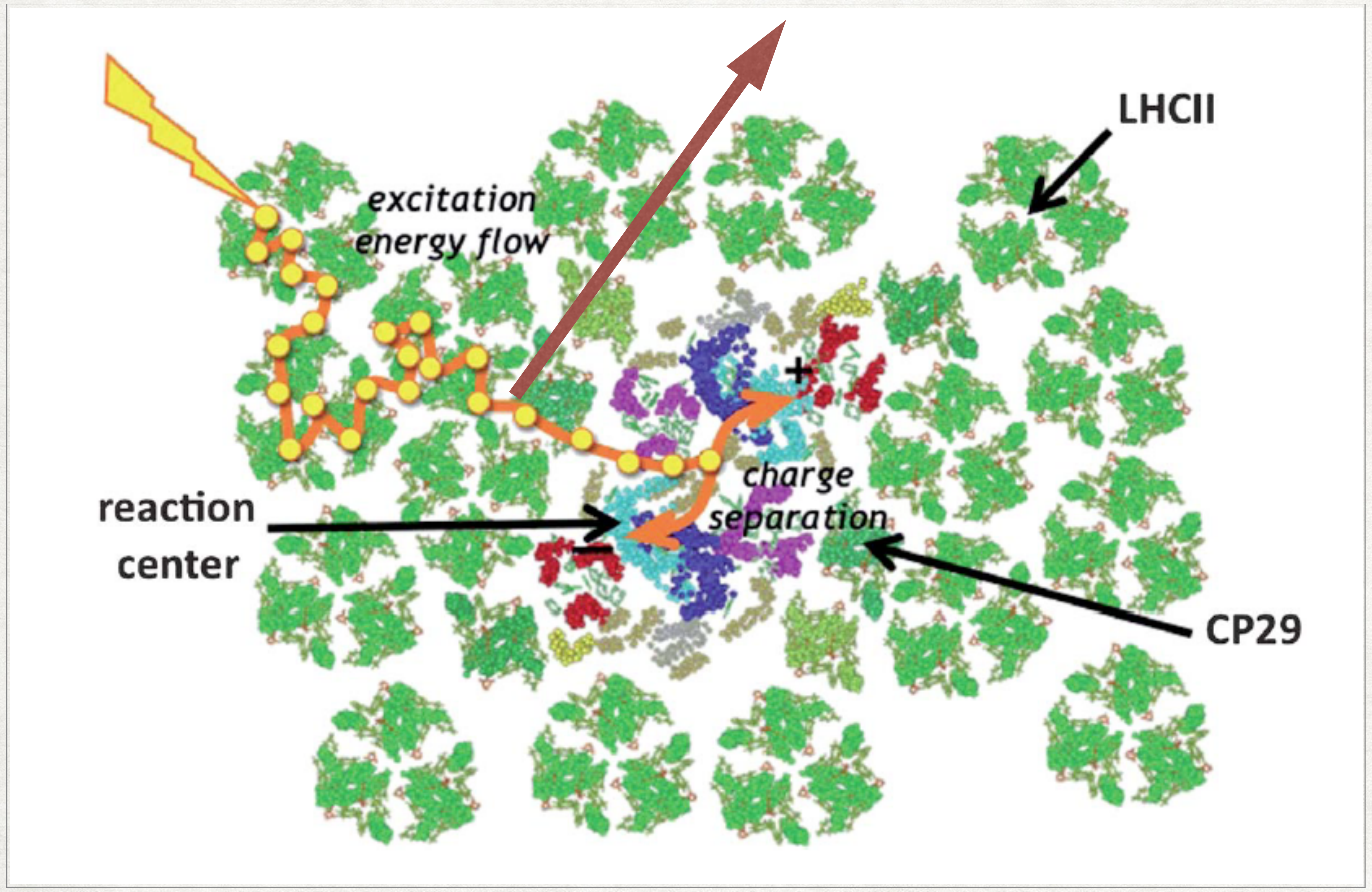
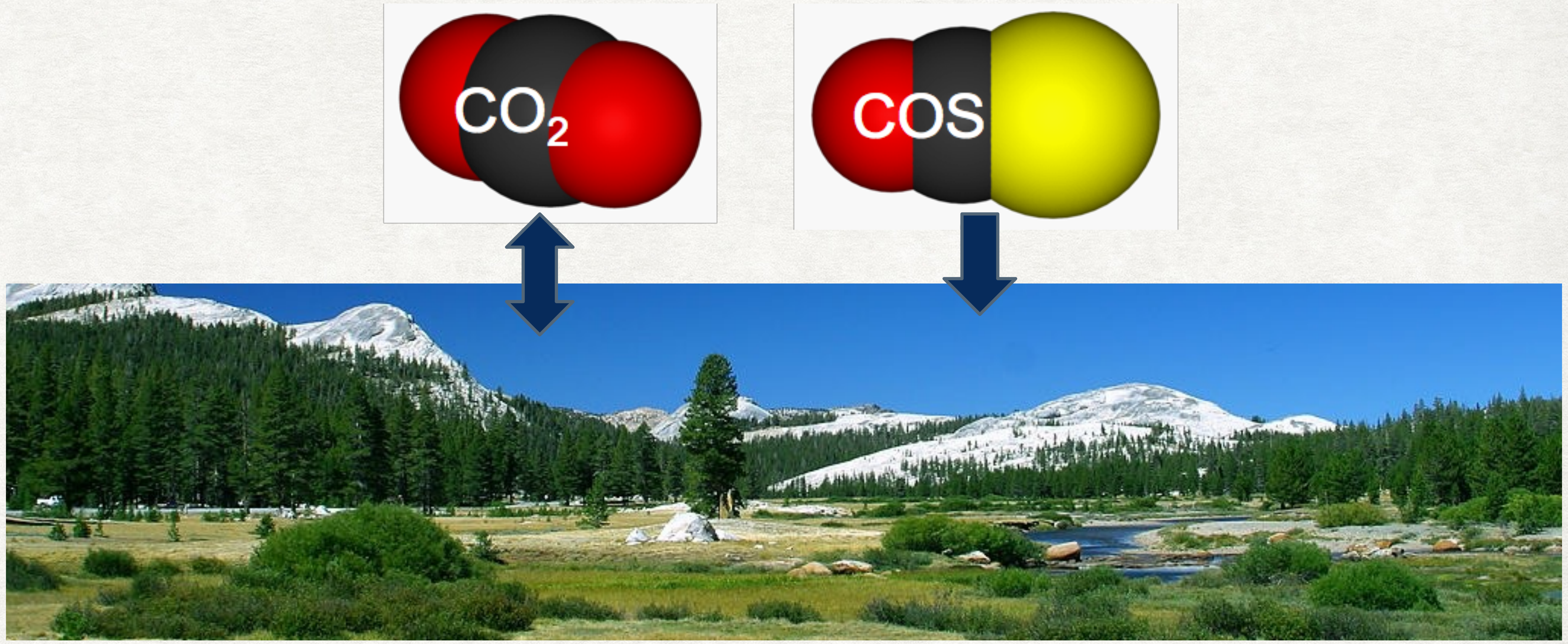
CARNEGIE SCIENCE

NEW TOOLS FOR INVESTIGATING THE CARBON CYCLE: THE BACKGROUND

Chlorophyll Fluorescence



Carbonyl Sulfide



Next-Generation Approach for Detecting Climate-Carbon Feedbacks: Space-Based Integration of Carbonyl Sulfide (OCS), CO2, and Solar Induced Fluorescence (SIF). Sept. 18, 2017

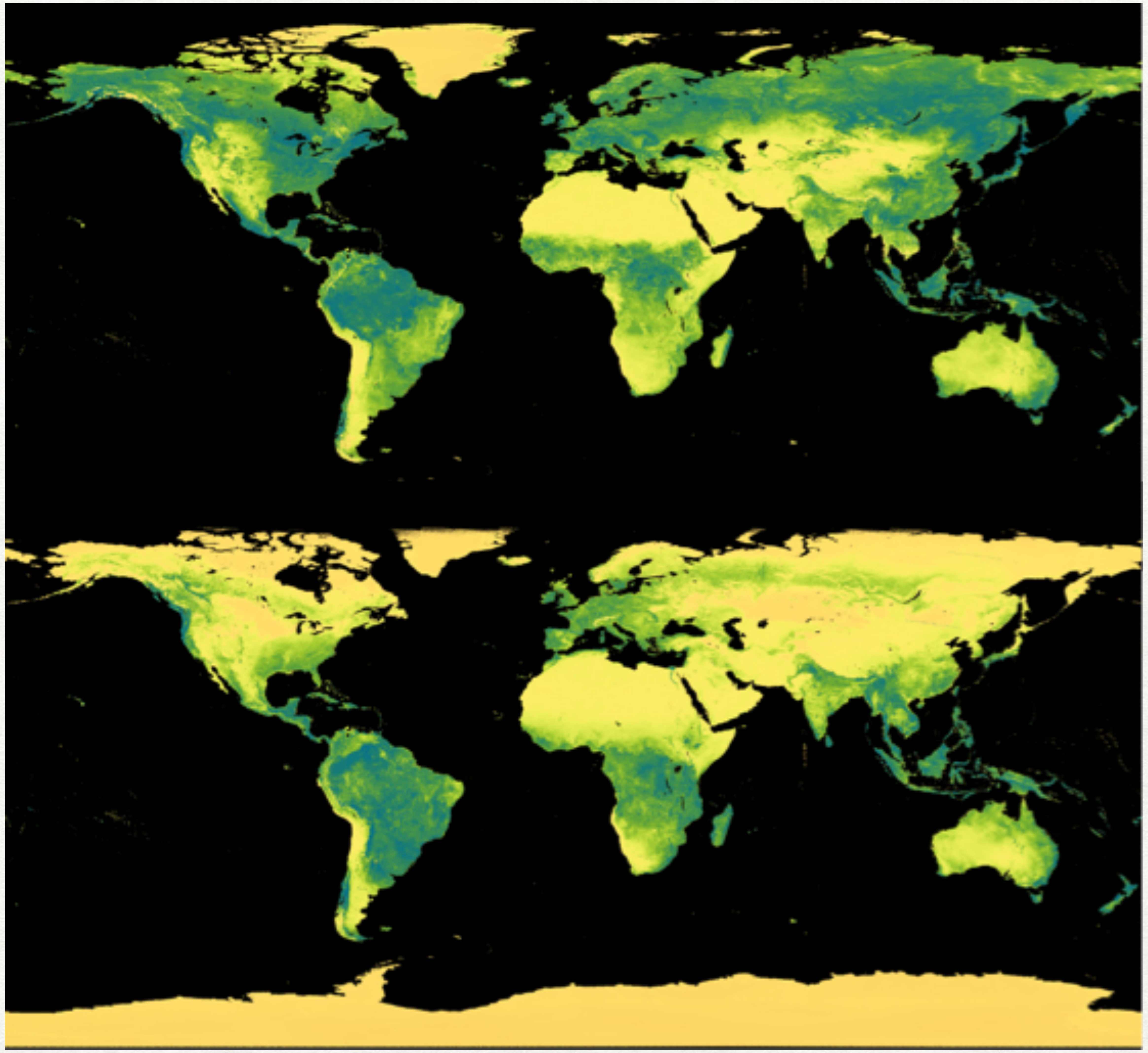
Early steps: Remote Sensing

AVHRR

and

NDVI

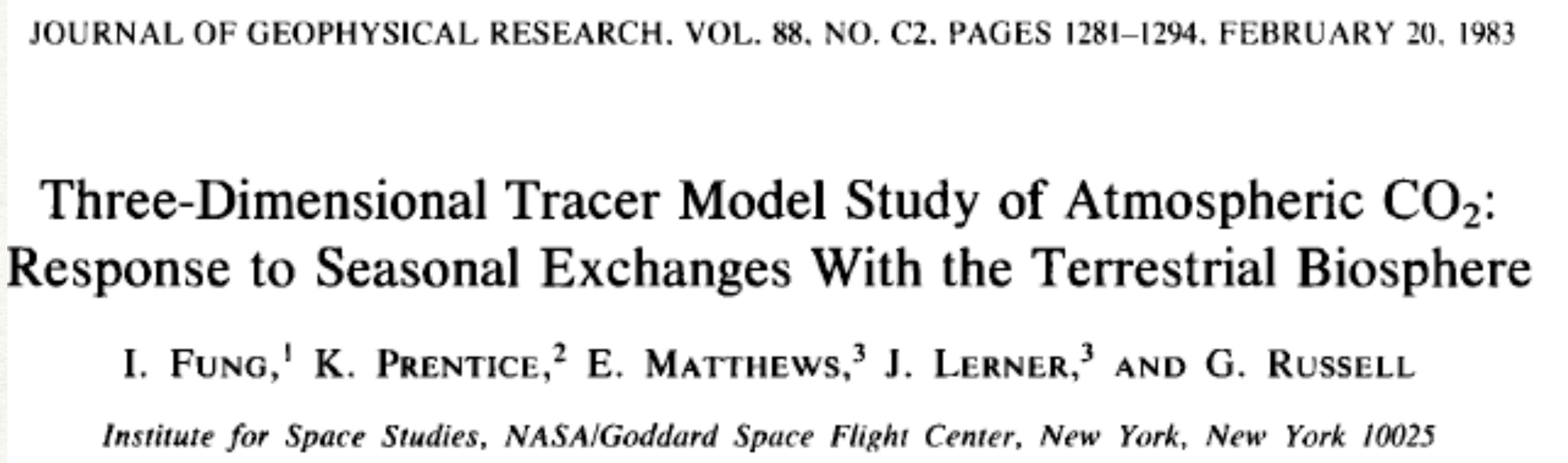
Jim Tucker



Cover of **Nature** ca. 1986

Models of Atmospheric CO_2

Inez Fung



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. C2, PAGES 1281–1294, FEBRUARY 20, 1983

Three-Dimensional Tracer Model Study of Atmospheric CO_2: Response to Seasonal Exchanges With the Terrestrial Biosphere

I. Fung,[1] K. Prentice,[2] E. Matthews,[3] J. Lerner,[3] and G. Russell

Institute for Space Studies, NASA/Goddard Space Flight Center, New York, New York 10025

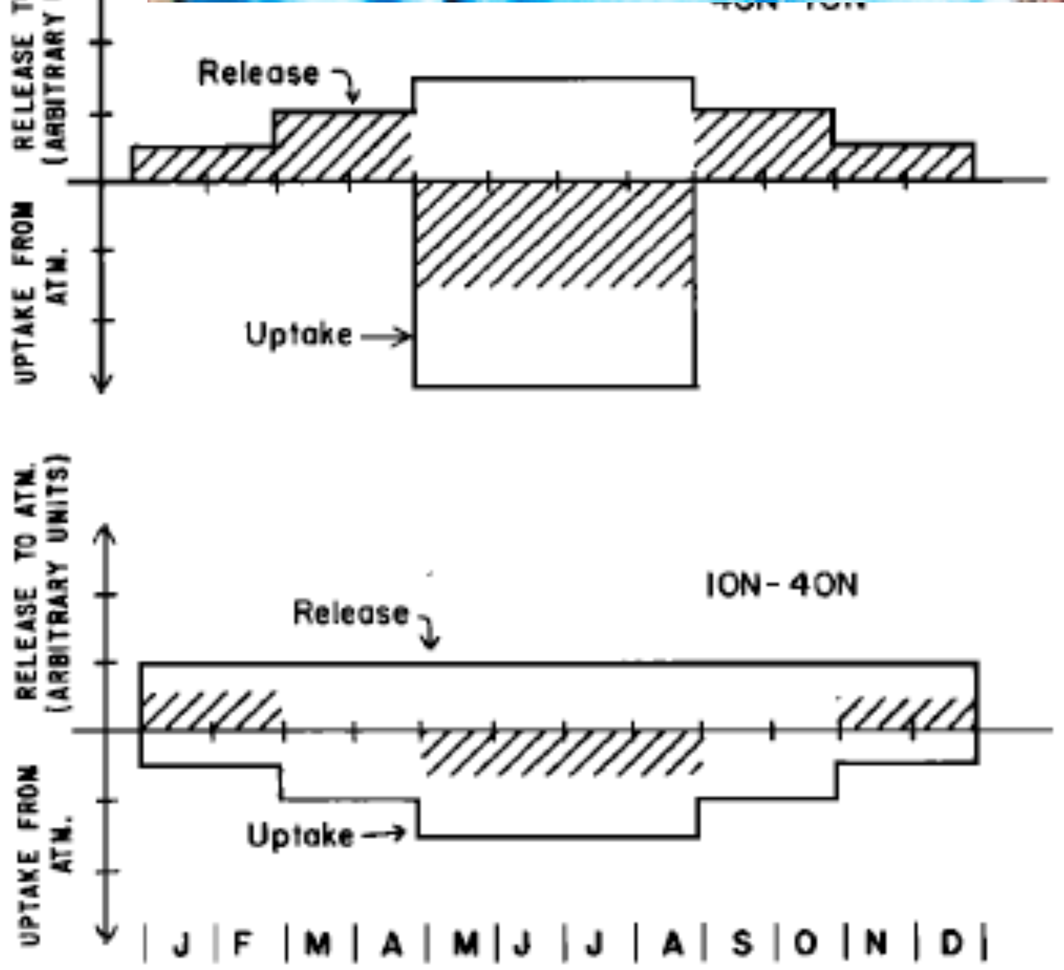


Fig. 3. Seasonality of biospheric uptake and release of CO_2 [after *Azevedo*, 1982] employed in experiment 3.

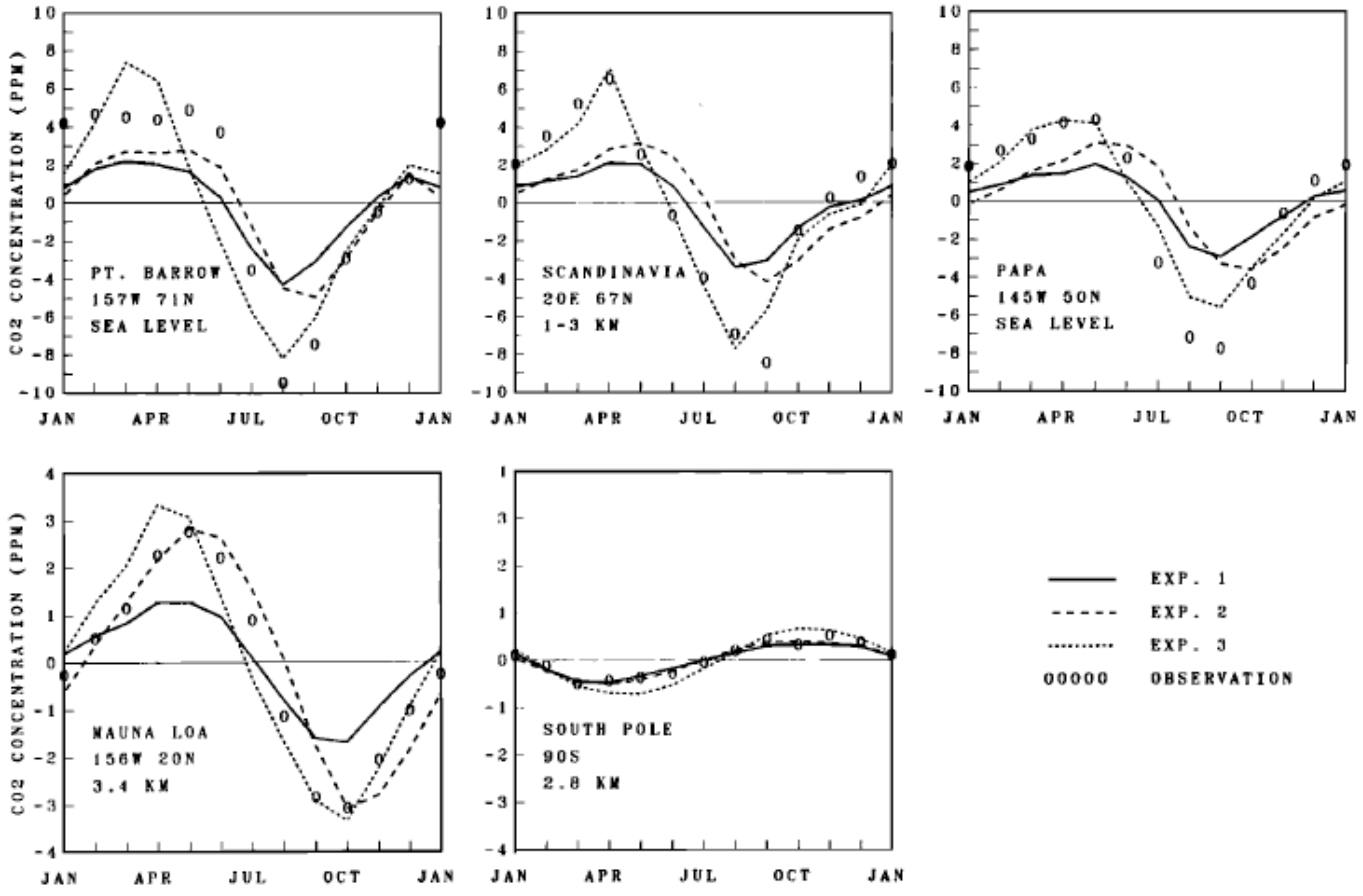
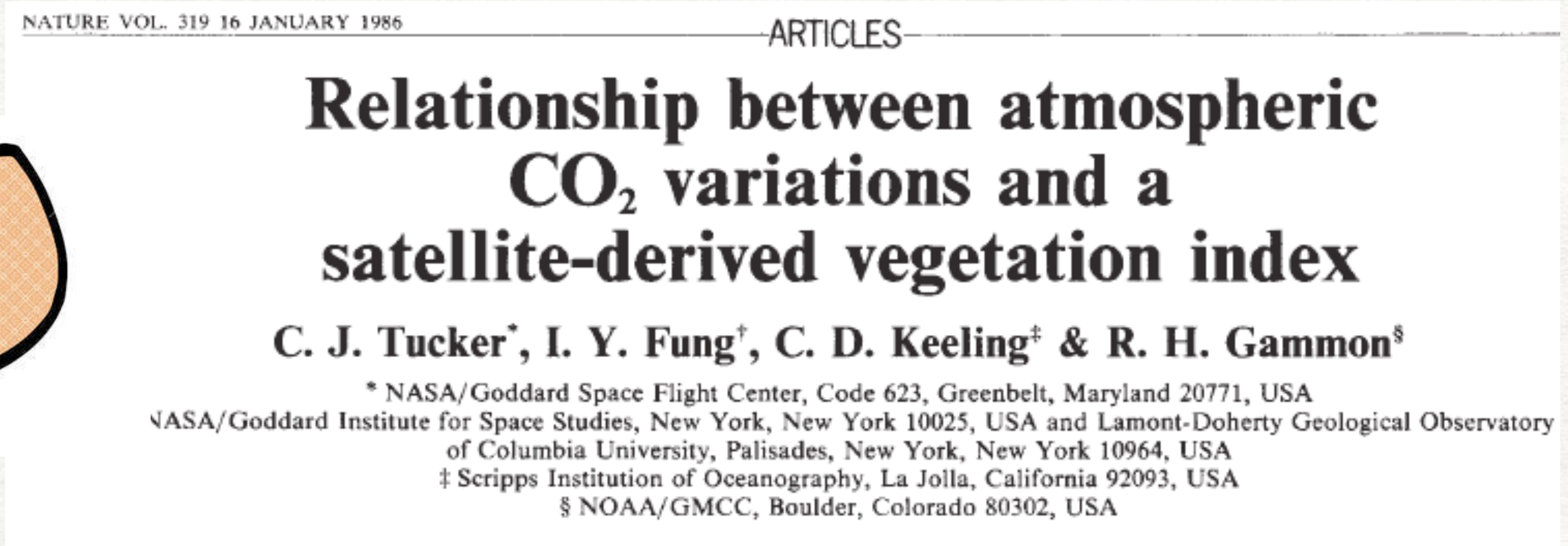


Fig. 4. Model simulated and observed annual cycles of CO_2 at five locations. Observations for Point Barrow, Papa, Mauna Loa, and the south pole are taken from *Pearman and Hyson* [1980] and that for Scandinavia from *Bolin and Bischof* [1970].

Integration Remote Sensing, Atmospheric Measurements and Models

The Flying Carpet Plots



NATURE VOL. 319 16 JANUARY 1986 ARTICLES

Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index

C. J. Tucker*, I. Y. Fung†, C. D. Keeling‡ & R. H. Gammon§

* NASA/Goddard Space Flight Center, Code 623, Greenbelt, Maryland 20771, USA
NASA/Goddard Institute for Space Studies, New York, New York 10025, USA and Lamont-Doherty Geological Observatory
of Columbia University, Palisades, New York, New York 10964, USA
‡ Scripps Institution of Oceanography, La Jolla, California 92093, USA
§ NOAA/GMCC, Boulder, Colorado 80302, USA

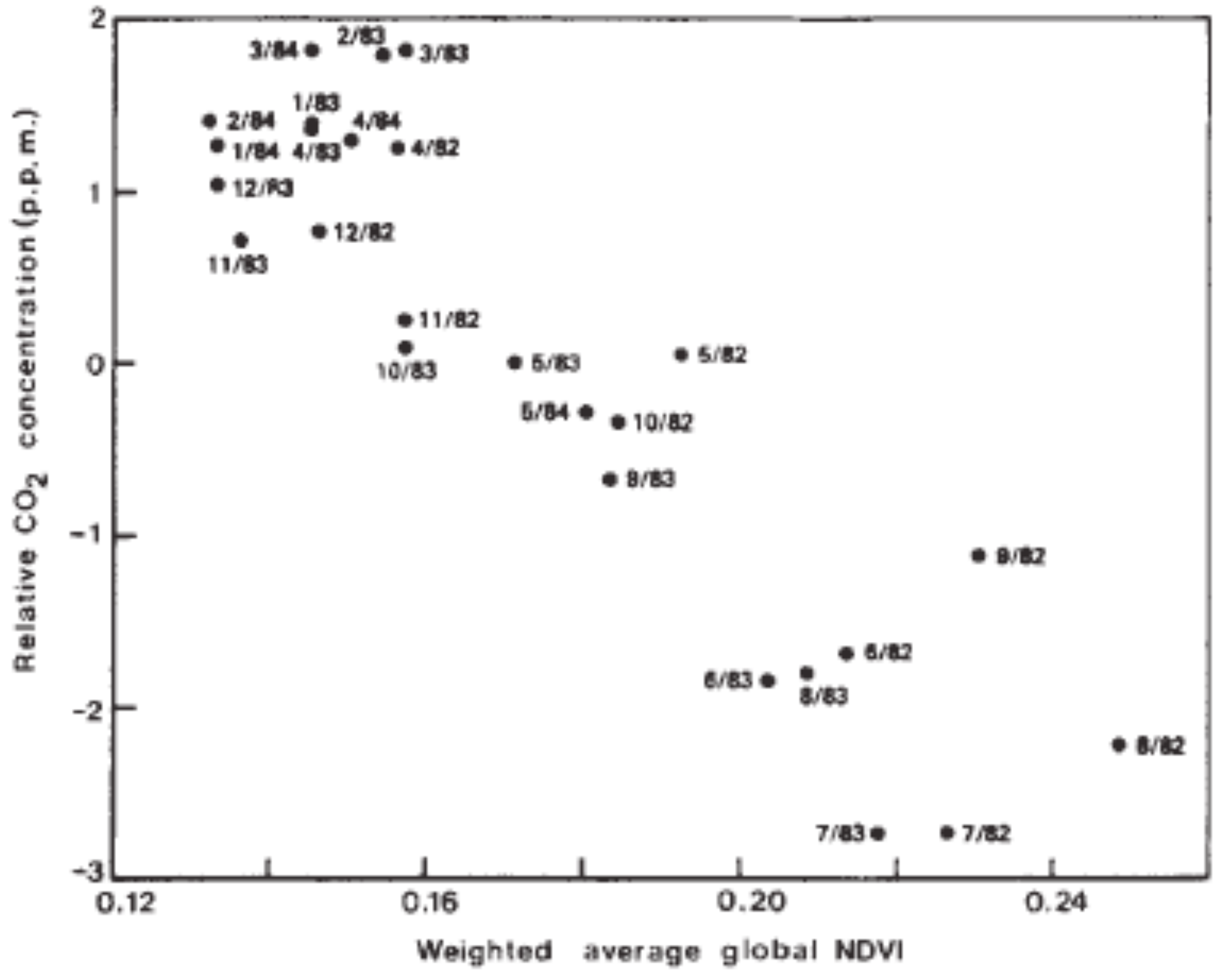


Fig. 4 The globally averaged atmospheric CO_2 concentration plotted against the globally averaged NDVI with a time lag of 1 month. The CO_2 data are from the global network of 20 NOAA/GMCC stations.

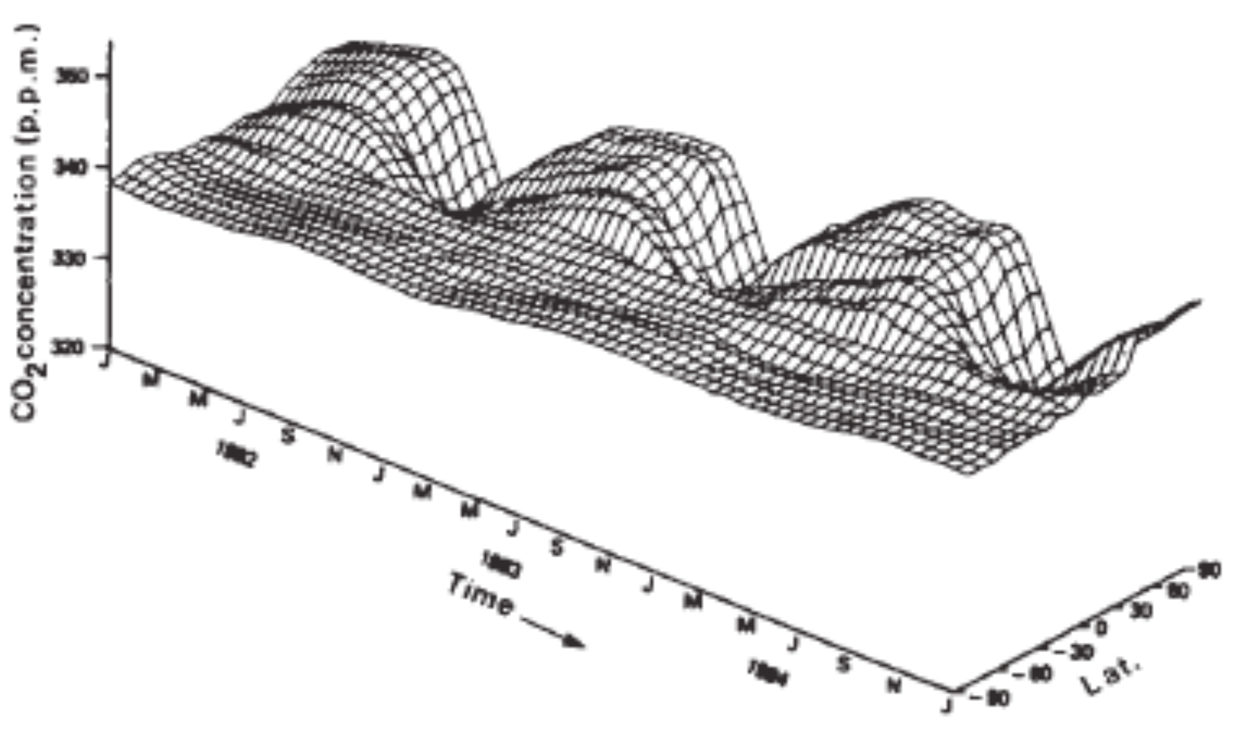
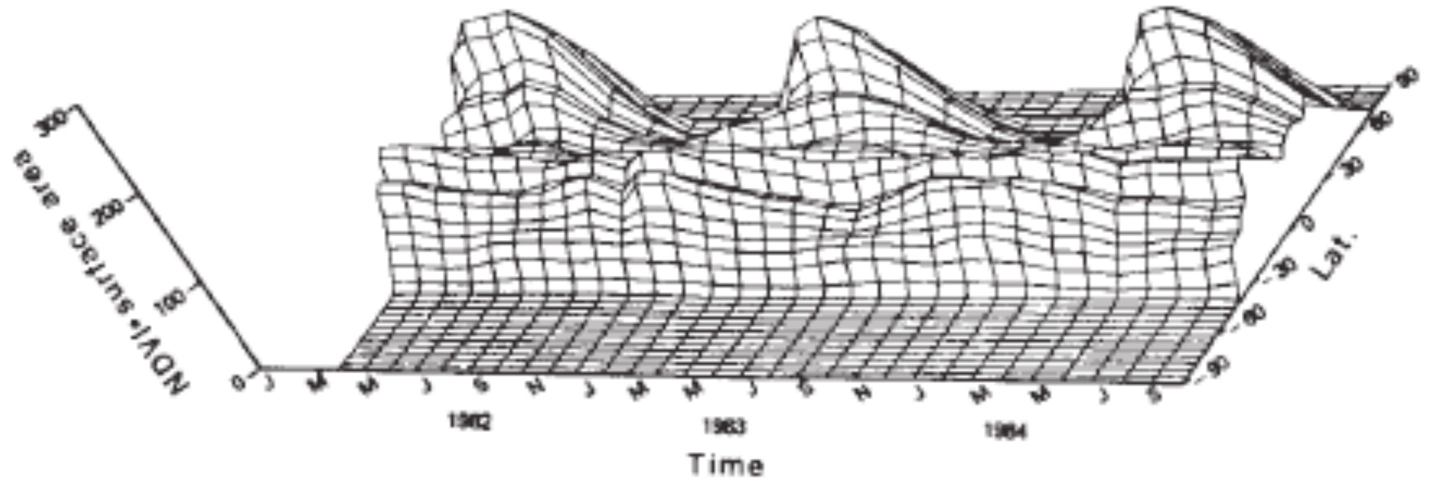


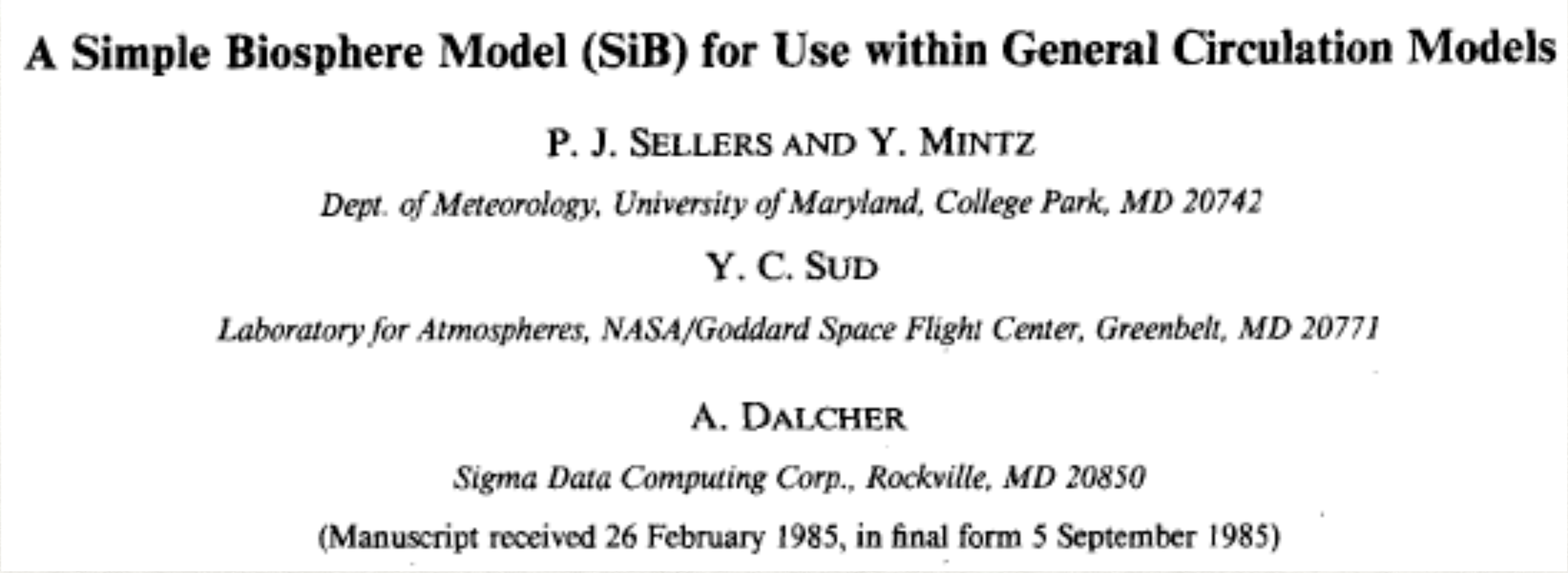
Fig. 1 Variation of global atmospheric CO_2 concentrations with latitude and time based on the NOAA/GMCC flask measurements for 1982–84.



CARNEGIE SCIENCE

Including Biology in the Models

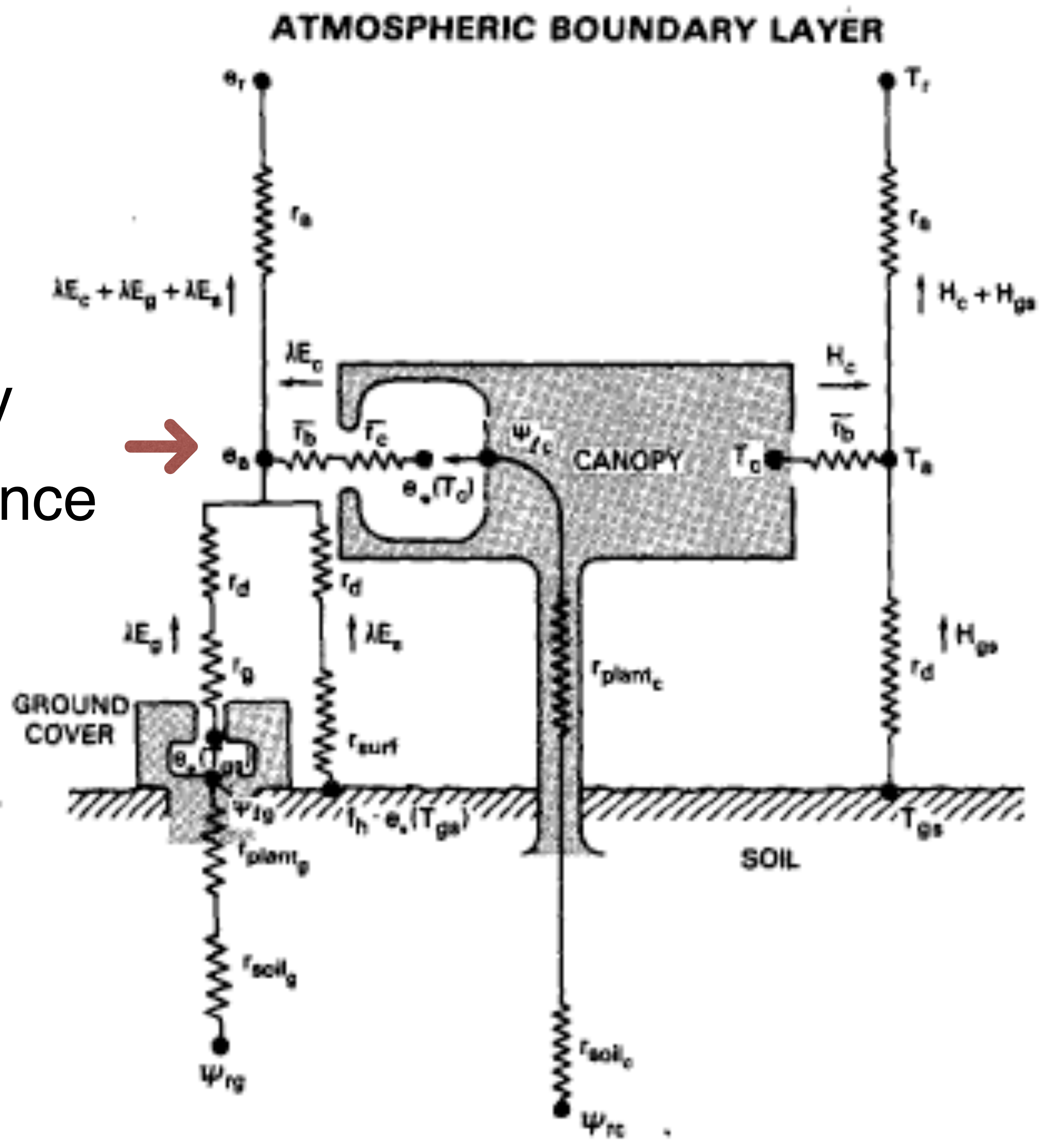
Piers Sellers



A Simple Biosphere Model (SiB) for Use within General Circulation Models

P. J. SELLERS AND Y. MINTZ
Dept. of Meteorology, University of Maryland, College Park, MD 20742
Y. C. SUD
Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, MD 20771
A. DALCHER
Sigma Data Computing Corp., Rockville, MD 20850

(Manuscript received 26 February 1985, in final form 5 September 1985)



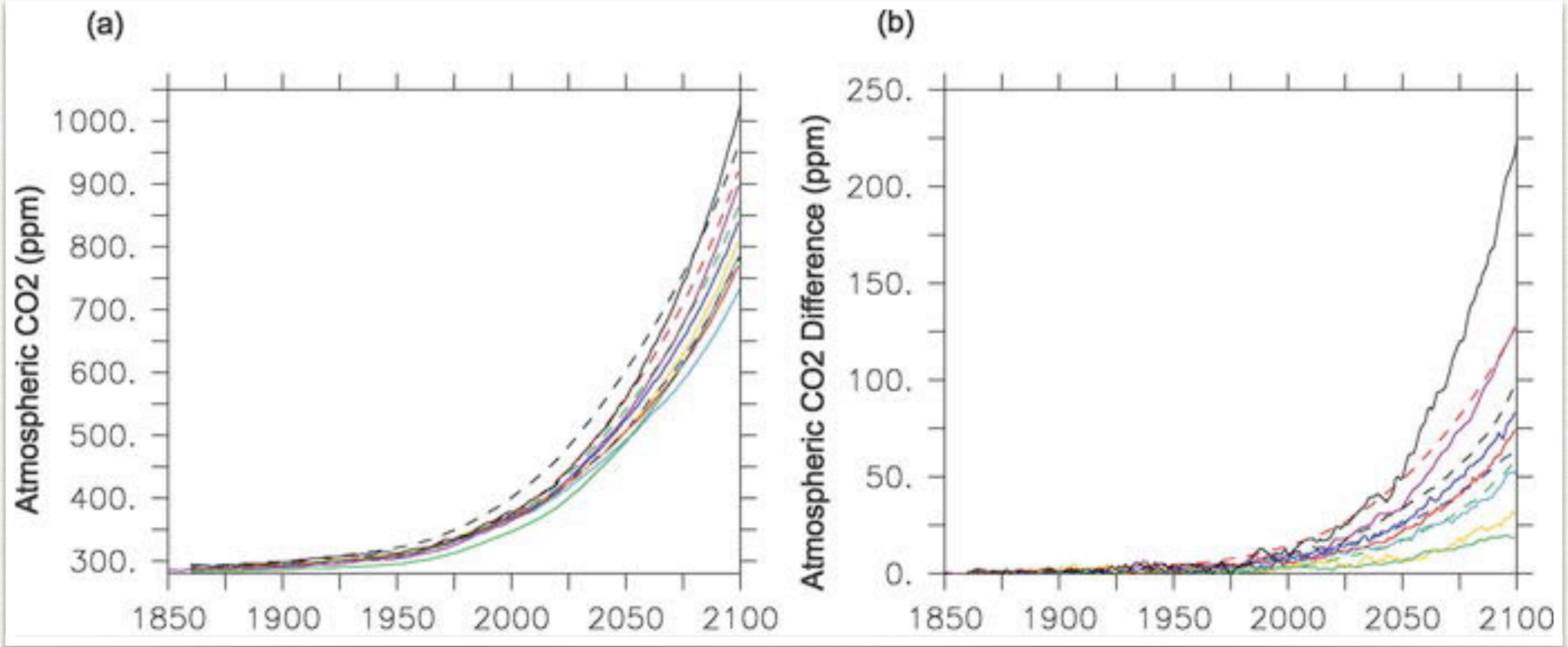
Canopy

Conductance →

FIG. 2. Framework of the Simple Biosphere (SiB). The transfer pathways for latent and sensible heat flux are shown on the left- and right-hand sides of the diagram respectively. The treatment of radiation and intercepted water has been omitted for clarity. Symbols are defined in Table 2.

CARNEGIE SCIENCE

Climate-Carbon Feedbacks



Friedlingstein, P. et al. Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks J. Clim. 27, 511–526 (2014).

Atmospheric Carbon Net Annual Increase 4

Atmosphere
(800)

120 +3

Photosynthesis

60

Plant respiration

9

Fossil fuels, cement, and land-use change

Plant biomass
(550)

60

Net terrestrial uptake
3

Soil carbon

Microbial respiration and decomposition

90 +2

Air-sea gas exchange

90

Surface ocean
(1000)

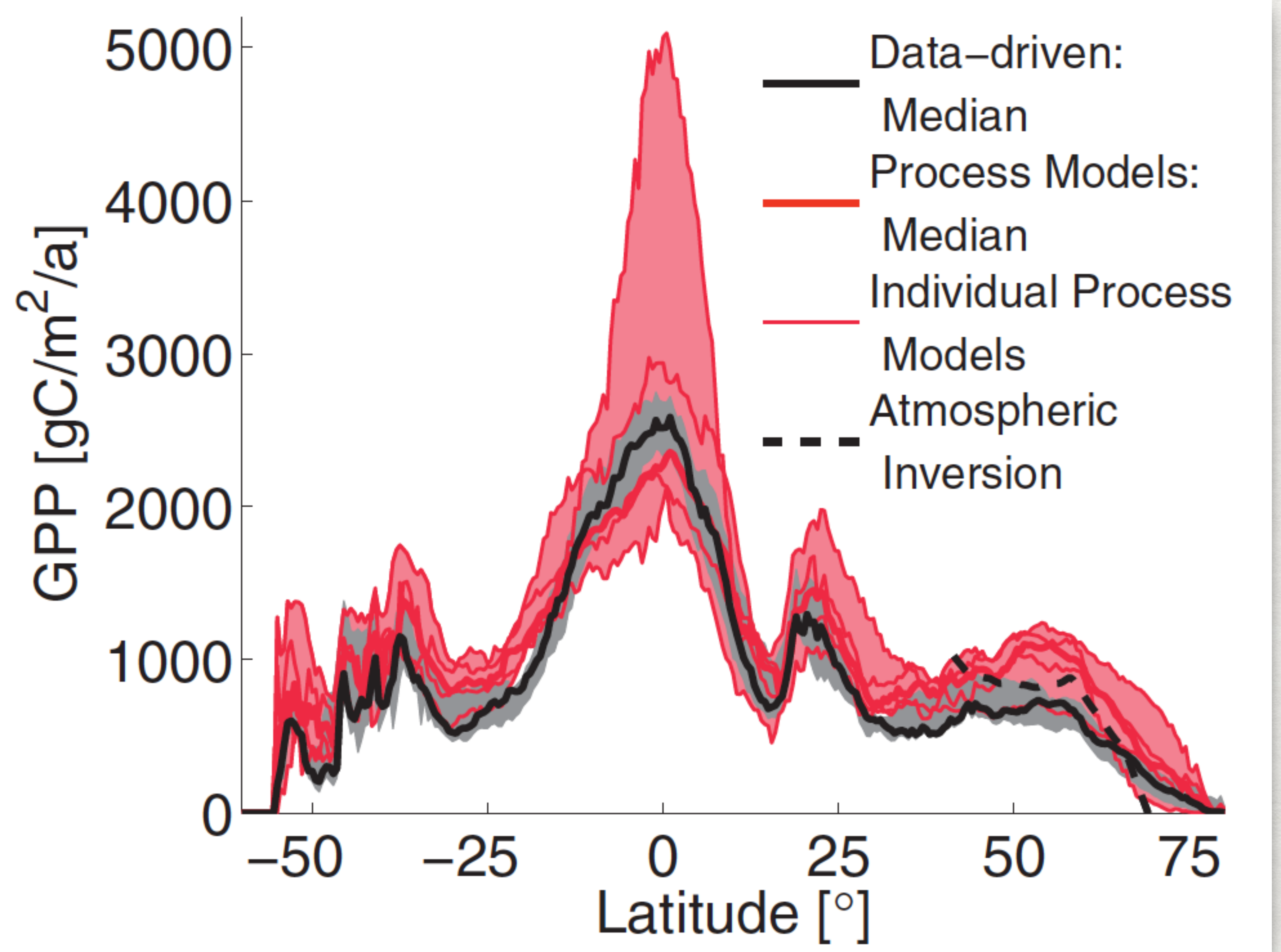
Phytoplankton photosynthesis

Respiration and decomposition

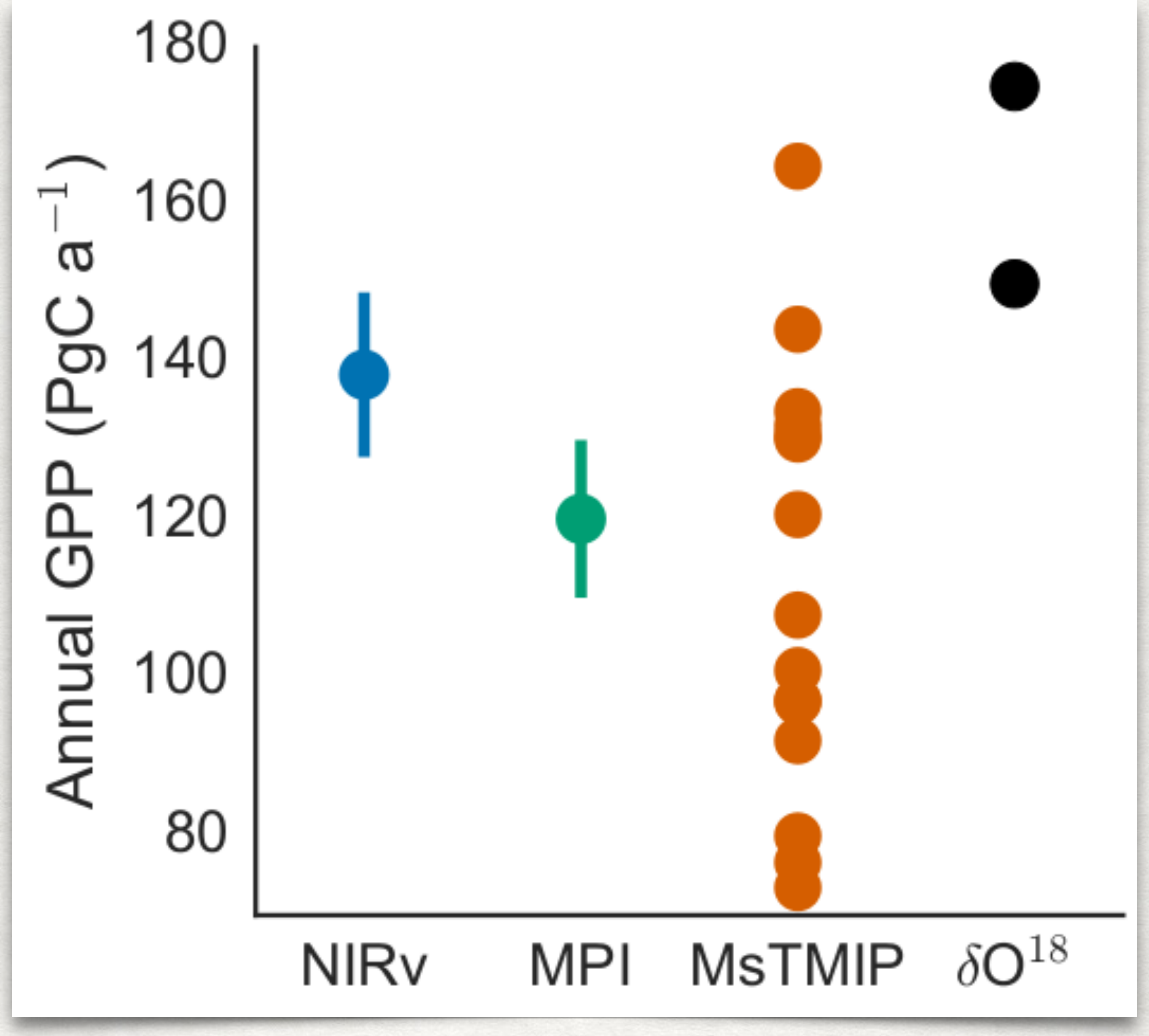
GtC/y: Gigatons of carbon/year

Numbers in parentheses refer to stored carbon pools. Red indicates carbon from human emissions.

We don’t do global photosynthesis very well



Grayson Badgley
Lea Anderegg
Joe Berry
many others



Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., et al. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. Science,, 329(5993), 834–838. http://doi.org/10.1126/science.1184984

CARNEGIE SCIENCE

Chlorophyll Fluorescence is a “new” remote sensing product

Plascyk, J. A. (1975). The MK II Fraunhofer Line Discriminator (FLD-II) for Airborne and Orbital Remote Sensing of Solar-Stimulated Luminescence. Optical Engineering, 14(4), 339–0. http://doi.org/10.1117/12.7971842

Guanter, L., Alonso, L., Gómez-Chova, L., Amorós-López, J., Vila, J., & Moreno, J. (2007). Estimation of solar-induced vegetation fluorescence from space measurements. Geophysical Research Letters, 34(8), L08401. http://doi.org/10.1029/2007GL029289

Frankenberg, C., Butz, A., & Toon, G. C. (2011). Disentangling chlorophyll fluorescence from atmospheric scattering effects in O 2A-band spectra of reflected sun-light. GEOPHYSICAL RESEARCH LETTERS, 38(3), L03801. doi: 10.1029/2010GL045896

Joiner, J., Yoshida, Y., Vasilkov, A. P., Yoshida, Y., Corp, L. A., & Middleton, E. M. (2011). First observations of global and seasonal terrestrial chlorophyll fluorescence from space. Biogeosciences, 8(3), 637–651. doi:10.5194/bg-8-637-2011

Retrievals now from: GOSAT, GOME-2 & OCO-2

FLEX is selected and scheduled for launch in 2020’s!

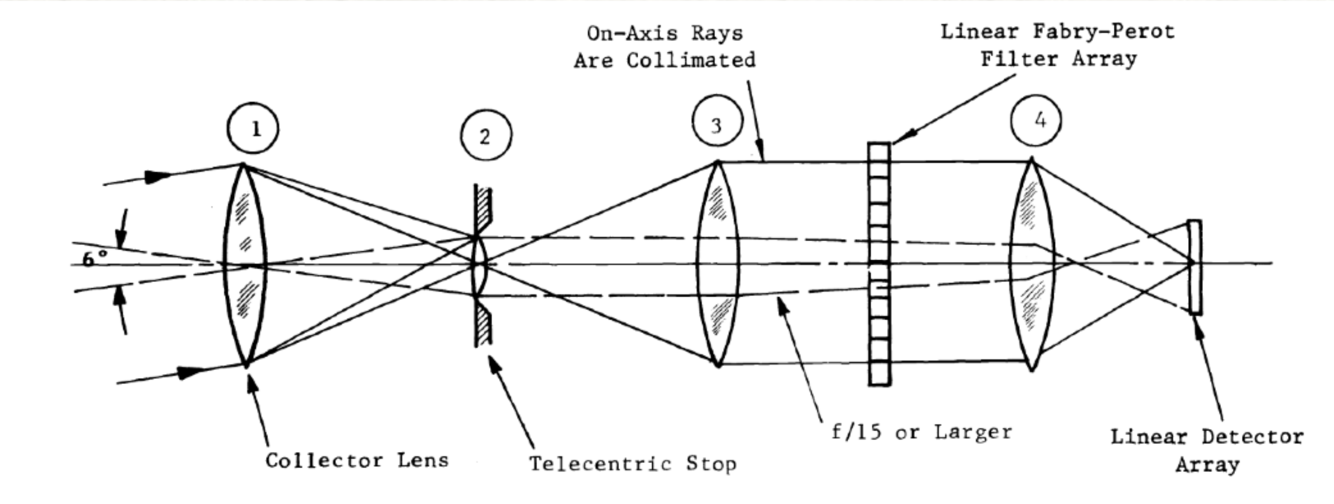
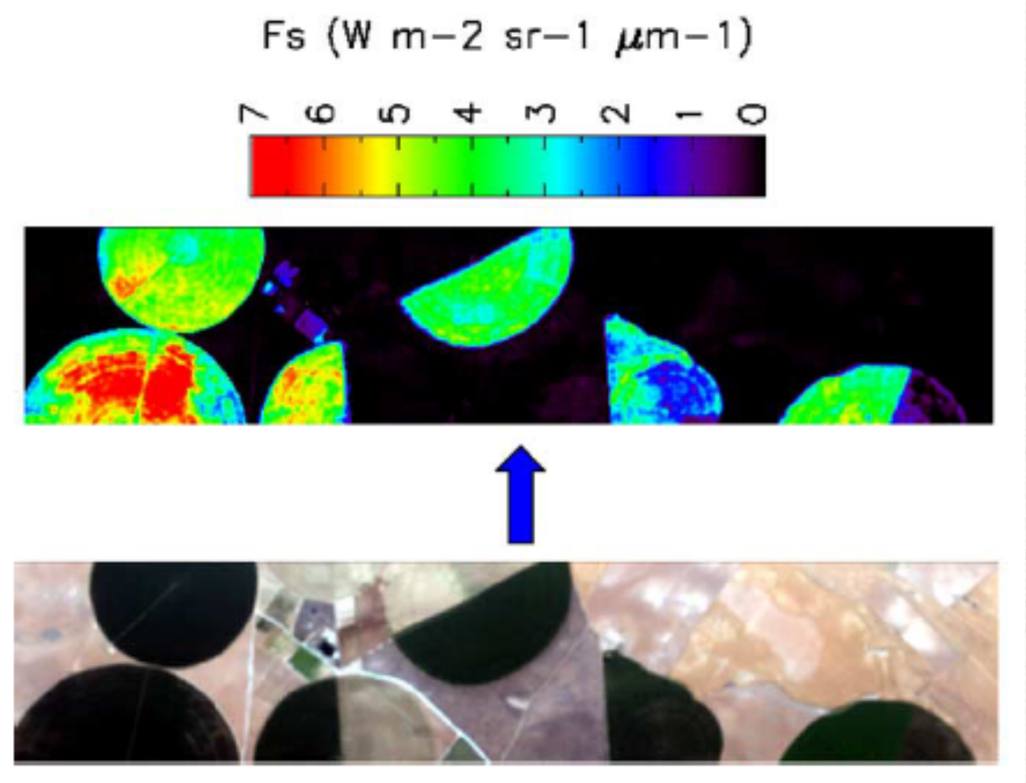
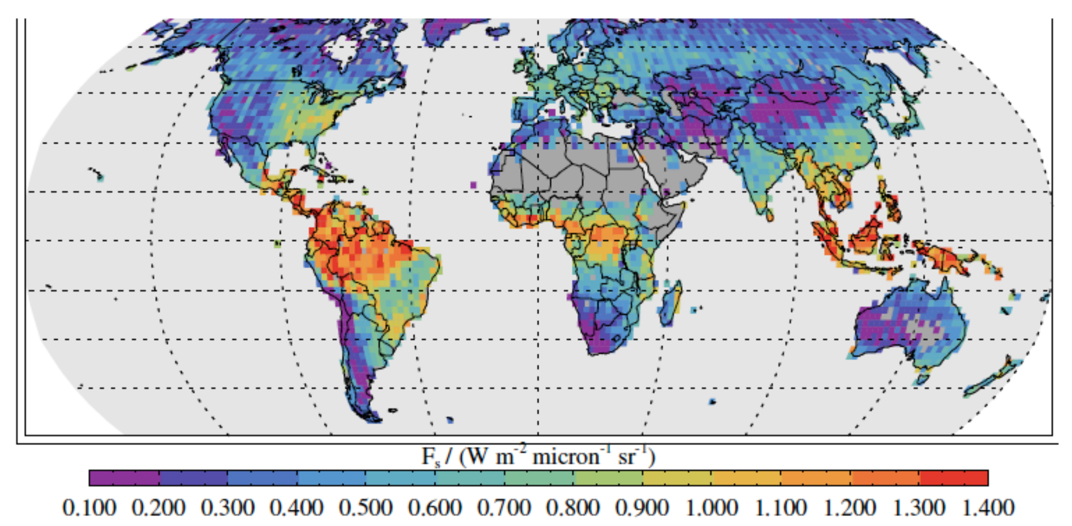


Fig. 9. Optical Schematic for Orbital FLD

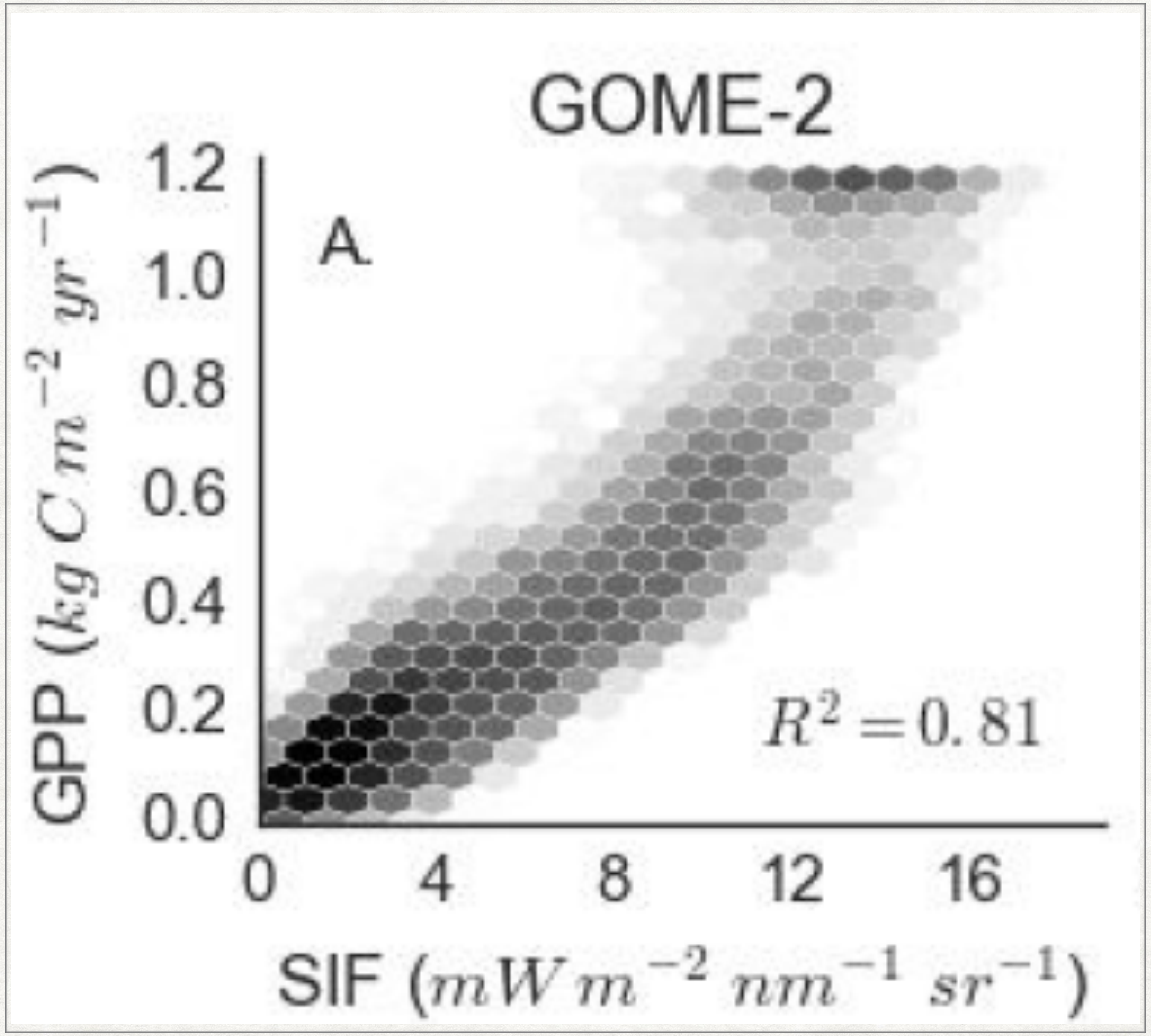




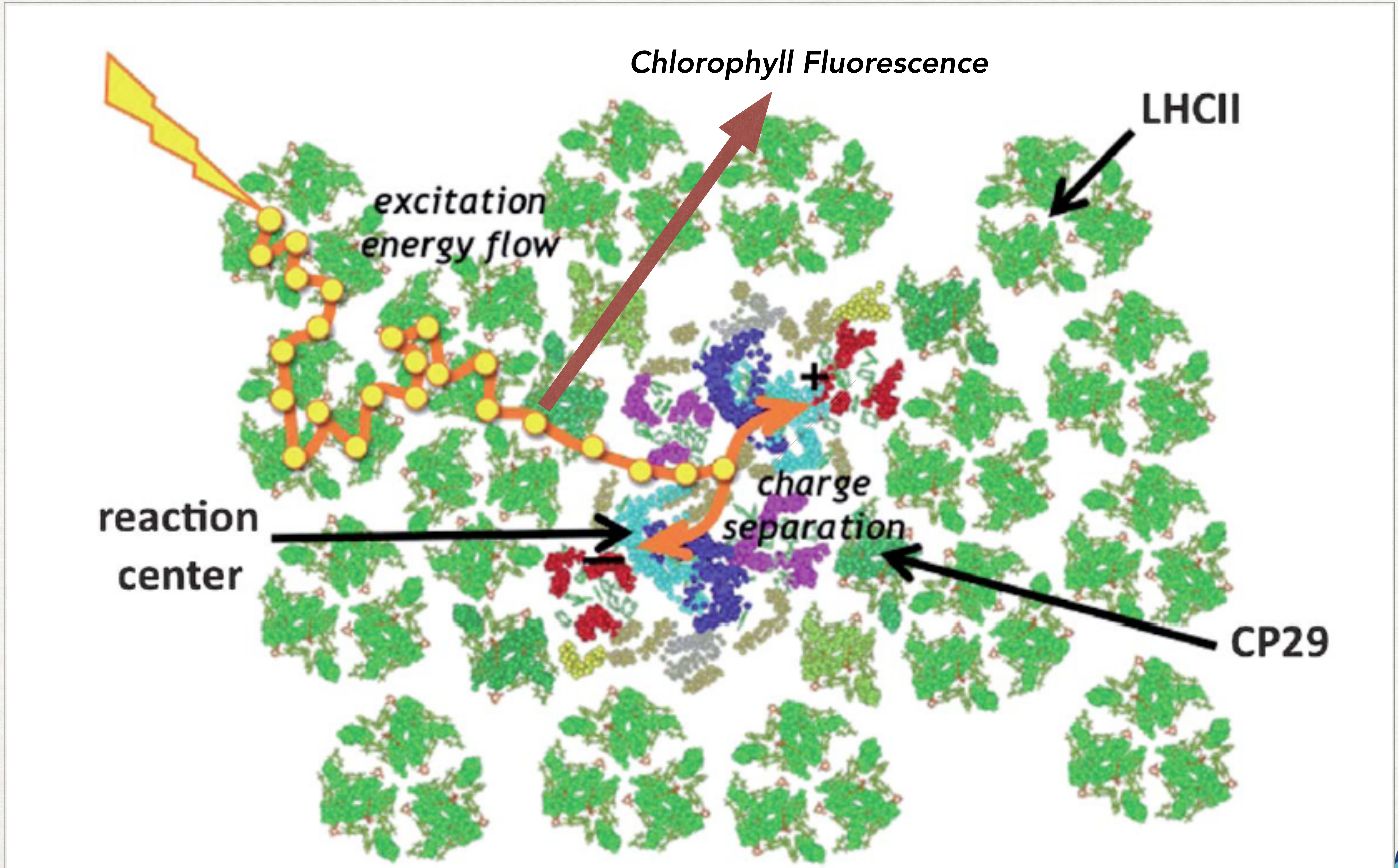
Frankenberg et al, GRL (2011b)

SIF is correlated with GPP

Monthly MPI-GPP at 0.5° *vs* SIF (GOME-2)

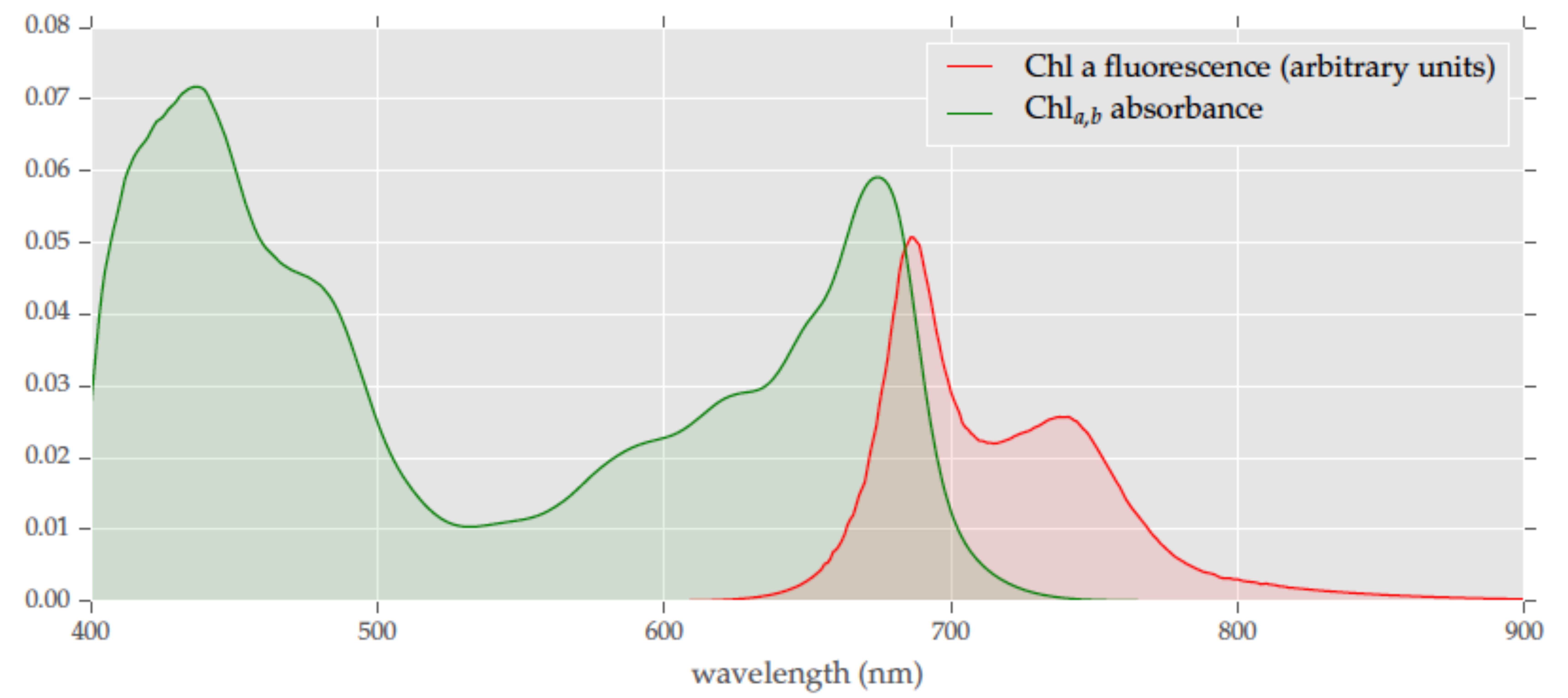


SIF Results from the Decay of an Excited Chlorophyll Molecule

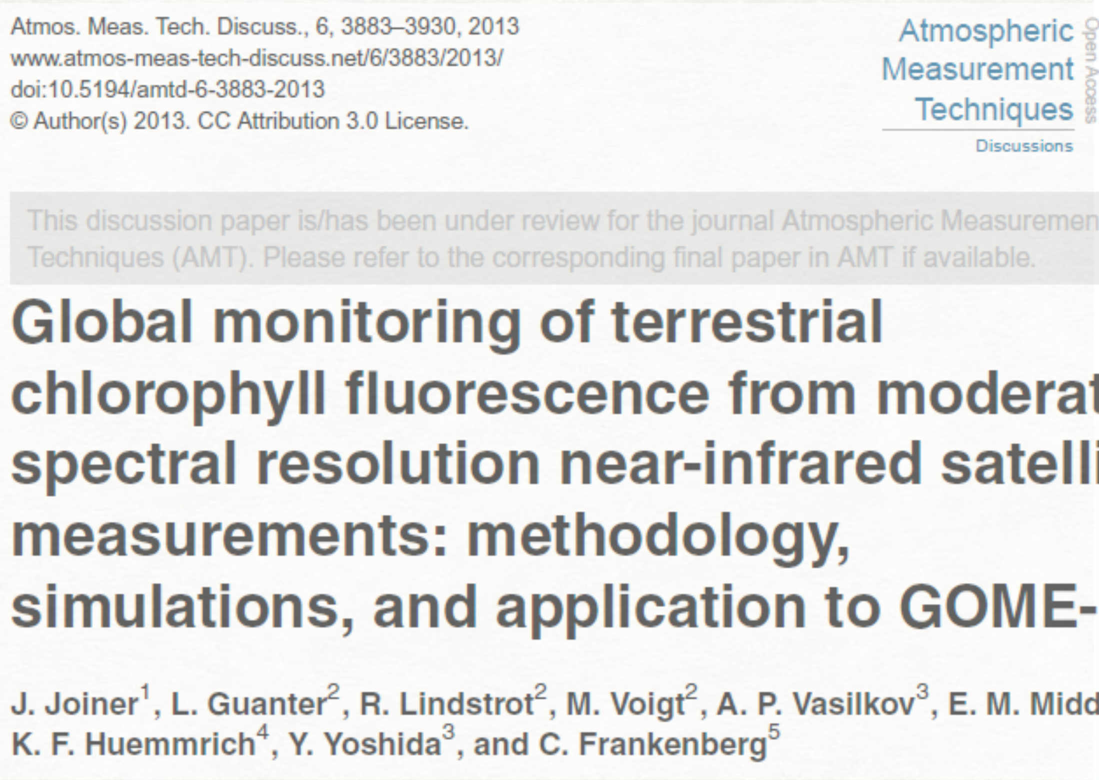


Fleming, G. R., Schlau-Cohen, G. S., Amarnath, K., & Zaks, J. (2012). Design principles of photosynthetic light-harvesting. Faraday Discussions, 155, 27. http://doi.org/10.1039/c1fd00078k

Solar induced Fluorescence (SIF) is Specific to Light Absorbed by Chlorophyll



SIF can be Detected from Space



Atmos. Meas. Tech. Discuss., 6, 3883–3930, 2013
www.atmos-meas-tech-discuss.net/6/3883/2013/
doi:10.5194/amtd-6-3883-2013
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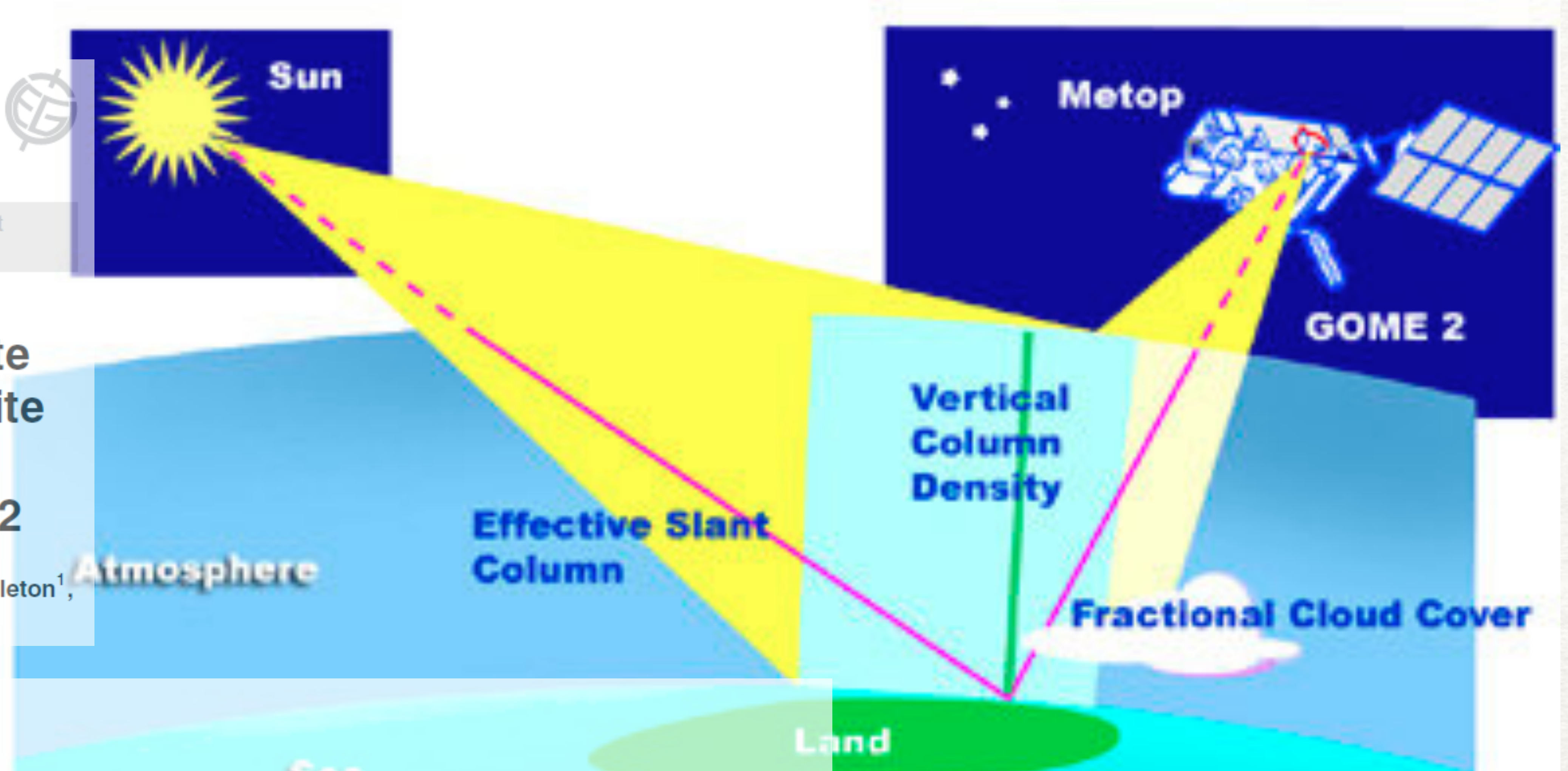
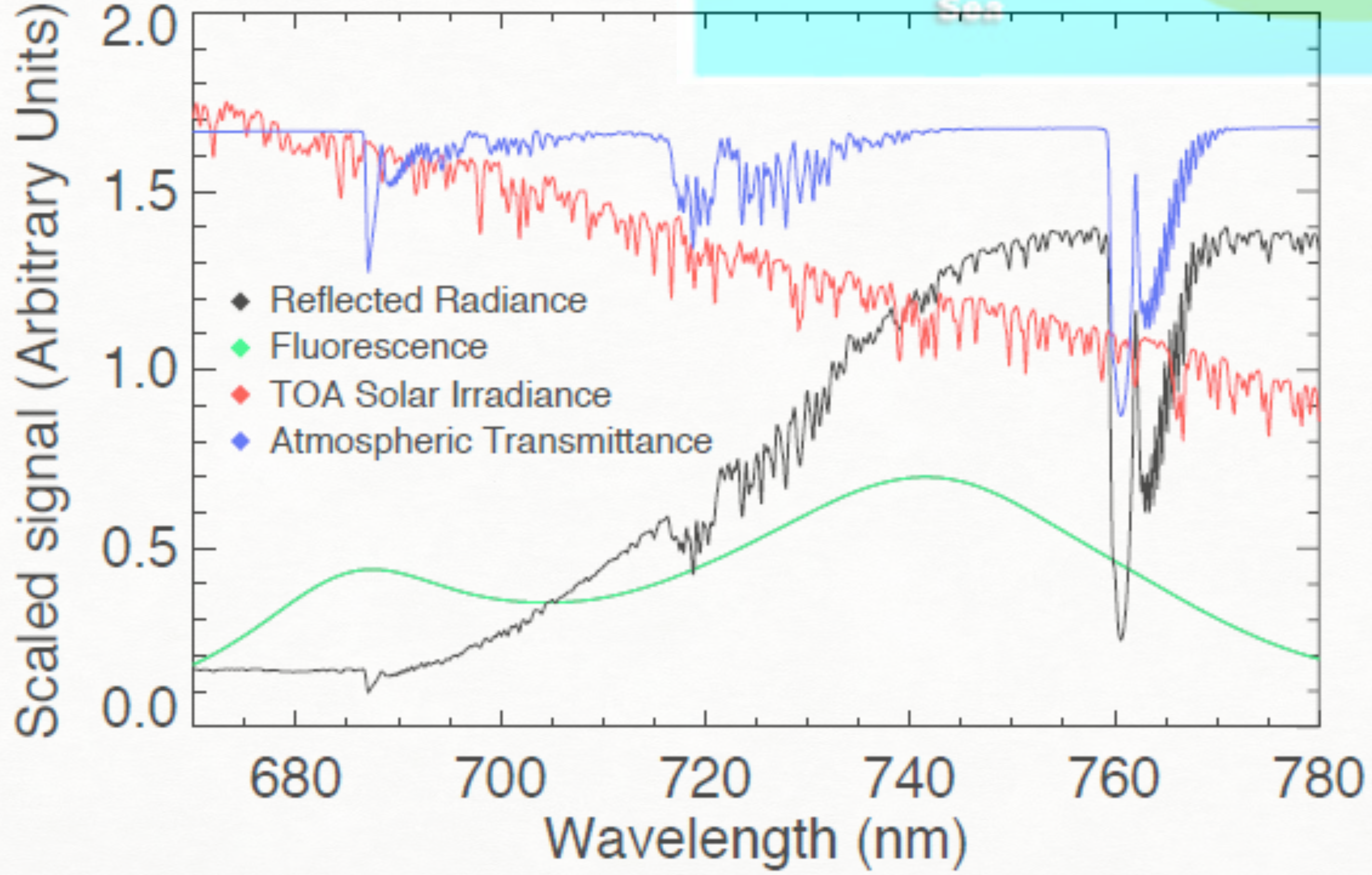
Atmospheric Measurement Techniques
Discussions

This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

Global monitoring of terrestrial chlorophyll fluorescence from moderate spectral resolution near-infrared satellite measurements: methodology, simulations, and application to GOME-2

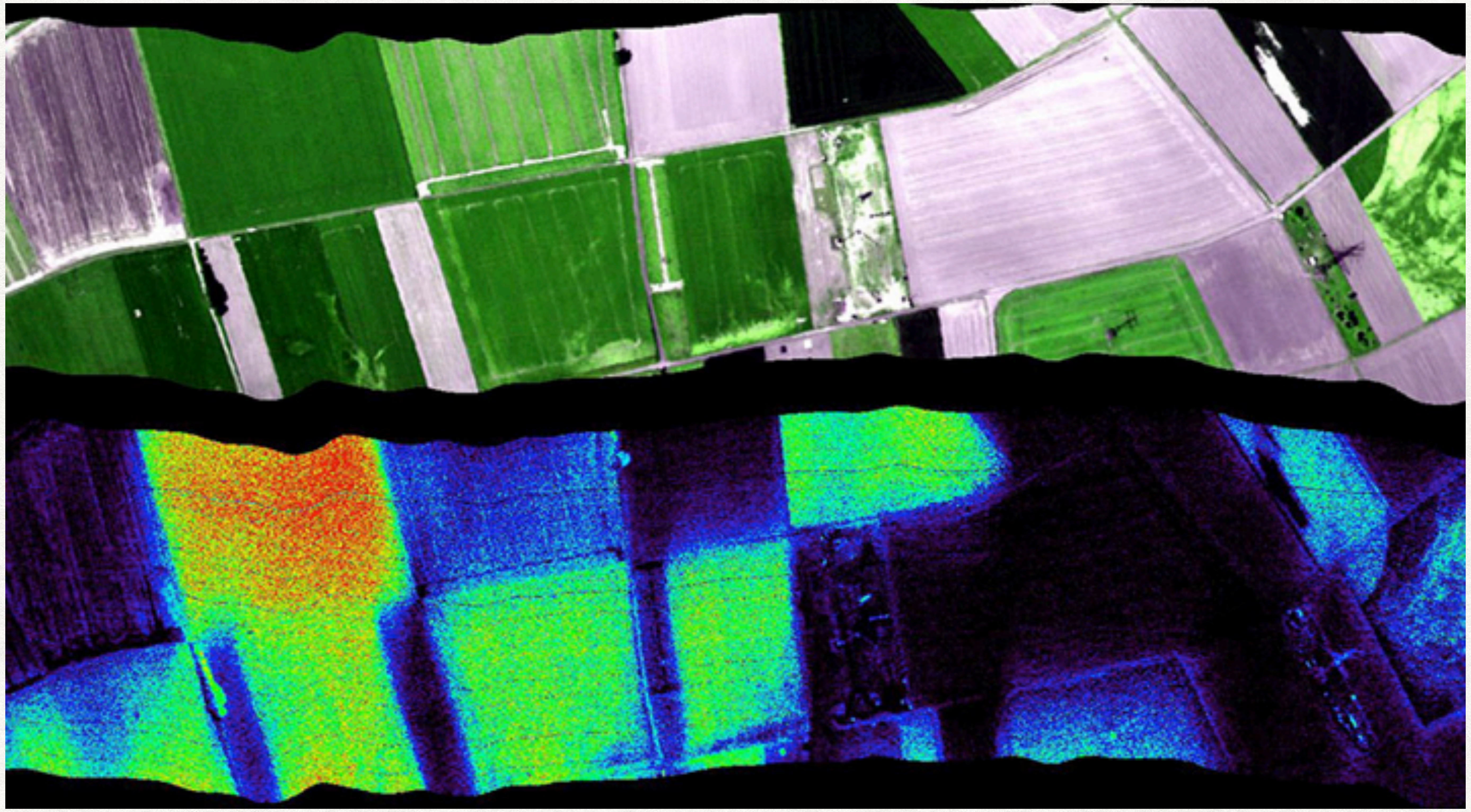
J. Joiner[1], L. Guanter[2], R. Lindstrot[2], M. Voigt[2], A. P. Vasilkov[3], E. M. Middleton[1], K. F. Huemmrich[4], Y. Yoshida[3], and C. Frankenberg[5]





GOME-2
40 x 60 km pixel
daily update
global coverage
9:30 AM crossing time

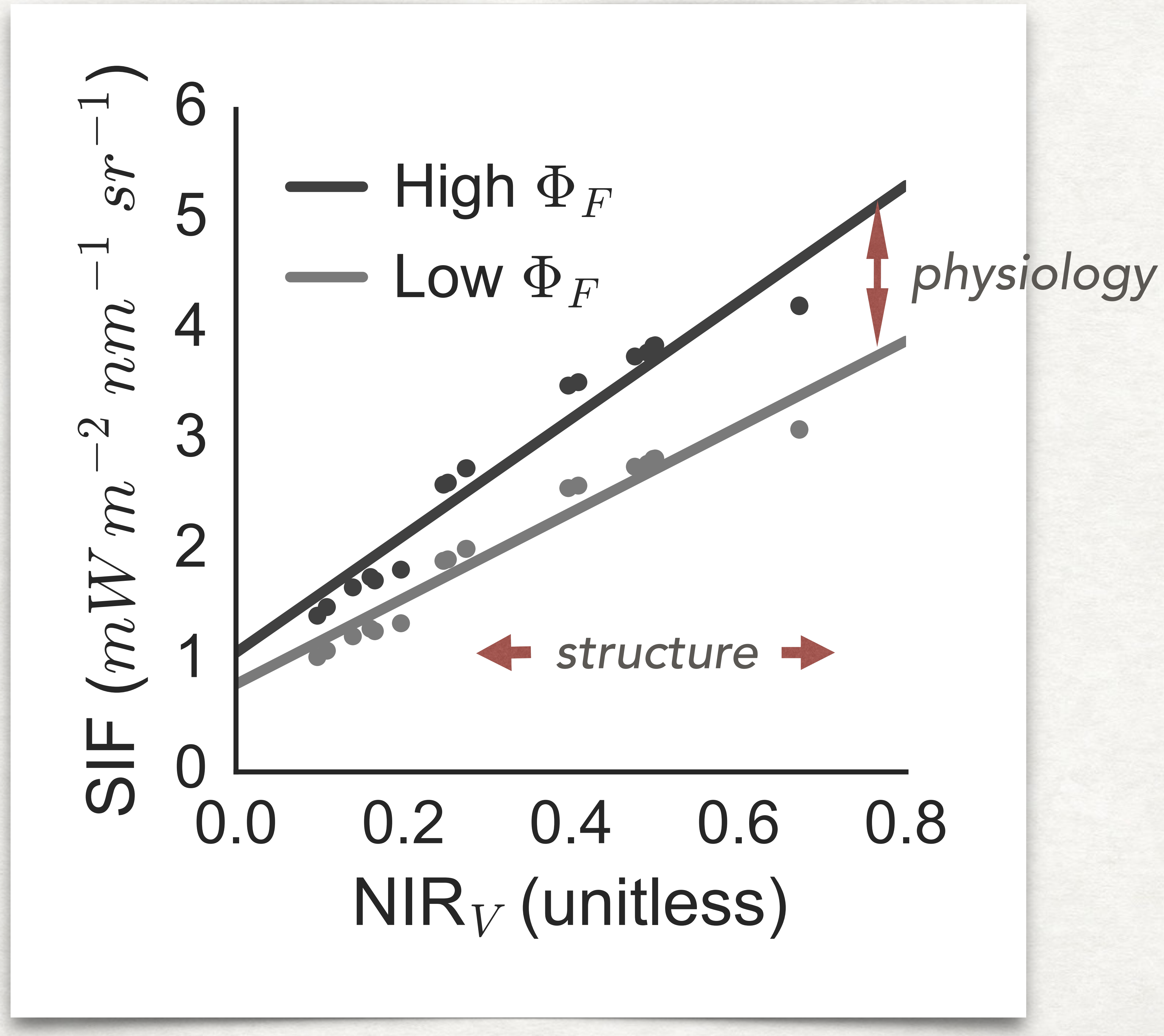
- SIF is specific to vegetation
- Reflectance "sees" the whole scene
- SIF is less sensitive to atmospheric scattering
- SIF radiance is correlated with GPP



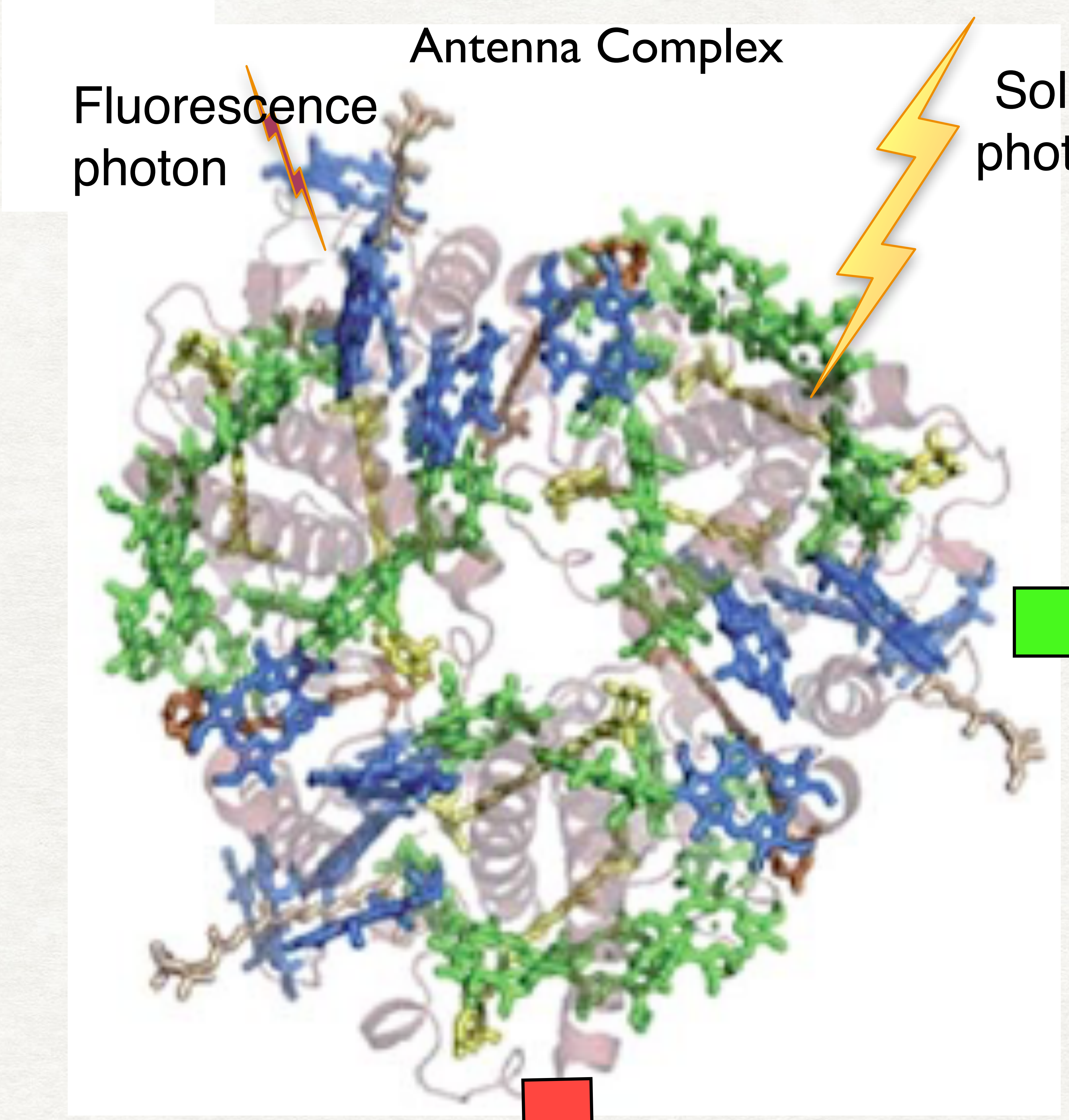
HyPlant (aircraft) Image of SIF and Greeness (Uwe Rascher)

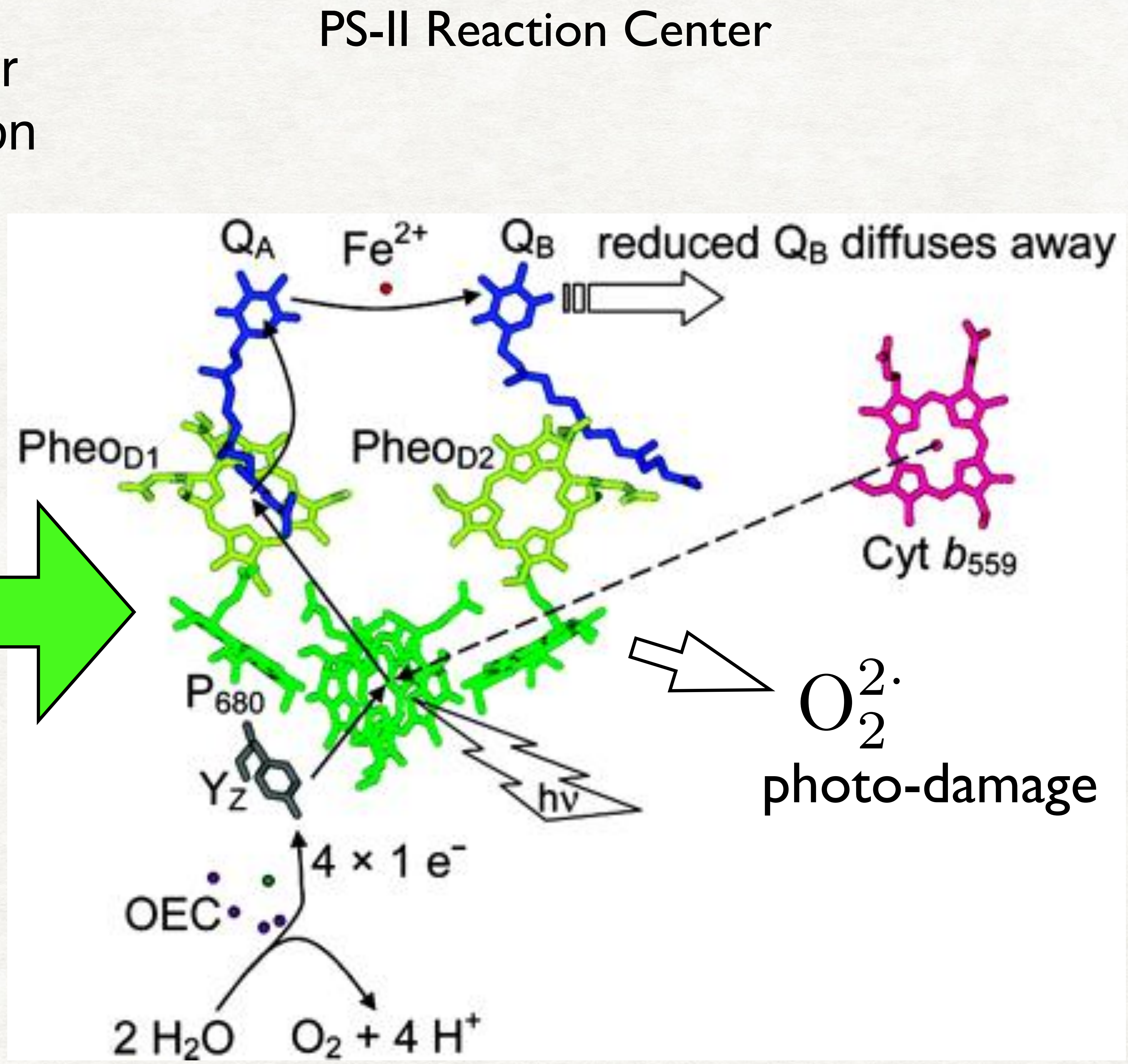
The correlation between SiF and GPP is based on:

- Physiological control of the yield of fluorescence (Φ_F)
- Structural properties of the canopy that effect leaf display



Physiology - PSII “decides” what to do with an absorbed photon

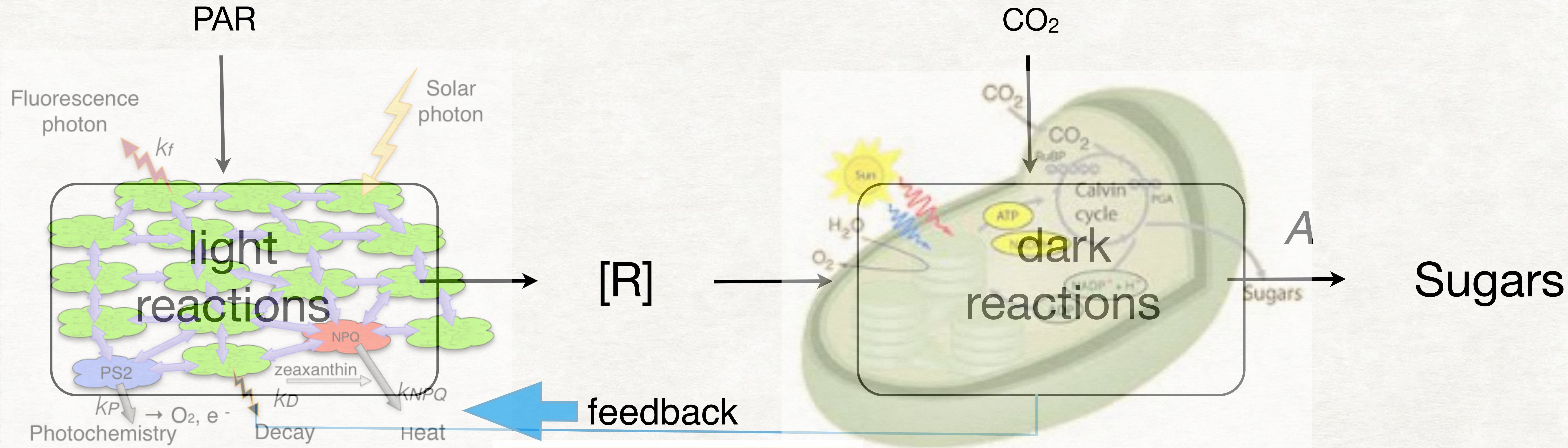




Non-photochemical Quenching

Fleming, G. R., Schlau-Cohen, G. S., Amarnath, K., & Zaks, J. (2012). Design principles of photosynthetic light-harvesting. Faraday Discussions, 155, 27. http://doi.org/10.1039/c1fd00078k

Interactions between the light and dark reactions:



PAR

CO2

light reactions

[R]

dark reactions

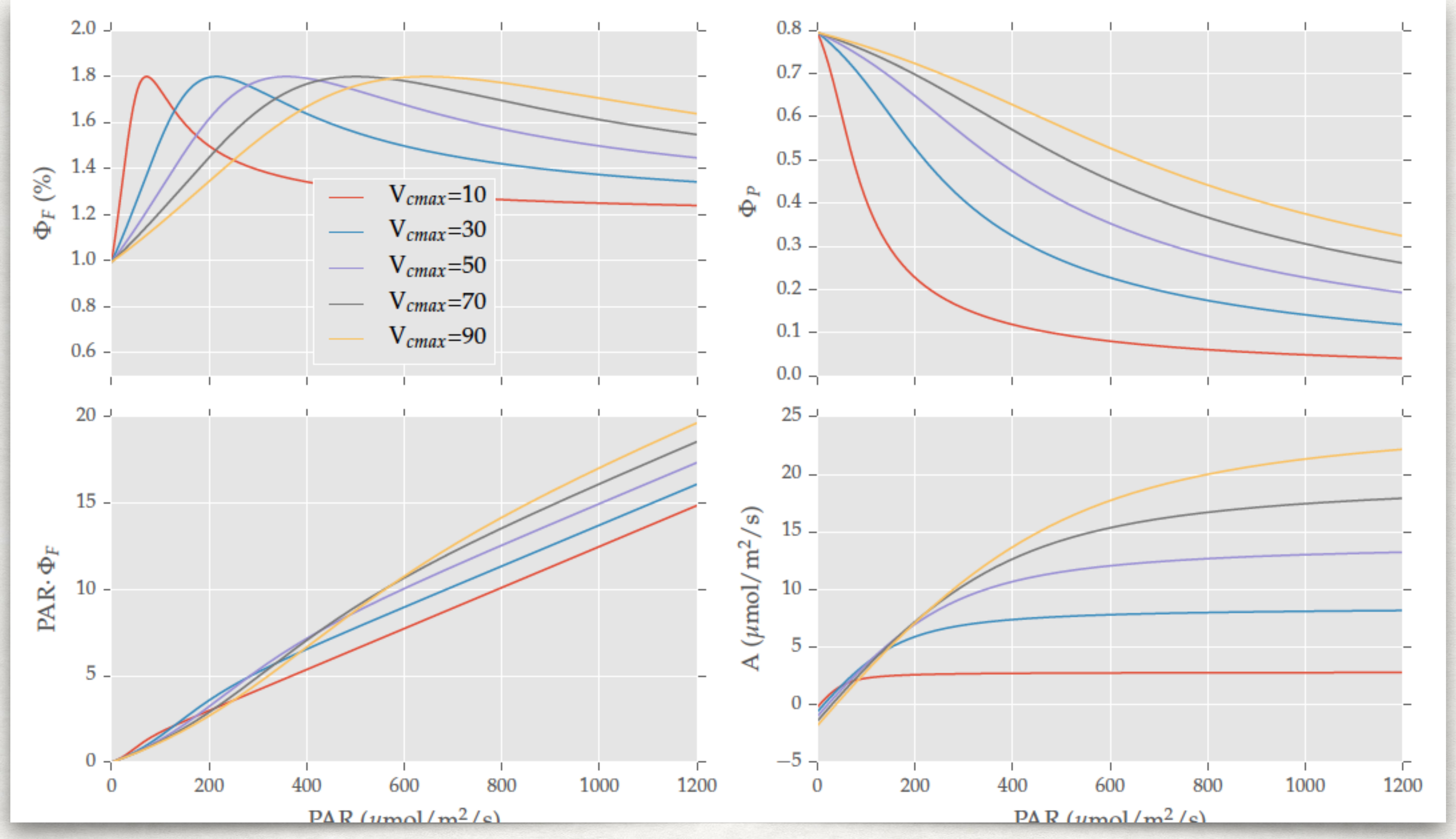
A

Sugars

feedback

$$A \approx \min \begin{cases} \text{light reactions } (W_{J}) \\ \text{dark reactions } (W_{C}) \end{cases}$$

Modeled Leaf Physiology

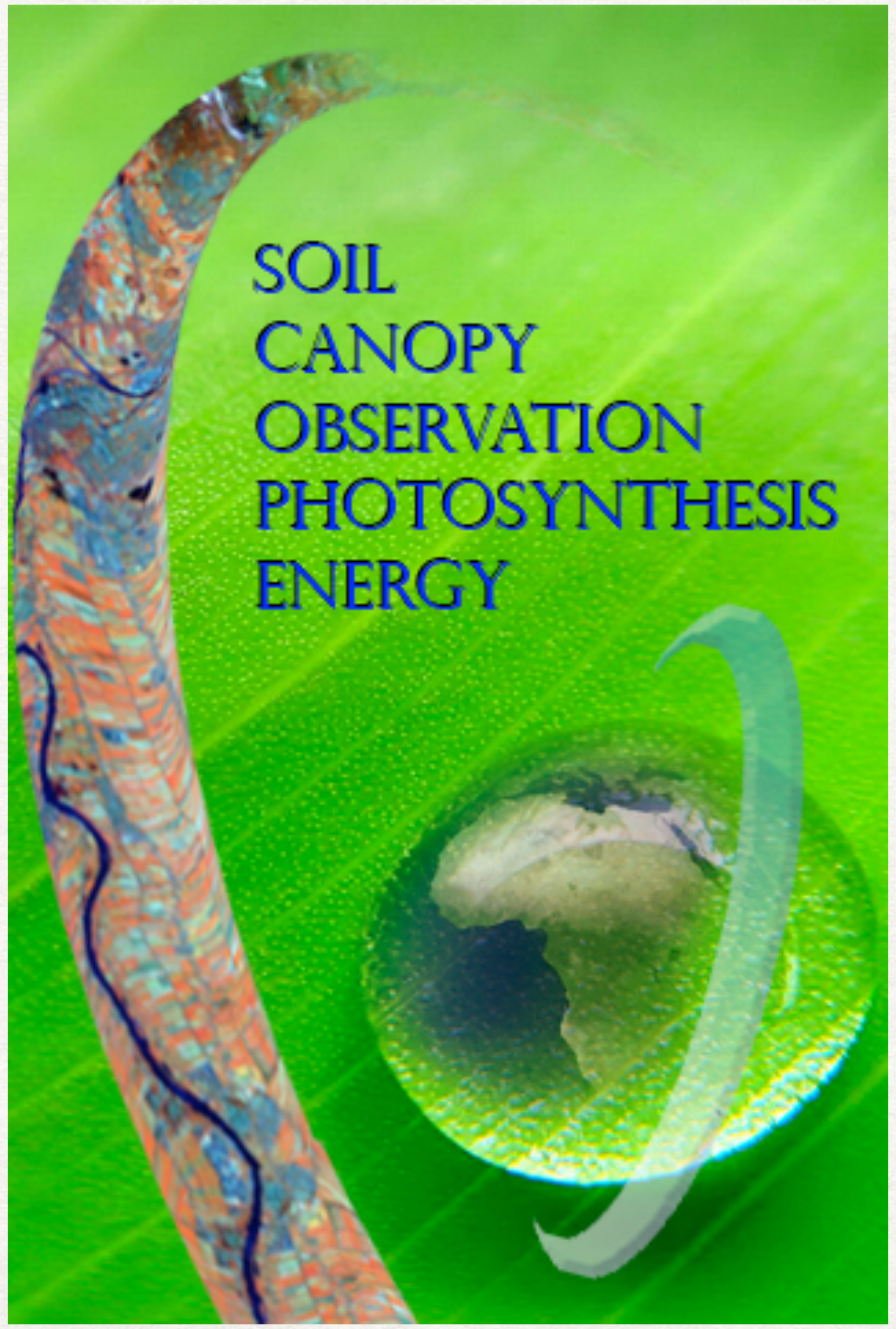


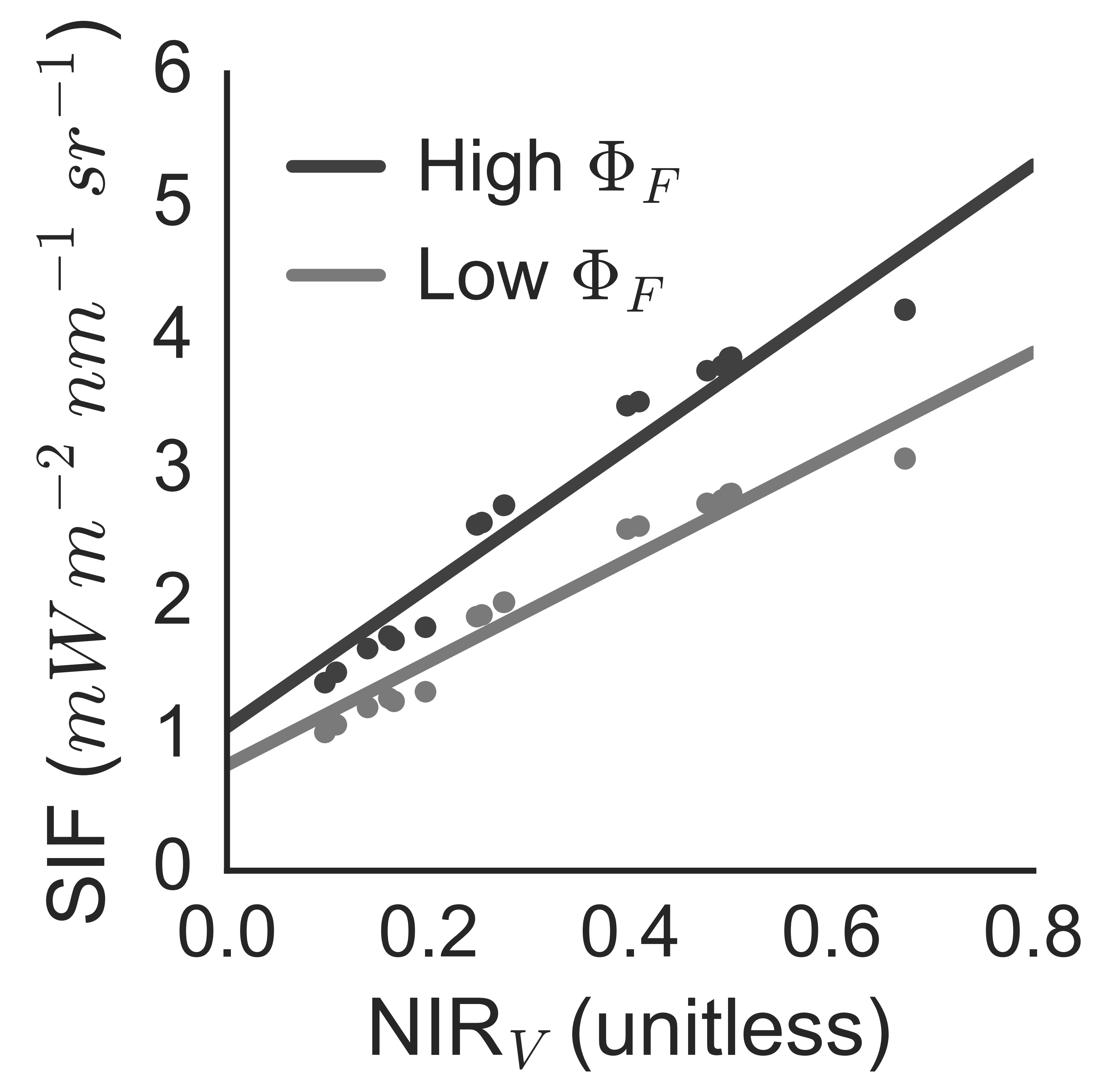
Summary: Physiology and SIF

- We have linked a fluorescence parameterization to a conventional photosynthesis model by inverting the Genty equation.
- This requires knowledge of one more *adjustable* leaf property, K_N^o. Requires PAM measurements.
- The V_{cm} RUBISCO (or effects of stress on it) have a large control on SIF.
- This parameterization has been added to SCOPE and the land surface models, SiB and CLM.

The Effect of Canopy Structure on SIF

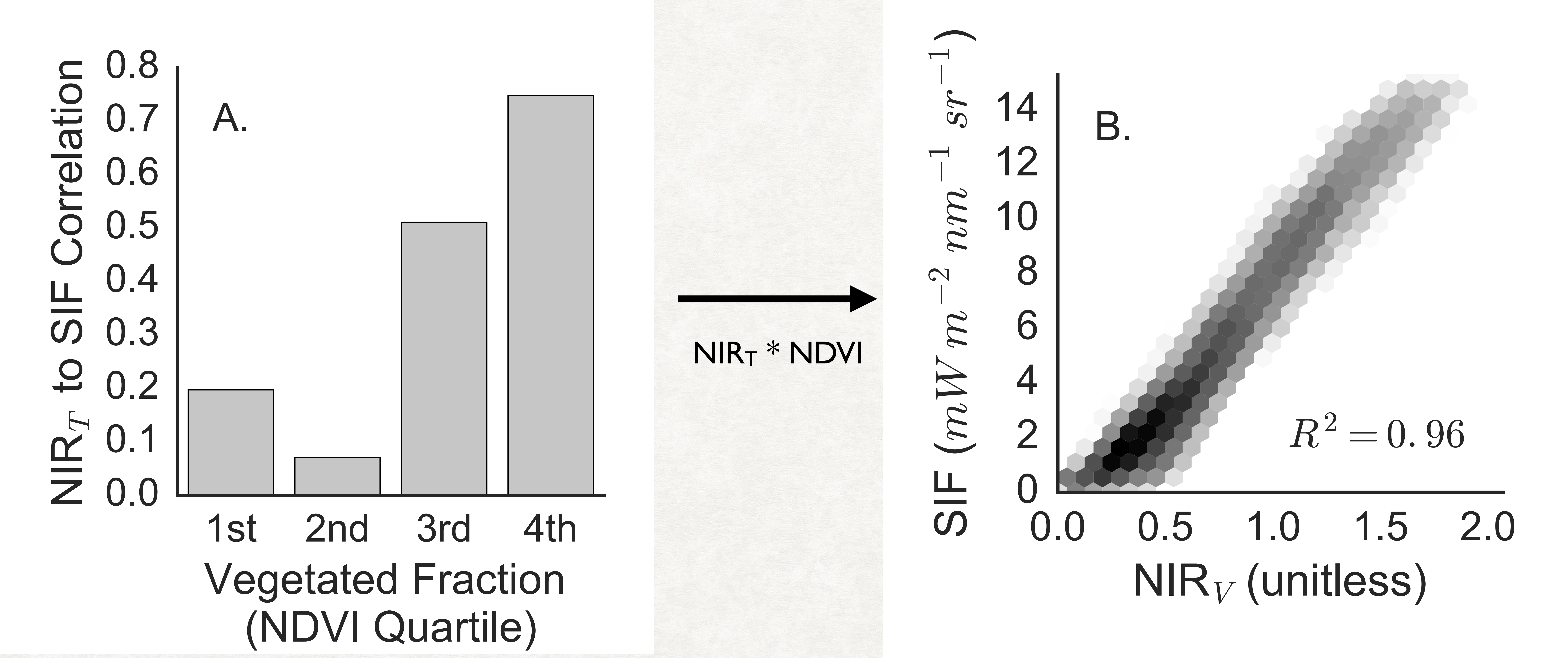
Modeling studies with SCOPE indicate that near infrared reflectance (NIR) from vegetation is strongly correlated with SIF and is sensitive to differences in fluorescence yield.





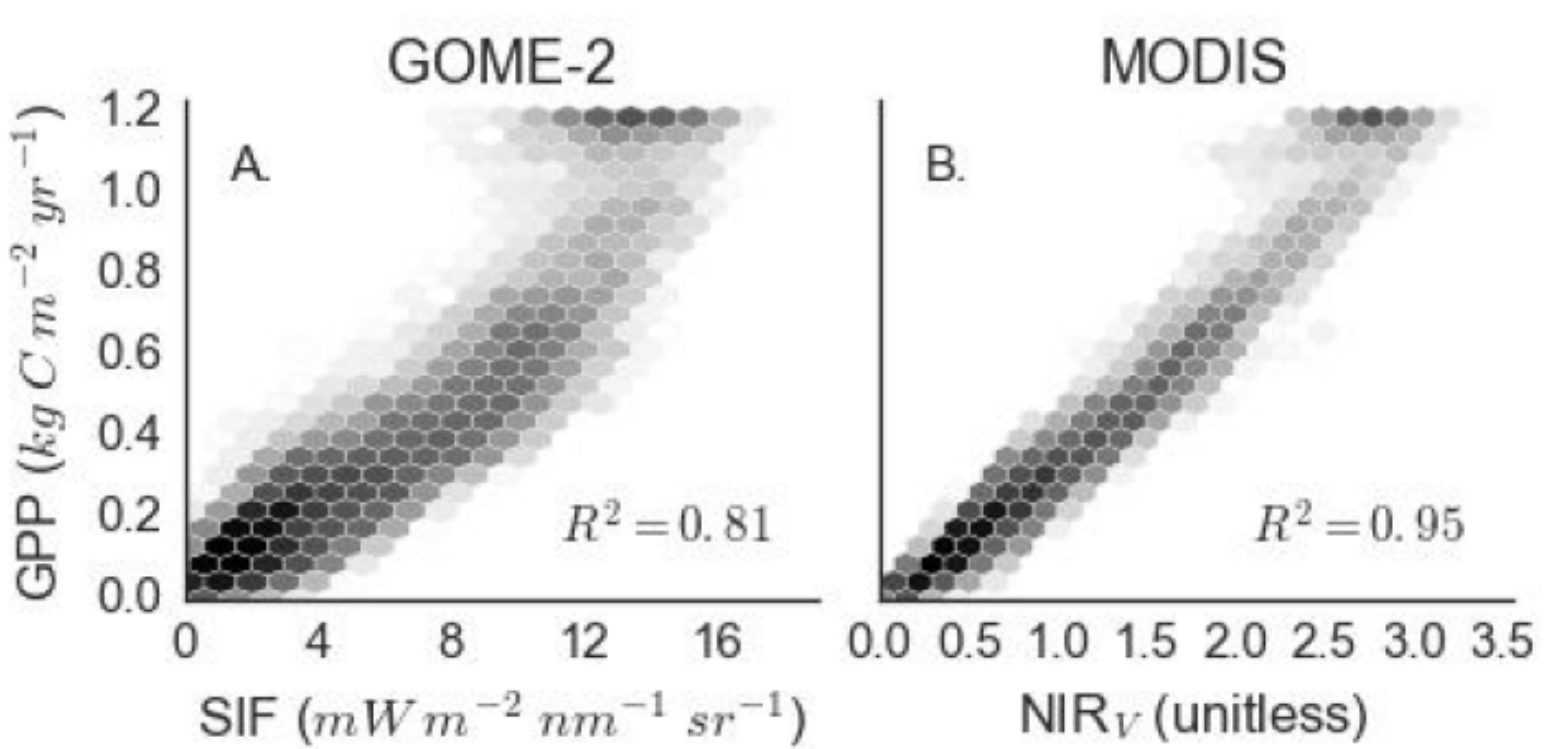
The probability that a fluorescence photon escapes is similar to that of a reflected NIR photon.

NDVI x NIR Radiance = NIR_V (vegetation)?



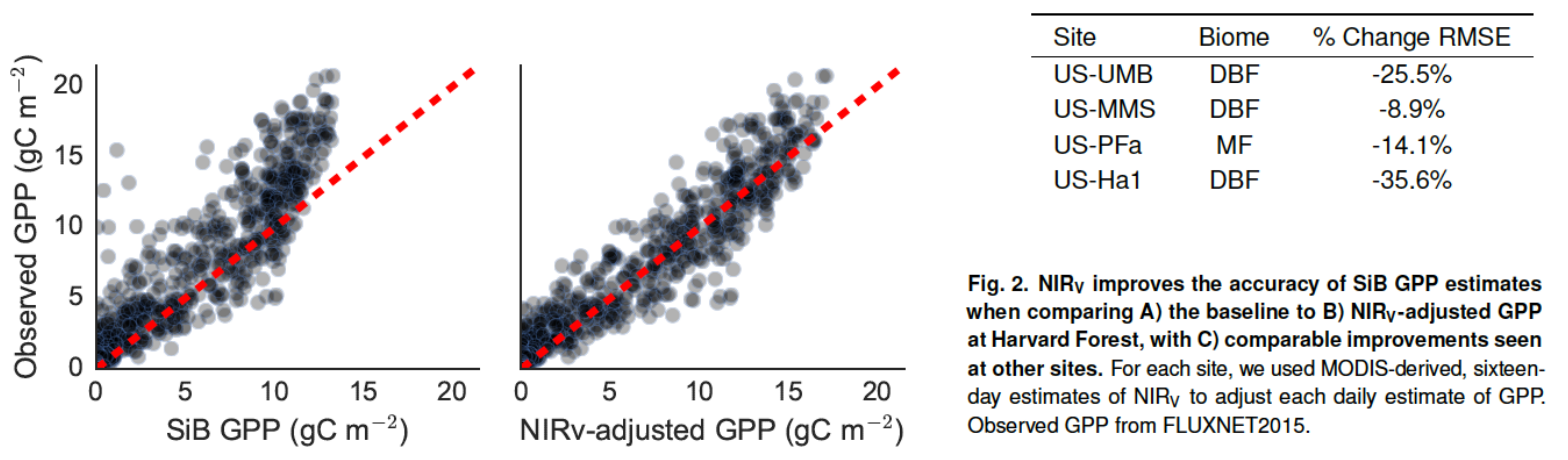
CAN WE USE NIR_V TO ESTIMATE GPP?

Monthly MPI-GPP at 0.5° *vs* SIF (GOME-2) or NIR_V (MODIS)



Badgley, G., Field, C. B., & Berry, J. A. (2017). Canopy near-infrared reflectance and terrestrial photosynthesis. Science Advances, 3(3), e1602244. http://doi.org/10.1126/sciadv.1602244

Making the canopy integration factor (π) in the SiB 3 proportional to SIF or NIR$_V$ improves the match to observation at AmeriFlux sites.



Site	Biome	% Change RMSE
US-UMB	DBF	-25.5%
US-MMS	DBF	-8.9%
US-PFa	MF	-14.1%
US-Ha1	DBF	-35.6%

Fig. 2. NIR$_V$ improves the accuracy of SiB GPP estimates when comparing A) the baseline to B) NIR$_V$-adjusted GPP at Harvard Forest, with C) comparable improvements seen at other sites. For each site, we used MODIS-derived, sixteen-day estimates of NIR$_V$ to adjust each daily estimate of GPP. Observed GPP from FLUXNET2015.

Final Thoughts on SIF:

- SIF is turning out to be surprisingly useful:
  - Seems to be proportional to GPP;
  - Indicates drought;
  - Indicates beginning and end of growing season.
  - Seems to be related to Vcm Rubisco
- It is also a hot topic in fundamental research on photosynthesis - connection to another community.
- NIR_V is a good proxy for SIF, but the latter would probably be more reliable if we had an appropriate satellite.
- OCS exchange may provide another way to check on GPP

Submitted in response to Earth Venture Instrument-4 AO #NNH12ZDA006O-EVI 4 November 18, 2016

FOLIAGE

Fluorescence Observatory for monitoring vegetation Light-use efficiency, AGriculture, & Ecosystem function

Principal Investigator: Dr. Joseph Berry
Carnegie Institution for Science
Joseph A Berry

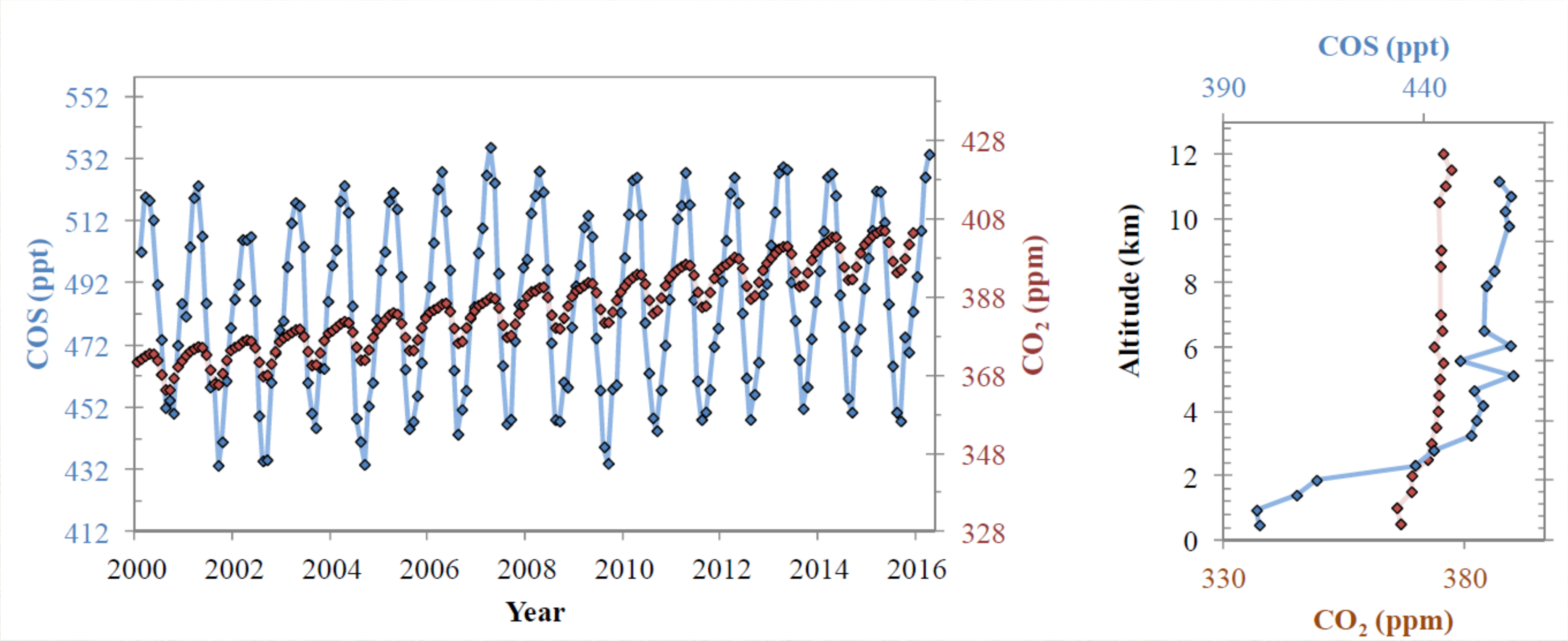
Authorizing Official: Matthew P. Scott, President
Carnegie Institution for Science
Matthew Scott

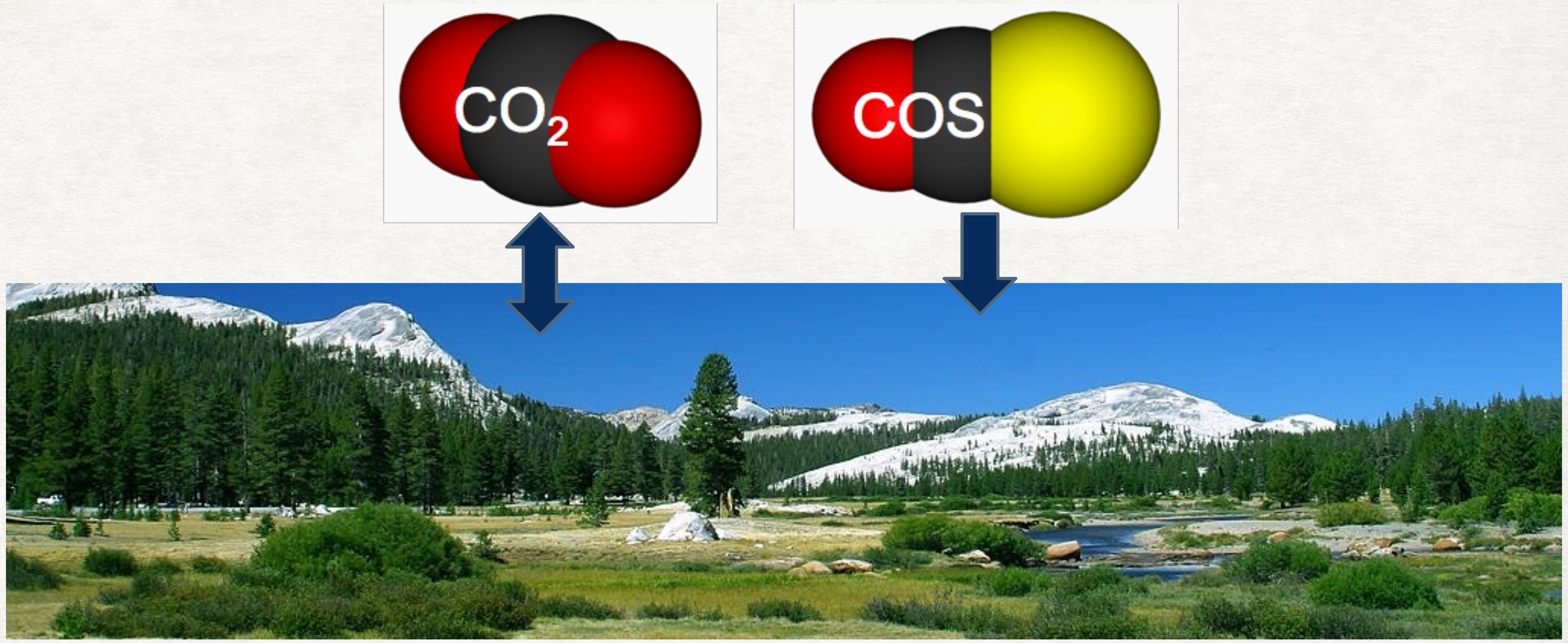
CARNEGIE
SCIENCE

Atmospheric CO_2 and OCS concentration

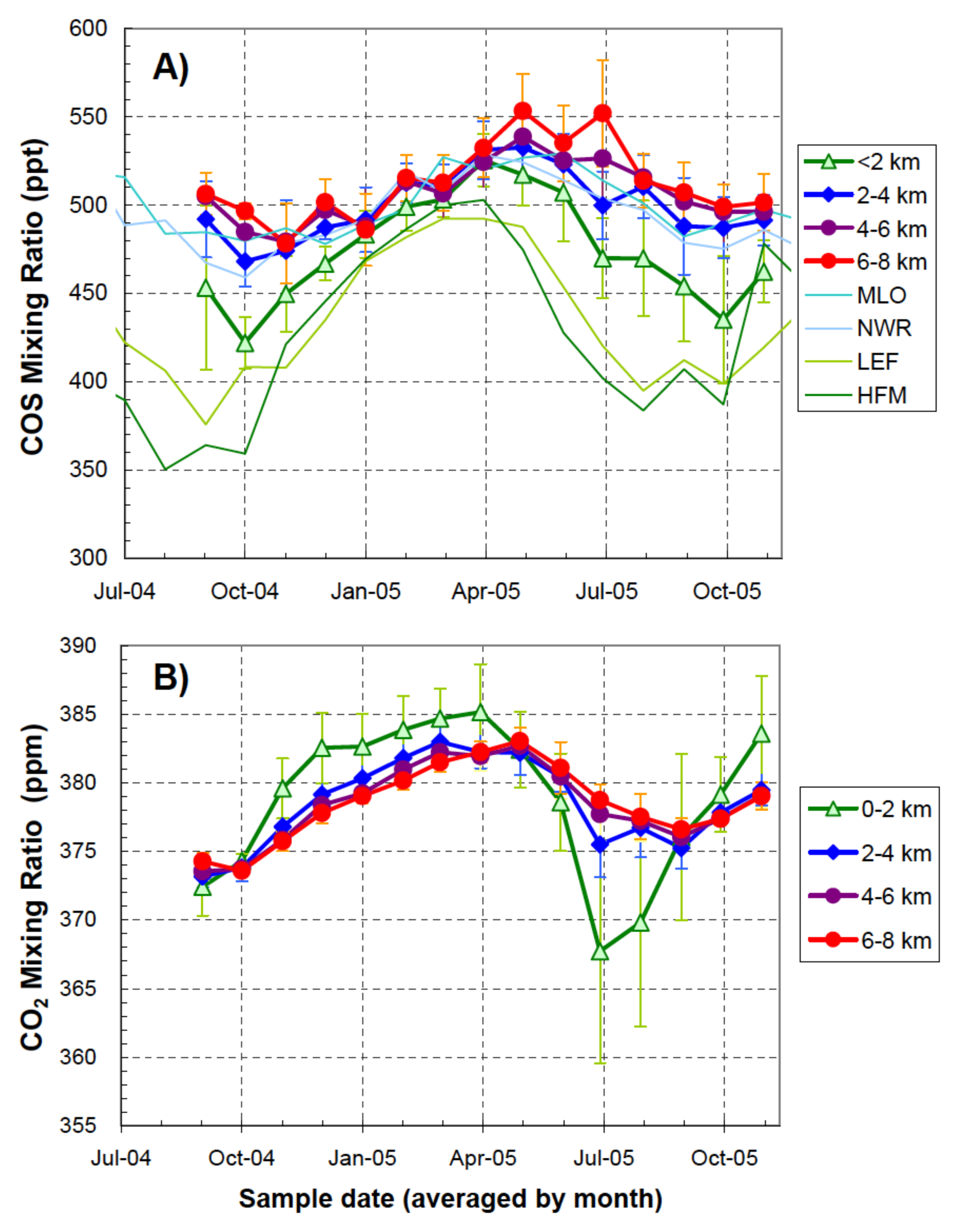
Carbonyl sulfide (COS or OCS)

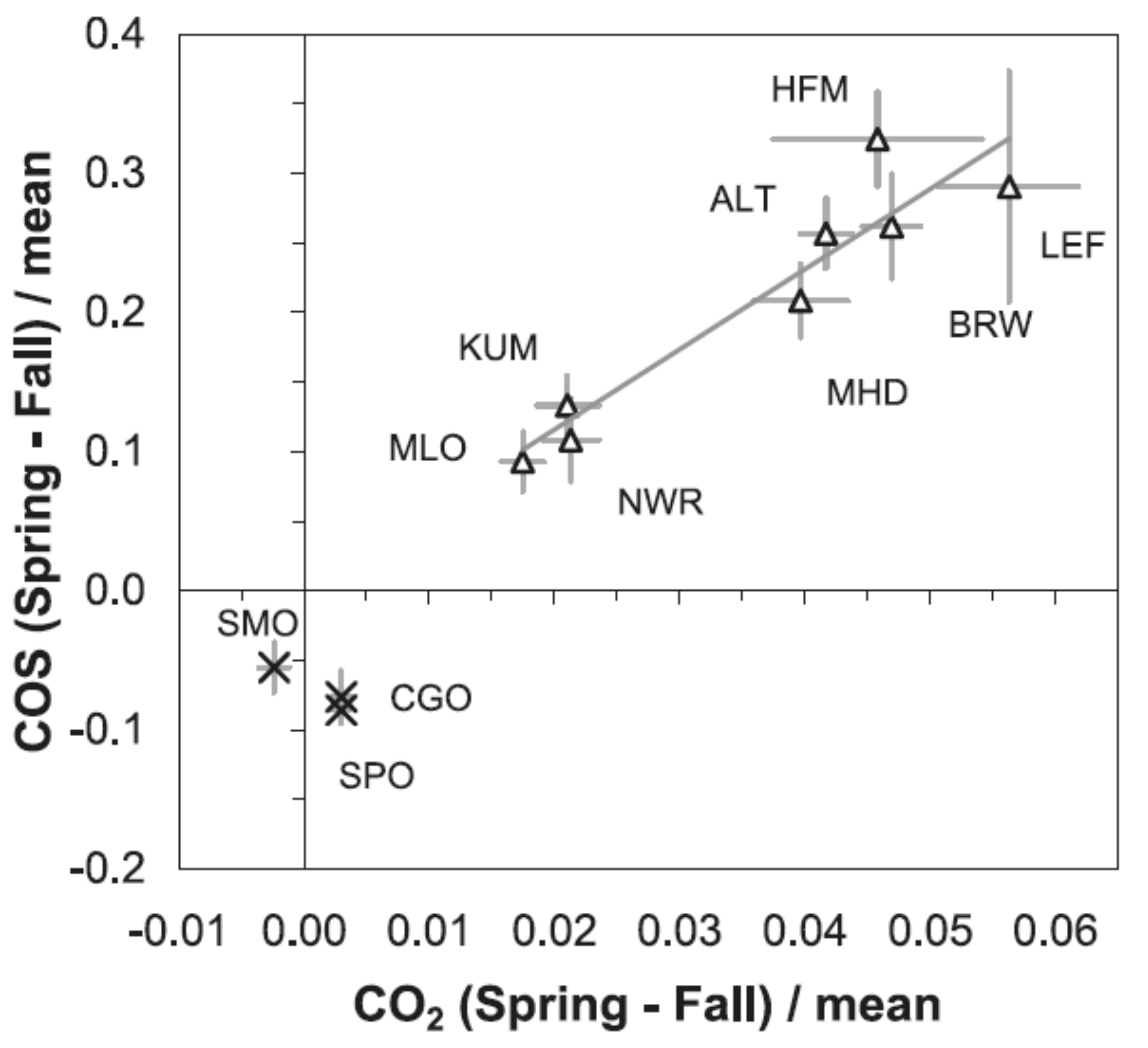
A new tracer for terrestrial photosynthesis





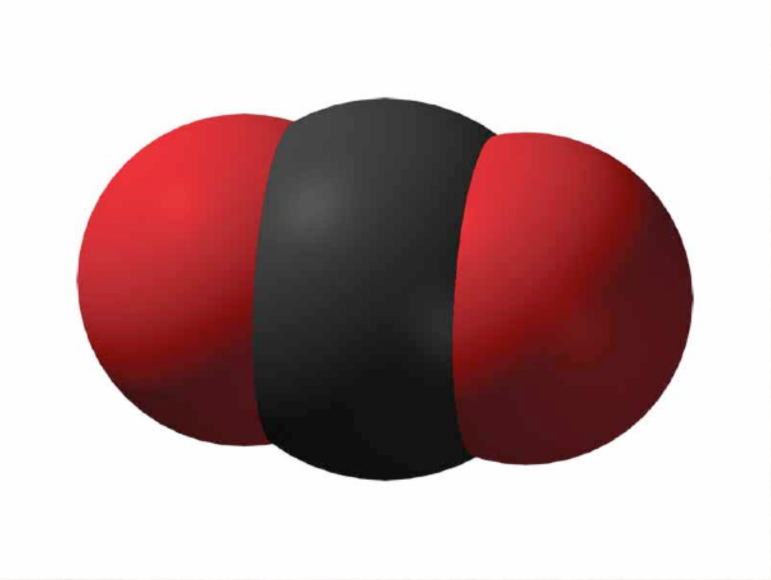
There is strong covariation of CO_2 and OCS in the global atmosphere





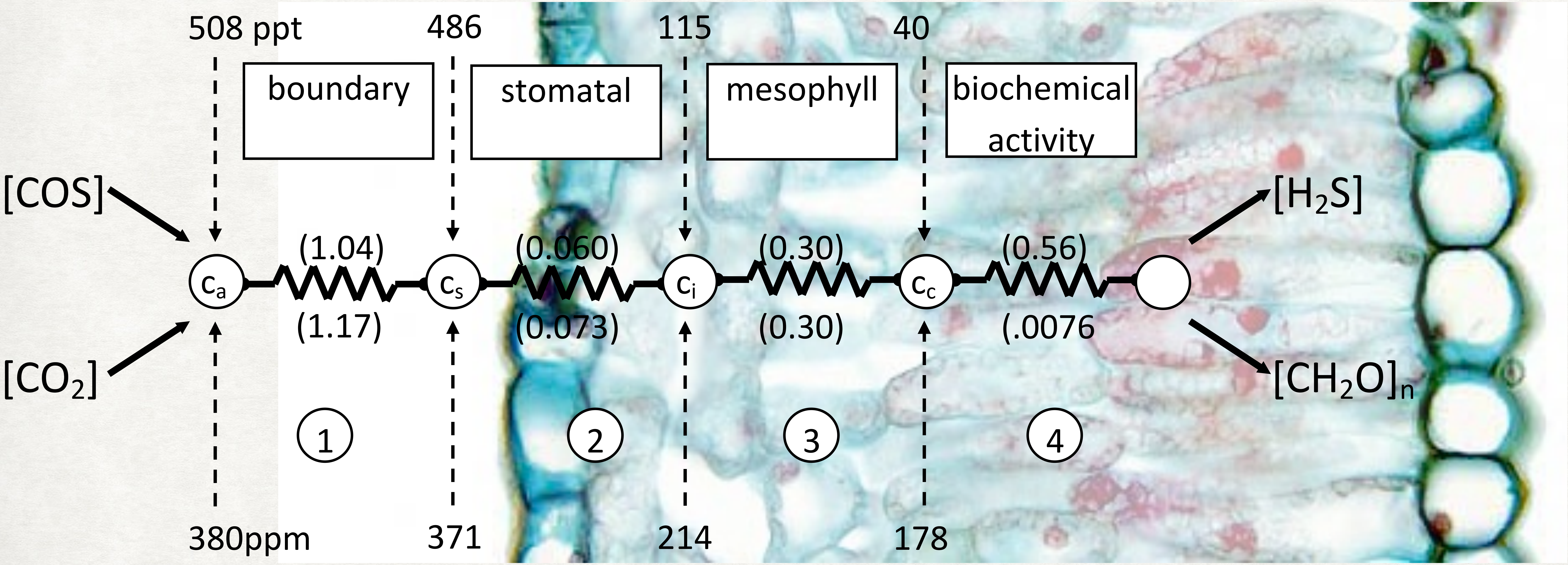
Montzka, S. A., Calvert, P., Hall, B. D., Elkins, J. W., Conway, T. J., Tans, P. P., & Sweeney, C. (2007). On the global distribution, seasonality, and budget of atmospheric carbonyl sulfide (COS) and some similarities to CO_2. **Journal of Geophysical Research,** 112(D9), 1–15. http://doi.org/10.1029/2006JD007665

Properties



	CO_2	OCS or COS
atmospheric concentration	400 ppm	500 ppt
turnover time	~7 years	~2 years
net biosphere exchange (terrestrial)	weak uptake	strong uptake
key enzymes	Rubisco + respiration	Carbonic-anhydrase

Leaf Uptake OCS follows the same path as CO_2



508 ppt
486
115
40

boundary
stomatal
mesophyll
biochemical activity

[COS]
[CO_2]

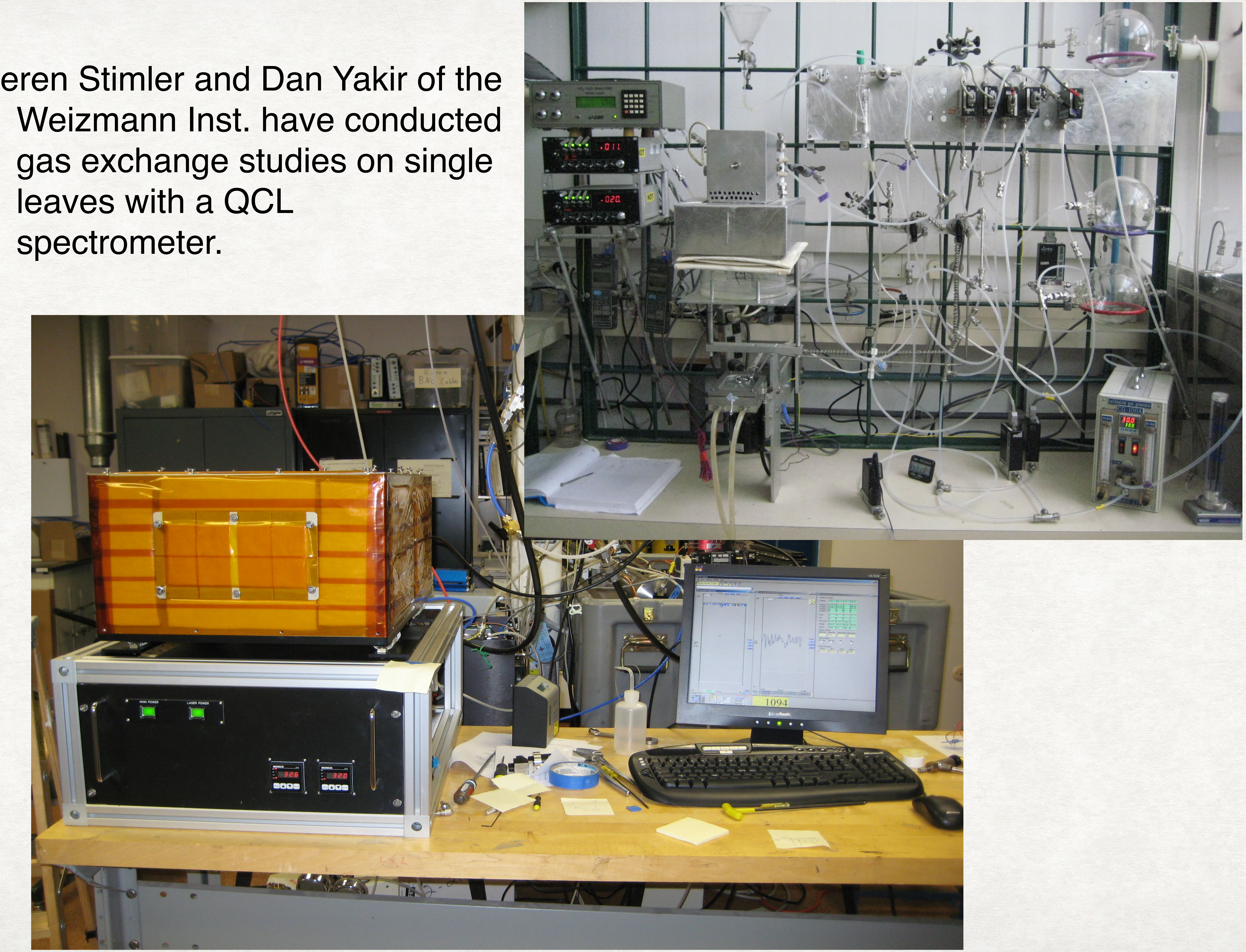
c_a (1.04) (1.17) c_s (0.060) (0.073) c_i (0.30) (0.30) c_c (0.56) (.0076

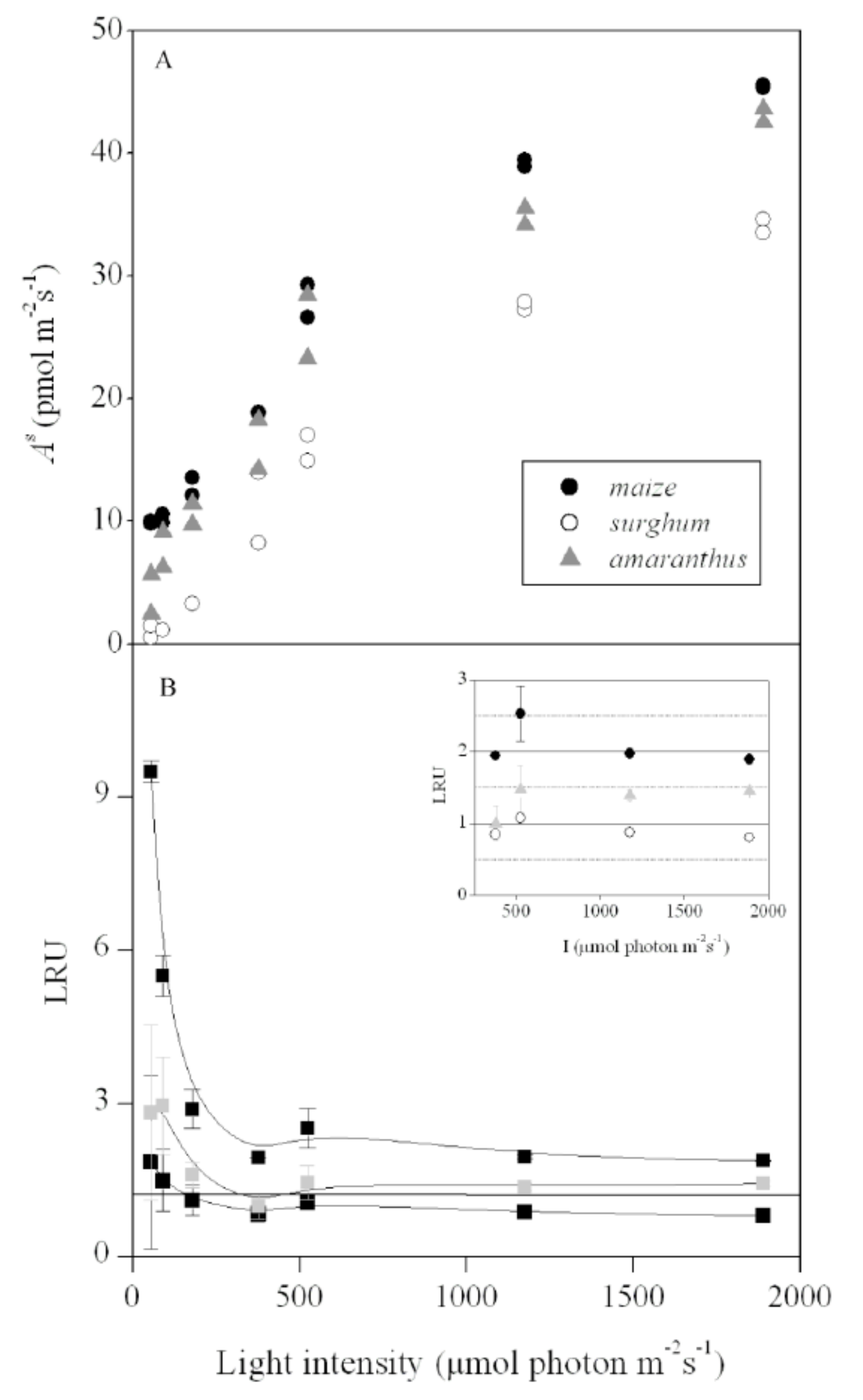
[H_2S]
[CH_2O]$_n$

① ② ③ ④

380ppm
371
214
178

Keren Stimler and Dan Yakir of the Weizmann Inst. have conducted gas exchange studies on single leaves with a QCL spectrometer.





Uptake of both CO_2 and COS is stimulated by light. In the case of CO_2 this is expected because synthesis of the CO_2 acceptor, RuBP requires light. No energy is required for hydrolysis of COS.

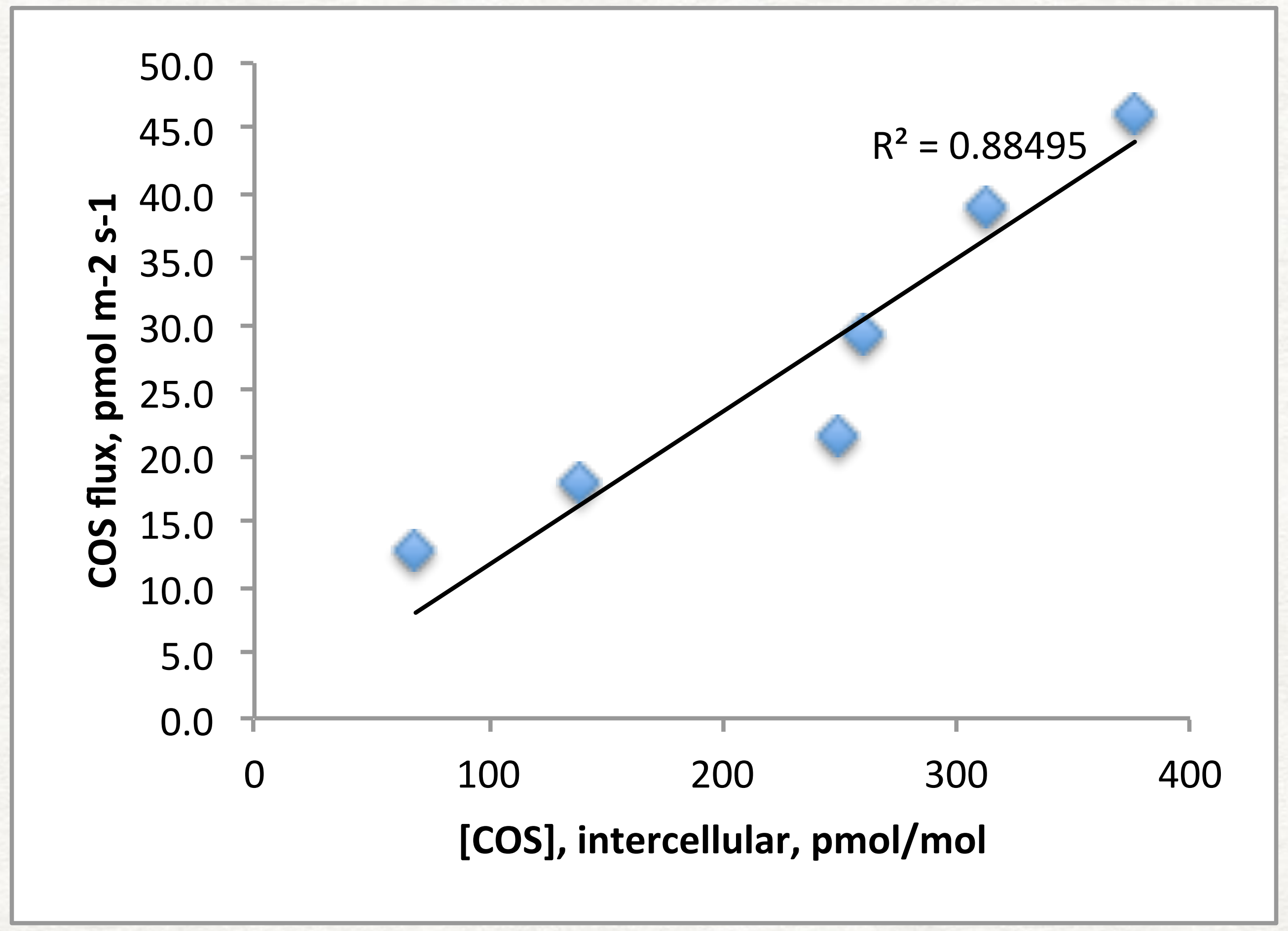
Uptake of OCS is largely controlled by stomatal conductance (*gsw*) which is linked to photosynthesis (J_{CO2}).

$$gsw = m \cdot J_{\mathrm{CO_2}} \cdot \frac{[\mathrm{H_2O}]_v}{[\mathrm{CO_2}]} + b$$

The intercept term (*b*) becomes important at low light.

Coding it into a model

$$J_{\mathrm{COS}} = [\mathrm{COS}] \cdot (\frac{1.55}{gbw} + \frac{1.92}{gsw} + \frac{1}{g_{\mathrm{cell}}})^{-1}$$



Uptake of COS is linear on [COS]

$$g_{\mathrm{cell(COS)}} = f(\mathrm{diffusion,\ biochemistry})$$

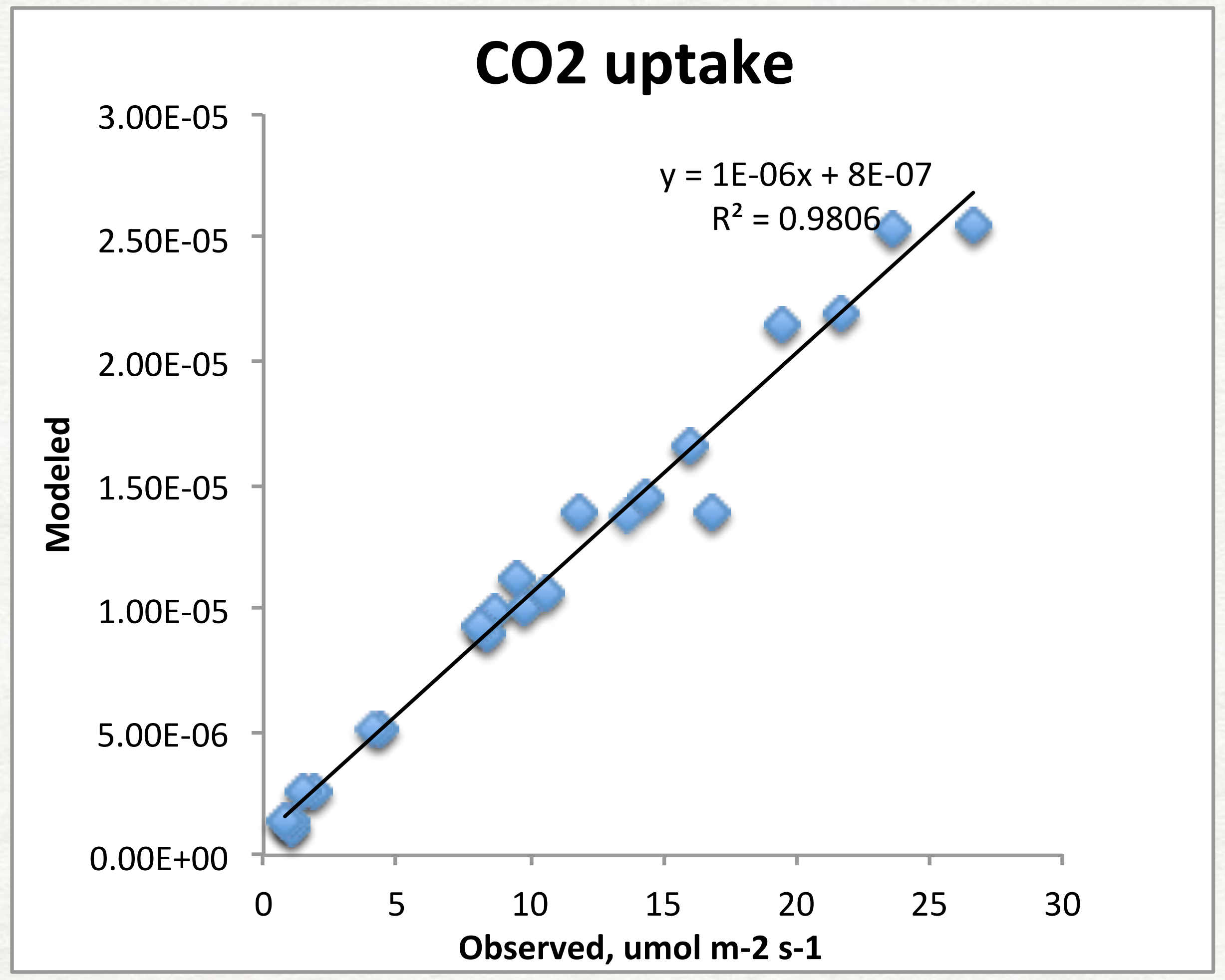
$$g_{\mathrm{cell}}(\mathrm{COS}) = v_m(gi3 \cdot C_3 + gi4 \cdot C_4)$$

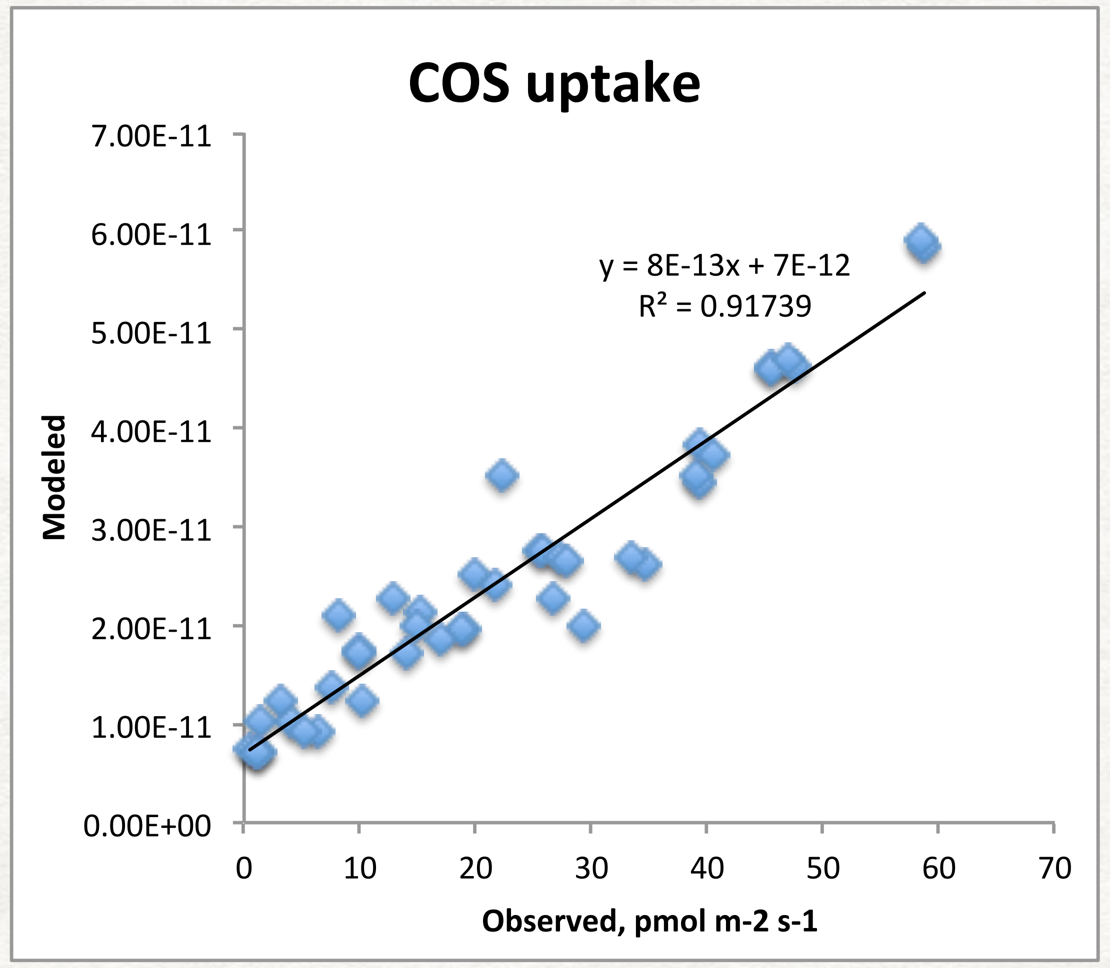
logical

scaling factors

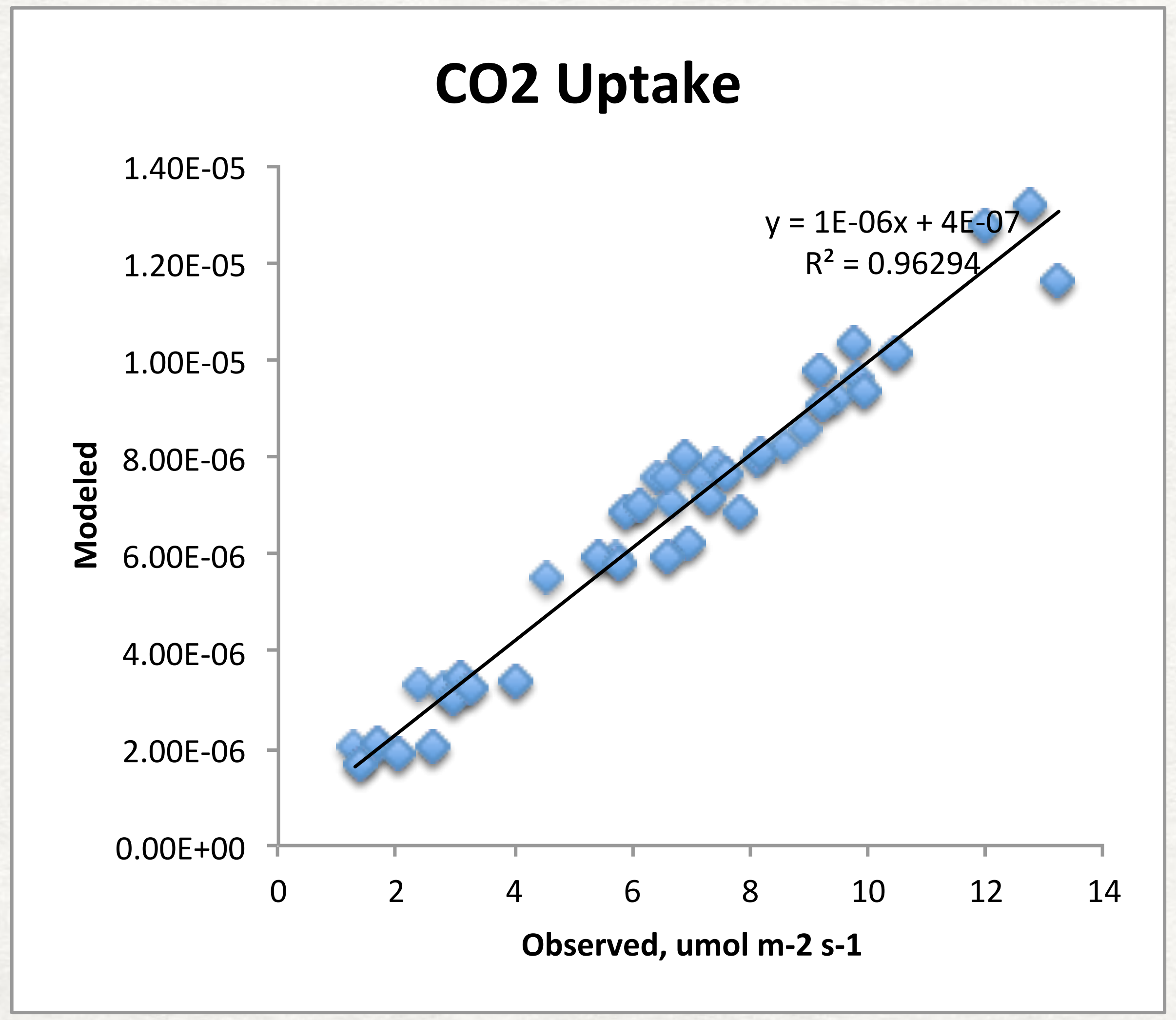
Rubisco activity, *f(T,stress)*

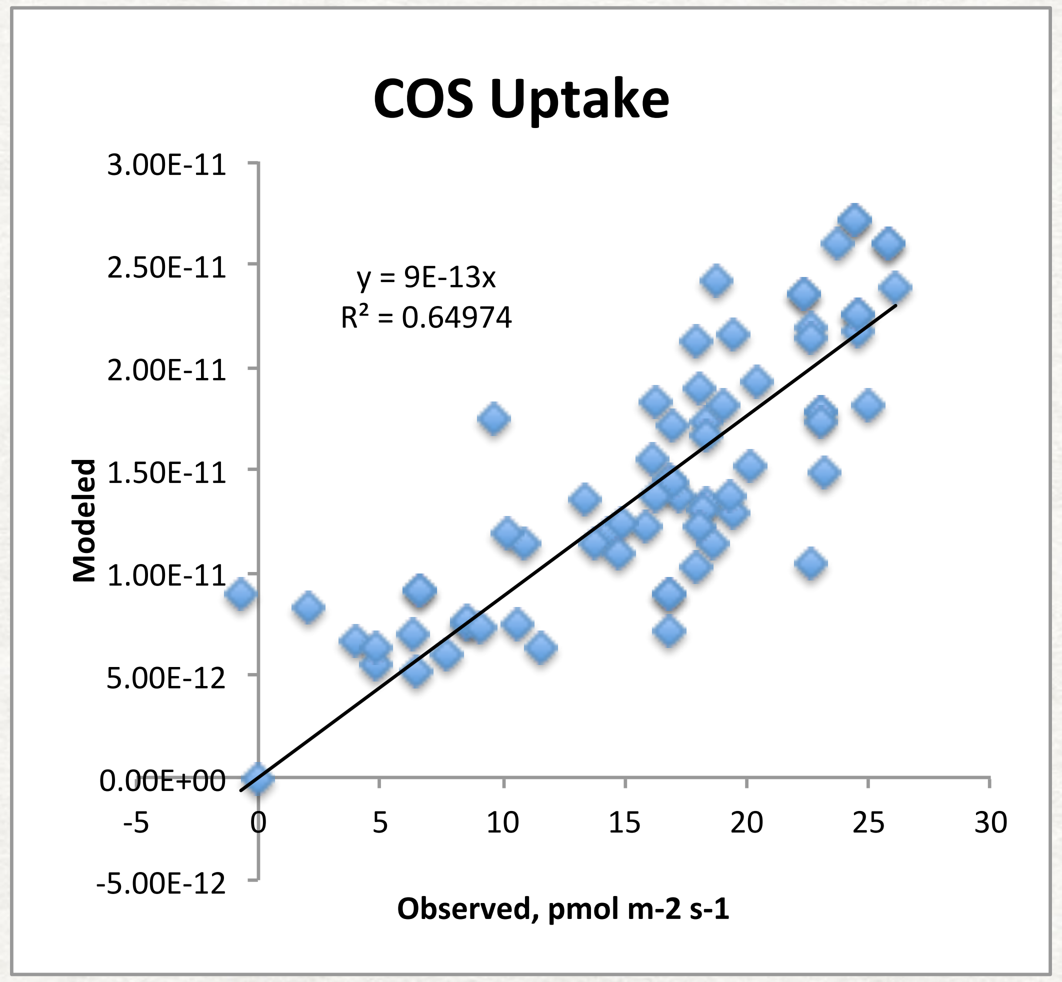
C_4 Light Response



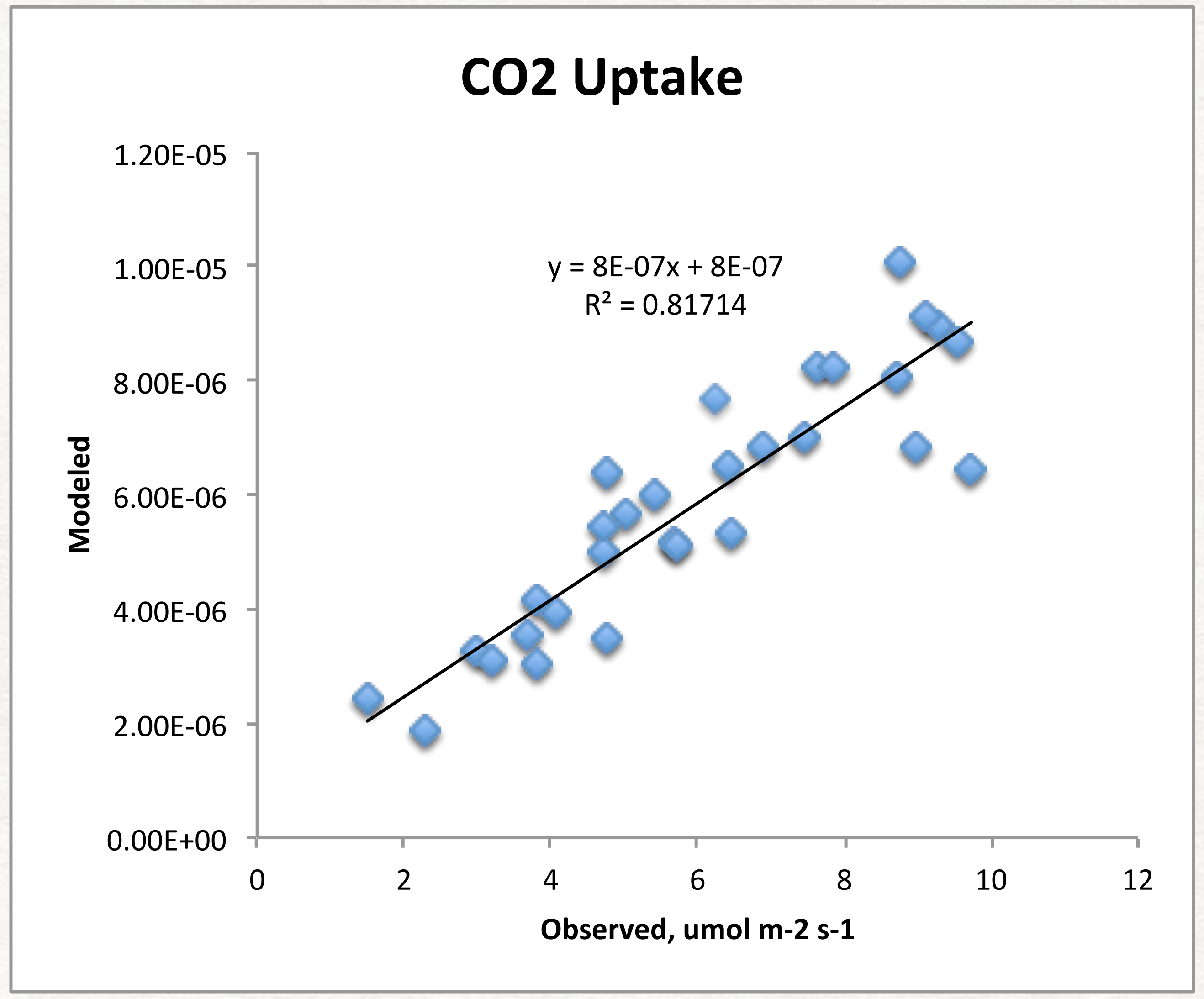


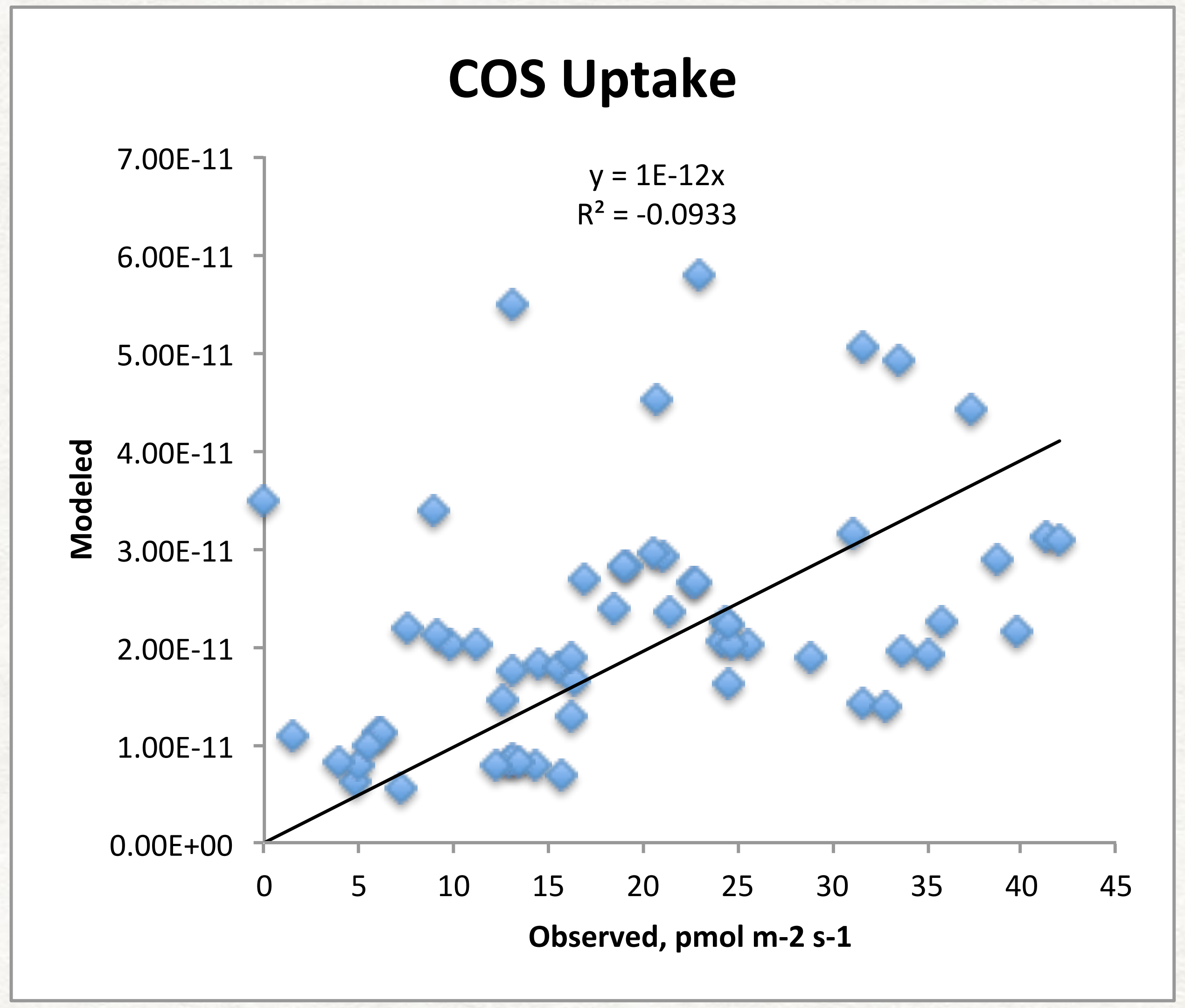
C_3 Light Response





C_3 Temperature Response

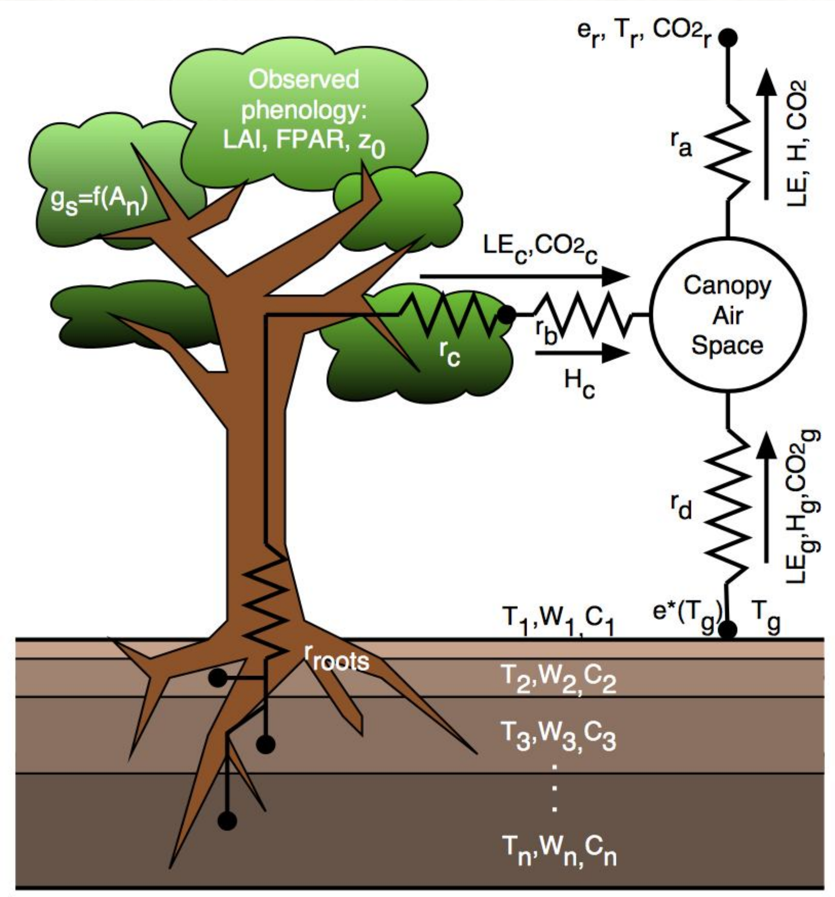


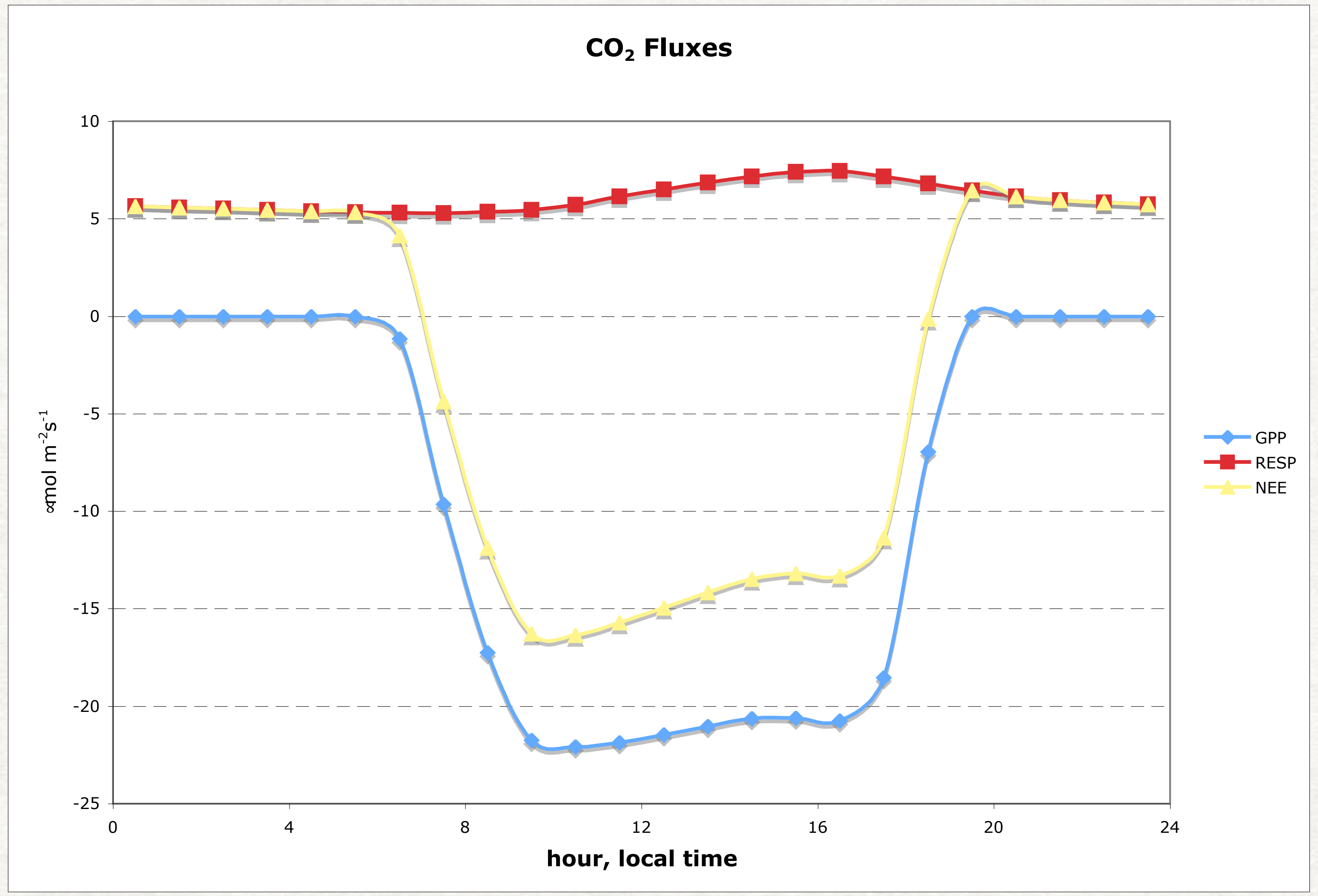


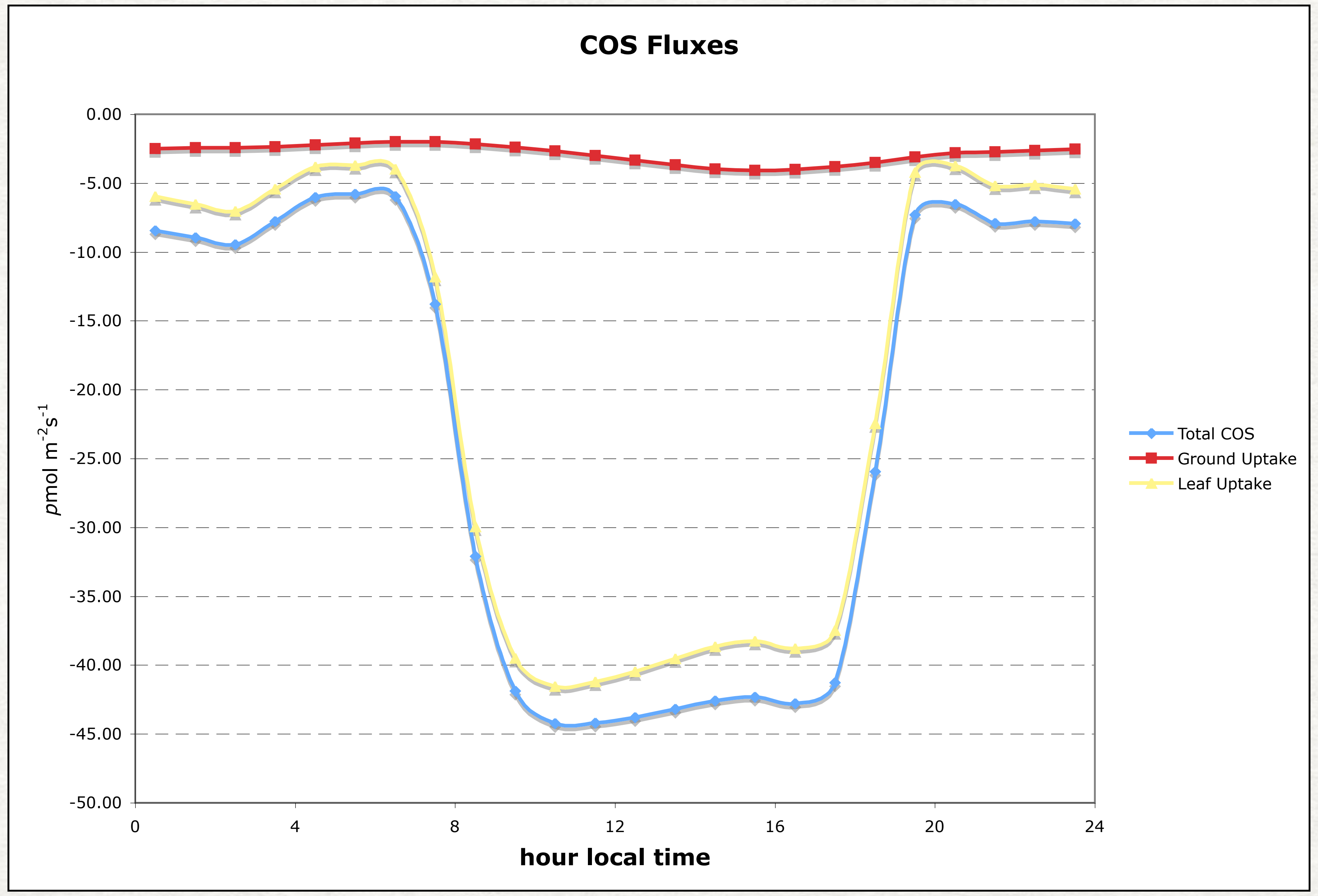
Summary:

- CO_2 uptake was modeled with a fitted V_{max} for each leaf - no other adjustments.
- COS uptake was modeled using that V_{max} with additional adjustments to the scaling factors, *gi3 or gi4*.
- These differed from species to species by at least a factor of 3 - presumably due to differences in the ratio of carbonic anhydrase to Rubisco.
- Much of the noise is due to inaccuracy in modeling *gsw*.

Diurnal Patterns of CO_2 and OCS Exchange



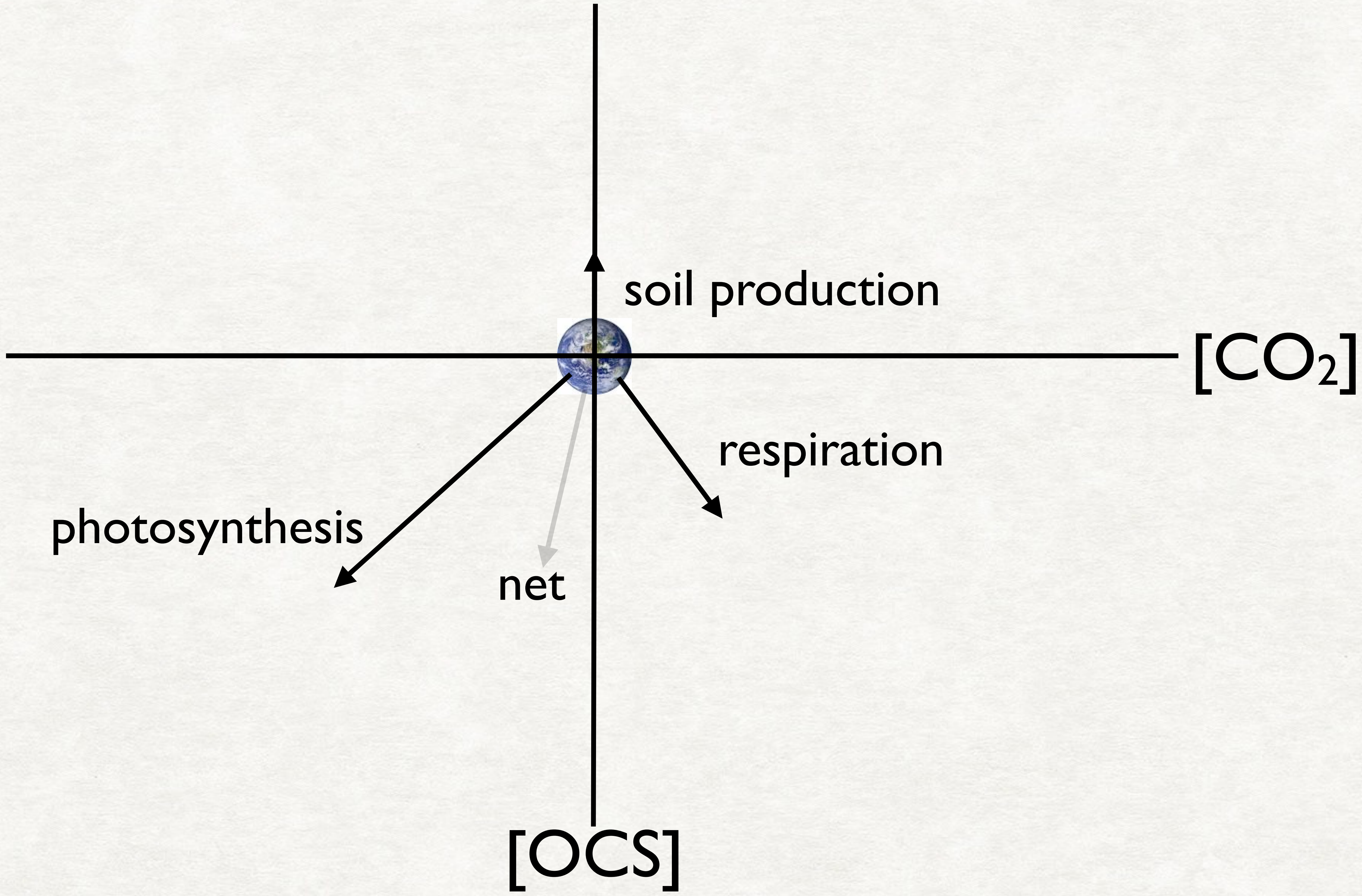




Night air is different than day air.

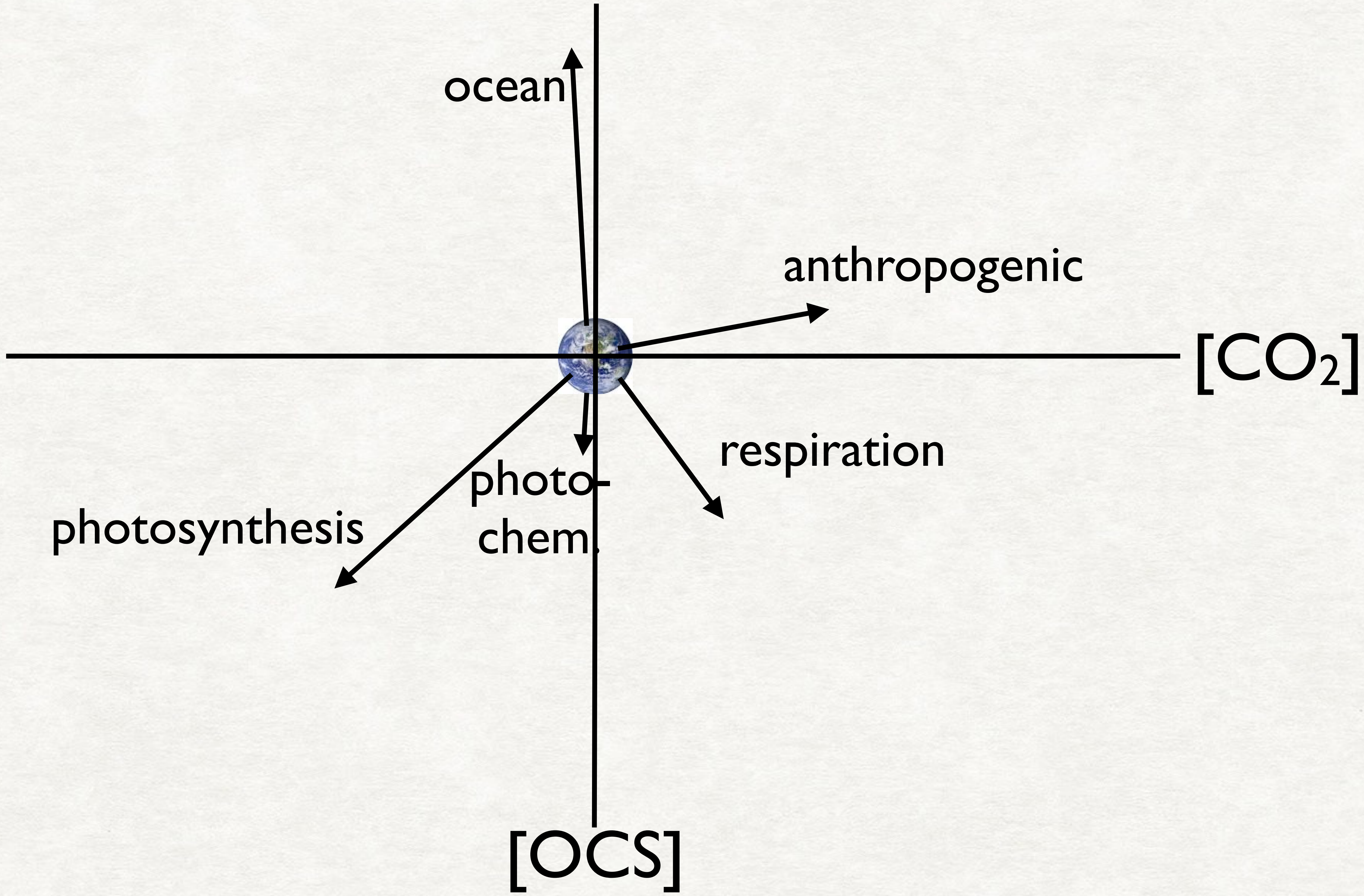
	CO2	OCS
day	↓	↓
night	↑	↓

Exchange processes "pull" the atmosphere in different directions in CO_2 - OCS space



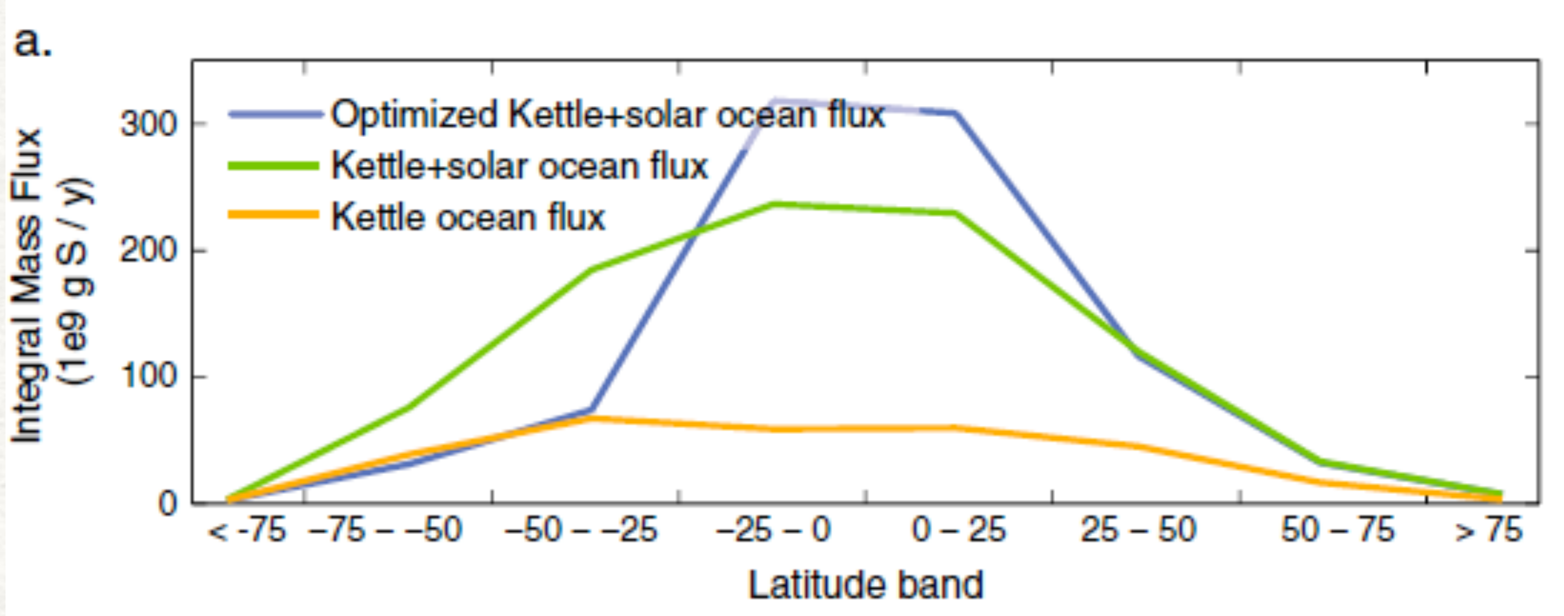
I have only discussed OCS exchange in photosynthesis,
respiration and soil production of OCS will be topics of later discussion.

The atmosphere integrates the impact of all exchanges (global)



A coupled model of the global cycles of carbonyl sulfide and CO_2: A possible new window on the carbon cycle

Joe Berry,[1] Adam Wolf,[2] J. Elliott Campbell,[3] Ian Baker,[4] Nicola Blake,[5] Don Blake,[5] A. Scott Denning,[4] S. Randy Kawa,[6] Stephen A. Montzka,[7] Ulrike Seibt,[8] Keren Stimler,[9] Dan Yakir,[9] and Zhengxin Zhu[6]



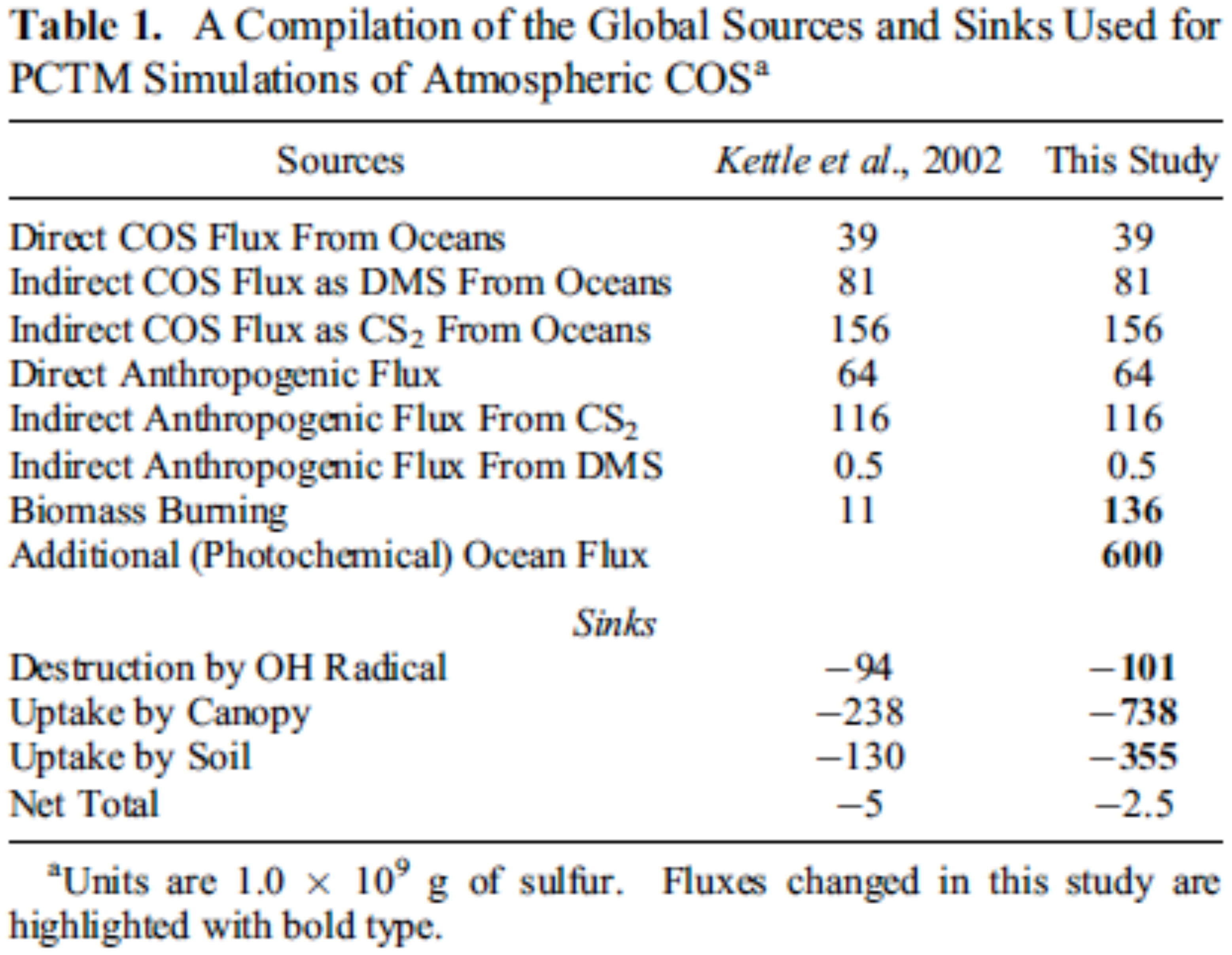
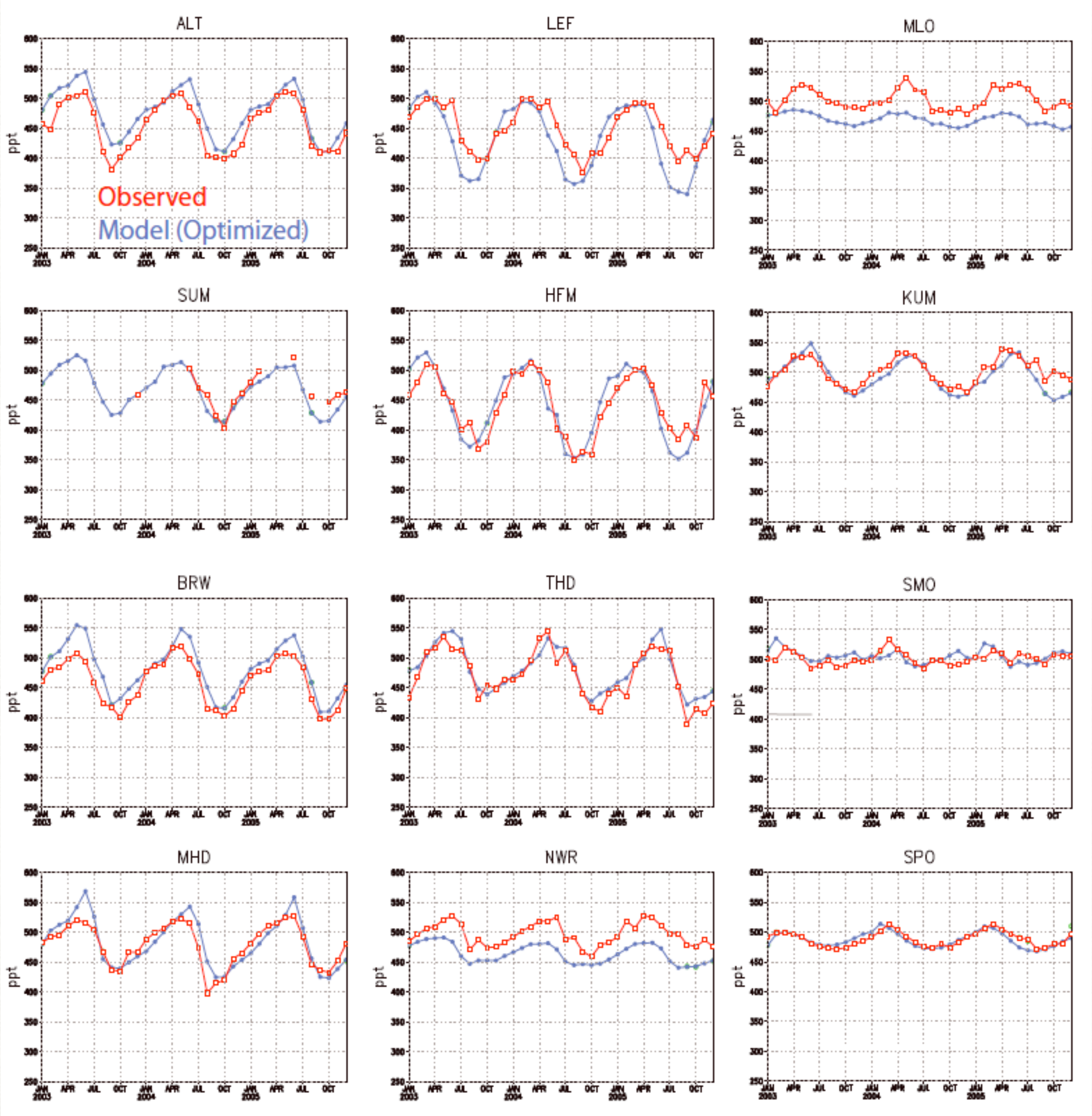


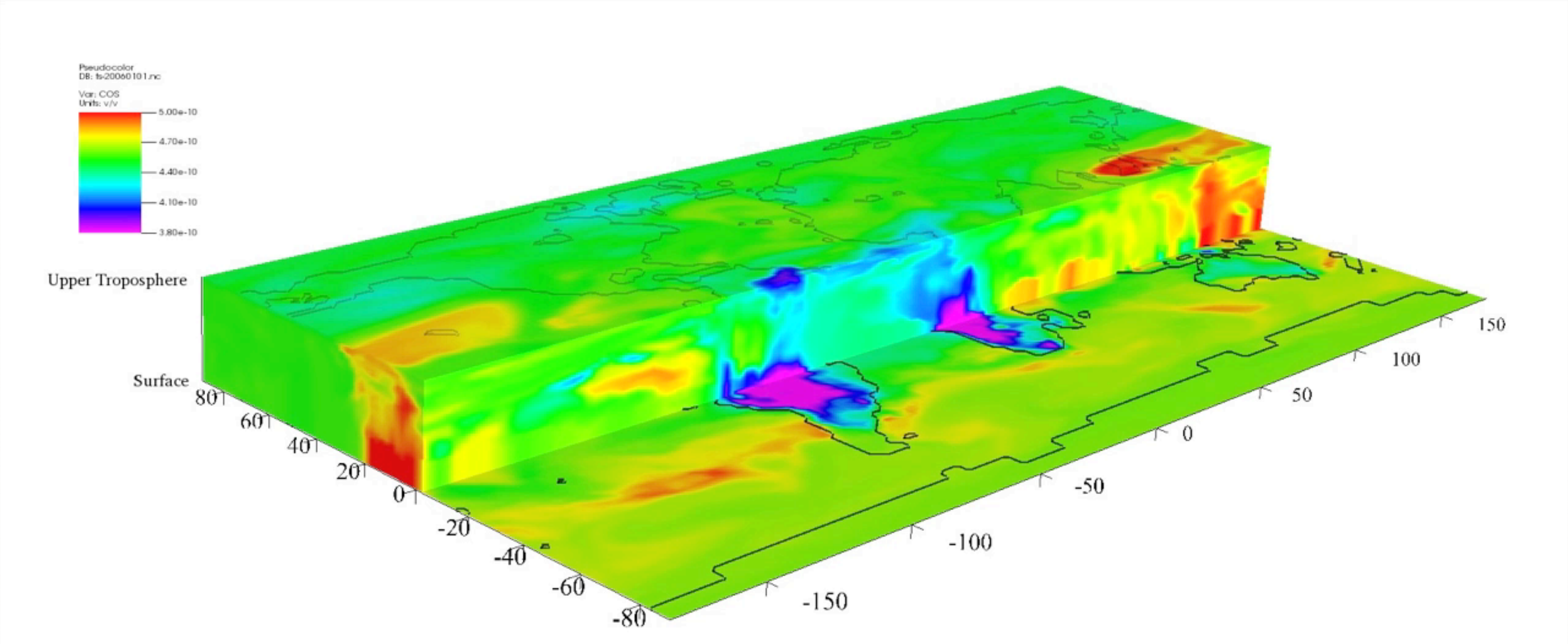
Table 1. A Compilation of the Global Sources and Sinks Used for PCTM Simulations of Atmospheric COS[a]

Sources	*Kettle et al.*, 2002	This Study
Direct COS Flux From Oceans	39	39
Indirect COS Flux as DMS From Oceans	81	81
Indirect COS Flux as CS_2 From Oceans	156	156
Direct Anthropogenic Flux	64	64
Indirect Anthropogenic Flux From CS_2	116	116
Indirect Anthropogenic Flux From DMS	0.5	0.5
Biomass Burning	11	**136**
Additional (Photochemical) Ocean Flux		**600**
Sinks		
Destruction by OH Radical	−94	**−101**
Uptake by Canopy	−238	**−738**
Uptake by Soil	−130	**−355**
Net Total	−5	−2.5

[a] Units are 1.0×10^9 g of sulfur. Fluxes changed in this study are highlighted with bold type.



[OCS] vertical slice at Equator



Jim Stinecipher and Elliott Campbell (unpublished)

Carnegie Science

Conclusions:

- COS has potential to help estimate GPP and by difference Respiration at site-, regional-, and global-scales.
- COS should be highly correlated with solar induced fluorescence.
- Our work has led to a substantial revisions of the global budget of COS.
- We posit the existence of a large source in the tropical oceans. There is satellite evidence to support this. No *in situ* studies of mechanism.
- Models of soil uptake, soil production, anthropogenic production and ocean production (at least) are needed to complete the cycle.
- Inclusion of COS in data assimilation systems may help to understand the basis of inferred changes in net CO_2 exchange over the continents.