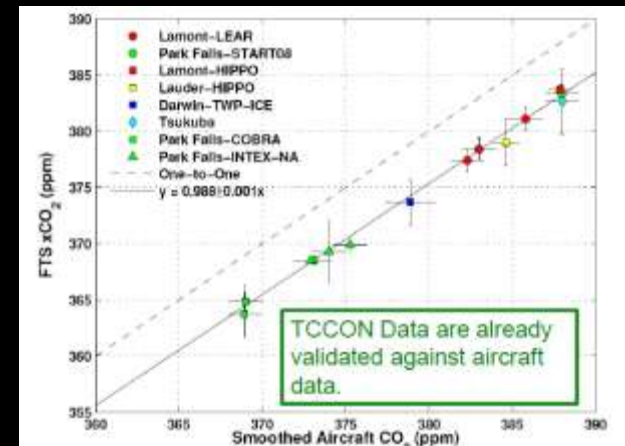


OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].



# Validating Space-based $X_{CO_2}$ against the Ground-Based Standard: TCCON

- The Total Carbon Column Observing Network (TCCON) provides a transfer standard between ground- and space-based measurements
  - TCCON measures the absorption of direct sunlight by  $CO_2$  and  $O_2$  in the same spectral regions used by OCO-2.
    - Validated against aircraft measurements
  - OCO-2 will acquire thousands of  $X_{CO_2}$  soundings over TCCON stations on a single overpass.





# Measuring CO<sub>2</sub> from Space



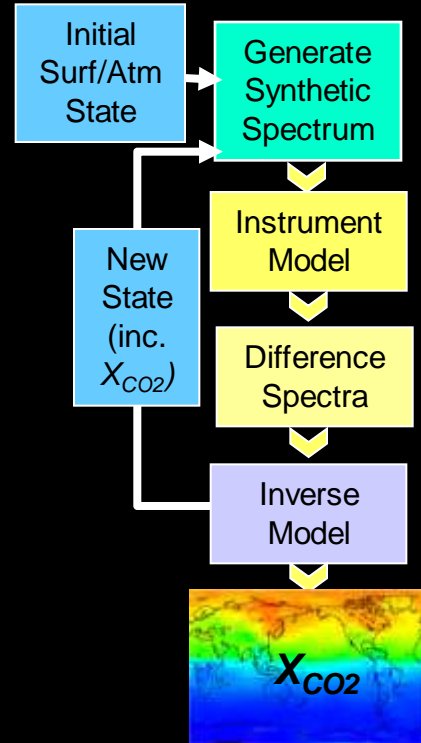
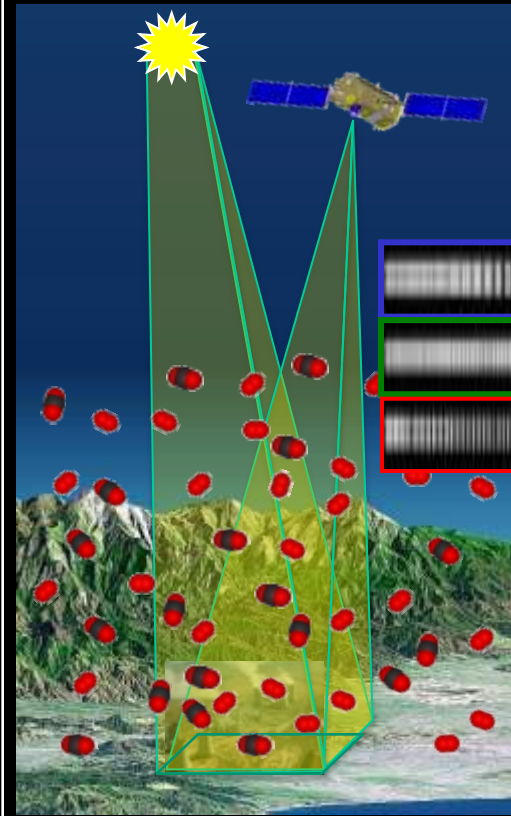
- Record spectra of CO<sub>2</sub> and O<sub>2</sub> absorption in reflected sunlight



- Retrieve variations in the *column averaged CO<sub>2</sub> dry air mole fraction, X<sub>CO2</sub>* over the sunlit hemisphere



- Validate measurements to ensure X<sub>CO2</sub> accuracy of 1 - 2 ppm (0.3 - 0.5%)







# GOSAT-OCO Collaboration



The OCO and GOSAT teams formed a close partnership during the implementation phases of these missions to:

- Cross calibrate the OCO instrument and TANSO-FTS
- Cross validate OCO and GOSAT  $X_{CO_2}$  retrievals against a common standard

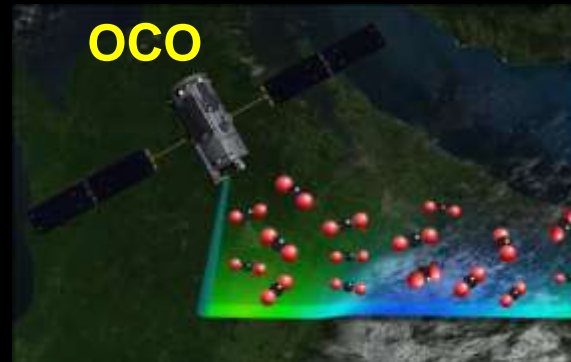
The primary objectives of this partnership were to:

- Accelerate understanding of this new data source
- Facilitate combining results from GOSAT and OCO



**GOSAT**

3-day ground track repeat cycle resolves weather



**OCO**

Continuous high resolution measurements along track





# The Launch of GOSAT & Loss of OCO



GOSAT launched successfully on 23 January 2009

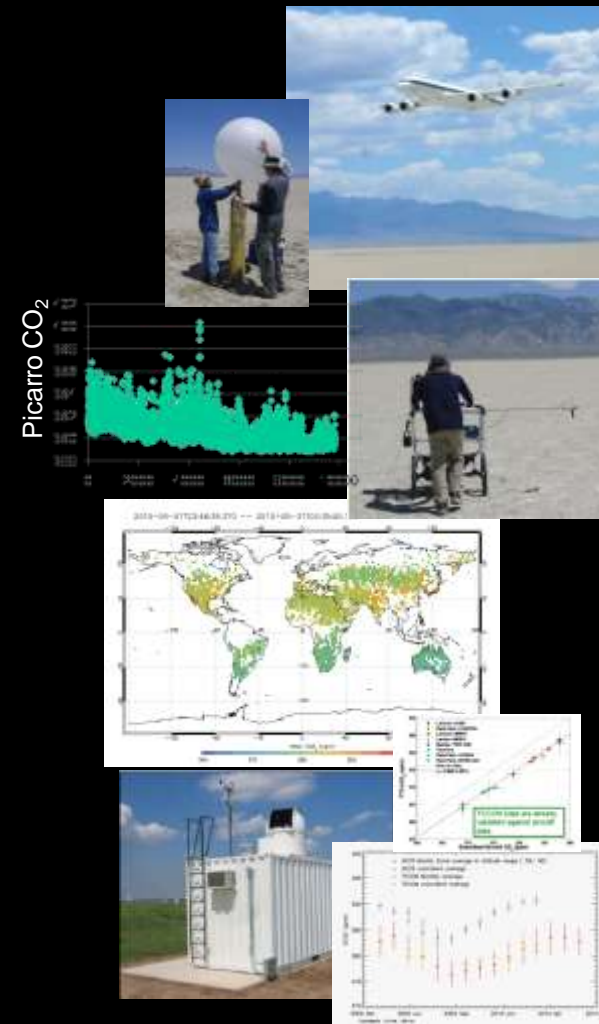


OCO was lost a month later when its launch system failed



# Scope of the ACOS/GOSAT Collaboration

- Immediately after the loss of OCO, the GOSAT Project manager invited the OCO Team to participate in GOSAT data analysis
- The ACOS team is collaborating closely with the GOSAT teams at JAXA and NIES to:
  - Conduct vicarious calibration campaigns in Railroad Valley, Nevada, U.S.A.
  - Retrieve  $X_{CO_2}$  from GOSAT spectra
    - Model development & testing
    - Data production and delivery
  - Validate GOSAT retrievals by comparing GOSAT retrievals with TCCON measurements and other data





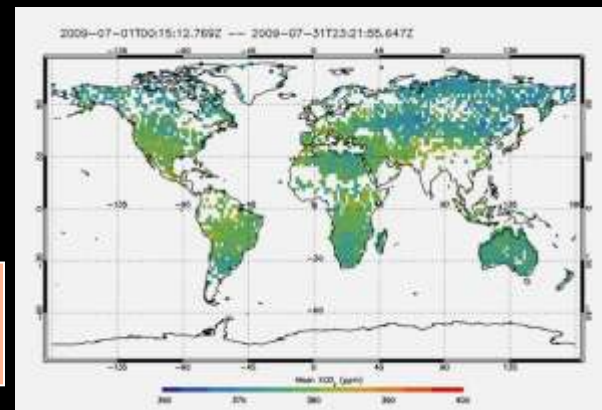
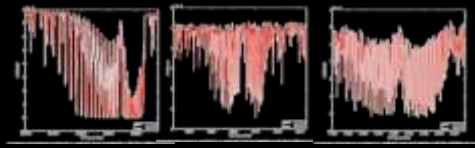
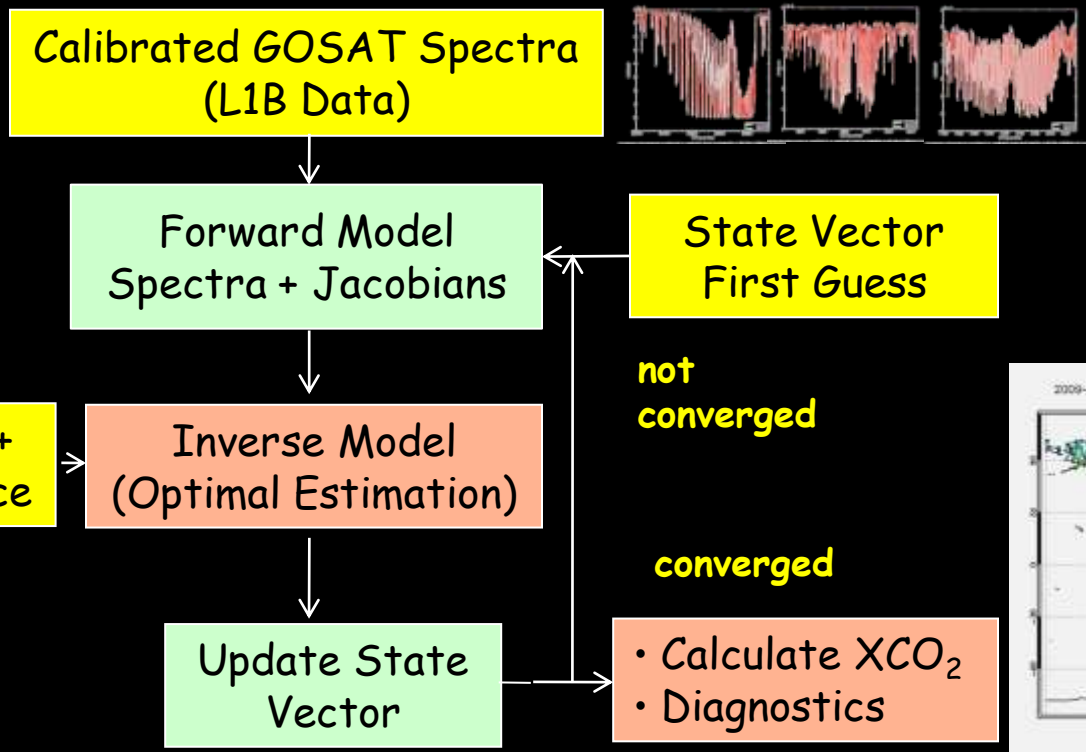
# Retrieving $X_{CO_2}$ from GOSAT Data



The OCO Retrieval Algorithm was modified to retrieve  $X_{CO_2}$  from GOSAT measurements

- “Full-physics” forward model
- Inverse model based on optimal estimation

State Vector
CO <sub>2</sub> profile (full)
H <sub>2</sub> O profile (scale factor)
Temperature profile (offset)
Aerosol Profiles
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift (+ stretch)





# Screening Improves Accuracy

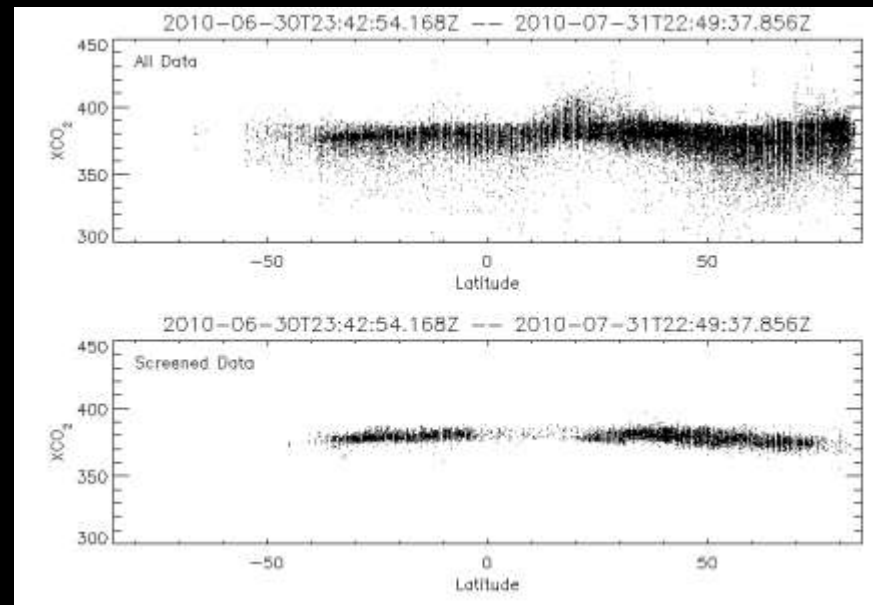
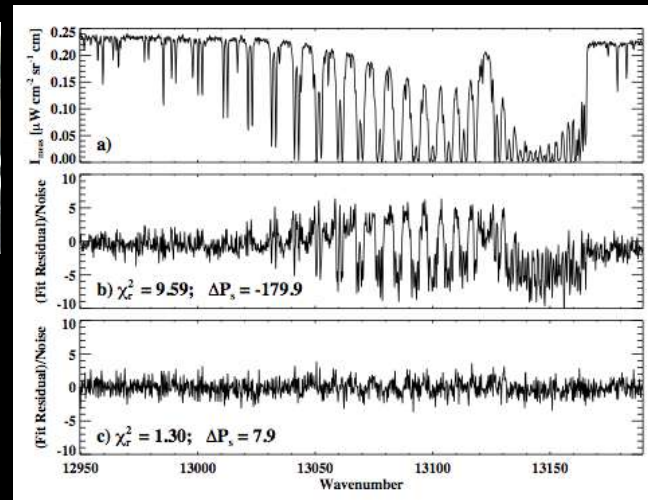


## Pre-screening for Clouds:

- A Spectroscopic cloud screening algorithm based on the O<sub>2</sub> A-band is currently being used for GOSAT

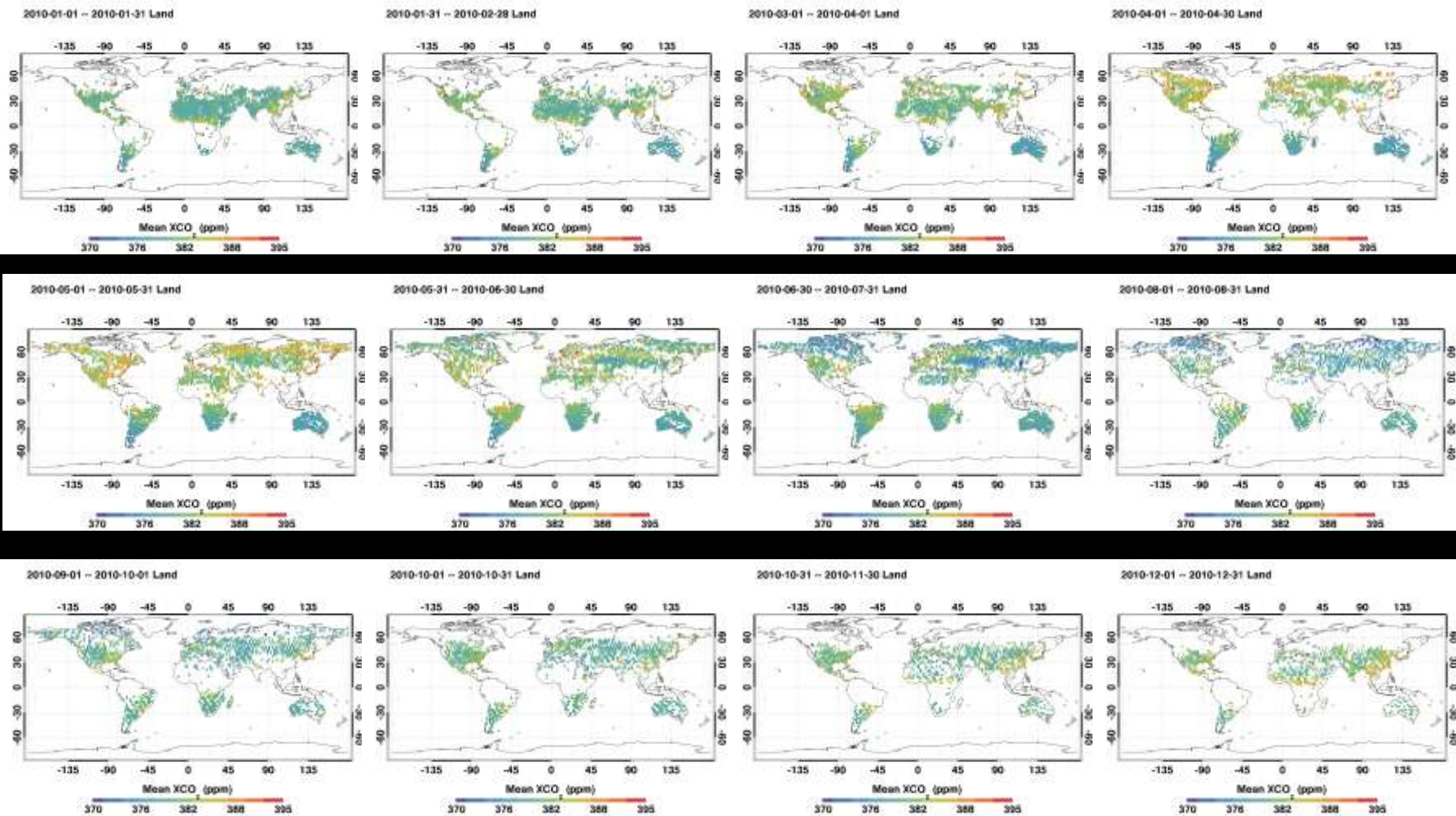
## Errors can be further reduced by post-screening retrievals:

- Measurement SNR
- Convergence
- Goodness of spectral fit
- Surface pressure error
- Evidence for clouds or optically thick aerosols
- *A posteriori* retrieval error



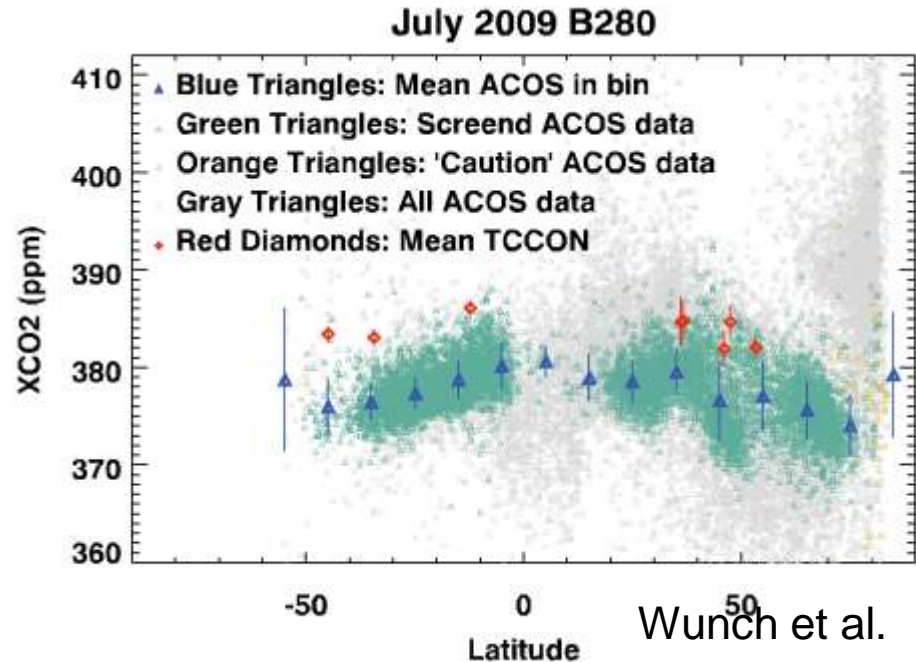
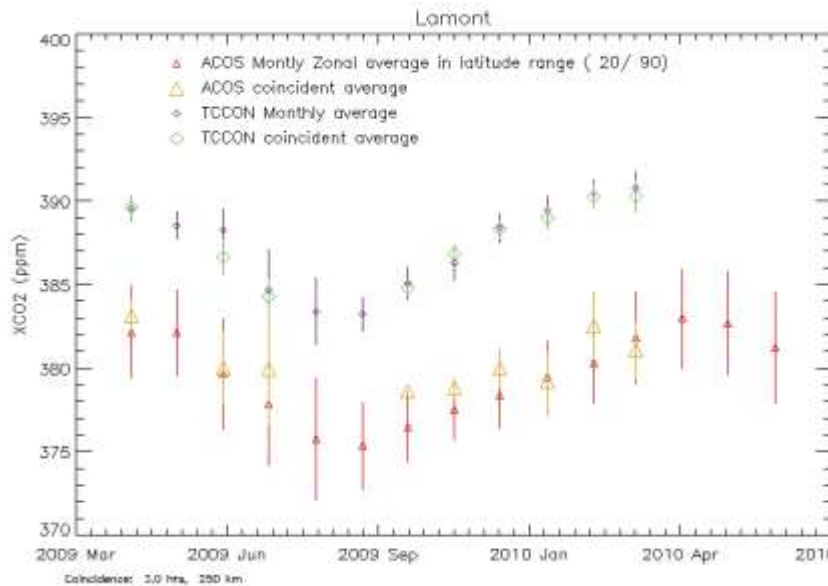


# A Year of ACOS/GOSAT X<sub>CO2</sub>





# Comparisons of GOSAT and TCCON



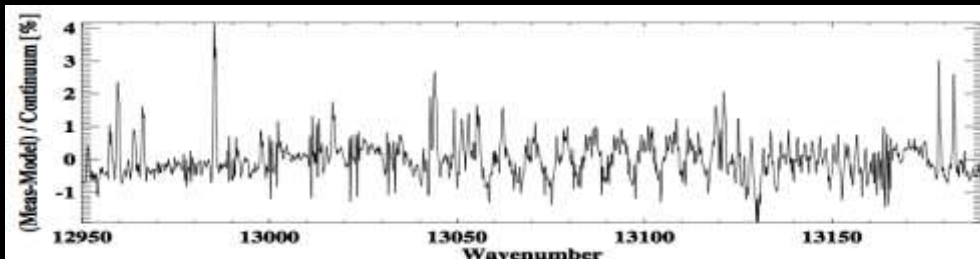
- ACOS GOSAT retrievals show
  - A consistent global bias of  $\sim 2\%$  (7 ppm) in  $X_{CO_2}$  when compared with TCCON and aircraft measurements.
  - $X_{CO_2}$  variations that are a factor of 2 - 3 larger than that from TCCON.



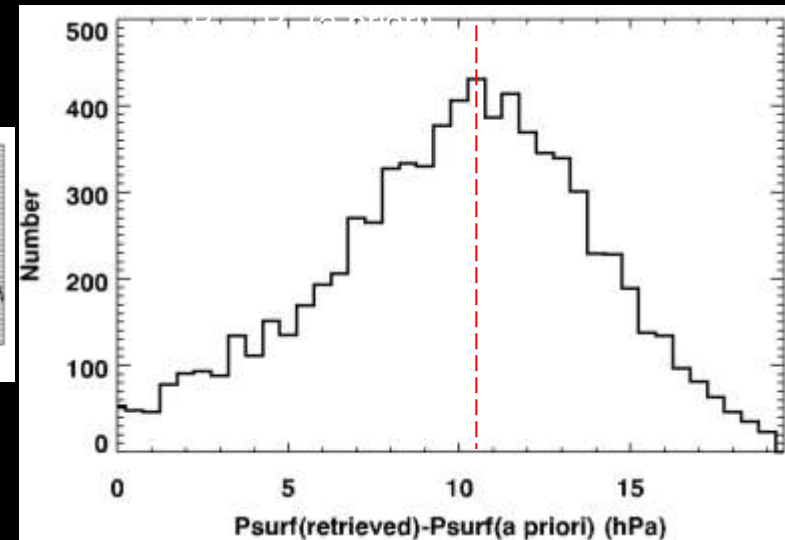
# Sources of Bias in the $X_{\text{CO}_2}$ Maps



- About half of the global 2% bias is caused by airmass bias associated with a  $\sim 10$  hPa (1%) high surface pressure bias
  - Radiometric and spectroscopic calibration errors
    - Non linearity and ILS corrections currently being implemented
  - Uncertainties in the  $\text{O}_2$  A-band absorption cross sections
    - Oversimplified treatment of line mixing and line shape
- Improvements in the  $\text{CO}_2$  spectroscopy and aerosol retrieval approach are also being implemented to address remaining bias



Typical  $\text{O}_2$  A-band retrieval residuals.

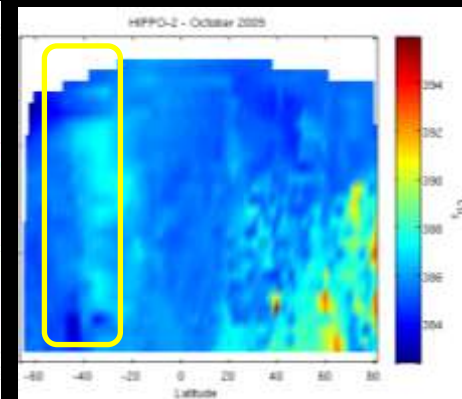
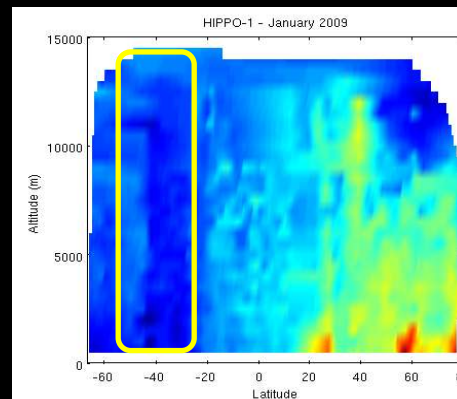




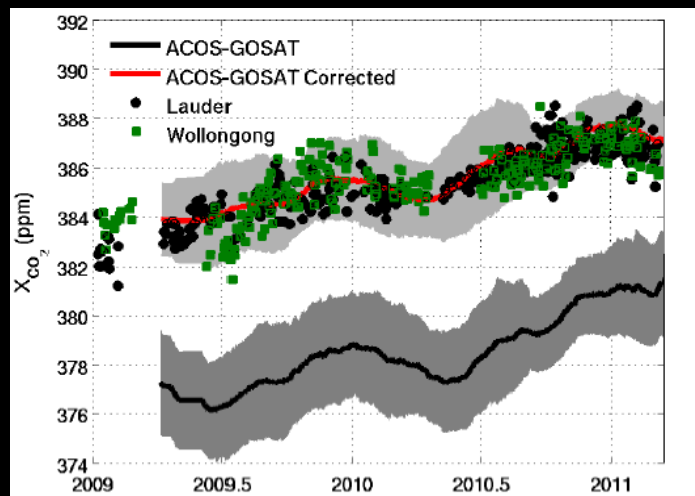


# Bias Correction from Validation Program

- ACOS  $X_{CO_2}$  products retrieved over the southern hemisphere, which has little known variability, have been assessed to identify other sources of bias
- Wunch et al. have identified biases associated with:
  - Difference between ABO2 and SCO2 albedos
  - Surface pressure difference
$$dP = P_{ret} - P_{ECMWF}$$
  - Air mass
  - A-band Signal Level
- A multivariate formula has been developed to correct these biases



HIPPO-1 and HIPPO-2 show little CO<sub>2</sub> variability over the Southern Hemisphere.



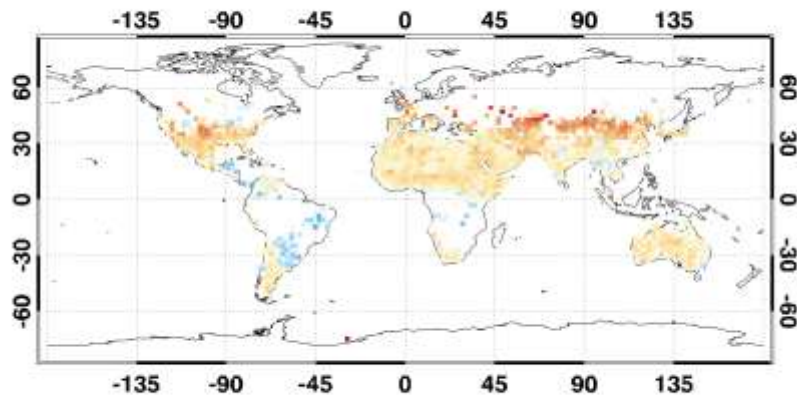
The corrections substantially improve the fits over SH TCCON sites



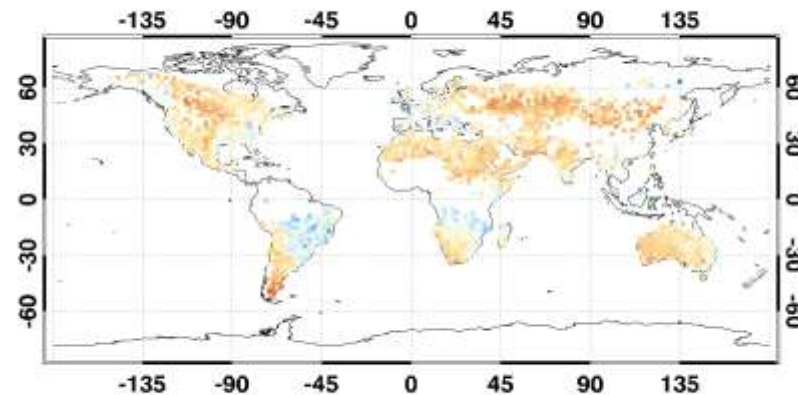
# Impact of Know Biases on Retrieved Global $X_{CO_2}$ Distribution



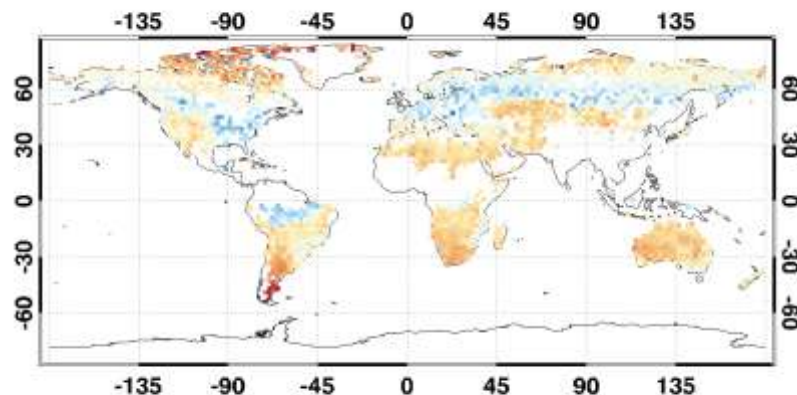
2010-01-01 -- 2010-01-31 Land Delta XCO<sub>2</sub> (multi parameter)



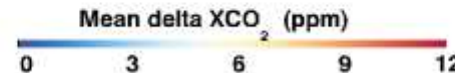
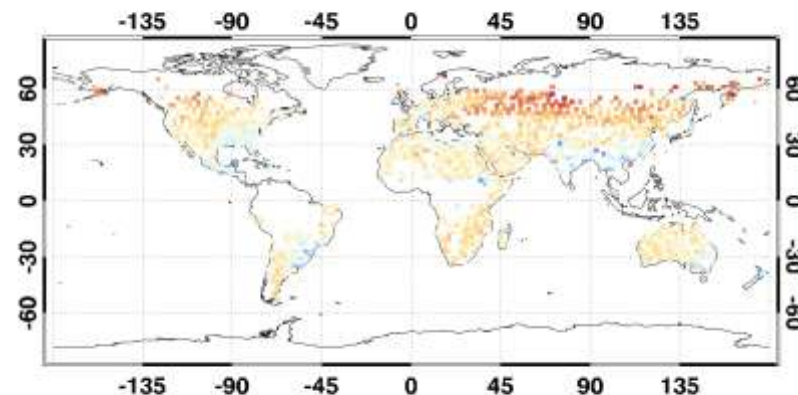
2010-04-01 -- 2010-04-30 Land Delta XCO<sub>2</sub> (multi parameter)



2010-06-30 -- 2010-07-31 Land Delta XCO<sub>2</sub> (multi parameter)



2010-10-01 -- 2010-10-31 Land Delta XCO<sub>2</sub> (multi parameter)





# The Loss of OCO and the Birth of OCO-2

- NASA's Orbiting Carbon Observatory (OCO) was designed to provide the measurements needed to estimate the atmospheric CO<sub>2</sub> dry air mole fraction ( $X_{\text{CO}_2}$ ) with the sensitivity, accuracy, and sampling density needed to quantify regional scale carbon sources and sinks over the globe and characterize their behavior over the annual cycle.
- February 2009: The OCO spacecraft was lost when its launch vehicle's fairing failed to deploy
- December 2009: The U.S. Congress added funding to the NASA FY2010 budget to restart the OCO Mission
- The OCO-2 spacecraft bus and instrument are currently on track for a February 2013 launch

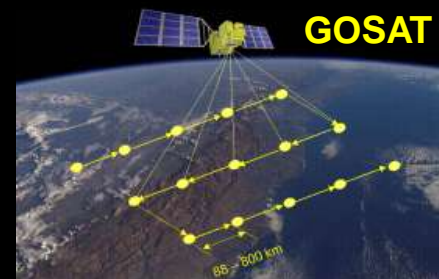




# Comparison of GOSAT and OCO-2

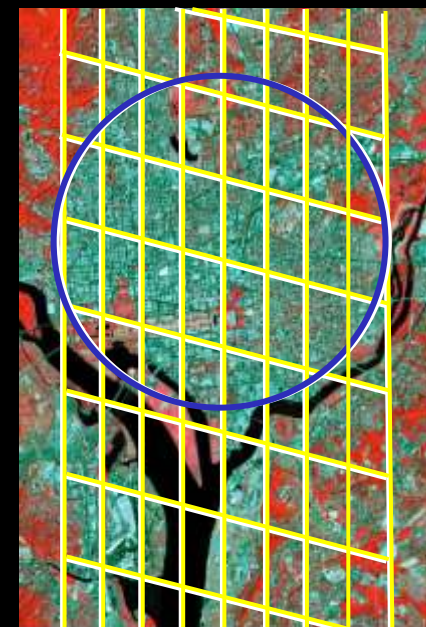
## • GOSAT (2009)

- Optimized for spectral and spatial coverage
- Collects 10,000 soundings every day
  - 10-15% are sufficiently cloud free for CO<sub>2</sub> & CH<sub>4</sub> retrievals, limited coverage of oceans.
- 3-4 ppm (1%) precision: can detect strong sources



## • OCO-2 (2013)

- Optimized for high sensitivity and resolution
- Collects up to 10<sup>6</sup> measurements each day over a narrow swath
  - Smaller footprint ensures that >20% all soundings are cloud free
  - 1 ppm (0.3%) precision adequate to detect weak sources & sinks
- Produces global maps in Nadir and Glint on alternate 16-day repeat cycles, to yield global maps in both models once each month





# OCO Mission Overview



3-Channel Spectrometer

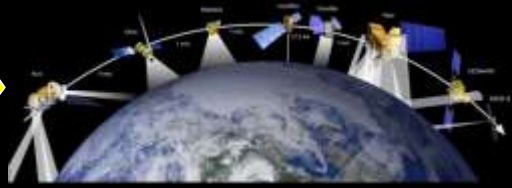
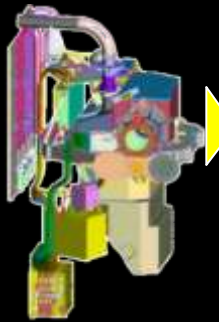
Dedicated Spacecraft bus

Dedicated Launch Vehicle

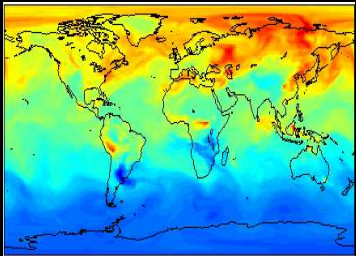
"Routine" Mission Operations

Formation Flying as part of the A-Train Constellation

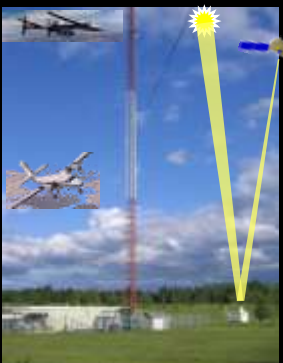
NASA NEN (GSFC) and SN (TDRSS)



Products Delivered to a NASA Archive



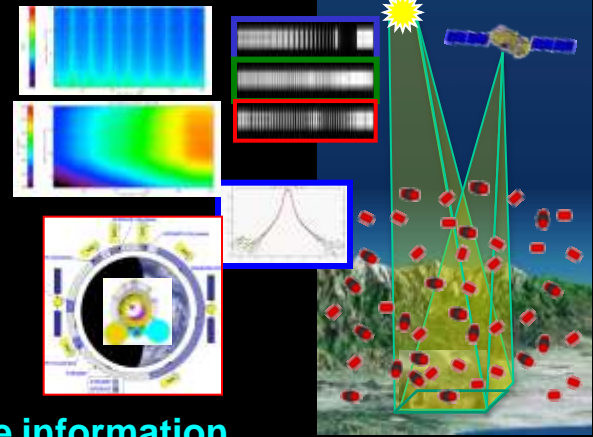
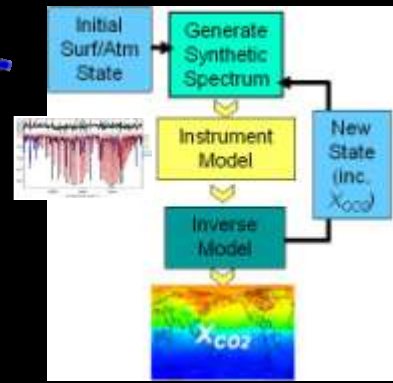
Validation Program



Science Data Operations Center (JPL)

L2 X<sub>CO2</sub> Retrieval

Calibrate Data



Please visit <http://oco.jpl.nasa.gov> for more information



# Conclusions

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO<sub>2</sub> and other greenhouse gases
- The principal advantages of space based measurements include:
  - Spatial coverage (especially over oceans and tropical land)
  - Sampling density (needed to resolve CO<sub>2</sub> weather)
- The principal challenge is the need for high precision
- To reach their full potential, space based CO<sub>2</sub> measurements must be validated against surface measurements to ensure their accuracy.
  - The TCCON network is providing the transfer standard
- Need a long-term vision to establish and address community priorities
  - Must incorporate ground, air, space-based assets and models
  - Must balance calls for new observations with need to maintain climate data records