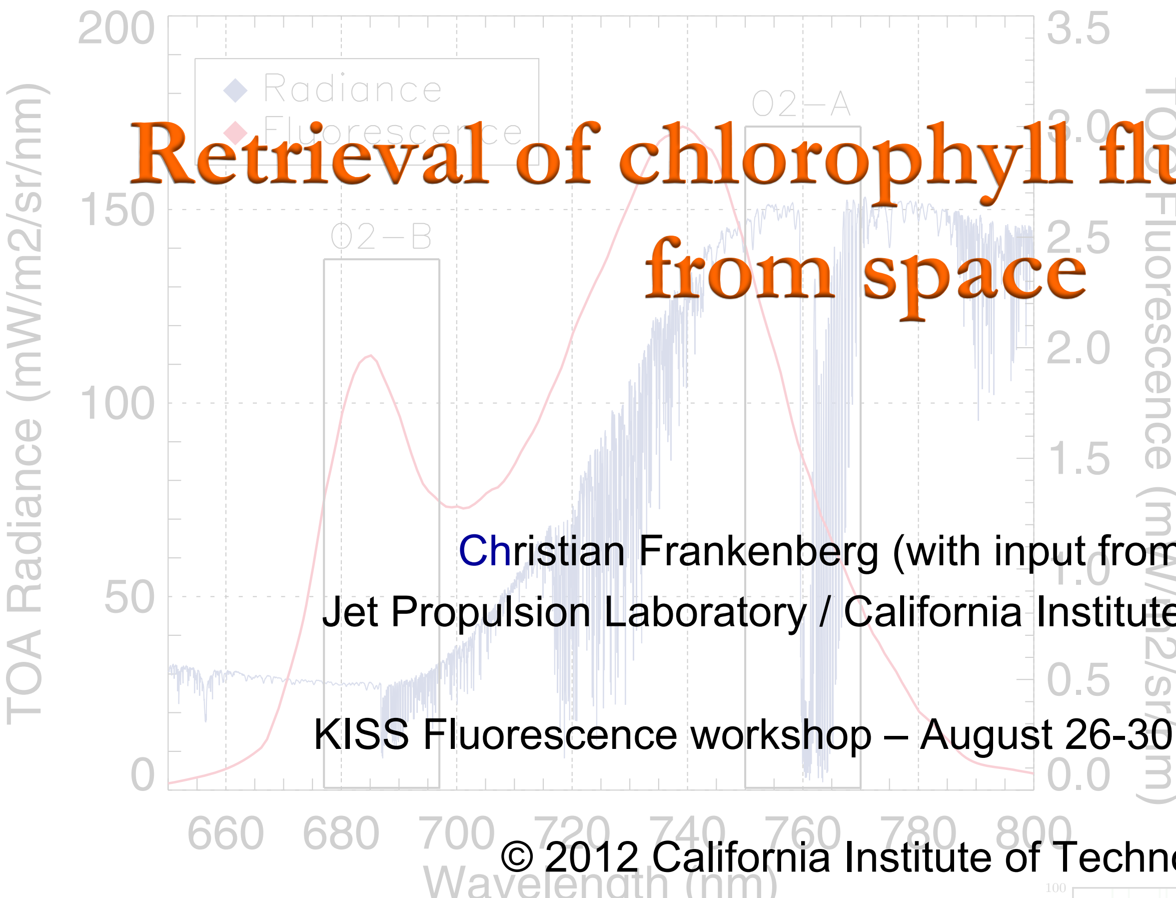
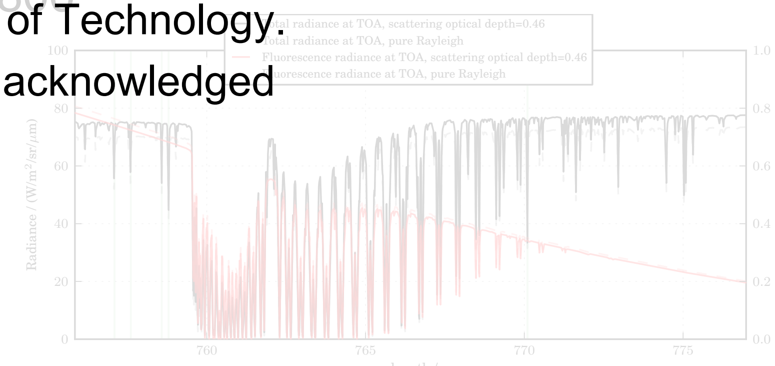
Retrieval of chlorophyll fluorescence from space



Christian Frankenberg (with input from others)
Jet Propulsion Laboratory / California Institute of Technology

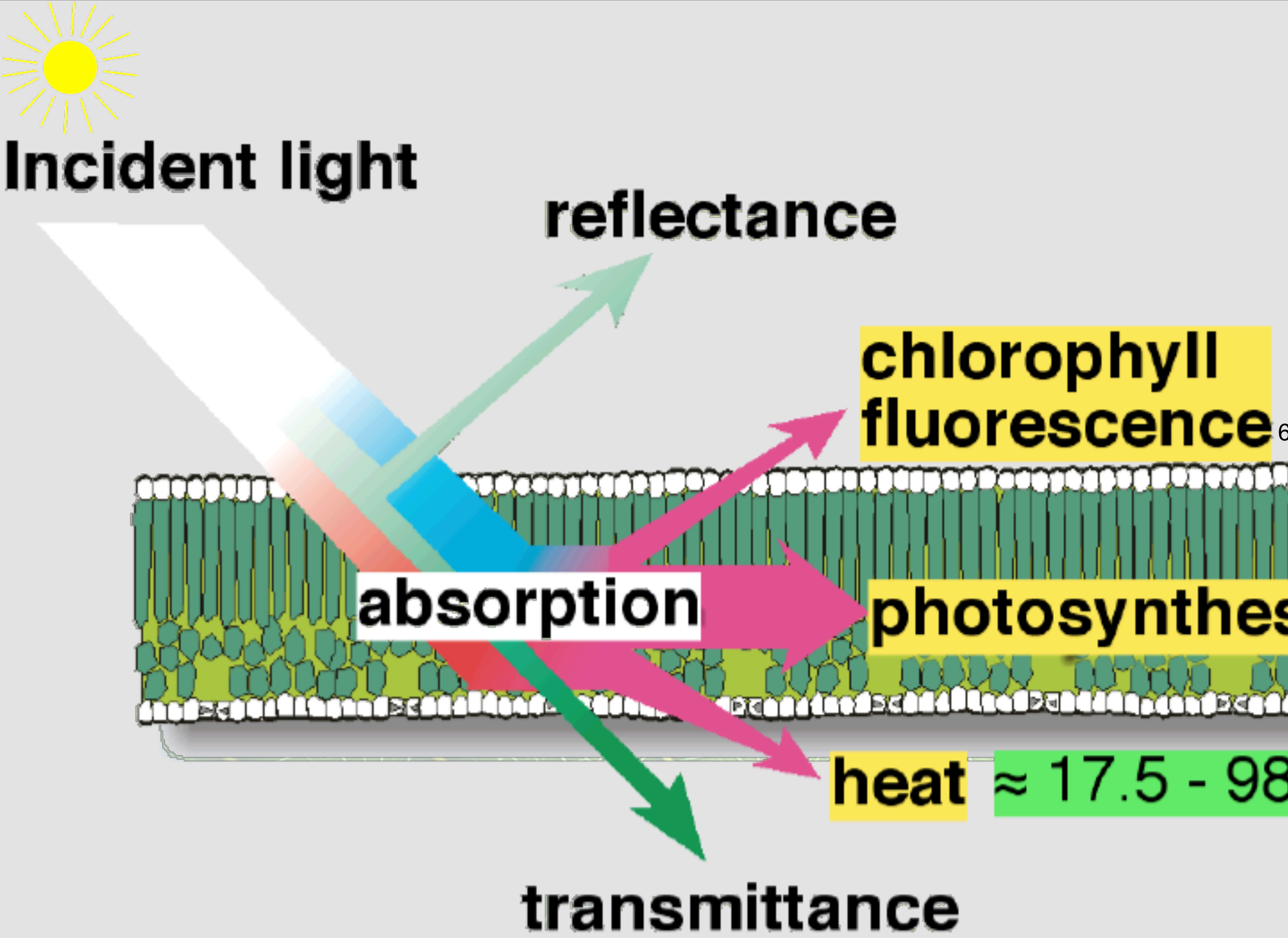
KISS Fluorescence workshop – August 26-30, Pasadena, CA

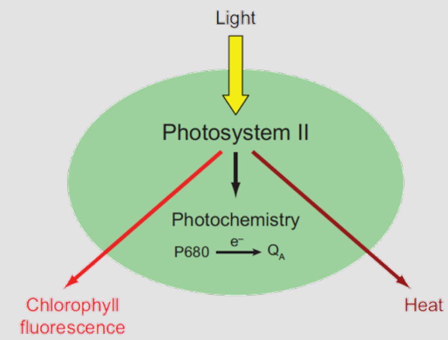


Outline

- Motivation
- The fluorescence signal and how it is manifested in measurements
- Methods for retrieving fluorescence from
  - ground
  - space
- Initial results from the Japanese GOSAT satellite

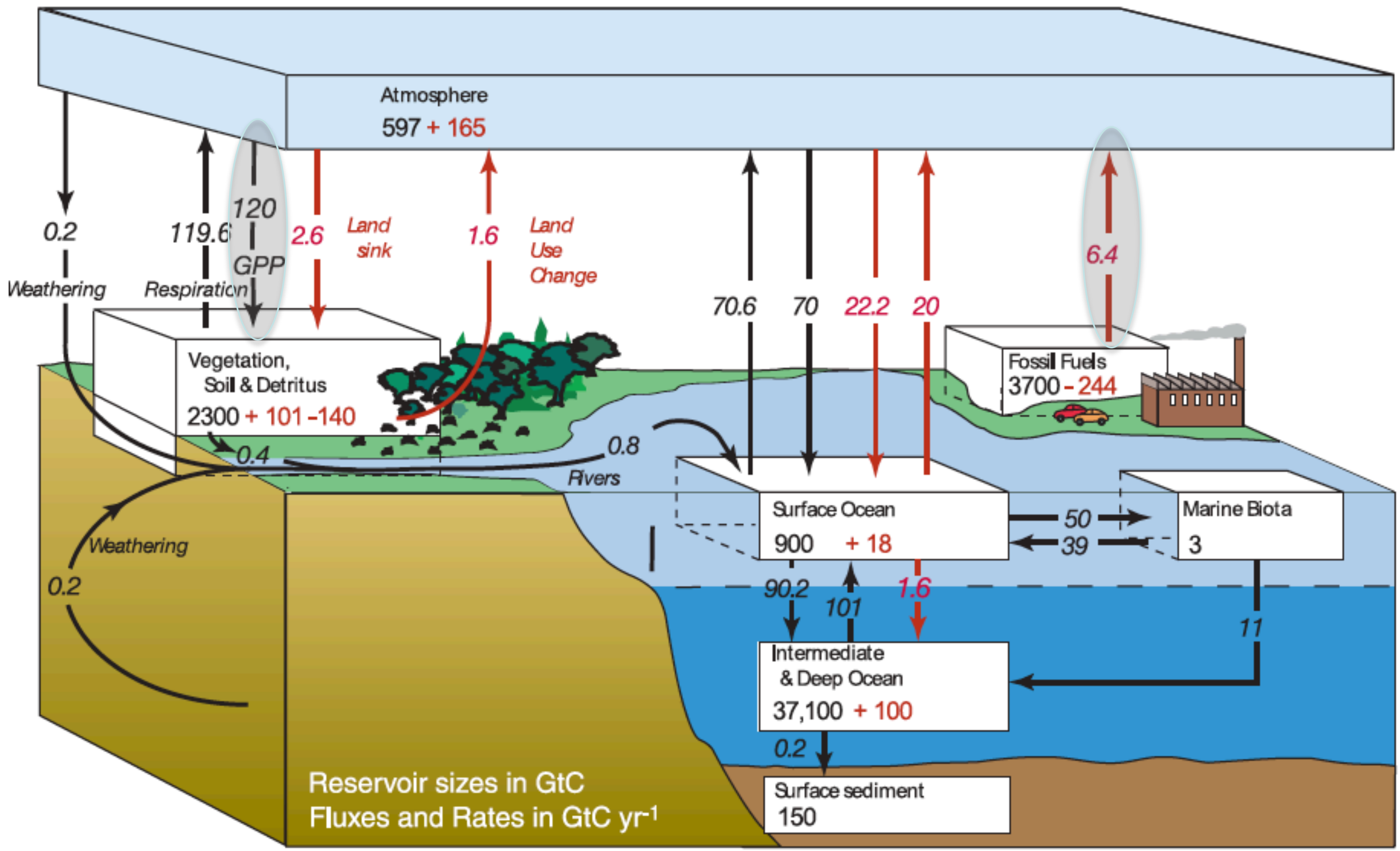
Chlorophyll fluorescence always a by-product of photosynthesis





The global carbon cycle (IPCC AR4)

Focus on Gross Primary Production (GPP)



Introduction

- Gross primary production (GPP) through photosynthesis by terrestrial ecosystems constitutes the largest global carbon sink
- Two main spatially explicit approaches to quantify GPP globally:
  1) Meteorology-driven full land surface carbon cycle models (coupled or uncoupled);
  2) Remote sensing-driven and/or flux tower based semi-empirical models
- Uncertainties in existing approaches:
  1) Model sensitivities, parameterization
  2) Indirectly inferred from “greenness”

Carbon cycle, synergy with net flux measurements

On an annual basis, natural CO_2 fluxes are almost balanced

OCO-2 will enable inversion of net fluxes (not disentangling uptake from respiration)

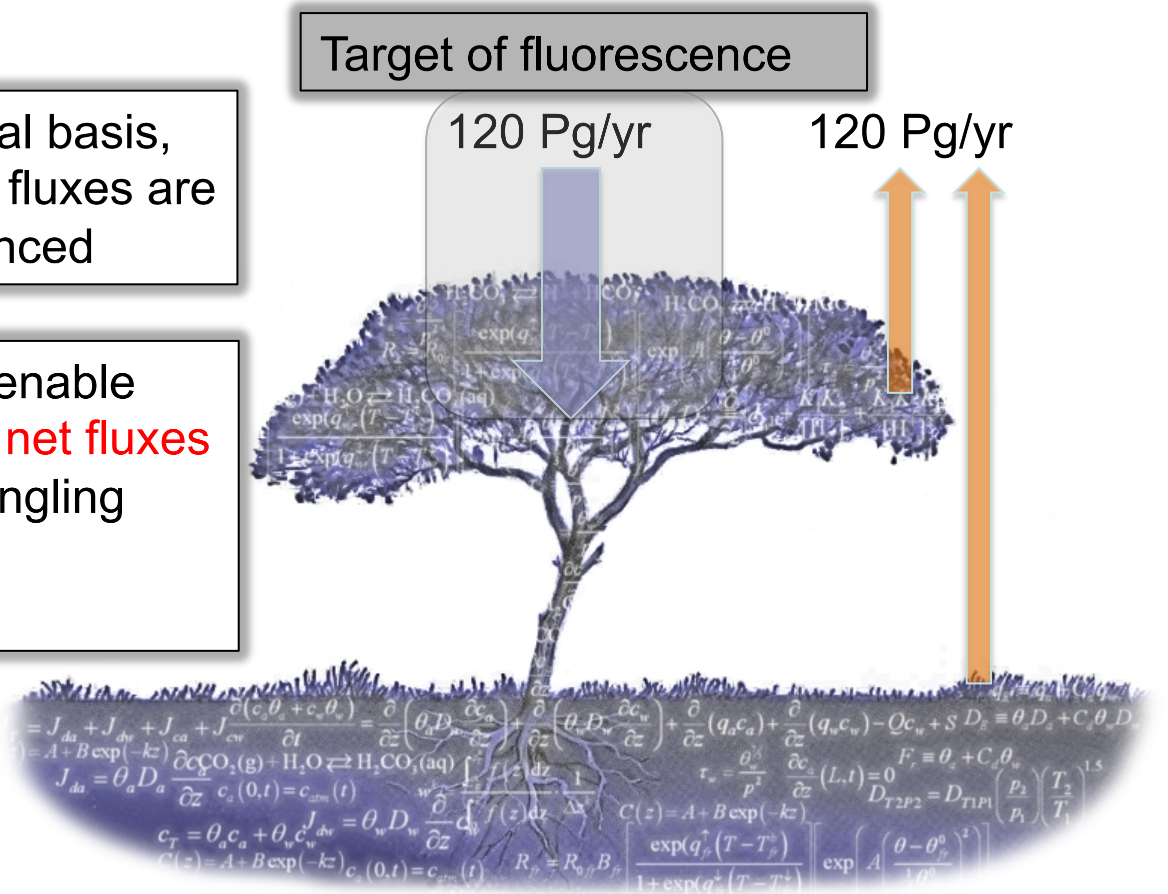
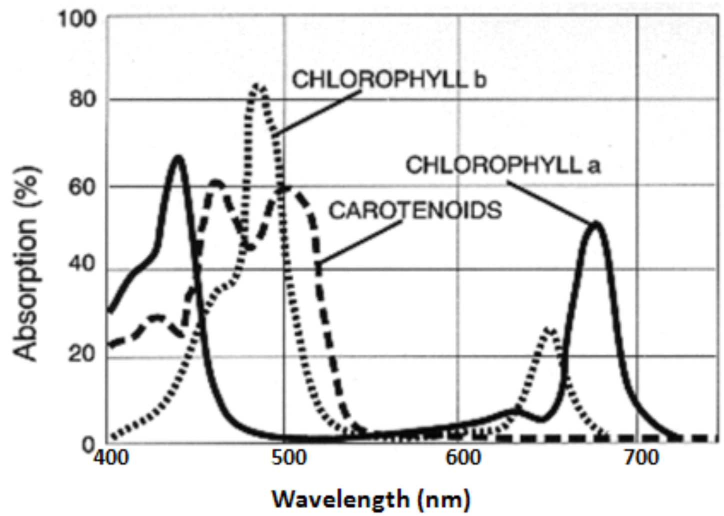
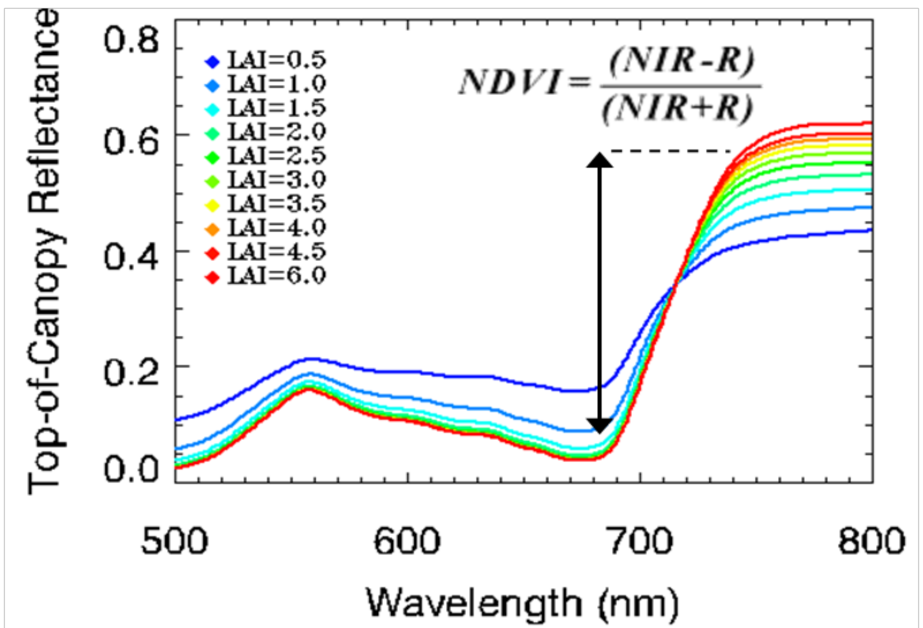


Figure from MPI-BGC Jena

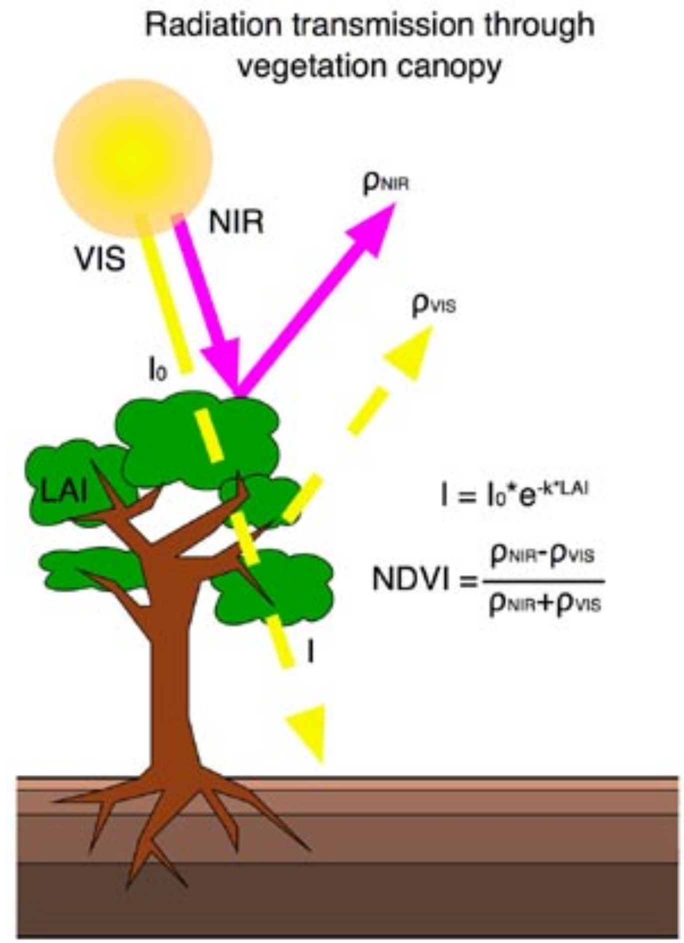
(traditional) Optical Remote Sensing Parameters (mainly based on absorption spectrum of chlorophyll)



http://www.myledlightingguide.com/Blog/Images/PicB3.png

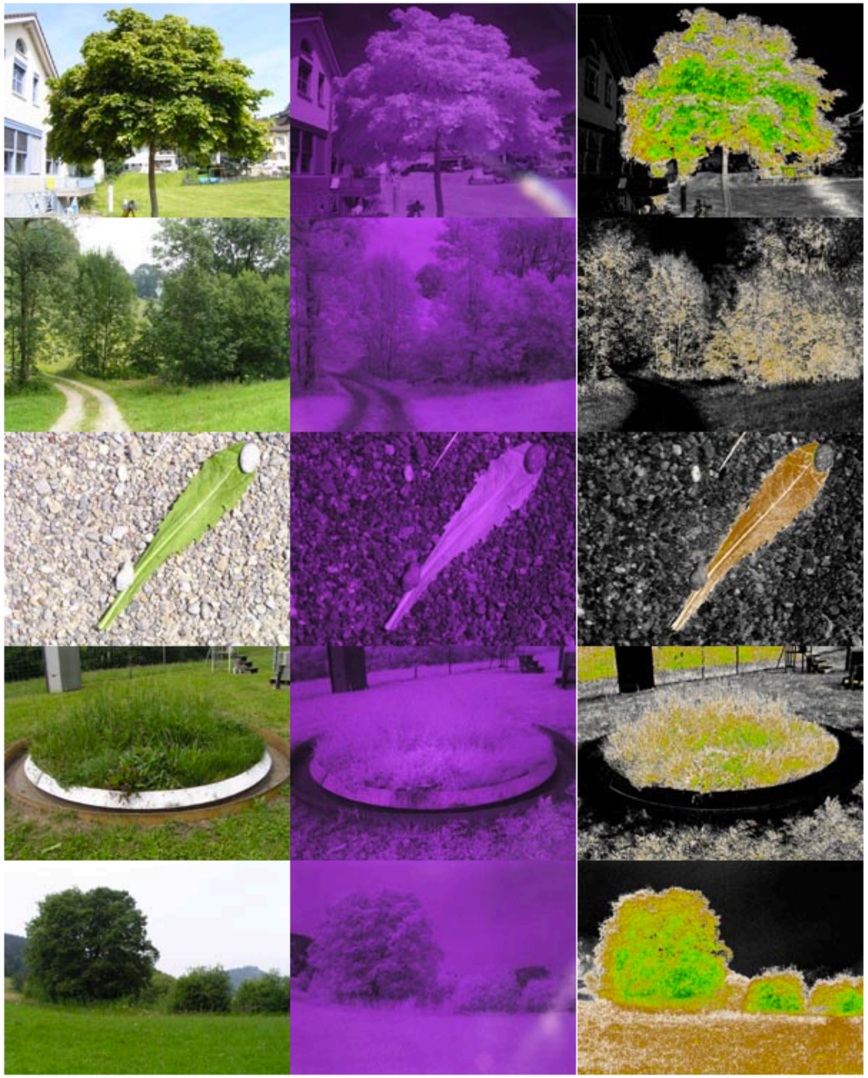


From Luis Guanter



http://bluemarble.ch/

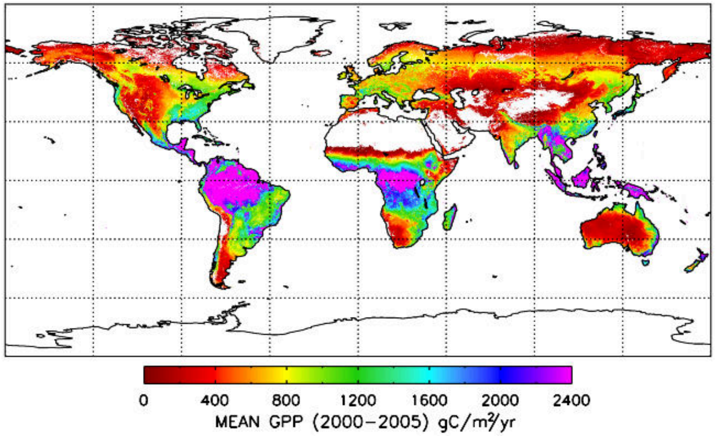
(traditional) Optical Remote Sensing parameters



VIS NIR NDVI

http://bluemarble.ch/

(traditional) Optical Remote Sensing parameters
Satellite example: MODIS, the vegetation RS work-horse



From NTSG website (MODIS derived GPP)

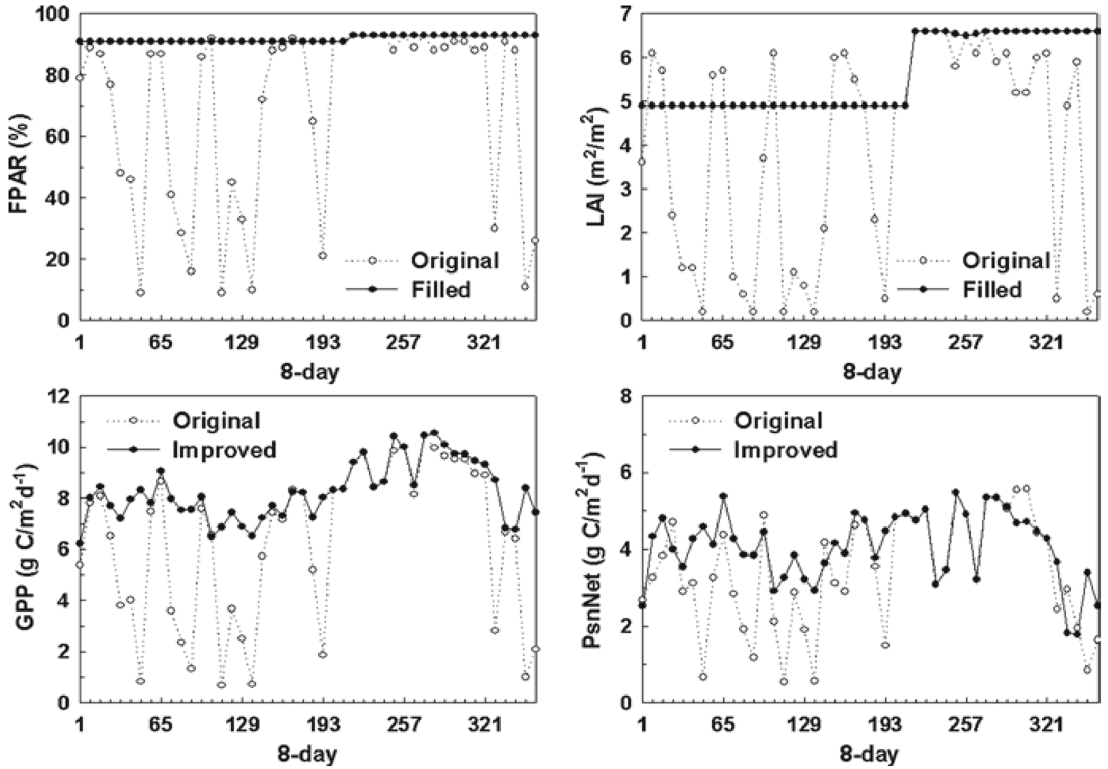


Fig. 28.6 An example depicting temporal filling unreliable 8-day Collection-4 FPAR/LAI, and therefore improved 8-day GPP and PsnNet for one MODIS 1-km pixel located in Amazon basin (lat = –5.0, lon = –65.0) (Zhao et al. 2005)

Pros:

- High spatial resolution (sub-km)
- Full global mapping (no sampling)

Cons:

- Susceptible to atmospheric contamination
- Can saturate in dense forests
- Indicative of greenness, not activity (hence modeling for GPP needed)

Chlorophyll Fluorescence

Daumard et al, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING (2010)
A Field Platform for Continuous Measurement of Canopy Fluorescence

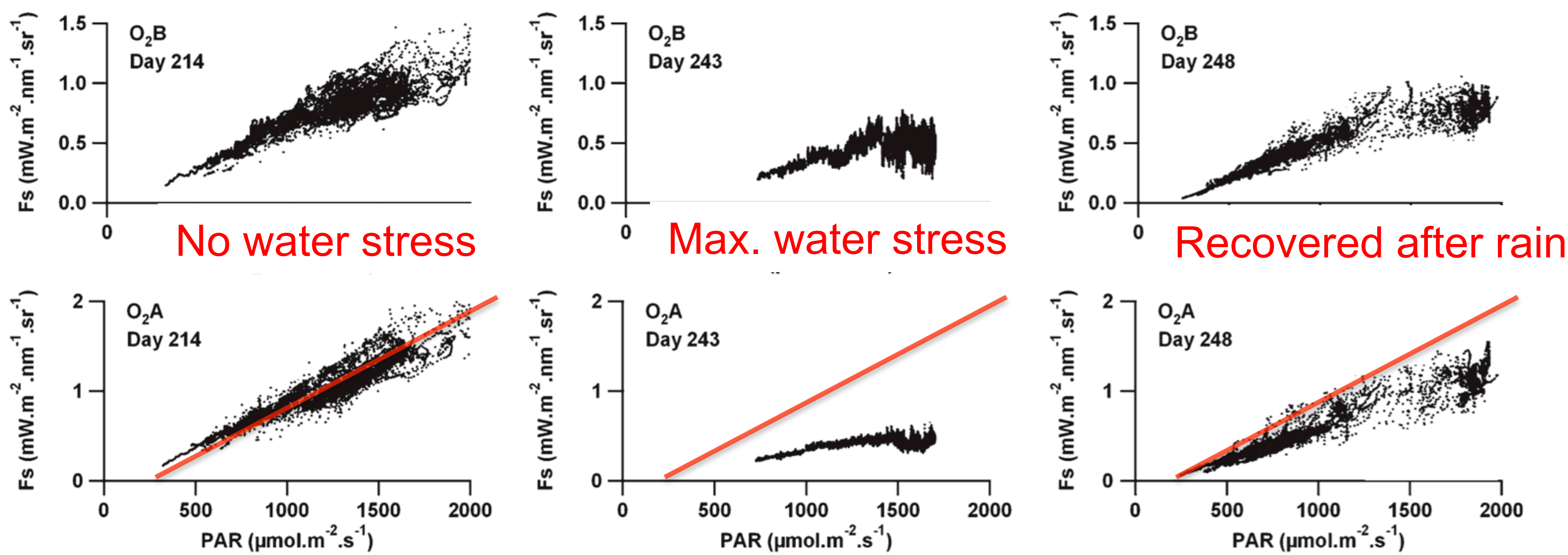
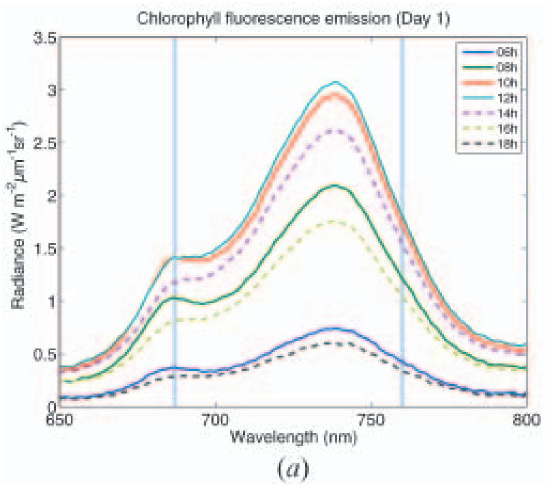


Fig. 10. Fluorescence flux (Fs) versus PAR for three days: 214 no water stress, 243 maximal water stress effect, 248 after rainy days, and reversion of water stress.

"It is worth noting that neither the chlorophyll content of leaves (almost constant with a value of 49.3 ± 2.4 µg · cm−2) nor the NVDI indicates a noticeable variation during the measuring campaign. This emphasizes the greater sensitivity of PRI and fluorescence parameters to physiological changes in the sorghum field than chlorophyll or NDVI."

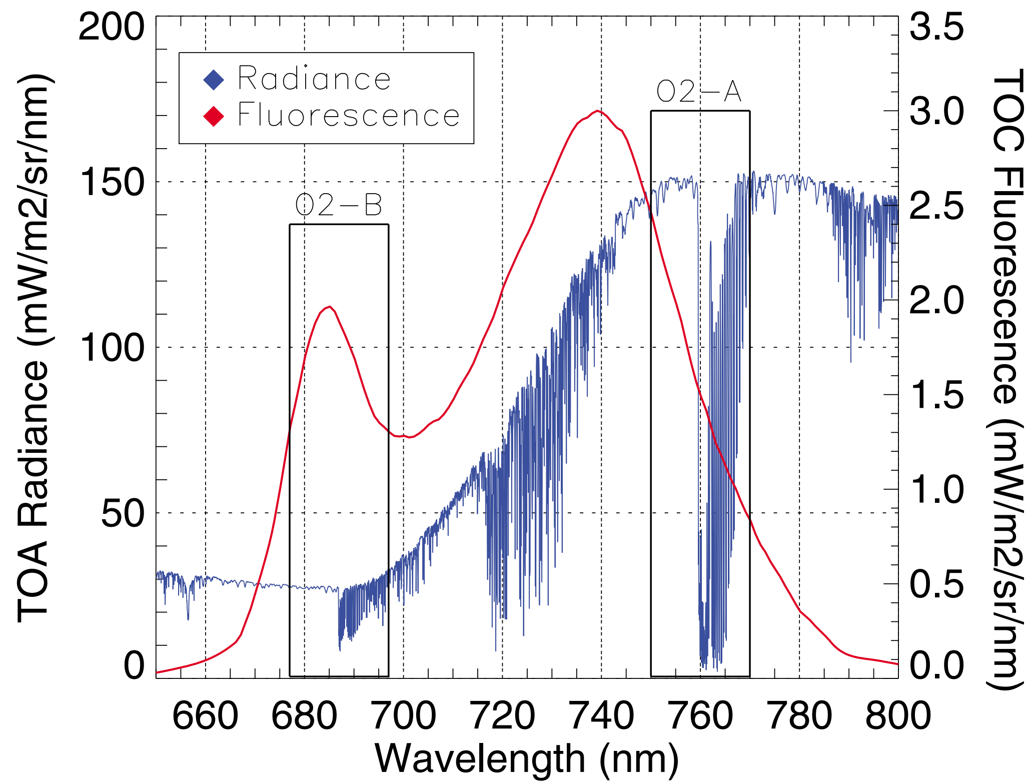
Chlorophyll fluorescence



Fluorescence emission spectra
Amoros-Lopez et al, Int. Journal of Remote Sensing (2008)

"The studied cases show that the ChF emission is mainly driven by the photosynthetic active radiation during the whole cycle, but the fluorescence yield is severely reduced during the central hours of the day when the plant is under stress due to light and heat."

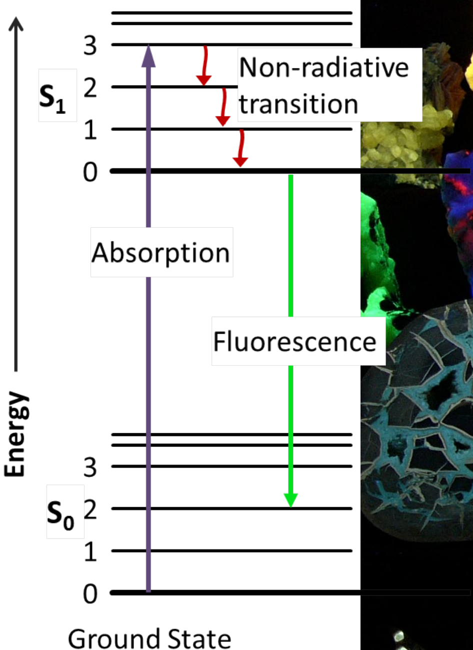
Reflectance and Fluorescence emission spectrum
Guanter et al, JGR, 2010

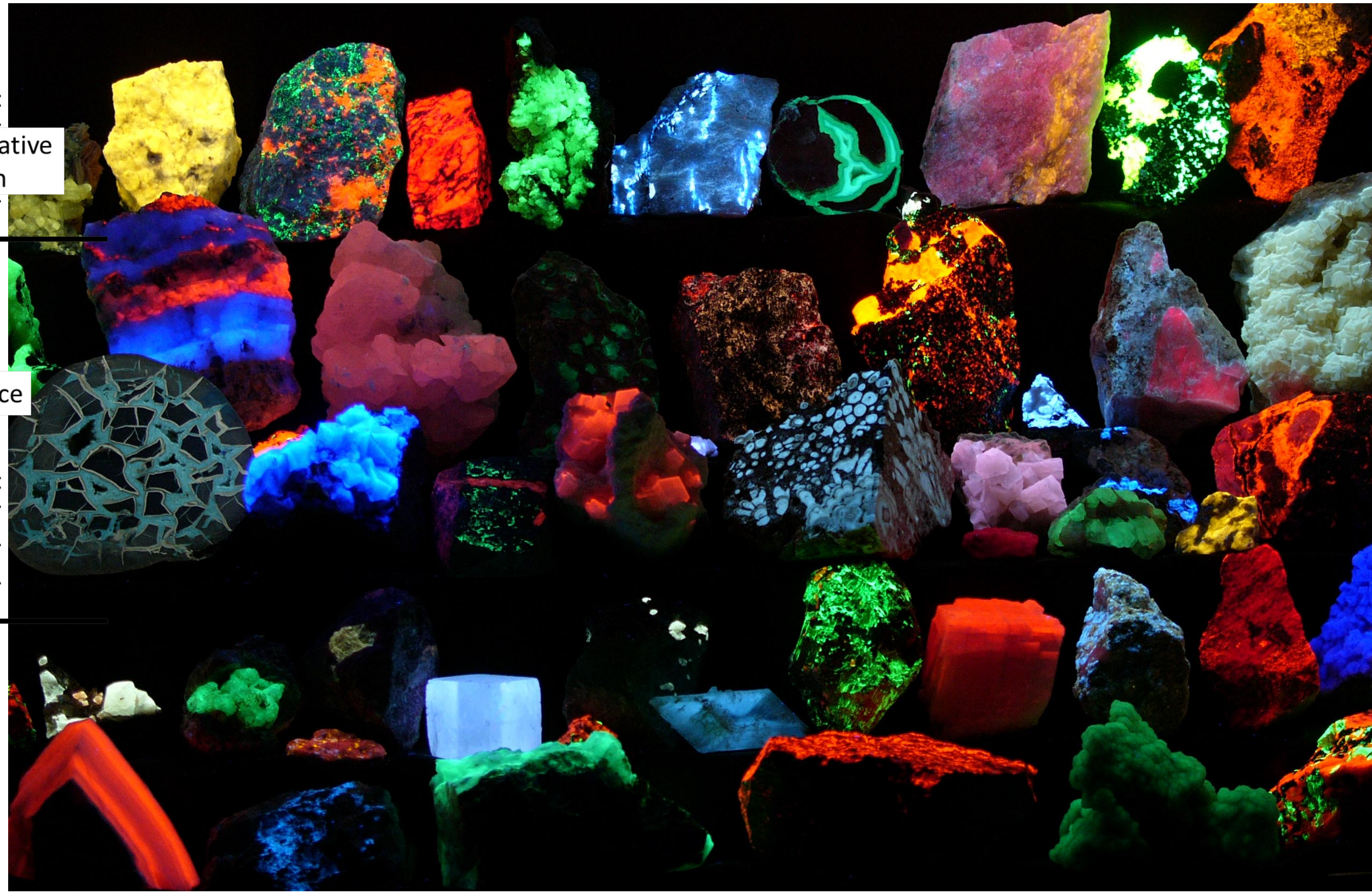


Fluorescence detection

If only it was that easy…

(For chlorophyll fluorescence from space, we can't just switch the NIR red light off)

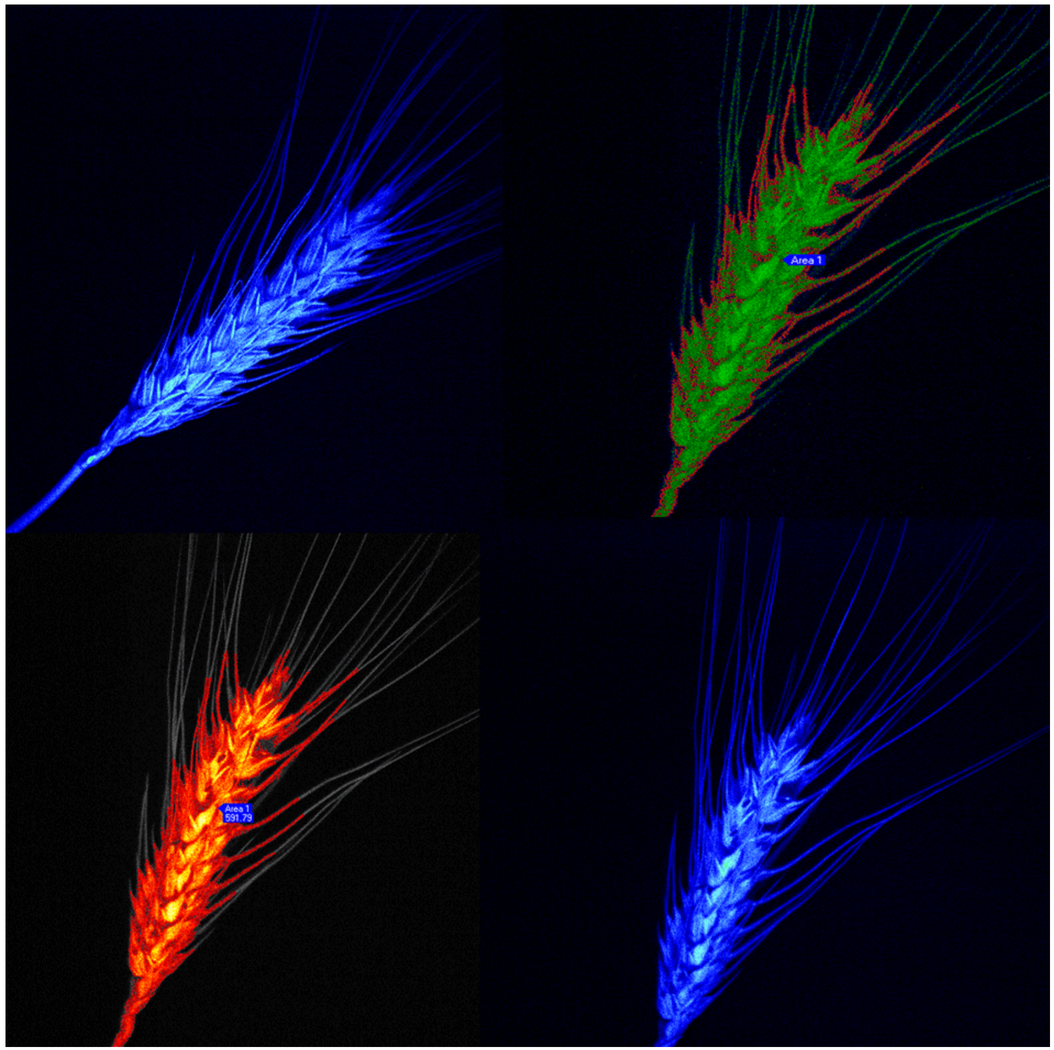




Fluorescent minerals emit visible light when exposed to ultraviolet light (from Wikipedia)

Fluorescence detection

But in the laboratory, you can filter out incoming NIR light and photograph chlorophyll emission using NIR sensitive detectors…

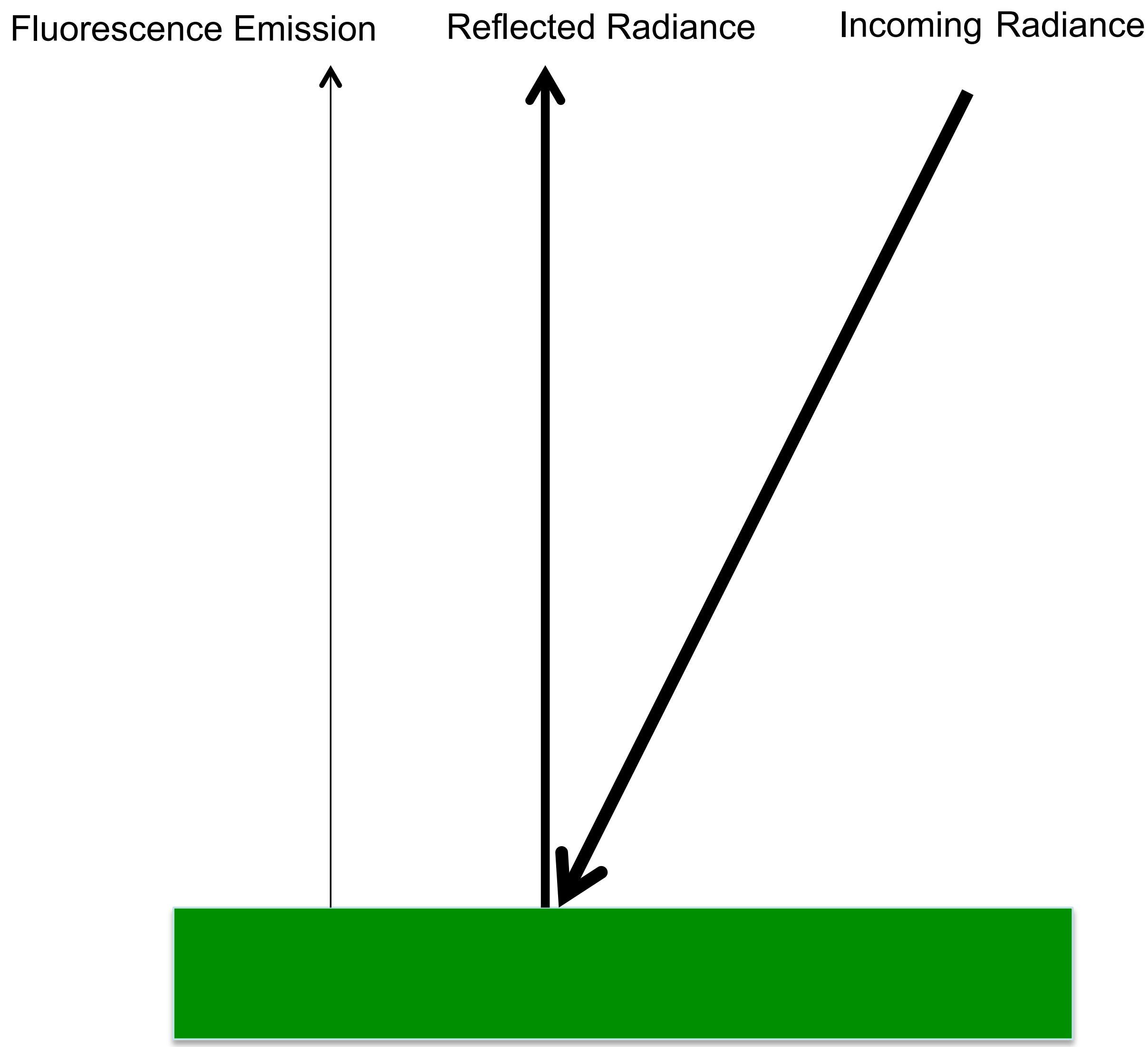


Chlorophyllx4, © Image by Eleanor Gates-Stuart, http://stellrscope.com/tag/chlorophyll-fluorescence-imaging/

Chlorophyll fluorescence

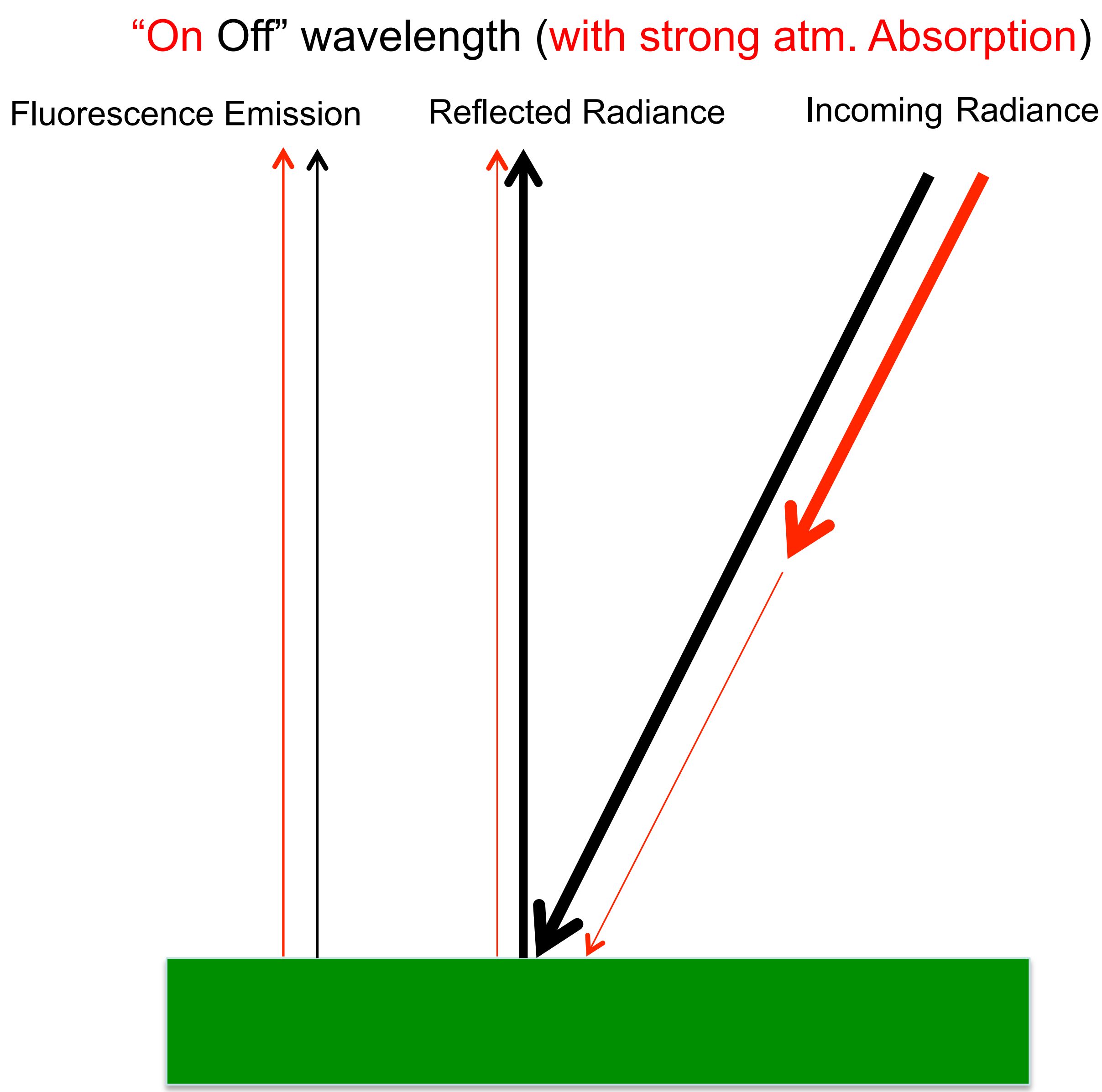
Basic problem for fluorescence retrievals:

- Fluorescence emission is "*contaminated*" with reflected solar light in the far red / near infrared.
- This reflected solar light dominates the signal (about 100 times stronger).
- Need "on/off" wavelengths where the atmosphere (or incoming light) is opaque.

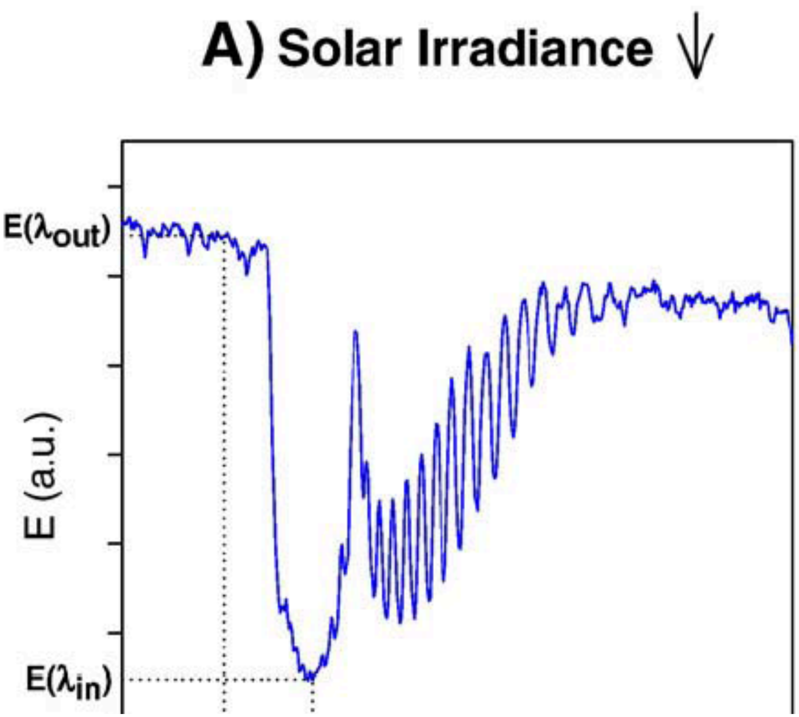


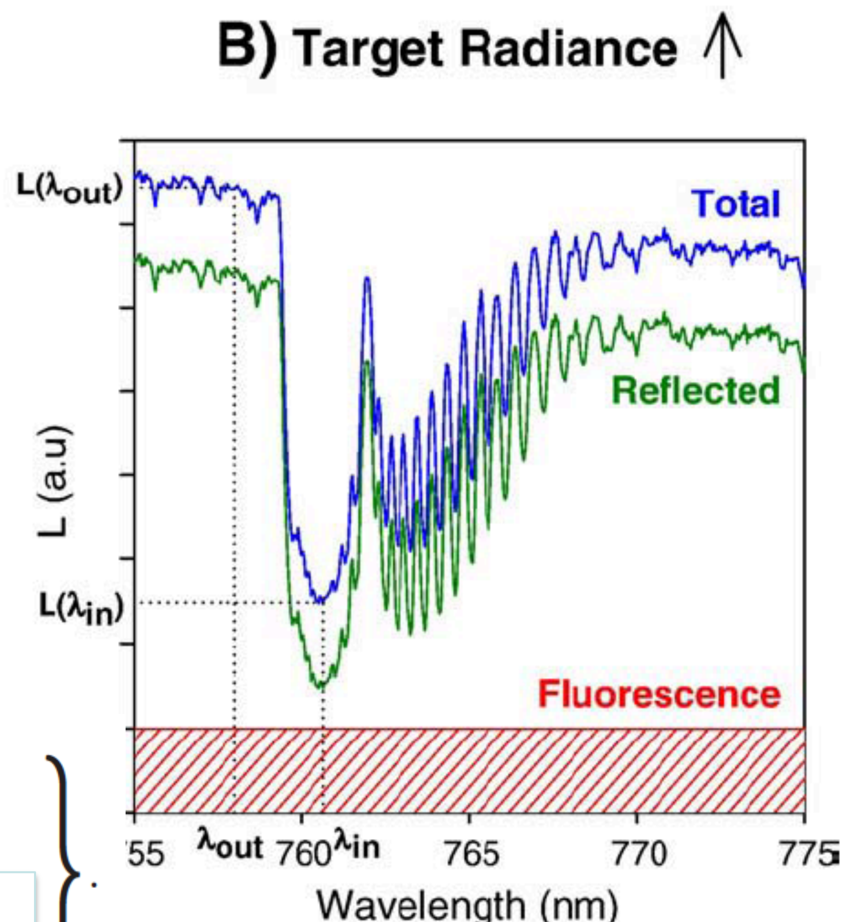
Chlorophyll fluorescence

In spectral regions with high atmospheric absorption (e.g. strong oxygen absorption bands), the fluorescence emission <u>at canopy level</u> can dominate the measured radiance (as opposed to transparent regions, where it barely adds to the signal)



On-ground retrieval methods
(review by Meroni et al, RSE 2009)





$$r = \frac{L(\lambda_{out}) - L(\lambda_{in})}{E(\lambda_{out}) - E(\lambda_{in})} \cdot \pi$$

$$F = \frac{\quad L(\lambda_{in}) \quad}{\quad}$$

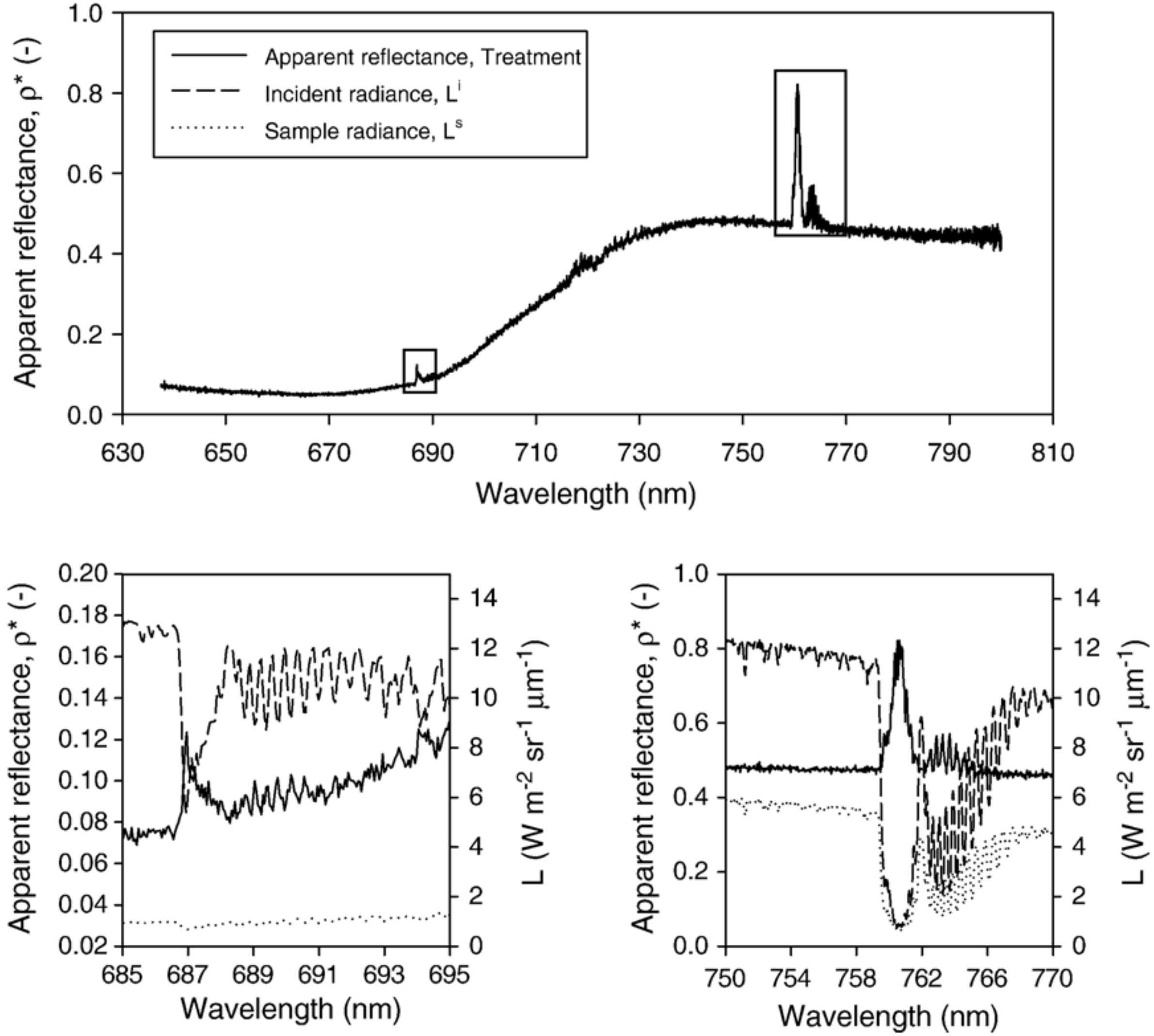
For $E(\lambda_{in}) \rightarrow 0$)

Sensitivity of the method improves with degree of atmospheric saturation

O_2 bands ideal as almost saturated (depending on instrument spectral resolution and position)

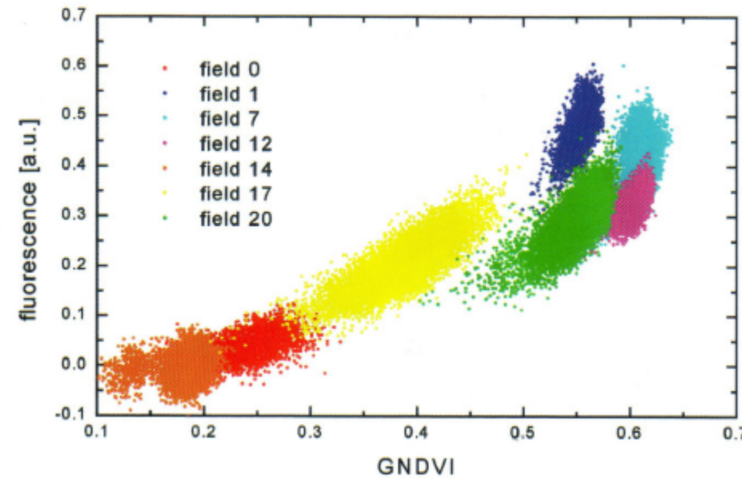
On-ground retrieval methods
(Meroni & Colombo, RSE, 2006)

Above the canopy, apparent reflectance (outgoing/incoming) in the oxygen bands is clearly increased and can be used to determine the F_s contribution.



Airborne fluorescence studies (Maier et al 2003)

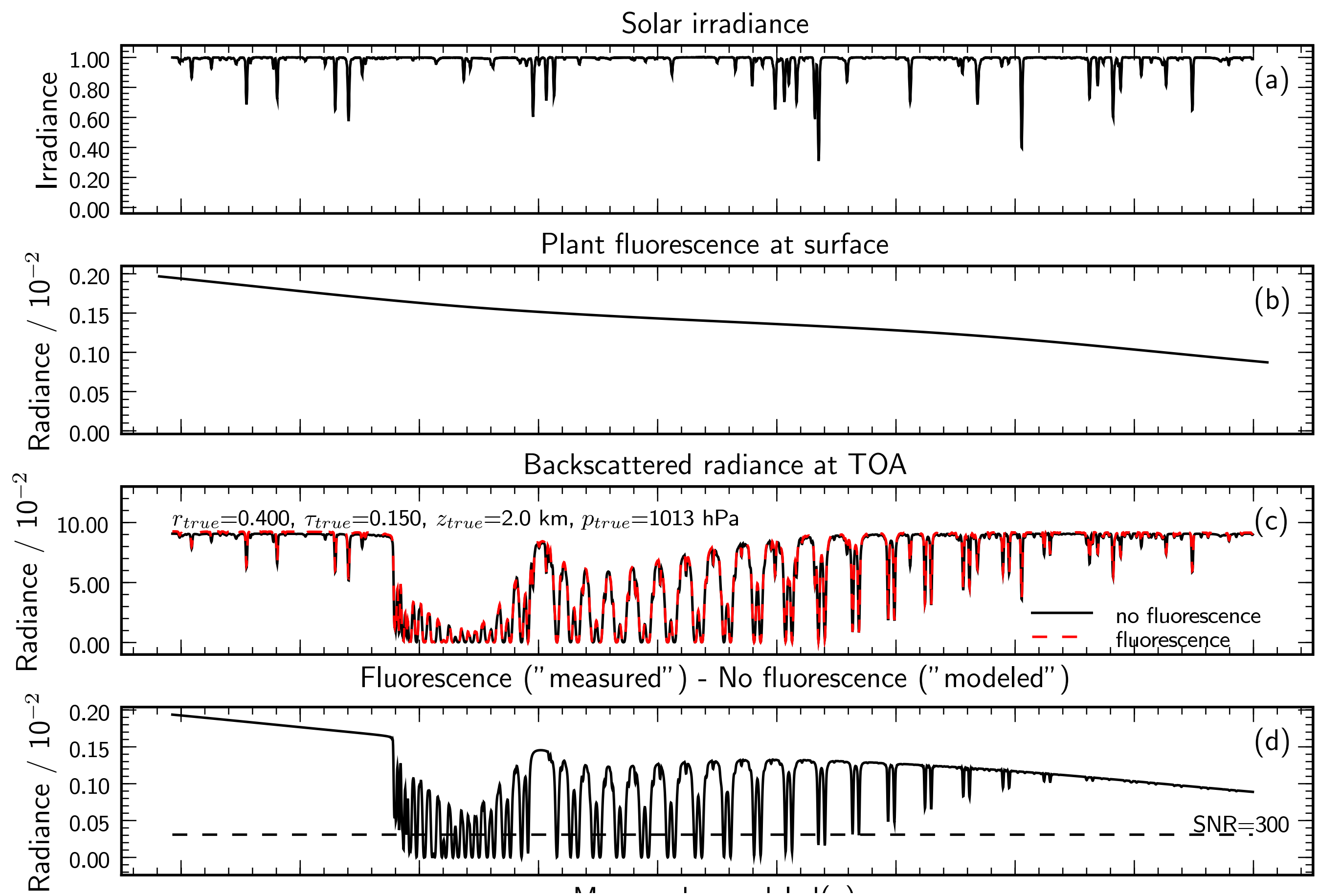
Plate 16–1. ROSIS images from the Barrax test site on 29 June 2000 at 12:23UTC (flight altitude was 3048 m above ground). (a) true color image with field marking. (b) sun-induced fluorescence in relative units. (c) GNDVI.



From airplane O_2 lines still usable (depending on altitude) and high spatial resolution allows use of reference targets (in heterogeneous terrain).
NDVI and fluorescence correlated but relationship differs per field → independent information

Chlorophyll fluorescence – complication from space
(O_2 A-band only for now)

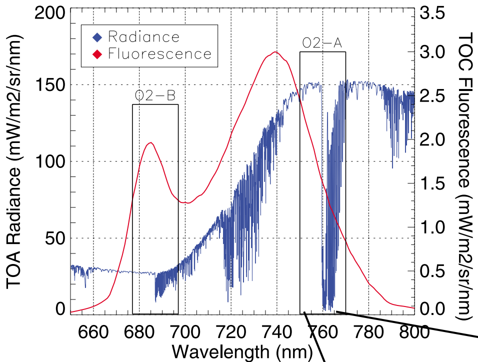
If the observer is in space (satellite), the emitted fluorescence spectrum is re-absorbed and atmospheric scattering contributes to the signal within the absorption bands.



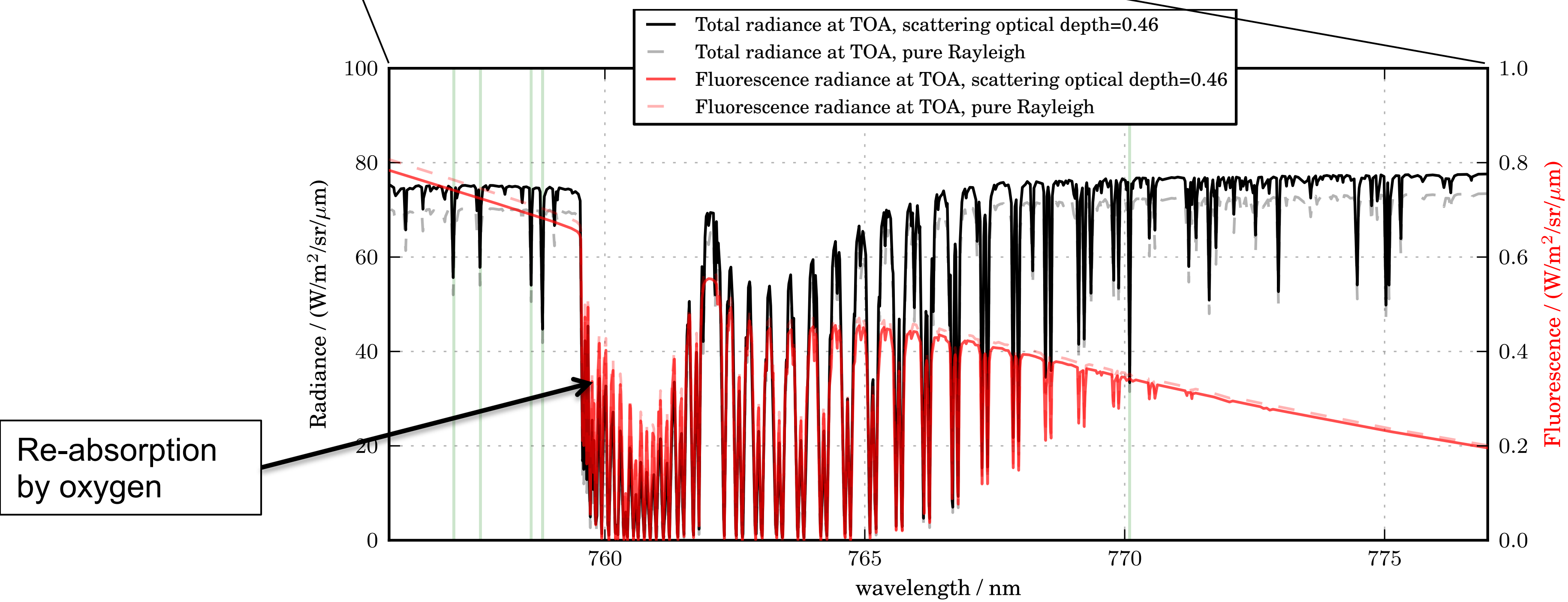
Simulated radiances

Frankenberg, Butz, Toon (ancillary material), GRL, 2011

Chlorophyll fluorescence – complication from space
(O_2 A-band only for now)



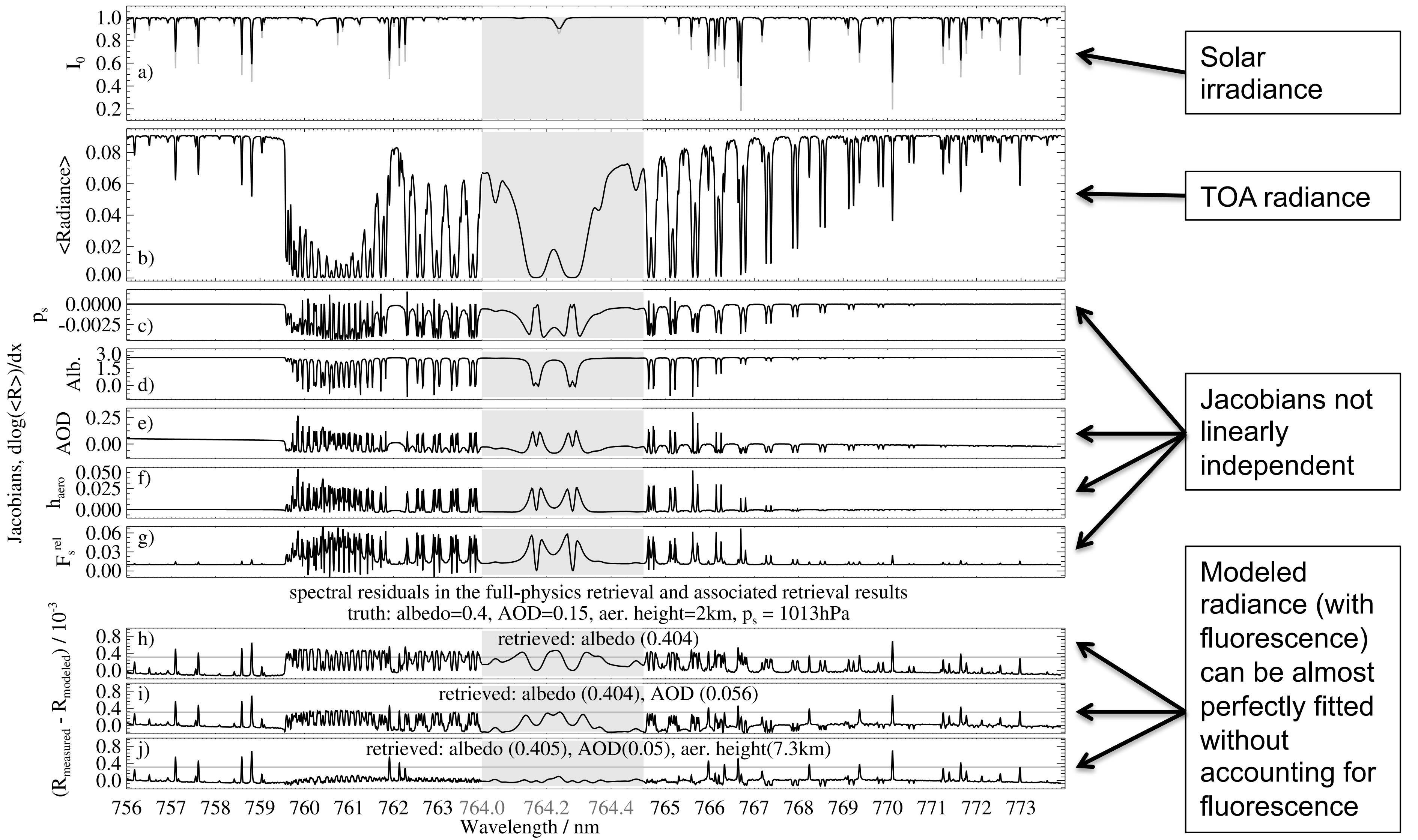
If the observer is in space (satellite), the emitted fluorescence spectrum is re-absorbed and atmospheric scattering contributes to the signal within the absorption bands.



Modeled total radiance and fluorescence emission in a scattering scene; note the different scale (factor 100)

Frankenberg et al, AMT, 2012

Chlorophyll fluorescence – complication from space
(O_2 A-band only for now)



Jacobians of the top-of-atmosphere radiance with respect to various atmospheric parameters (surface pressure, Albedo, aerosol optical depth, height of aerosol layer and Fluorescence signal.

Frankenberg, Toon, Butz, GRL, 2011

Chlorophyll fluorescence – complication from space

How to tackle the problem: 1) Use of reference surfaces

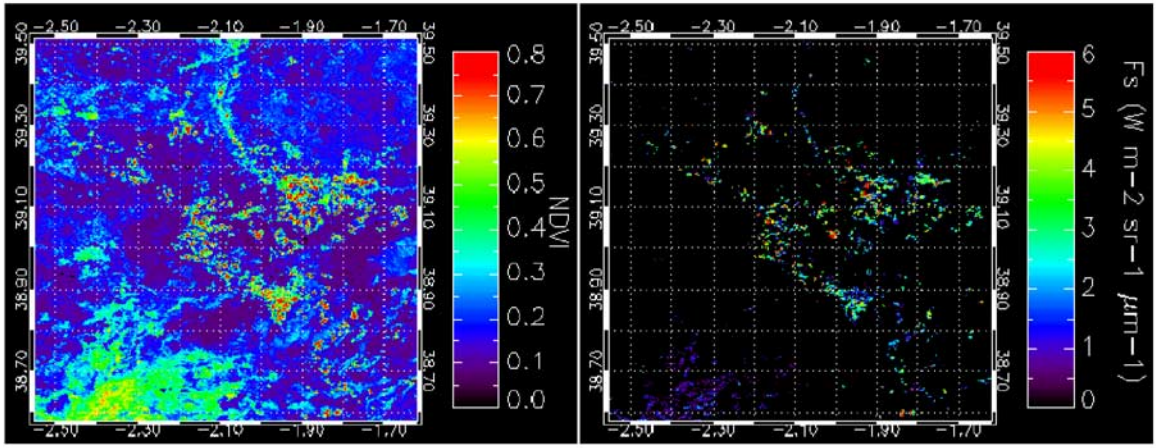


Figure 1. MERIS-derived NDVI and F_s maps over the Barrax study site in 14 July 2004.

Use of low resolution O_2 A-band spectra (MERIS) and reference targets with no fluorescence:

Idea: Atmospheric conditions are similar for reference area and vegetated areas → provides knowledge on atmospheric condition to disentangle F_s from scattering.

Prerequisite: Barren surface must exist + scattering spatially less variable than F_s (will work for corn-field like areas but not extended homogenous areas like large forests.

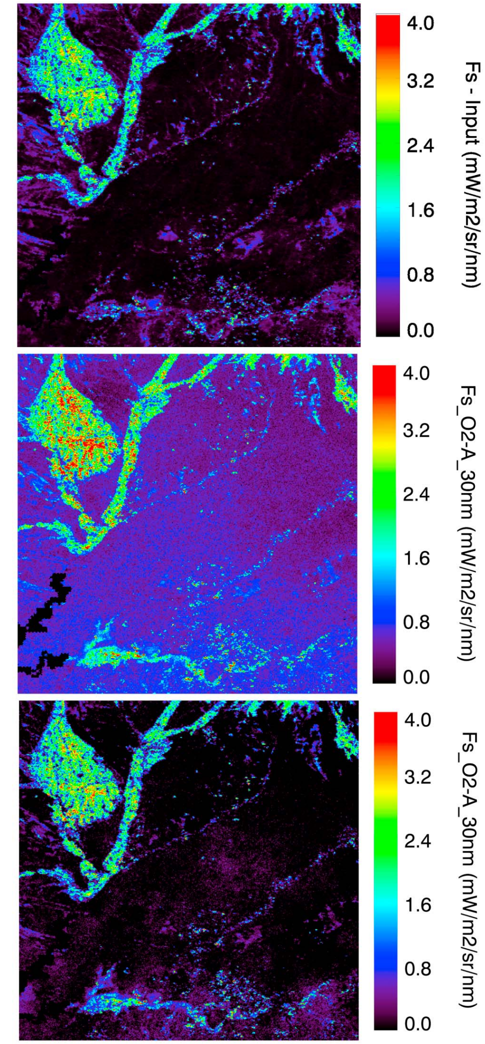


Figure 10. Input and retrieved F_s maps in O_2-A with the FLD-S approach before and after the normalization by reference soil targets.

Guanter et al, GRL, 2007, JGR 2010

Chlorophyll fluorescence – complication from space

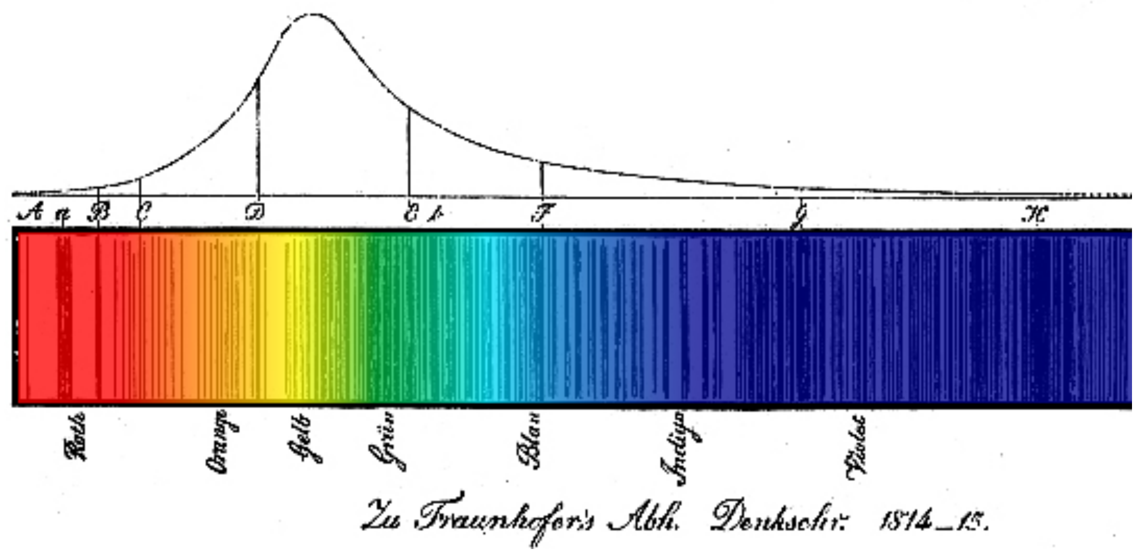
How to tackle the problem: 2) Use solar lines.

Joseph von Fraunhofer

Born	6 March 1787 Straubing, Bavaria
Died	7 June 1826 (aged 39)

The solar spectrum is not a pure black-body spectrum but exhibits absorption lines from elements (e.g. Fe, Mg, Na) present in colder outer layers.

However, dark features are very narrow.



Chlorophyll fluorescence – complication from space

How to tackle the problem: 2) Use solar lines.

306 IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. IM-24, NO. 4, DECEMBER 1975

The Fraunhofer Line Discriminator MKII—An Airborne Instrument for Precise and Standardized Ecological Luminescence Measurement

JAMES A. PLASCYK AND FRED C. GABRIEL, MEMBER, IEEE

***Abstract*—The Fraunhofer line discriminator Mark II (FLD-II) is an airborne photometric instrument for the remote measurement, on a precise and quantitative scale, of solar-stimulated luminescence. The luminescence may originate in such diverse sources as oil spills and chemical pollutants, the chlorophyll of normal or stressed vegetation, and fluorescent tracer dyes used to study current flow and dispersion in large bodies of**

strument is the precise quantitative distinction between reflected sunlight and luminescence, which may be orders of magnitude weaker.

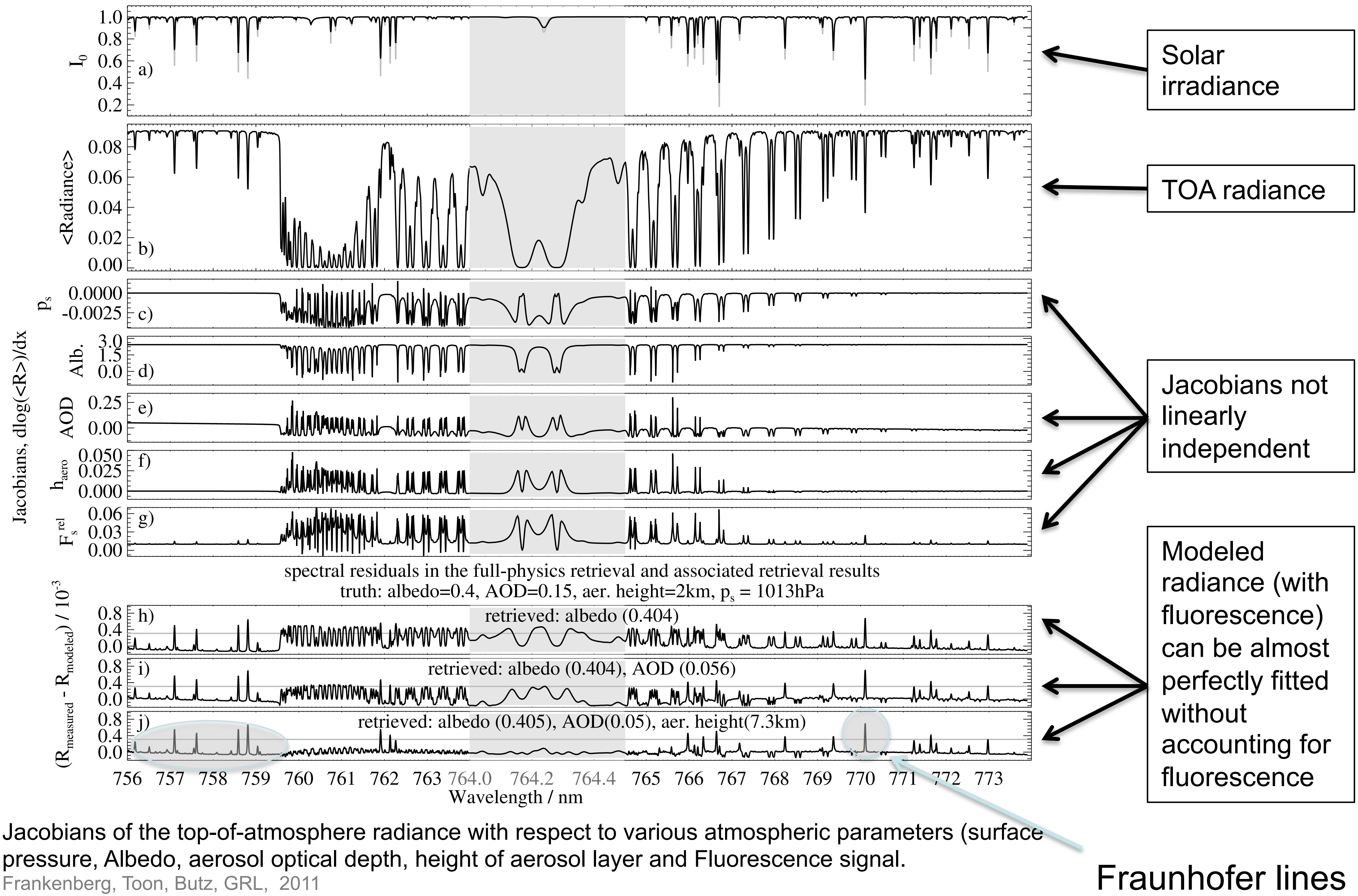
II. OPERATING PRINCIPLES

An elegant technique, first devised by lunar astrono-

Fig. 1. Solar and scene spectral distribution.

Plascyk always had Fraunhofer lines in mind, never really O_2

Chlorophyll fluorescence – complication from space
(O_2 A-band only for now)



Jacobians of the top-of-atmosphere radiance with respect to various atmospheric parameters (surface pressure, Albedo, aerosol optical depth, height of aerosol layer and Fluorescence signal.

Frankenberg, Toon, Butz, GRL, 2011

Chlorophyll fluorescence – complication from space

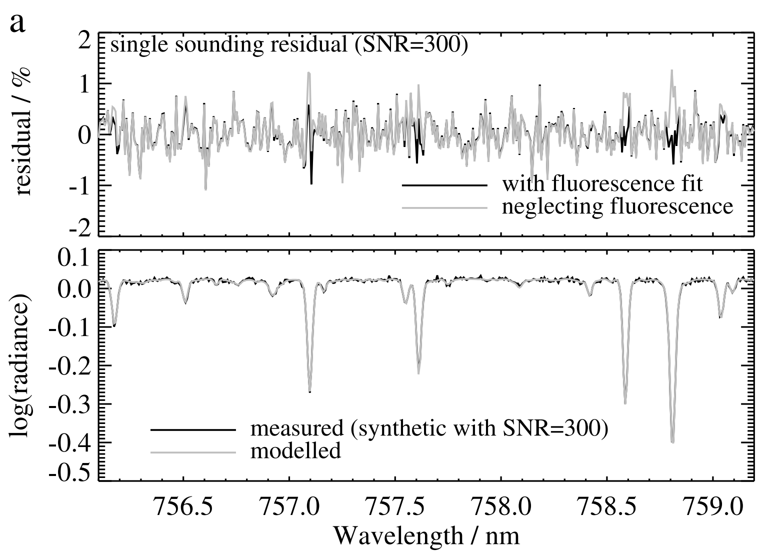
How to tackle the problem: 2) Use solar lines.

- Advantage: In the absence of inelastic scattering (e.g. rotational Raman scattering causing the Ring-effect in the UV/Vis!), the fractional depth of solar absorption features is not changed within the atmosphere → no reabsorption in the Earth's atmosphere and no interference with atmospheric scattering.

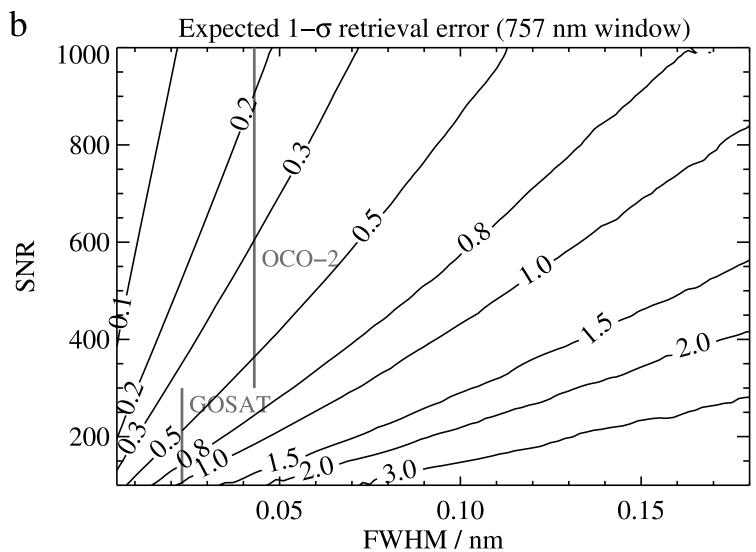
- Challenge: High spectral resolution needed to resolve Fraunhofer lines: Tradeoff between spectral resolution (FWHM, Full width at half maximum) and spatial resolution!

Chlorophyll fluorescence – complication from space

How to tackle the problem: 2) Use solar lines.



Main disadvantage: High single measurement noise



Frankenberg, Toon, Butz, GRL, 2011

Use full spectral fitting routines to quantify the in-filling of Fraunhofer lines due to Fluorescence.

GOSAT (and OCO-2 in the future) are the first instruments to provide high resolution spectra in the O_2 A-band (but not covering the full F_s emission spectrum)

Fractional depth of solar lines (difference to continuum radiance within the line in log(radiance) space) only changed by F_s:

$$\vec{f}\left(F_s^{rel}, a\right) = \log\left(< \vec{I}_0 + F_s^{rel} >\right) + \sum_{i=0}^{n} a_i \cdot \lambda^i,$$

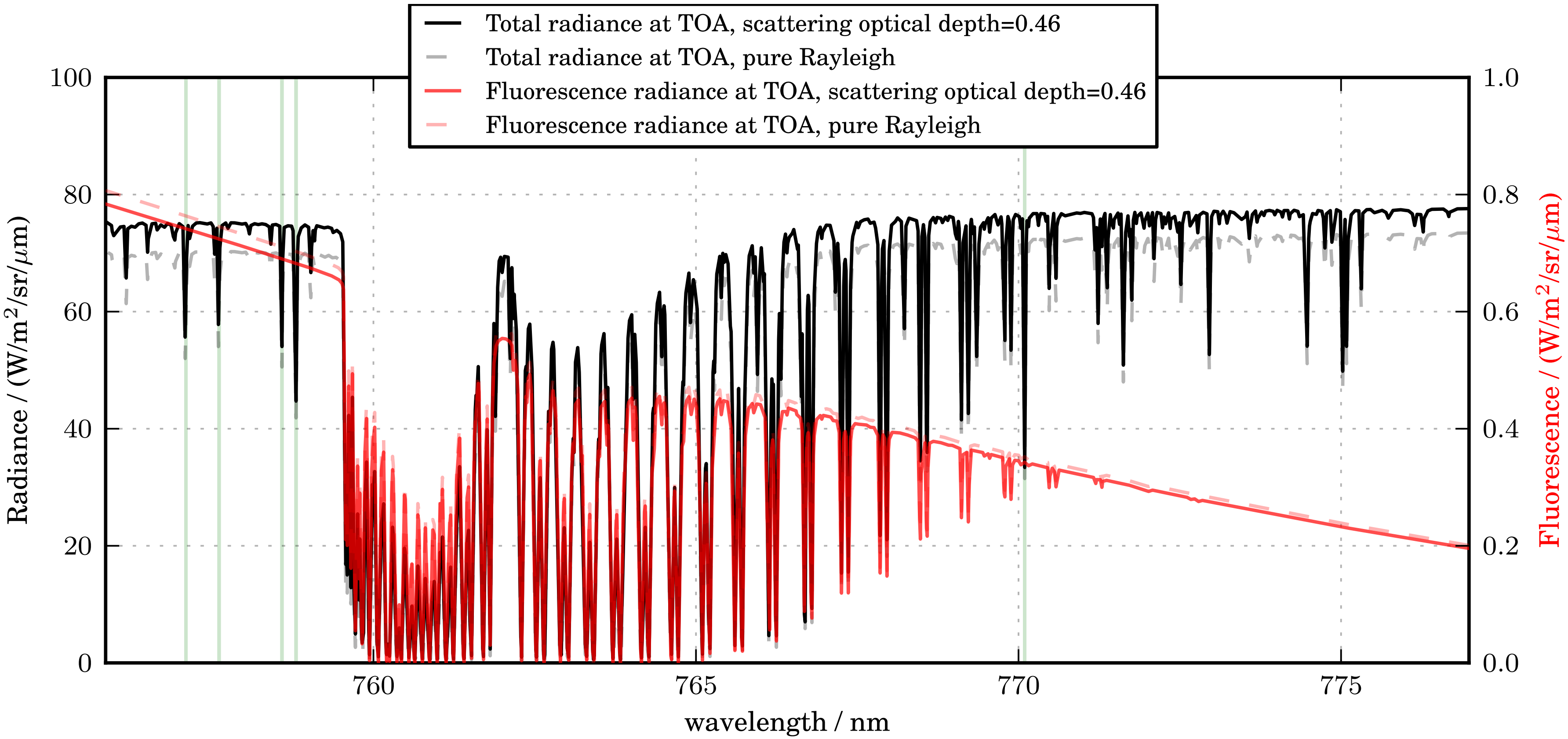
$$\arg\ \min \| S_\epsilon^{-1/2} \left(\vec{y} - \vec{f}\left(F_s^{rel}, a\right)\right) \|_2,$$

No radiative transfer modeling necessary if Fraunhofer lines only are concerned!

Chloroplyll fluorescence – complication from space

How to tackle the problem: 2) Use solar lines.

Leverage from OCO-2 efforts: Implementing propagation of fluorescence into the orbit simulator, simulating complex realistic radiances in scattering atmospheres.

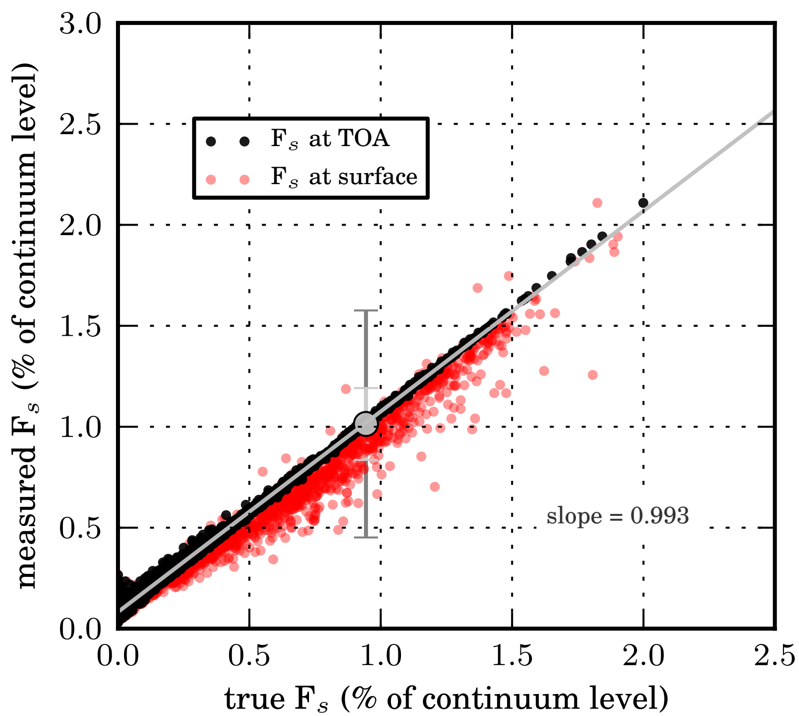


C. Frankenberg, C. O'Dell, L. Guanter, and J. McDuffie, AMT, 2012

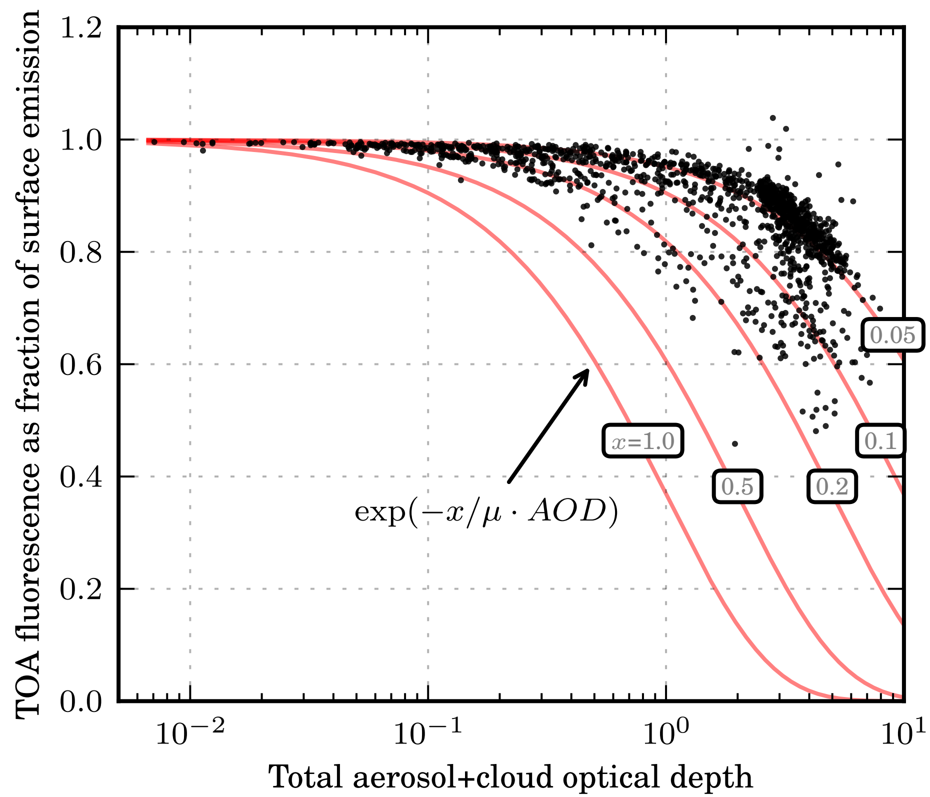
Chlorophyll fluorescence – complication from space

How to tackle the problem: 2) Use solar lines.

Simulate F_s retrievals as done for GOSAT:
Retrieved vs. true (at TOA and surface) very consistent.



Fraction of surface fluorescence reaching top-of-atmosphere (TOA) as a function of optical depth → very insensitive to scattering, may eventually be one of the biggest advantages!



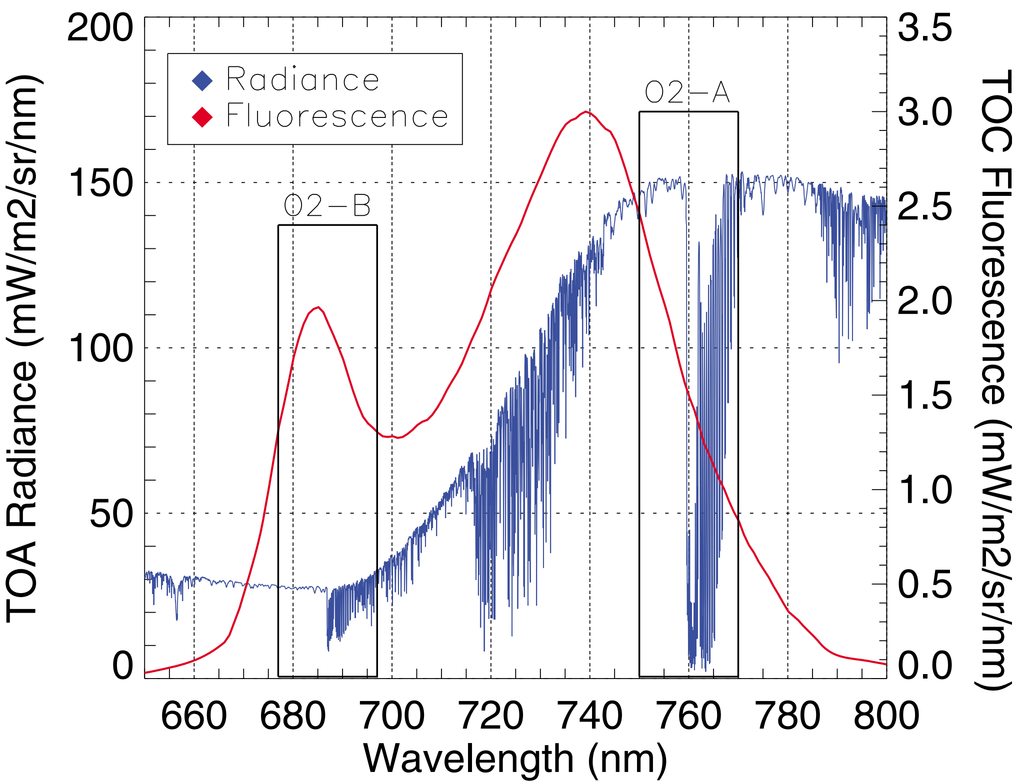
C. Frankenberg, C. O'Dell, L. Guanter, and J. McDuffie, AMT, 2012

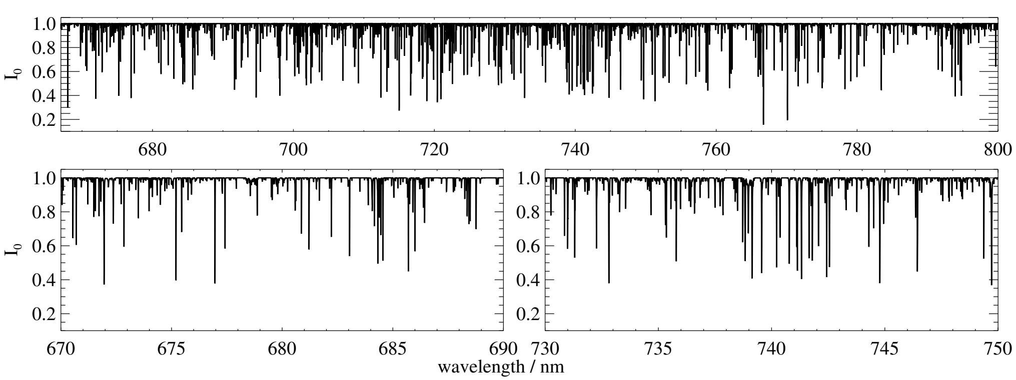
Chlorophyll fluorescence – complication from space

How to tackle the problem: 3) Use entire emission spectrum (FLEX)

Reflectance and Fluorescence emission spectrum

Guanter et al, JGR, 2010





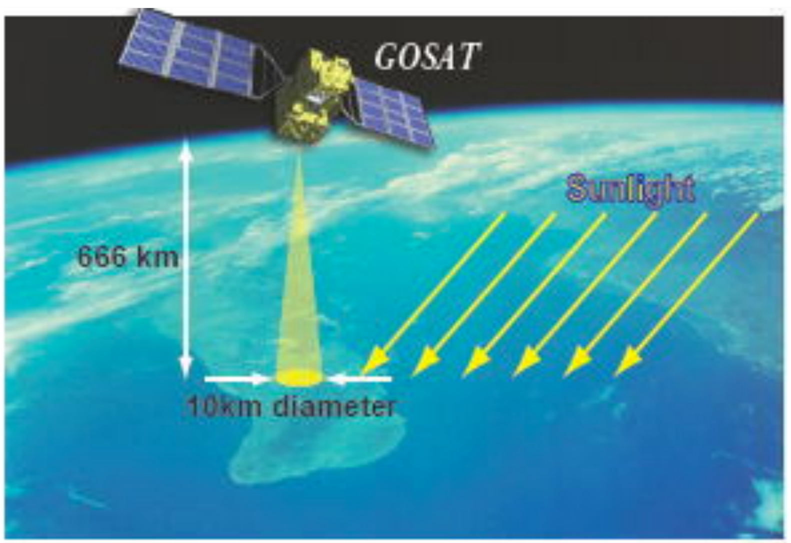
While F_s retrievals using the O_2 A-band alone (without Fraunhofer lines) is ill-posed, the use of the full spectral range may alleviate the problem (e.g. fractional contribution of F_s is much higher at shorter wavelengths.

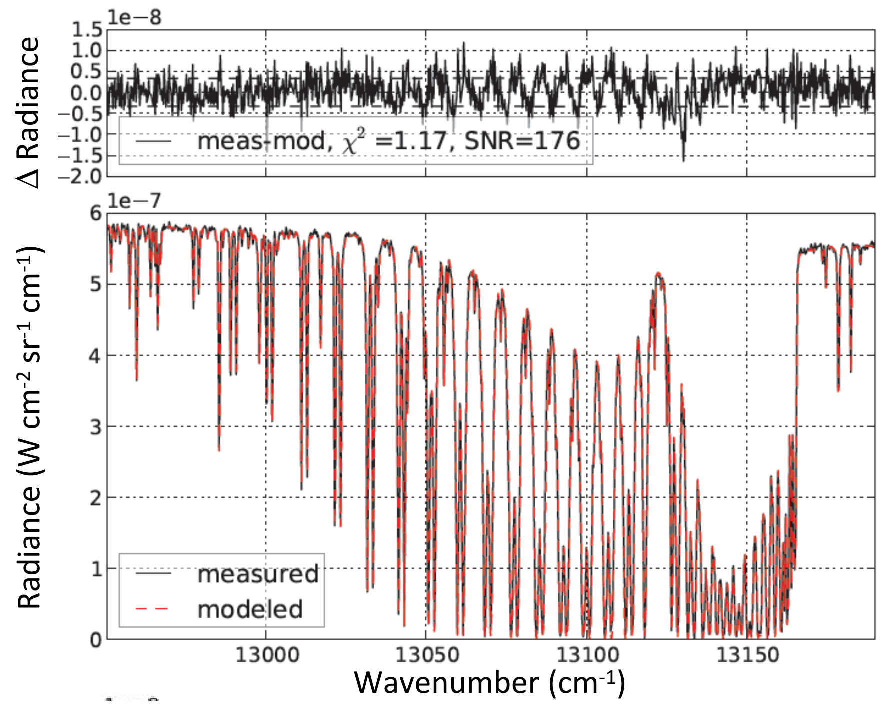
Biggest advantages: Covering the red-edge will allow LAI/FAPAR/chl. content retrievals in addition + F_s ratios at different wavelengths are also powerful indicators for photosynthetic activity.

Best of both worlds (personal opinion): Have high spectral resolution to sample Fraunhofer lines AND extend the wavelength range to cover the short wavelength F_s peak.

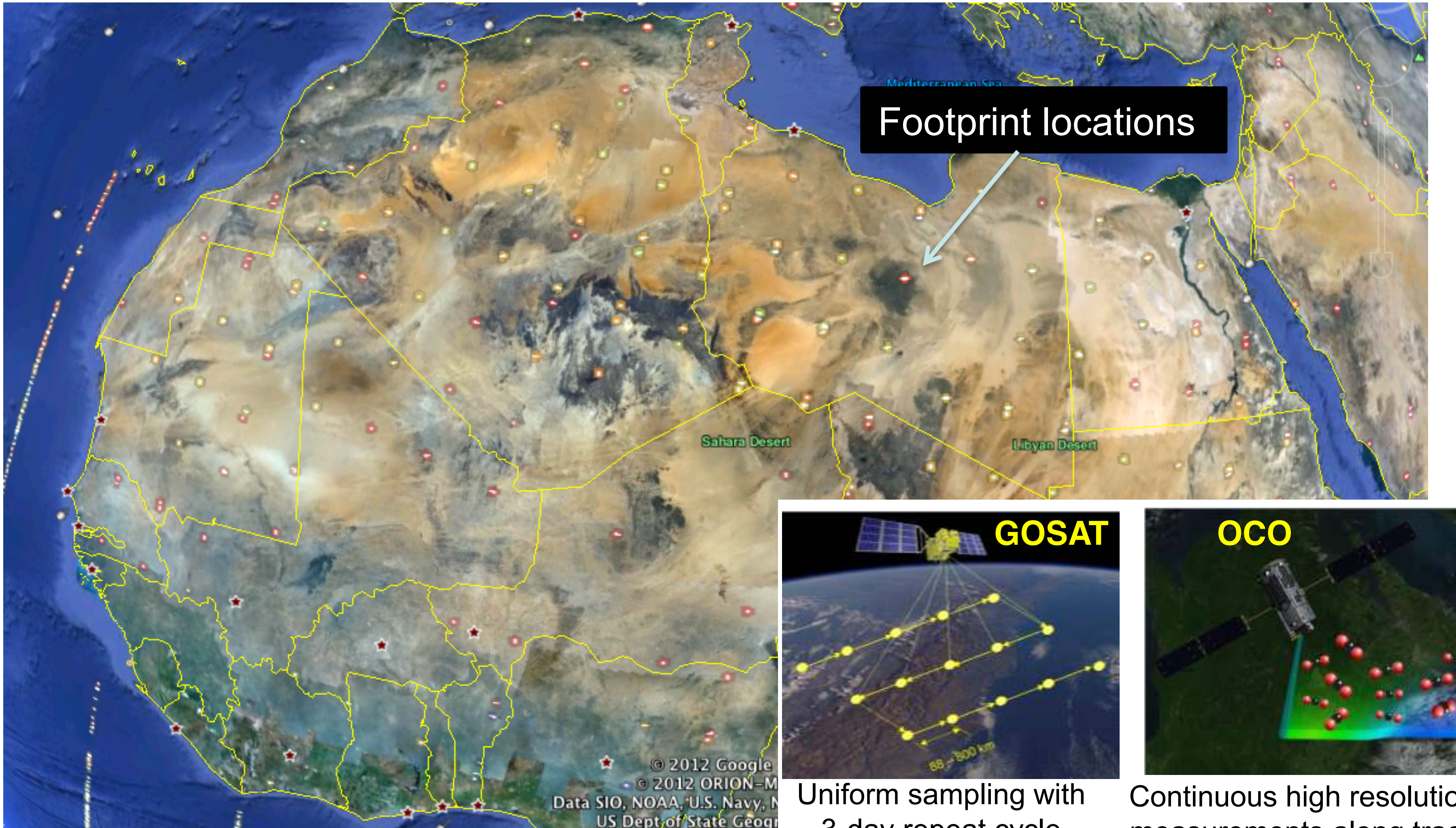
Application in the real world: Using GOSAT radiances.

Figure 1. Overview of GOSAT (©JAXA)





Application in the real world: Using GOSAT radiances.



Uniform sampling with 3-day repeat cycle

Continuous high resolution measurements along track

Do not forget: GOSAT is NOT a mapper as intended to measure long-lived trace gases, not surface properties!

Fluorescence from GOSAT
(retrieval paper and first real retrievals)

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L03801, doi:10.1029/2010GL045896, 2011

Disentangling chlorophyll fluorescence from atmospheric scattering effects in O_2 A-band spectra of reflected sun-light

C. Frankenberg,[1] A. Butz,[2] and G. C. Toon[1]

Received 18 October 2010; revised 24 November 2010; accepted 13 December 2010; published 1 February 2011.

[1] Global retrieval of solar induced fluorescence emitted by terrestrial vegetation can provide an unprecedented measure for photosynthetic efficiency. The GOSAT (JAXA, launched Feb. 2009) and OCO-2 (NASA, to be launched 2013) satellites record high-resolution spectra in the O_2 A-band region, overlapping part of the chlorophyll fluorescence spectrum. We show that fluorescence cannot be unambiguously discriminated from atmospheric scattering effects using O_2 absorption lines. This can cause systematic biases in retrieved scattering parameters (aerosol optical thickness, aerosol height, surface pressure, surface albedo) if fluorescence is neglected. Hence, we demonstrate an efficient alternative fluorescence least-squares retrieval method based solely on strong Fraunhofer lines in the vicinity of the O_2 A-band, disentangling fluorescence from scattering effects. Not only does the Fraunhofer line fit produce a more accurate estimate of fluorescence emission, but it also allows improved retrievals of atmospheric aerosols from the O_2 A-band. **Citation:** Frankenberg, C., A. Butz, and G. C. Toon (2011), Disentangling chlorophyll fluorescence from atmospheric scattering effects in O_2 A-band spectra of reflected sun-light, *Geophys. Res. Lett.*, *38*, L03801, doi:10.1029/2010GL045896.

1. Introduction

[2] Remote sensing of terrestrial vegetation is an important tool for monitoring its status and carbon flux estimation. From space, information is mainly based on indices such as the Normalized Difference Vegetation Index (NDVI), derived from hyper-spectral reflectance measurements in the visible to near-infrared spectral region. In the photosynthesis process, visible solar energy absorbed by chlorophyll can either be used for carbon fixation, be dissipated into heat, or be re-emitted via fluorescence at longer wavelengths. This so-called solar-induced chlorophyll fluorescence [*Krause and Weis*, 1991; *Baker*, 2008, and references therein] offers a more direct measure of photosynthetic activity. Its retrieval from space is the concept behind the scientific Fluorescence Explorer (FLEX) satellite mission, submitted to the European Space Agency (ESA) Earth Explorer program call in 2005.

[3] The fluorescence emission (F_s) adds a small offset of up to about 10 Wm^{-2} sr^{-1} μm^{-1} [*Entcheva Campbell et al.*, 2008] to the reflected solar spectrum over the 660–800 nm region with maxima at approximately 690 and 740 nm. This results in absorption lines appearing slightly shallower than otherwise. The fluorescence spectrum encompasses the strongly saturated O_2A (around 765 nm) and the weaker B-band (around 685 nm). The small reduction in the fractional depths of O_2 and Fraunhofer absorption lines due to F_s is especially noticeable in saturated lines and can be used to retrieve fluorescence if spectra are recorded near the fluorescence source [*Plascyk and Gabriel*, 1975]. *Meroni et al.* [2009] provide a literature overview of common retrieval techniques for fluorescence signals, which are widely used for assessing photosynthetic activity [*Krause and Weis*, 1984, 1991; *Flexas et al.*, 2002; *Freedman et al.*, 2002; *Zarco-Tejada et al.*, 2003; *Moya et al.*, 2004; *Rascher et al.*, 2009], including gross primary production (GPP) [*Damm et al.*, 2010].

[4] Recent satellite missions aiming at measuring atmospheric abundances of carbon dioxide (CO_2) could enable retrievals of chlorophyll fluorescence as they feature high-resolution near-infrared spectrometers to record the O_2 A-band at 0.765 μm. The Greenhouse Gases Observing Satellite (GOSAT) [*Hamazaki et al.*, 2005; *Kuze et al.*, 2009] was launched on 23 January 2009, while the Orbiting Carbon Observatory (OCO) [*Crisp et al.*, 2004] suffered from a launch failure (launch of OCO-2 planned for early 2013).

[5] *Guanter et al.* [2010] provide the first study on the impact of aerosols on fluorescence retrievals and acknowledge potentially large errors, especially in the O_2 A-band. However, there is so far no study on I) the effect of fluorescence on the retrieval of scattering properties and II) on how to fully decouple the two effects in the absence of prior information on either. The goal of this paper is to bridge the gap between the vegetation and atmospheric communities by investigating the impact of scattering as well as fluorescence on high-resolution spectra. We will show that from space-borne measurements of the O_2 A-band, fluorescence cannot be distinguished from the impacts of aerosols, albedo and surface pressure. However, we demonstrate a retrieval purely based on Fraunhofer lines outside the O_2 A-band, successfully isolating the fluorescence signal from scattering effects. We report the performance of the algorithm on the basis of simulated measurements according to GOSAT and OCO-2 specifications, paving the way towards space-based retrievals of chlorophyll fluorescence with current satellites.

2. The Retrieval Problem From Space

[6] Near the surface, fluorescence retrieval methods based on O_2 absorption lines work well since atmospheric scattering between the plants and the observer can be neglected and the atmospheric effect on the downwelling irradiance is normalized by means of measurements over reference panels located next to the canopy under study. In observations from space, as first performed by *Guanter et al.* [2007] using the MERIS imager with focus on a small region, the retrieval is

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[2]SRON Netherlands Institute for Space Research, Utrecht, Netherlands.

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doi:10.5194/bg-8-637-2011

Biogeosciences

First observations of global and seasonal terrestrial chlorophyll fluorescence from space

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Abstract. Remote sensing of terrestrial vegetation fluorescence from space is of interest because it can potentially provide global coverage of the functional status of vegetation. For example, fluorescence observations may provide a means to detect vegetation stress before chlorophyll reductions take place. Although there have been many measurements of fluorescence from ground- and airborne-based instruments, there has been scant information available from satellites. In this work, we use high-spectral resolution data from the Thermal And Near-infrared Sensor for carbon Observation – Fourier Transform Spectrometer (TANSO-FTS) on the Japanese Greenhouse gases Observing SATellite (GOSAT) that is in a sun-synchronous orbit with an equator crossing time near 13:00 LT. We use filling-in of the potassium (K) I solar Fraunhofer line near 770 nm to derive chlorophyll fluorescence and related parameters such as the fluorescence yield at that wavelength. We map these parameters globally for two months (July and December 2009) and show a full seasonal cycle for several different locations, including two in the Amazonia region. We also compare the derived fluorescence information with that provided by the MODIS Enhanced Vegetation Index (EVI). These comparisons show that for several areas these two indices exhibit different seasonality and/or relative intensity variations, and that changes in fluorescence frequently lead those seen in the EVI for those regions. The derived fluorescence therefore provides information that is related to, but independent of the reflectance.

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1 Introduction

Vegetation is the functional interface between the Earth's terrestrial biosphere and the atmosphere. Terrestrial ecosystems absorb approximately 120 Gt of carbon annually through the physiological process of photosynthesis. About 50% of the carbon is released by ecosystem respiration processes within short time periods. The remaining carbon is referred to as Net Primary Production (NPP). Disturbances and long term changes of ecosystems release parts of this carbon within the time frame of centuries. There are currently great uncertainties for the human impact on the magnitude of these processes.

Photosynthesis is the conversion by living organisms of light energy into chemical energy and fixation of atmospheric carbon dioxide into sugars; it is the key process mediating 90% of carbon and water fluxes in the coupled biosphere-atmosphere system. Until now, most of the information that has been acquired by remote sensing of the Earth's surface about vegetation conditions has come from reflected light in the solar domain. There is, however, one additional source of information about vegetation productivity in the optical and near-infrared wavelength range that has not been globally exploited by satellite observations. This source of information is related to the emission of fluorescence from the chlorophyll of assimilating leaves; part of the energy absorbed by chlorophyll cannot be used for carbon fixation and is thus re-emitted as fluorescence at longer wavelengths (lower energy) with respect to the absorption.

The fluorescence signal originates from the core complexes of the photosynthetic machinery where energy conversion of absorbed photosynthetically active radiation (APAR) occurs. Because the photosynthetic apparatus is an organized structure, the emission spectrum of fluorescence that originates from it is well known; it occurs as a convolution of

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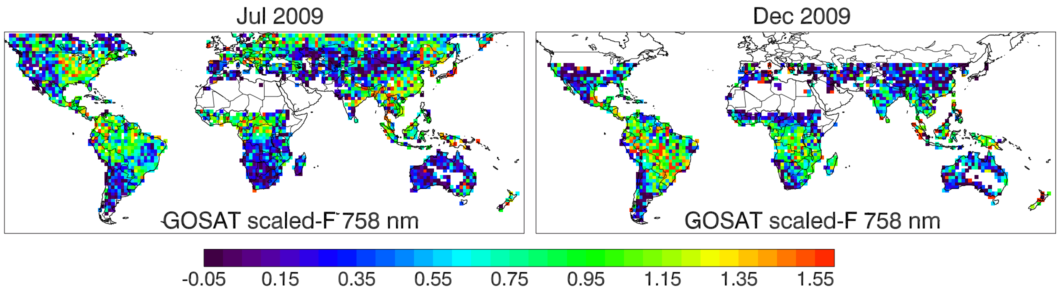
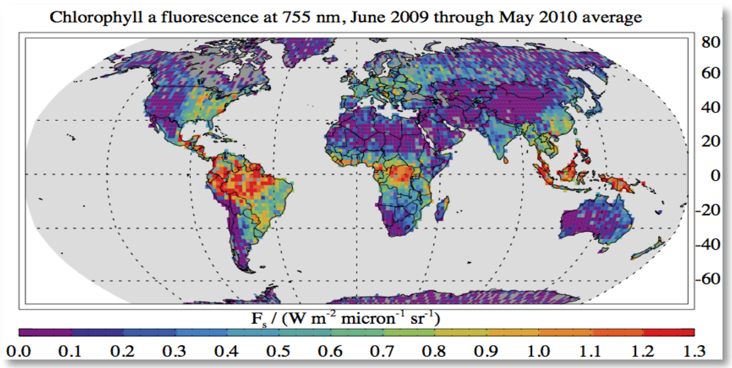
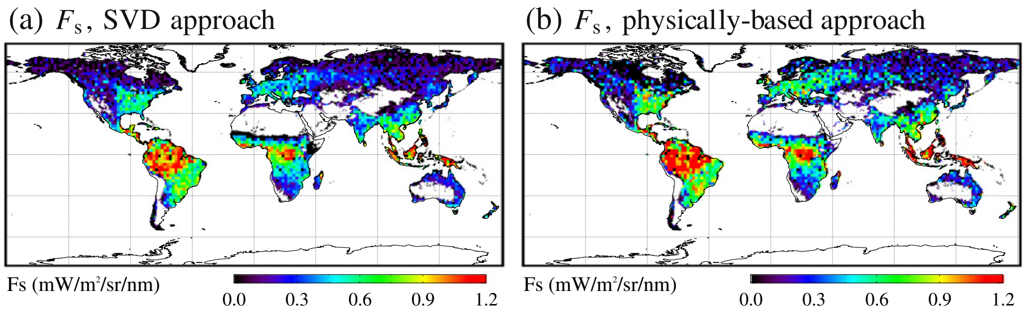
Fluorescence from GOSAT (three different retrievals groups)



Joiner et al
Biogesciences 2010, AMT 2012
Use of measured solar spectra and/or measured spectra over vegetation free areas



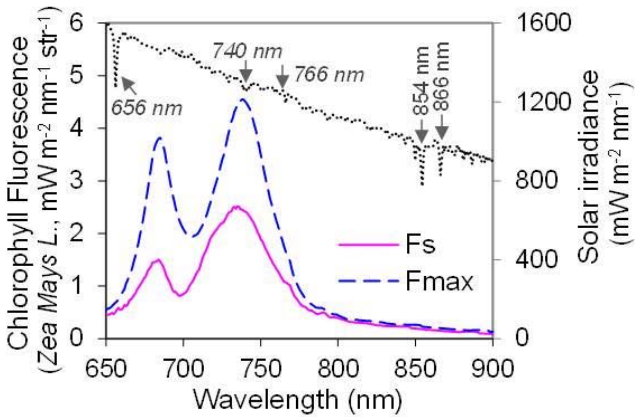
Frankenberg et al
GRL 2010, 2011
Use of high resolution solar model and instrument model (ILS)



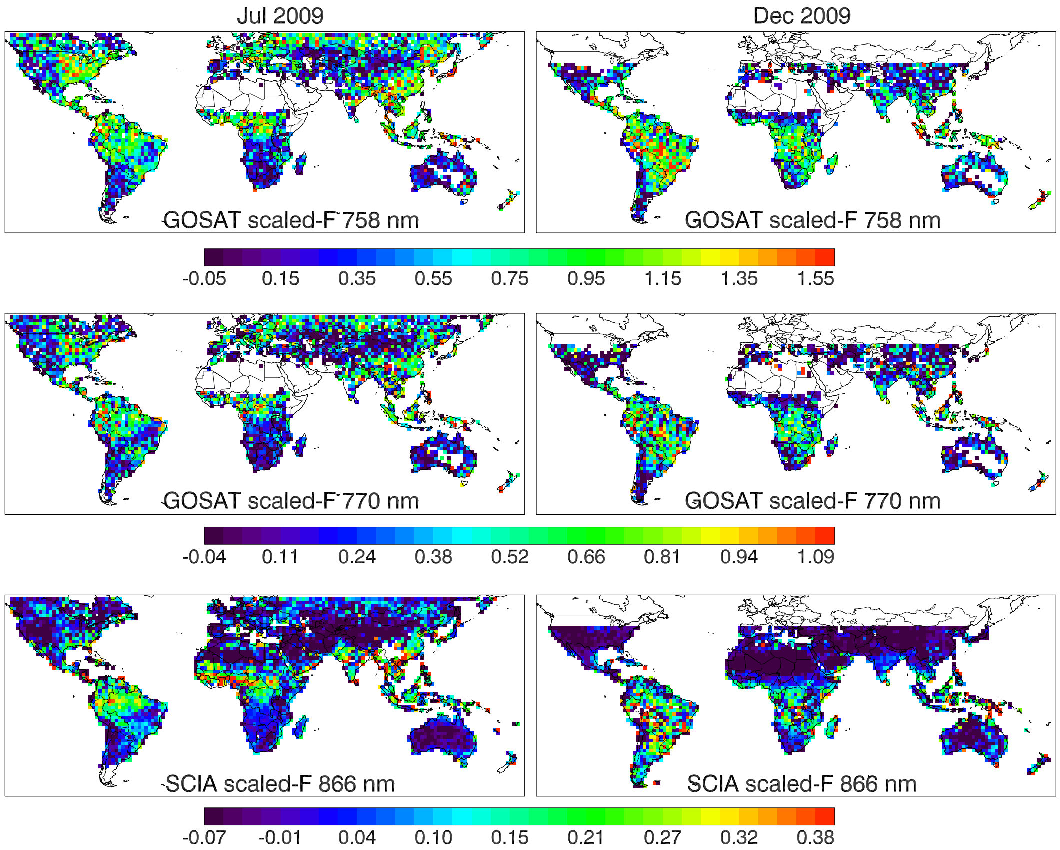
Guanter et al
RSE 2012
Physics based (high resolution modeling) + fast Singular Value Decomposition methods.

→ Despite differences in the techniques, methods agree well

Fluorescence from SCIAMACHY



Spectral resolution too low to sample fine Fraunhofer lines near 750nm but sufficient to use the wide Ca II line at 866.5 nm

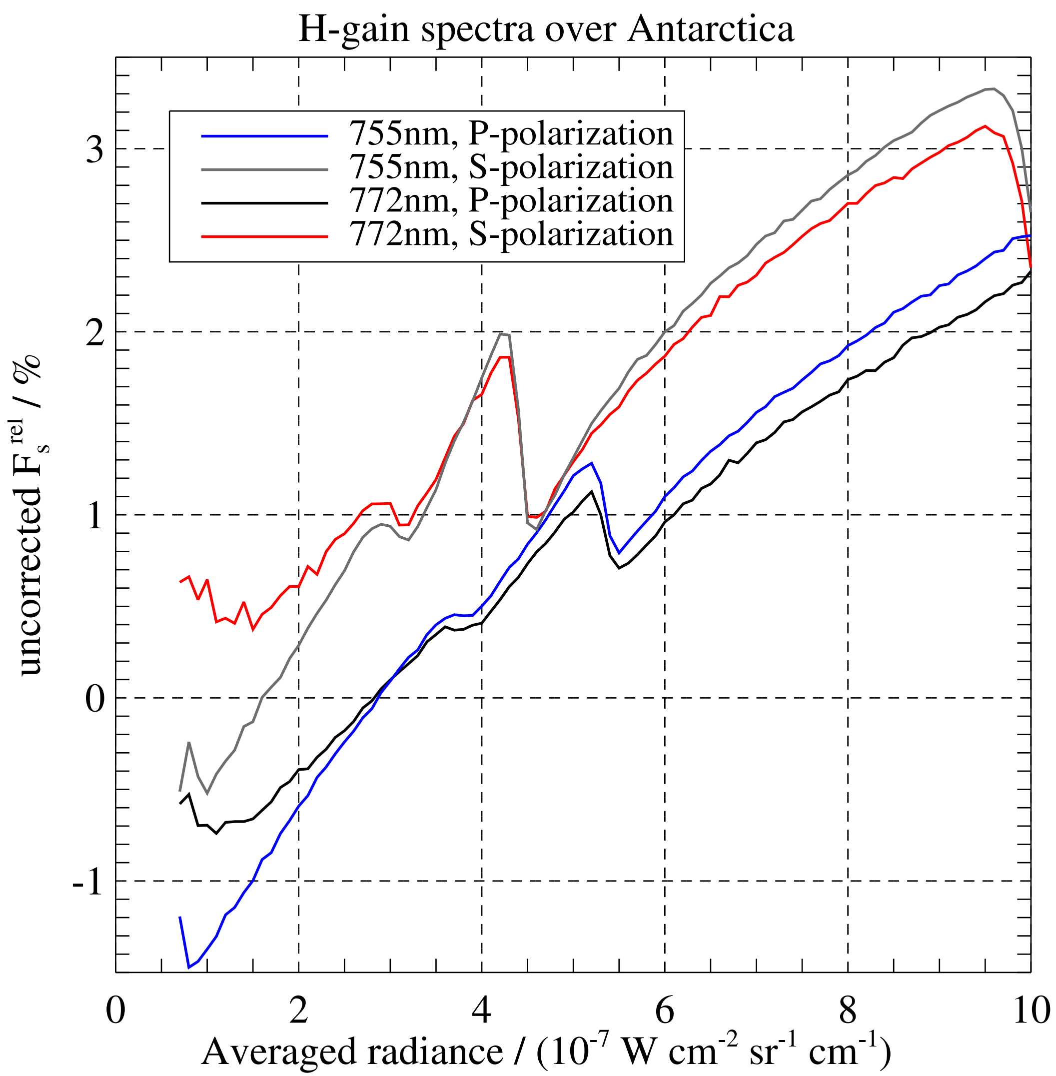


Joiner et al
Biogesciences 2010, AMT 2012

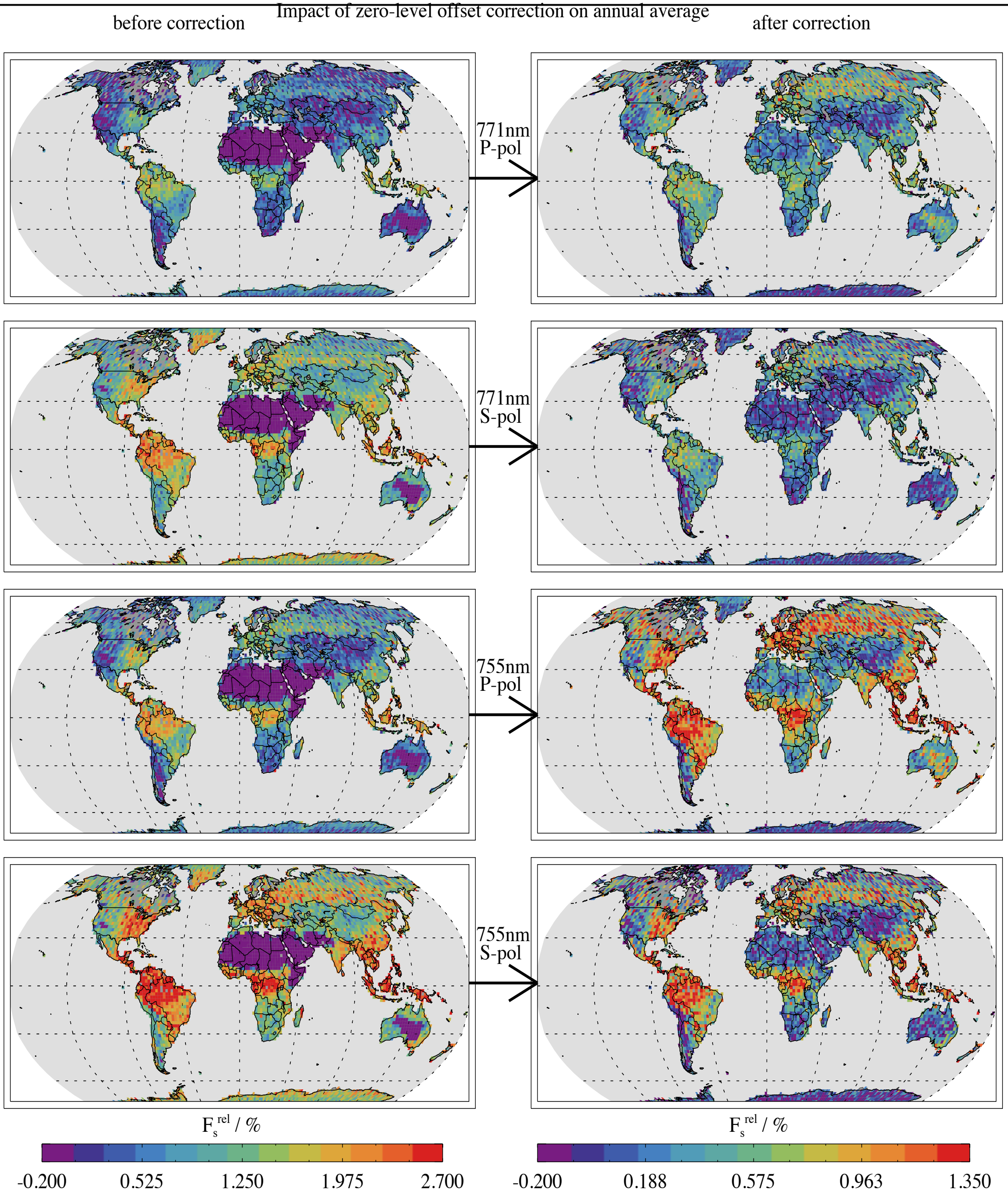
Facing reality:
Detection of a zero level offset in the GOSAT FTS

From now on, focus on JPL efforts (please note work by Joiner and Guanter though!).

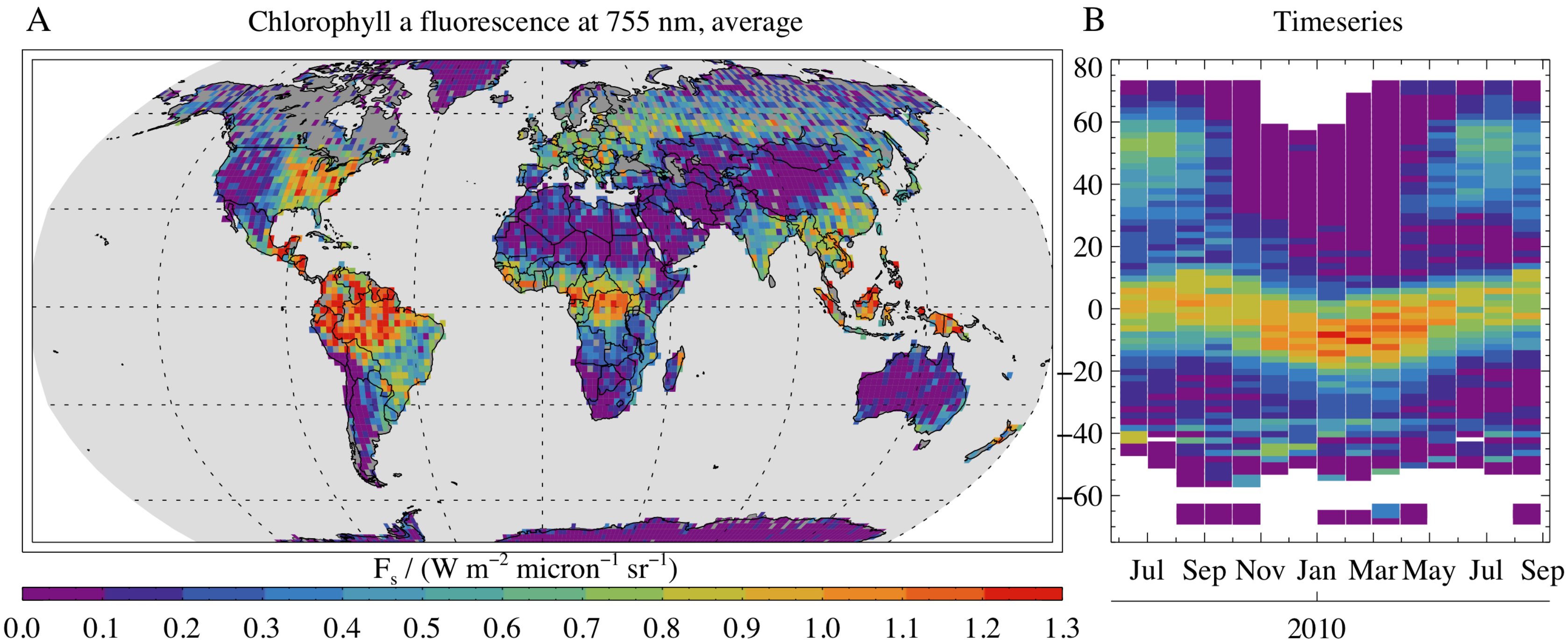
- Initial GOSAT F_s retrievals caused headache as high F_s was retrieved over Antarctica
- Signal could be traced down to an FTS zero-level offset
- Empirical correction now in place (from all retrieval groups)
- → beware of zero level offset in FTS systems and spectral straylight in gratings spectrometers



Impact of the offset on the retrieval

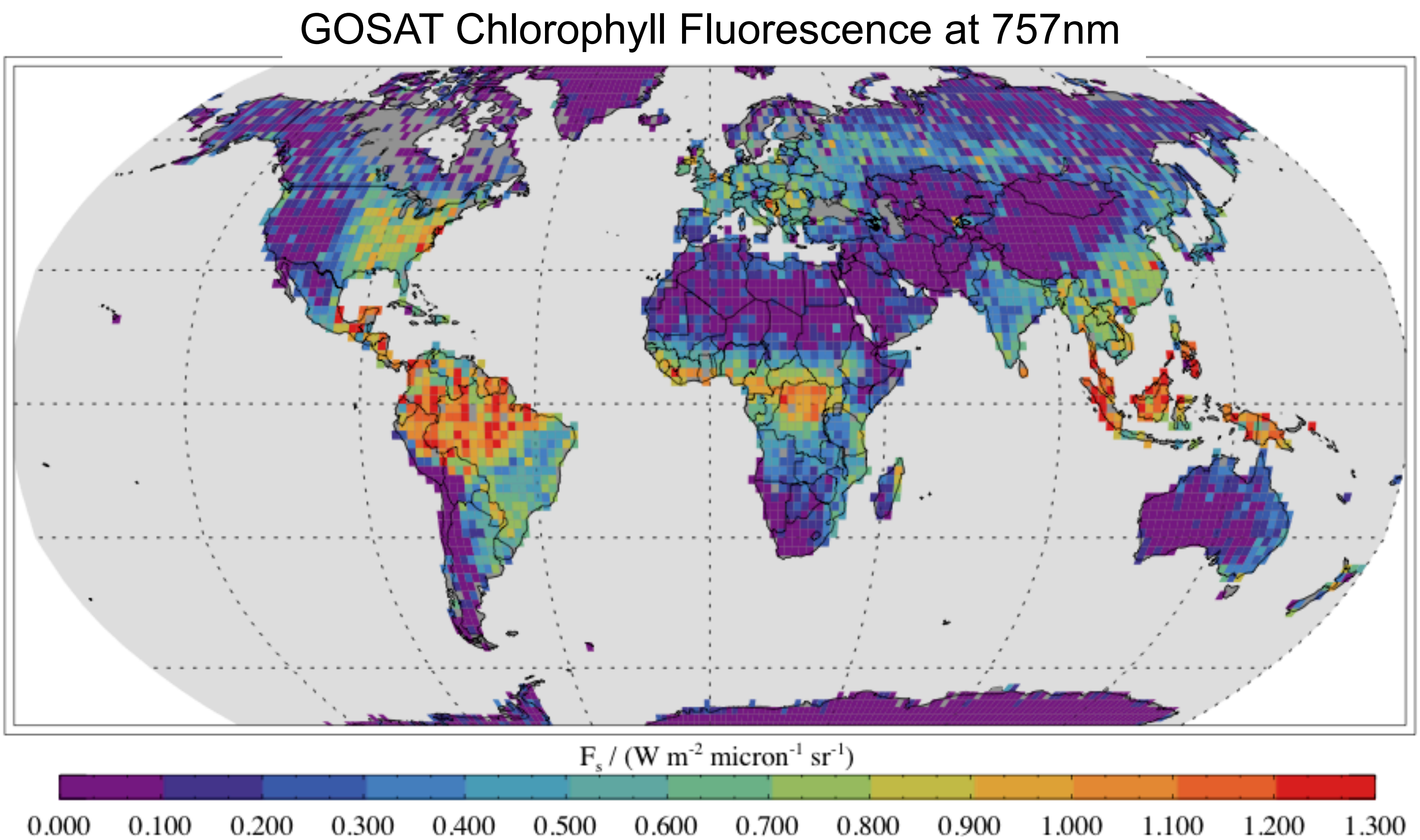


Global fluorescence retrieval from GOSAT, annual average



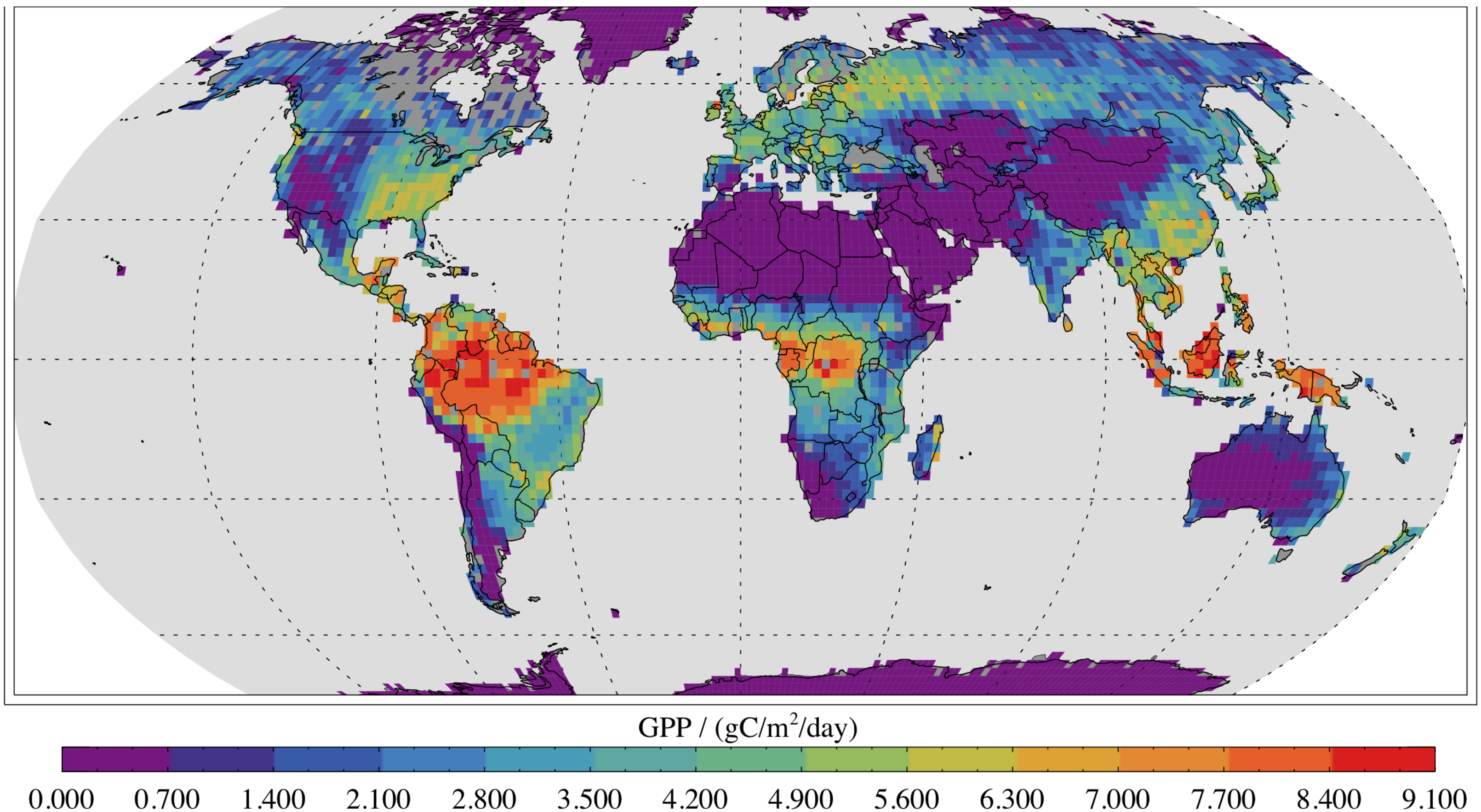
C. Frankenberg, Fisher e al, GRL, 2011

GOSAT Fluorescence and MPI-BGC GPP

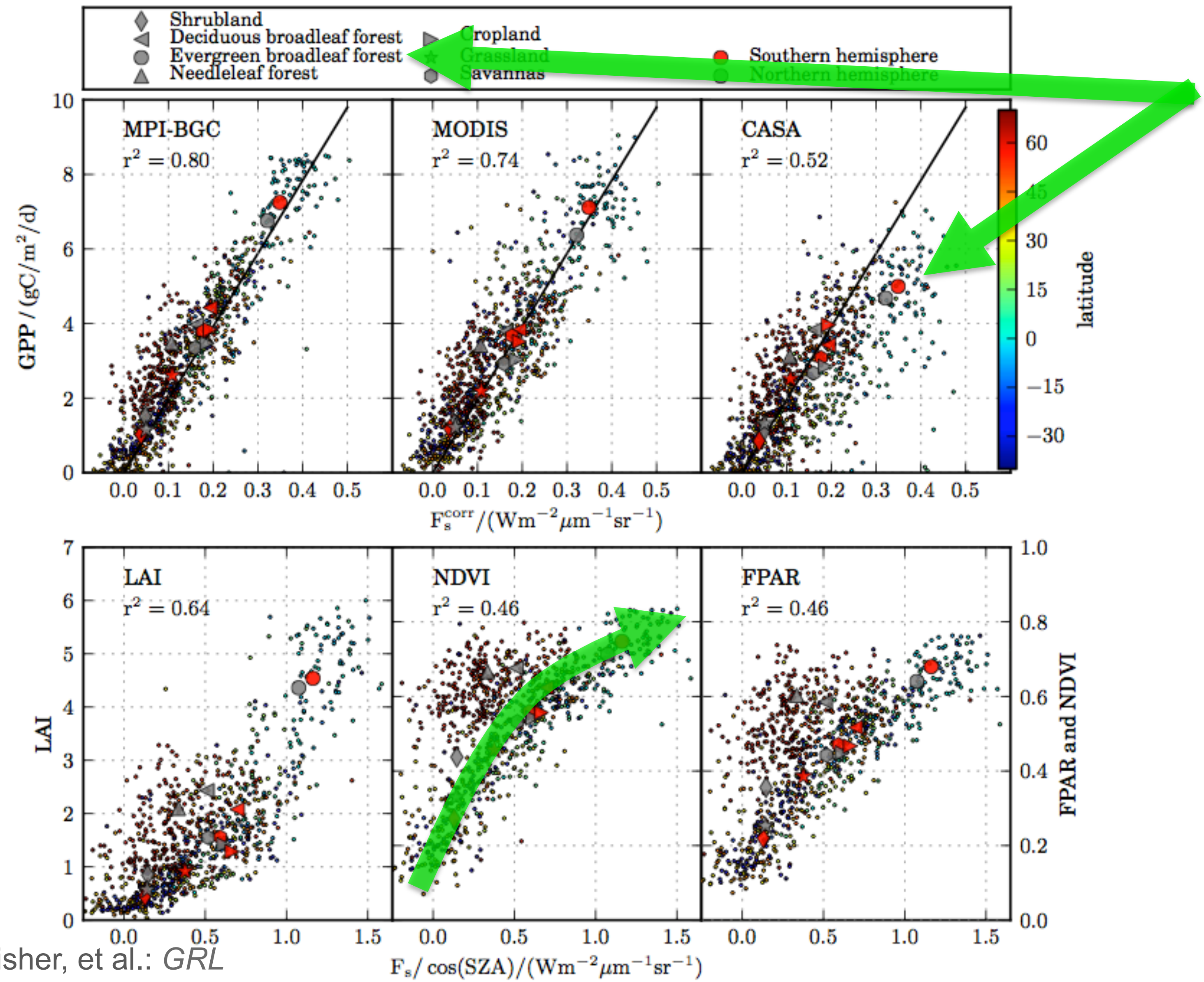


GOSAT Fluorescence and MPI-BGC GPP

Gross Primary Production (GPP), MPI-BGC (Beer et al, Science, Jung et al, JGR)

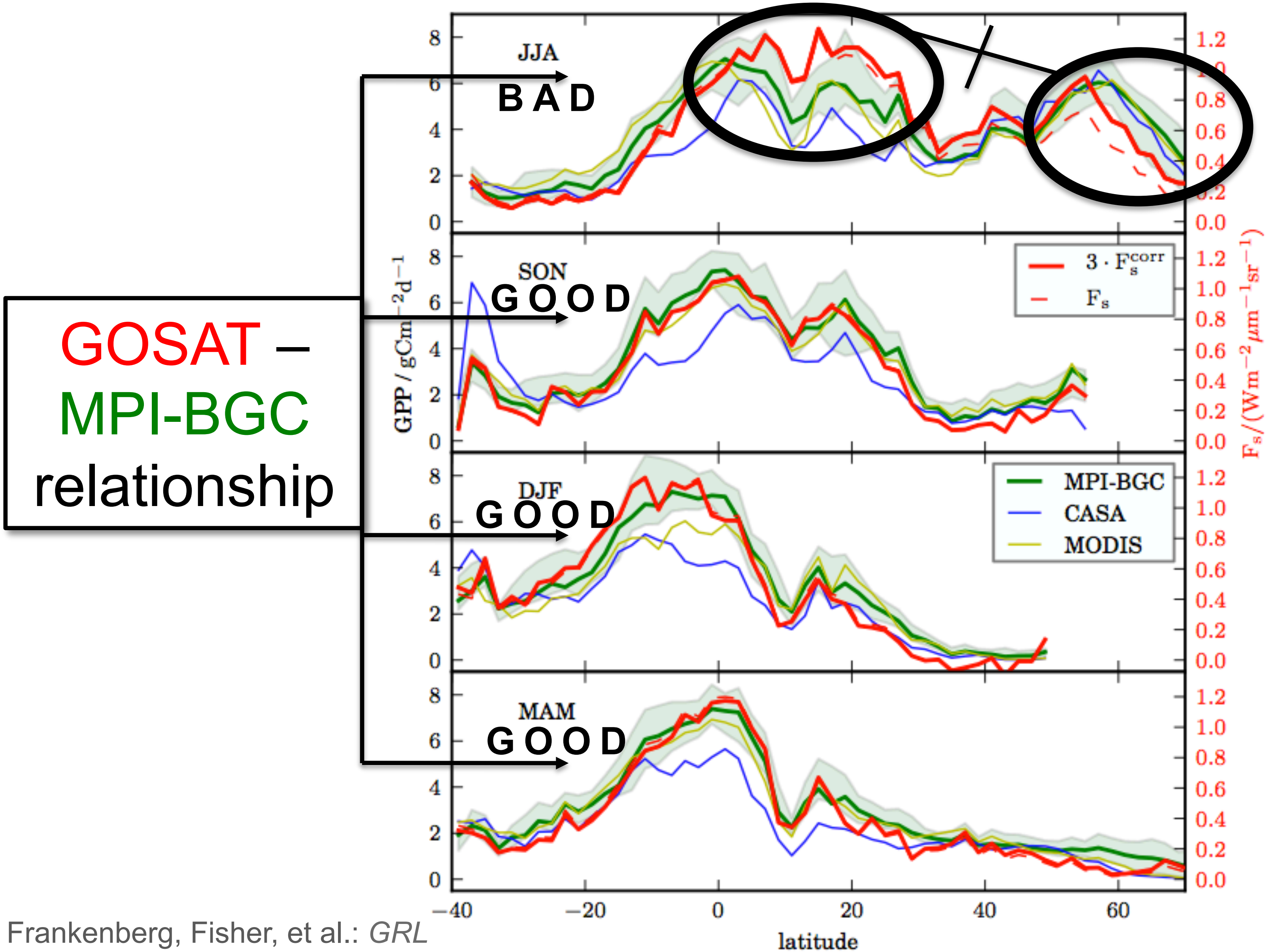


Results: F_s - GPP



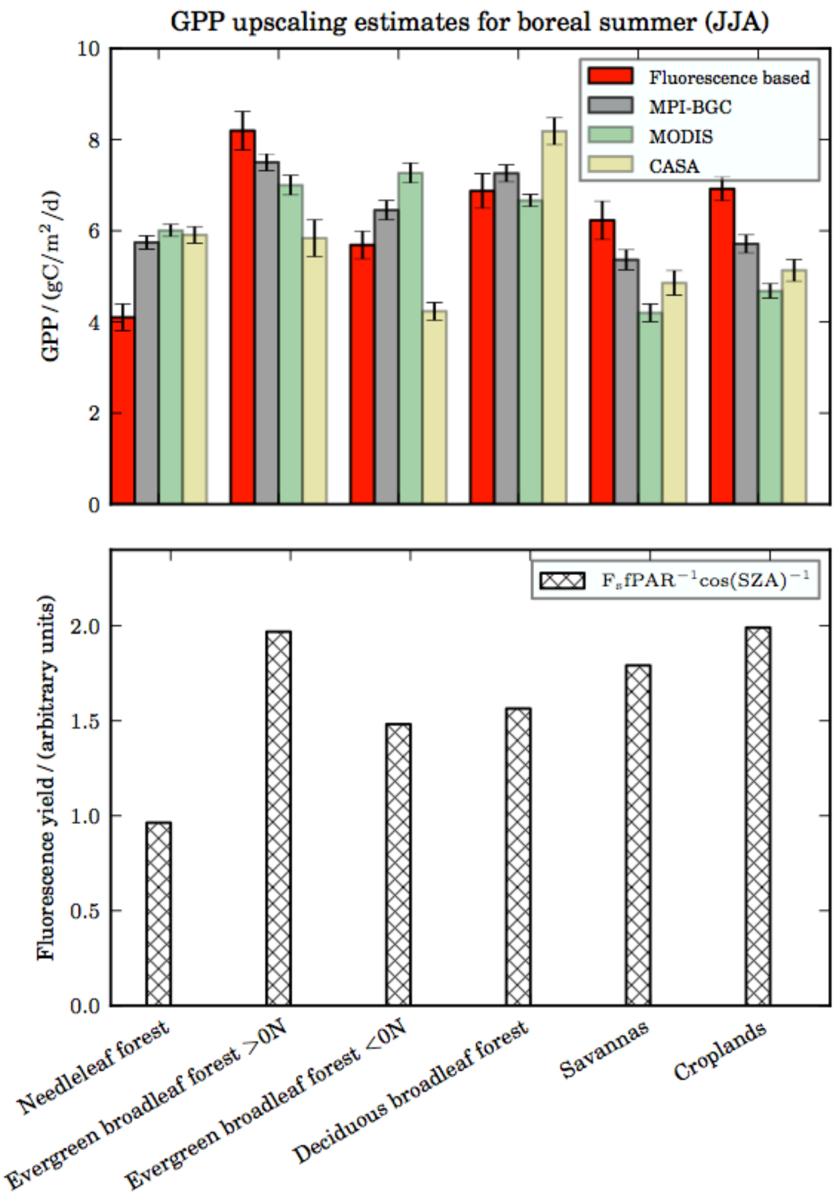
Frankenberg, Fisher, et al.: *GRL*

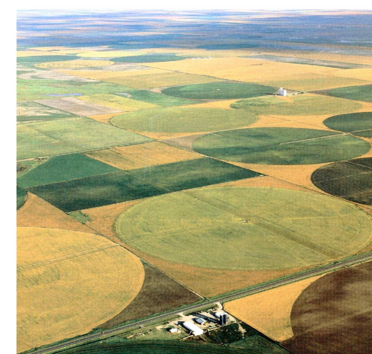
Results



Frankenberg, Fisher, et al.: *GRL*

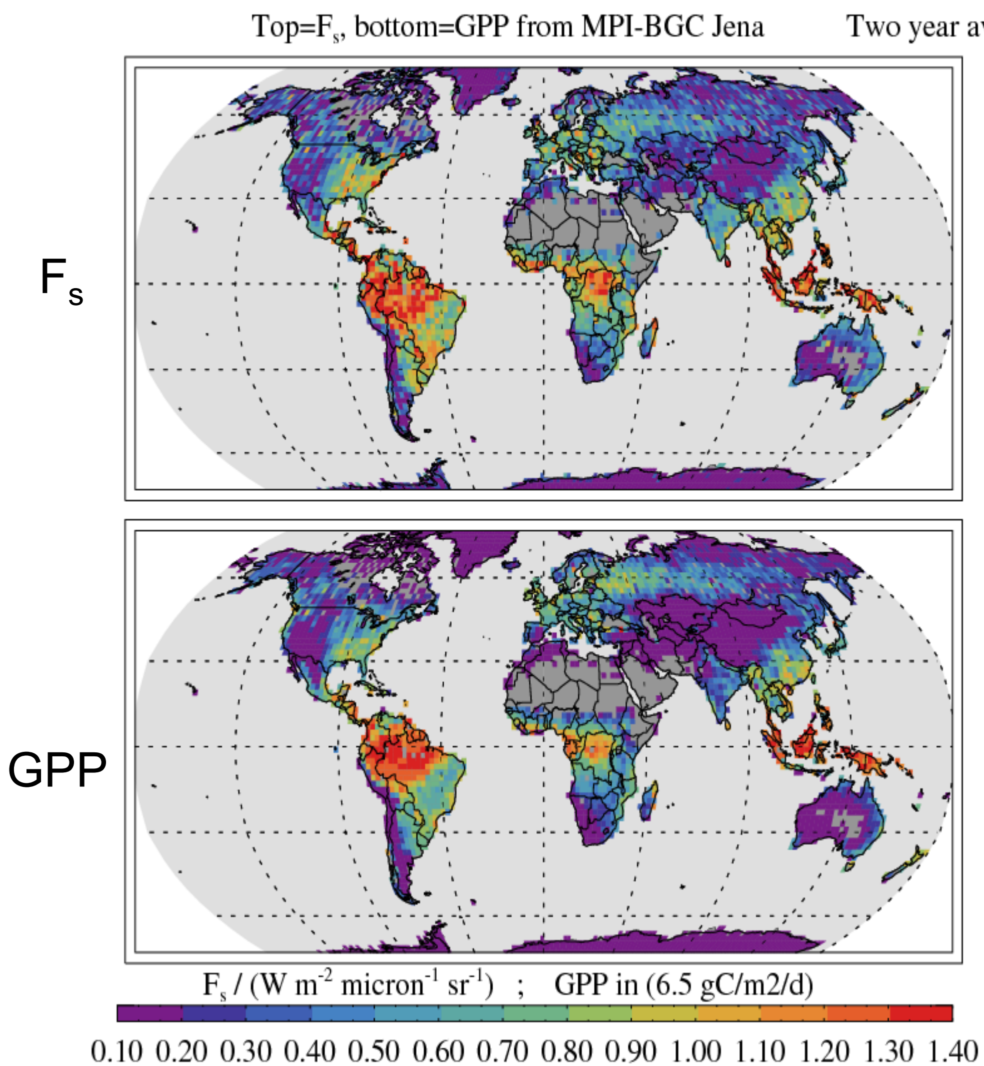
Results

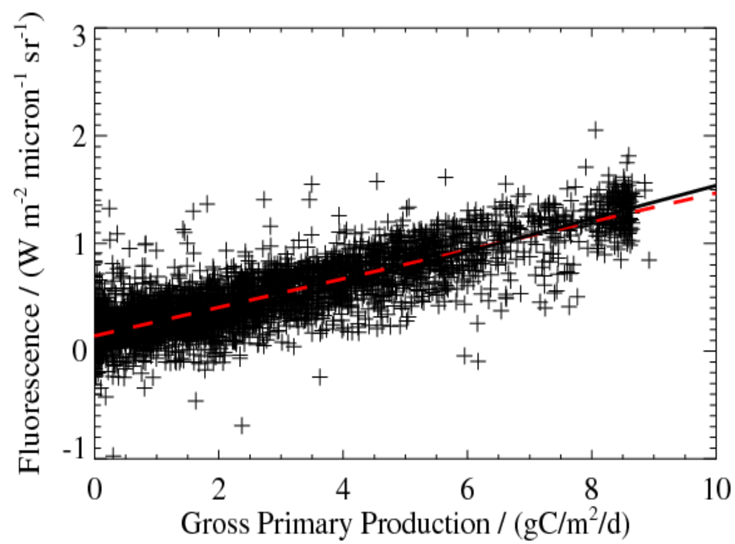




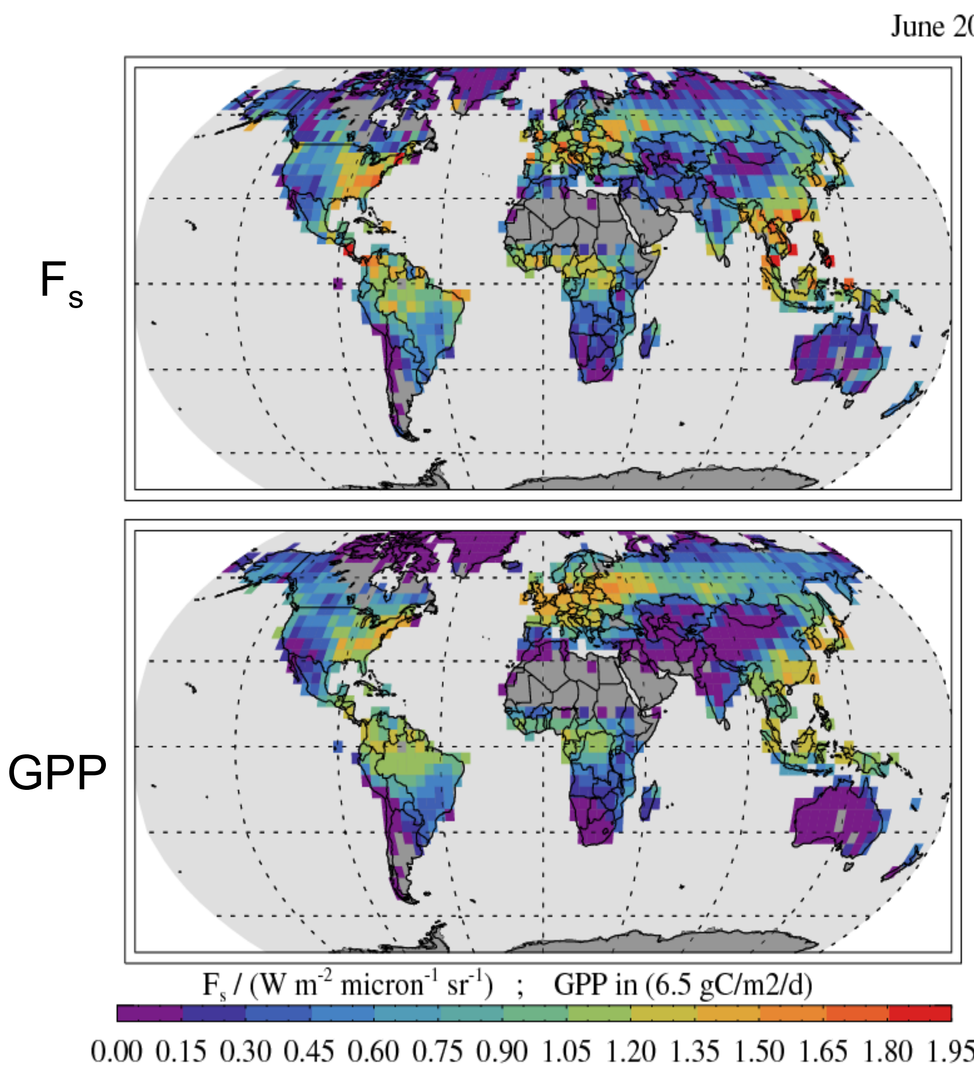
Frankenberg, Fisher, et al.: *GRL*

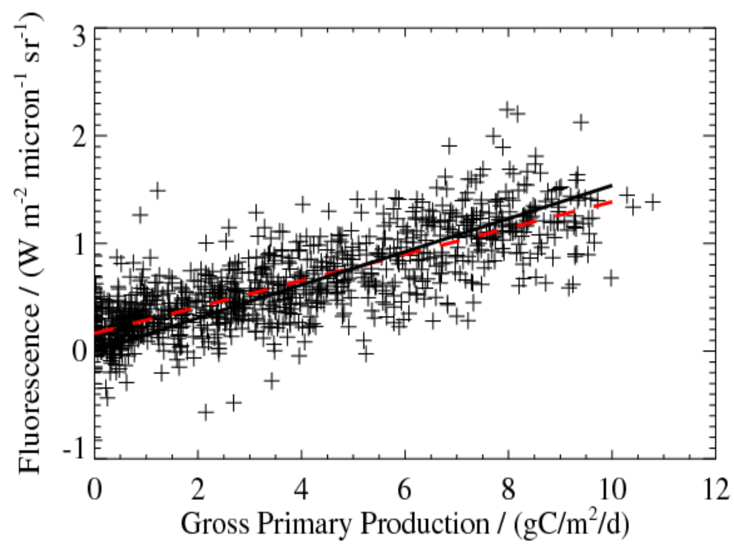
Comparison with GPP, two year average



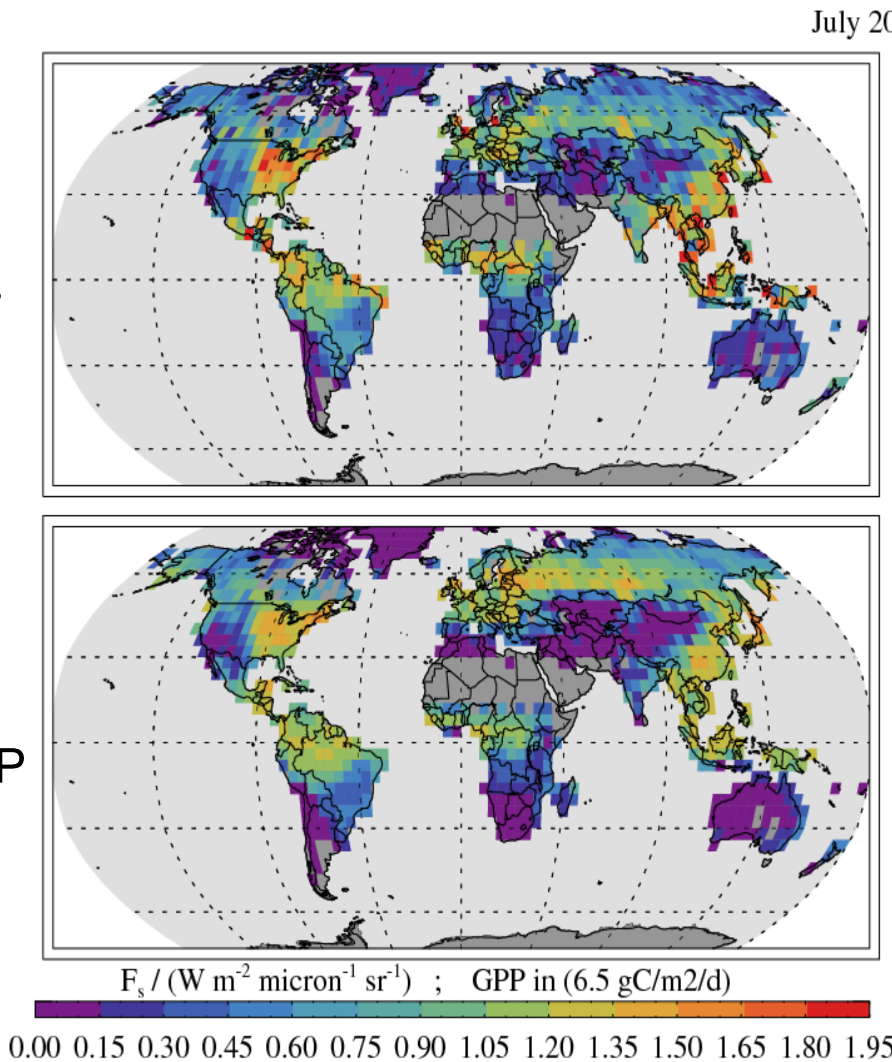


June 2009


June 2009
F_s
GPP
F_s / (W m^-2 micron^-1 sr^-1) ; GPP in (6.5 gC/m2/d)
0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95


Fluorescence / (W m^-2 micron^-1 sr^-1)
Gross Primary Production / (gC/m^2/d)
3
2
1
0
-1
0 2 4 6 8 10 12

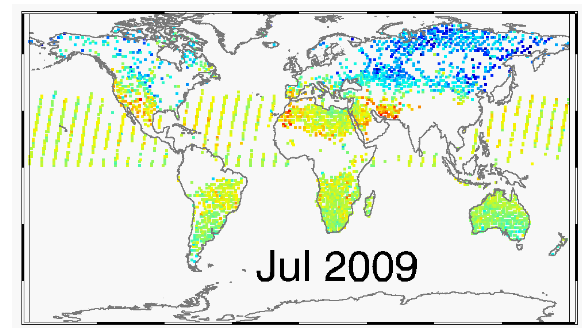
July 2009

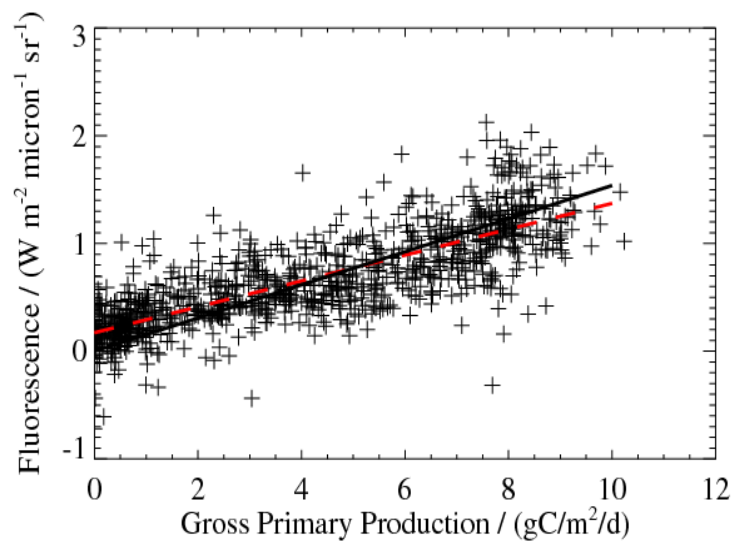


F_s

GPP

ACOS XCO_2

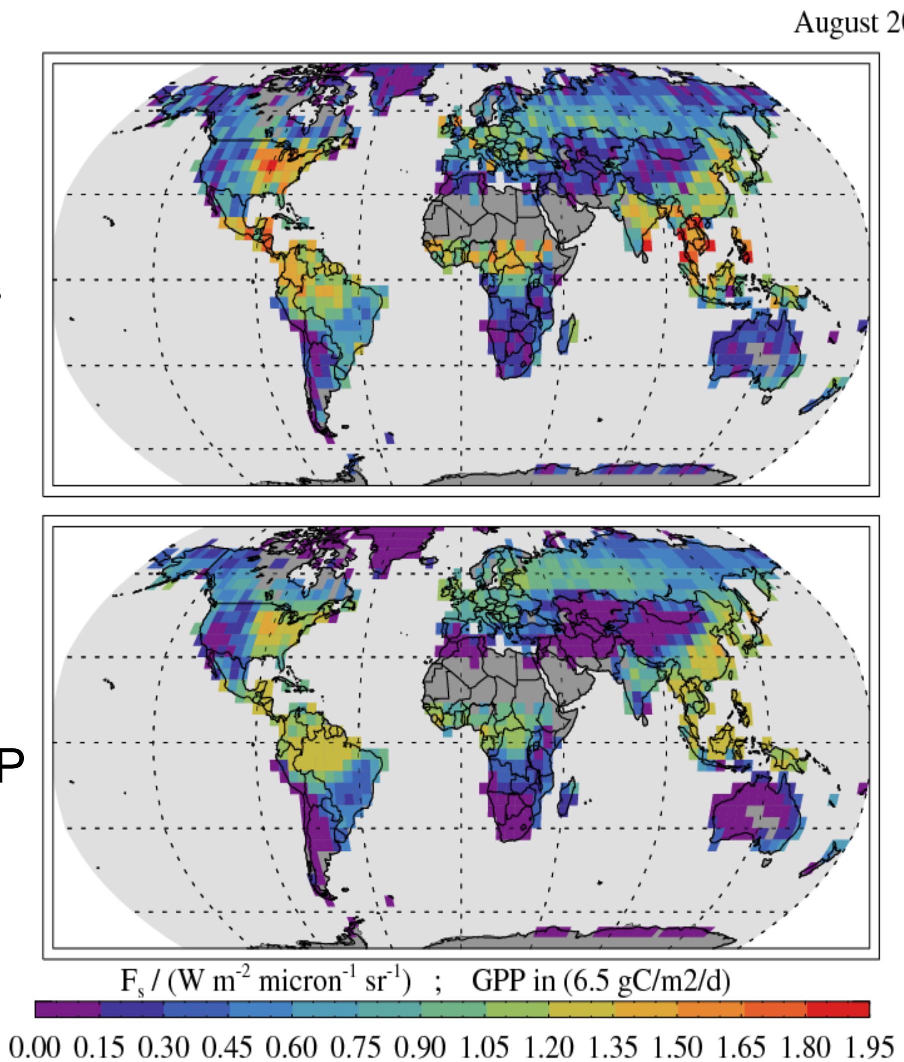




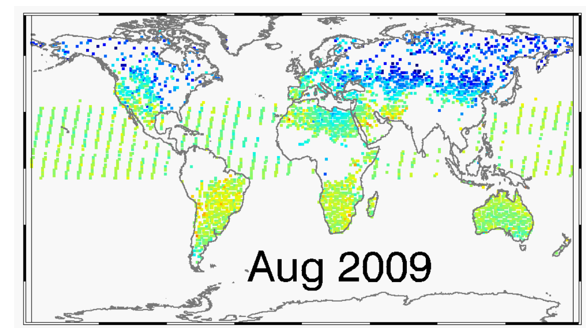
August 2009

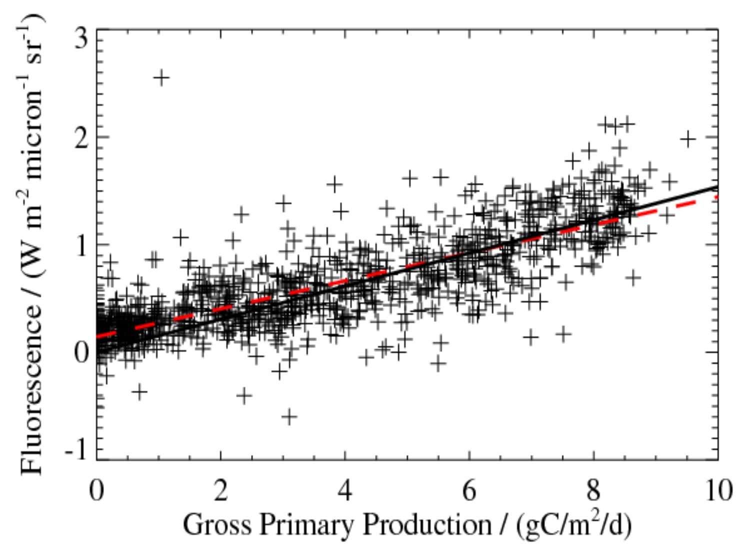
F$_s$

GPP



ACOS XCO$_2$



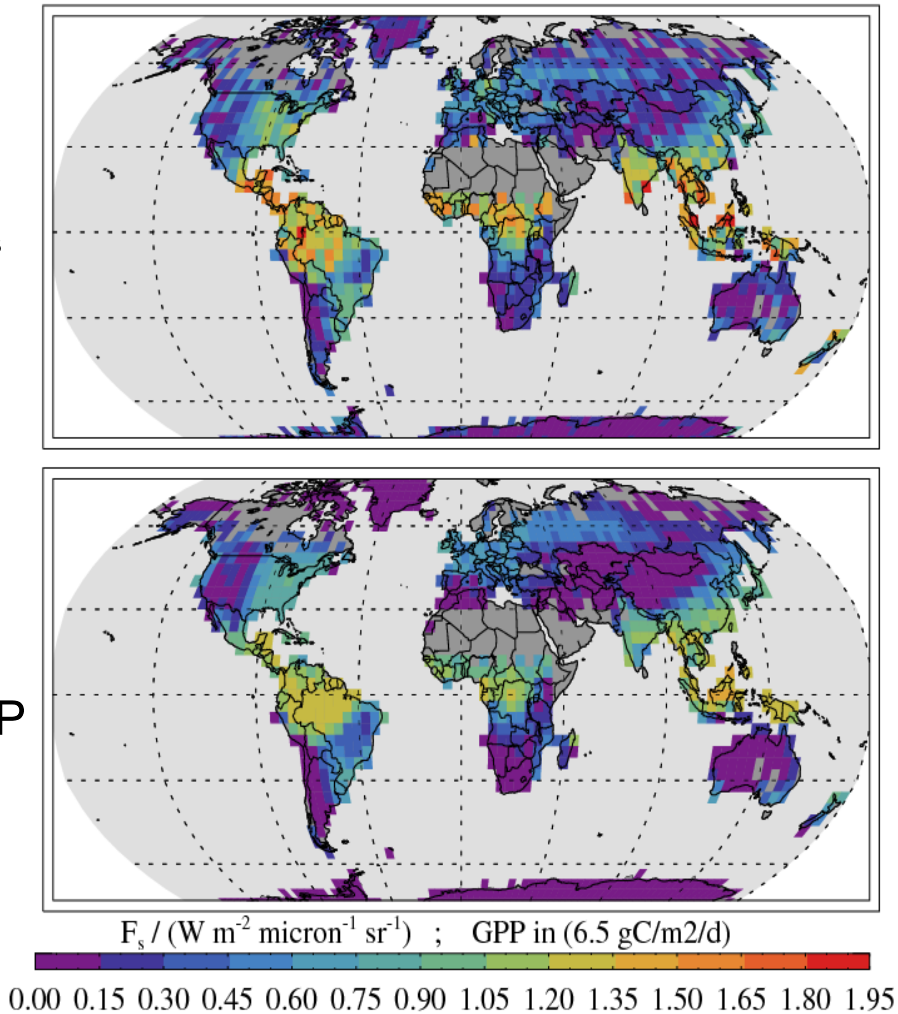


September 2009

September 2009

F_s

GPP



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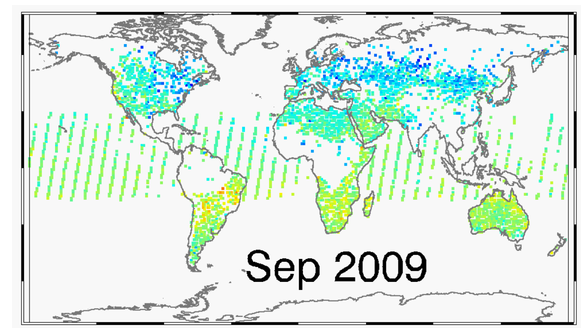
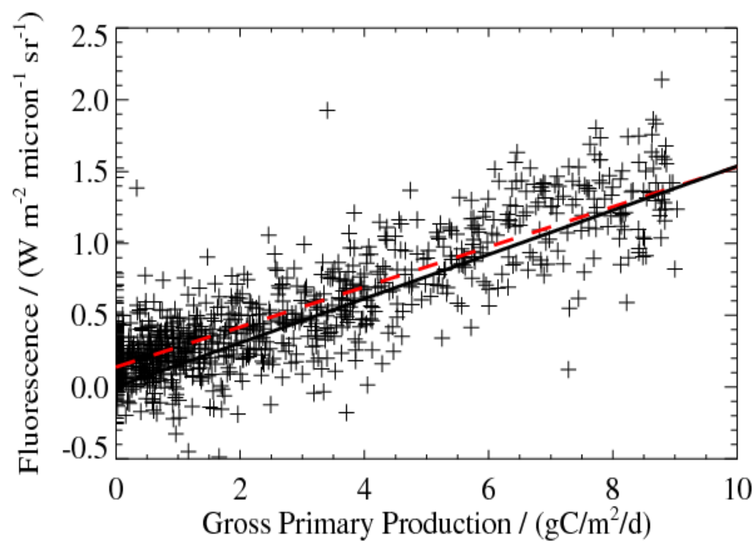


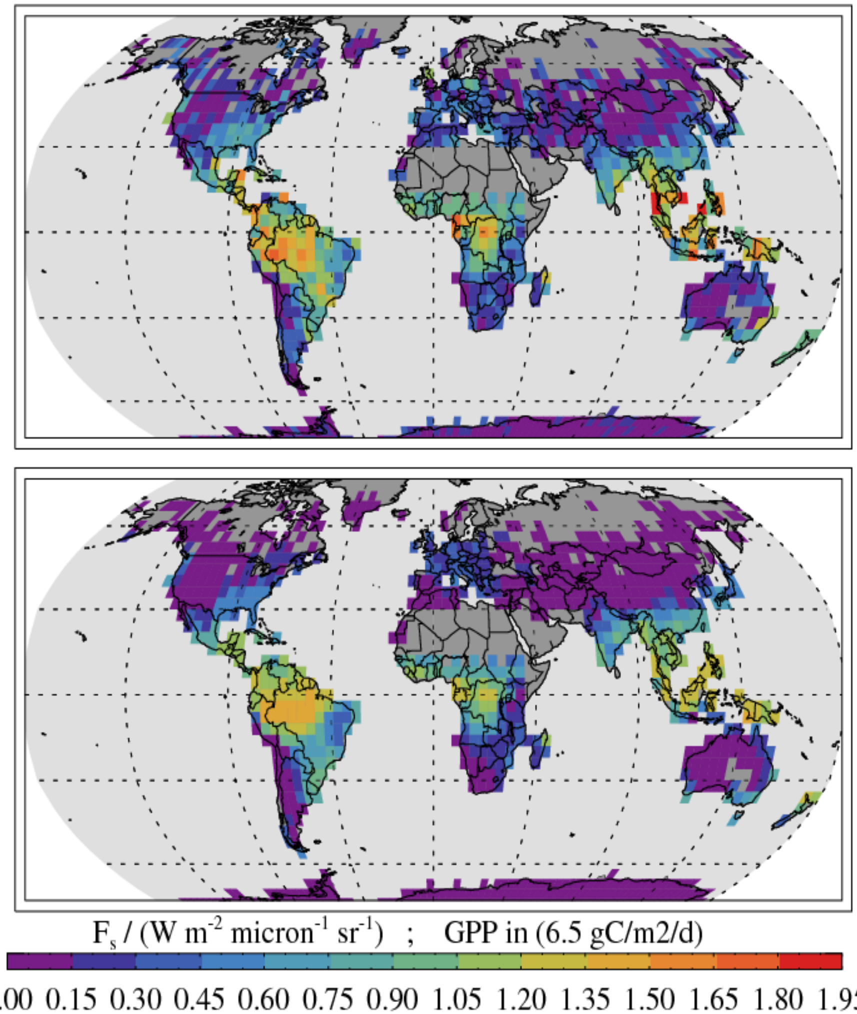


October 2009

October 2009

F$_s$

GPP



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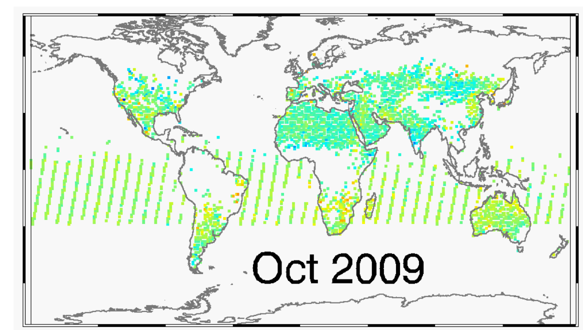
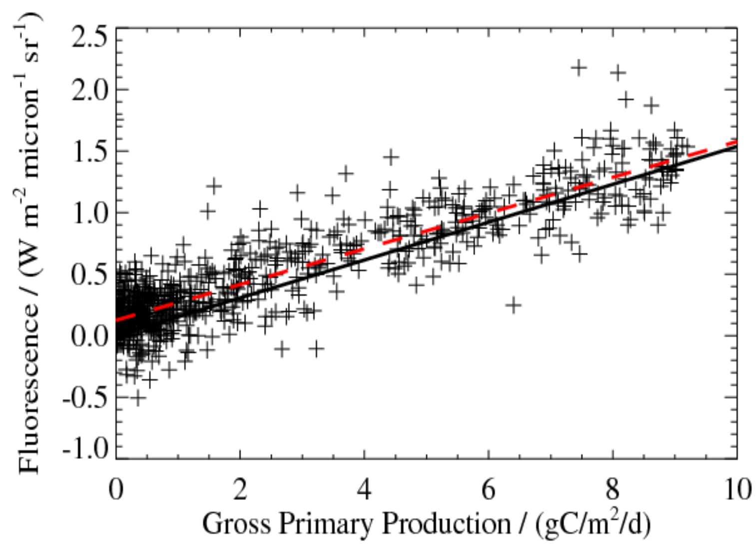
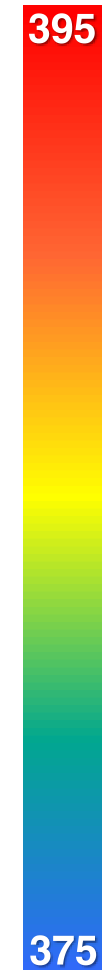


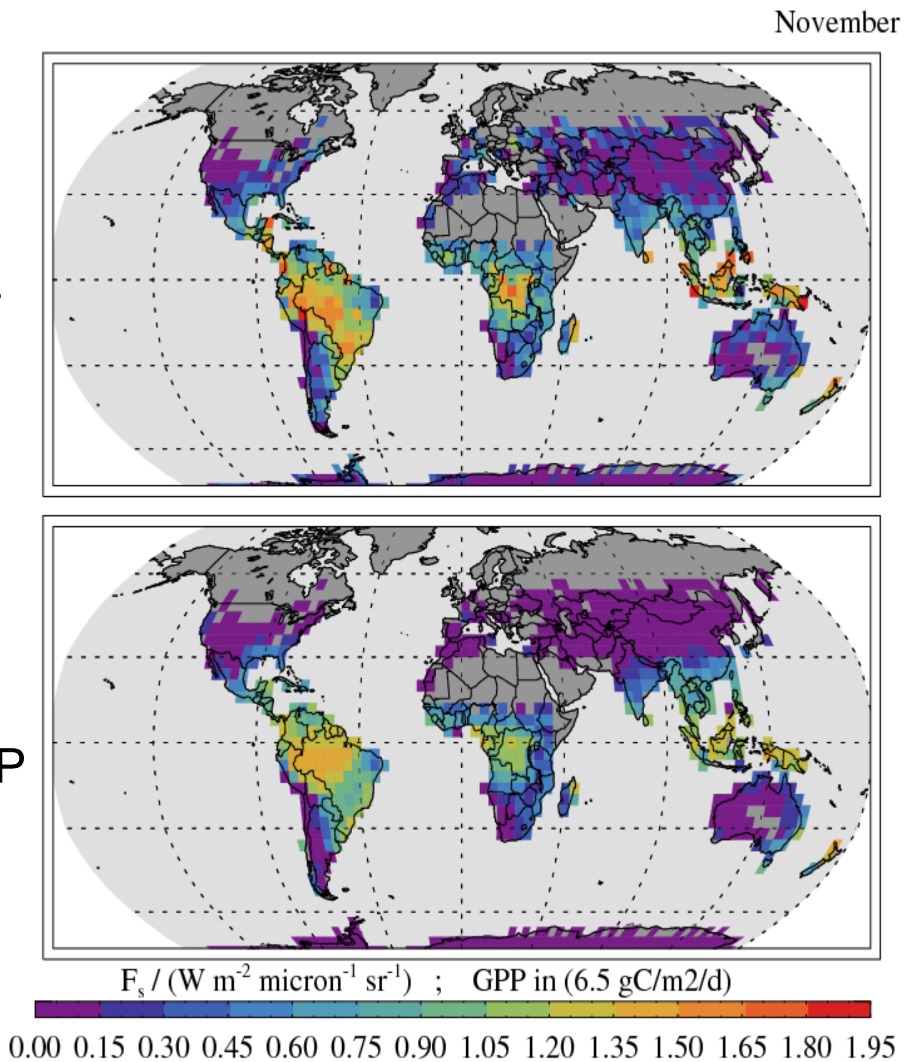




November 2009

F_s

GPP



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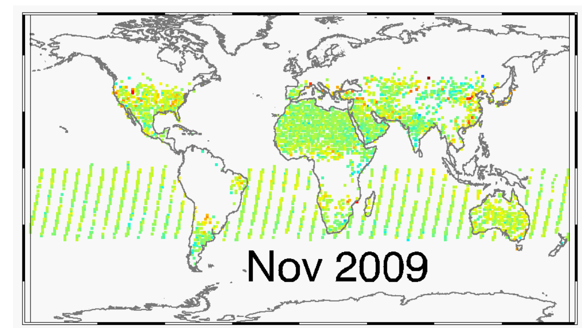
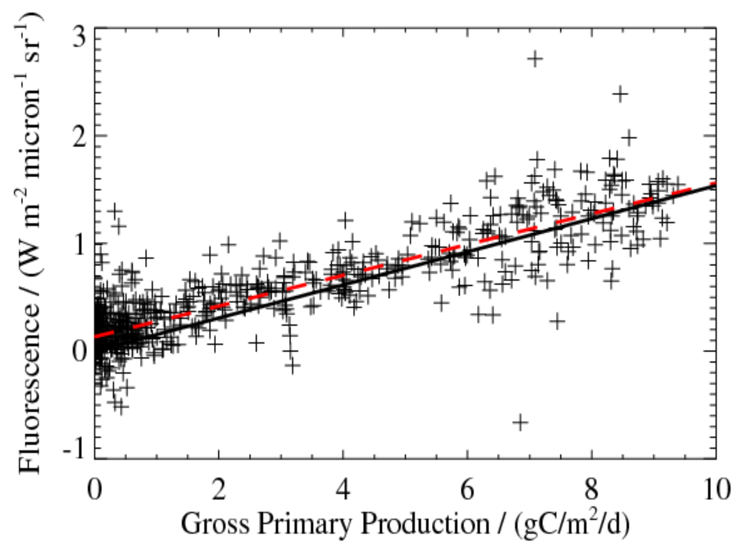
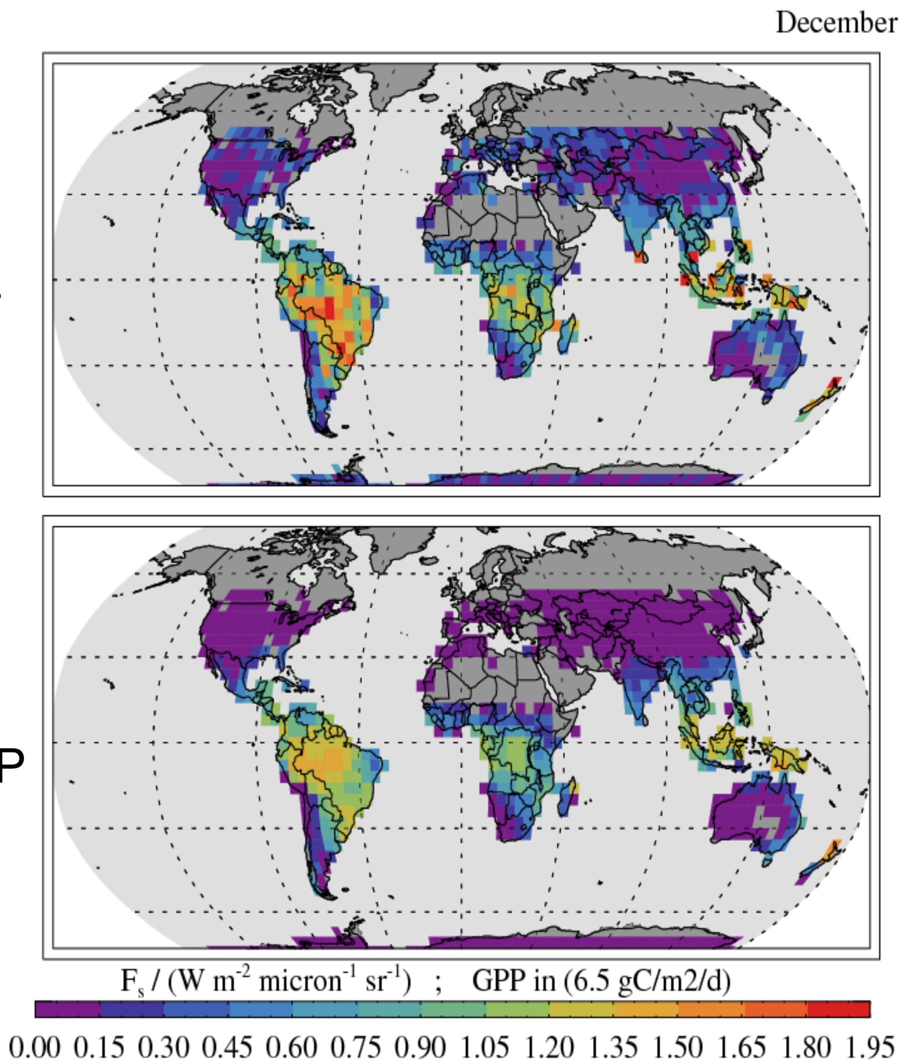




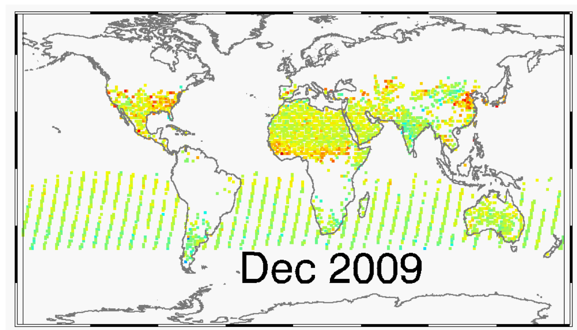
December 2009

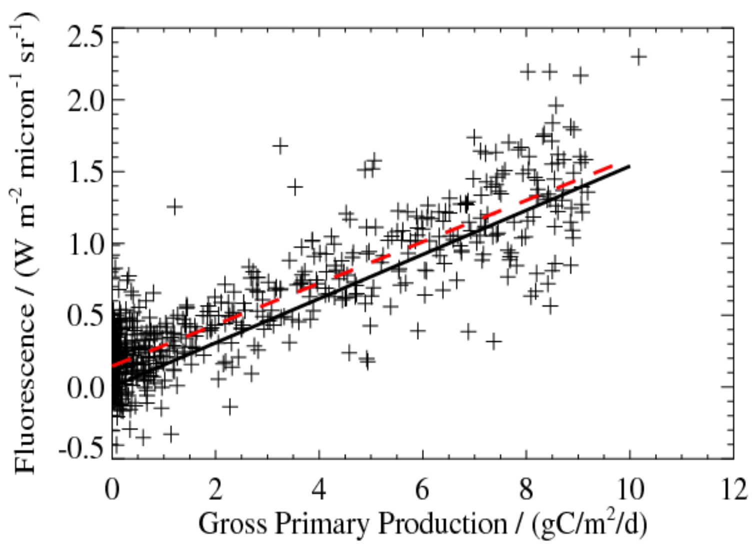
F_s

GPP



ACOS XCO_2



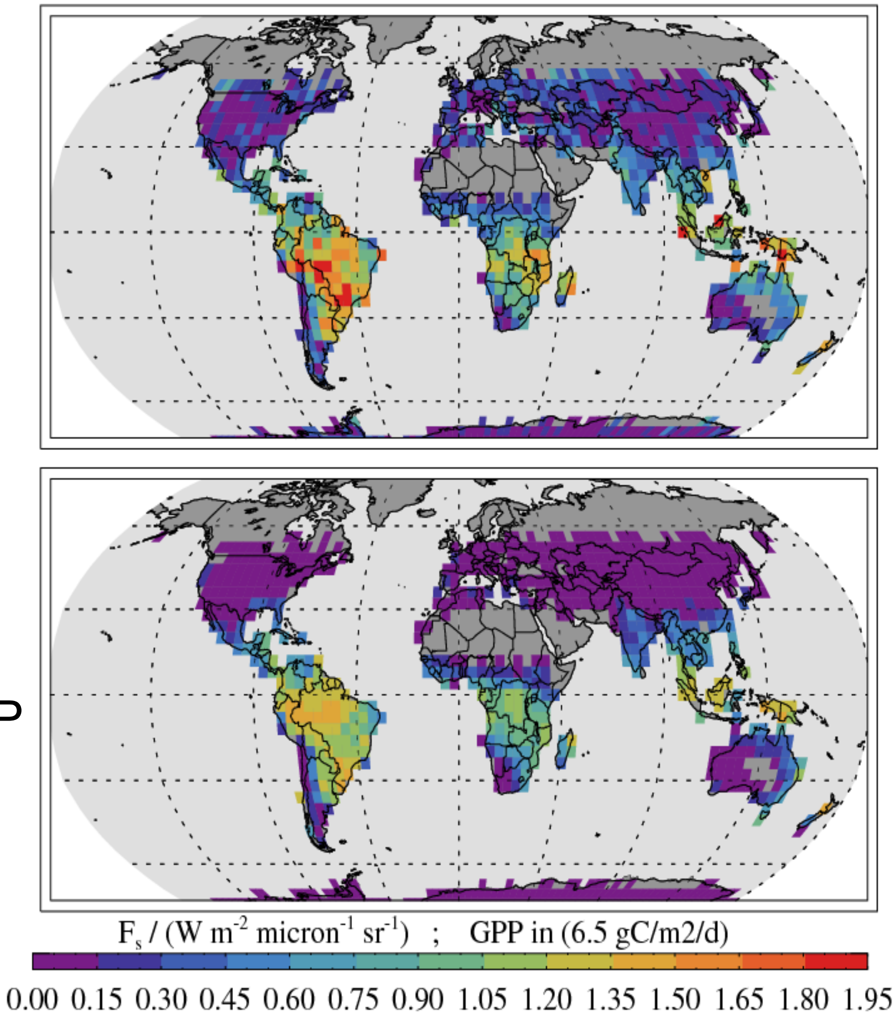


January 2010

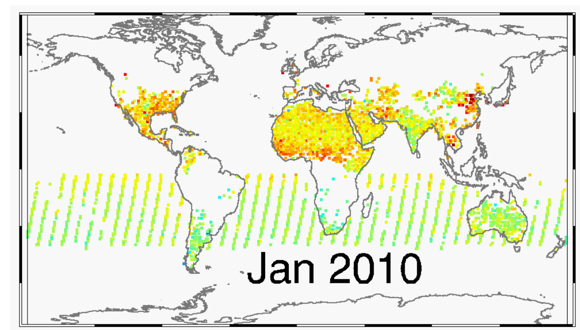
January 2010

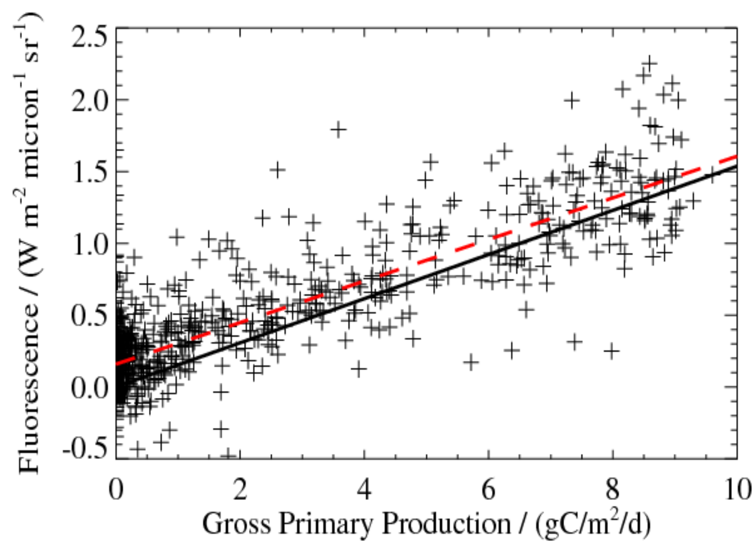
F_s

GPP

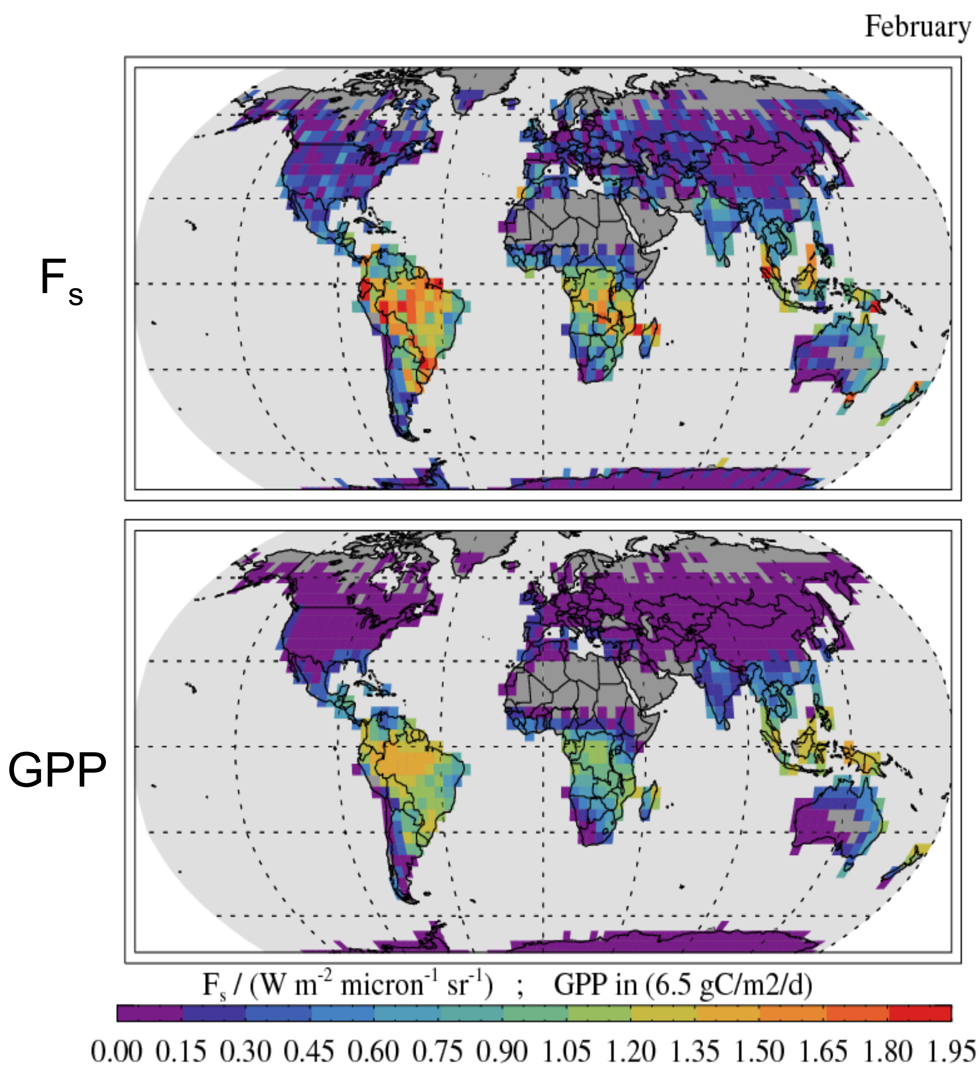


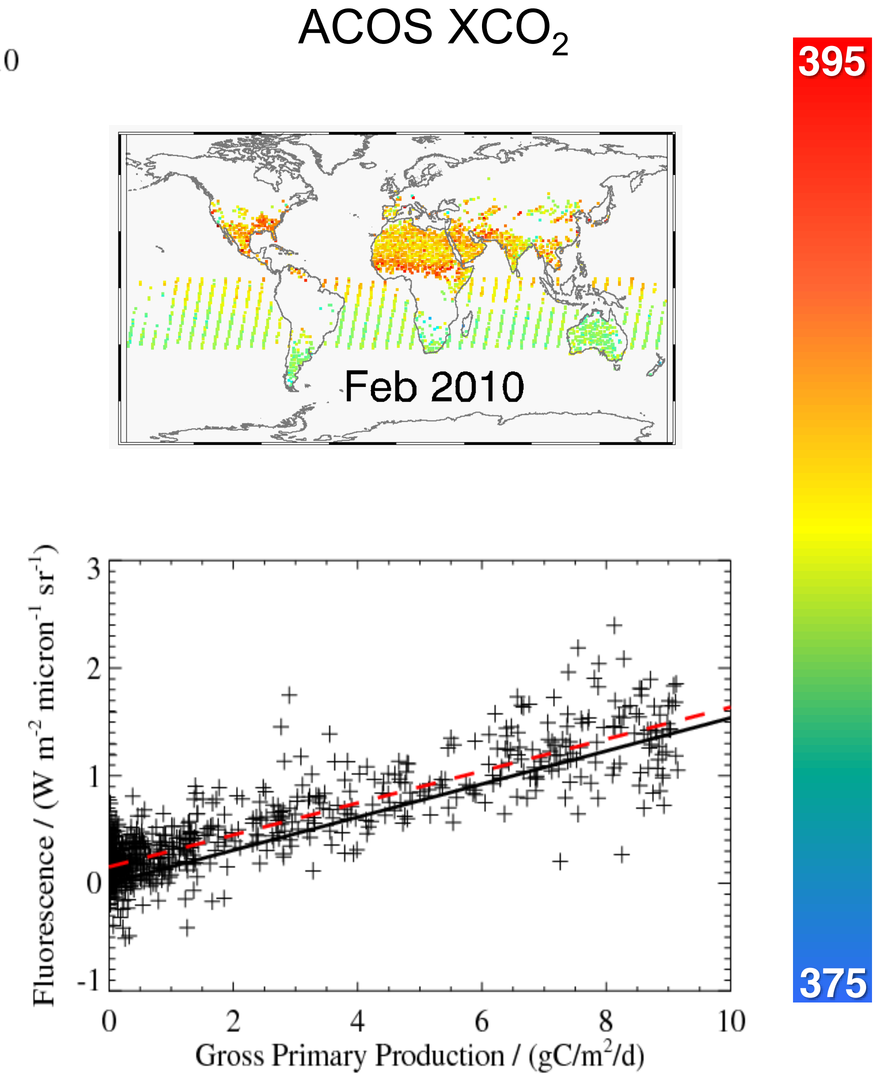
ACOS XCO_2



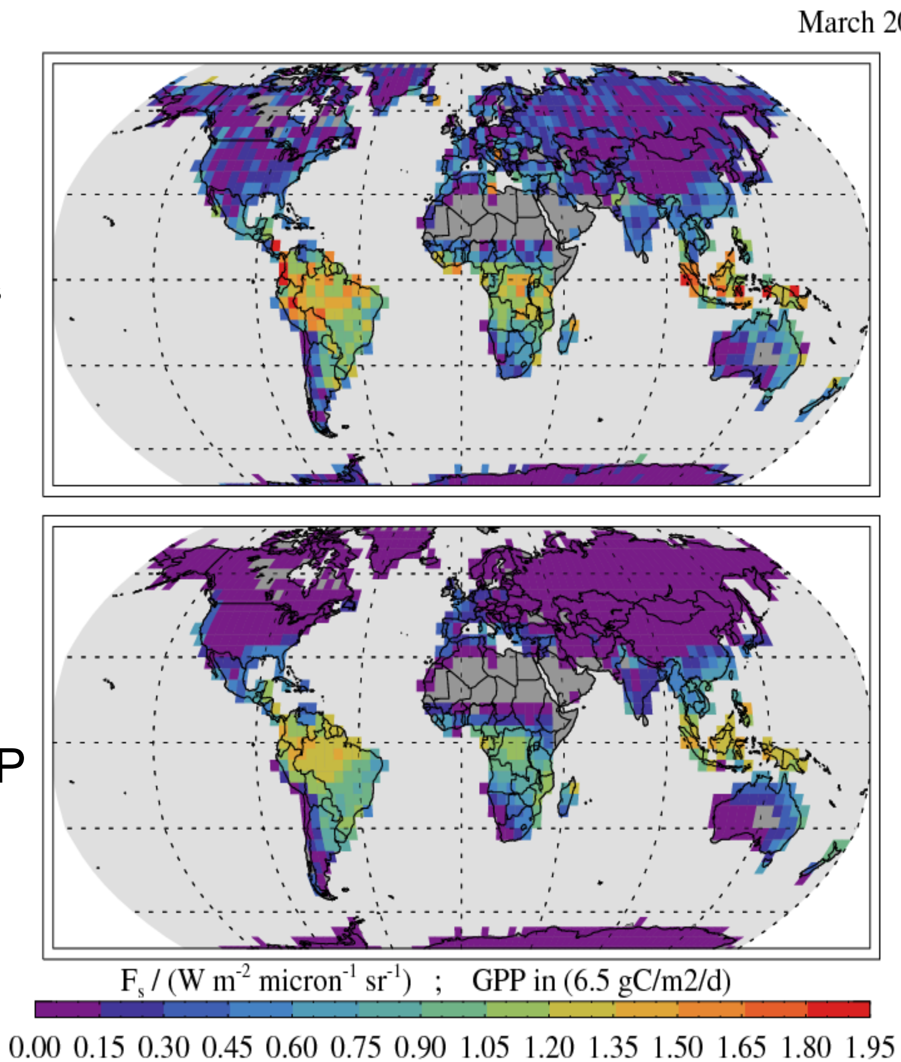


February 2010

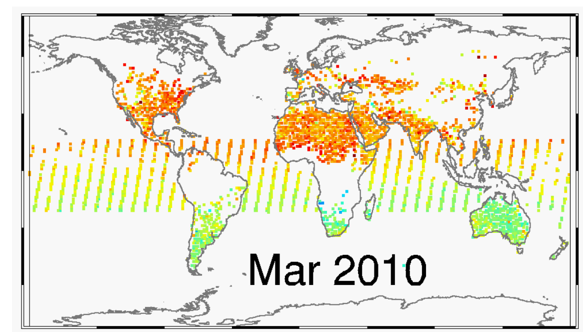


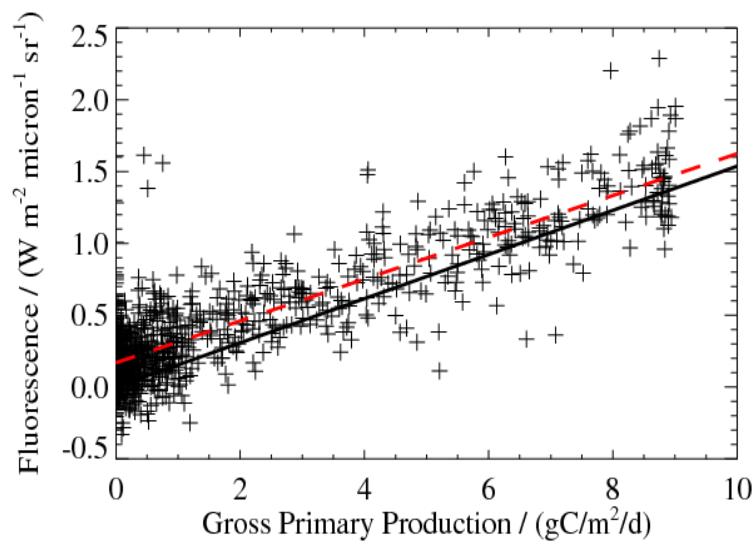


March 2010

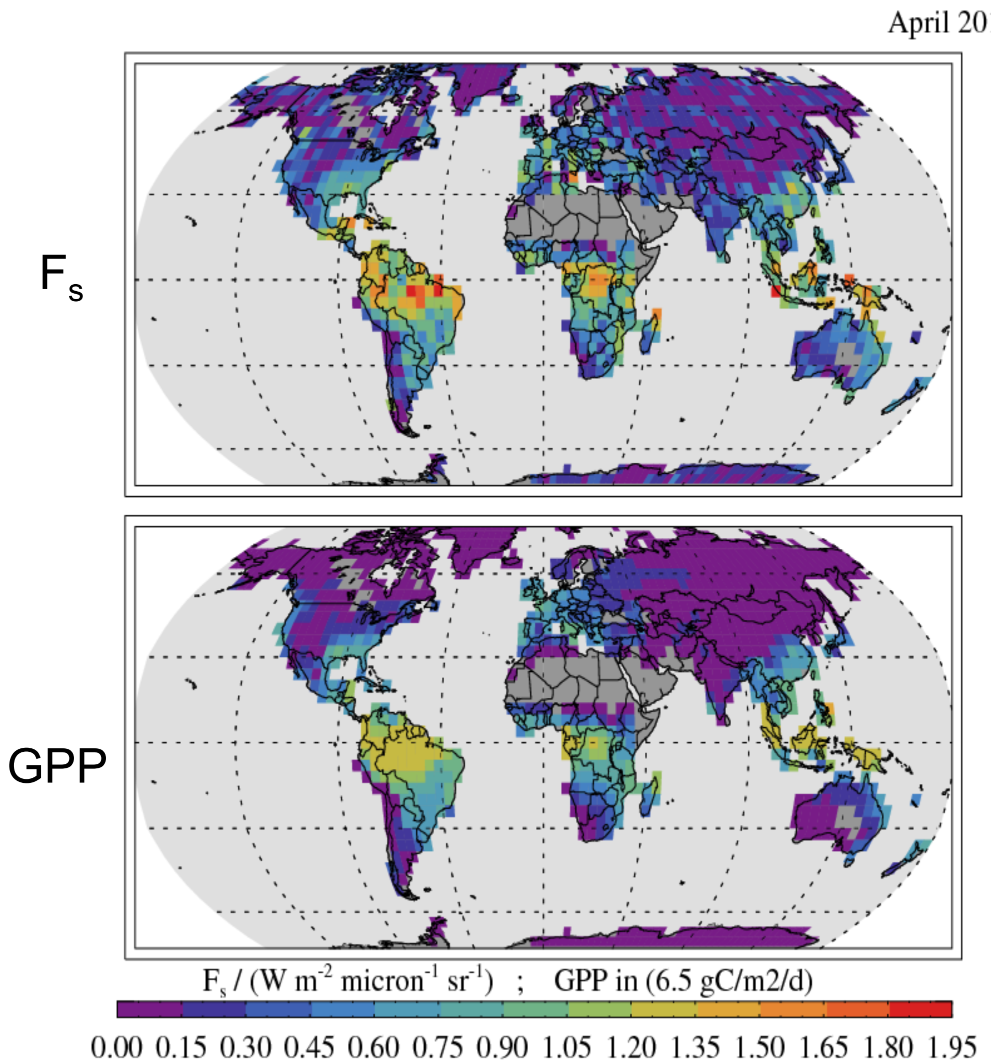


ACOS XCO_2

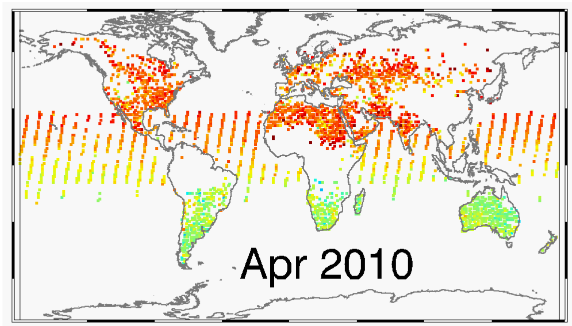


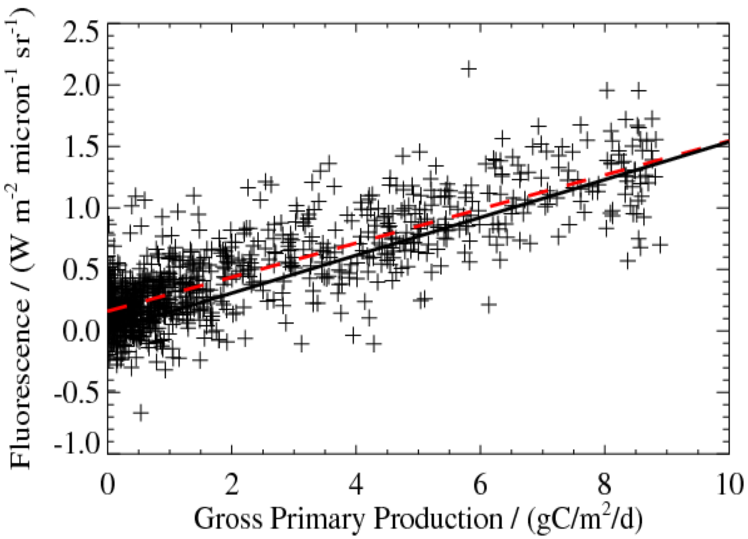


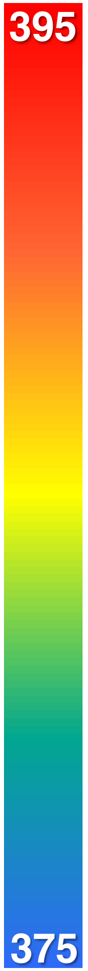
April 2010



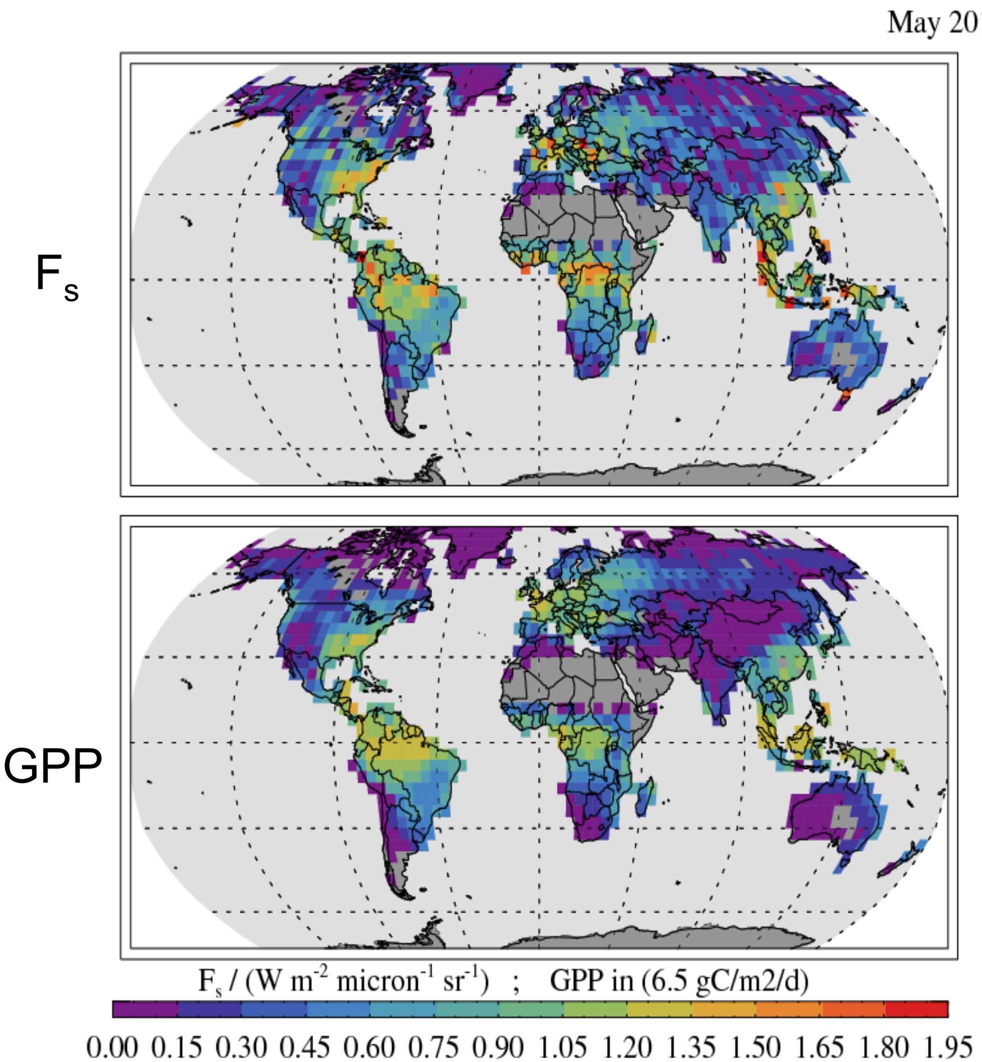
ACOS XCO_2



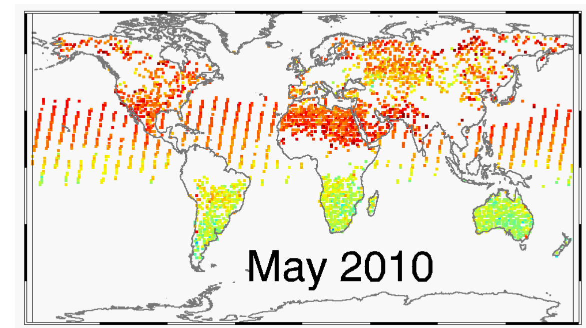


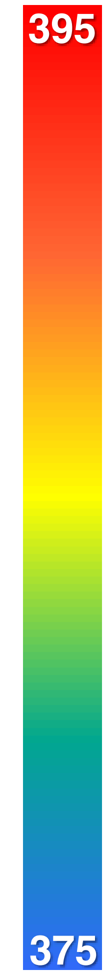


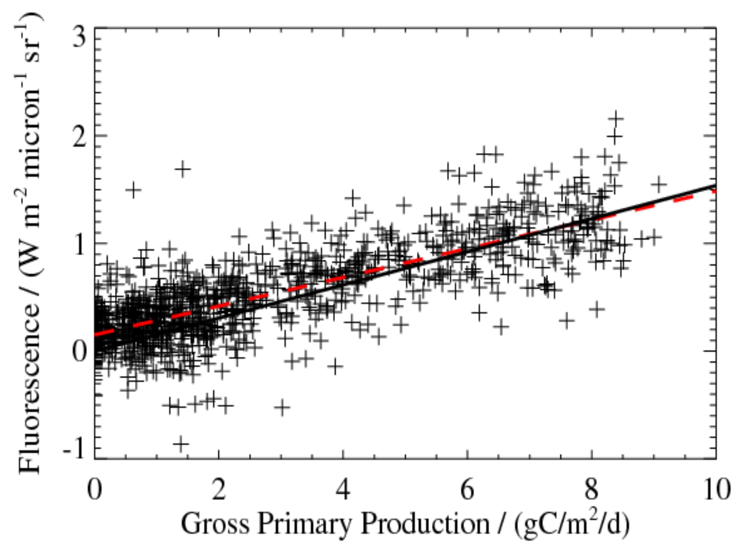
May 2010



ACOS XCO_2







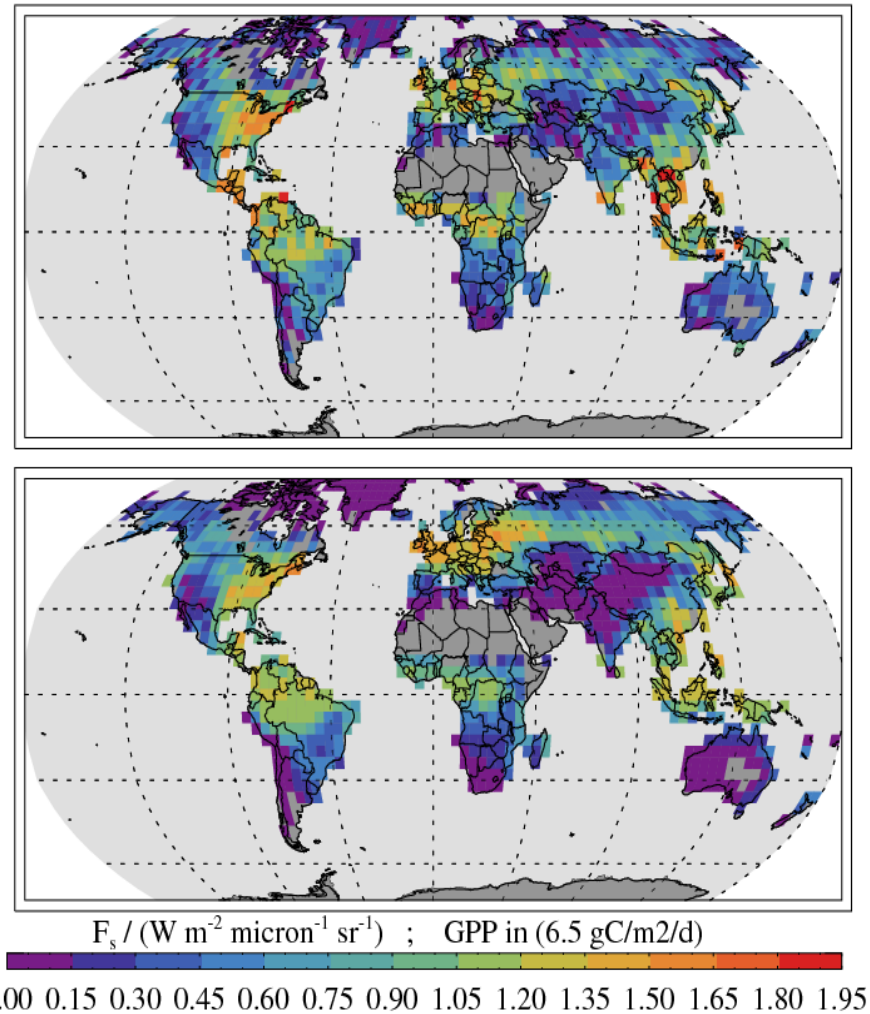
June 2010

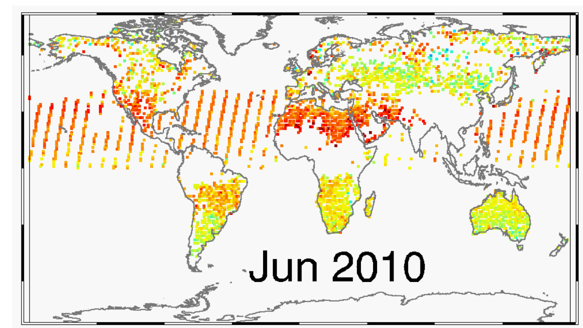
ACOS XCO_2

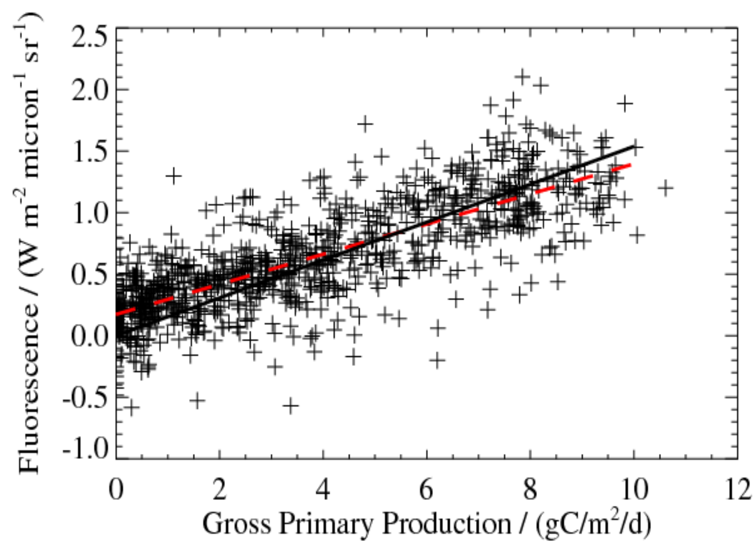
June 2010

F_s

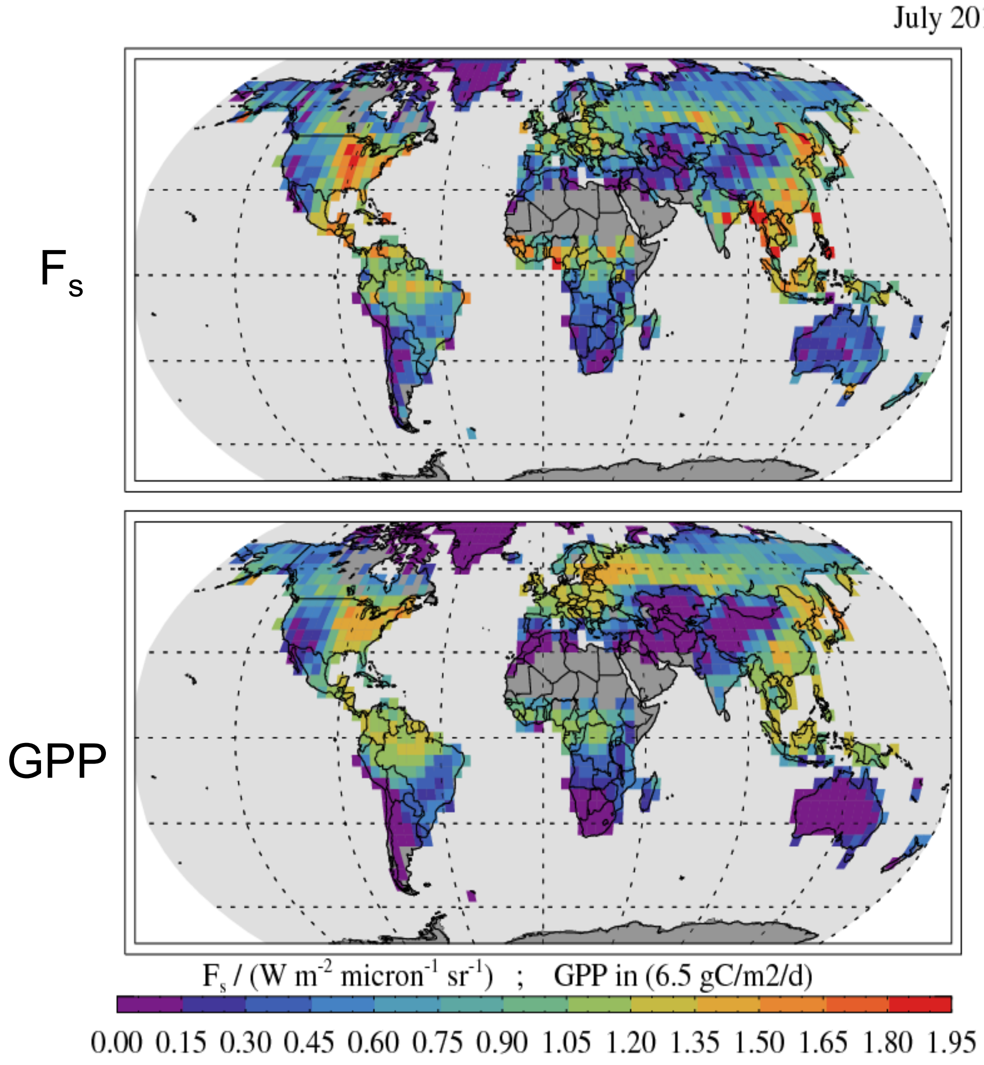
GPP



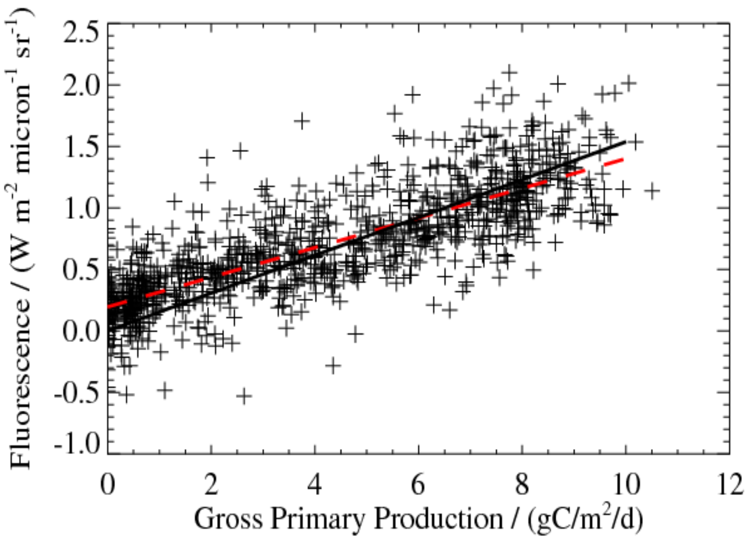




July 2010



July 2010
F$_s$
GPP
F_s / (W m^{-2} micron^{-1} sr^{-1}) ; GPP in (6.5 gC/m2/d)
0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95



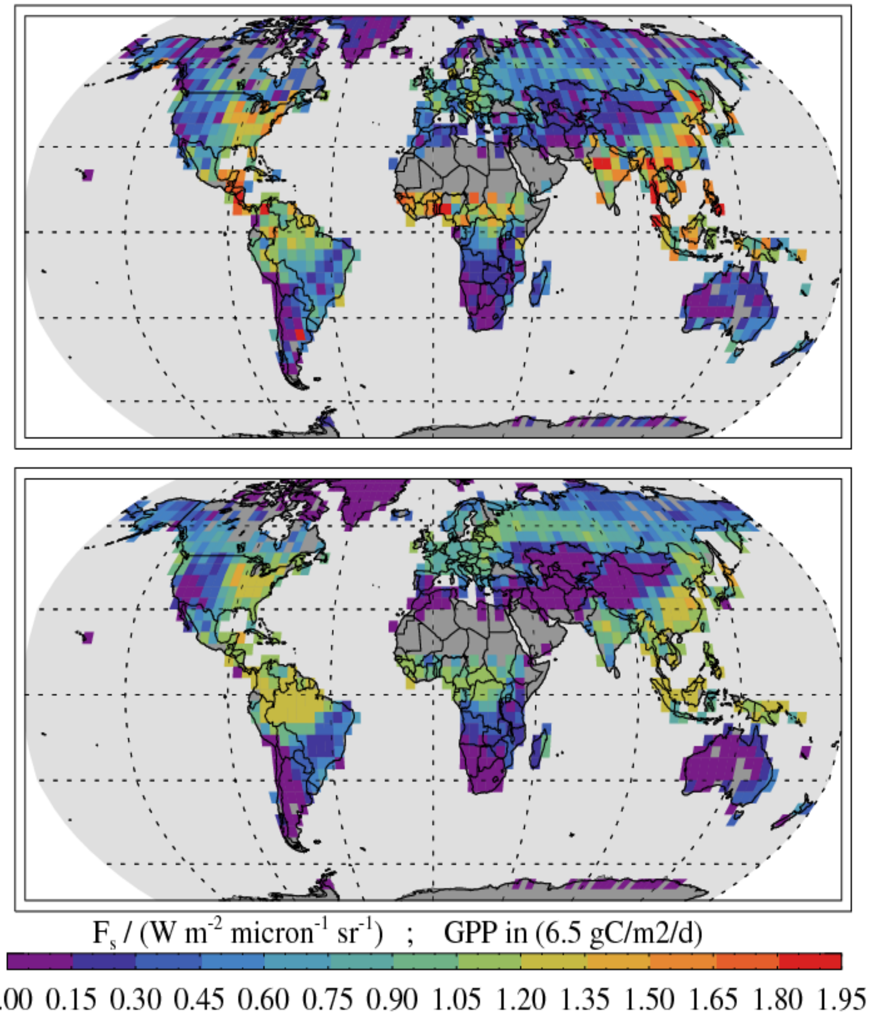
Fluorescence / (W m^{-2} micron^{-1} sr^{-1})
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0 2 4 6 8 10 12
Gross Primary Production / (gC/m^2/d)

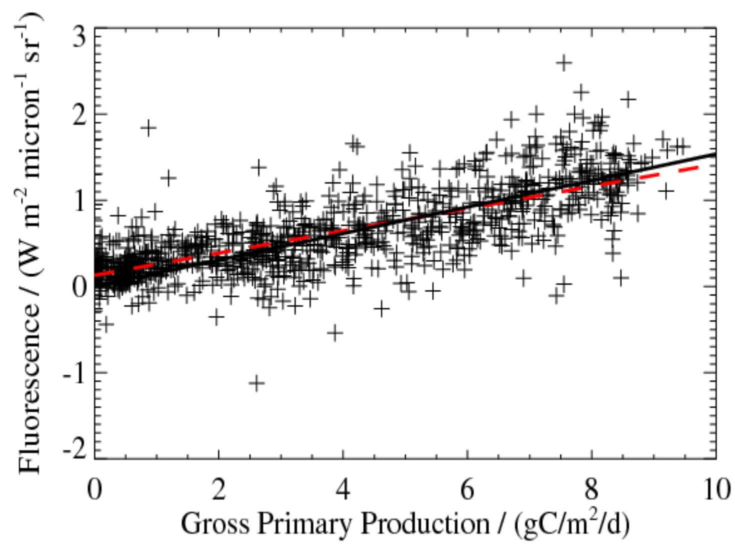
August 2010

August 2010

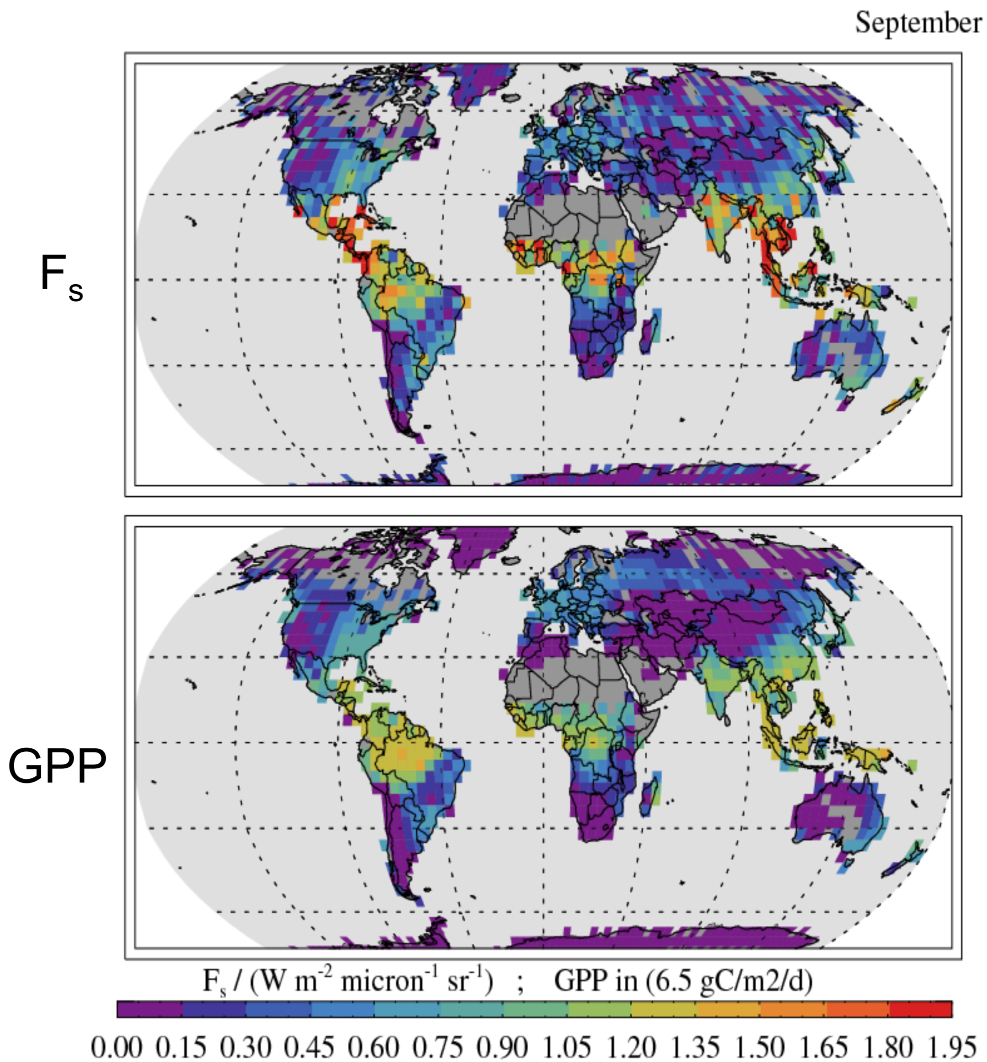
F_s

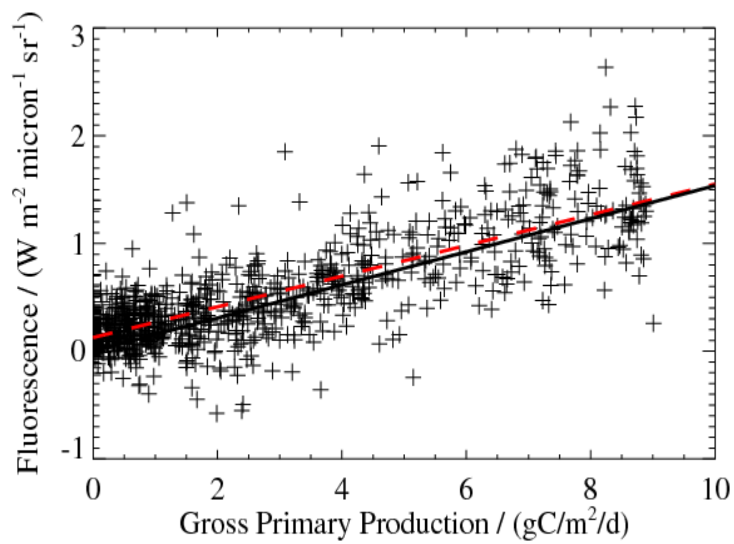
GPP



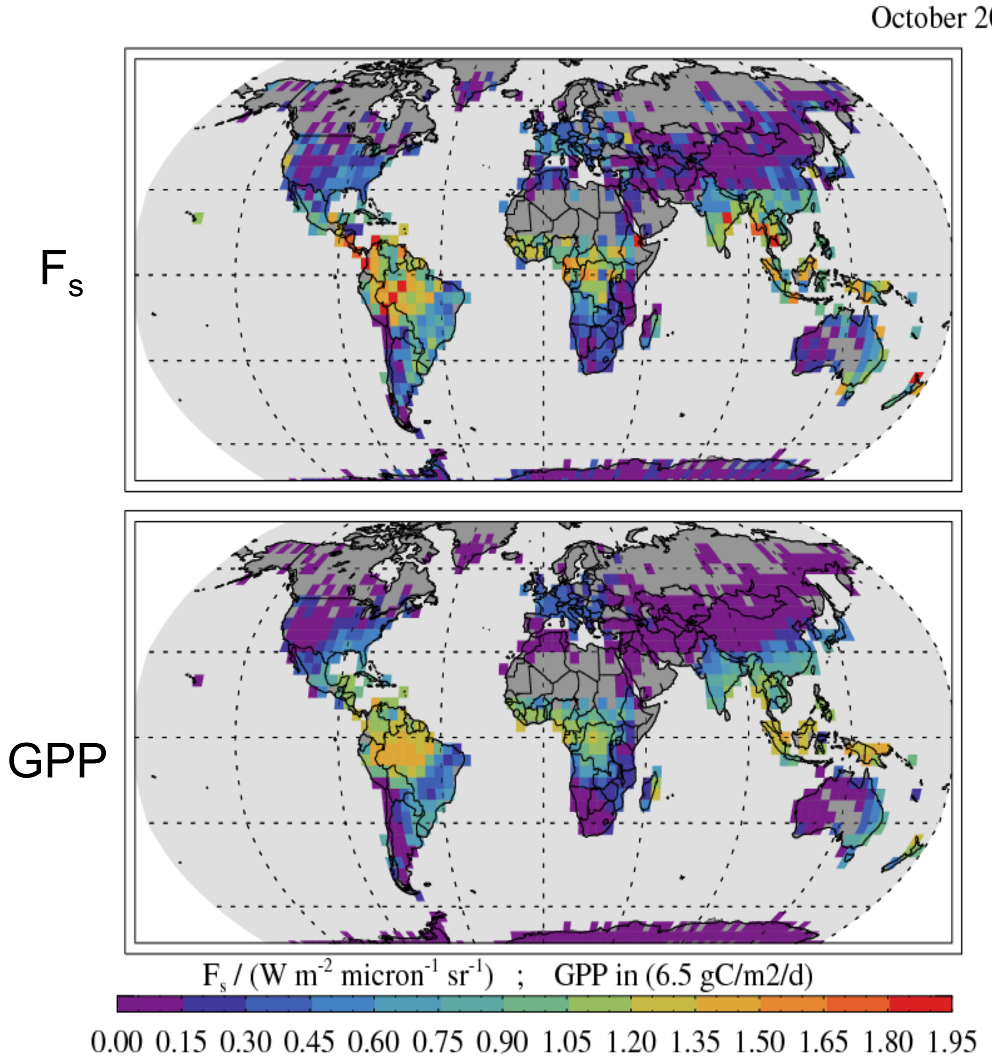


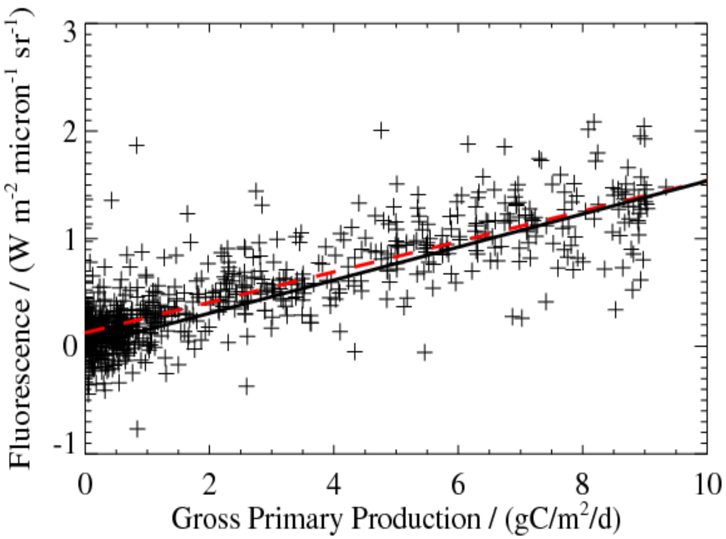
September 2010



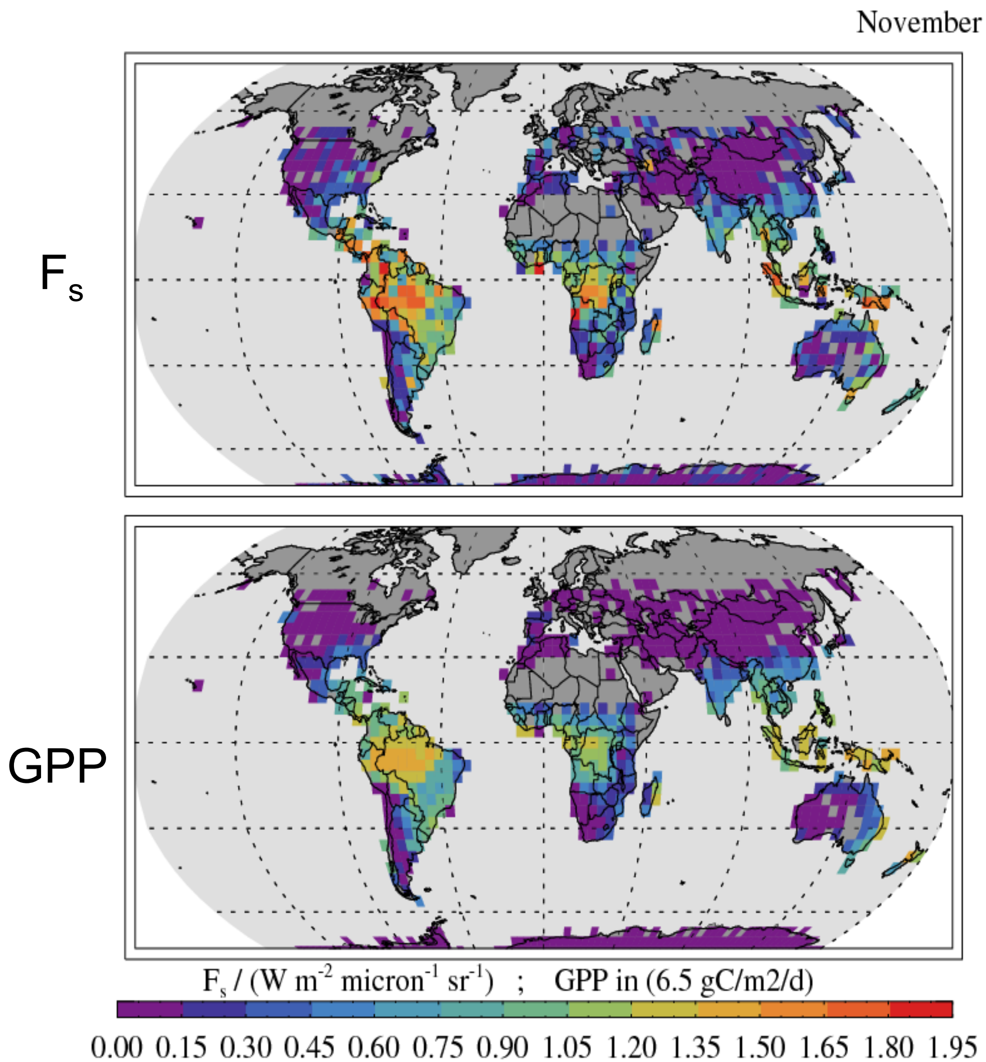


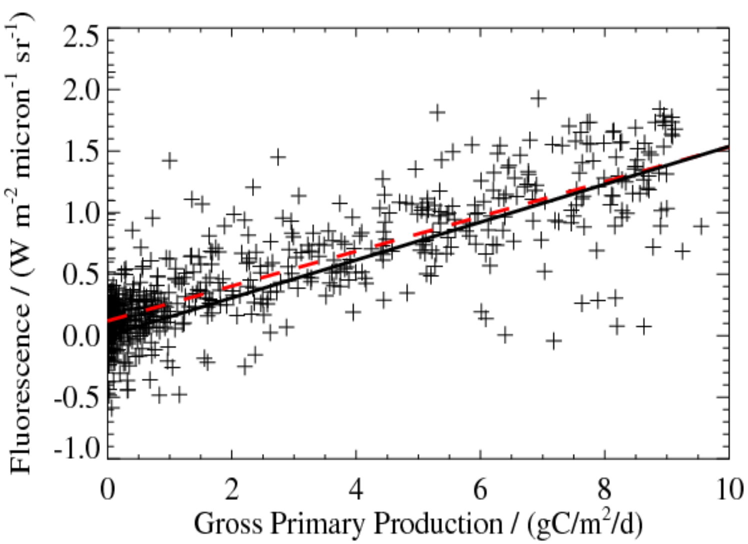
October 2010





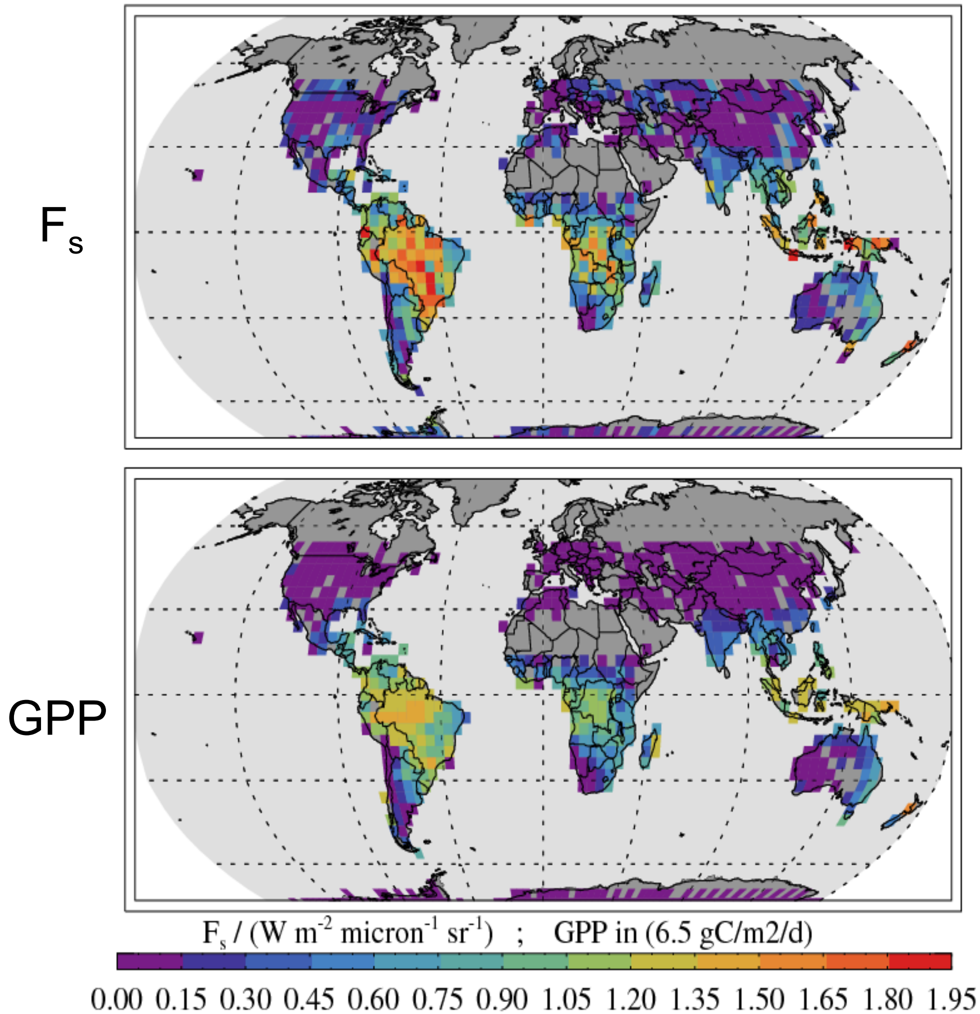
November 2010

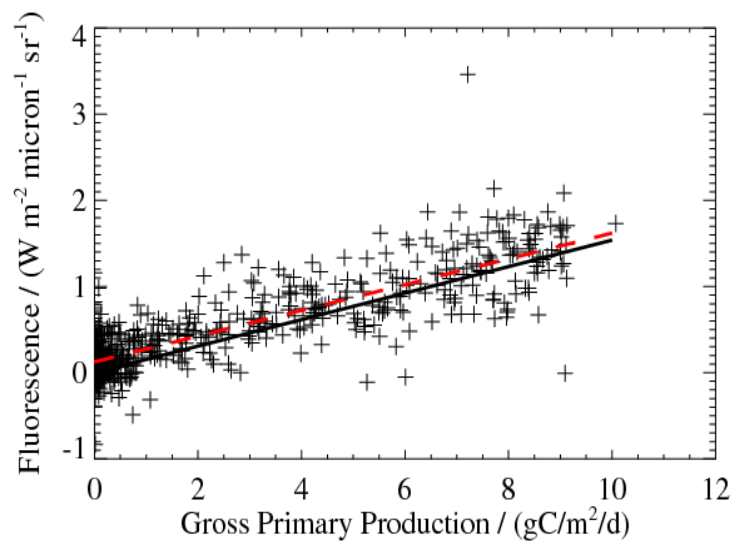




December 2010

December 2010



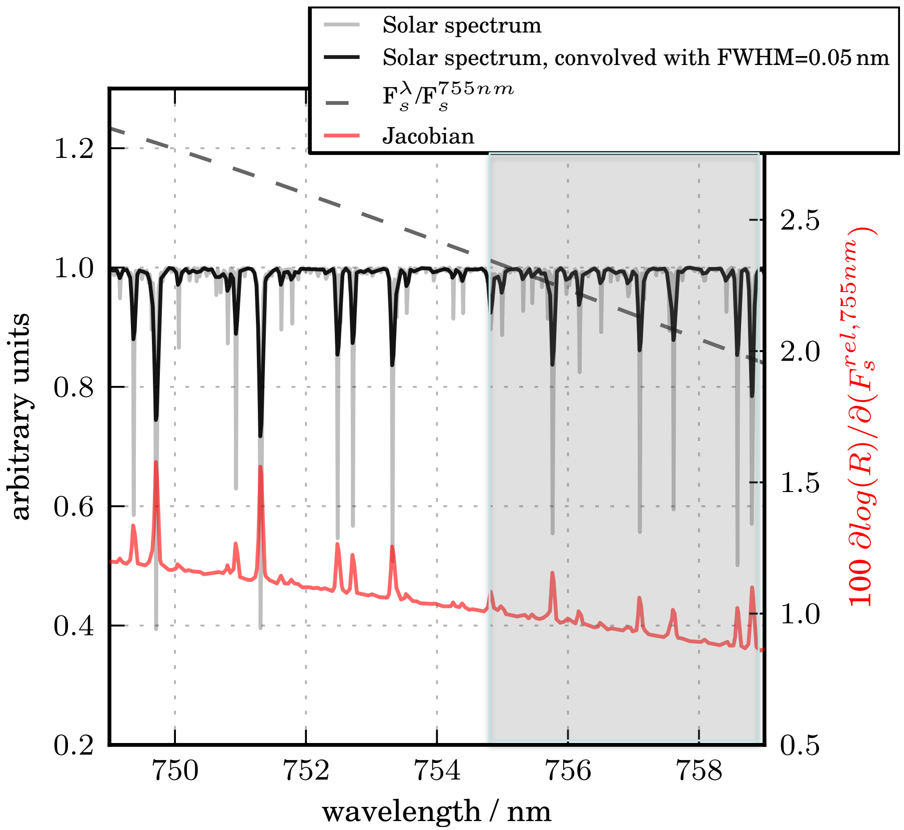


Honest assessment

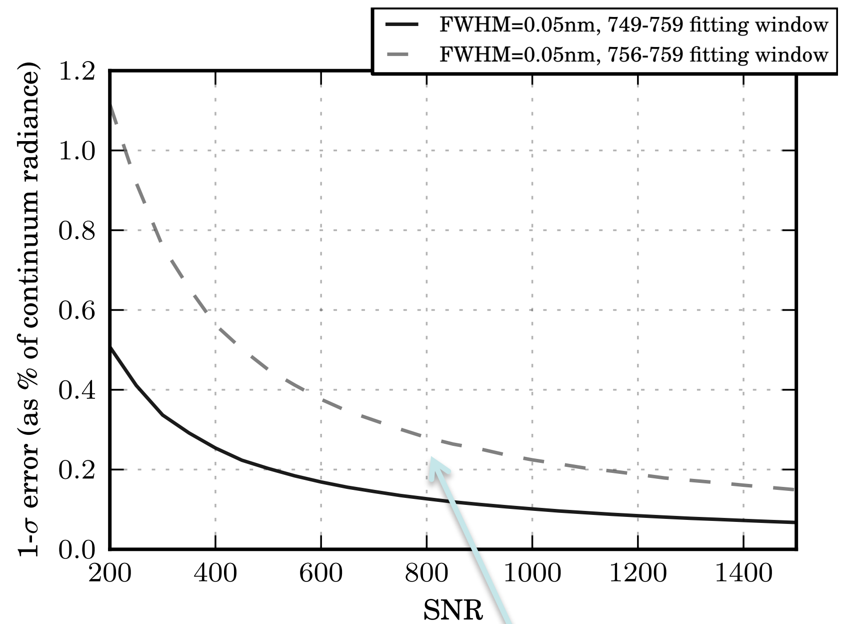
- While GOSAT provides unique new data, the application of F_s is still hampered by high single measurement noise and incomplete (and infrequent) sampling.
- OCO-2 will partially alleviate the first problem as it will provide 50 times more data, beating down standard errors and having <2x2km^2 ground pixels. However, it will also NOT be a mapper, covering <2-3% of the Earth's surface (both instruments are designed to measure trace gases, not surface properties)
- The Fraunhofer line retrieval method is very robust, embarrassingly simple and now proven. More dedicated missions (such as FLEX) using high spectral resolution covering both Fluorescence peaks would greatly improve both F_s retrievals and allow for LAI/chlorophyll retrievals at the same time.

Simple steps that could be done…

Enlarge the spectral range



Improve SNR and FWHM



Factor 2 difference in precision (like having 4 times more samples)!

C. Frankenberg, C. O'Dell, L. Guanter, and J. McDuffie, AMT, 2012

CONCLUSIONS

- The retrieval of chlorophyll fluorescence from space IS feasible, now proven with real data (and method validated on ground).
- The Fraunhofer line retrieval method is simple, fast and robust. Most importantly, it is VERY insensitive to atmospheric scattering, being able to sense F_s through thin clouds.
- The raw F_s retrieval, without the application of a single ancillary dataset or model assumption, has more predictive skill in estimating GPP than any other current remote sensing measurement.
- Chlorophyll fluorescence retrievals from GOSAT and OCO-2 in conjunction with their global atmospheric CO_2 measurements will provide an exceptional combination of a vegetation and atmospheric perspective on the global carbon budget, constraining our model predictions for future atmospheric CO_2 abundances.