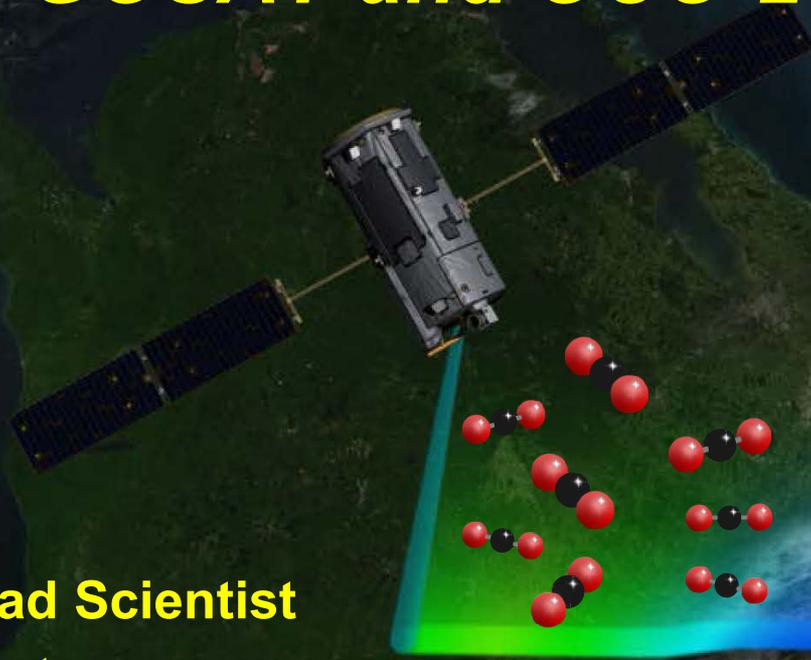




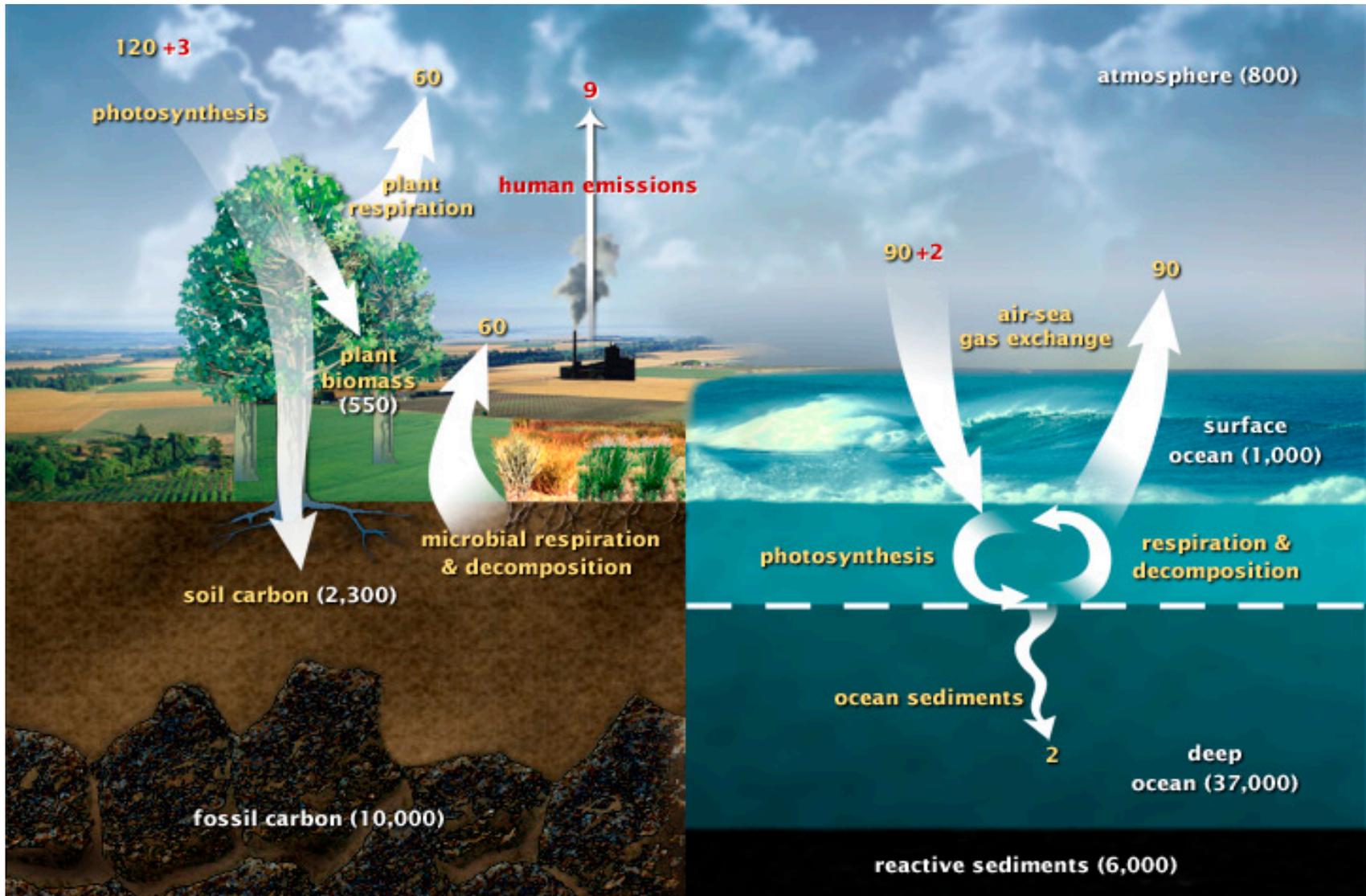
Monitoring the Carbon Cycle from Space: The GOSAT and OCO-2 Missions



David Crisp
ACOS and OCO-2 Lead Scientist
Jet Propulsion Laboratory,
California Institute of Technology
February 29, 2012

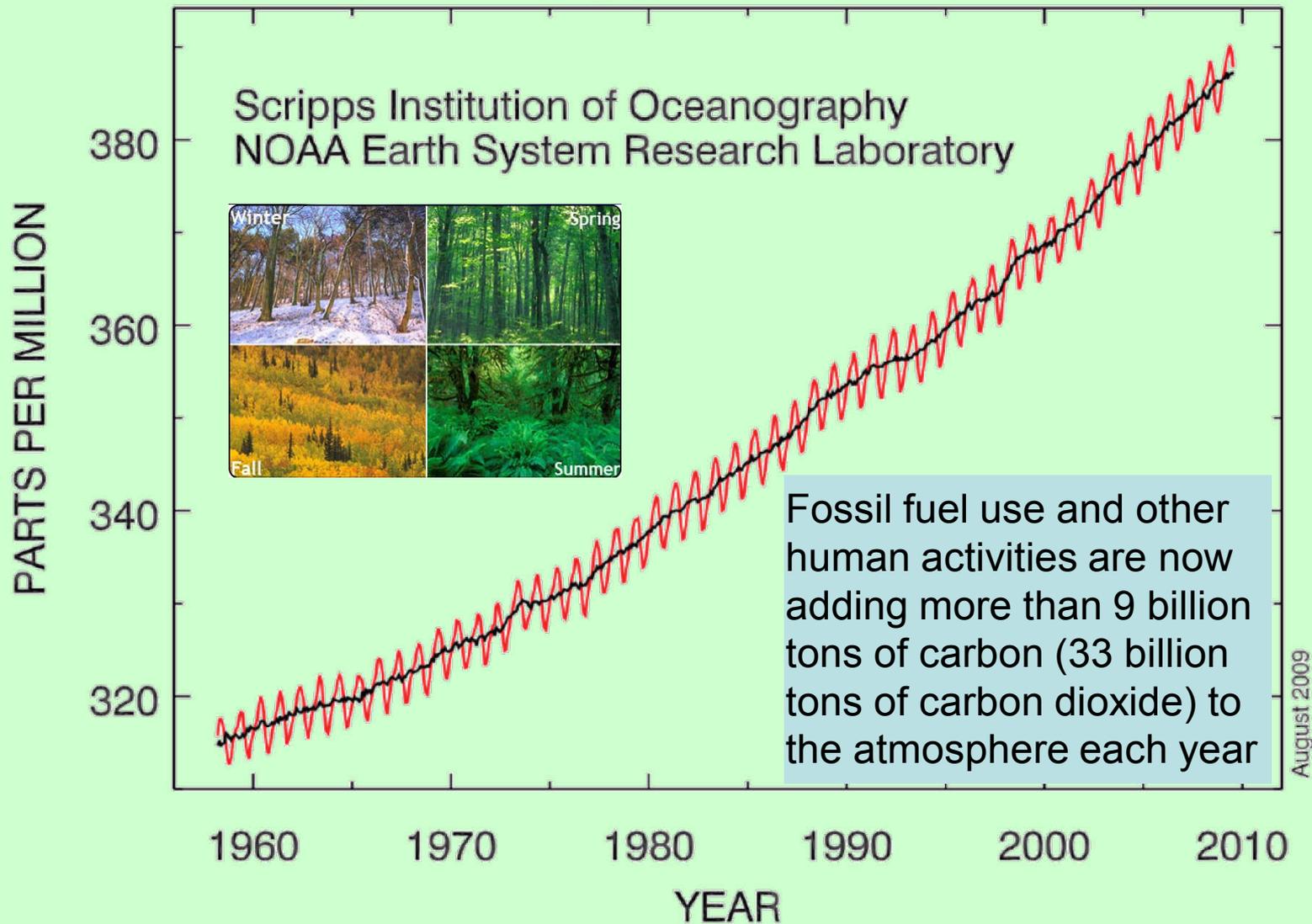


The Carbon Cycle



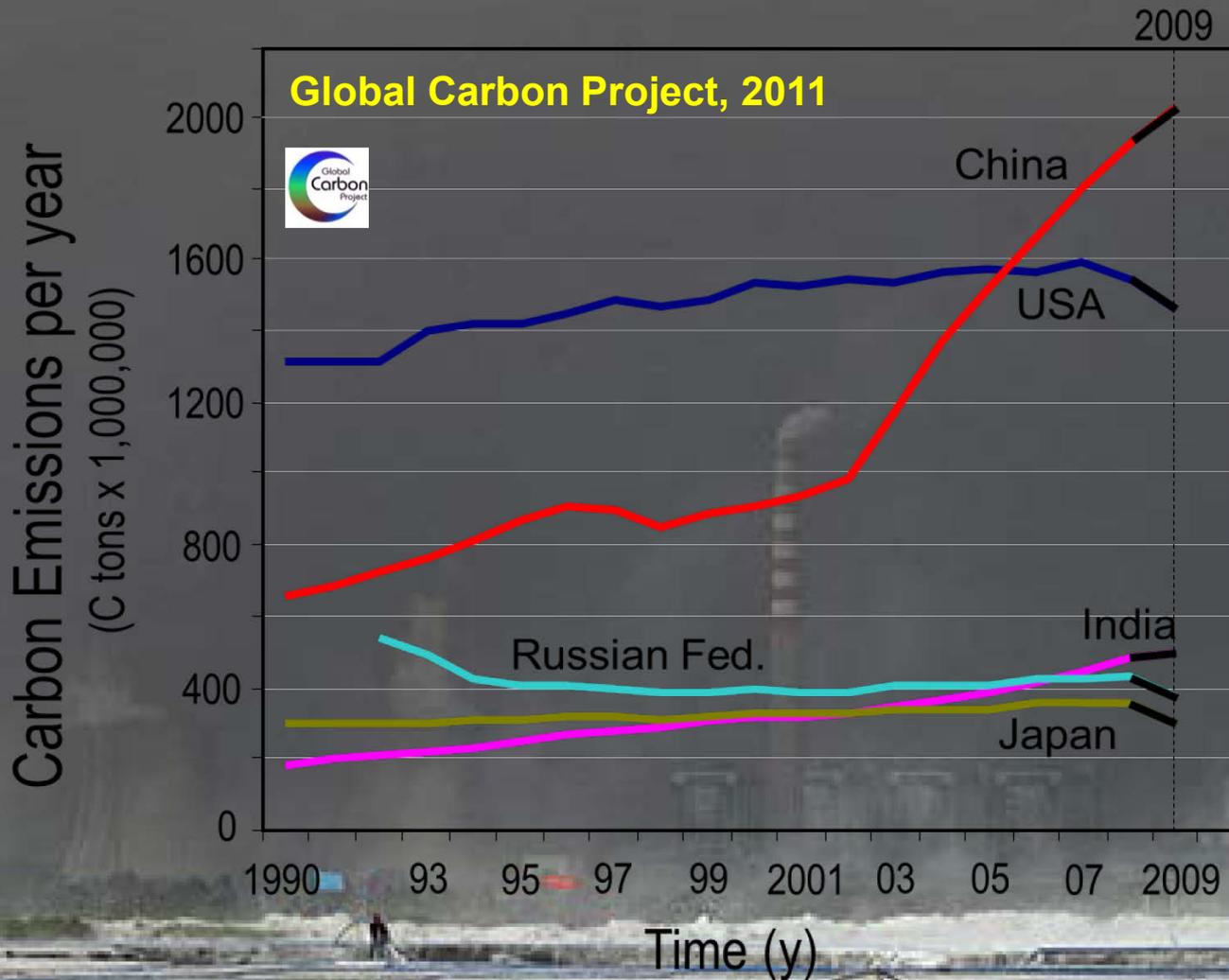


The Atmospheric Carbon Dioxide Record





Fossil Fuel CO₂ Emissions: Top Emitters



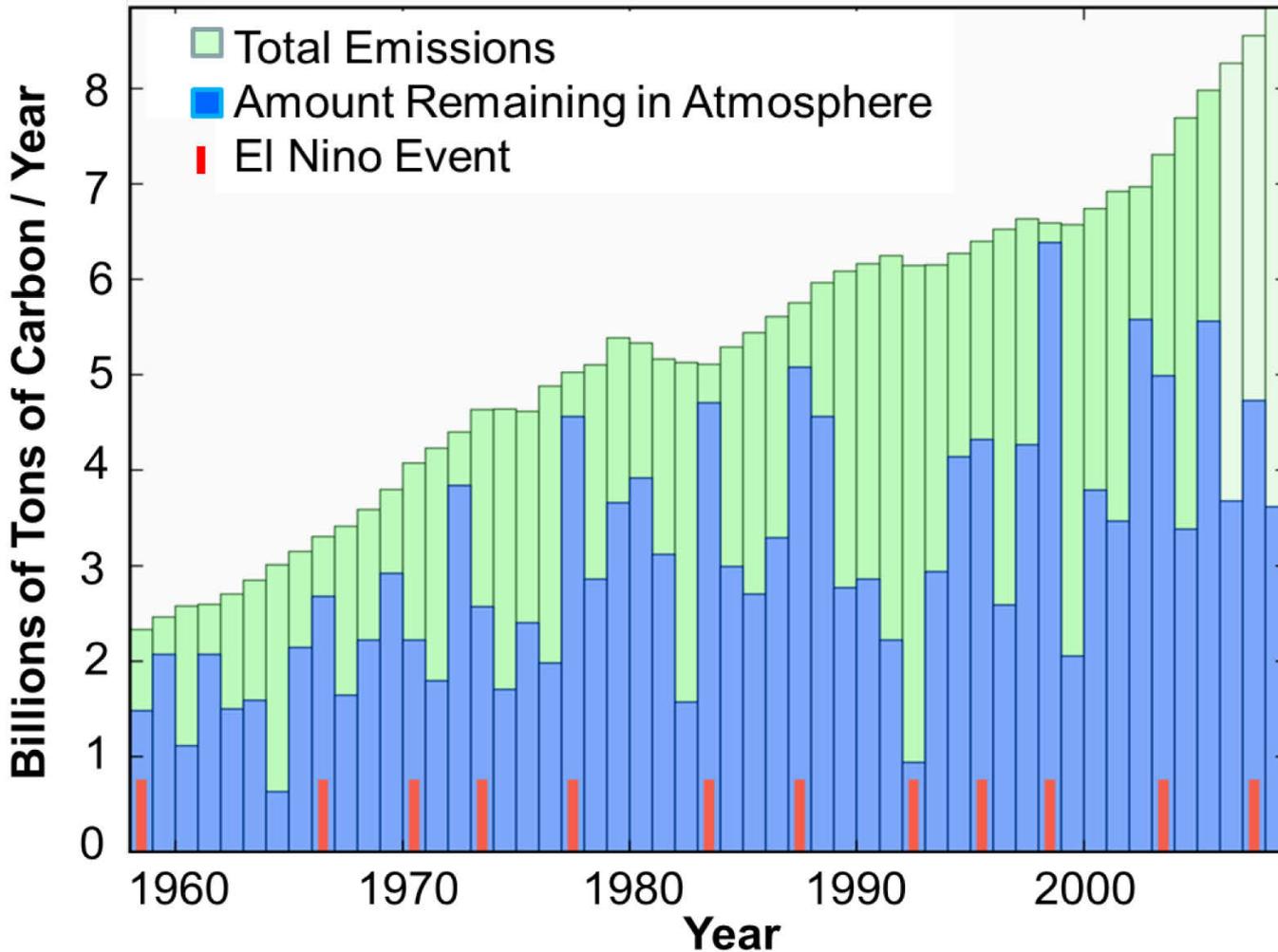
In recent years, the largest increases in fossil fuel emissions have occurred in developing countries.

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 Processes Regulate CO₂ Sinks?



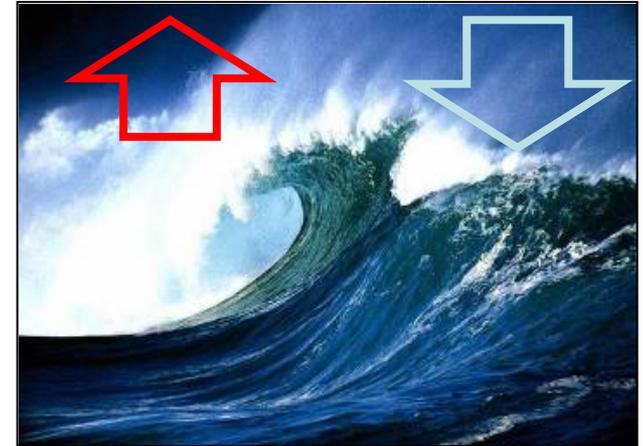
Why does the amount of CO₂ that stays in the atmosphere change so much from year to year?

We don't know.



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 CO₂?
 - Why does the sink strength vary dramatically from year to year?
 - Will the nature, location and strength of these CO₂ sinks change in the future?





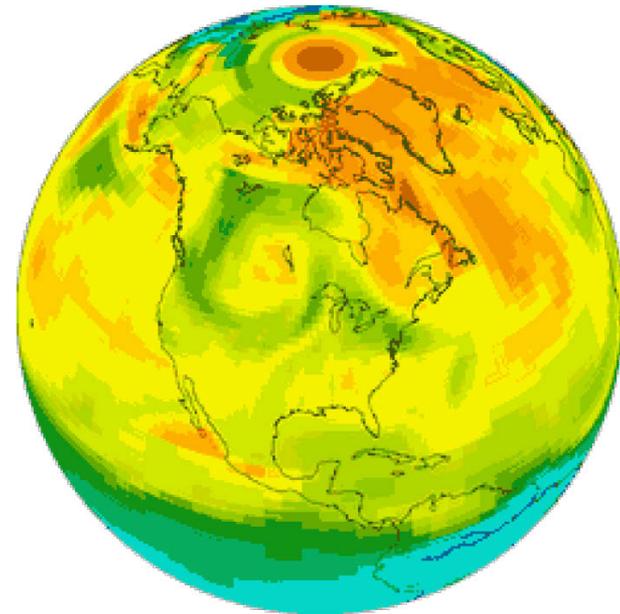
Global Measurements from Space are Essential for Monitoring Atmospheric CO₂

- 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



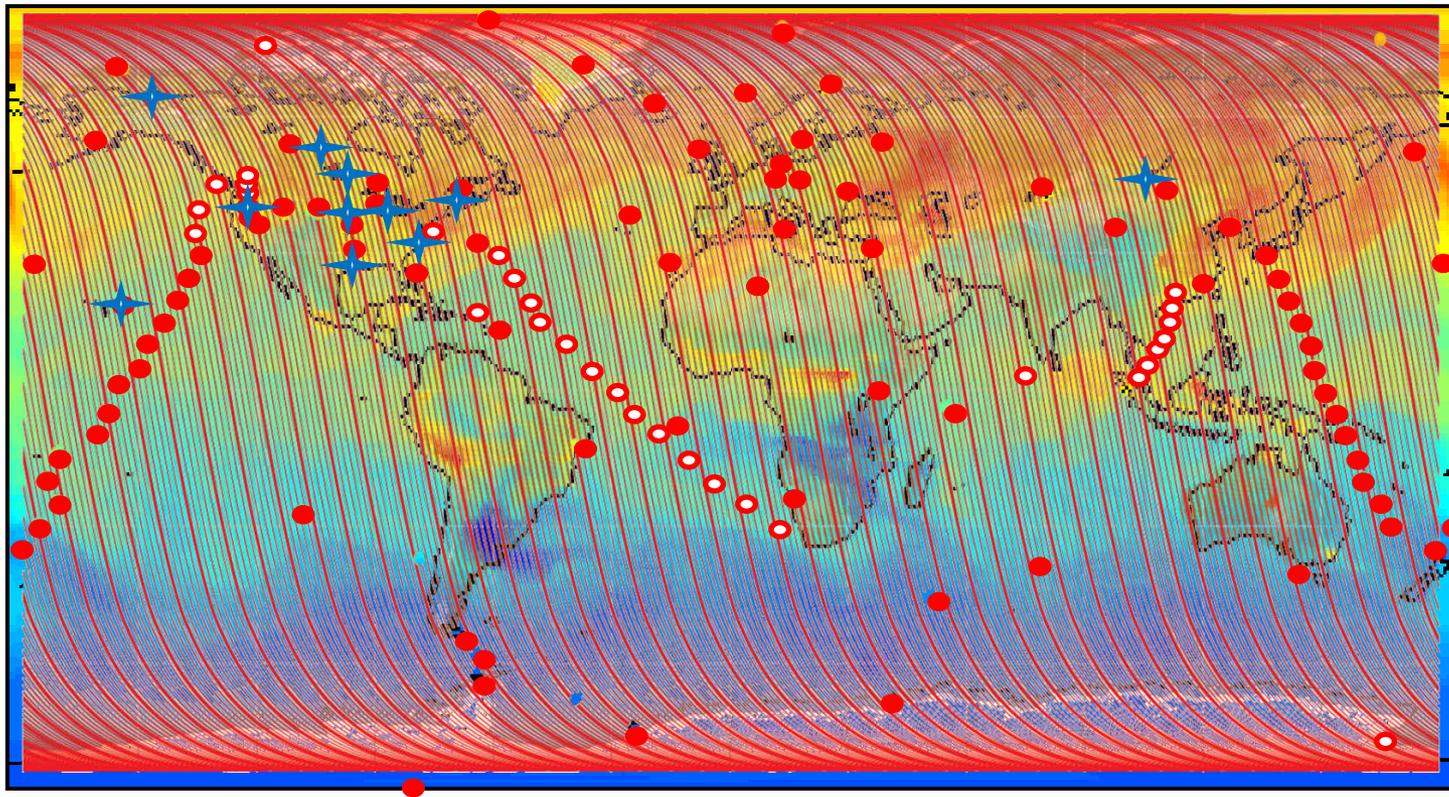
Plumes from medium-sized power plants (4 MtC/yr) elevate X_{CO_2} levels by ~2 ppm for 10's of km downwind [Yang and Fung, 2010].



These variations are superimposed on a background of “CO₂ weather”



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



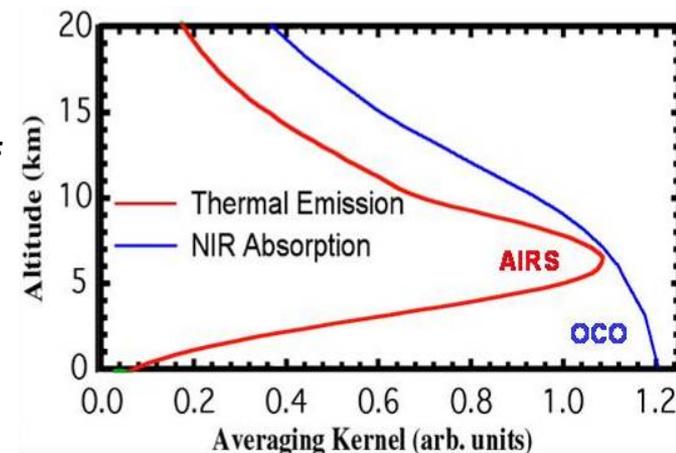
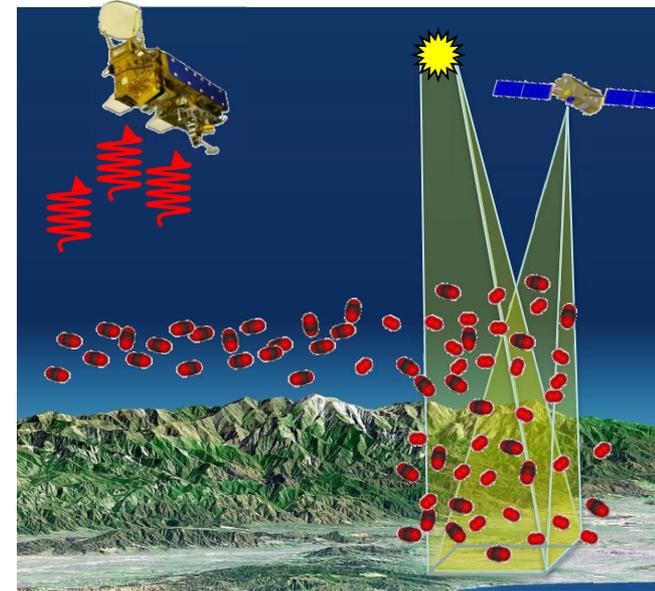
- Ground based measurements - greater precision and sensitivity to CO₂ near the surface, where sources and sinks are located.
- Space-based measurements – improve spatial coverage & resolution.
- Source/Sink models - assimilate space and ground-based data to provide global insight into CO₂ sources and sinks



Measuring CO₂: Synergy of Solar and Thermal

Atmospheric CO₂ can be inferred from both thermal IR or solar remote sensing data

- Thermal IR instruments (AIRS, TES, IASI) measure CO₂ above the mid-troposphere
 - Directly measure the greenhouse forcing by CO₂ in the present climate
 - Provides limited information on sources/sinks
- Solar NIR instruments (GOSAT, OCO-2) measure the total CO₂ column
 - Most sensitive to surface fluxes
 - Provides insight needed to predict future rates of CO₂ buildup and climate impacts
- Combining solar NIR and thermal IR measurements could provide insight into vertical atmospheric transport of CO₂





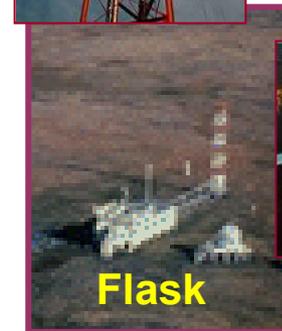
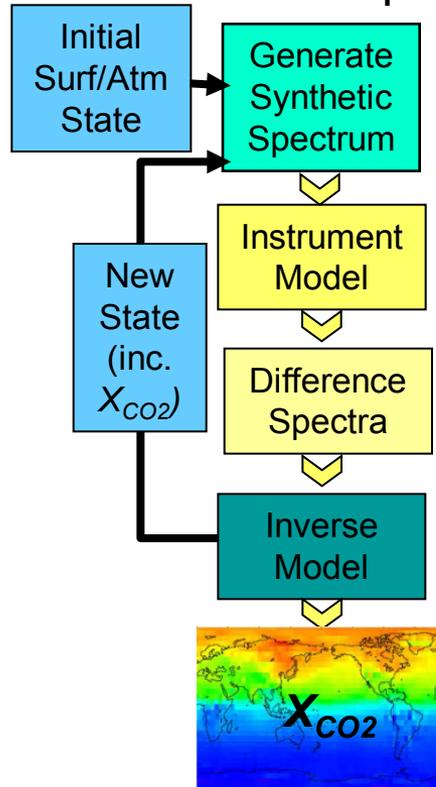
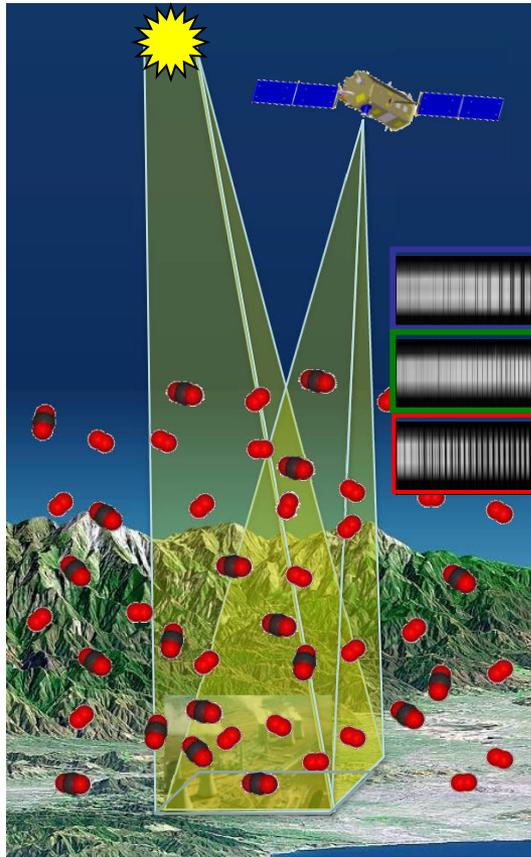
Measuring CO₂ using Reflected Sunlight

- Record spectra of CO₂ and O₂ absorption in reflected sunlight



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

- Validate measurements to ensure X_{CO2} accuracy





Driving Requirements for Space Based CO₂ Measurements

Requirements that drive the design of space-based CO₂ missions include:

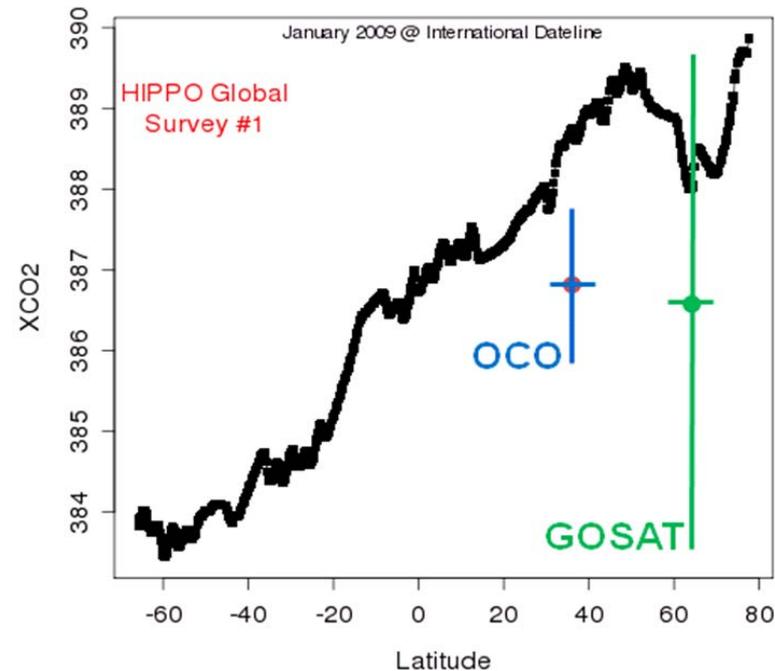
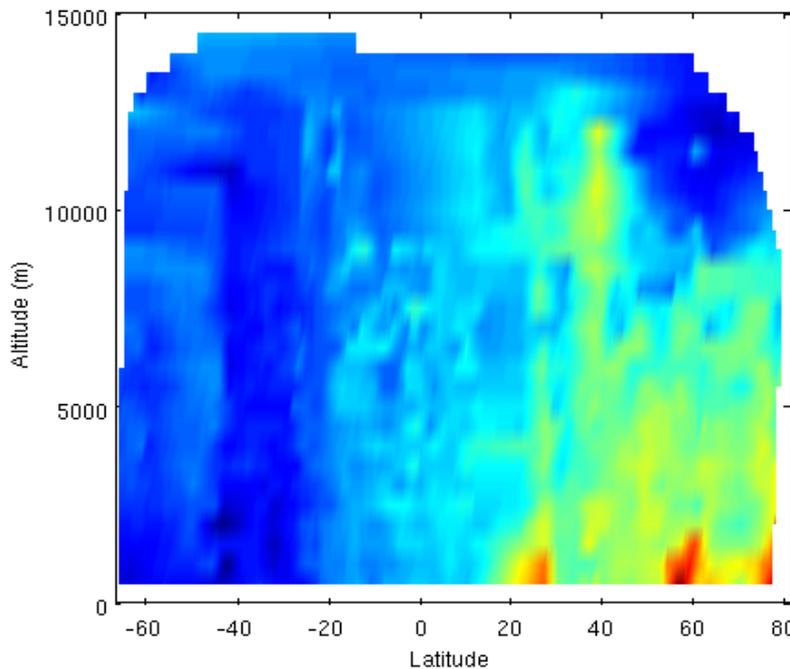
- Sensitivity (Precision)
 - Spatial variations in X_{CO_2} are small (< 2%)
- Accuracy
 - Small biases can introduce large regional-scale flux errors
- Spatial coverage
 - Ocean and land
 - Limited to clear sky
- Spatial resolution
 - Adequate to resolve spatial gradients
- Lifetime
 - Atmospheric CO₂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



High precision is Essential for Monitoring CO₂ Sources and Sinks from Space

- CO₂ sources and sinks must be inferred from small spatial variations in the (390 ±5 ppm) background CO₂ distribution
- The largest CO₂ variations occur near surface
- Space based NIR observations constrain column averaged CO₂, 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]

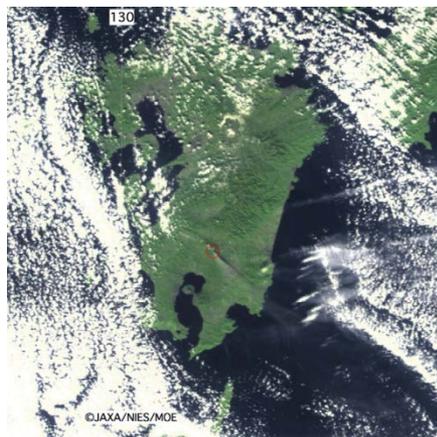
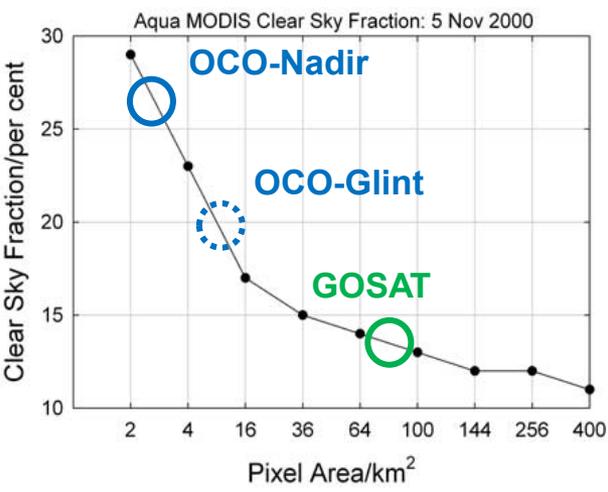
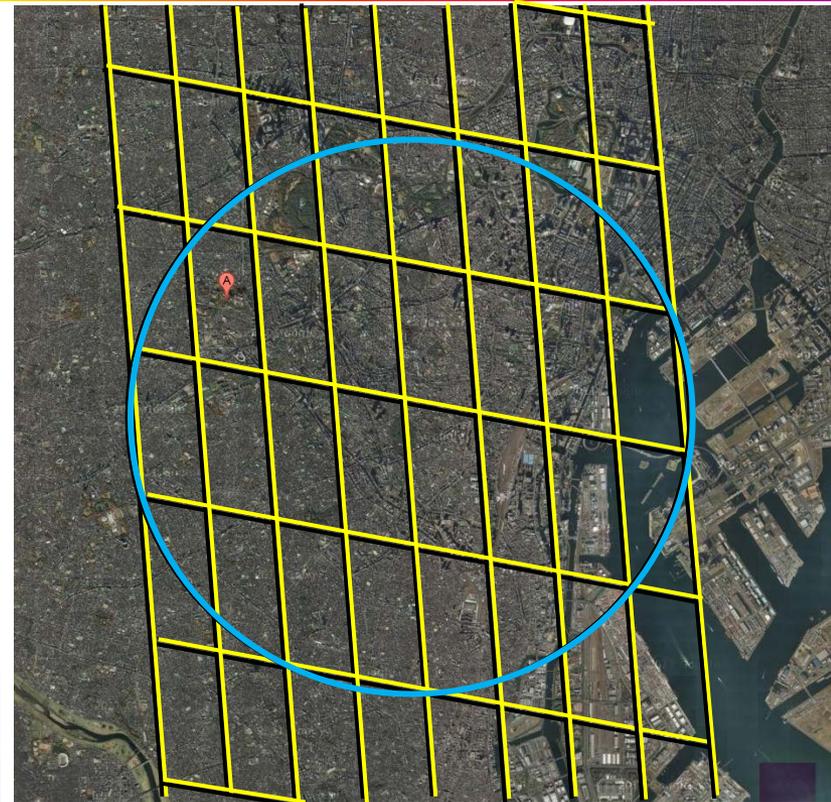




Spatial Resolution

A Small Footprint:

- Increases sensitivity to CO₂ point sources
 - Minimum measurable CO₂ flux is inversely proportional to footprint size
- Increases probability of recording cloud free soundings in partially cloudy regions
- Reduces biases associated with optical pathlength uncertainties over rough topography





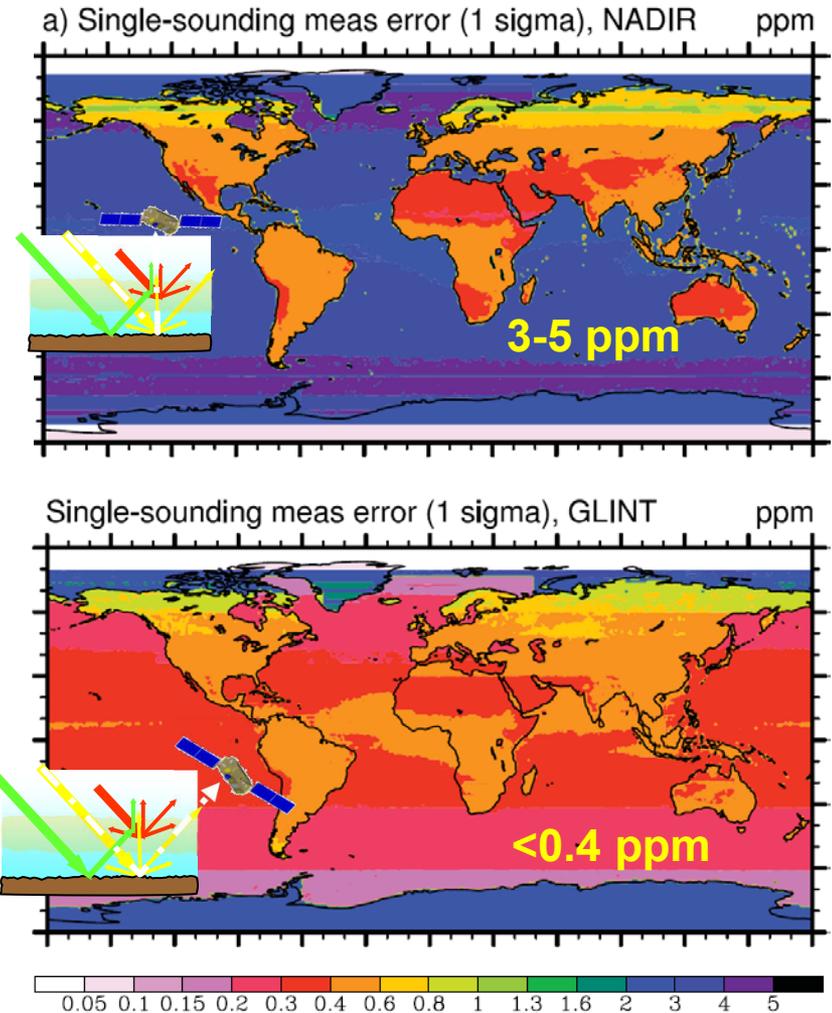
Coverage: Obtaining Precise Measurements over Oceans as well as Continents

- The ocean covers 70% of the Earth and absorbs/emits 10 times more CO₂ than all human activities combined
- Coverage of the oceans is essential to minimize errors from CO₂ transport in and out of the observed domain

Near IR solar measurements of CO₂ over the ocean are challenging

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

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

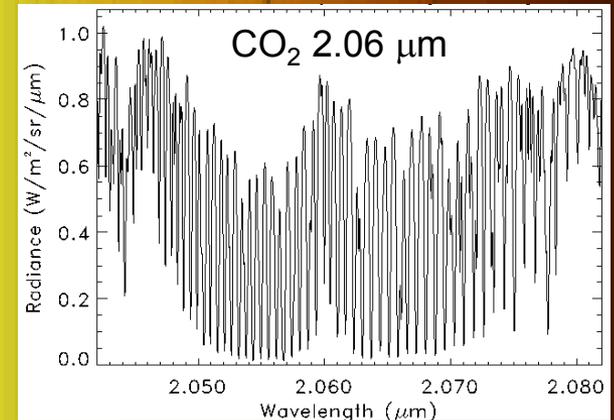
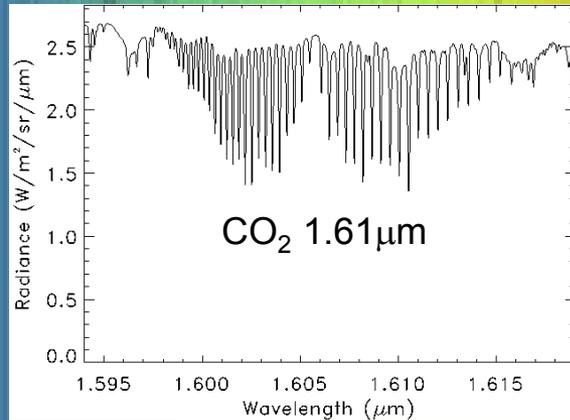
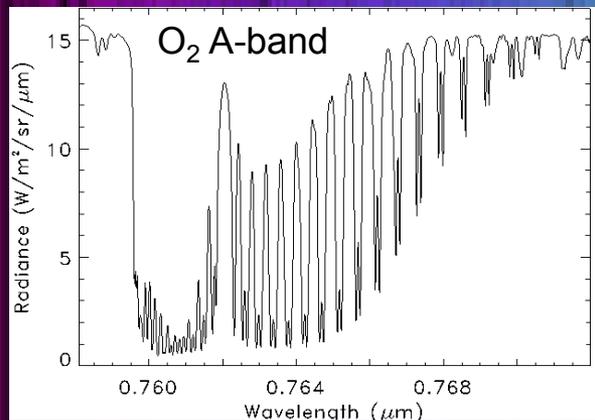
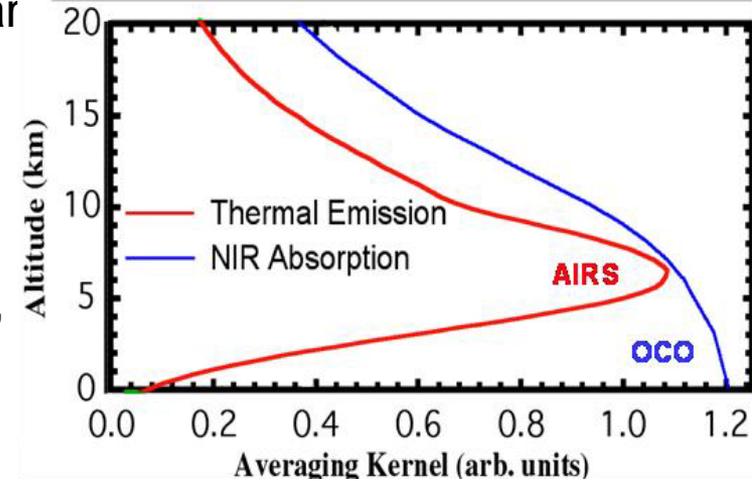


OCO single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].



Making Precise CO₂ Measurements from Space

- High resolution spectra of reflected sunlight in near IR CO₂ and O₂ bands used to retrieve the column average CO₂ dry air mole fraction, X_{CO_2}
 - 1.61 μm CO₂ band: Column CO₂
 - 2.06 μm CO₂ band: Column CO₂, Aerosols
 - 0.76 μm O₂ A-band: *Surface pressure*, clouds, aerosols
- Why high spectral resolution?
 - Enhances sensitivity, minimizes biases



Clouds/Aerosols, Surface Pressure

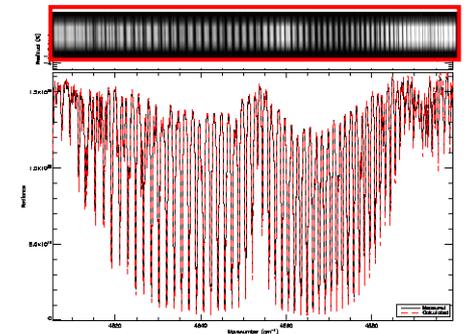
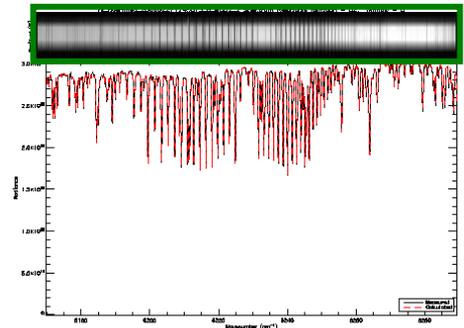
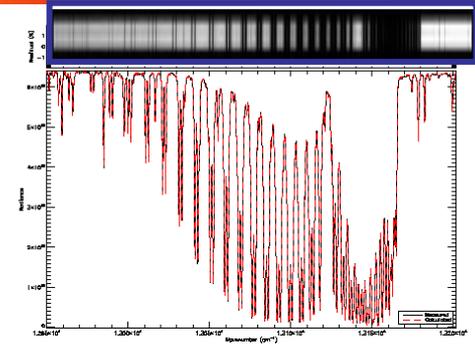
Column CO₂

Clouds/Aerosols, H₂O, Temperature



Information Content of Spectra

- O₂ A-band at 760 nm provides constraints on surface pressure, optical path length, and thin cloud/aerosol distribution
- Absorption in weak CO₂ band at 1610 nm is almost linearly dependent on CO₂ column
- Strong CO₂ band at 2060 nm
 - Somewhat less sensitive to the CO₂ 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

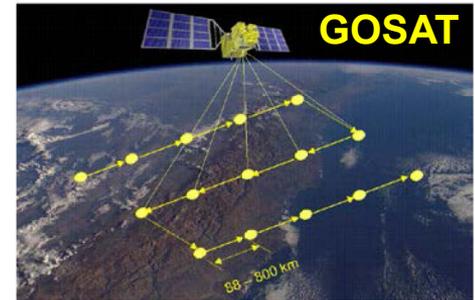




Remote Sensing of CO₂ using Reflected Sunlight: GOSAT and OCO/OCO-2

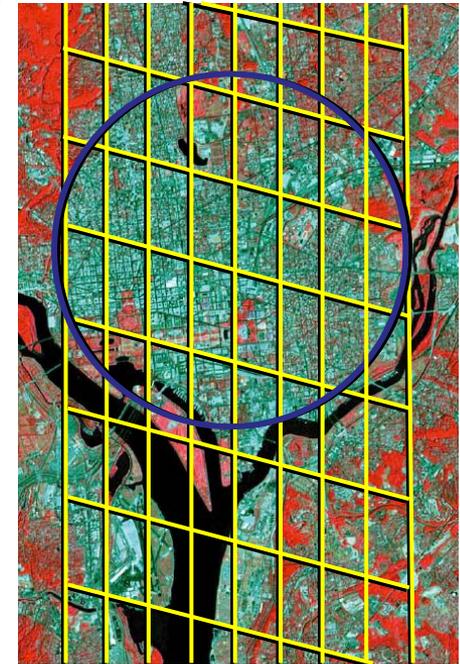
- **GOSAT (2009)**

- Optimized for spectral and spatial coverage
- Collects 10,000 soundings every day
 - 10-15% are sufficiently cloud free for CO₂ & CH₄ 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 10⁶ 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





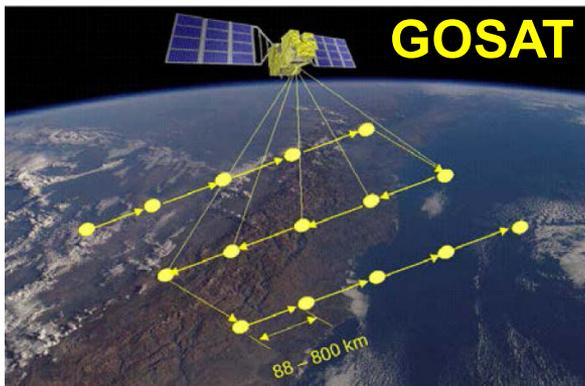
GOSAT-OCO Collaboration

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

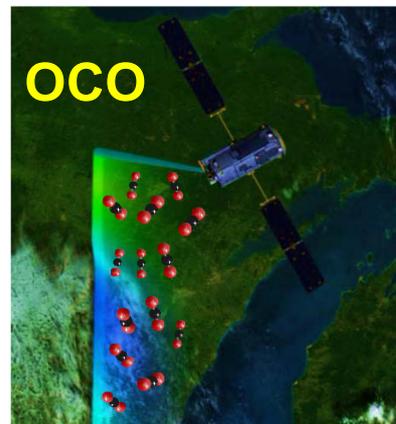
- Cross calibrate the OCO instrument and TANSO-FTS
- Cross validate OCO and GOSAT X_{CO_2} retrievals against a common standard

The primary objectives of this partnership were to:

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



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

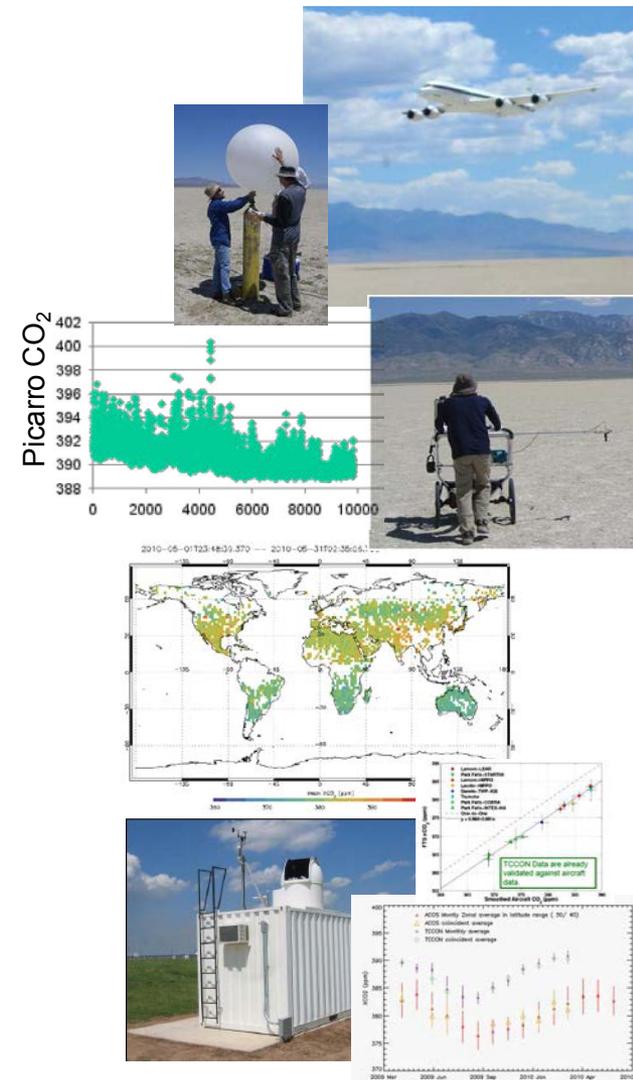


OCO was lost a month later when its launch system failed



The ACOS/GOSAT Collaboration

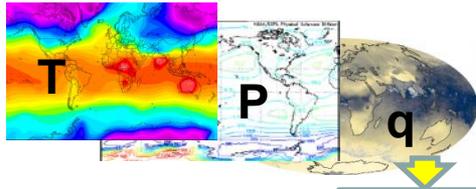
- Immediately after the loss of OCO, the GOSAT Project manager invited the OCO Team to participate in GOSAT data analysis
- The ACOS team is collaborating closely with the GOSAT teams at JAXA and NIES to:
 - Conduct vicarious calibration campaigns in Railroad Valley, Nevada, U.S.A.
 - Retrieve X_{CO_2}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



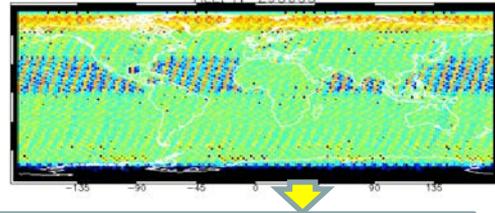


Retrieving X_{CO_2} from GOSAT Spectra

Interpolated Meteorology

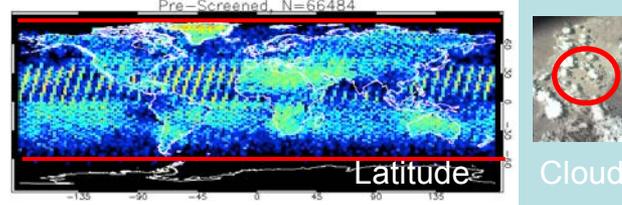


Level 1B Data



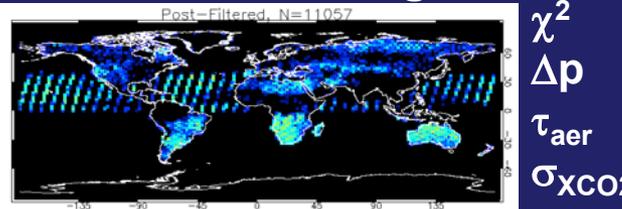
- Evolved from the OCO Retrieval Algorithm
 - Optimal Estimation
 - “Full Physics”
 - 3-band (ABO2, WCO2, SCO2)

Pre-Processing Filter

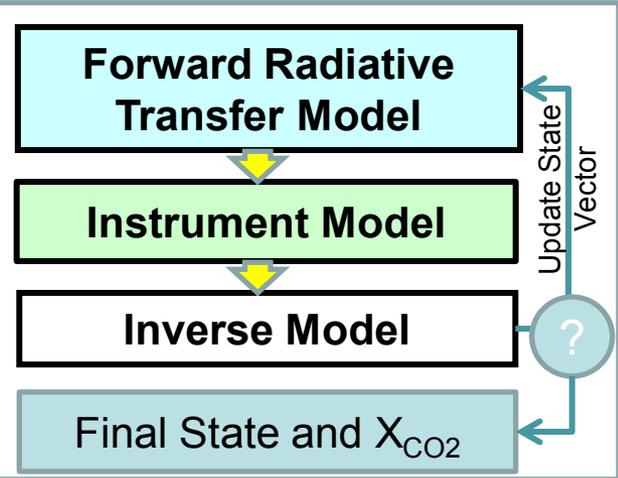


X_{CO_2} Retrieval Algorithm

Post-Processing Filter

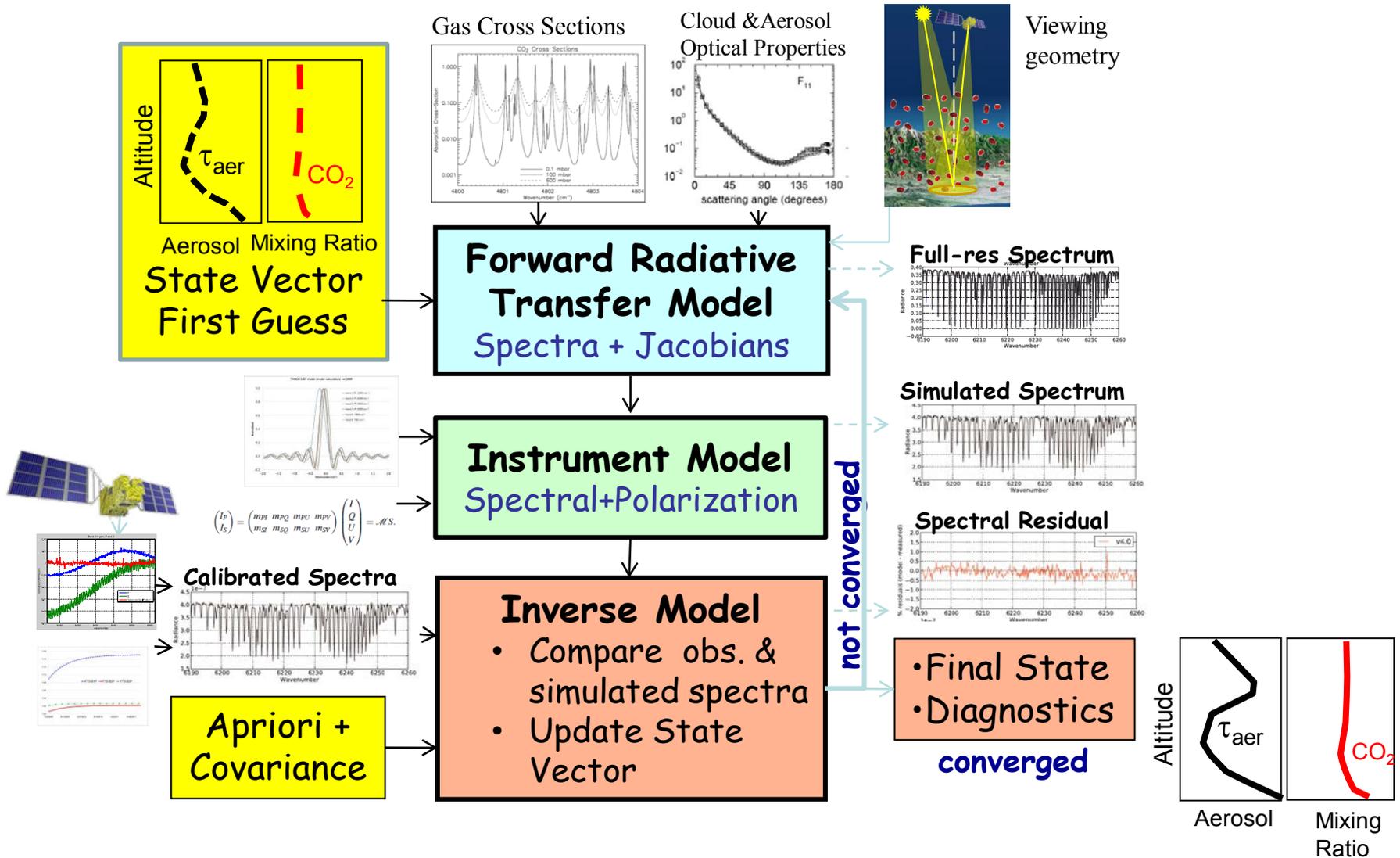


State Vector
CO ₂ profile (full)
H ₂ O profile (scale factor)
Temperature profile (offset)
AOD, Height (4 types)
Surface Pressure
Albedo (Mean, Slope)
Wavelength Shift
Band 1 Zero-Level Offset (GOSAT only)



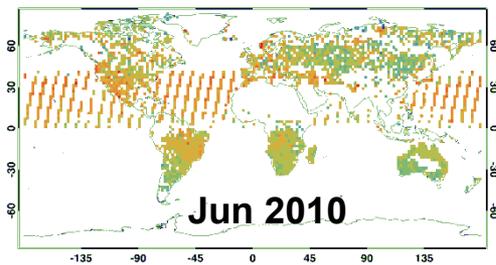
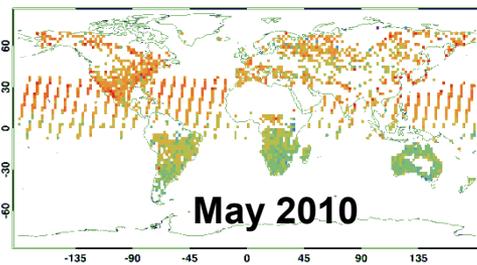
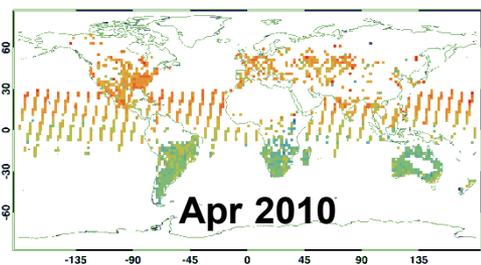
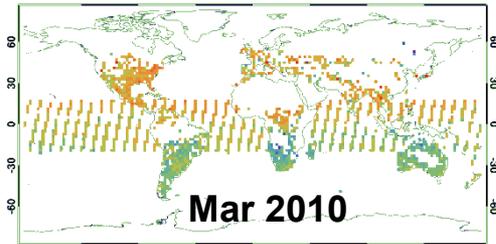
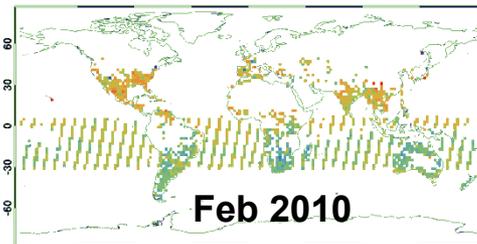
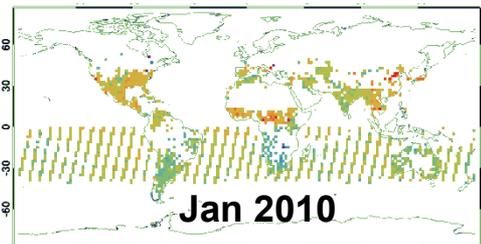
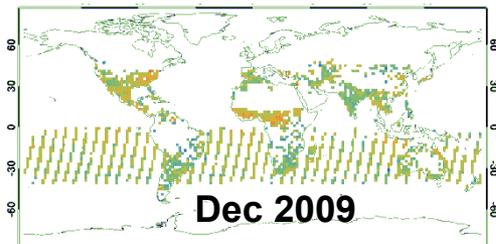
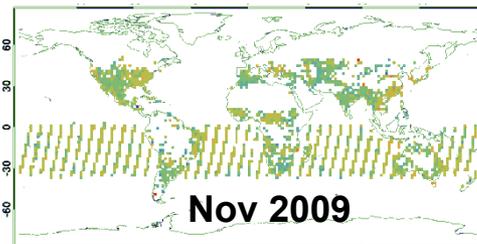
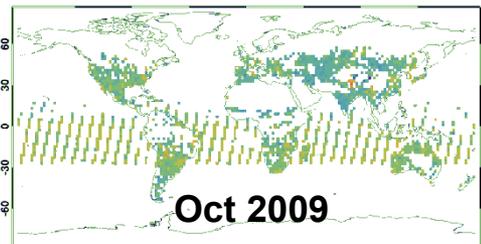
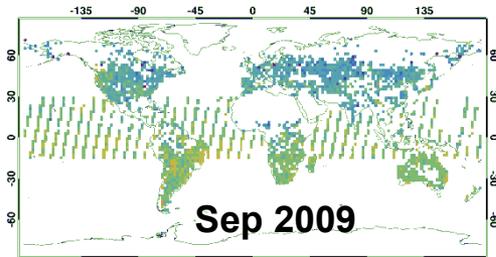
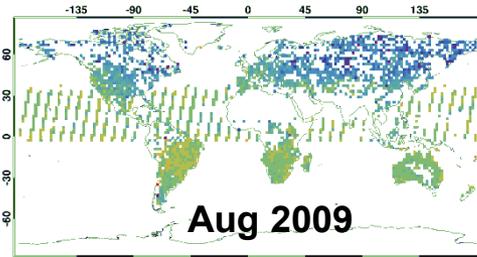
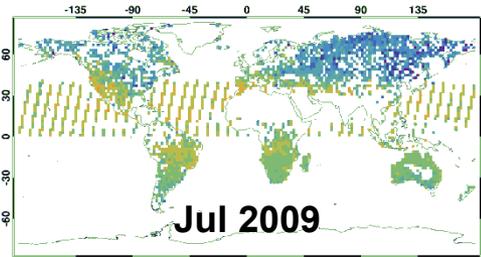


The ACOS X_{CO_2} Retrieval Algorithm



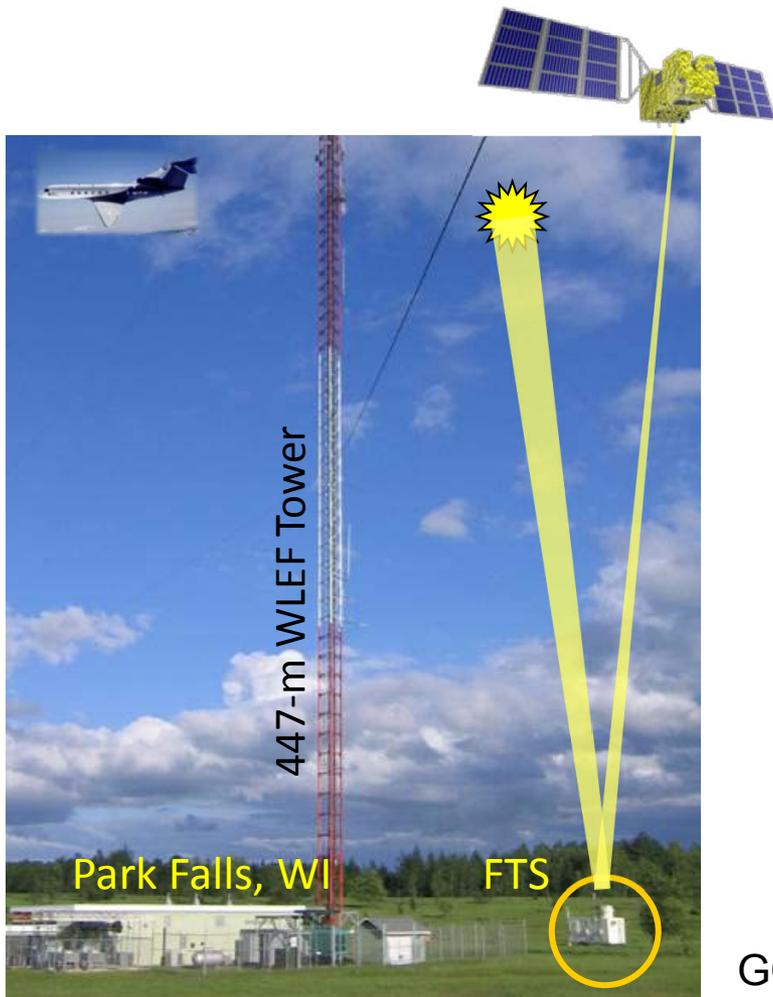


ACOS GOSAT X_{CO_2} Seasonal Cycle (H-Gain Only)

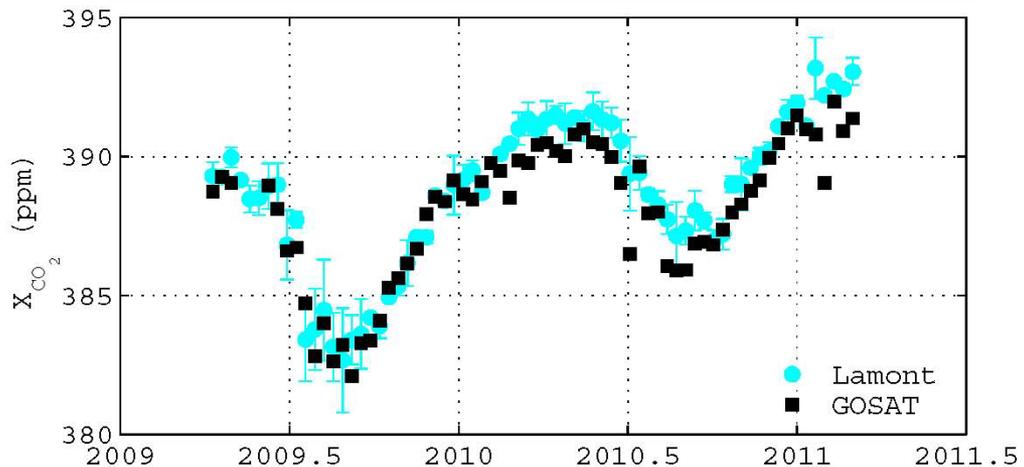
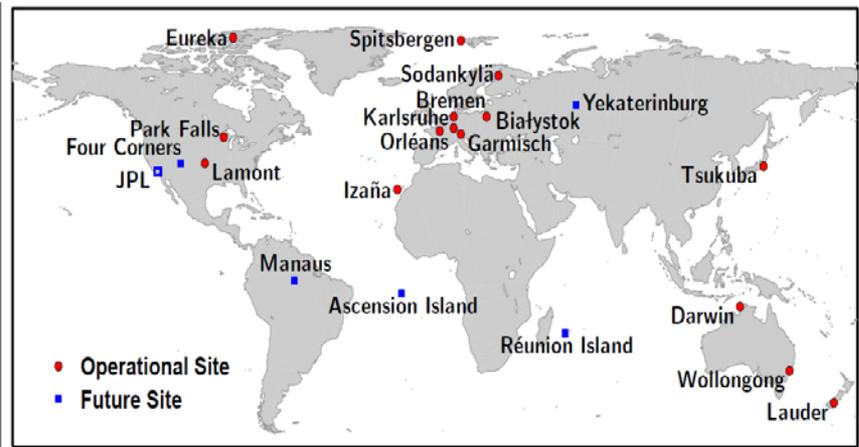




Validation of GOSAT Products against TCCON Reduces Regional Scale Bias



Near-simultaneous observations are acquired over TCCON station.



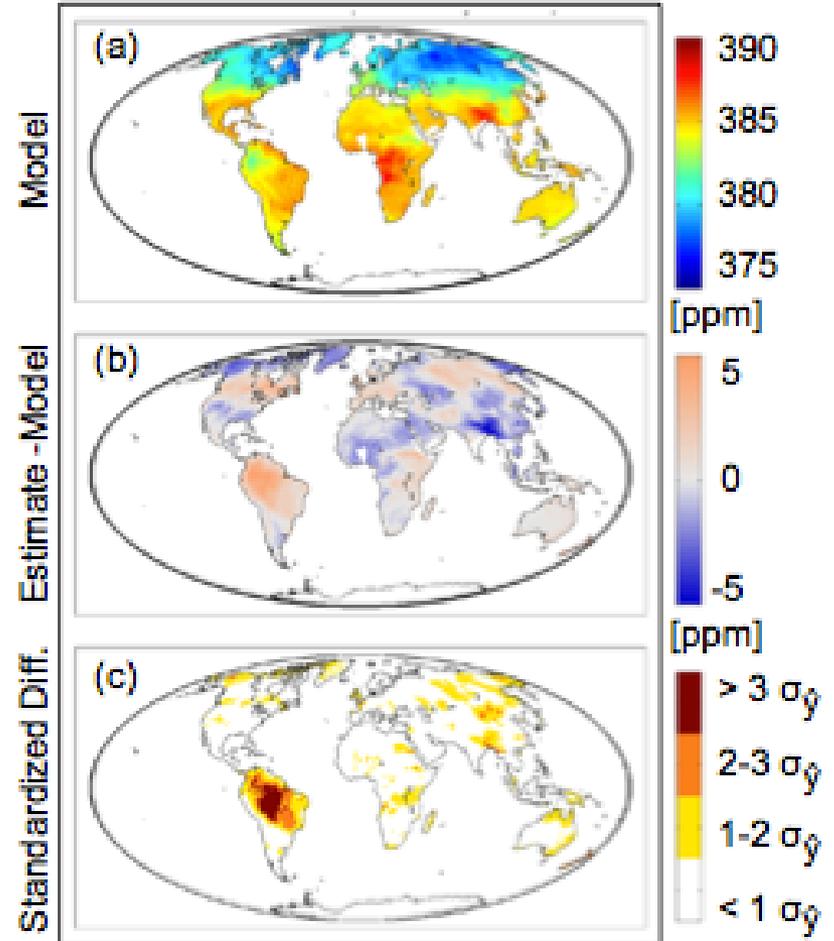
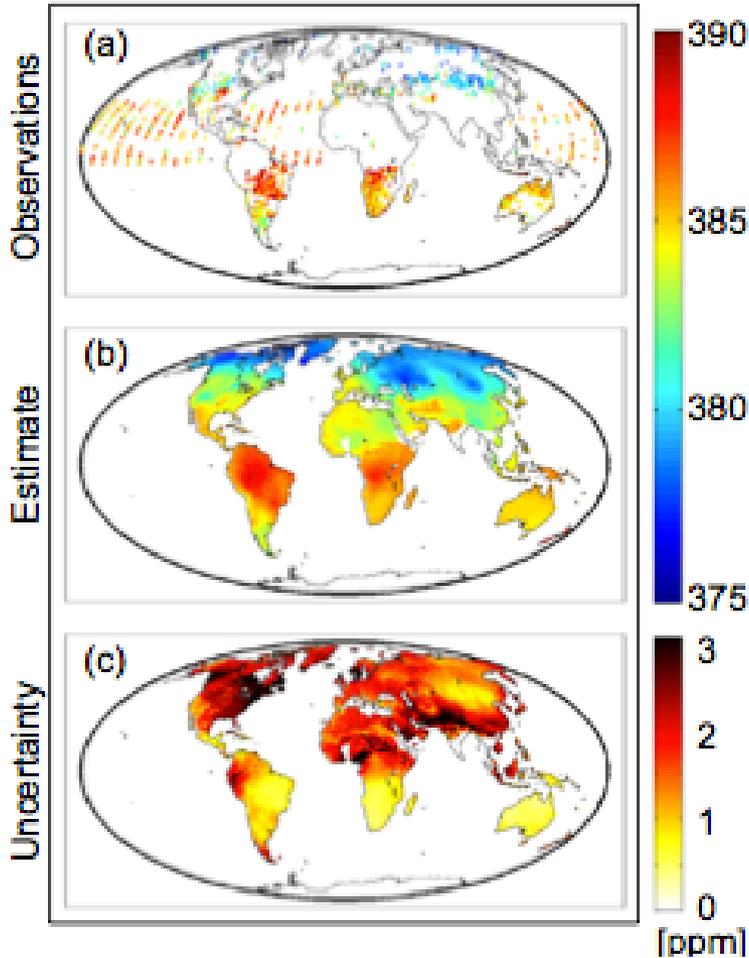
GOSAT X_{CO_2} retrievals are compared with those from the ground based Total Carbon Column Observing Network (TCCON) to verify their accuracy



Comparing GOSAT Gap-Filled Maps with Models

August 7-12, 2009

August 7-12, 2009

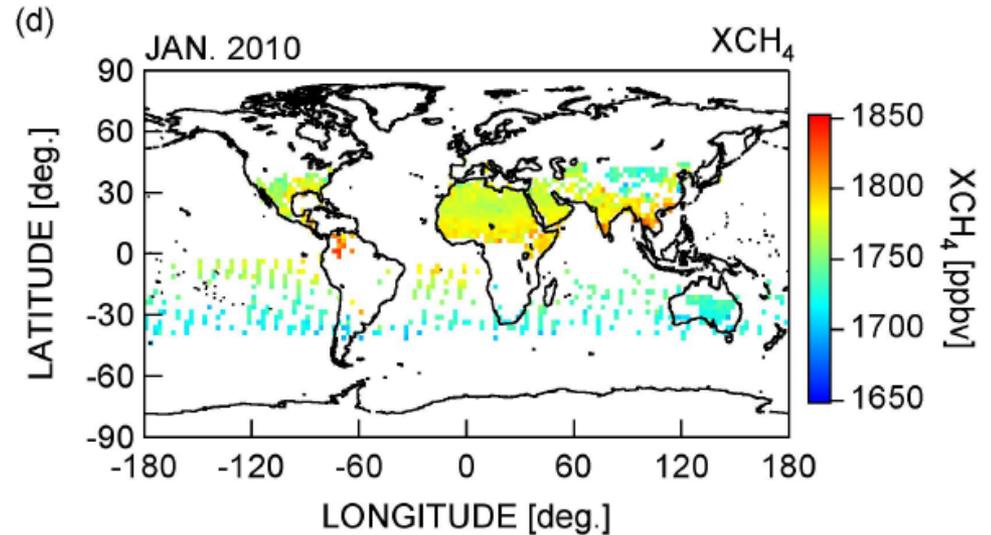
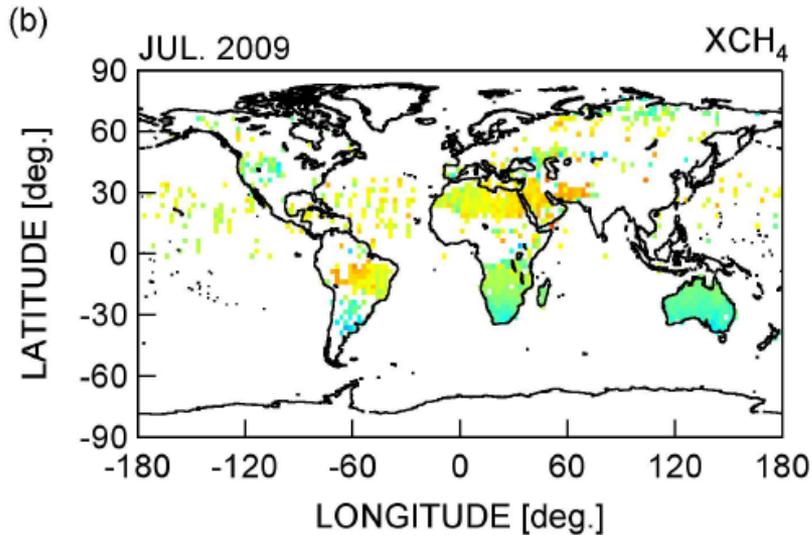


Hammerling, Michalak, O'Dell, & Kawa (GRL, under review)



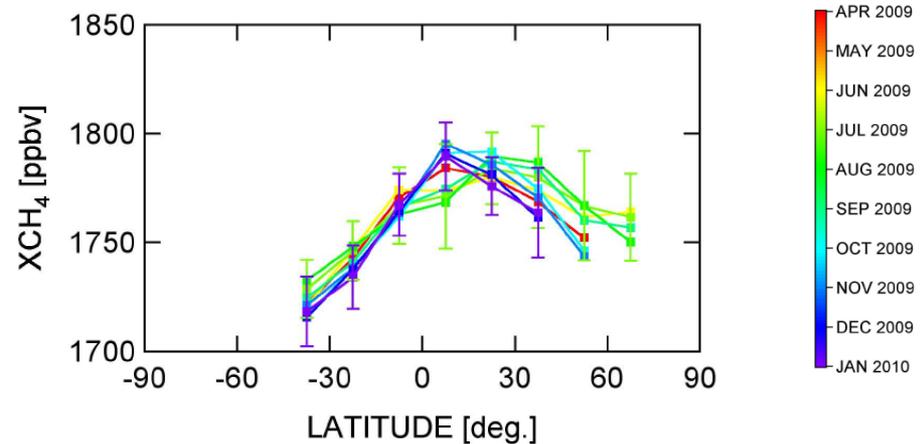
GOSAT Methane Retrievals

Yoshida et al. GOSAT CH₄ Retrievals, 2011



Monthly-average X_{CH_4} for July 2009 and January 2010 within $2.5^\circ \times 2.5^\circ$ grid boxes.

GOSAT observations are also being used to retrieve global maps of the column averaged methane dry air mole fraction, X_{CH_4} , the second most abundant atmospheric carbon species.

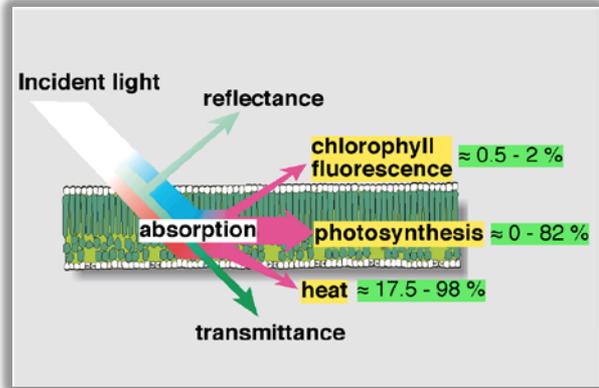


Latitude Distribution of zonal mean X_{CH_4} .



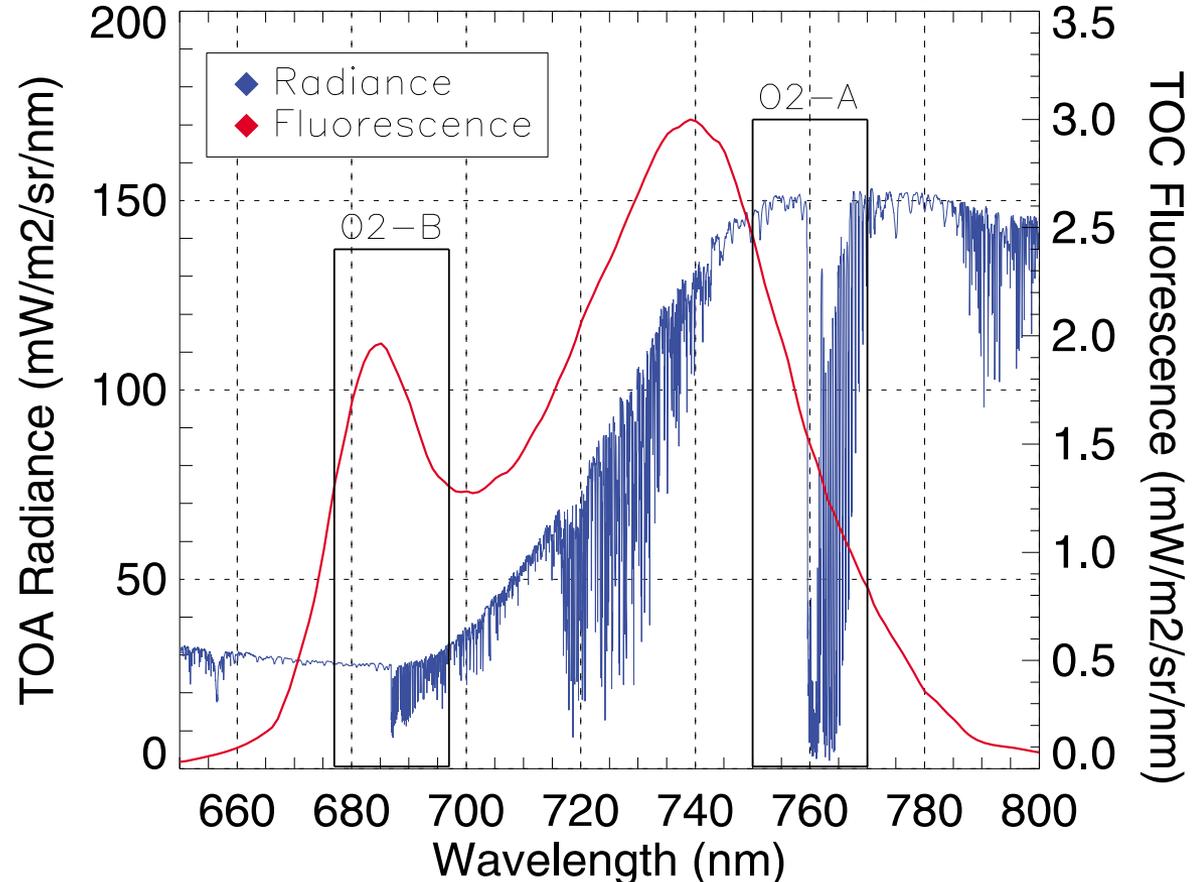
New Carbon Cycle Products: Chlorophyll Fluorescence

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 CO₂ uptake by the plant



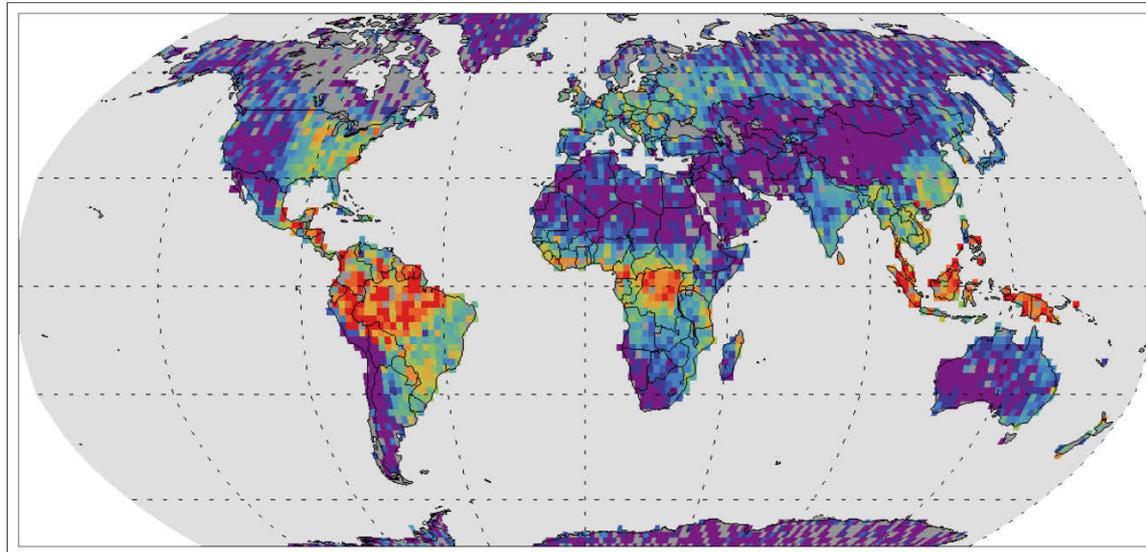
Chlorophyll fluorescence can be quantified by monitoring the filling of solar Fraunhofer lines in the GOSAT O₂ A-band channel.



Global Maps of Chlorophyll Fluorescence from GOSAT Measurements

Courtesy of C. Frankenberg et al. 2011.

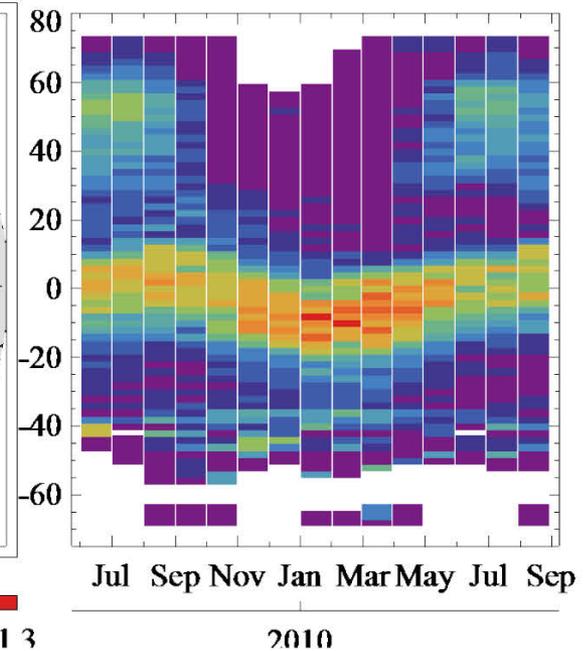
A Chlorophyll a fluorescence at 755 nm, June 2009 through May 2010 average



$F_s / (\text{W m}^{-2} \text{ micron}^{-1} \text{ sr}^{-1})$

00 01 02 03 04 05 06 07 08 09 10 11 12 13

B Timeseries

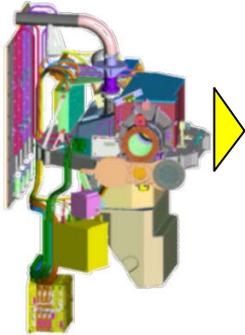


- **The Good News:** Global maps of chlorophyll fluorescence from GOSAT observations are providing new tools for studying the global carbon cycle.
- **The Bad News:** Neglecting chlorophyll fluorescence can introduce biases in space based X_{CO_2} retrievals that use O_2 A-band to constrain the optical path



The Next Step: The OCO-2 Mission

3-Channel Spectrometer (JPL)



Dedicated Spacecraft bus (OSC)



Dedicated Launch Vehicle



Mission Operations (OSC)



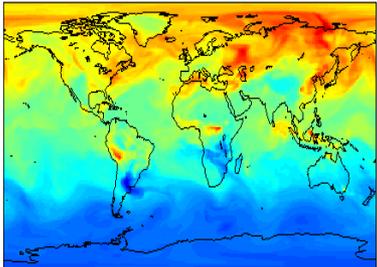
Formation Flying as part of the A-Train Constellation



NASA NEN (GSFC) and SN (TDRSS)



Products Delivered to the NASA Archive



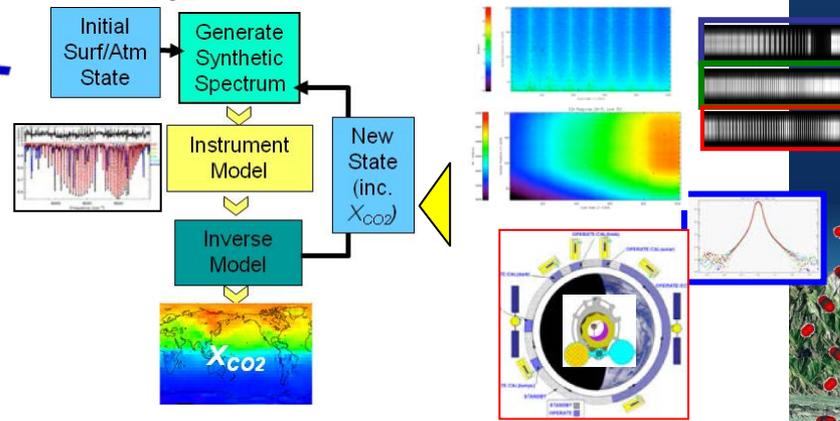
Validation Program



Science Data Operations Center (JPL)

L2 X_{CO2} Retrieval

Calibrate Data



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

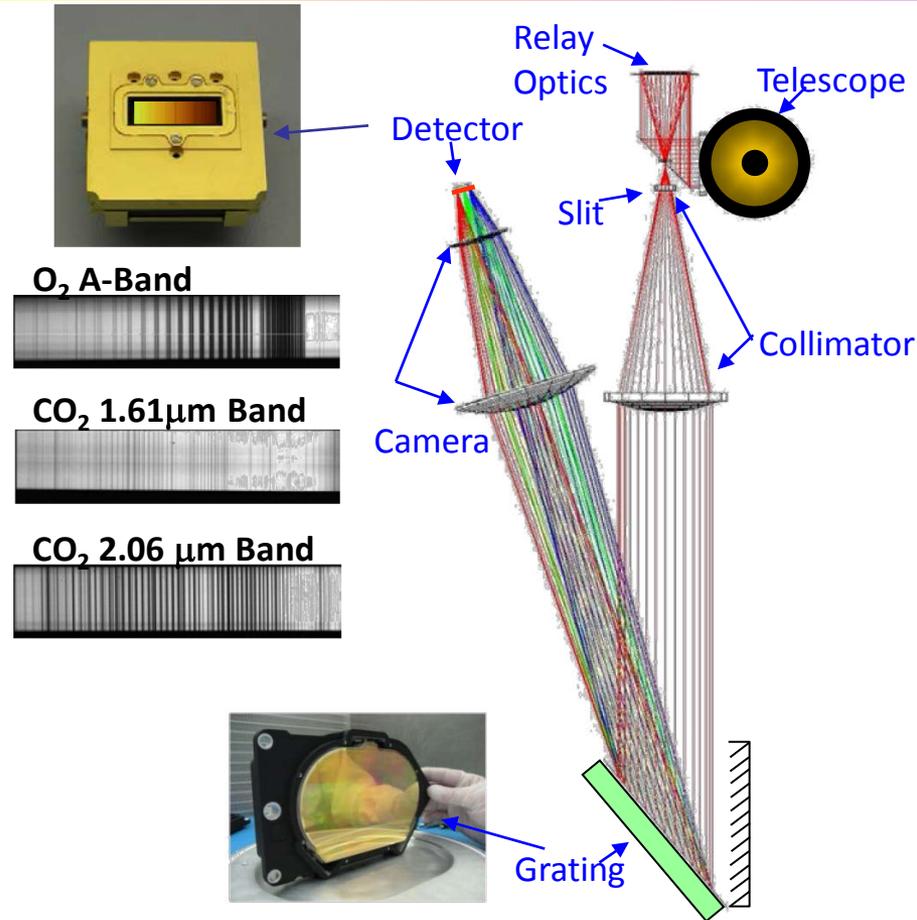


The OCO Instrument – Optimized for Sensitivity

- 3 co-bore-sighted, high resolution, imaging grating spectrometers
 - O₂ 0.765 μm A-band
 - CO₂ 1.61 μm band
 - CO₂ 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 stray light anomalies found in OCO pre-flight testing
- New cryocooler replaces obsolete unit

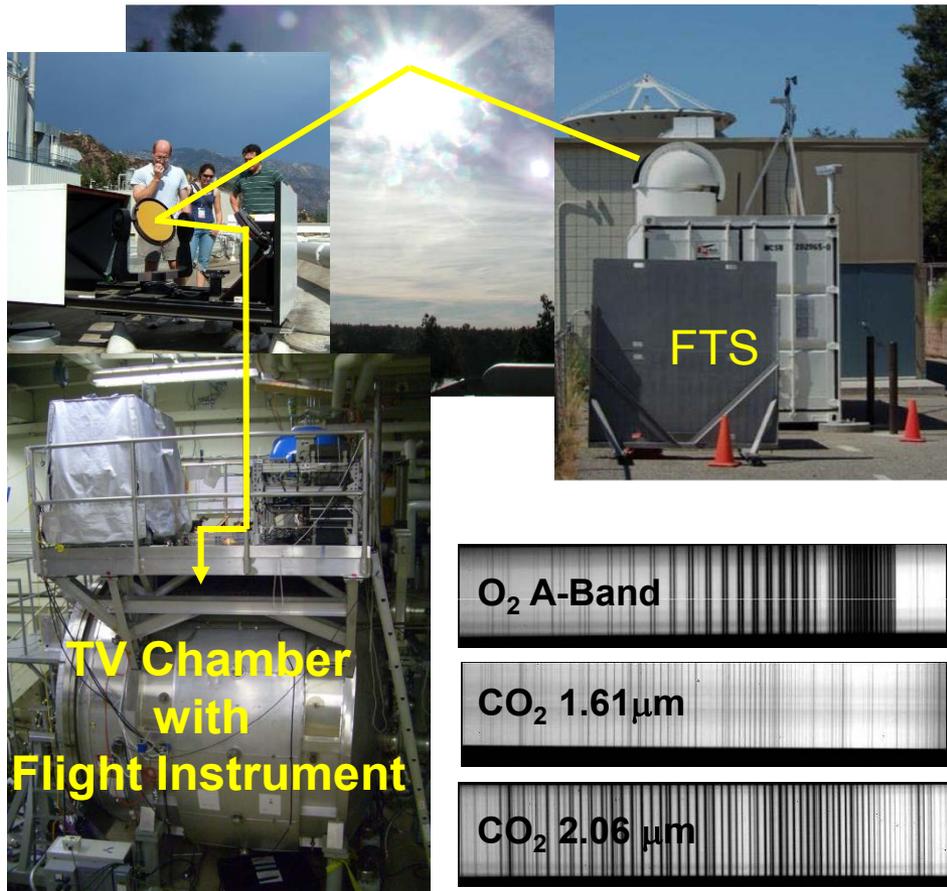


The OCO-2 instrument is more sensitive than the GOSAT TANSO-FTS, especially over dark scenes, and takes 48 to 96 times as many soundings over each orbit.

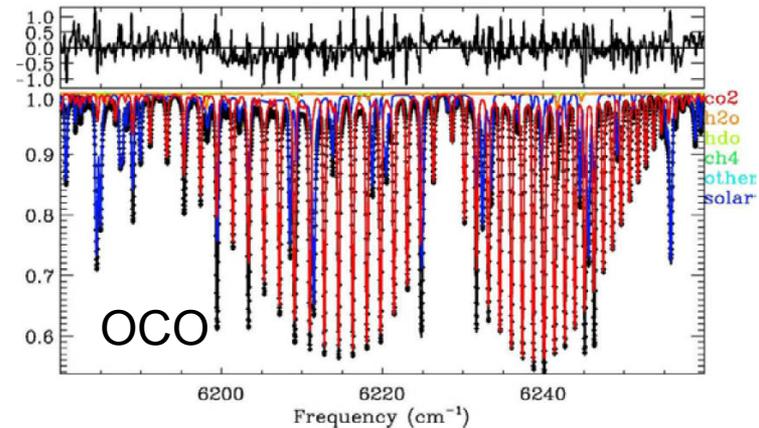
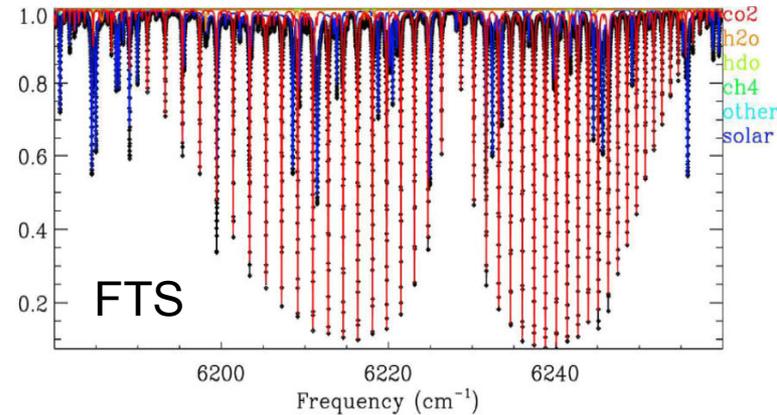


Pre-Flight Instrument Qualification and Characterization

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



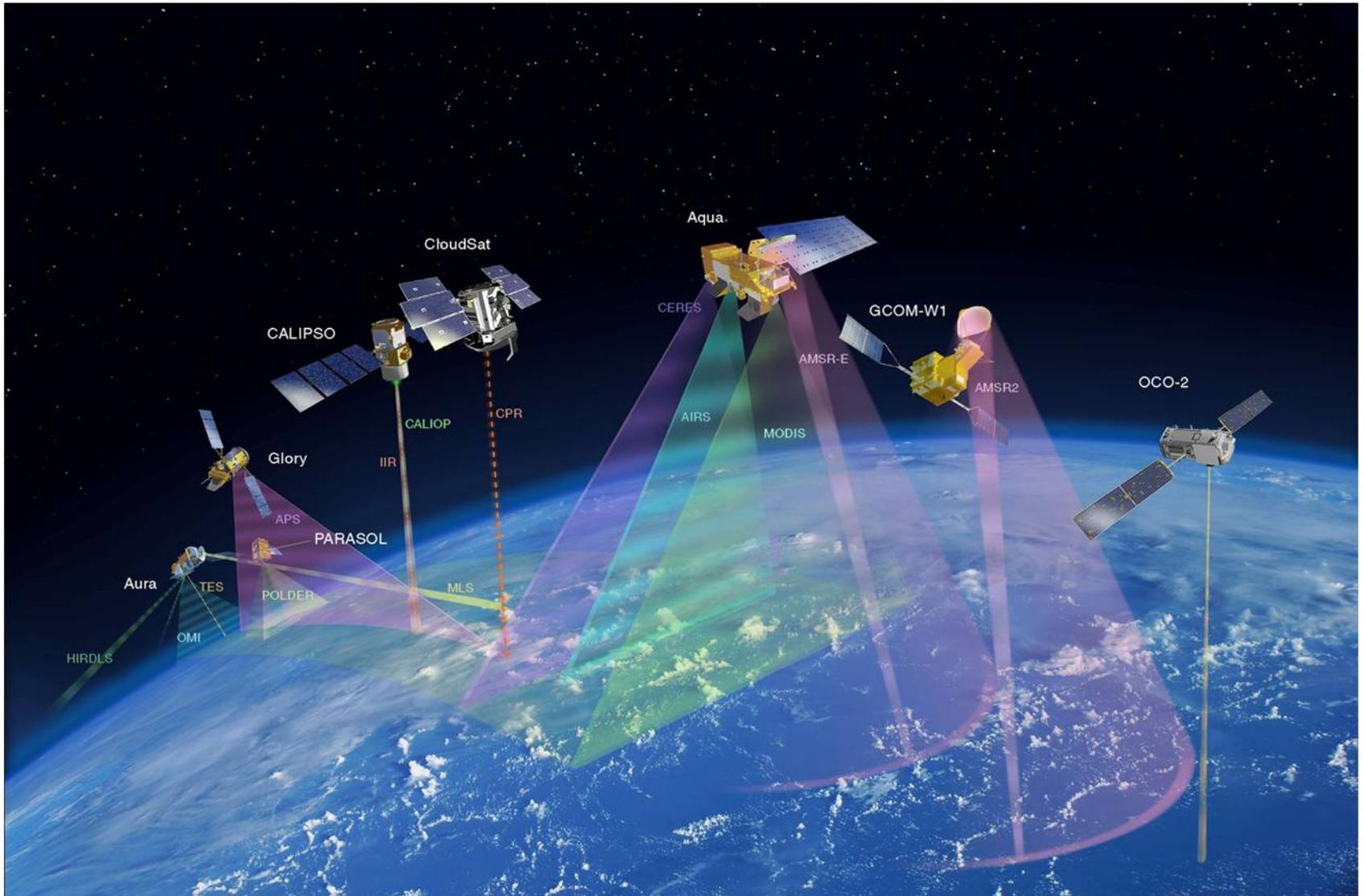


Instrument + Spacecraft Bus = Observatory





Flying in Formation in the A-Train

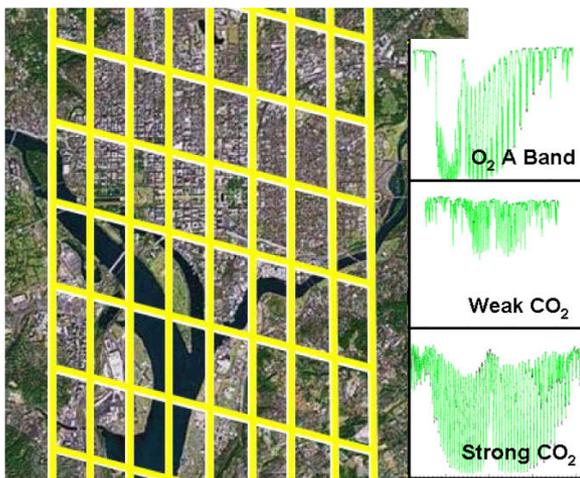
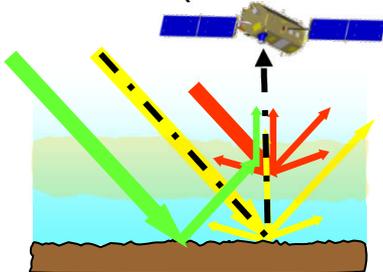




Observation Modes Optimize Sensitivity and Accuracy

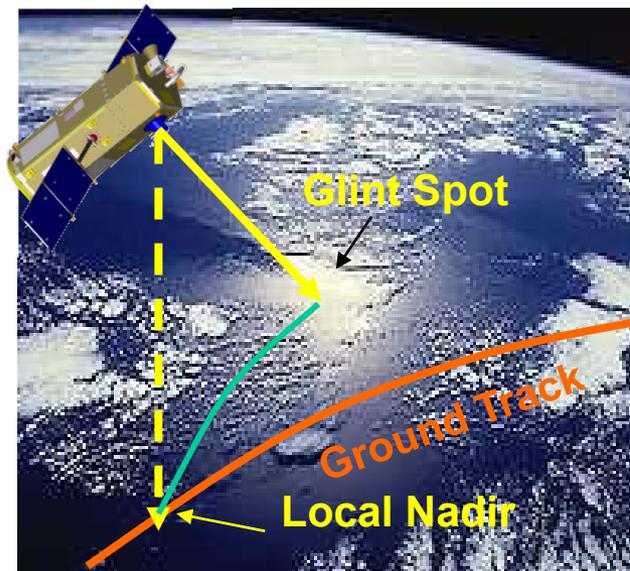
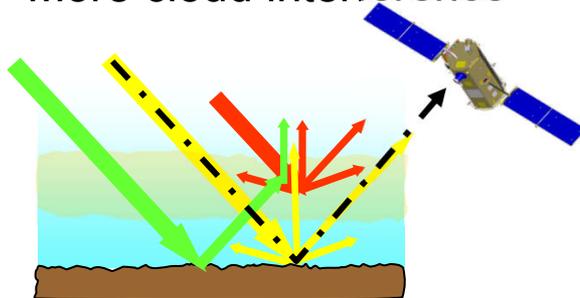
Nadir Observations:

- + Small footprint (< 3 km²)
- Low Signal/Noise over dark surfaces (ocean, ice)



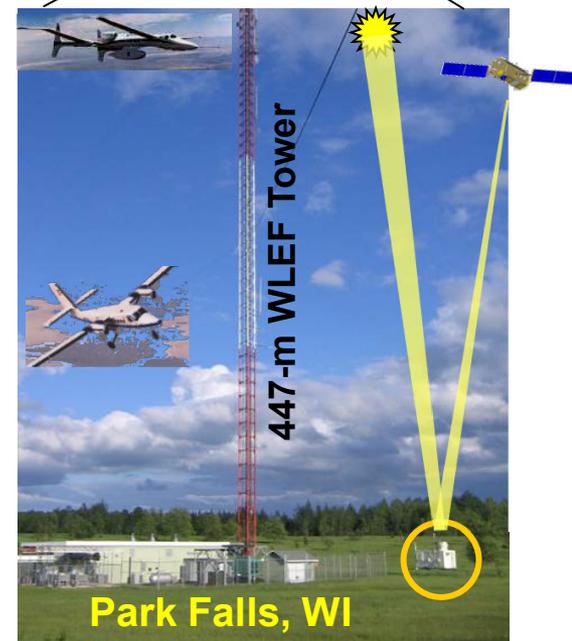
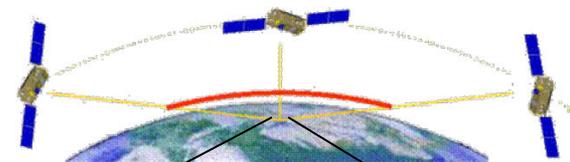
Glint Observations:

- + Improves Signal/Noise over oceans
- More cloud interference



Target Observations:

- Validation over ground based FTS sites, field campaigns, other targets





Conclusions

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO₂ 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 learning how to retrieve precise estimates of XCO₂ from space based measurements
- OCO-2 and GOSAT-2 are the next logical steps needed to:
 - Find the natural “sinks” that are currently absorbing over half of the CO₂ emitted by human activities
 - Quantify CO₂ emissions sources on the scale of individual countries
 - Provide the data needed to assess the effectiveness of future greenhouse gas mitigation policies