Remote Sensing of Greenhouse Gases

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Outline

- Motivation for Measuring GHGs
- In situ measurements – why space-based remote sensing?
- Ground-based remote sensors for GHGs
- Past, present and future satellite missions
- Emissions estimates
- Potential of solar induced fluorescence

Motivation – IPCC AR5 SPM

- "The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification."

- Our contribution - "Annual CO_2 emissions from fossil fuel combustion and cement production were 8.3 [7.6 to 9.0] GtC yr^{-1} averaged over 2002–2011 (high confidence) and were 9.5 [8.7 to 10.3] GtC yr^{-1} in 2011, 54% above the 1990 level. Annual net CO_2 emissions from anthropogenic land use change were 0.9 [0.1 to 1.7] GtC yr^{-1} on average during 2002 to 2011 (medium confidence)."

Motivation – IPCC AR5 SPM

- What are the impacts? - "It is now *very likely* that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and *likely* that human influence has more than doubled the probability of occurrence of heat waves in some locations."
- What can we do? – "Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. "
- "The current uncertainties in biogeochemistry models account for about 2 degree C of uncertainty in projections of future climate change." Scott Denning, CSU

Motivation

- Goal: Monitor emissions at the nation scale (at least) with enough precision to enforce climate/carbon treaties.
- Goal: Provide global measurements in “hard to reach” locations such as the Southern Ocean to better understand large scale sources and sinks.
- Goal: Provide global measurements to monitor natural ecosystem “tipping points,” such as catastrophic permafrost melt.
- Goal: Provide global measurements to validate ecosystem level measurements to improve process level understanding.

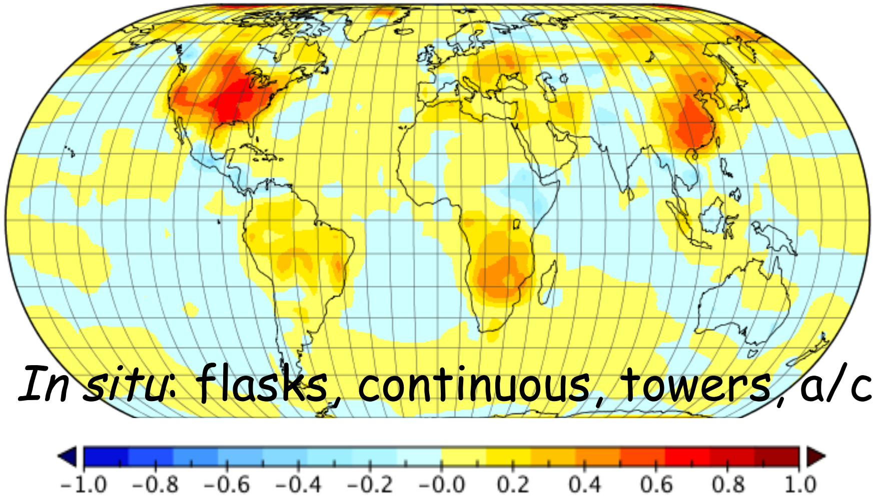
In Situ Measurements

- Flask samples
- Eddy covariance towers
- Aircraft

Global Observing Network – NOAA CarbonTracker

- Are these measurements sufficient?

Reduction in Error of "Best Guess"



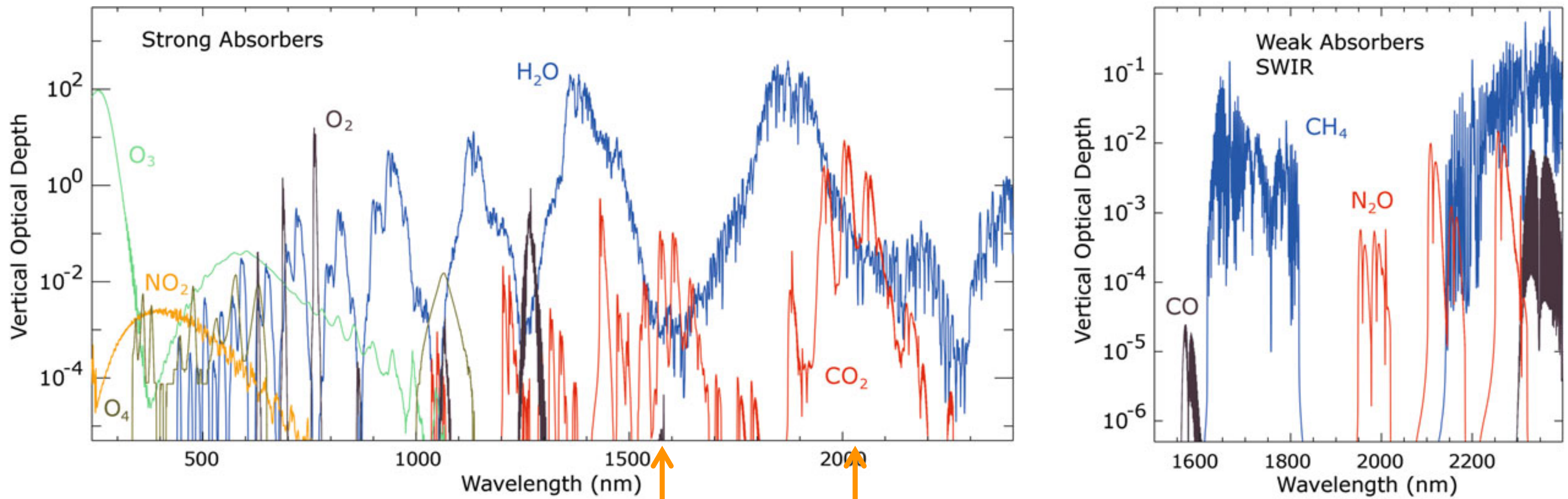
Courtesy David Baker

Issues with In Situ Measurements

- Coverage
- Spatial Footprint
- Location biases (PBL height)
- Transport biases (plumes)

Remote Sensing of Trace Gases

- The bands depicted below are most useful for trace gas retrievals
- Retrievals require knowledge of collocated temperature, moisture and pressure – soundings, NWP models, other proxies - uncertainty



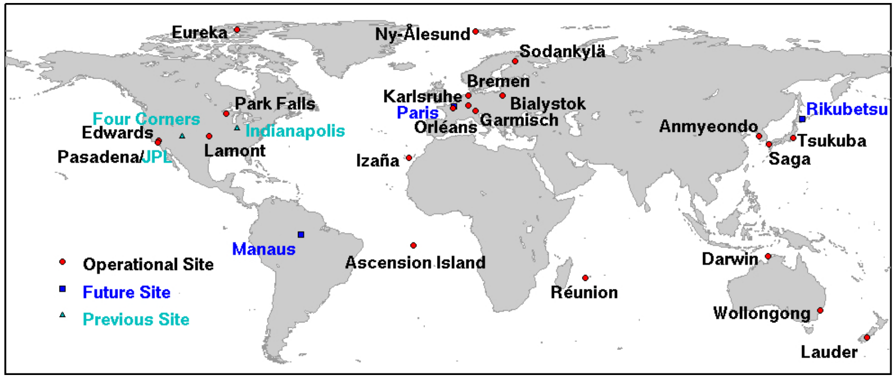
(from the SCIAMACHY book at http://www.sciamachy.org/)

"Weak" CO2 Band

"Strong" CO2 Band

Ground Based Remote Sensors - TCCON

- Total Column Concentration Observing Network – main purpose is to validate space-based measurements.
- Sun-facing Fourier Transform Spectrometer (FTS)
- Records direct solar spectra in the near-infrared spectral region -> retrievals of CO_2, CH_4, CO, H_2O, and others



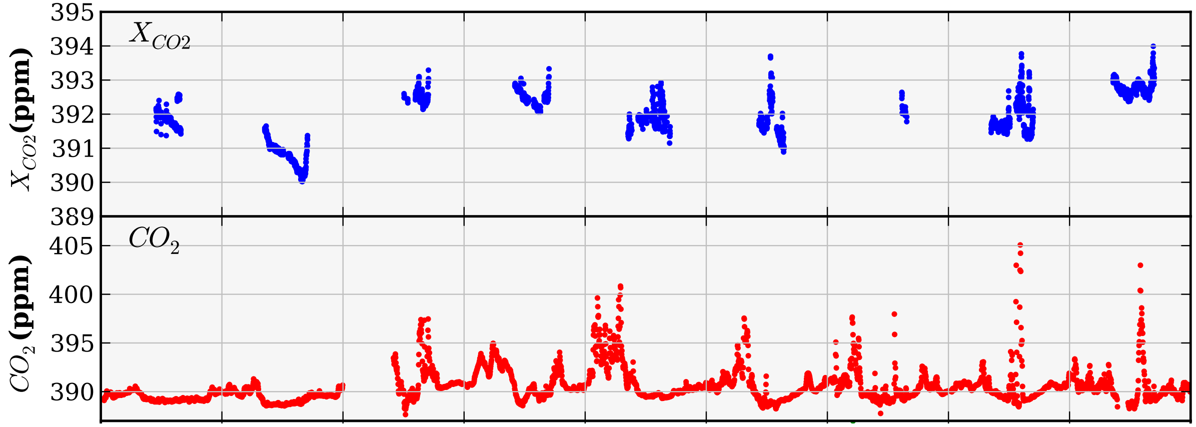
TCCON at ARM SGP site in Lamont, OK

Ground Based Remote Sensors - TCCON

- Column integrated measurement* (rather than point sample from flask or tower)

Column integrated CO_2

Point Sampled CO_2



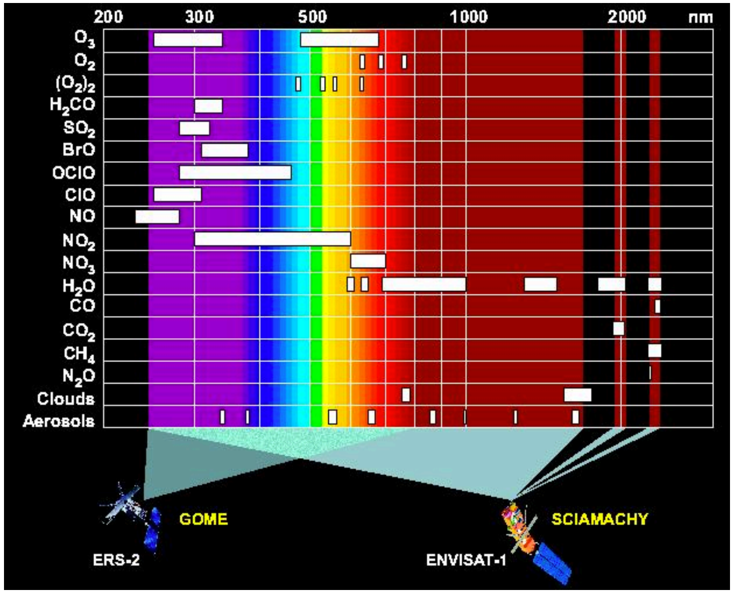
*Note the difference in range

Courtesy: Peter Rayner

- Smaller fluctuations = less sensitivity to strong sources <u>and</u> transport variability

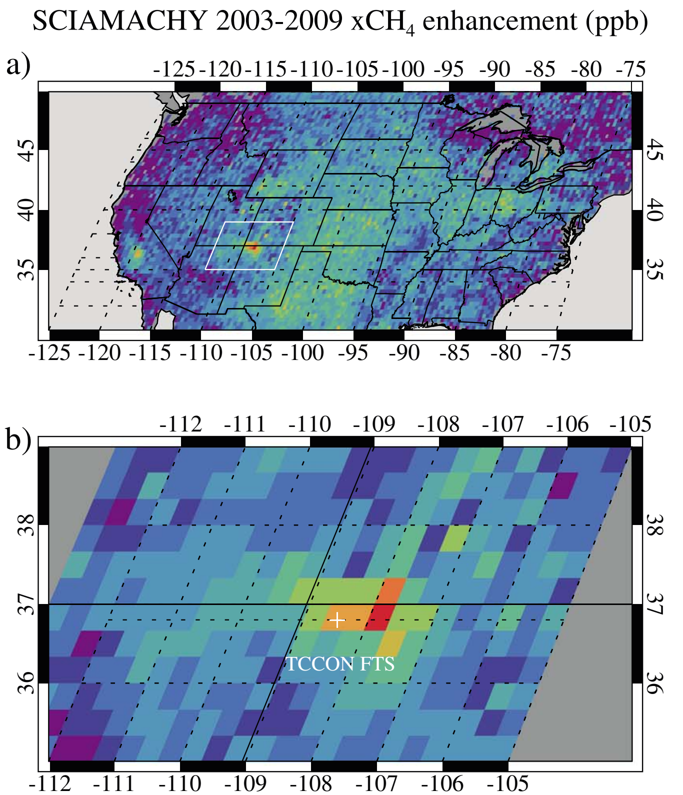
GHG Measurements from Space

- GOME – launched on ERS-2
  - designed for ozone
  - some atmospheric chemistry
  - aerosols
  - 40km IFOV
  - Replaced by GOME-2 in 2006
- SCIAMACHY – launched on Envisat
  - 2002 to 2012
  - Retrievals of CO2, CH4, O2, O3, etc
  - 30km x 60km IFOV
  - Mapping (wide swath) configuration
  - nadir only pointing – no ocean obs



Comparing spectral coverage of SCIAMACHY and GOME

GHG Measurements from Space – Visible Methane at Four Corners



AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061503

Key Points:

- Four Corners exhibits largest CH_4 anomaly seen from space

Four corners: The largest US methane anomaly viewed from space

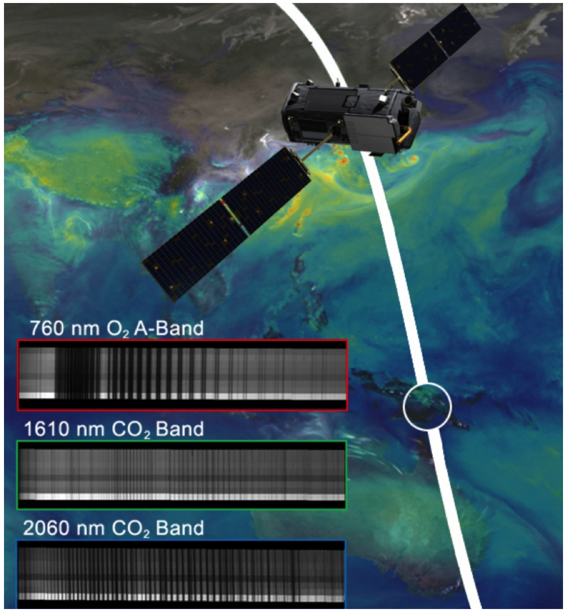
Eric A. Kort[1], Christian Frankenberg[2], Keeley R. Costigan[3], Rodica Lindenmaier[3,4], Manvendra K. Dubey[3], and Debra Wunch[5]

Using SCIAMACHY data together with TCCON observations, researchers at JPL and LANL were able to quantify the largest point source of methane on the planet. The anomaly is about an order of magnitude larger than current best estimates – correlates with large open mining sites and fossil fuel power production.

GHG Measurements from Space

- GOSAT – 2009 – Present
  - First dedicated GHG mission
  - CO_2, CH_4, O_2
  - 10.5km footprint (4 sec averaging time)
  - Less observations than expected
    - pointing mechanism failure
    - lower SNR than originally thought

- OCO-2 – 2014 (data by early 2015)
  - CO_2, O_2
  - 2km footprint
  - Still in testing mode
  - Laboratory tests indicate extremely high precision (0.2-1.0ppm)
  - Flies in the A-train with CloudSat and others for simultaneous validation of atmos variables (clouds and aerosols)



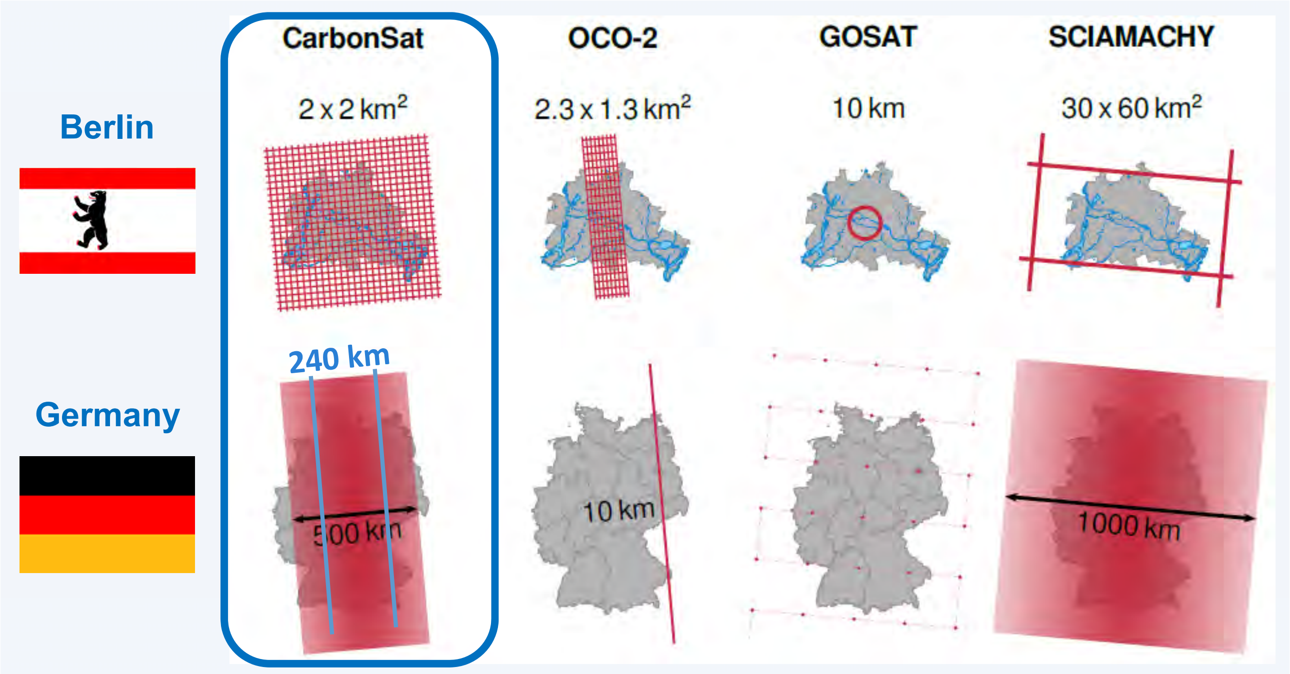
Courtesy: David Crisp

GHG Measurements from Space

- Other existing instruments with CO_2 bands
  - AIRS
  - TES
- Not optimal for CO_2 emissions estimates – sensitive to the upper troposphere and stratosphere,

Proposed Future Missions

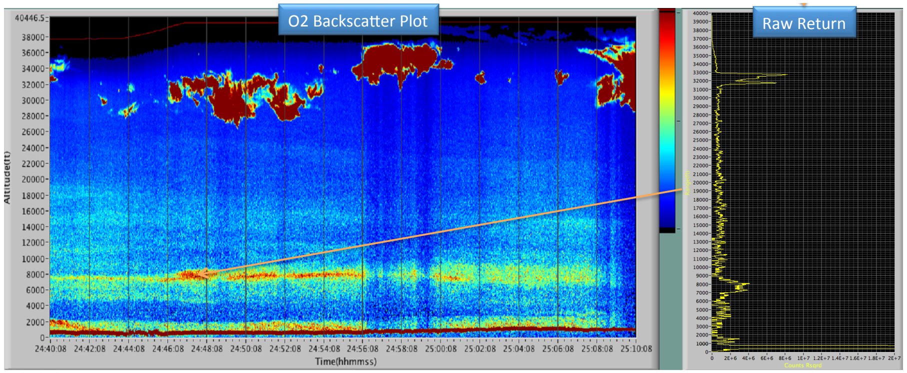
- CarbonSat
  - CO_2, CH_4
  - Mapping instrument, rather than sampling instrument

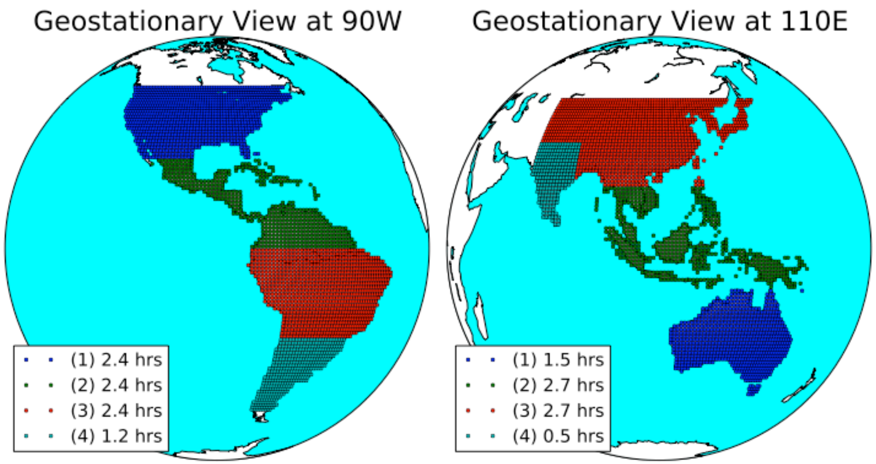


Comparison of FOVs and swath widths of various missions.

Proposed Future Missions

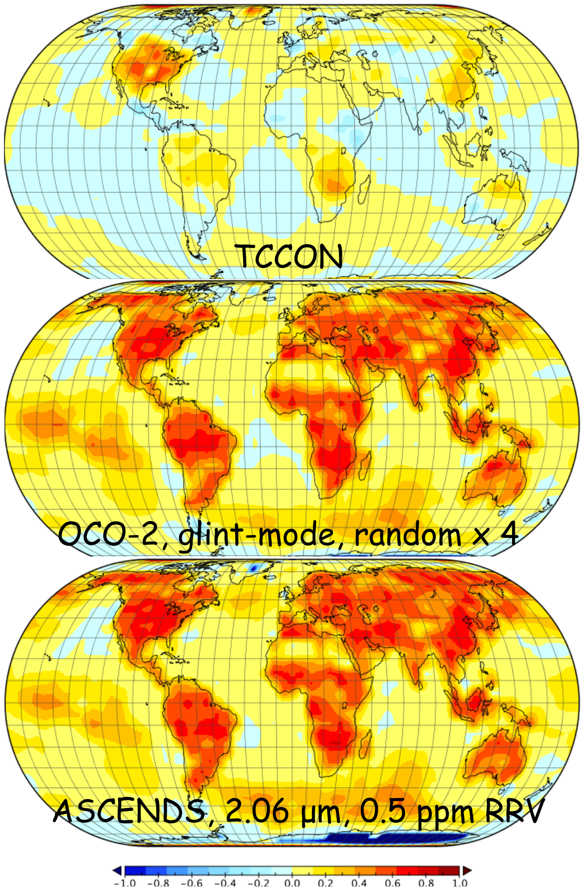
- ASCENDS
  - Currently in pre-formulation
  - Several different laser instruments proposed by JPL, GSFC, LaRC
  - Yearly test flights indicate high precision, low bias
- GeoCARB
  - Geostationary measurements of CO_2, CH_4
  - Nominal placements at 110E or 75W
  - Frequent scanning allows very low uncertainty estimates of emissions over short time scales at the national/regional spatial scale
  - Complements current LEO observations (similar to weather applications)





Using CO_2 Measurements to Infer Emissions

- CO_2 is a passive tracer
  - Known wind speed+direction -> can trace concentrations back to their sources
  - Data assimilation approaches are used to combine a "best guess" of the emissions distribution with new information from observations
- Uncertainties in these estimates account for measurement uncertainties as well as model uncertainties
- OSSE work (pictured at right) helps to understand the impact of individual observing systems

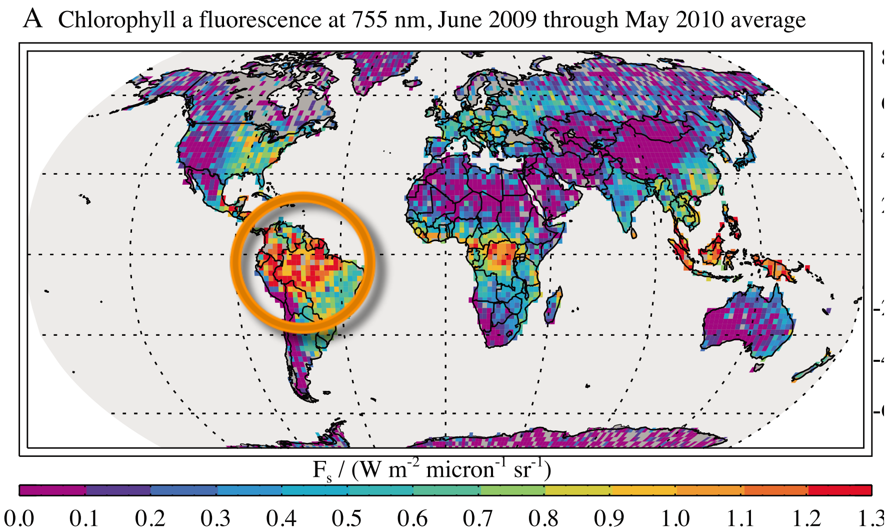


Reduction in Error over "Best Guess" emissions

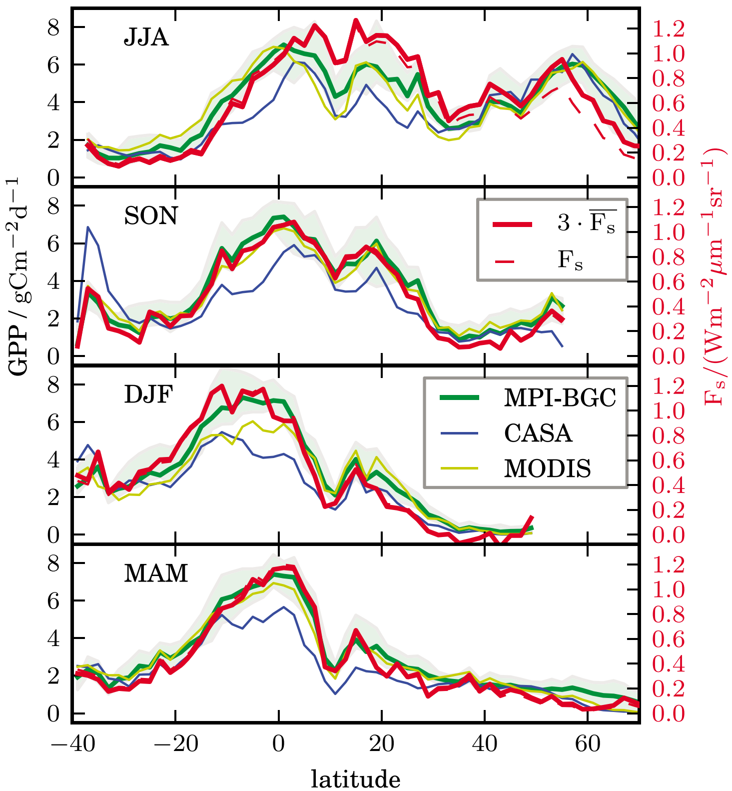
Solar Induced Fluorescence (SIF)

- Emissions estimates give the net flux of CO_2 at the surface, and other proxies must be used to partition the flux into component processes
- During photosynthesis, plants actually release photons ("fluoresce") at various wavelengths to avoid damage, and the amount they fluoresce is strongly correlated with Gross Primary Productivity (GPP), an important component of the net flux.
- Recently, an algorithm was discovered for recovering SIF from the bands that current and future GHG satellites are measuring in – "GPP for free"?

Solar-induced fluorescence (SIF)



Averaged SIF from GOSAT



From Frankenberg et al (GRL, 2012)

Zonally averaged SIF alongside 3 model predictions of GPP

Conclusions

- Both ground-based and space-based remotely sensed GHG measurements are critical to meeting the challenges presented by the carbon-climate problem
- Satellite observations provide the necessary coverage and precision for better understanding global, regional, and local scale emissions, but in the future, we need both Polar Orbiting and Geostationary measurements (like in meteorological applications).
- Ground based observations provide calibration and validation, as well as continuous site monitoring (e.g. Four Corners, etc)
- SIF appears to be a promising avenue for disentangling carbon cycle processes, and is retrievable from the satellites mentioned here, meaning there's now more than a 10 year record.