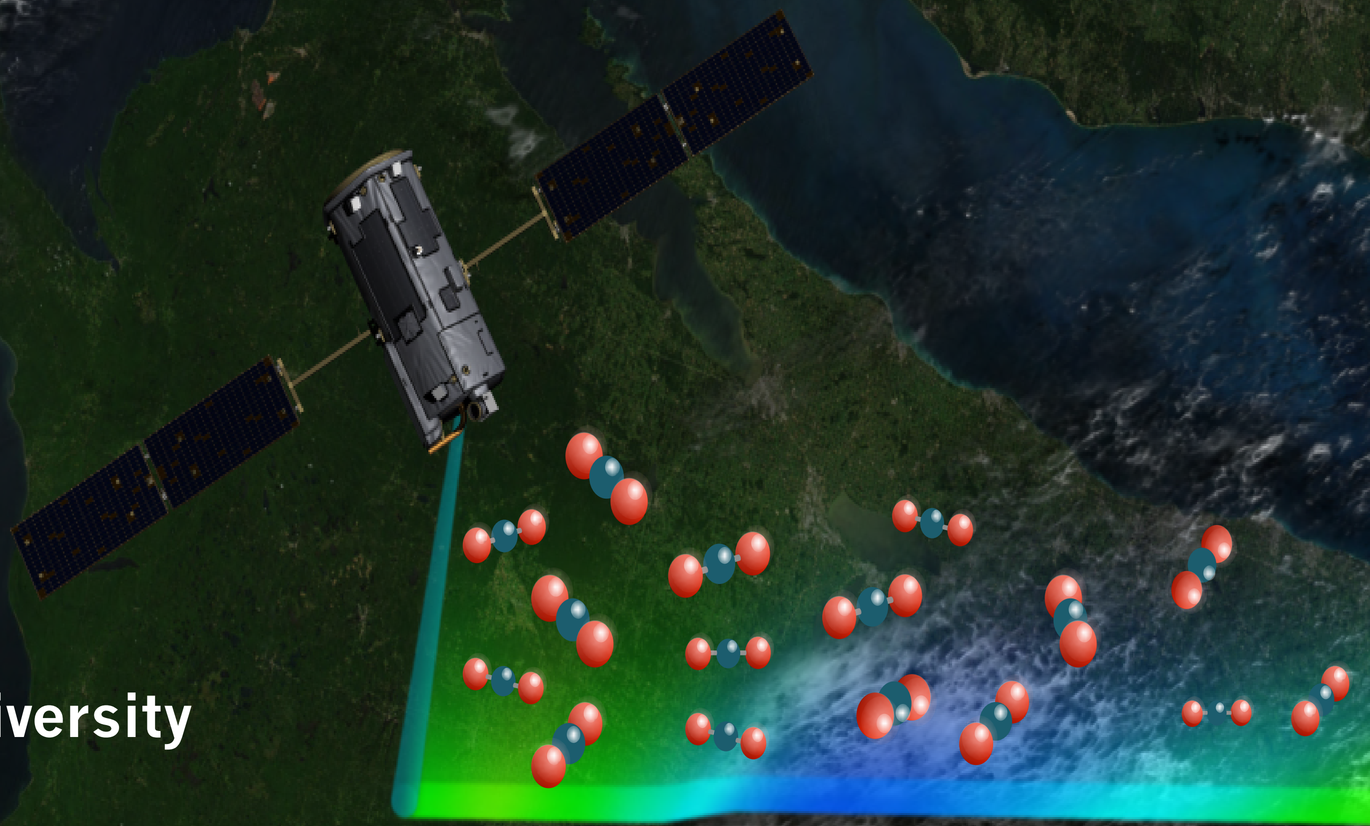
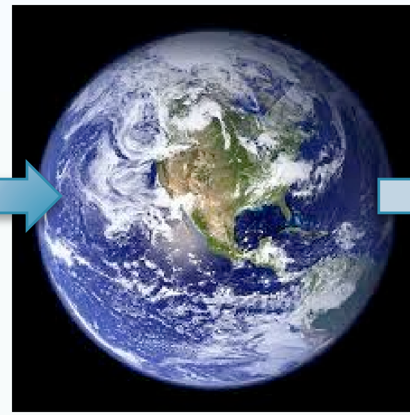
Greenhouse Gas Measurements from Space



Chris O'Dell
Colorado State University

Climate Forcings & Feedbacks

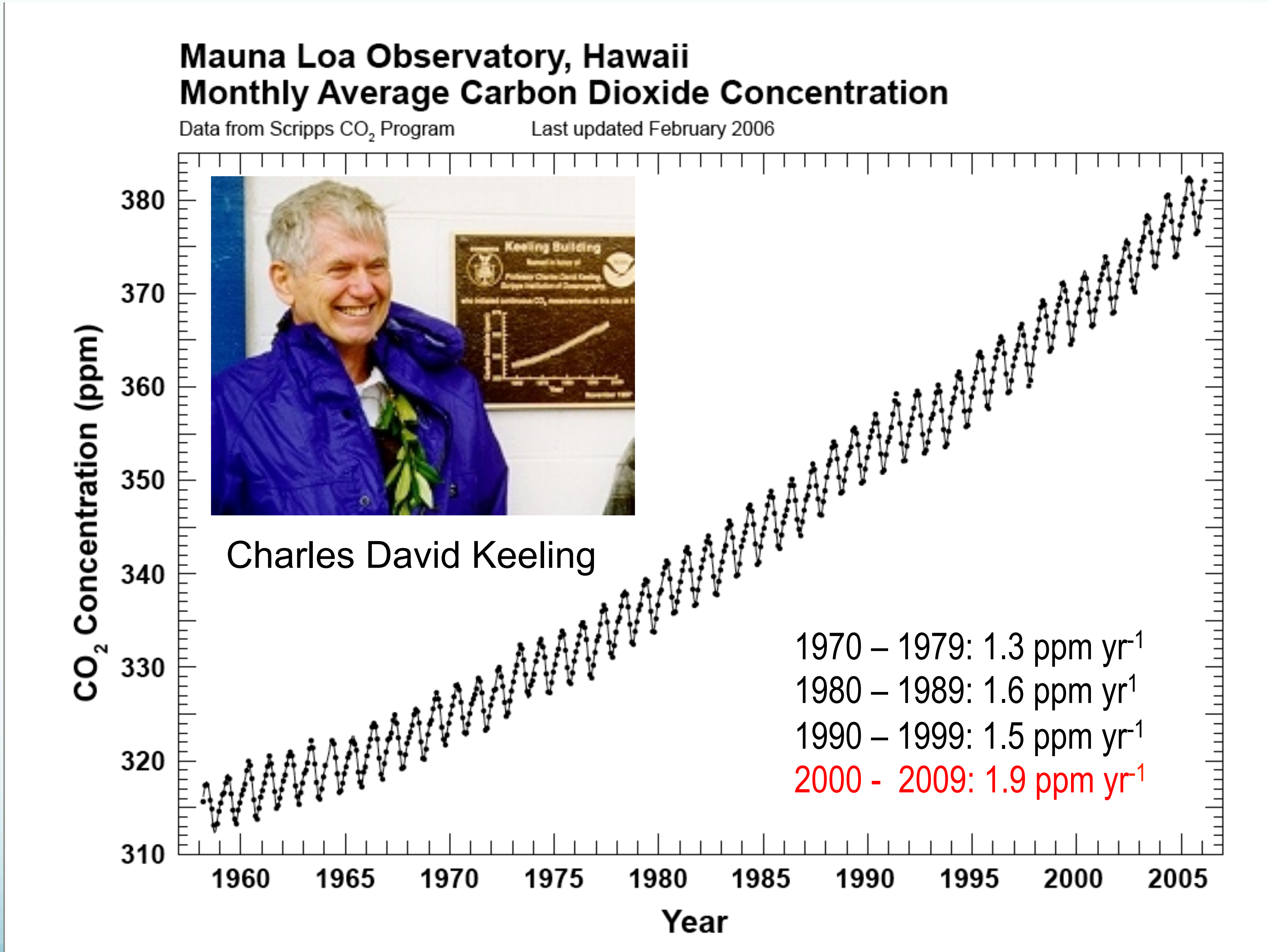
Forcings
Greenhouse Gases
Aerosols
Volcanic Eruptions
Solar Forcing



Temperature Change

Feedbacks
Water Vapor (Fast)
Clouds (Fast)
Snow/Ice Albedo (Medium)
Carbon cycle (slow)
Melting Permafrost (Slow)
Ice Sheets (Slow)

Very large uncertainty here!


Mauna Loa Observatory, Hawaii
Monthly Average Carbon Dioxide Concentration
Data from Scripps CO_2 Program
Last updated February 2006
CO_2 Concentration (ppm)
310
320
330
340
350
360
370
380
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Year
Charles David Keeling
1970 – 1979: 1.3 ppm yr^{-1}
1980 – 1989: 1.6 ppm yr^{1}
1990 – 1999: 1.5 ppm yr^{-1}
2000 - 2009: 1.9 ppm yr^{-1}

Fate of Anthropogenic CO_2 Emissions (2000-2009)

1.1±0.7 PgC y^{-1}

\+

7.7±0.5 PgC y^{-1}

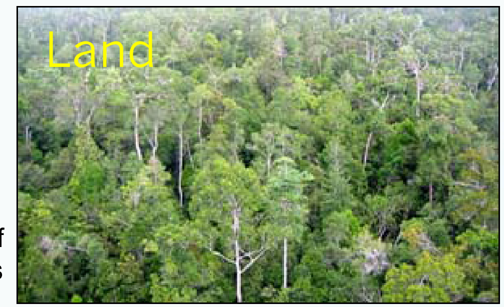
4.1±0.1 PgC y^{-1}

47%

2.4 PgC y^{-1}

27%

Calculated as the residual of all other flux components

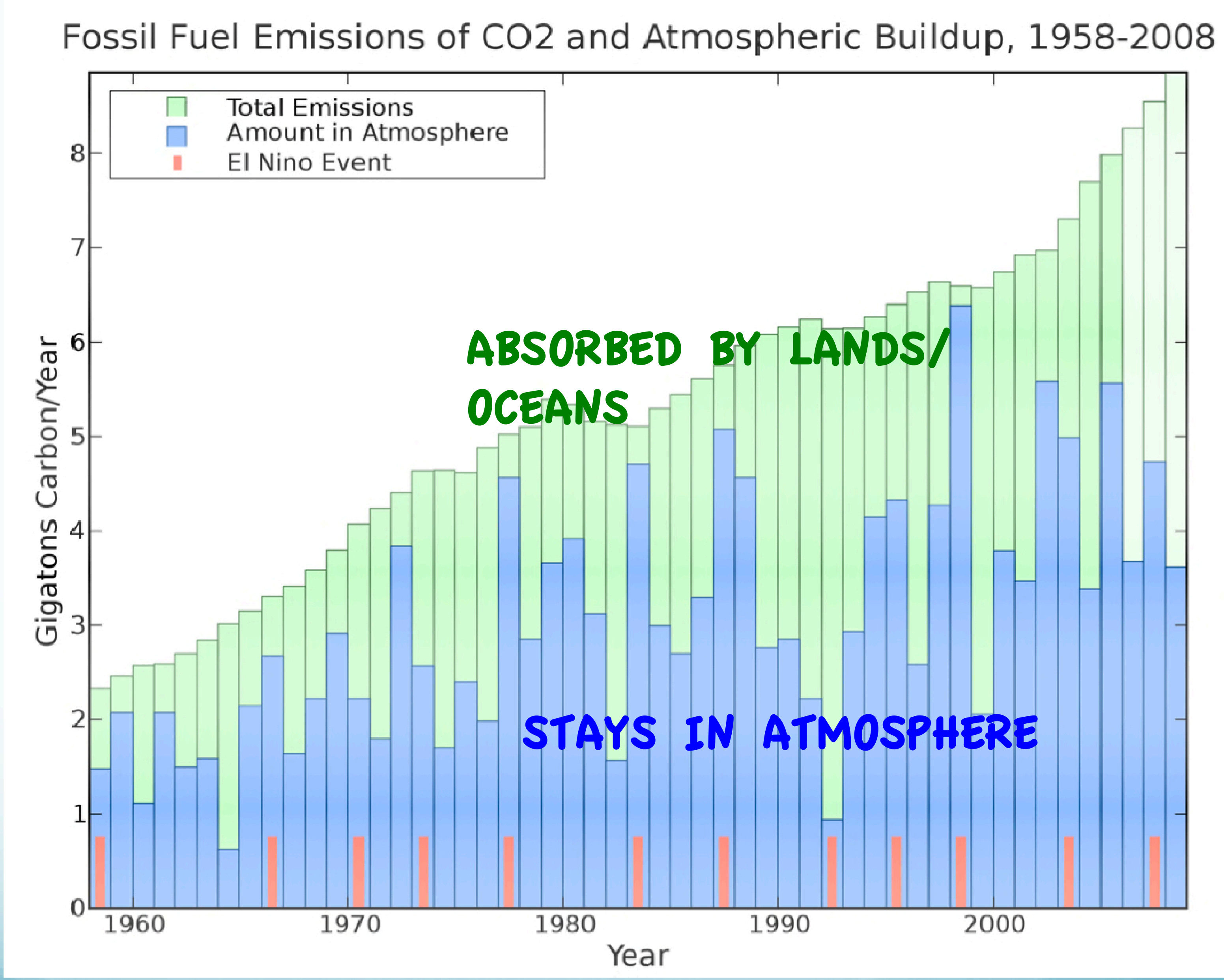


26%

2.3±0.4 PgC y^{-1}

Average of 5 models

Global Carbon Project 2010



Fossil Fuel Emissions of CO2 and Atmospheric Buildup, 1958-2008
Total Emissions
Amount in Atmosphere
El Nino Event
Gigatons Carbon/Year
0
1
2
3
4
5
6
7
8
1960
1970
1980
1990
2000
Year
ABSORBED BY LANDS/ OCEANS
STAYS IN ATMOSPHERE

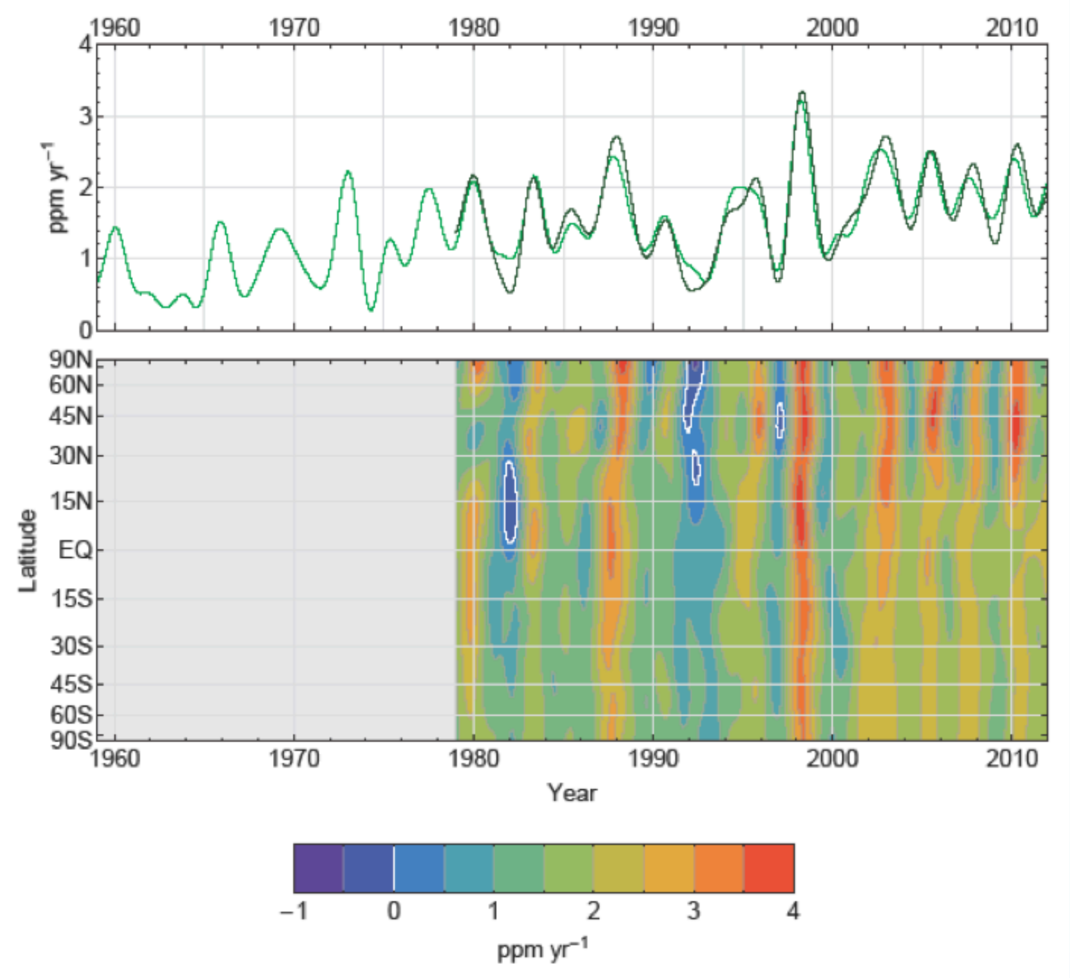
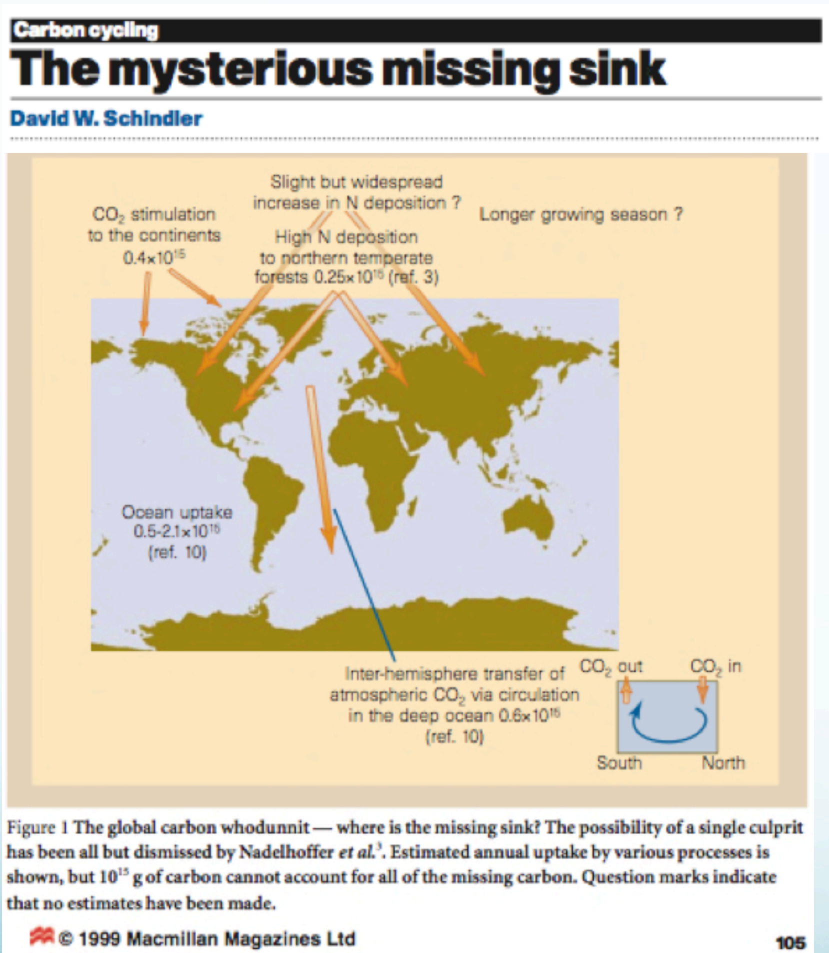


Figure 6.12: (Top) Global average atmospheric CO_2 growth rate, computed from the observations of the SIO network (light green line, Keeling et al., (2005), updated) and from the marine boundary layer air reference measurements of the NOAA-GMD network (dark green line; Conway et al., 1994; Dlugokencky and Tans, 2013). (Bottom) Atmospheric growth rate of CO_2 as a function of latitude determined from the NOAA-ESRL network, representative of stations located in the marine boundary layer at each given latitude (Masarie and Tans, 1995; Dlugokencky and Tans, 2013). Sufficient observations are available only since 1979.

Questions about the Land-based carbon sinks


Carbon cycling

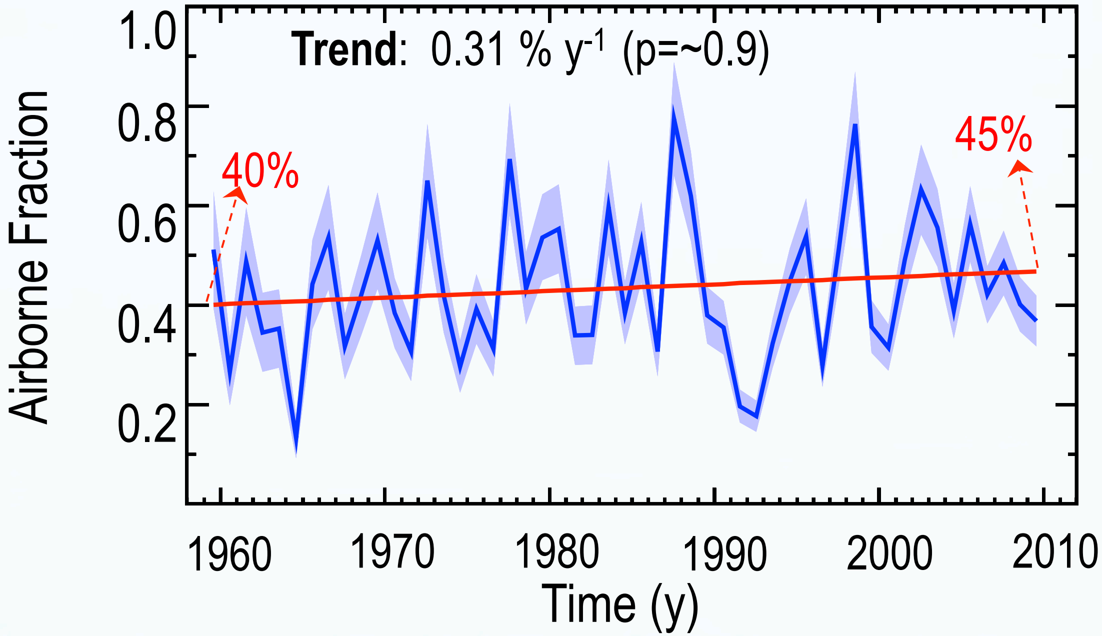
The mysterious missing sink

David W. Schindler

Figure 1 The global carbon whodunnit — where is the missing sink? The possibility of a single culprit has been all but dismissed by Nadelhoffer *et al.*[3]. Estimated annual uptake by various processes is shown, but 10^{15} g of carbon cannot account for all of the missing carbon. Question marks indicate that no estimates have been made.

- *Where are the carbon sinks?* North America? Tropics?
- *What are the mechanisms?*
  - Forest regrowth?
  - CO_2 Fertilization?
  - Nitrogen Deposition?
- *Will they Saturate? (depends on the mechanism)*

CO_2 Airborne Fraction



In the past 50 years, the fraction of CO2 emissions that remains in the atmosphere each year has likely increased, from about 40% to 45% ... Changes in the CO2 sinks are highly uncertain, but they could have a significant influence on future atmospheric CO2 levels. It is therefore crucial to reduce the uncertainties.

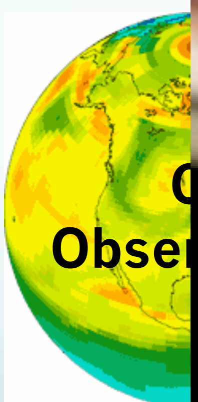
Le Quéré et al. 2009, Nature Geoscience

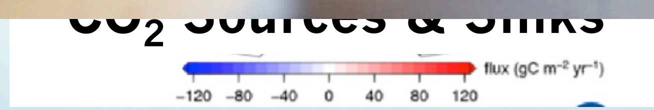
Future GHG emissions may require monitoring

- Current country-wide emissions estimates are largely self-reported. (‘‘Bottom-Up Estimates’’)
- If/when there is a global price on carbon emissions, there will be an incentive to under-report one’s emissions.
- Independent and globally consistent emissions monitoring is therefore highly desirable.

“Top-Down” approach to CO_2 sources and sinks

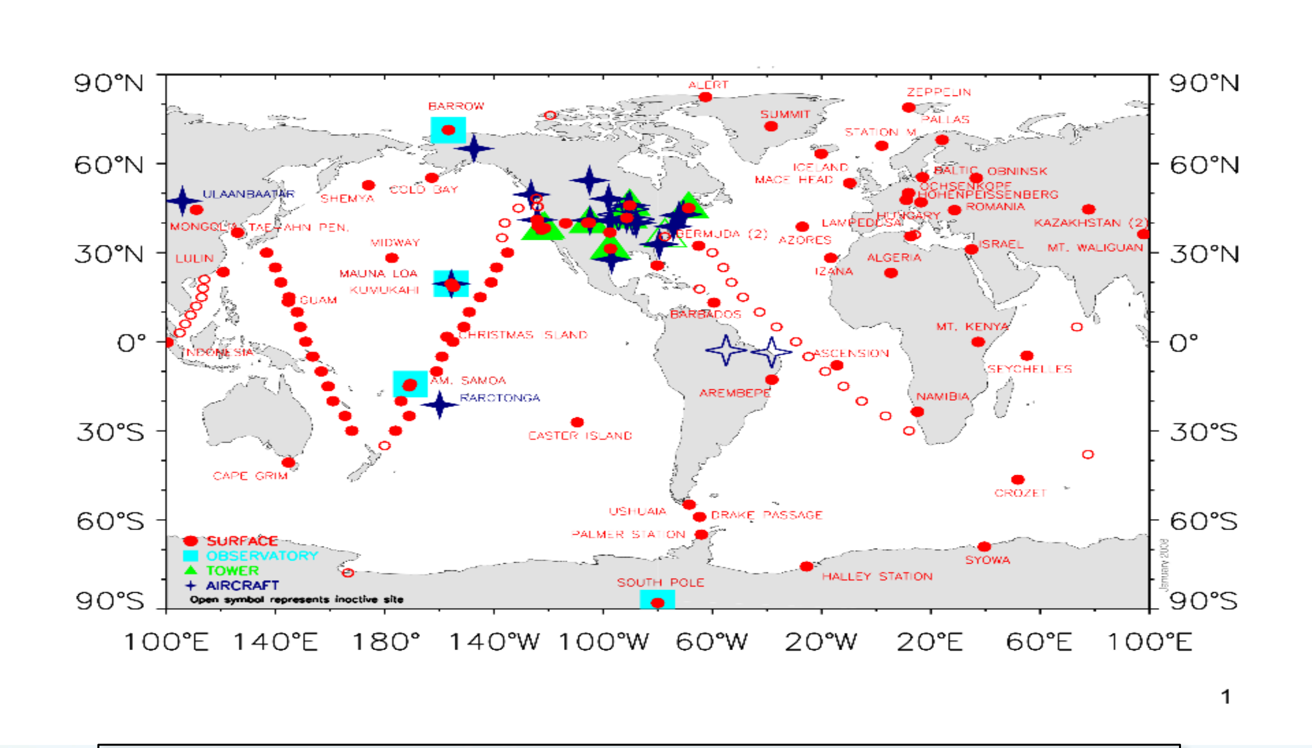
models of the
cean, and
pheric
ort, these
s can “back
hat emissions
f have been to
global map of





http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/

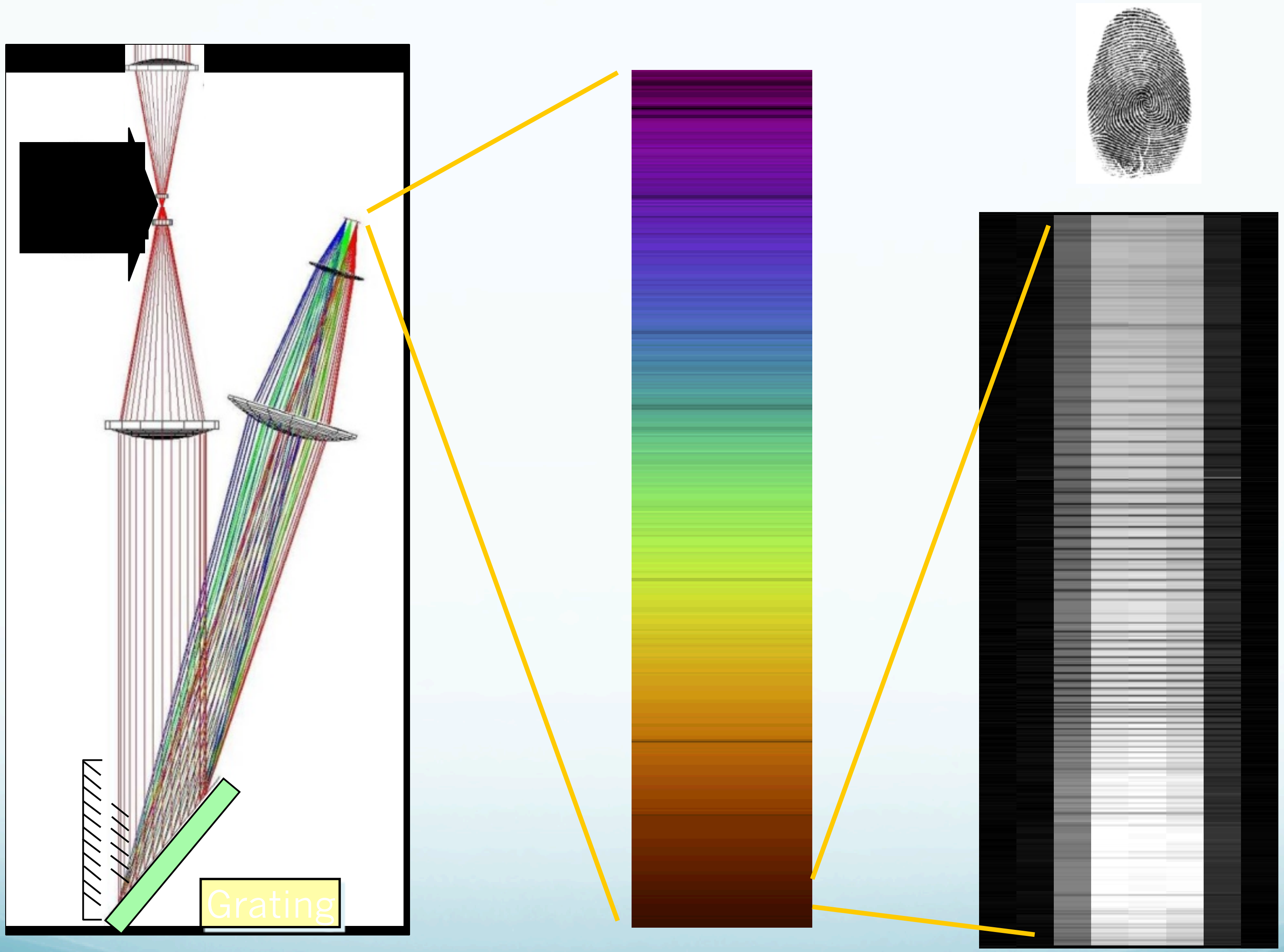
Measurements of CO_2 come primarily from ground



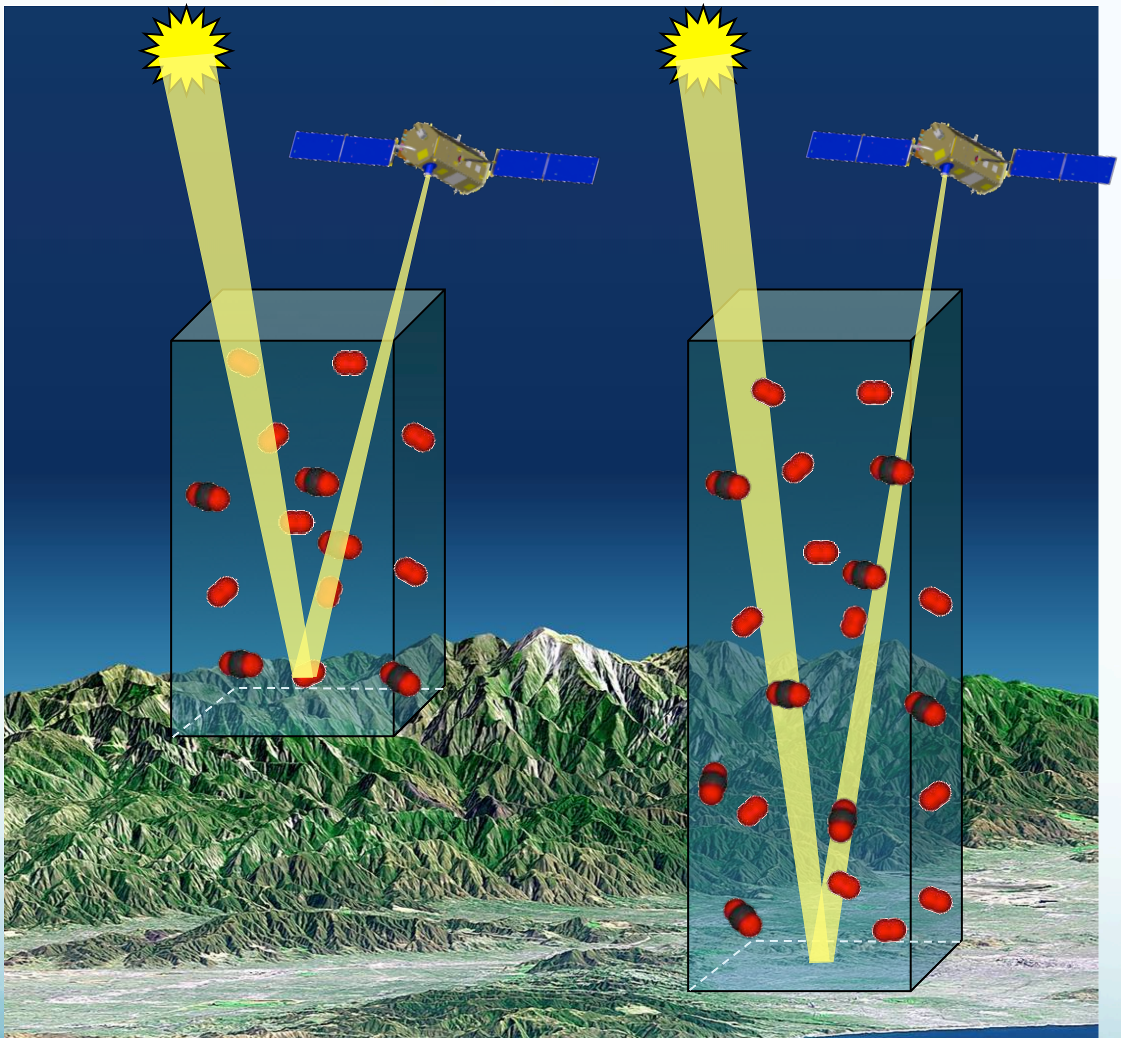
We'd like to complement the sparse in-situ network with global satellite observations!

Source: NOAA ESRL

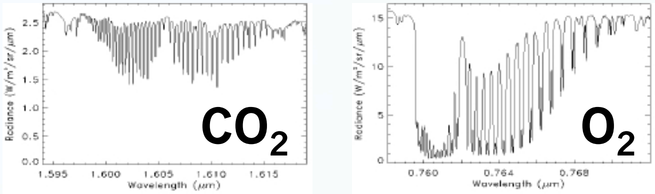
Measuring an invisible gas from space



Measuring Carbon Dioxide in Reflected Sunlight

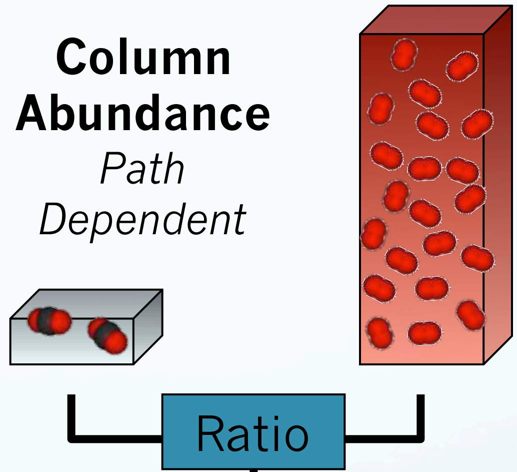


Measured Spectra



Column Abundance

Path Dependent



X_{CO2}

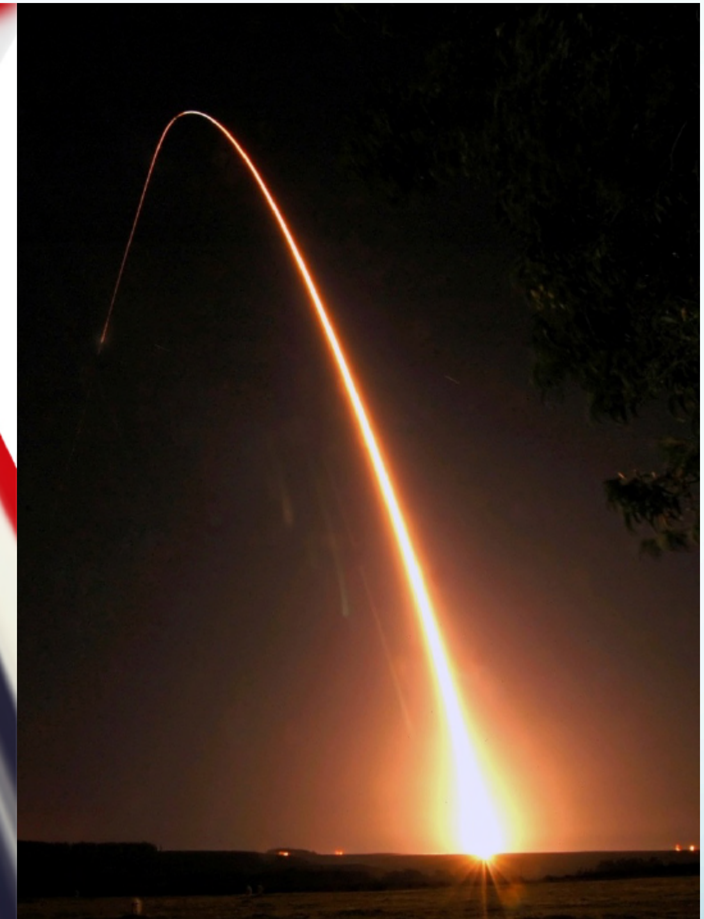
Path Independent Mixing Ratio

GOSAT

Greenhouse gases Observing SATellite

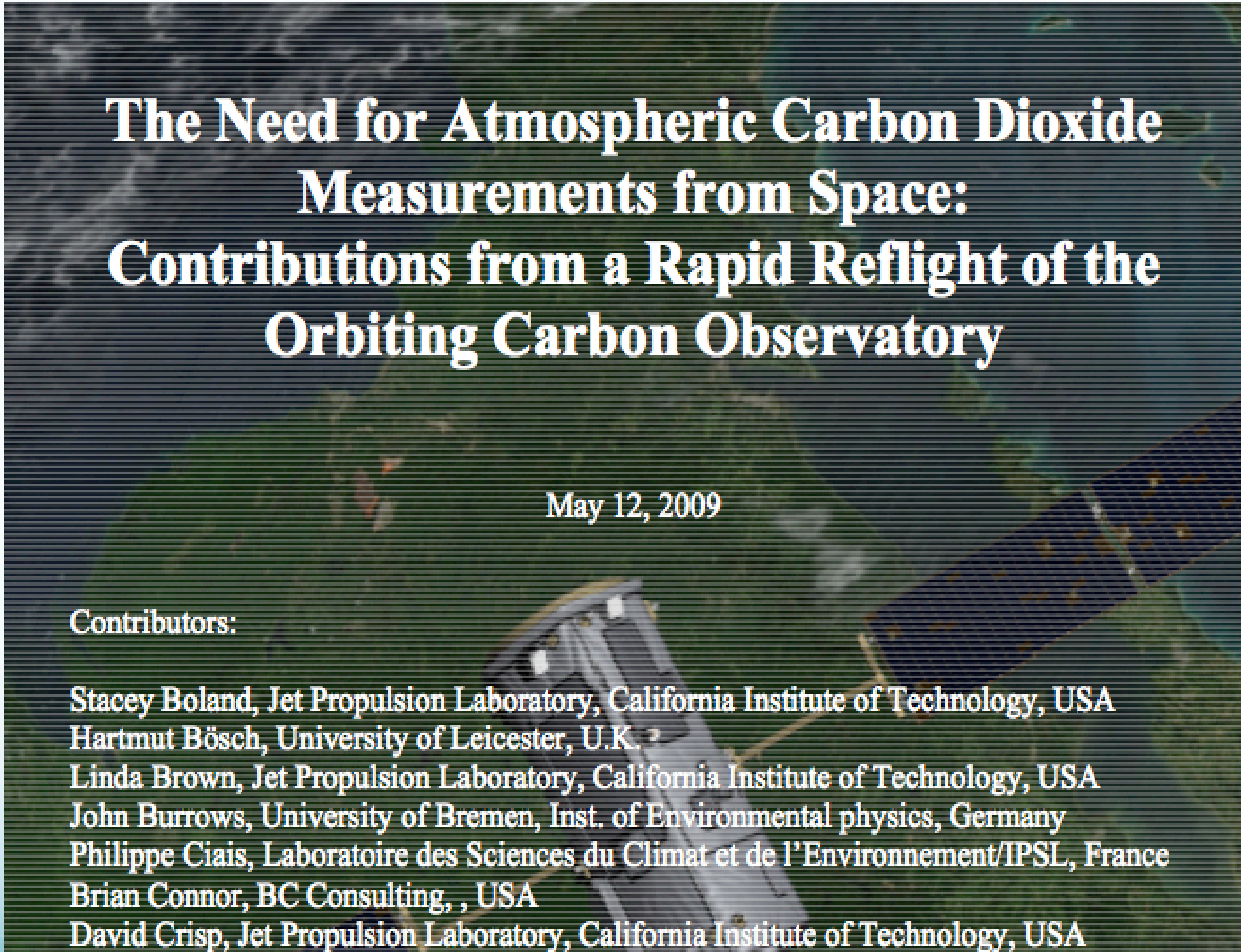
OCO

Orbiting Carbon Observatory



Launched successfully on 23 January 2009

Launch failed on February 24, 2009 when nose-cone failed to open & detach



The Need for Atmospheric Carbon Dioxide Measurements from Space: Contributions from a Rapid Reflight of the Orbiting Carbon Observatory

May 12, 2009

Contributors:

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Brian Connor, BC Consulting, , USA
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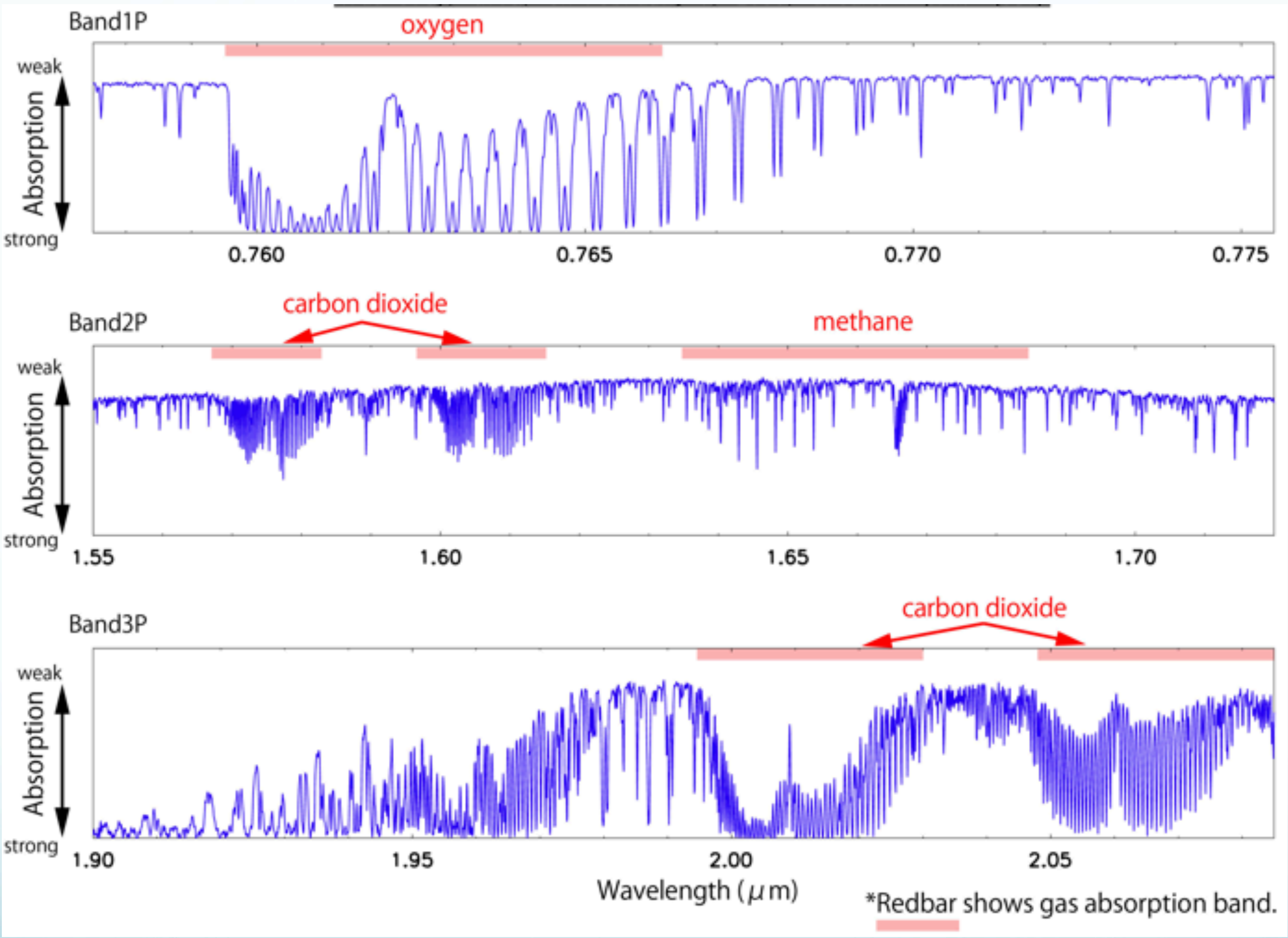
CO_2 & Methane from GOSAT



Surface CO_2 Simulation

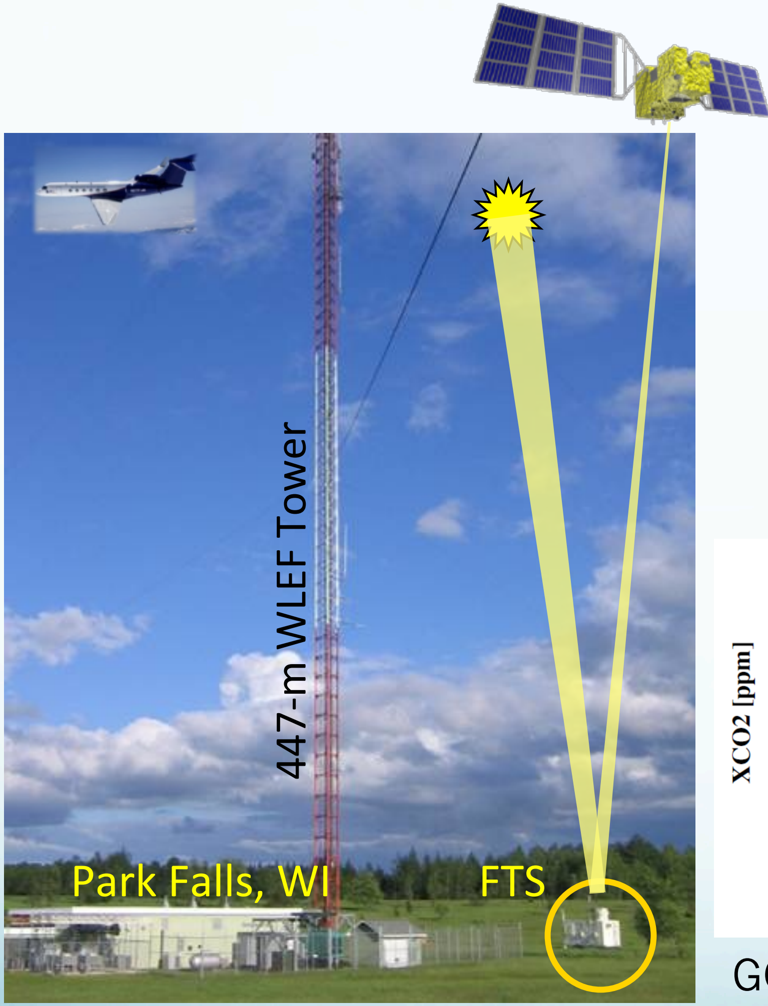
http://biodav.atmos.colostate.edu/parazoo/GlobalCO2_500m_sibgeos5_JJAS2004.mov

Courtesy N. Parazoo, CSU

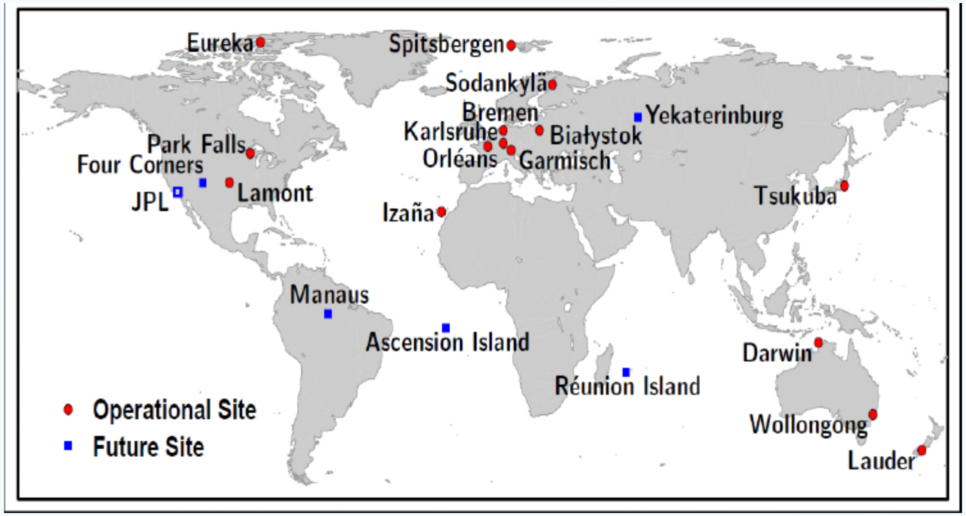
Challenges for Measuring Carbon Dioxide from Space

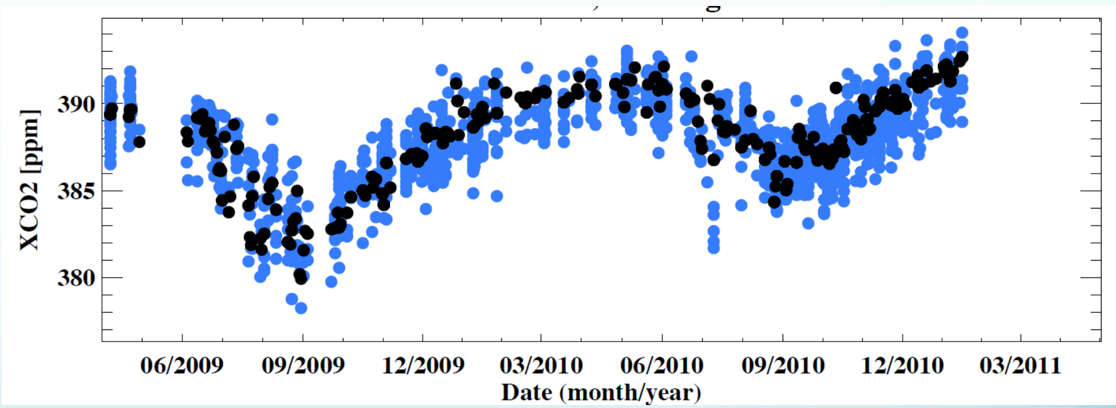
- Variations in Column-averaged CO_2 are small: 1-10 ppm out of ~ 390 ppm background.
- Measurements with accuracies of ~1-2 ppm are needed to improve over the current surface network
- Must have an accurate way to screen out thick clouds & aerosols (coaligned on-board imager or spectral technique)
- Thin & subvisible clouds+aerosols can cause errors of several ppm.

Validation Against TCCON



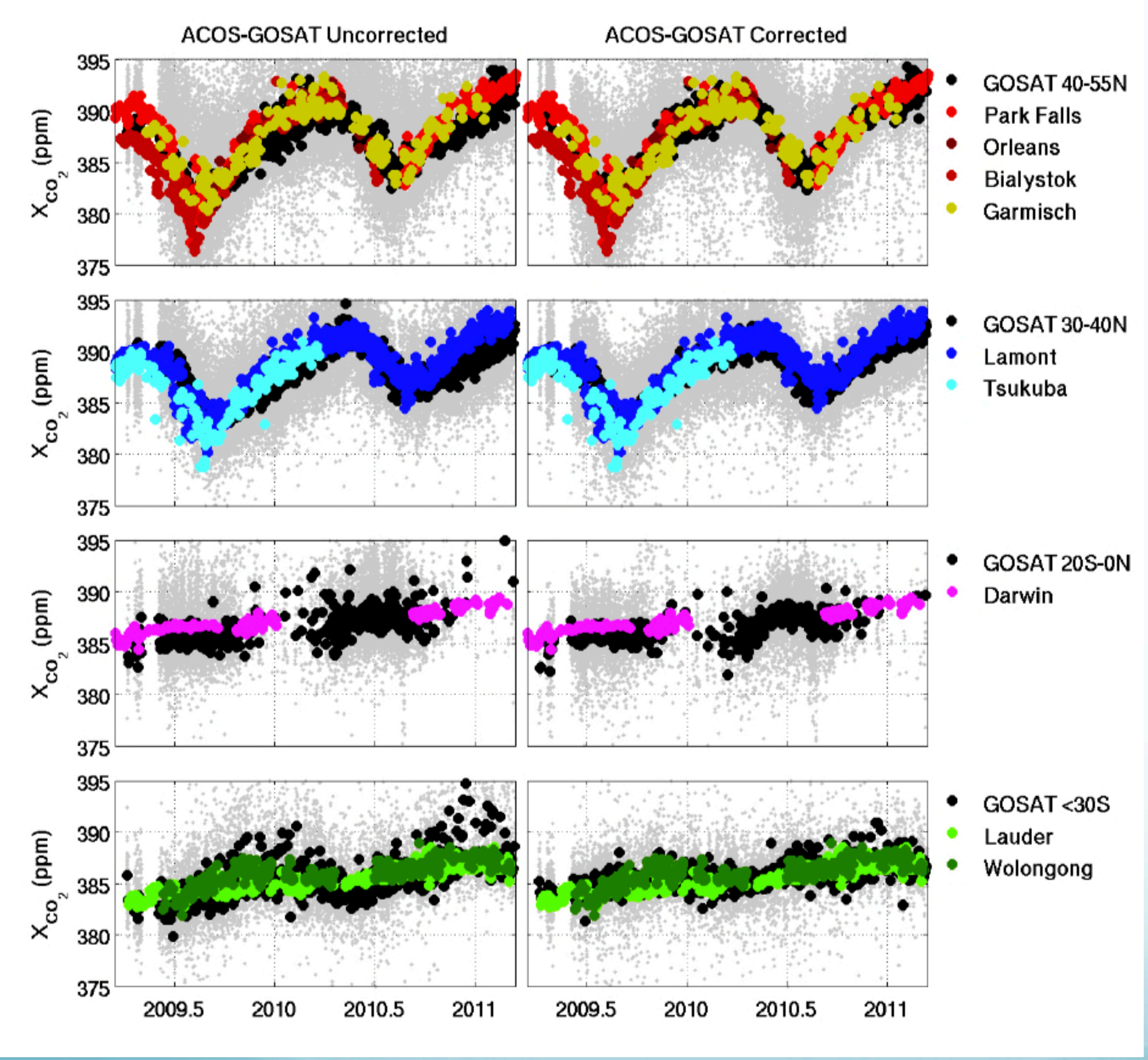
Near-simultaneous observations are acquired over TCCON station.





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

GOSAT Comparisons with Surface-based measurements

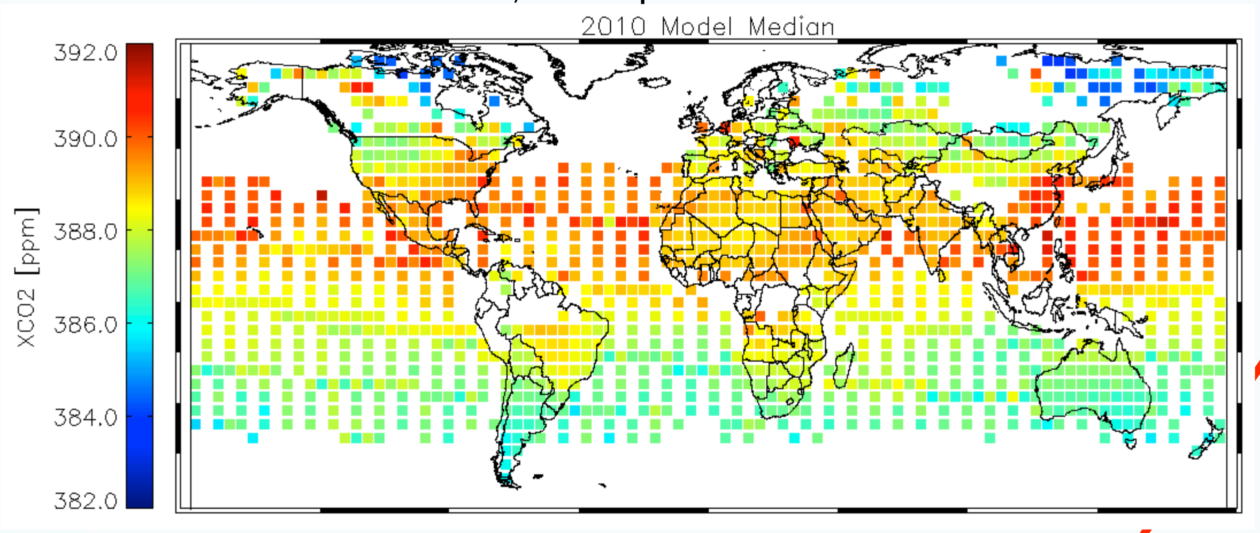


- The GOSAT seasonal cycles & trends closely match those at the ground validation sites.
- 1-sigma std. dev. vs. TCCON are ~ 2 ppm.
- So far we haven't answered the fundamental questions because data are quite noisy!

Figure from D. Wunch, Caltech

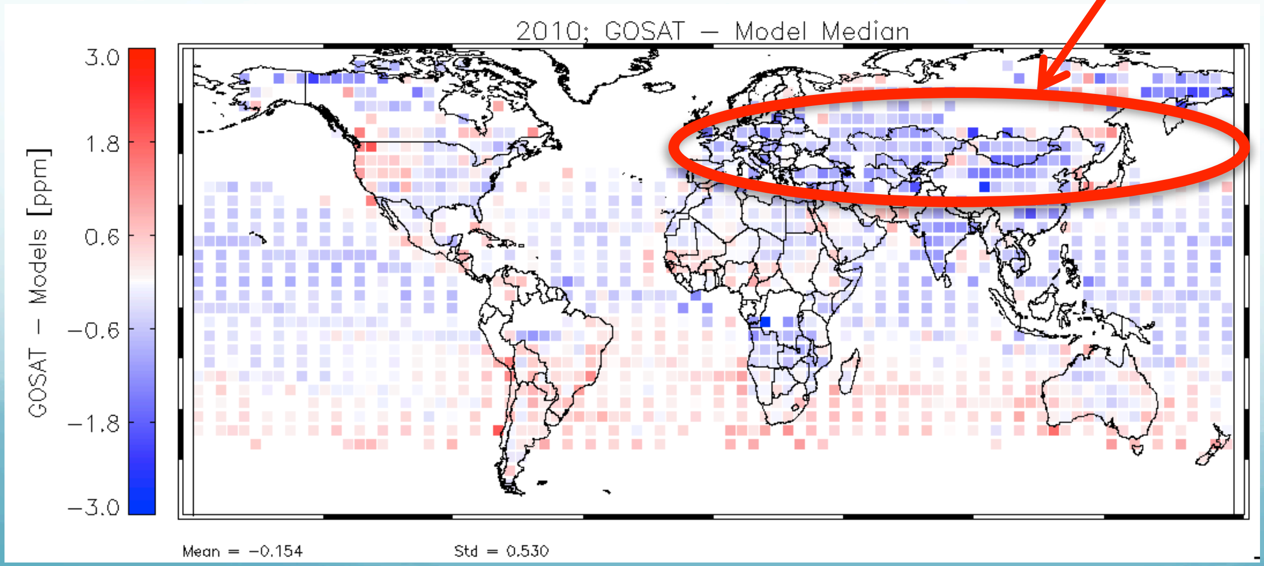
Comparisons vs. Ensemble of Models

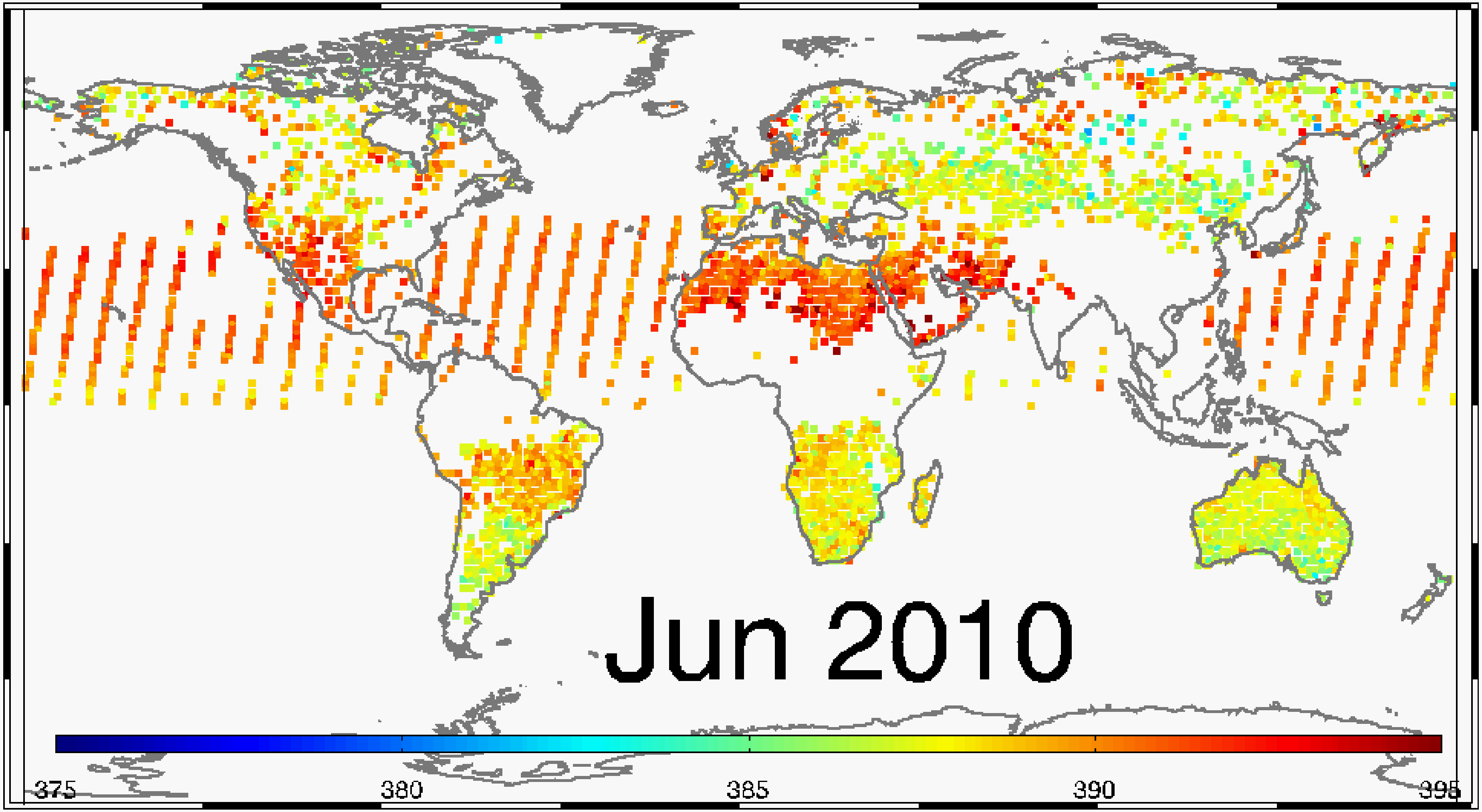
Ensemble of 7 Models, sampled at GOSAT observations



Bias, or indication of stronger drawdown in N.H. summer?

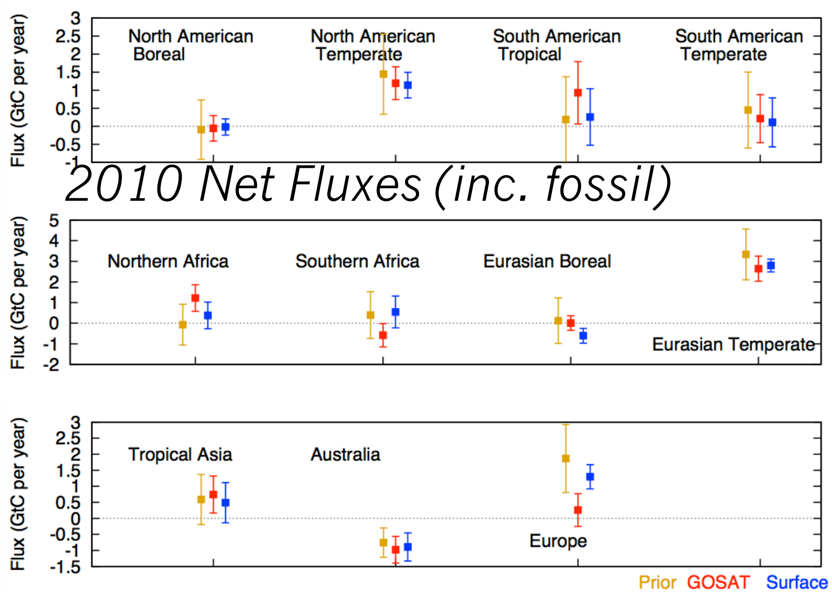
ACOS/GOSAT – MODEL Mean

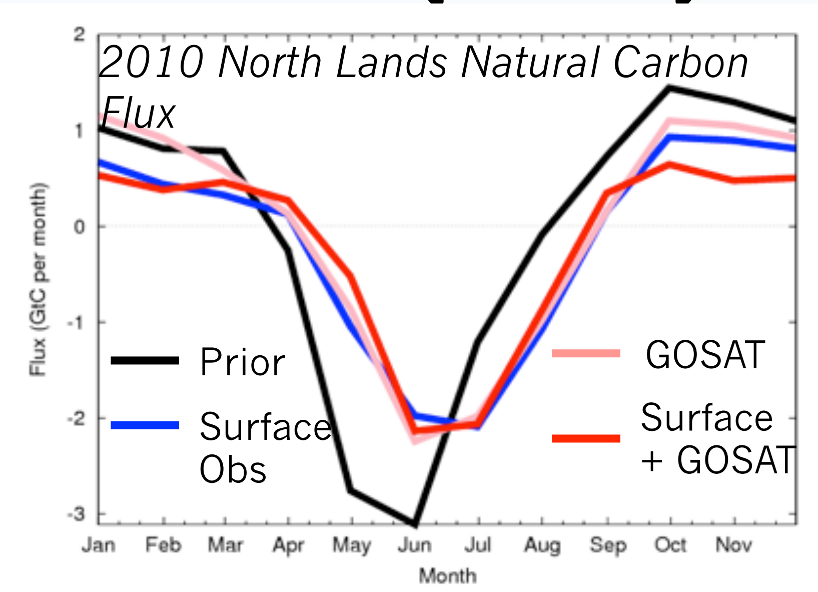




Jun 2010
375
380
385
390
395

LSCE+ACOS Flux Results (2010)





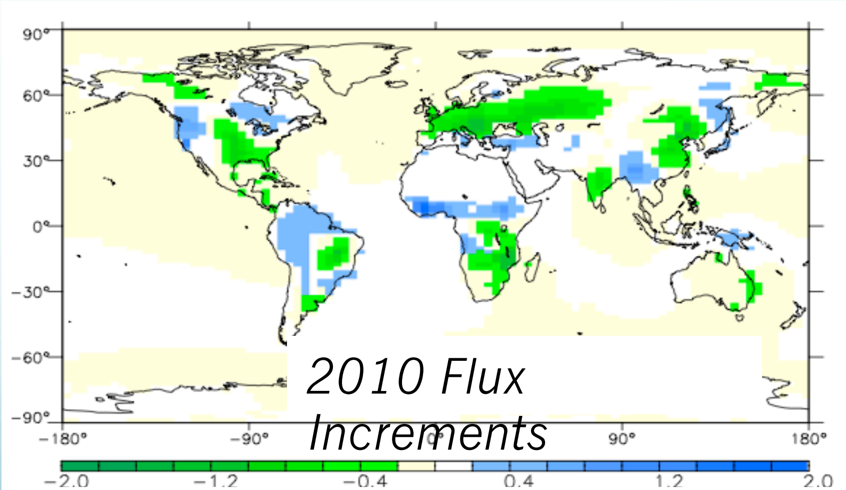
2010 CO_2 Growth Rate

Prior: 3.4 ± 1.9 ppm

Surface: 2.2 ± 0.2 ppm

GOSAT: 2.4 ± 0.2 ppm

NOAA: 2.4 ± 0.1 ppm

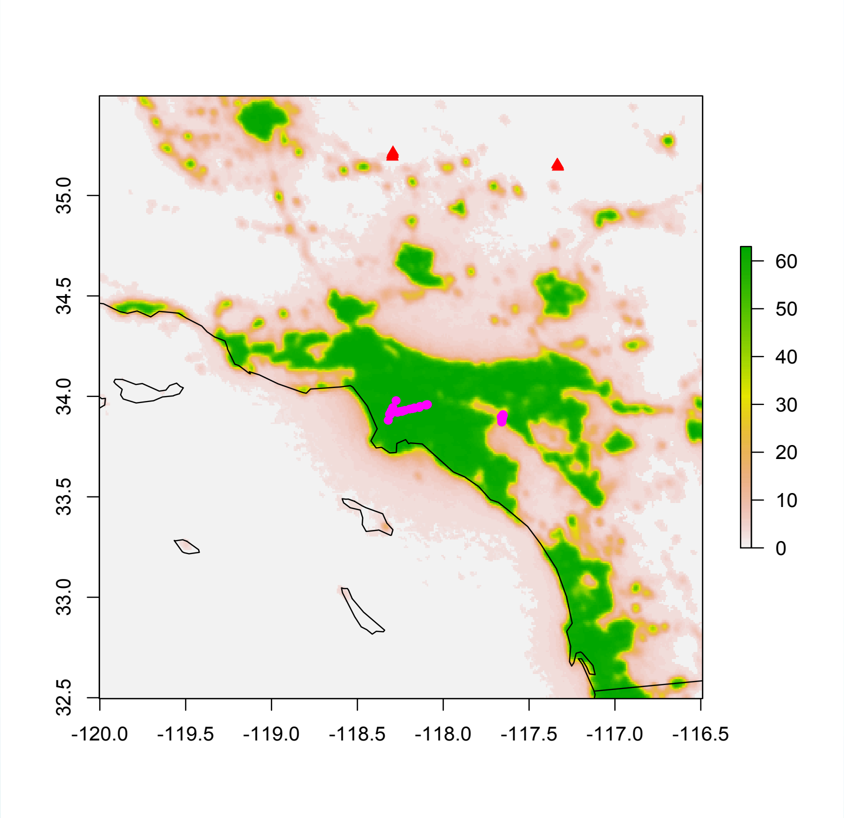


- General consistency between Surface and GOSAT
- Too little source in Europe?

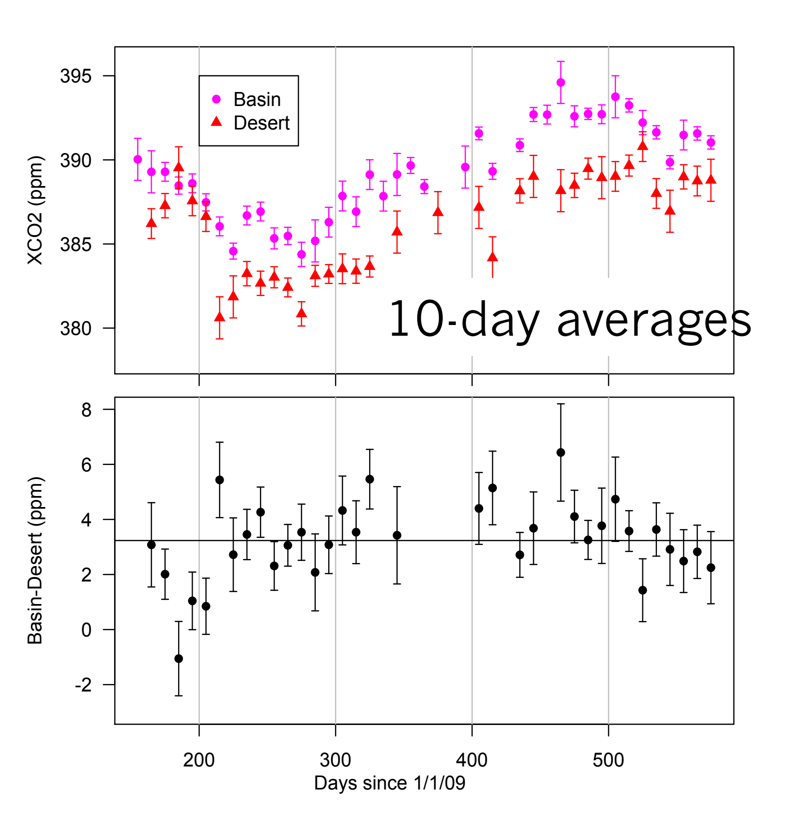
GOSAT Observations of Megacities?

- Can we see emissions on the city scale using differencing?
- ~70% of global energy-related emissions attributable to urban regions
- Megacities in developing countries growing at >4%/yr
- Biases in retrievals may partially cancel from urban to nearby rural regions

GOSAT Observations of Megacities



Selected GOSAT Footprints in LA Basin & surrounding desert, overplotted with night lights.

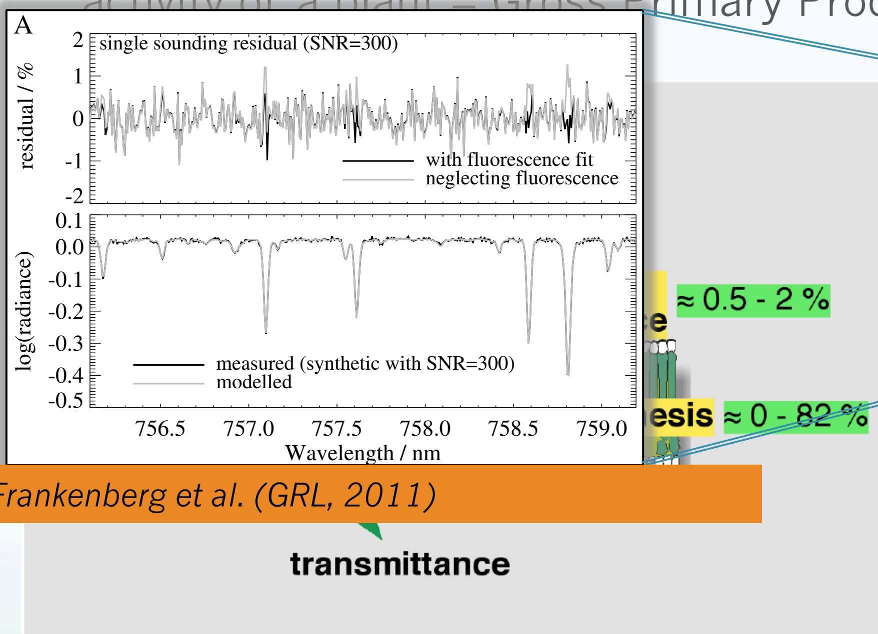


- Mean Basin-Desert difference = **3.2 ppm**
- **0.7 ppm** difference detectable at 95% conf.
- Translates to ability to detect 22% change in L.A. emissions.

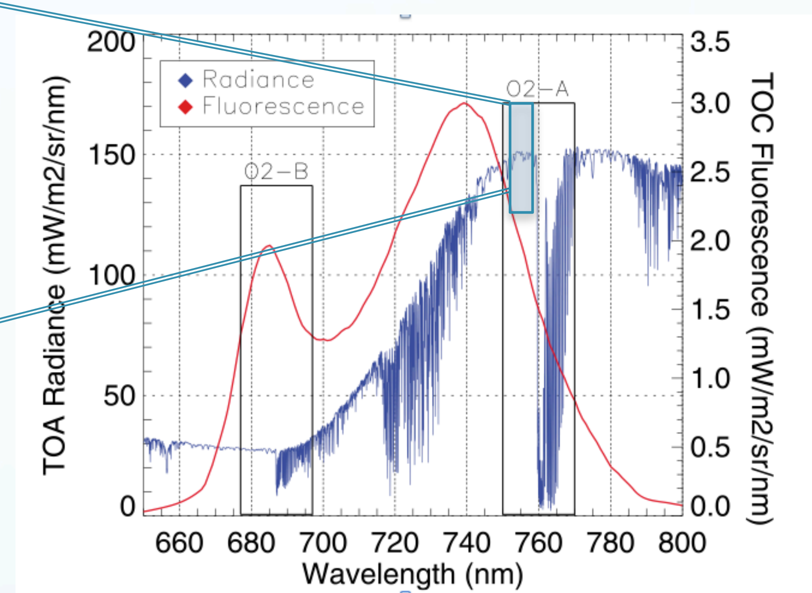
from Eric Kort (JPL)

Another spin-off: Chlorophyll Fluorescence

- Chlorophyll fluorescence may provide a **direct probe** into the photosynthetic activity of a plant = Gross Primary Production (GPP)



Frankenberg et al. (GRL, 2011)



- Can be viewed by the filling-in effect of Solar & Oxygen lines in the Oxygen-A band of GOSAT, OCO-2, etc.

- Retrieval based on the solar lines alone can determine fluorescence, with errors <~ 10%.

The CO_2 – fluorescence synergy

OCO & GOSAT measure NET CO_2 fluxes

Fluorescence enables monitoring of "Gross Primary Production" – the land-based sink.

Offers potential:

- To disentangle sources & sinks.
- Better process-level understanding (e.g. drought tolerance)

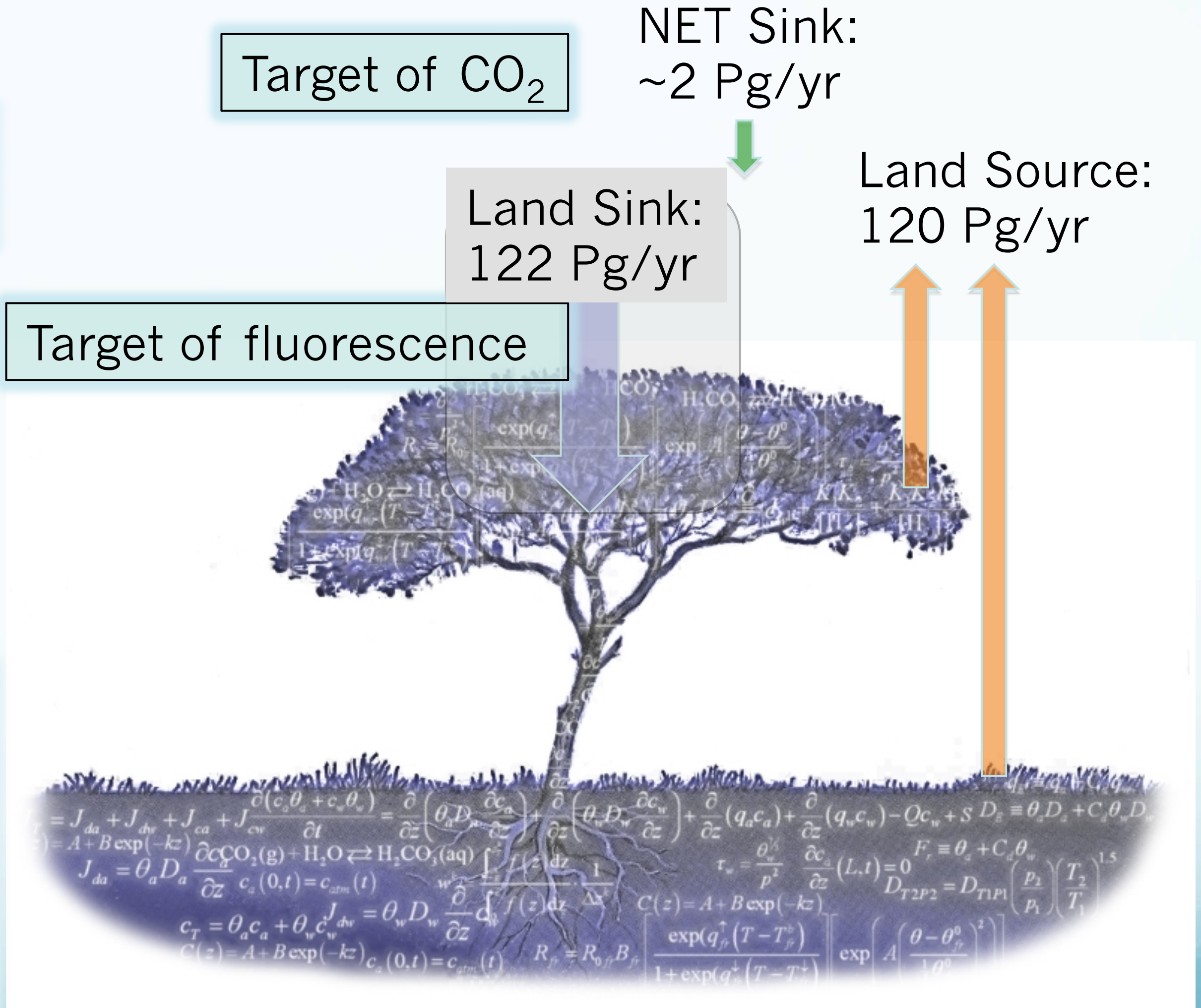


Figure from MPI-BGC Jena

Biogeosciences, 8, 637–651, 2011
www.biogeosciences.net/8/637/2011/
doi:10.5194/bg-8-637-2011

Biogeosciences

First observations of global and seasonal terrestrial chlorophyll fluorescence from space

J. Joiner[1], Y. Yoshida[2], A. P. Vasilkov[2], Y. Yoshida[3], L. A. Corp[4], and E. M. Middleton[1]

[1]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2]Science Systems and Applications Inc., 10210 Greenbelt, Rd., Ste 400, Lanham, MD, USA
[3]National Institute for Environmental Studies (NIES), Tsukuba-City, Ibaraki, Japan
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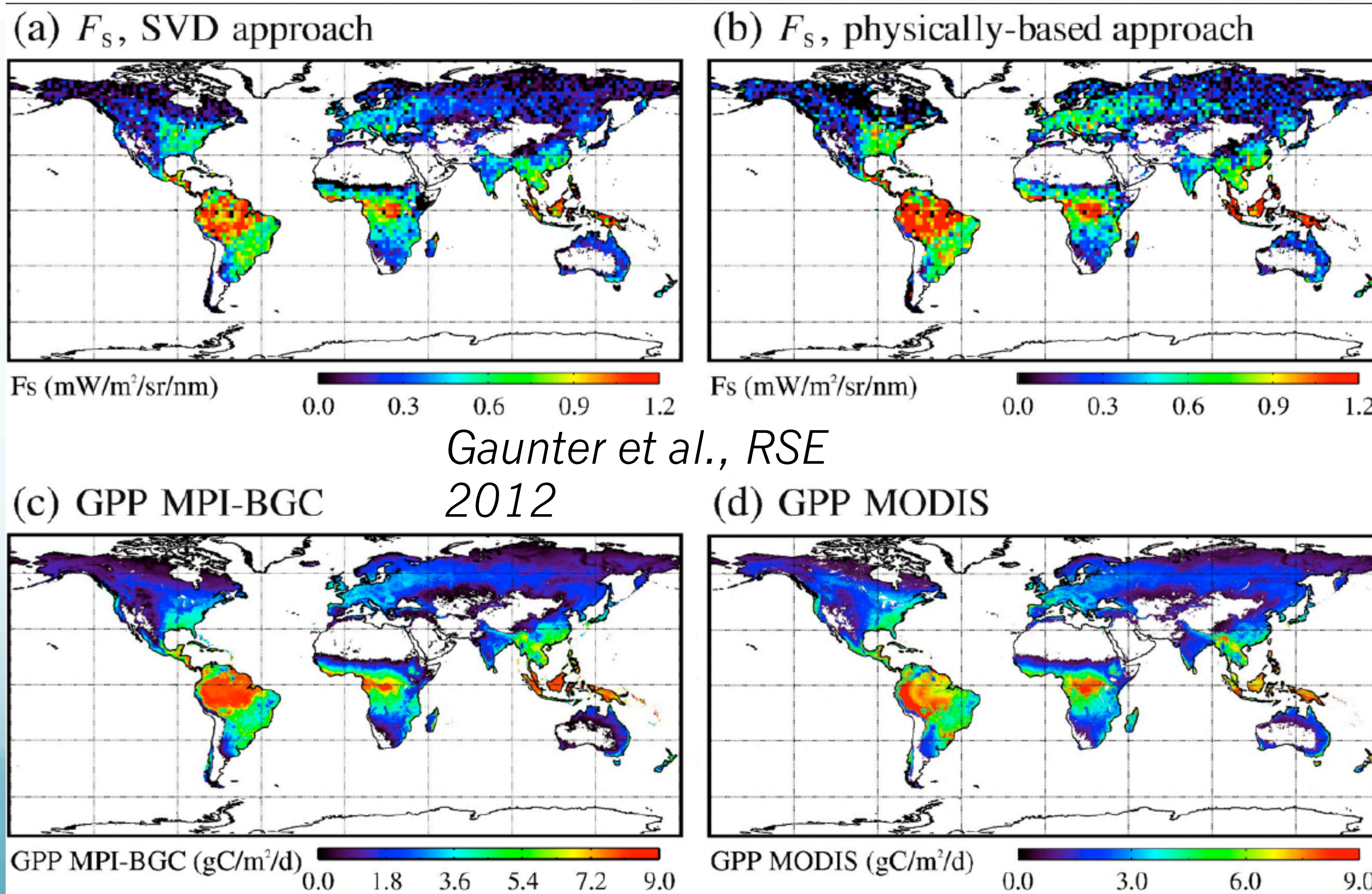
GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L17706, doi:10.1029/2011GL048738, 2011

New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity

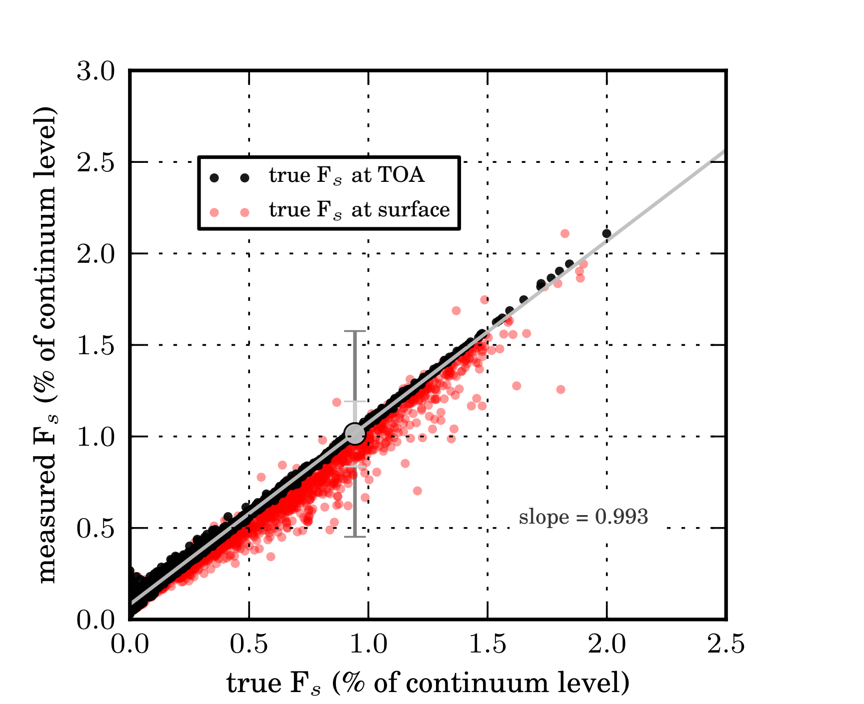
Christian Frankenberg,[1] Joshua B. Fisher,[1] John Worden,[1] Grayson Badgley,[1] Sassan S. Saatchi,[1] Jung-Eun Lee,[1] Geoffrey C. Toon,[1] André Butz,[2] Martin Jung,[3] Akihiko Kuze,[4] and Tatsuya Yokota[5]

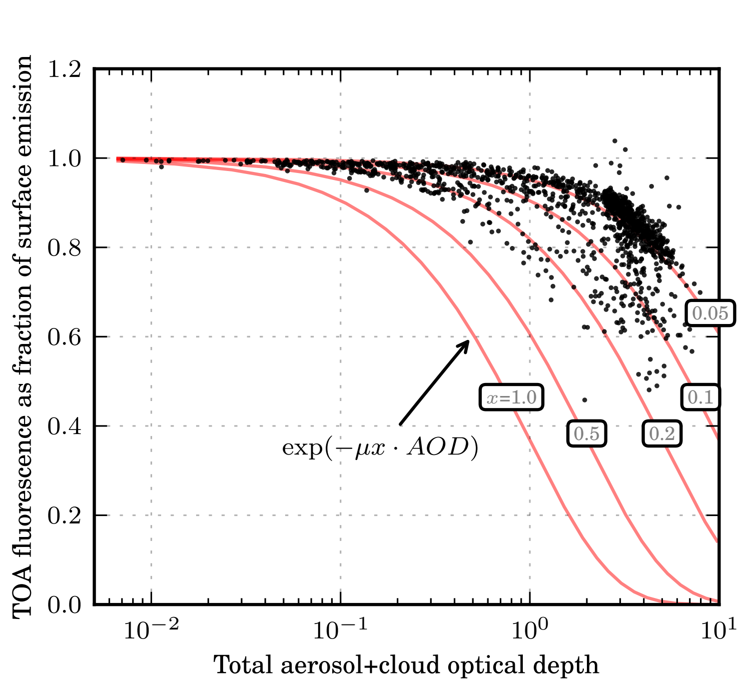
Received 30 June 2011; revised 11 August 2011; accepted 16 August 2011; published 14 September 2011.



Gaunter et al., RSE 2012

May work in cloudy conditions!



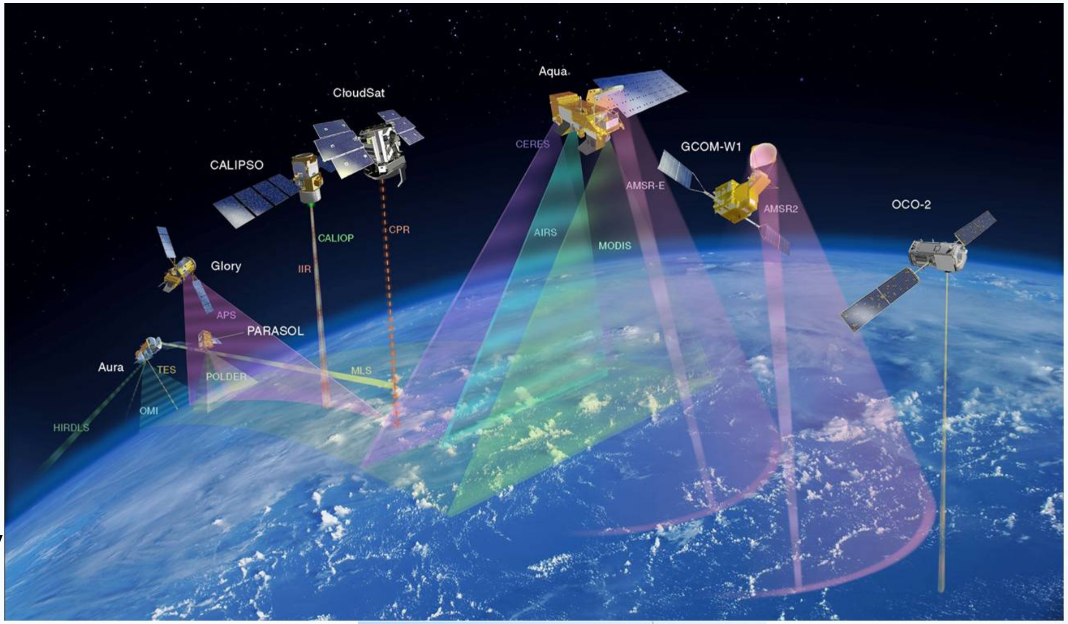


- Virtually no remotely-sensed land surface products work in all-sky conditions – can lead to clear-sky bias problems
- The signature of Fraunhofer lines in the solar spectrum is only erased via chlorophyll fluorescence; to first order it is unaffected by clouds.

Frankenberg, O'Dell, Gaunter, McDuffie, AMT 2012

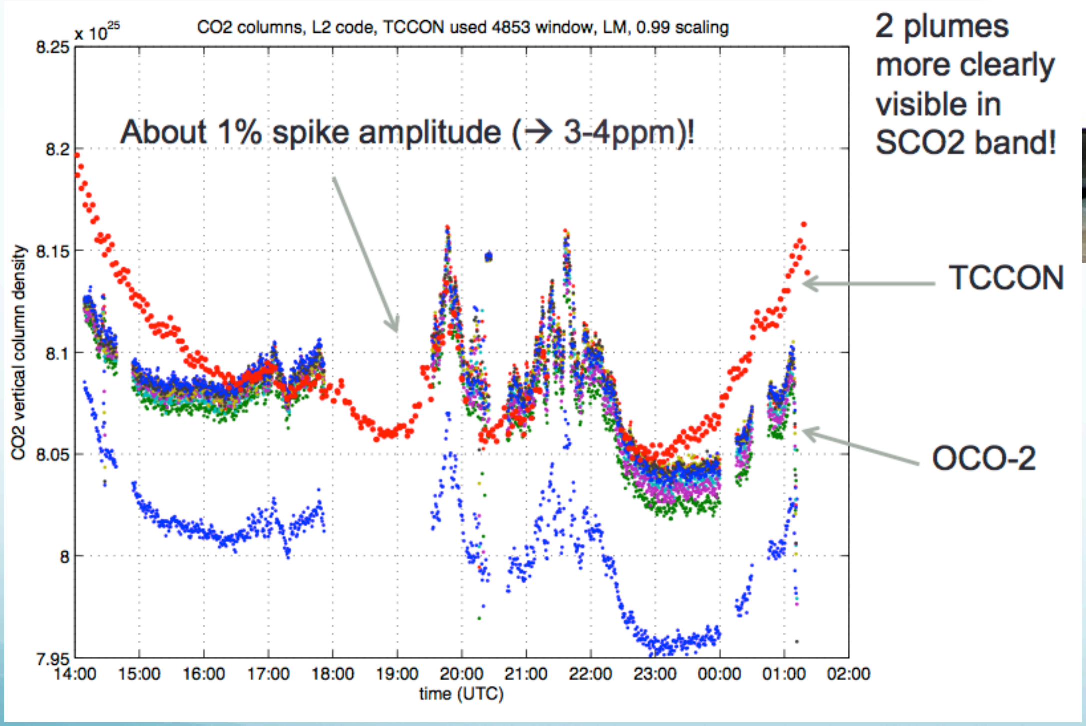
The awesomeness of OCO-2

- Will take 50-100x as many soundings as GOSAT.
- Has small 1.5 km footprint (compared to 10 km for GOSAT)
- Will fly at the head of the "A-Train", a constellation of many earth-observing satellites in a polar, sun-synchronous orbit.
- Amazing synergy is possible with other instruments in A-Train, particularly AIRS, CloudSat+Calipso
- Tentative Launch in July 2014



OCO-2 in the lab

OCO-2 being tested



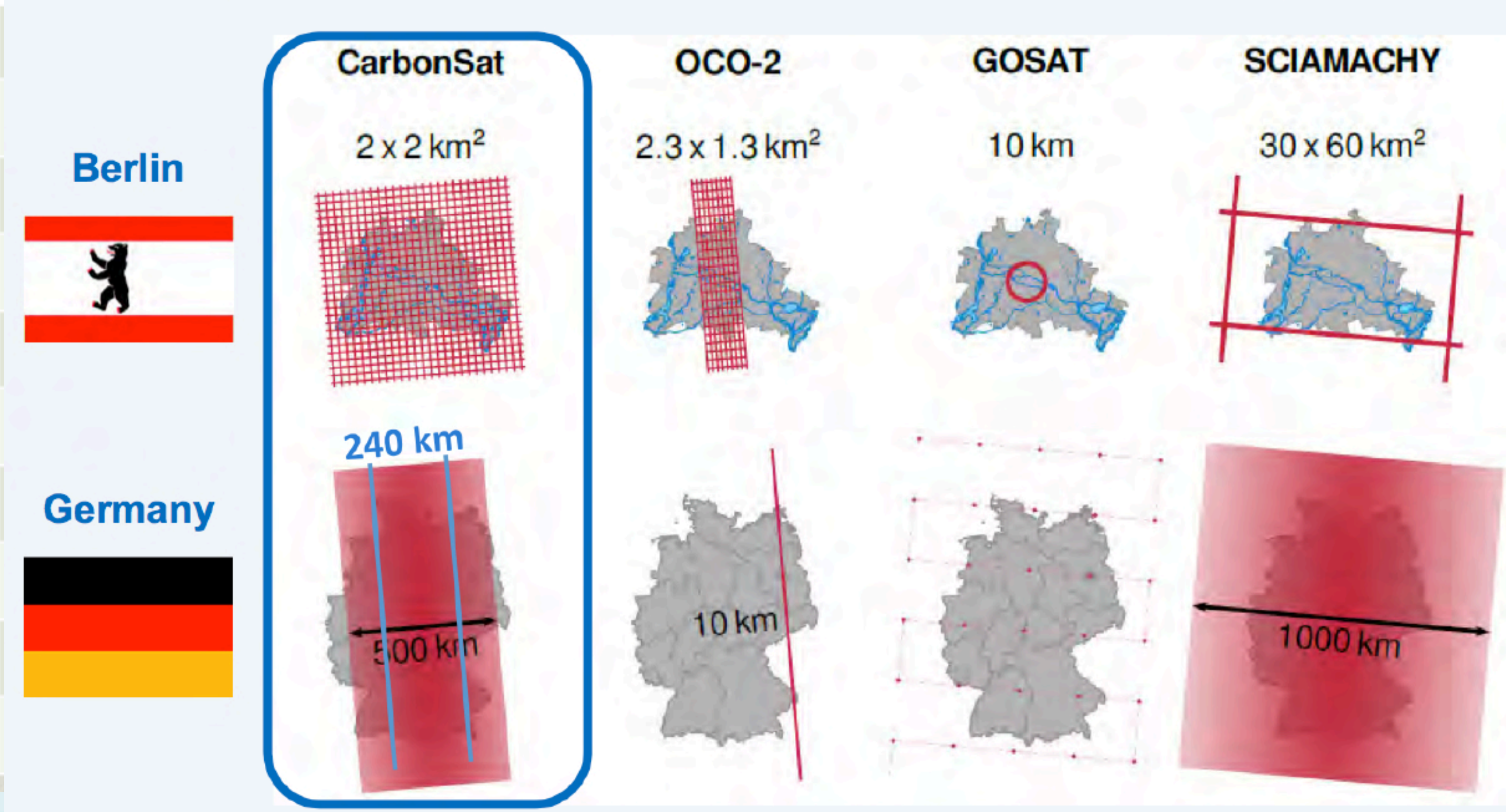
Sun viewed by OCO-2 at JPL: April 20, 2012

The coming swarm of GHG satellites

(Calender year)

Mission	Gases FOV
ESA SCIAMACHY	Many 30x60+ km
Japan GOSAT	CO2, CH4 10 km
NASA OCO-2	CO2 1x1.5 km
China TanSat	CO2 2x1 km
ESA TROPOMI	CO, CH4,,,, 7x7 km
CNES/DLR MERLIN	CH4 50 km
Japan GOSAT-2	CO2, CH4 3-4 km
CNES MicroCarb	CO2 15-25km2
ESA CarbonSat	CO2, CH4 2x2 km
NASA ASCENDS	CO2

2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025



CO2 Satellites : Nominal mission period

Non-CO2 Satellites : Nominal mission period

Extended mission period

Funded period

Technically feasible period

We are here.