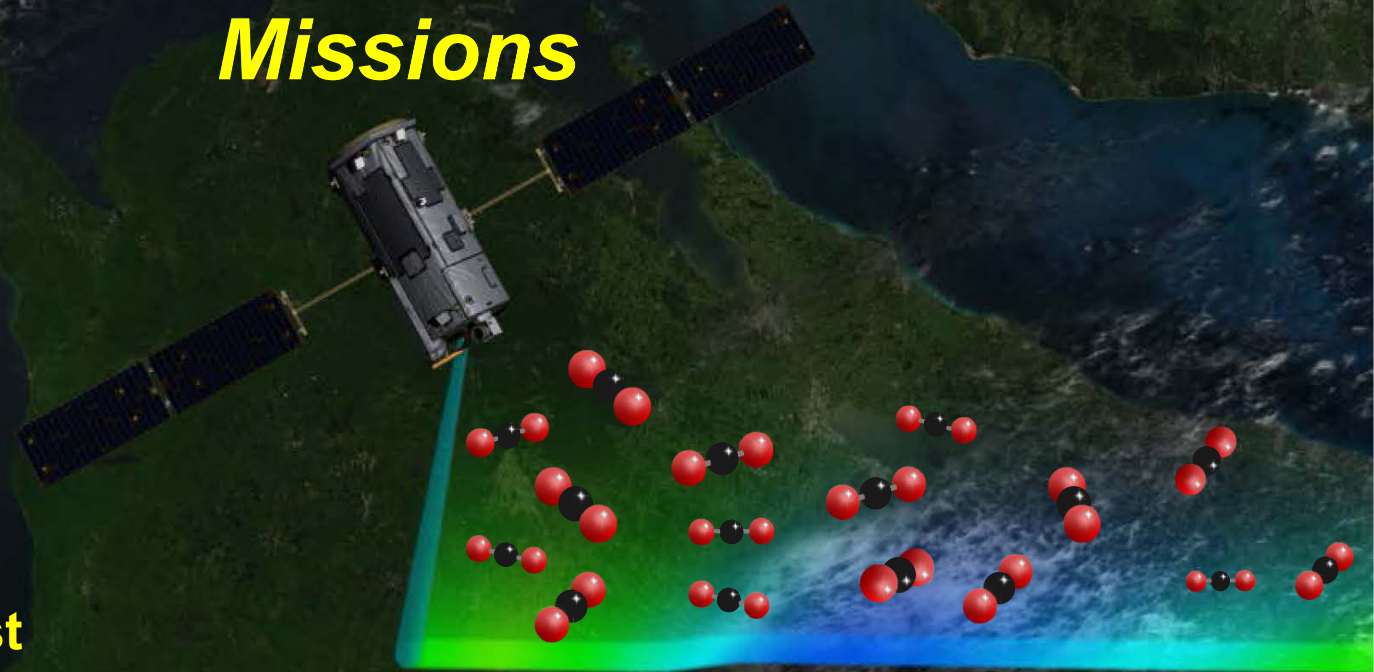
Carbon Dioxide Measurements from Space: The Japanese GOSAT and NASA OCO-2 Missions



David Crisp

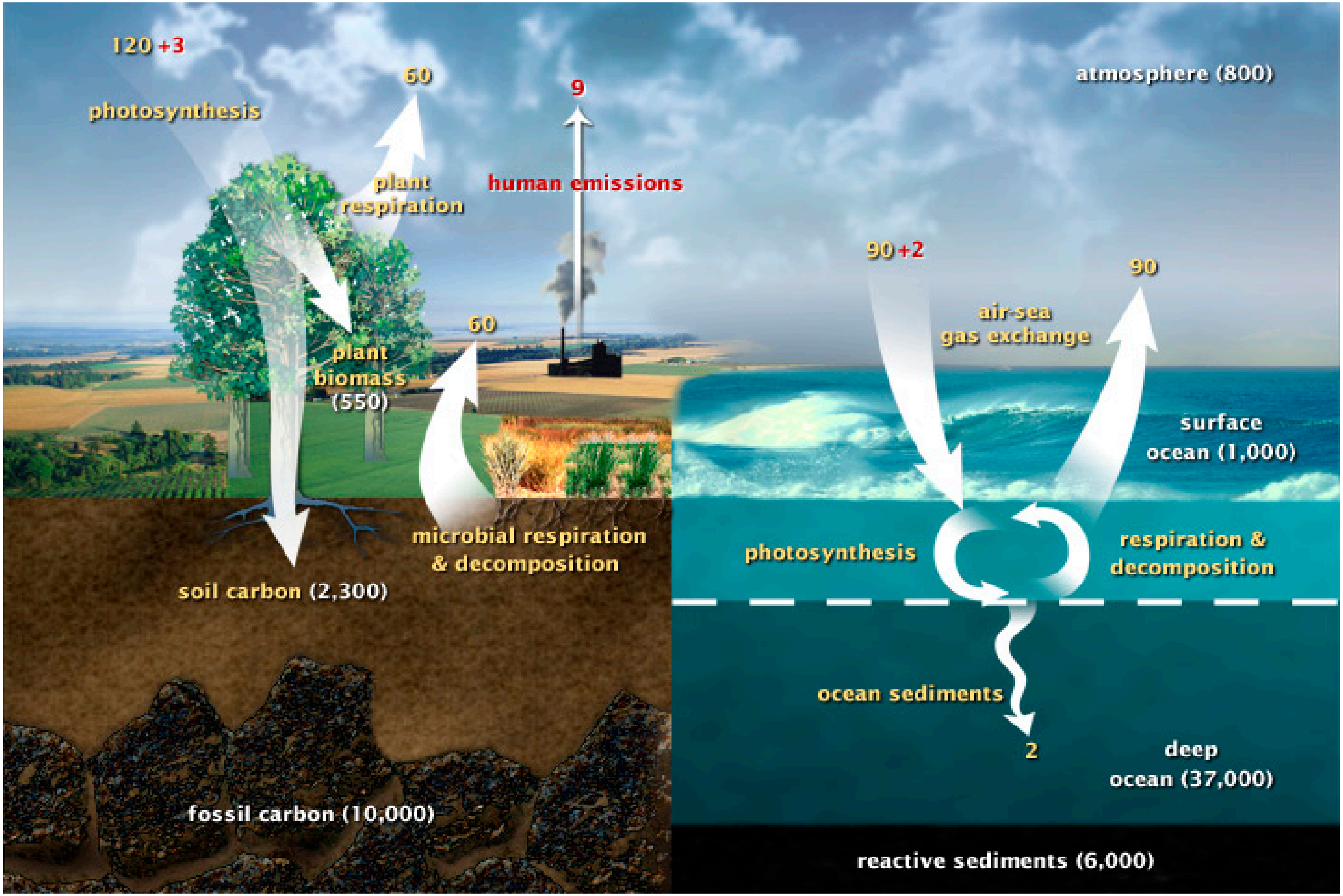
OCO-2 Lead Scientist

Jet Propulsion Laboratory,
California Institute of Technology

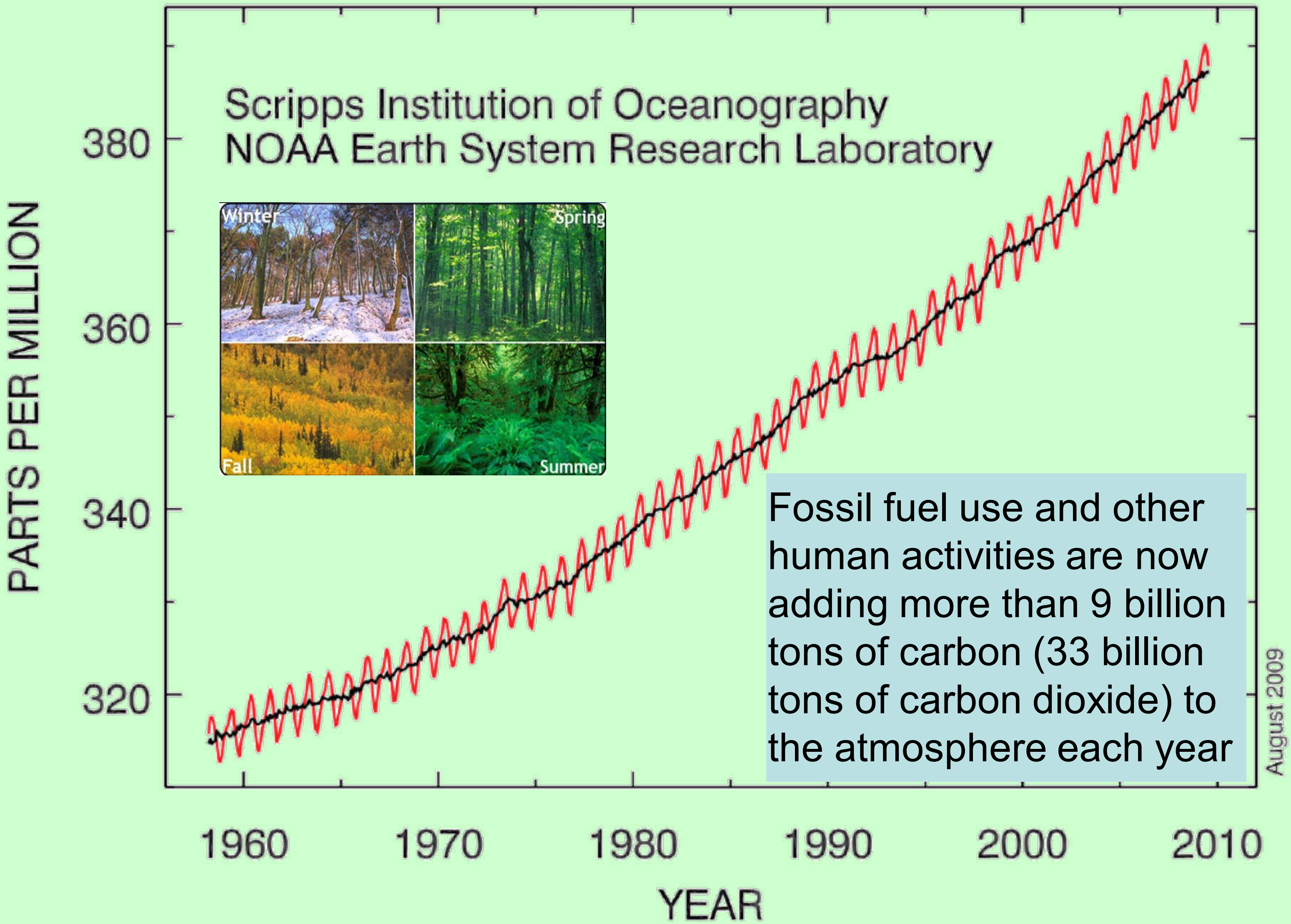
March 26, 2012

ACOS

The Carbon Cycle

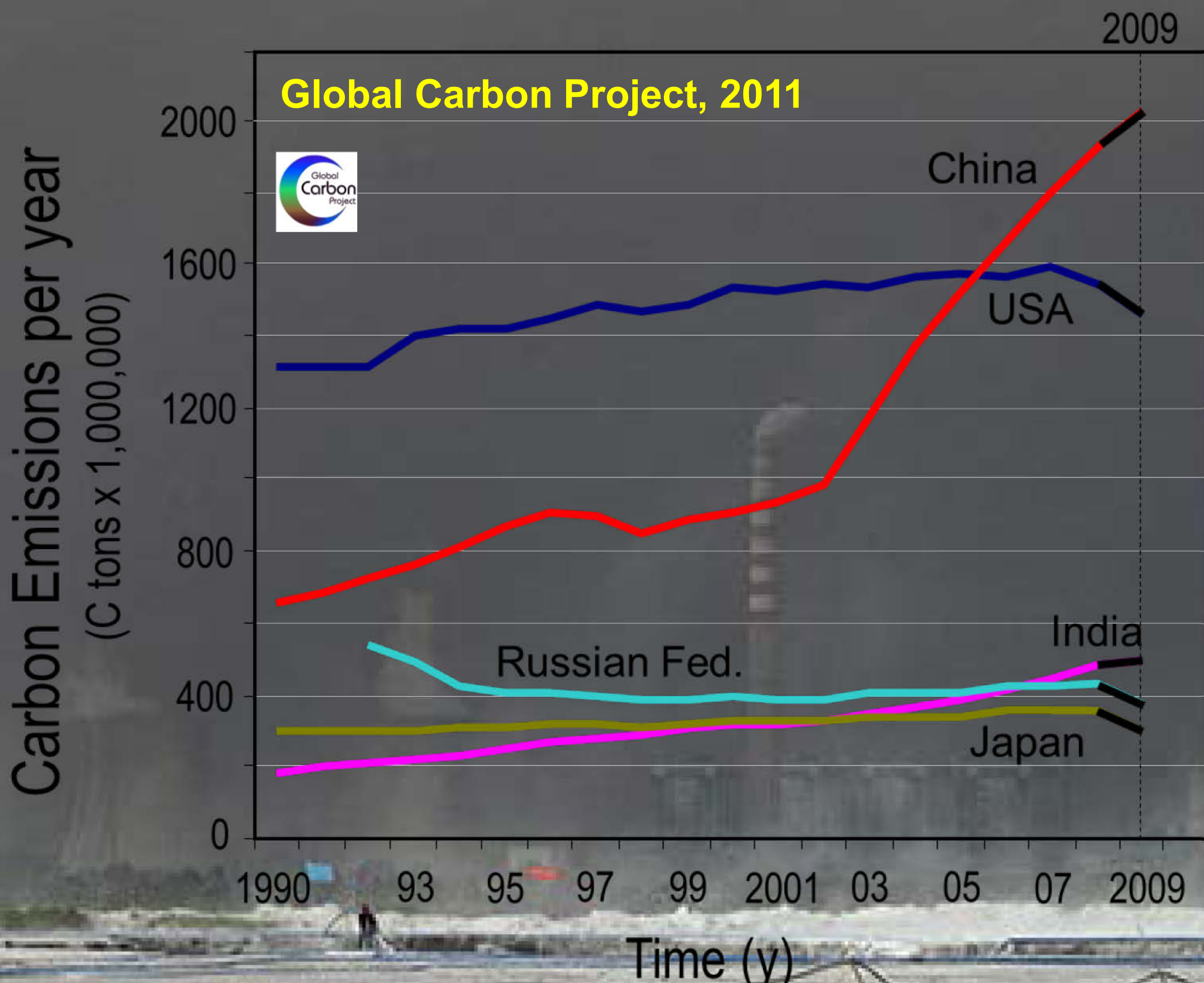


The Atmospheric Carbon Dioxide Record



Fossil fuel use and other human activities are now adding more than 9 billion tons of carbon (33 billion tons of carbon dioxide) to the atmosphere each year

Fossil Fuel CO_2 Emissions: Top Emitters



In recent years, the largest increases in fossil fuel emissions have occurred in developing countries.

Emissions by some developed countries declined due to the global economic crisis.

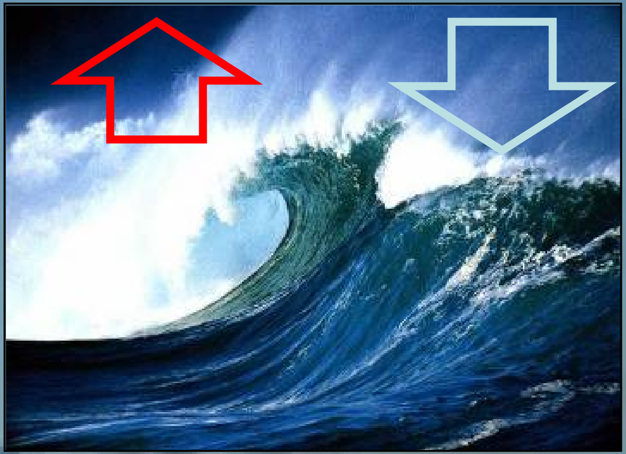
China is now the largest single emitter, but its per capita emissions are still well below those in the U.S.

What Controls Atmospheric Carbon Dioxide?

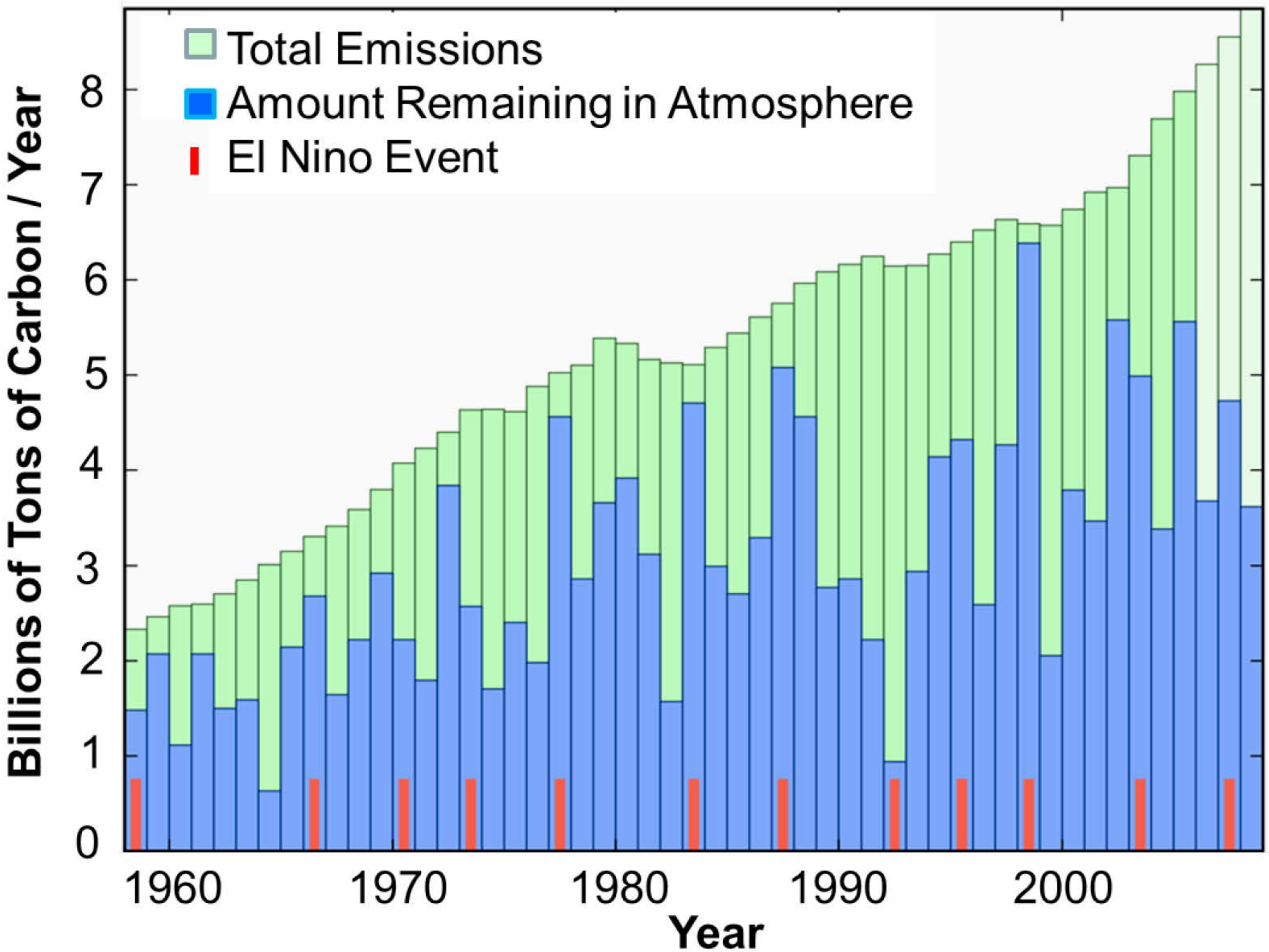
- Natural systems including the ocean and plants on land both absorb and emit carbon dioxide to the atmosphere

- Currently, these natural systems are
  - absorbing about half of the carbon dioxide emitted by human activities
  - limiting the rate of carbon dioxide buildup and its impact on the Earth's climate

- Fundamental questions:
  - What processes are responsible for absorbing this CO_2?
  - Why does the sink strength vary dramatically from year to year?
  - Will the nature, location and strength of these CO_2 sinks change in the future?



What Processes Regulate CO_2 Sinks?



What natural processes are currently absorbing almost half of the CO_2 emitted by human activities?

Why does the amount of CO_2 that stays in the atmosphere change so much from year to year?

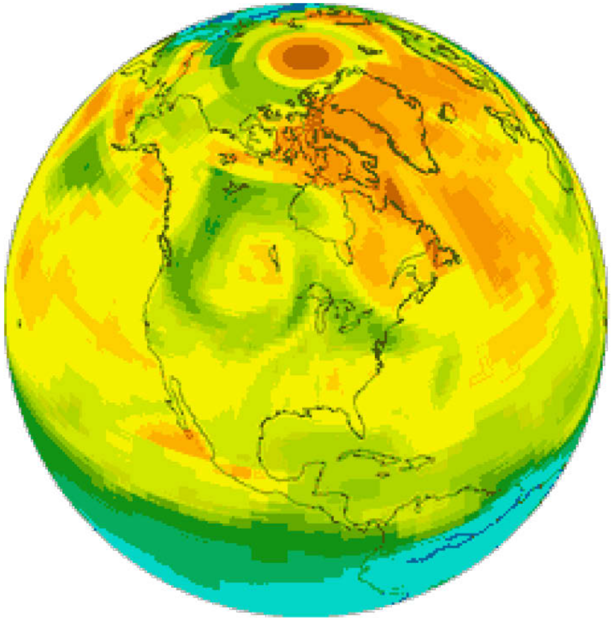
We don't know.

Global Measurements from Space are Essential for Monitoring Atmospheric CO_2

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

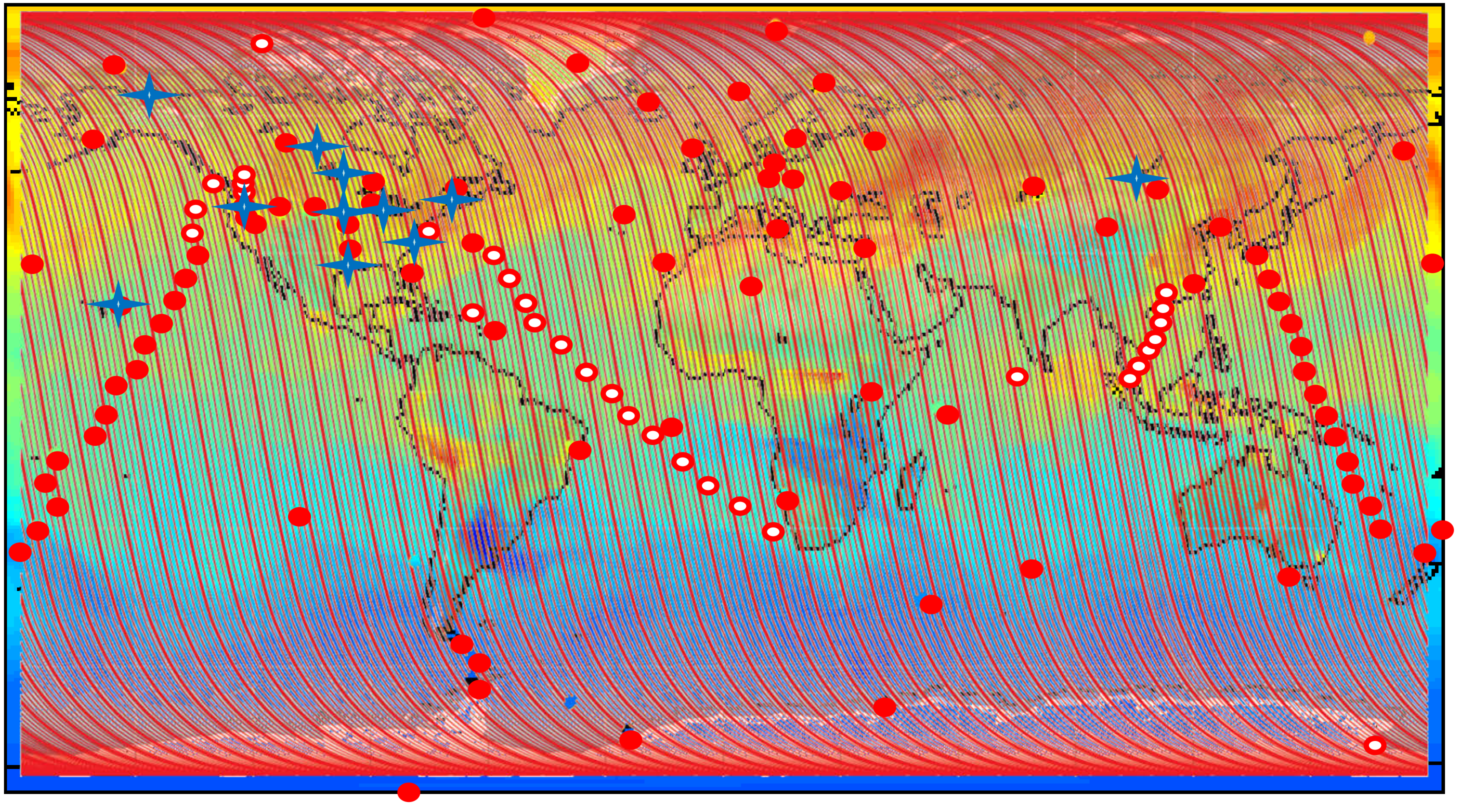
We can only manage what we can measure

Plumes from medium-sized power plants (4 MtC/yr) elevate X_{CO2} levels by ~2 ppm for 10's of km downwind [Yang and Fung, 2010].



These variations are superimposed on a background of "**CO_2 weather**"

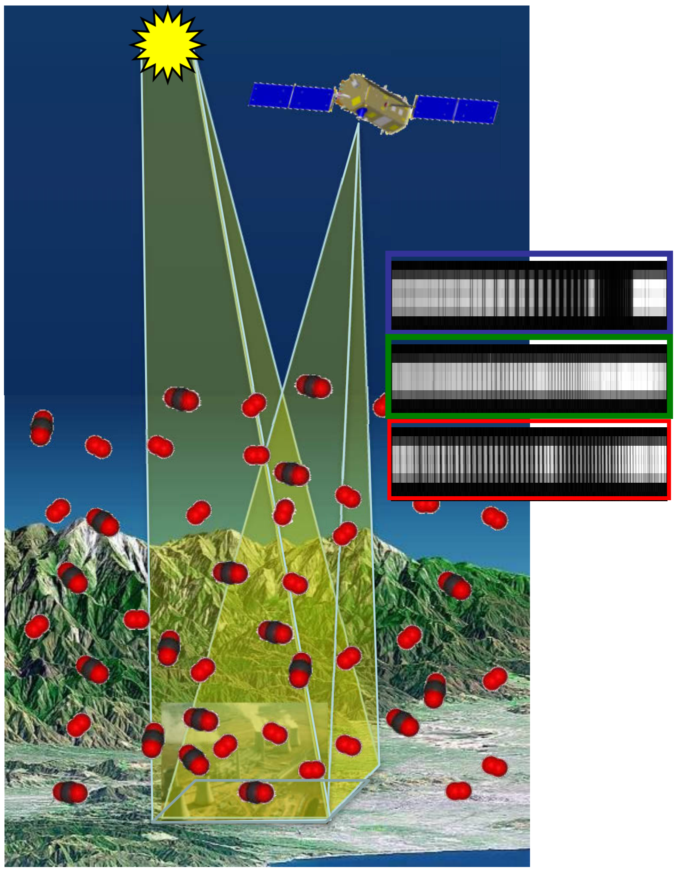
Primary Advantage of Space-based Data: Spatial Coverage at High Resolution



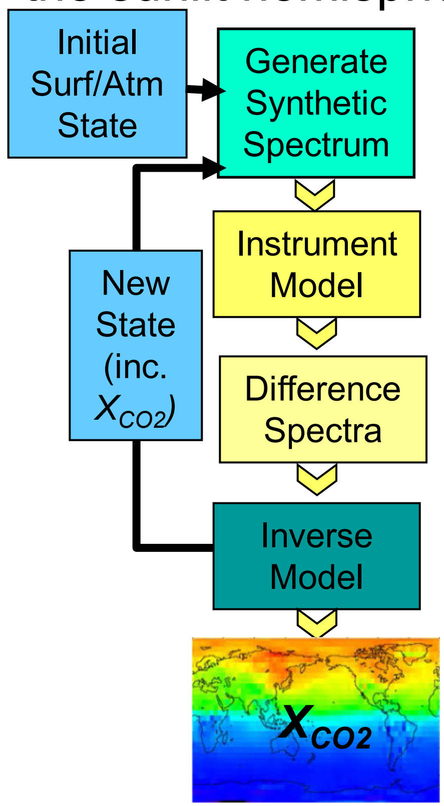
- Ground based measurements - greater precision and sensitivity to CO_2 near the surface, where sources and sinks are located.
- Space-based measurements – improve spatial coverage & resolution.
- Source/Sink models - assimilate space an ground-based data to provide global insight into CO_2 sources and sinks

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 - 2 ppm (0.3 - 0.5%)

Driving Requirements for Space Based CO_2 Measurements

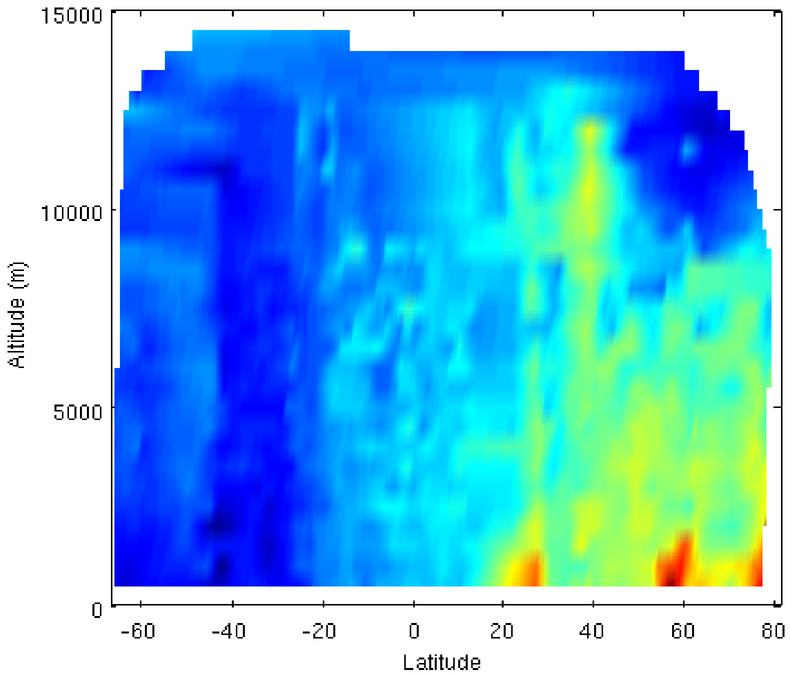
Requirements that drive the design of space-based CO_2 missions include:

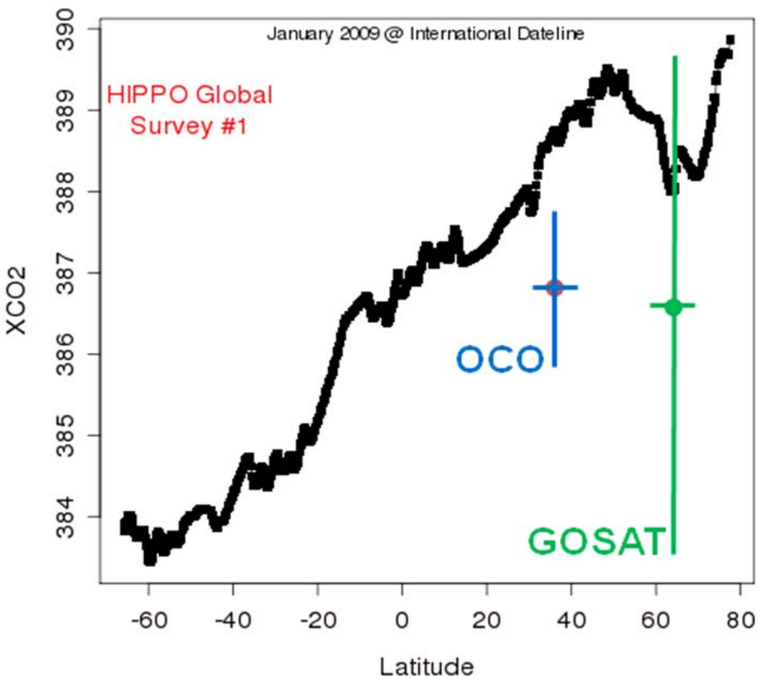
- Sensitivity (Precision)
  - Spatial variations in X_{CO2} are small (< 2%)
- Accuracy
  - Small biases can introduce large regional-scale flux errors
- Spatial coverage
  - Ocean and land
  - Limited to clear sky
- Spatial resolution
  - Adequate to resolve spatial gradients
- Lifetime
  - Atmospheric CO_2 varies over the seasonal cycle and from year to year

High precision is Essential for Monitoring CO_2 Sources and Sinks from Space

- CO_2 sources and sinks must be inferred from small spatial variations in the (387 ±5 ppm) background CO_2 distribution
- The largest CO_2 variations occur near surface
- Space based NIR observations constrain column averaged CO_2, X_{CO2}
- X_{CO2} must be measured with a precision of < 1 ppm on regional scales to resolve the small variations associated with sources and sinks

Small spatial gradients in X_{CO2} verified by pole-to-pole aircraft data [Wofsy et al. 2010]

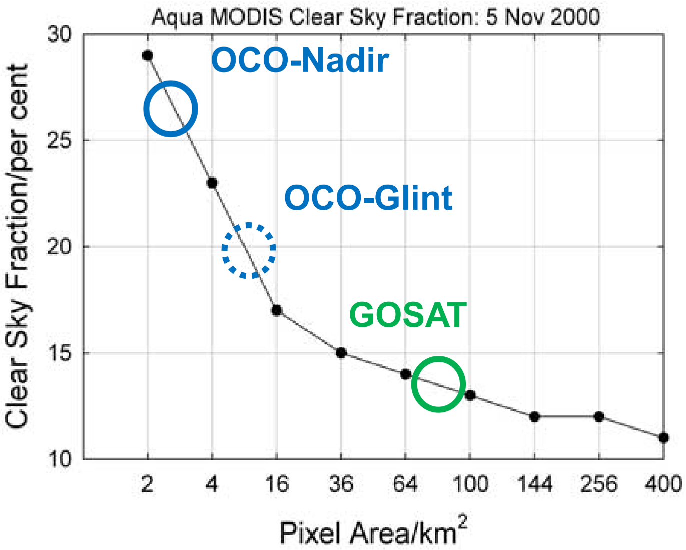


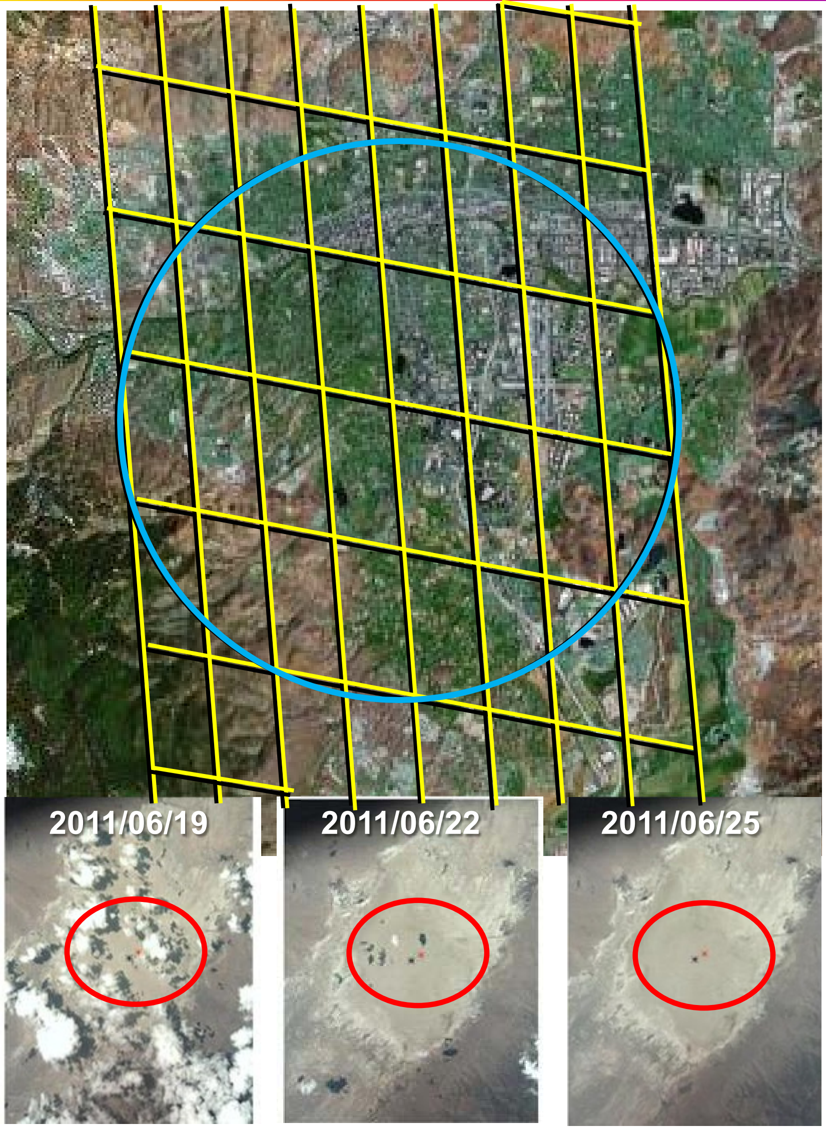


Spatial Resolution

A Small Footprint:

- Increases sensitivity to CO_2 point sources
  - Minimum measureable CO_2 flux is inversely proportional to footprint size
- Increases probability of recording cloud free soundings in partially cloudy regions
- Reduces biases associated with optical path length uncertainties over rough topography





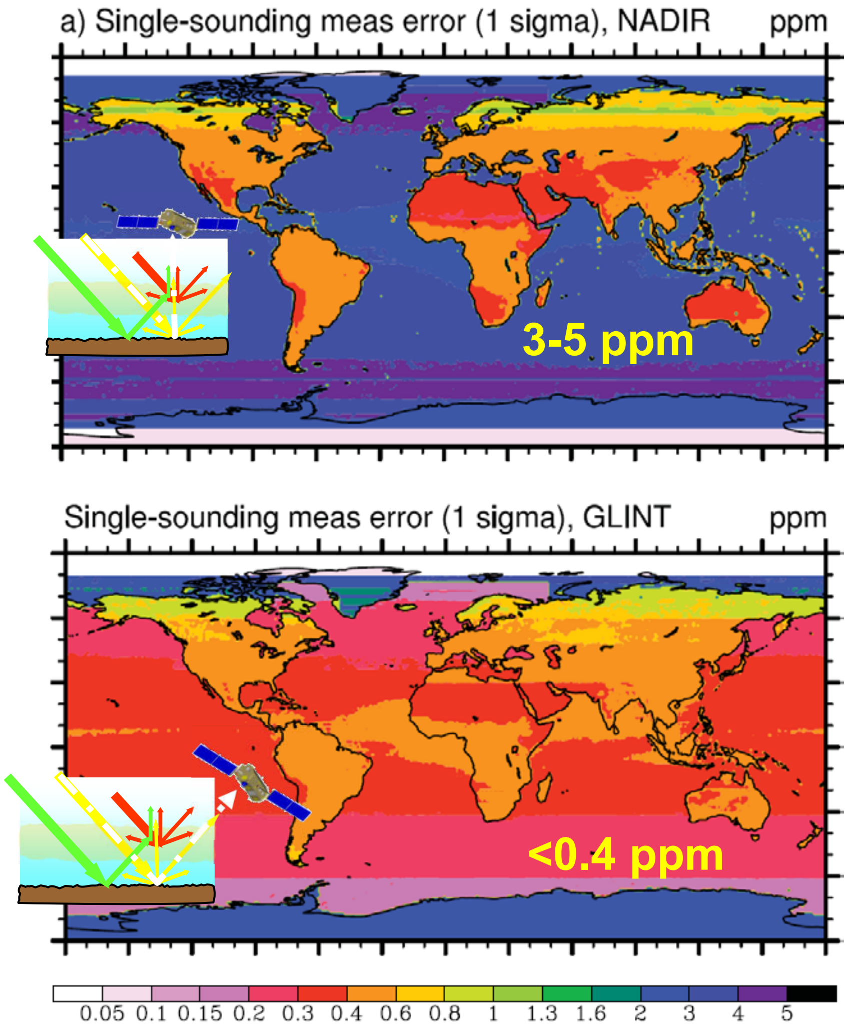
Coverage: Obtaining Precise Measurements over Oceans as well as Continents

- The ocean covers 70% of the Earth and absorb/emit 10 times more CO_2 than all human activities combined
- Coverage of the oceans is essential to minimize errors from CO_2 transport in and out of the observed domain

Near IR solar measurements of CO_2 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

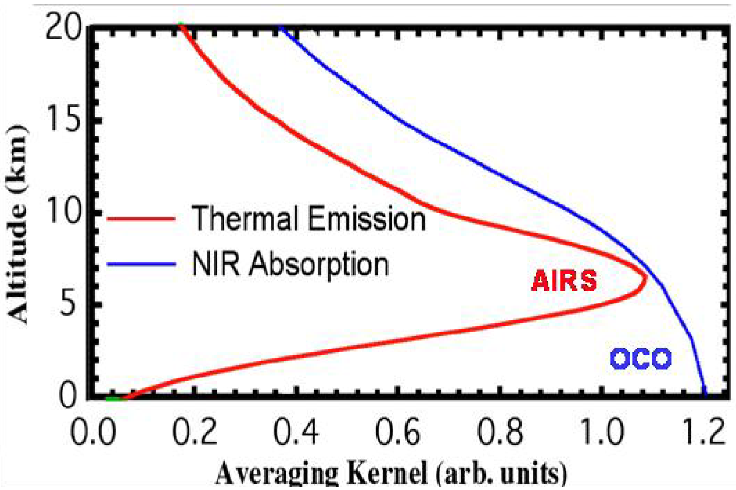
Glint and nadir measurements can be combined to optimize sensitivity over both oceans and continents

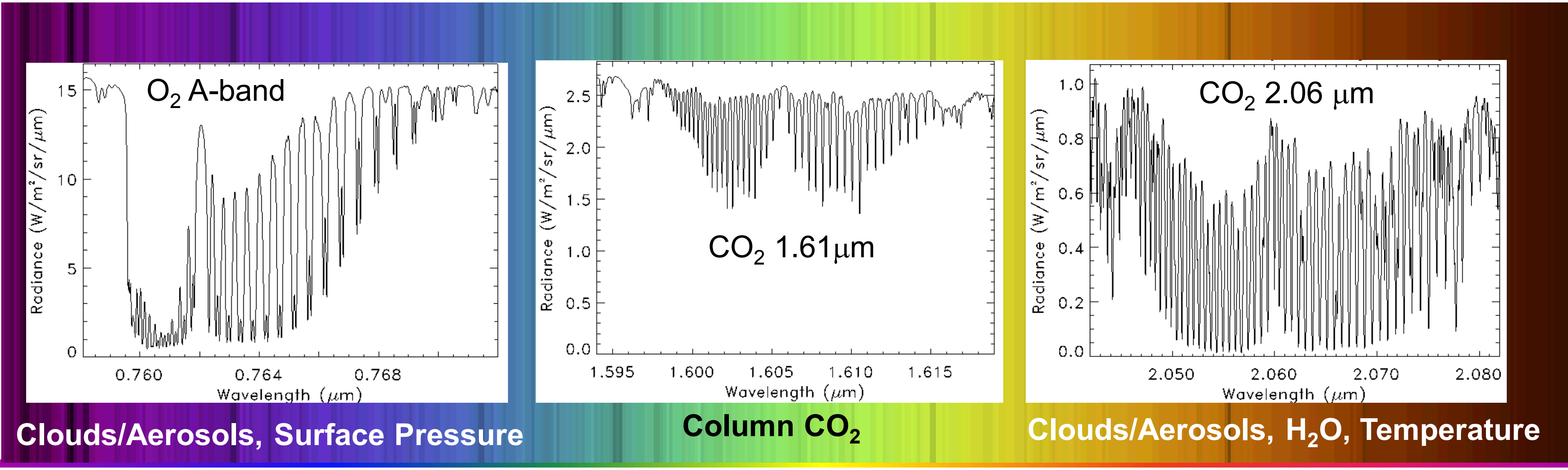


OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].

Making Precise CO_2 Measurements from Space

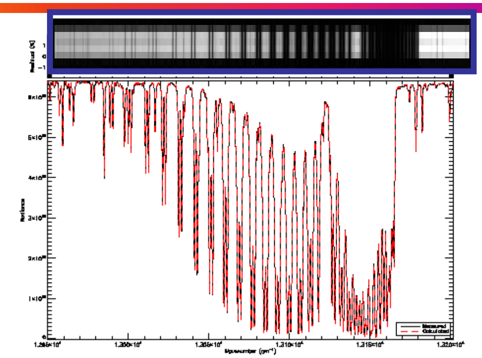
- High resolution spectra of reflected sunlight in near IR CO_2 and O_2 bands used to retrieve the column average CO_2 dry air mole fraction, X_{CO2}
  - 1.61 μm CO_2 band: Column CO_2
  - 2.06 μm CO_2 band: Column CO_2, Aerosols
  - 0.76 μm O_2 A-band: *Surface pressure*, clouds, aerosols
- Why high spectral resolution?
  - Enhances sensitivity, minimizes biases

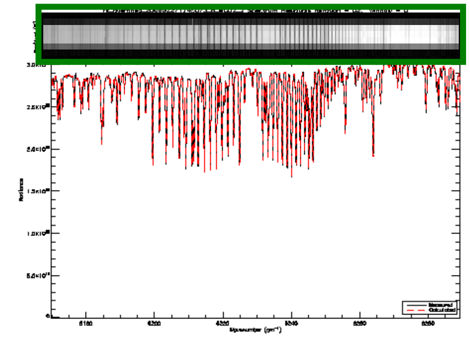


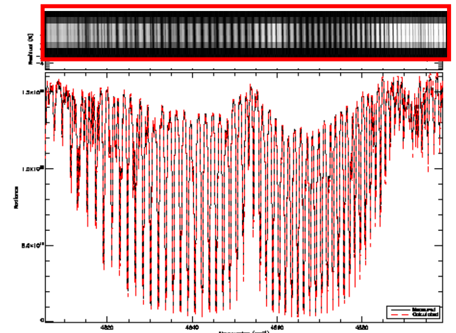


Information Content of Spectra

- O_2 A-band at 760 nm provides constraints on surface pressure, optical path length, and thin cloud/aerosol distribution
- Absorption in weak CO_2 band at 1610 nm is almost linearly dependent on CO_2 column
- Strong CO_2 band at 2060 nm
  - Somewhat less sensitive to the CO_2 column abundance
  - Very sensitive to clouds and aerosols
  - Also sensitive to water vapor column abundance and temperature profile
- Simultaneous retrievals in these three band provide X_{CO2} estimates

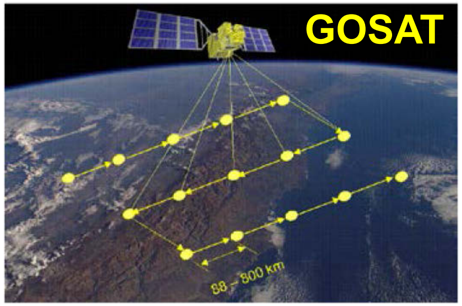


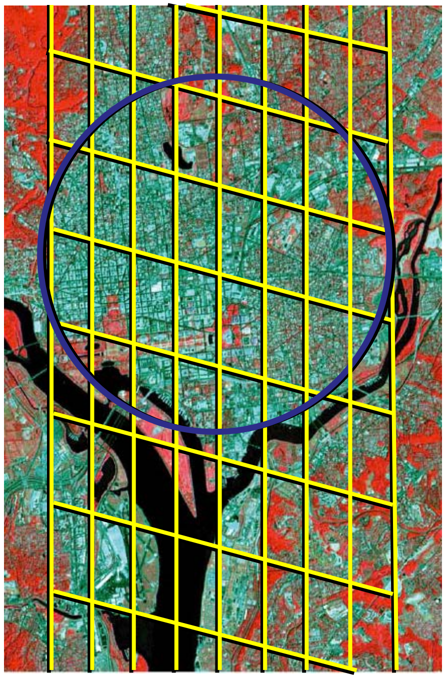




Remote Sensing of CO_2 using Reflected Sunlight: GOSAT and OCO/OCO-2

- **GOSAT (2009)**
  - Optimized for spectral and spatial coverage
  - Collects 10,000 soundings every day
    - 10-15% are sufficiently cloud free for CO_2 &CH_4 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 10^6 soundings/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, yielding global maps in both models once each month

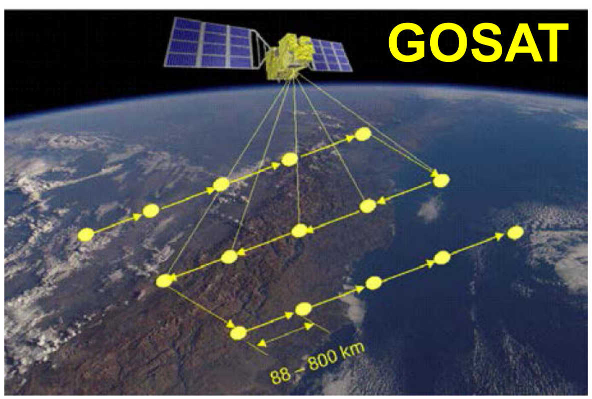
GOSAT-OCO Collaboration

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

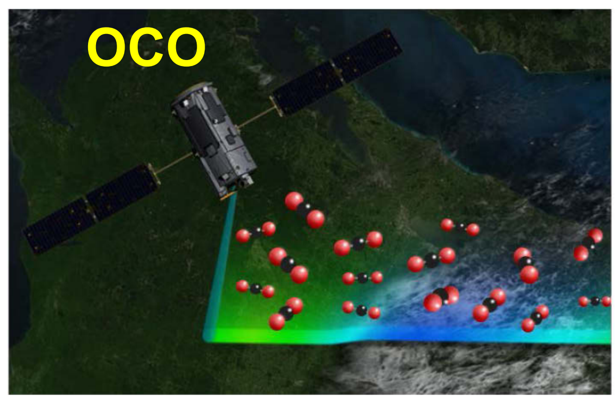
- Cross calibrate the OCO instrument and TANSO-FTS
- Cross validate OCO and GOSAT X_{CO2} retrievals against a common standard

The primary objectives of this partnership were to:

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



3-day ground track repeat cycle resolves weather



Continuous high resolution measurements along track

The Launch of GOSAT & Loss of OCO

GOSAT launched successfully on 23 January 2009

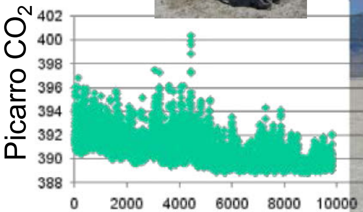
OCO was lost a month later when its launch system failed

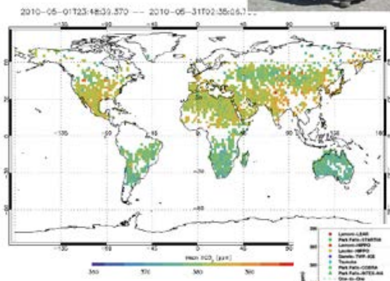
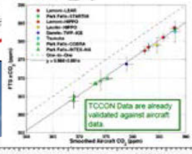
The ACOS/GOSAT Collaboration

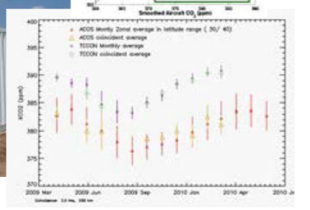
- Immediately after the loss of OCO, the GOSAT Project manager invited the OCO Team to participate in GOSAT data analysis

- 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_{CO2} from GOSAT spectra
    - Model development & testing
    - Data production and delivery
  - Validate GOSAT retrievals by comparing GOSAT retrievals with TCCON measurements and other data



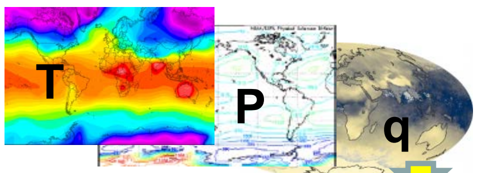


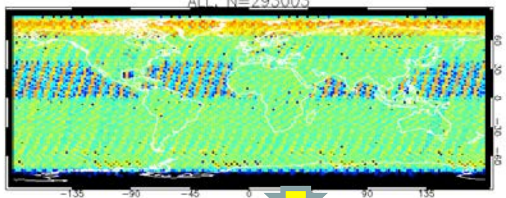


Retrieving X_{CO2} from GOSAT Spectra

Interpolated Meteorology

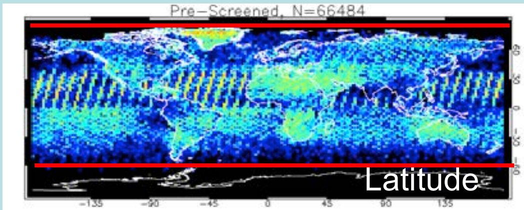


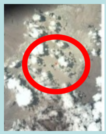
Level 1B Data



- Evolved from the OCO Retrieval Algorithm
  - Optimal Estimation
  - "Full Physics"
  - 3-band (ABO2, WCO2, SCO2)

Pre-Processing Filter



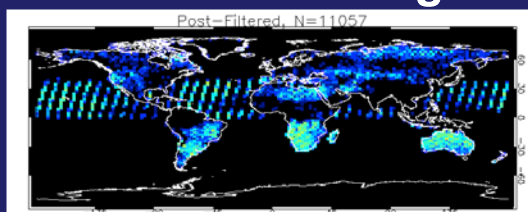


State Vector
CO_2 profile (full)
H_2O profile (scale factor)
Temperature profile (offset)
AOD, Height (4 types)
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift
Band 1 Zero-Level Offset (GOSAT only)

X_{CO2} Retrieval Algorithm

Forward Radiative Transfer Model → **Instrument Model** → **Inverse Model** → ? → Update State Vector / Final State and X_{CO2}

Post-Processing Filter



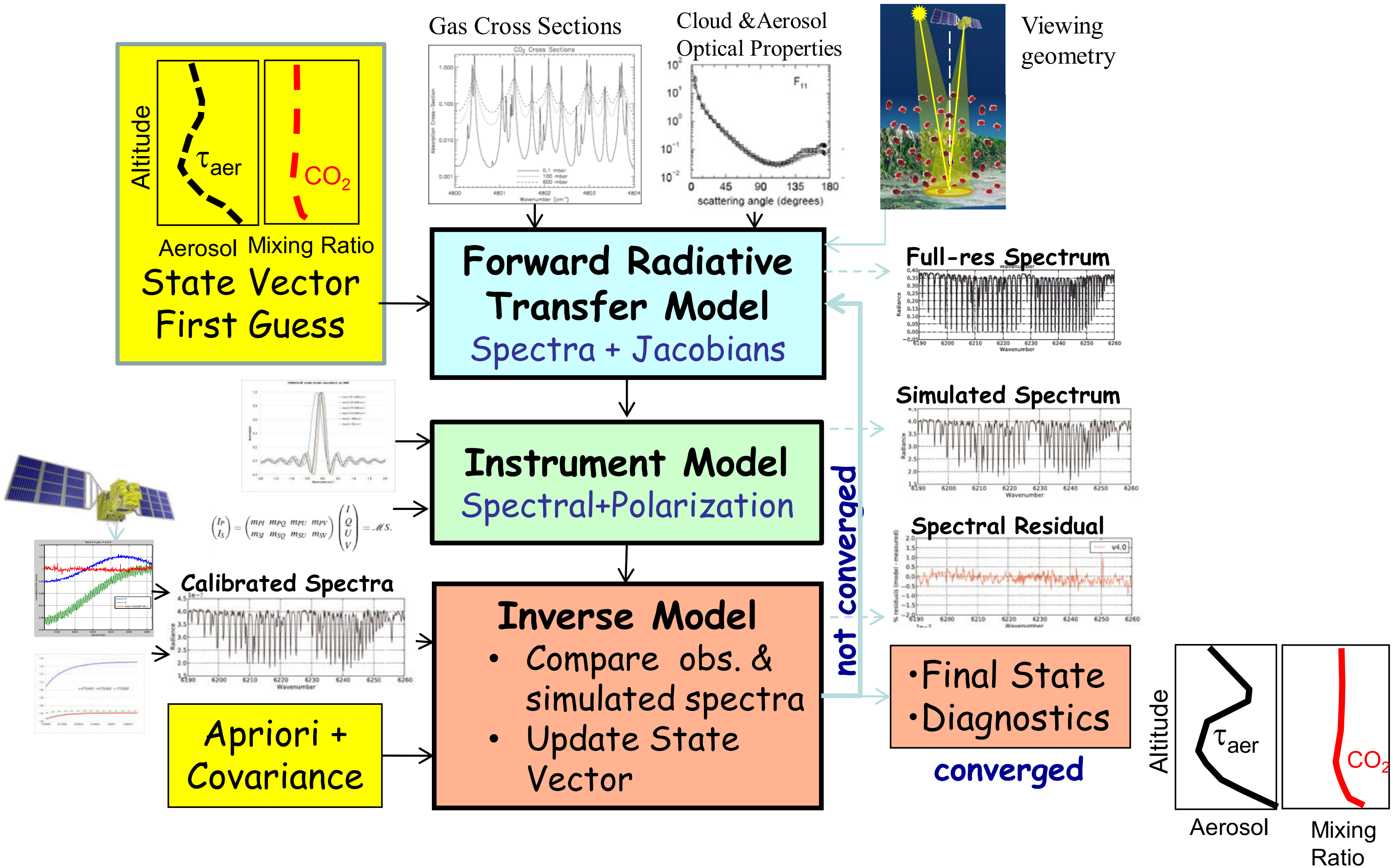
χ^2

Δp

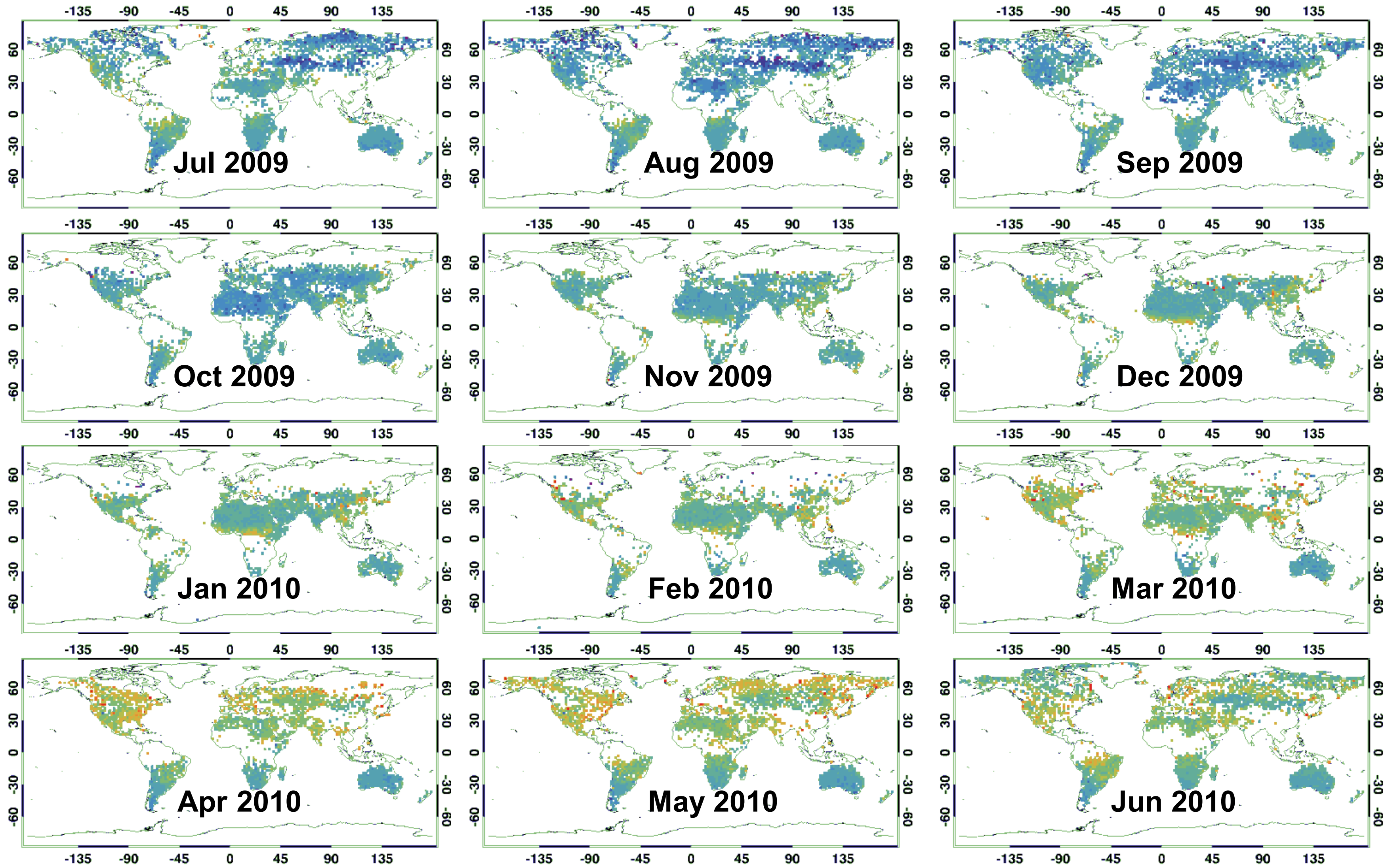
τ_{aer}

σ_{XCO2}

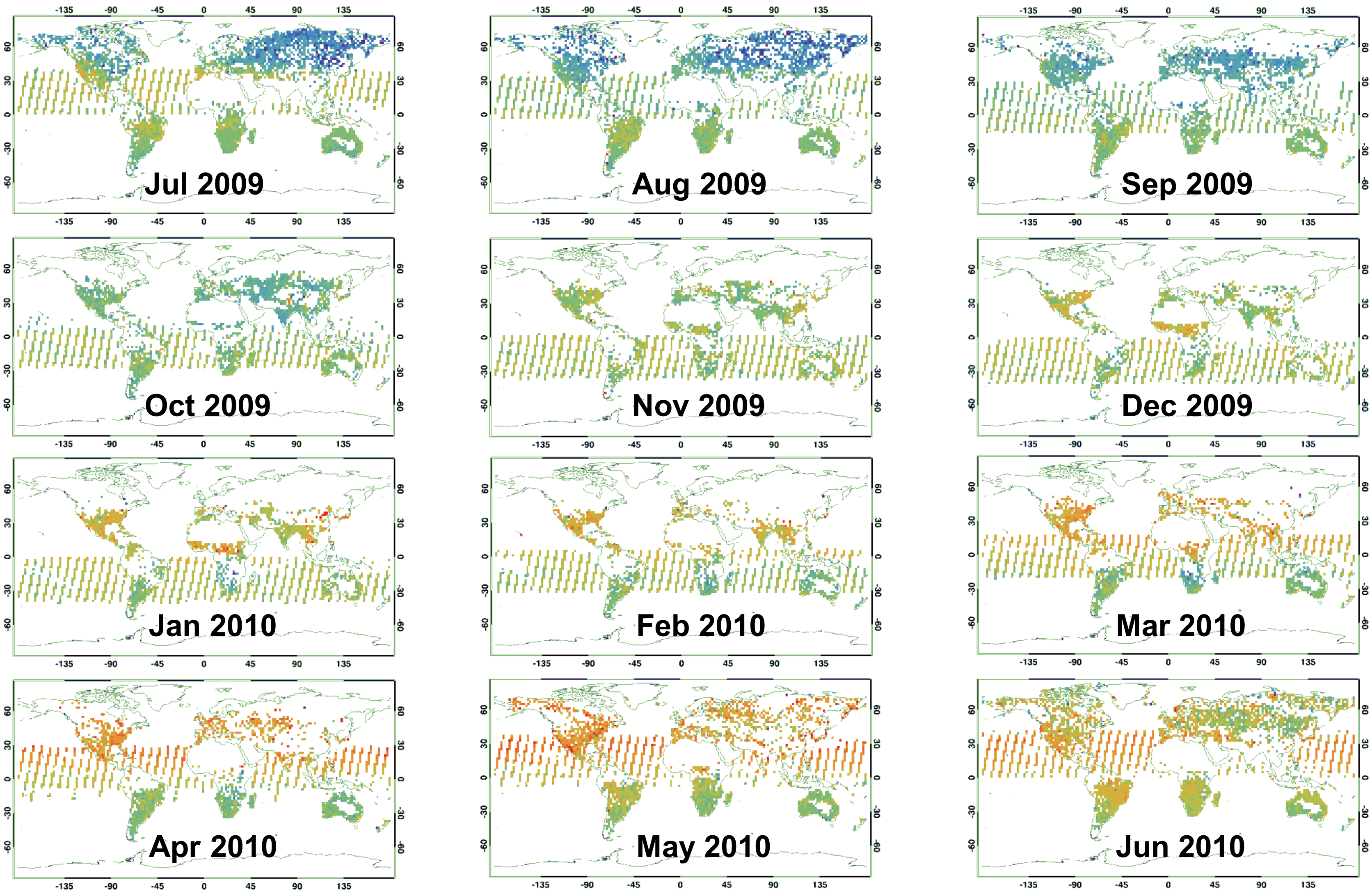
The ACOS X_{CO2} Retrieval Algorithm



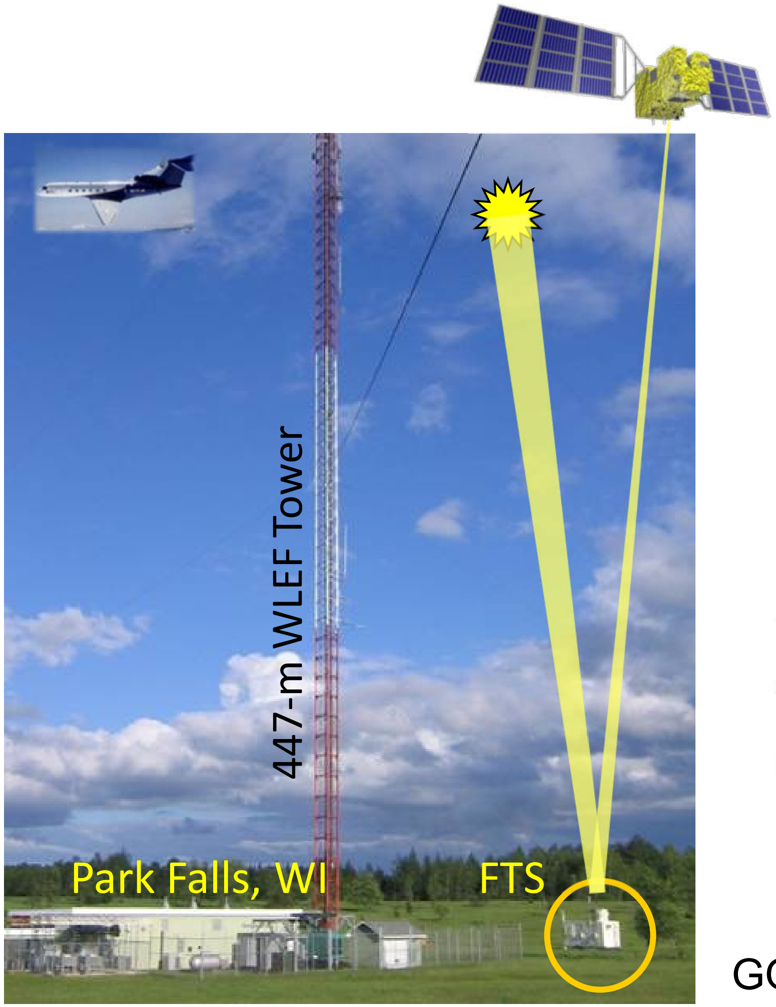
ACOS X_{CO2} Seasonal Cycle from GOSAT



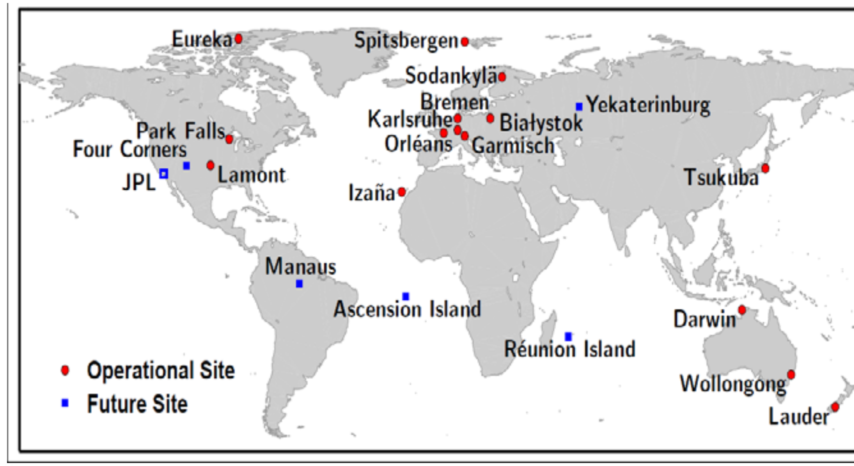
ACOS GOSAT X_{CO2} Seasonal Cycle (H-Gain Only)

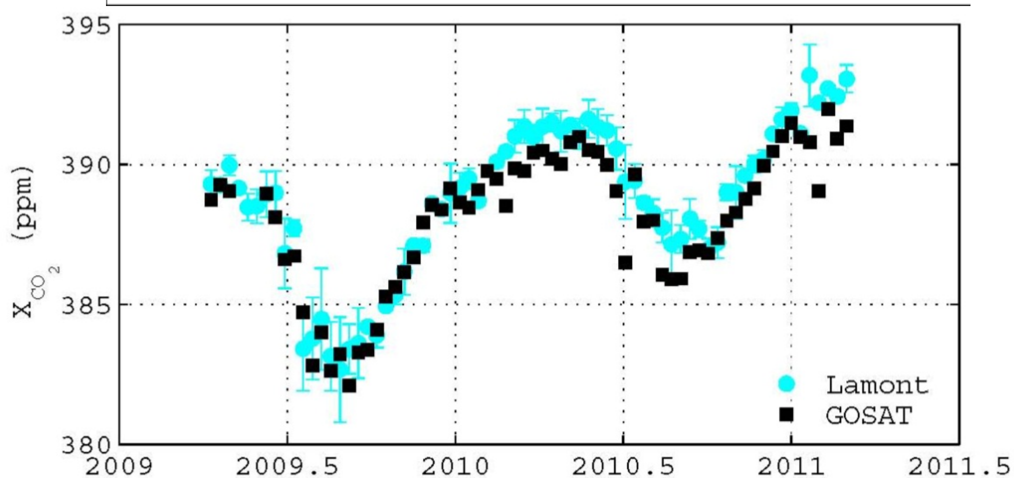


Validation of GOSAT Products against TCCON Reduces Regional Scale Bias



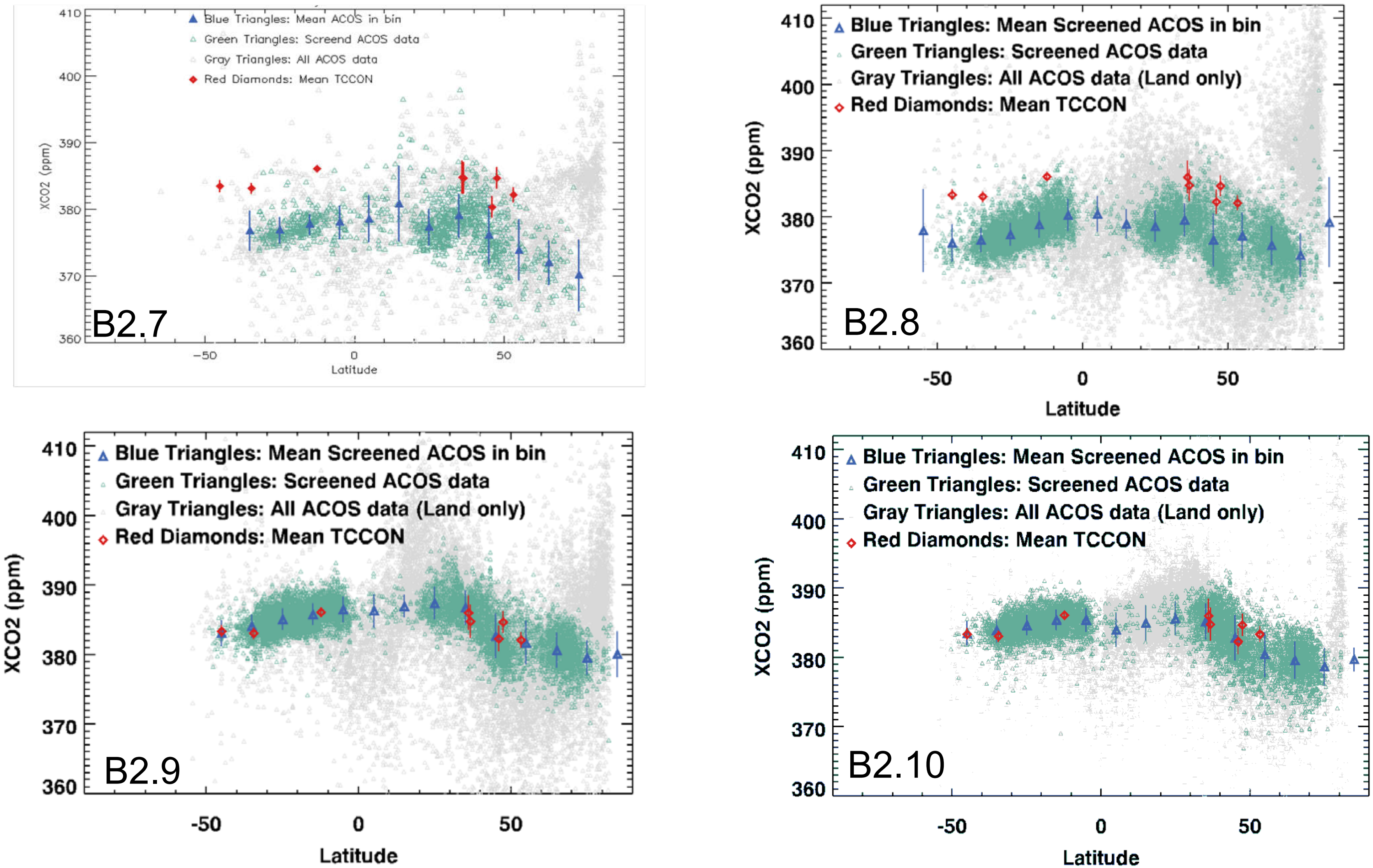
Near-simultaneous observations are acquired over TCCON station.



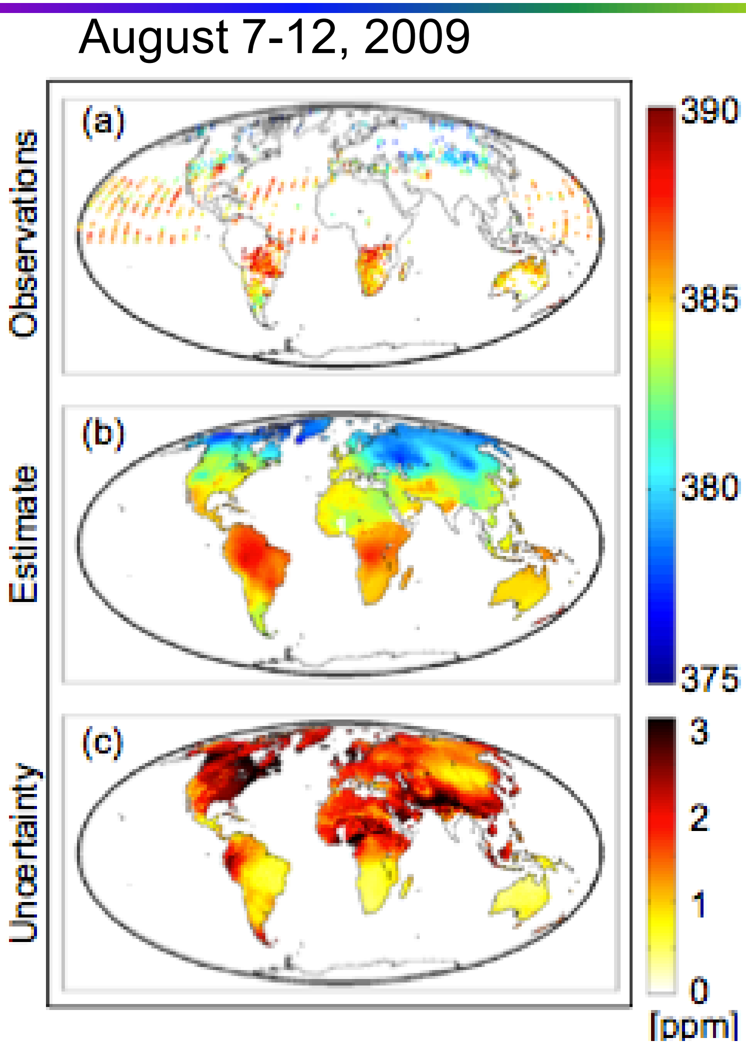


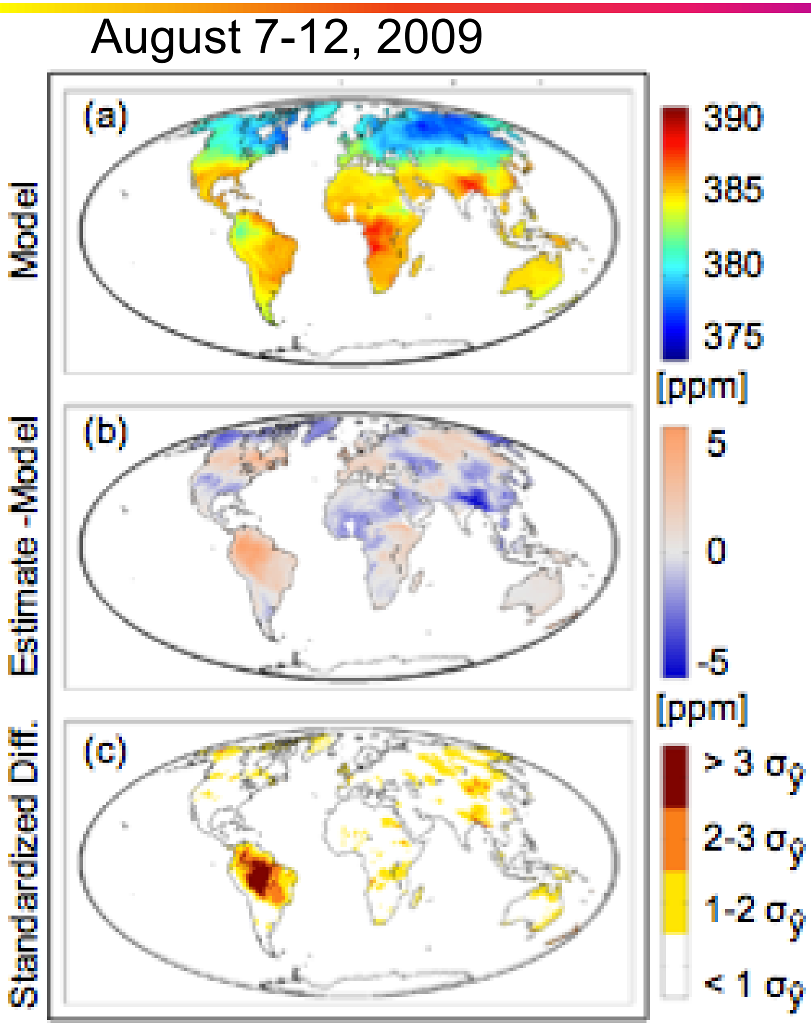
GOSAT X_{CO2} retrievals are compared with those from the ground based Total Carbon Column Observing Network (TCCON) to verify their accuracy

TCCON Comparisons Show Improvements over Time



Comparing GOSAT Gap-Filled Maps with Models

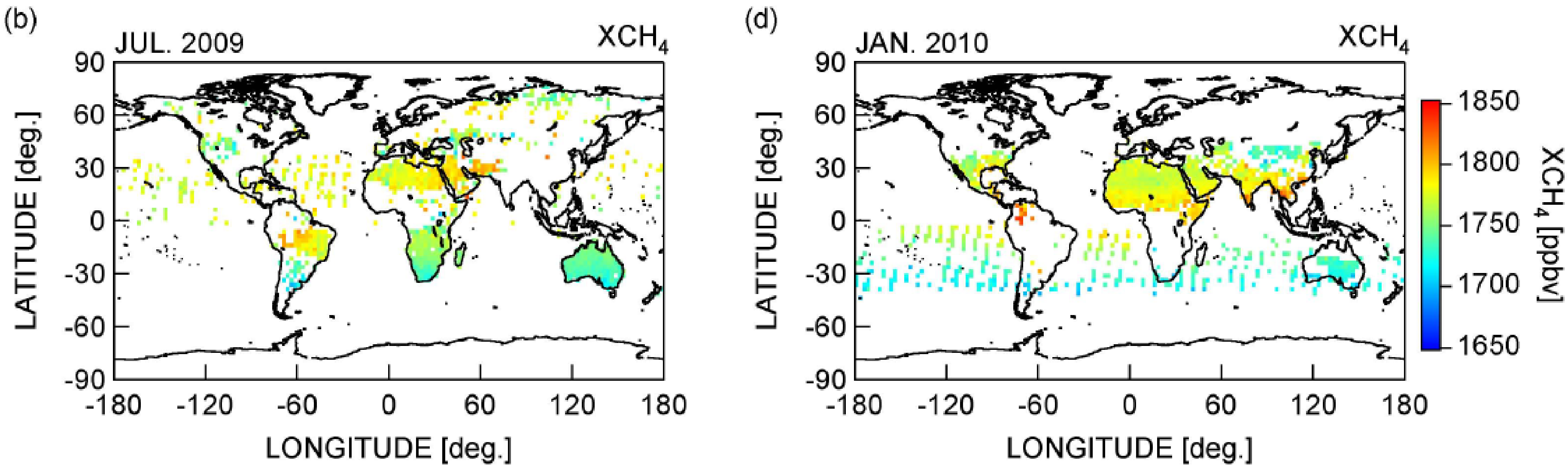




Hammerling, Michalak, O'Dell, & Kawa (GRL, under review)

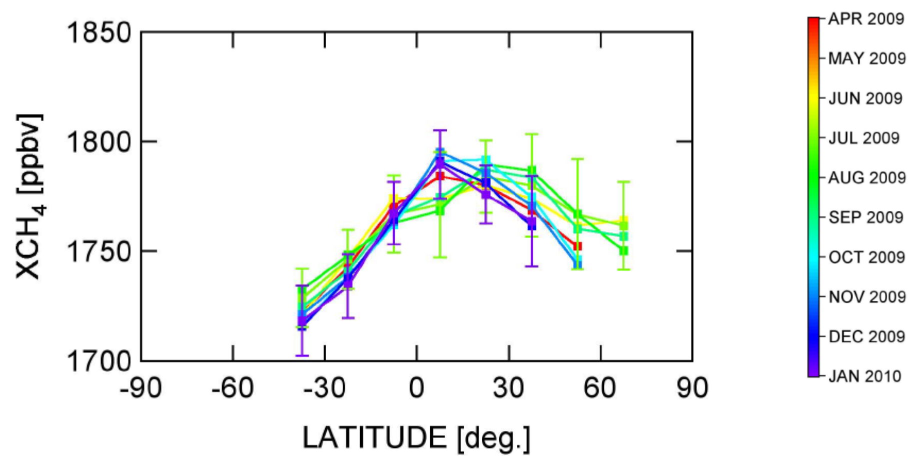
GOSAT Methane Retrievals

Yoshida et al. GOSAT CH_4 Retrievals, 2011



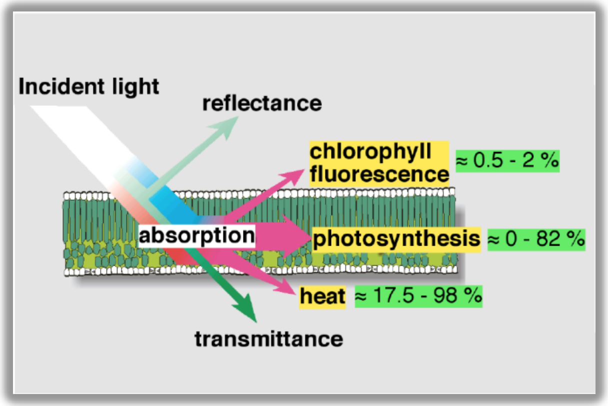
Monthly-average X_{CH4} for July 2009 and January 2010 within 2.5° x 2.5° grid boxes.

GOSAT observations are also being used to retrieve global maps of the column averaged methane dry air mole fraction, X_{CH4}, the second most abundant atmospheric carbon species.

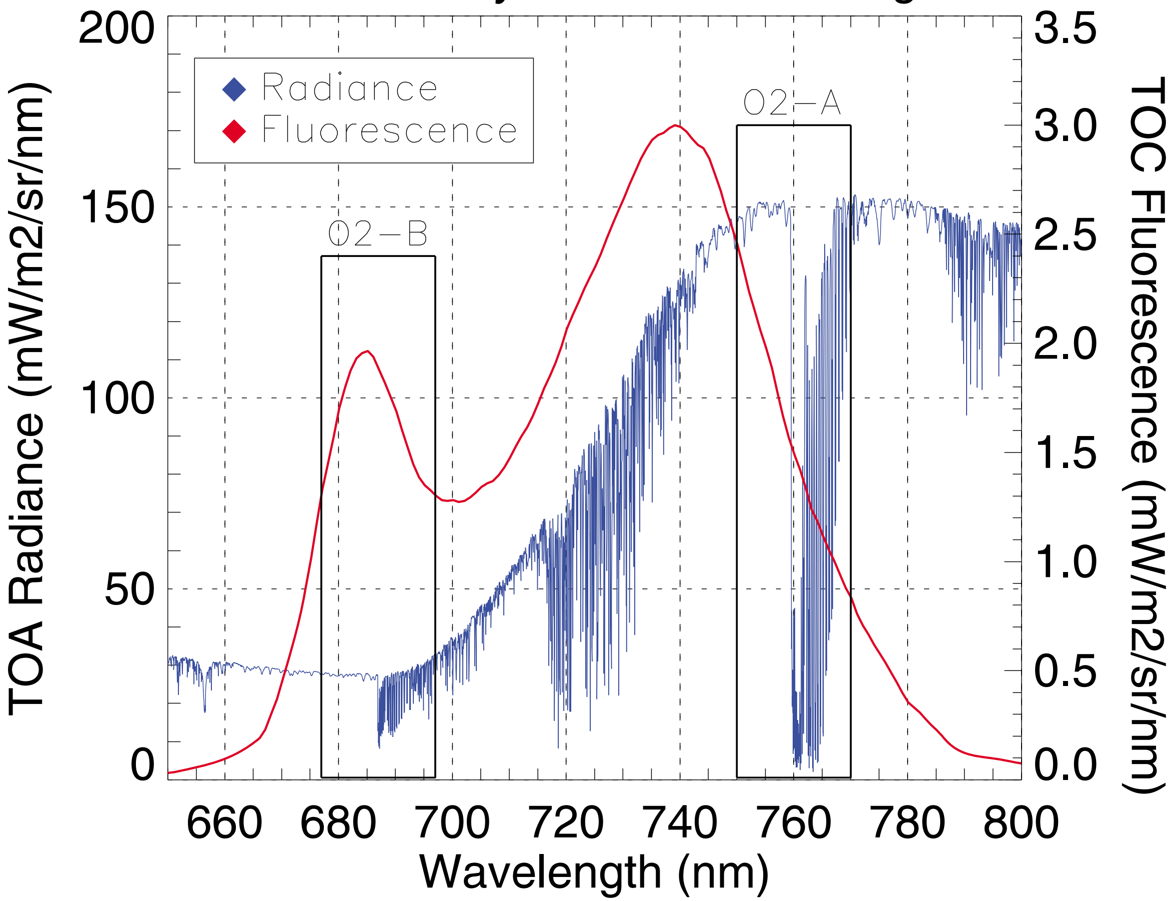


Latitude Distribution of zonal mean X_{CH4}.

New Carbon Cycle Products: Chlorophyll Fluorescence



Courtesy of C. Frankenberg et al. 2011.



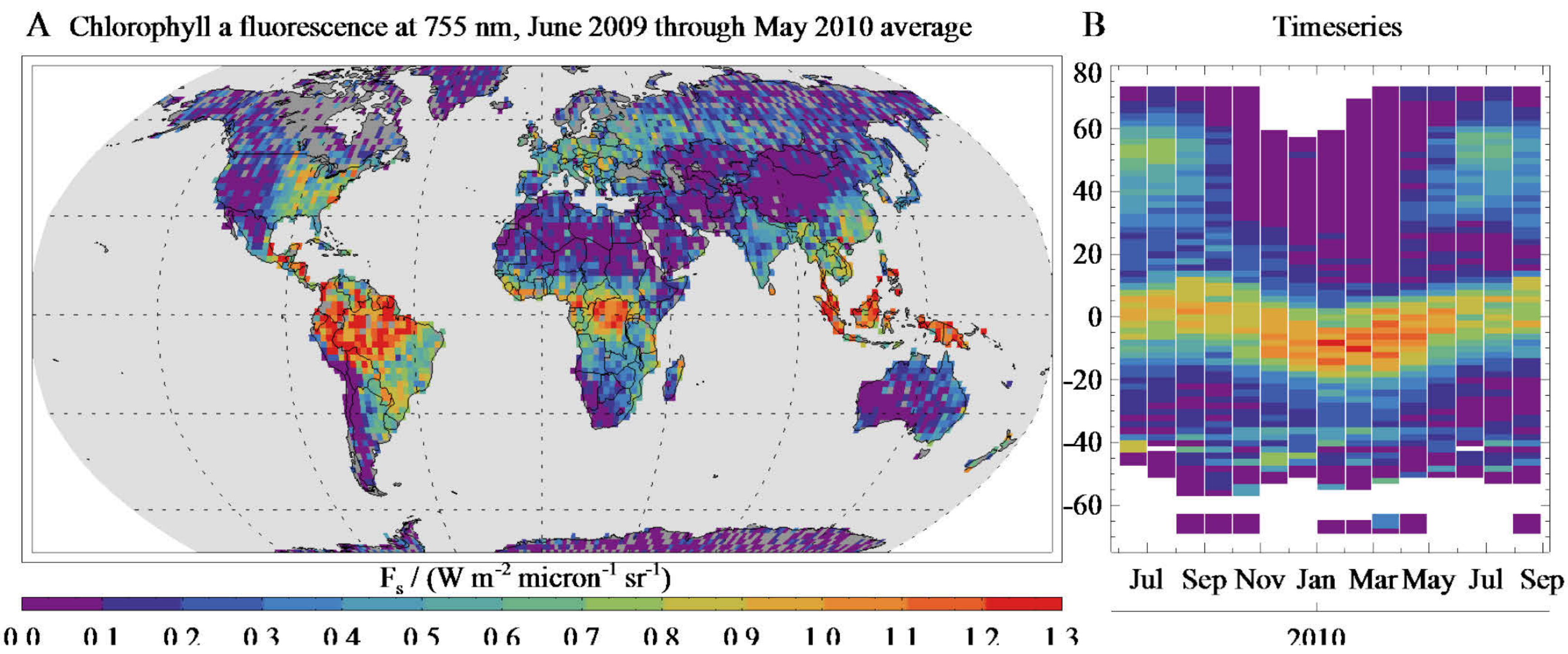
Chlorophyll Fluorescence

- Between 0.5 and 2% of the sunlight incident on a healthy plant is reemitted as fluorescence.
- The intensity of the fluorescence is proportional to the CO_2 uptake by the plant

Chlorophyll fluorescence can be quantified by monitoring the filling of solar Fraunhofer lines in the GOSAT O_2 A-band channel.

Global Maps of Chlorophyll Fluorescence from GOSAT Measurements

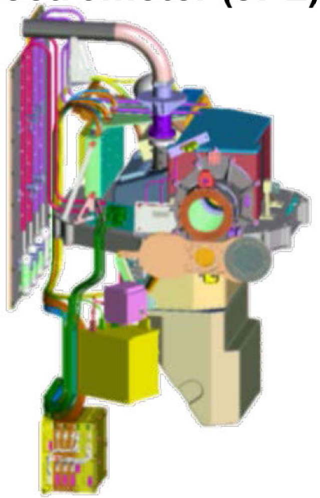
Courtesy of C. Frankenberg et al. 2011.



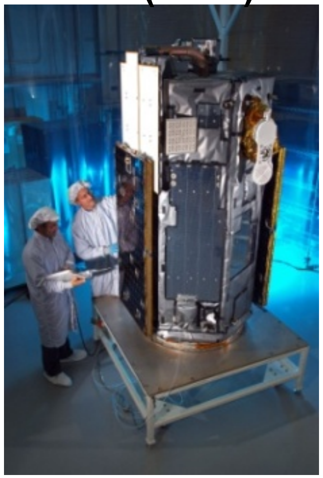
- **The Good News:** Global maps of chlorophyll fluorescence from GOSAT observations are providing new tools for studying the global carbon cycle.
- **The Bad News:** Neglecting chlorophyll florescence can introduce biases in space based of X_{CO2} retrievals that use O_2 A-band to constrain the optical path

The OCO-2 Mission is Under Development

3-Channel Spectrometer (JPL)



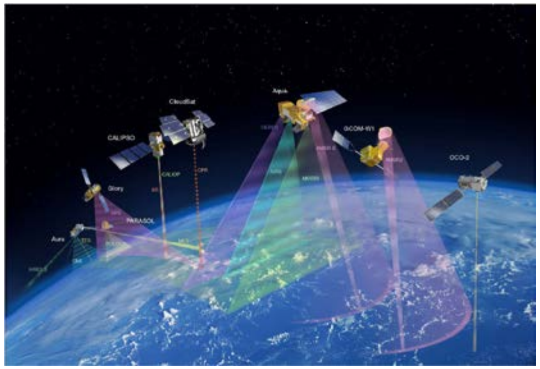
Dedicated Spacecraft Bus (OSC)



TBD Launch Vehicle

NASA NEN (GSFC) and SN (TDRSS)

Formation Flying as Part of the A-Train Constellation



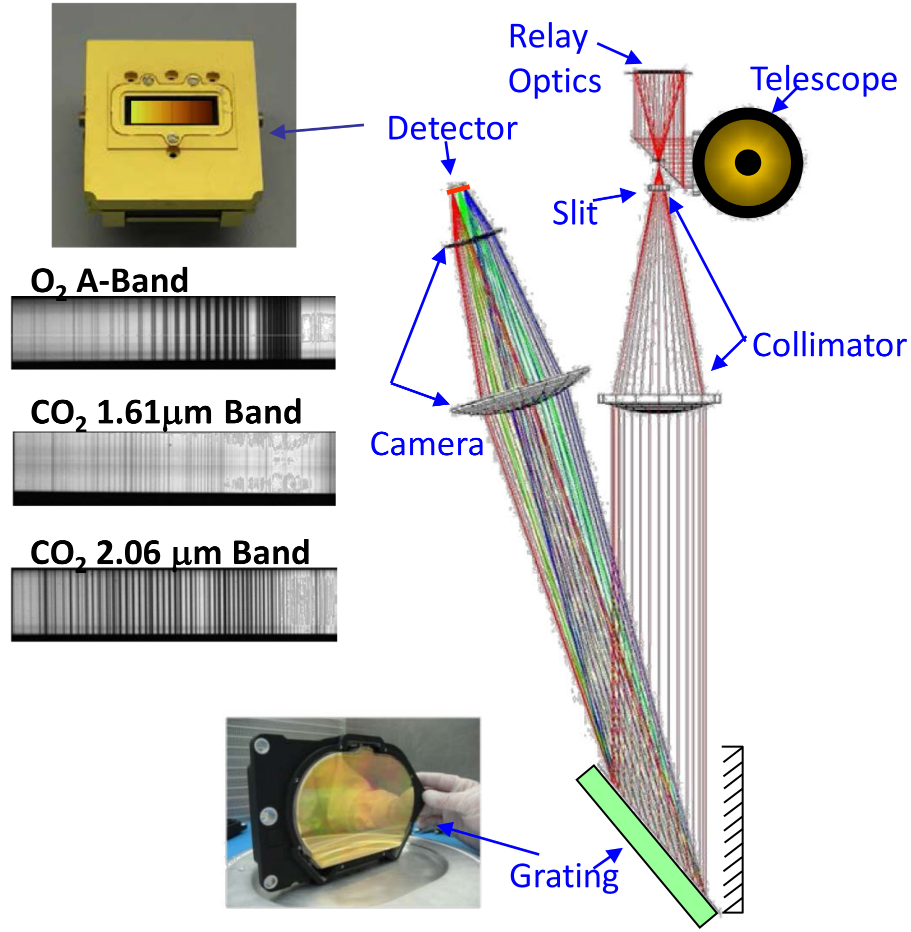
Mission Operations (OSC)

The OCO Instrument – Optimized for Sensitivity

- 3 co-bore-sighted, high resolution, imaging grating spectrometers
  - O_2 0.765 μm A-band
  - CO_2 1.61 μm band
  - CO_2 2.06 μm band
- Resolving Power ~ 20,000
- Optically fast: f/1.8 (high SNR)
- Swath: < 0.8° (10.6 km at nadir)
  - 8 cross-track footprints @ 3 Hz
  - 1.29 x 2.25 km at nadir
- Mass: 140 kg, Power: ~105 W

Changes from OCO

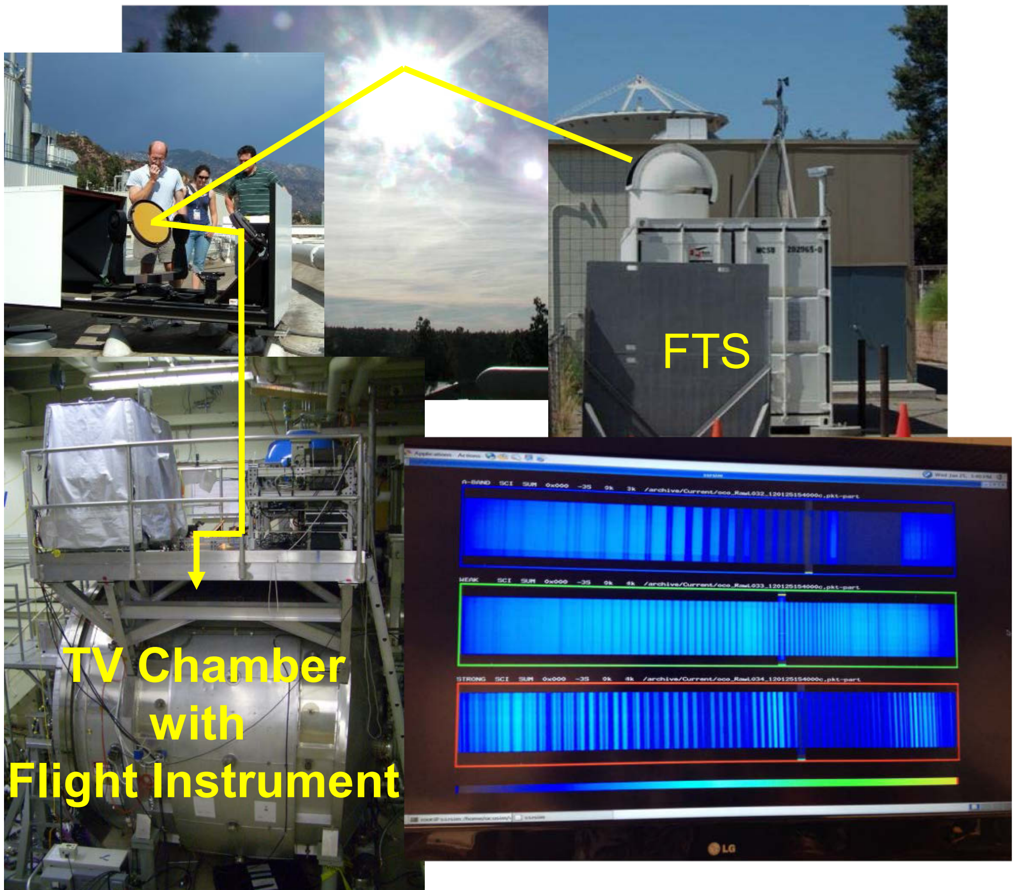
- Modified to mitigate residual image, slit alignment and stay light anomalies found in OCO pre-flight testing
- New cryocooler replaces obsolete unit



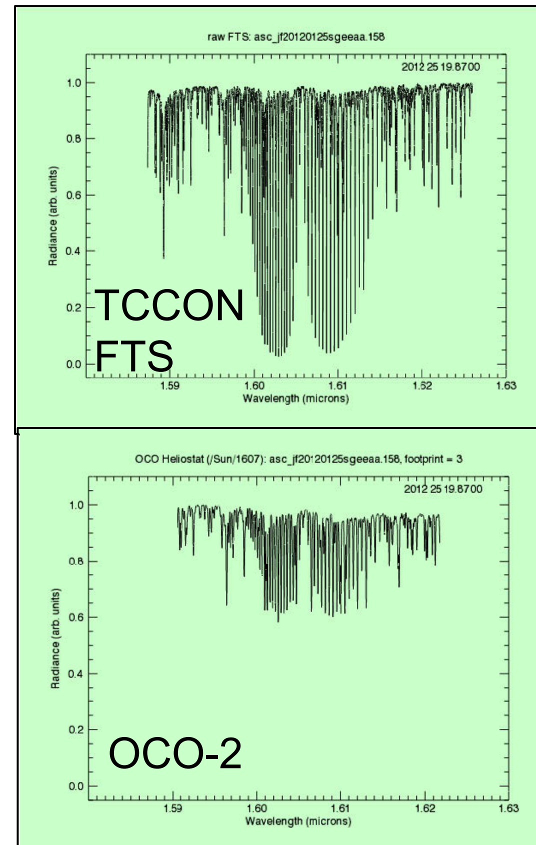
The OCO-2 instrument is more sensitive than the GOSAT TANSO-FTS, especially over dark scenes, and takes 48 to 96 times as many soundings over each orbit.

Pre-Flight Instrument Qualification and Characterization

Observations of the sun with the flight instrument taken during the thermo-vacuum tests provided an end-to-end test of the instrument performance.

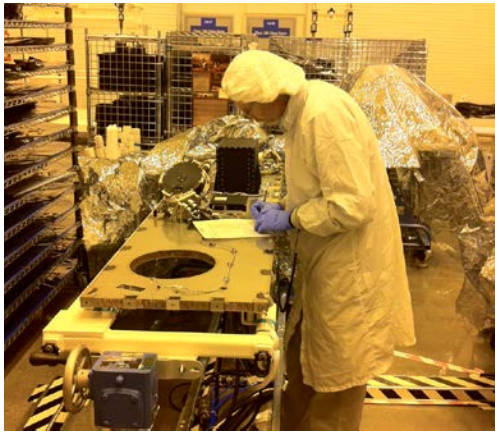


1.6 μm CO2

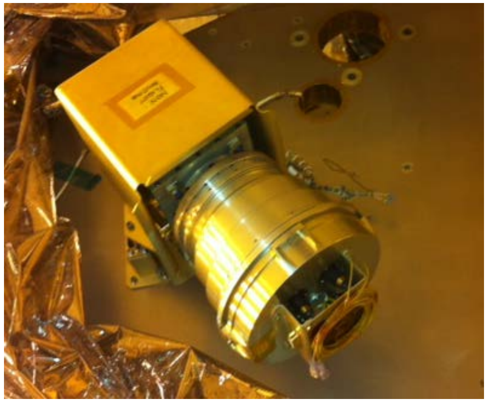


11:52 am on 25-Jan-2012

Spacecraft Bus I&T Underway at Orbital, Dulles

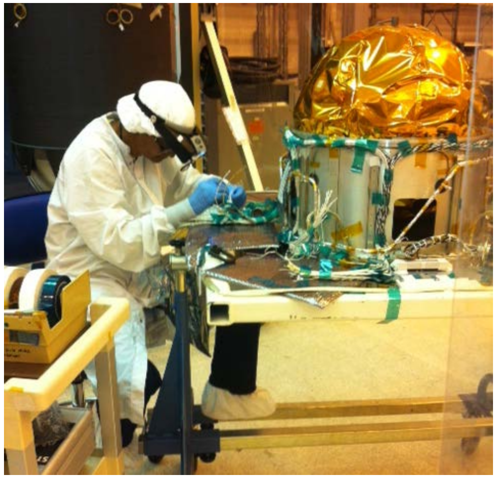


Credit: Orbital Sciences Corporation



Credit: John “Brad” Burt, JPL

Credit: Orbital Sciences Corporation



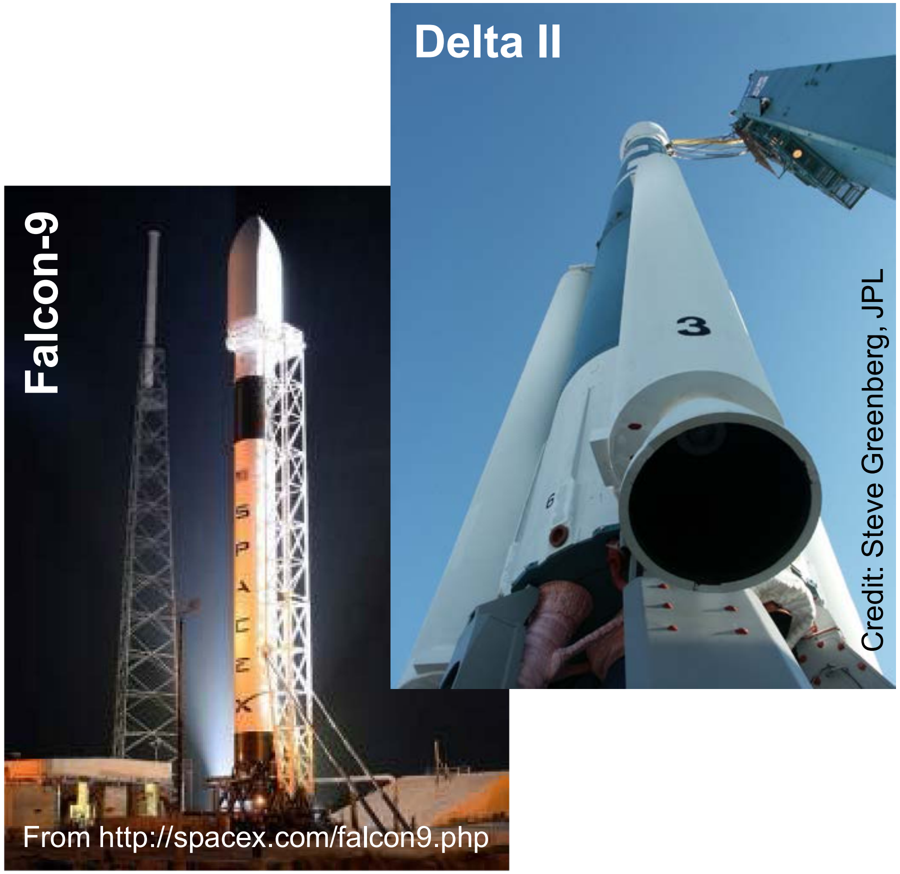
Credit: Orbital Sciences Corporation

- Activities are being performed at the Orbital Sciences Corporation facility in Dulles, VA
- The spacecraft structure, system harness, and avionic assemblies have been integrated and tested
- Most subcontracted items have been received, integrated, and tested
- Spacecraft bus delivery also expected this spring

Instrument + Spacecraft Bus = Observatory

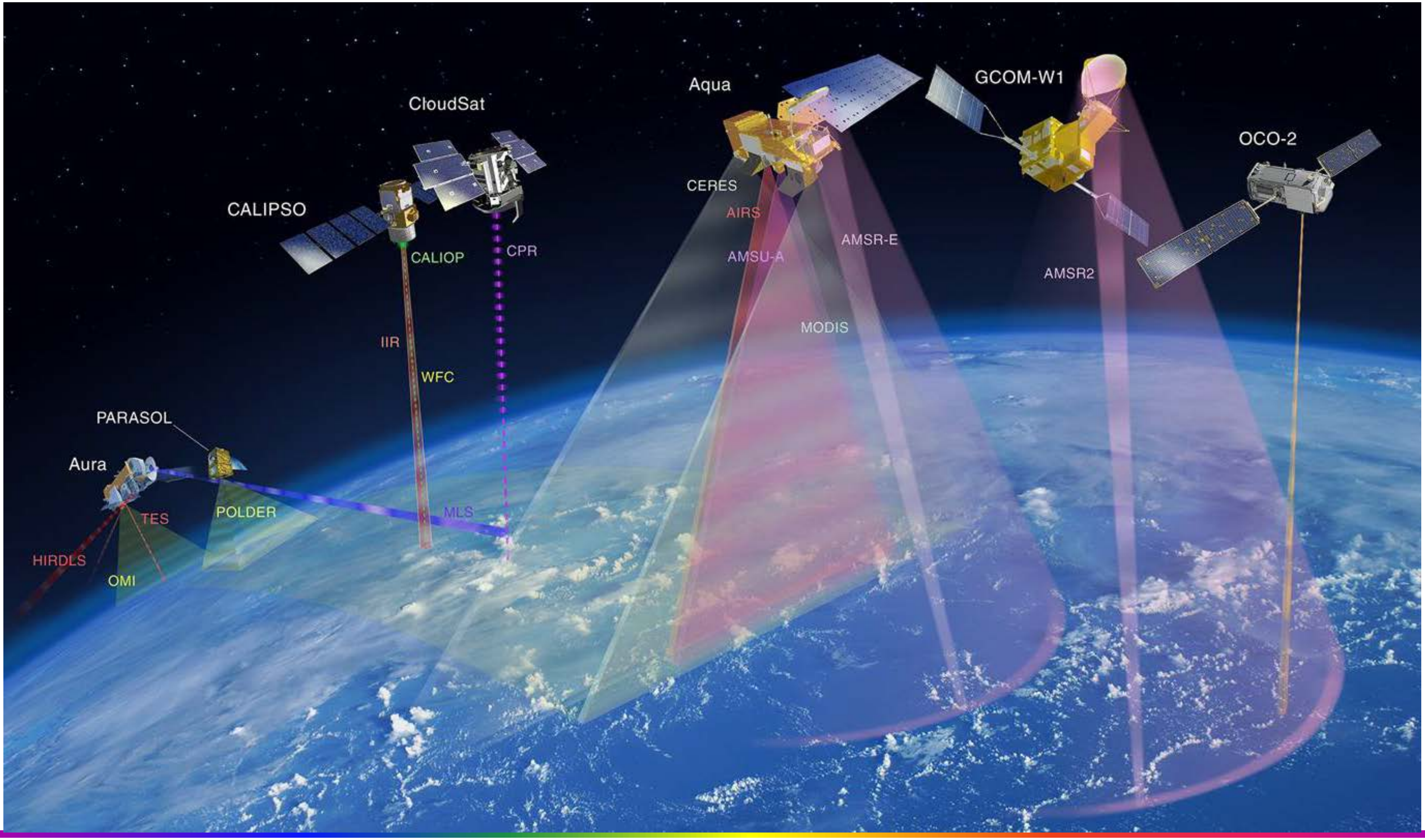
Launch Date Driven by Launch Service Provider

- No root cause identified for either OCO or Glory Taurus XL launch vehicle anomalies
- Competitive selection process for OCO-2 has commenced
- Please, no communications with prospective bidders until a selection is announced



A Couple of Possibilities for OCO-2

Flying in Formation in the A-Train



Conclusions

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO_2 and other greenhouse gases
  - These measurements will complement those from the existing ground-based greenhouse gas monitoring network with increased: spatial coverage and sampling density
- The principal challenge is the need for high precision (~0.3% or 1 ppm)
- GOSAT has provided a valuable pathfinder for analysis techniques
- OCO-2 is the first NASA mission designed to demonstrate the space-based measurement precision, coverage, and resolution needed to:
  - Quantify CO_2 emissions sources on the scale of individual states or countries
  - Find the natural "sinks" that are absorbing over half of the CO_2 emitted by human activities
  - Provide the data needed to assess greenhouse gas mitigation policies