New Methods for Measurement of Photosynthesis from Space

http://www.kiss.caltech.edu/study/photosynthesis/

Keck Institute for Space Studies

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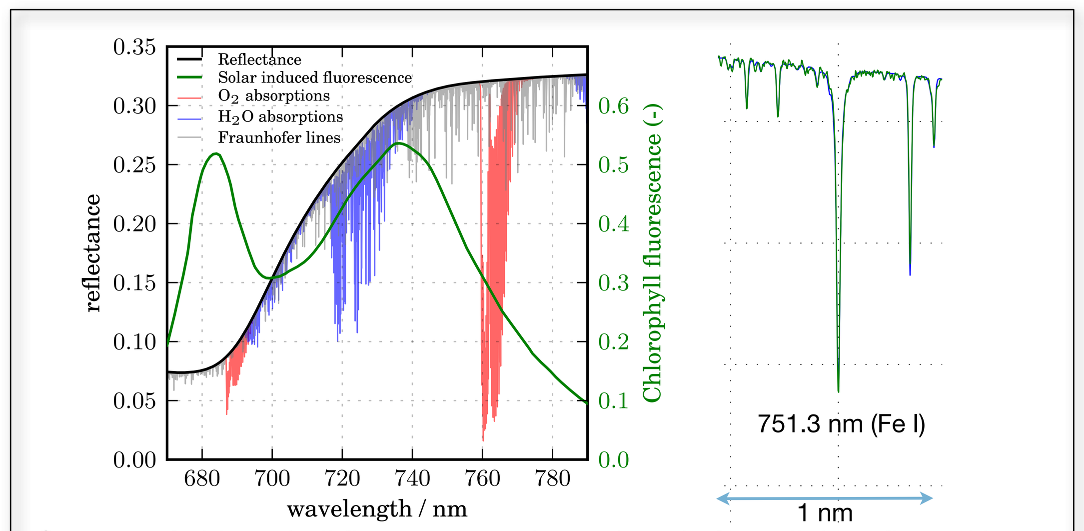
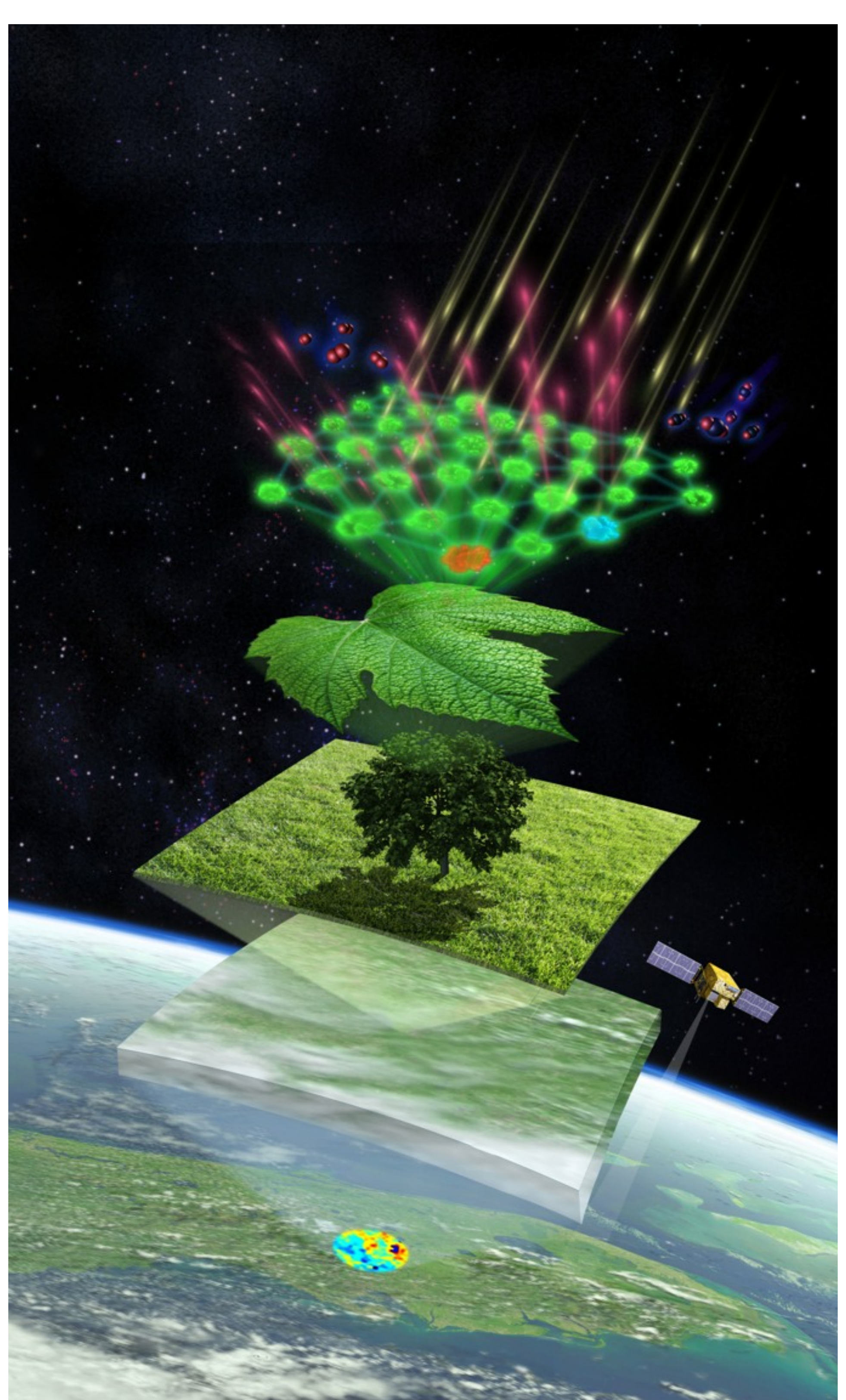
Introduction

Chlorophyll Fluorescence is an established tool in photosynthesis research. (A search for "chlorophyll fluorescence" on Google Scholar brings up half as many papers as "remote sensing" and 5x as many as "vegetation index"). It is widely used as an alternative to the exchange of gases for measurement of photosynthetic rate, and the paper describing this method (Genty et al. 1989) has >4,000 citations.

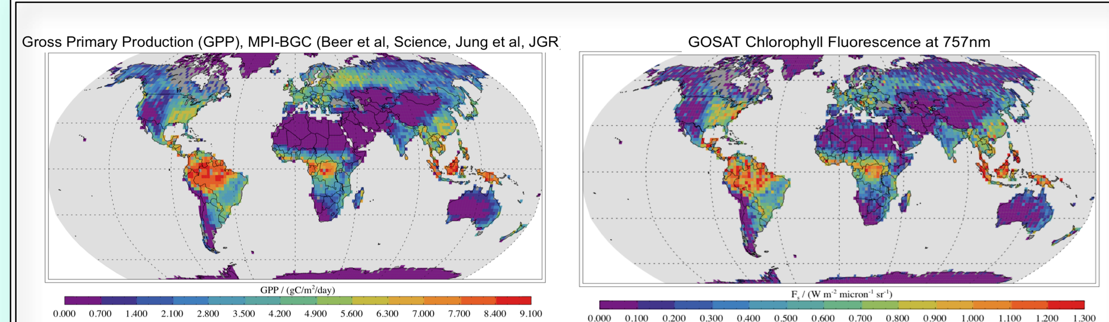
It has mostly been applied at the leaf and chloroplast scale. Prior to 2009, it had not been used to study photosynthesis at regional and global scales because it was difficult to separate light emitted as fluorescence from reflected sun light. This problem was solved independently by Joanna Joiner at GSFC and Christian Frankenberg at JPL by taking advantage of a spectrometer on the Japanese satellite, GOSAT that can resolve absorption lines in the solar spectrum known as Fraunhofer lines.



Spectra of chlorophyll fluorescence (green) and of sun light reflected by a leaf (black). The red and blue lines punctuating the reflected light are due to molecular oxygen and water vapor in Earth's atmosphere. The grey lines are due to constituents of the solar atmosphere. The depth of Fraunhofer lines (relative to the base line) is not changed by reflection or scattering. At the right is a blow-up of a single Fraunhofer line. The fraction of fluorescence light (no lines) mixed with reflected sunlight can be detected by analysis of the line depths.



Opportunistic retrievals from GOSAT and GOME-2 are now available, but neither satellite is optimized for fluorescence measurement. The FLEX mission proposed to the ESA would be the first to be designed specifically for this purpose, and an active program in fluorescence research exists (mostly in Europe) to support this mission.



Early studies showed a very good correlation between the intensity of solar induced fluorescence (SIF) and modeled GPP (Frankenberg et al., 2011).

To understand the relationship between SIF and GPP we need to dispose of two myths:

- **Myth 1**. Textbooks lead many to predict that fluorescence will go **up** when photosynthesis is inhibited (the light-use-efficiency (LUE) goes down).

  Mythbuster. Theory predicts and and observations confirm that fluorescence goes **down** together with LUE in full sun light (conditions of the satellite measurements).

- **Myth 2**. Many familiar with laboratory studies think that little can be learned from fluorescence measurements under constant light.

  Mythbuster. Significant changes in passive fluorescence are observed and these provide useful information on photosynthesis.

How does it work? Solar induced fluorescence (SIF) can be expressed as:

$$\mathrm{SIF} = \mathrm{PAR} \cdot \mathrm{fPAR} \cdot \epsilon_F$$

where PAR is the incident photosynthetically active light, fPAR is the fractional absorption of that light, and ε_F is the quantum yield for fluorescence emission (corrected for optical effects in the canopy).

This is analogous to a commonly used expression for gross primary productivity, (GPP);

$$\mathrm{GPP} = \mathrm{PAR} \cdot \mathrm{fPAR} \cdot \epsilon_P$$

where ε_P is the LUE for photosynthesis. These expressions can be combined to eliminate PAR and fPAR.

$$\mathrm{GPP} = \mathrm{SIF} \cdot \frac{\epsilon_P}{\epsilon_F}$$

If the ratio $\varepsilon_P/\varepsilon_F$ is constant, SIF should be a good proxy for photosynthetic rate whether the variation is by changes in fPAR, PAR or stress. Is it?

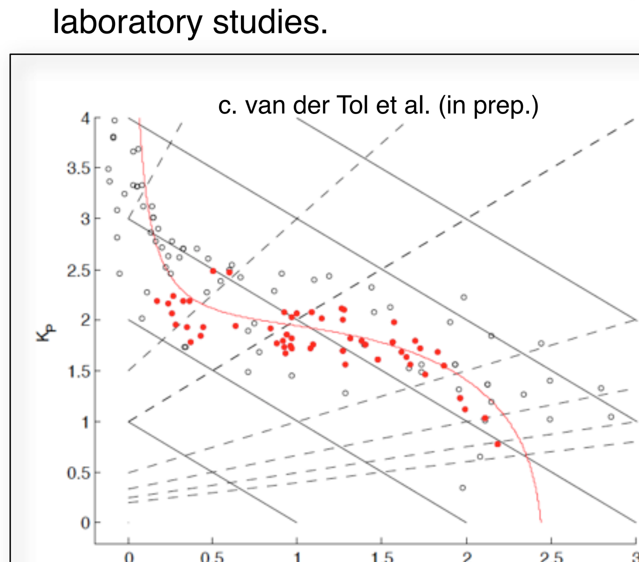
From first principles:

$$\frac{\epsilon_P}{\epsilon_F} \approx \frac{\Phi_P}{\Phi_F}$$
$$\Phi_F = k_F/(k_F + k_D + k_P + k_N)$$
$$\Phi_P = k_P/(k_F + k_D + k_P + k_N)$$
$$\Phi_P = \Phi_F \cdot k_P/k_F$$

Rate constants

$k_F =$ fluorescence
$k_D =$ radiationless decay
$k_P =$ photochemistry
$k_N =$ non-photochem.

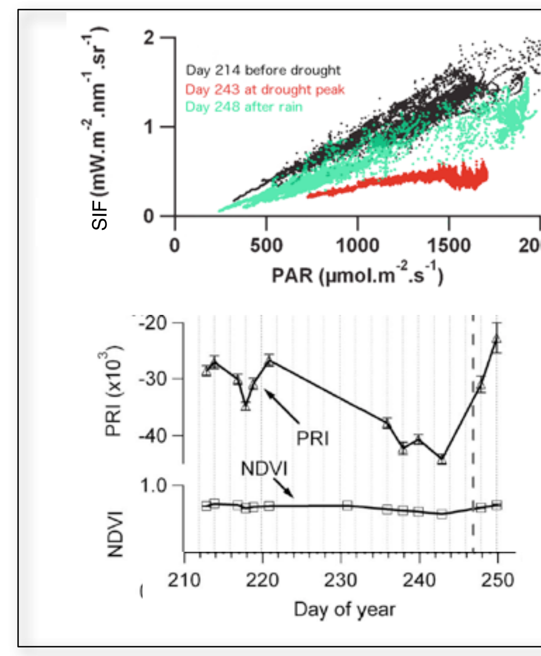
The light use efficiencies are analogous to the photon yields for photochemistry (Φ_P) and fluorescence (Φ_F) given in the expressions above. During photosynthesis the rate constants k_P and k_N are changed by feedback mechanisms that regulate the rate of electron transport, whereas k_D & k_F are constant. The solution to these equations shows that the ratio $\varepsilon_P/\varepsilon_F$ should be constant if the ratio k_P/k_F is constant. This can be tested by following the behavior of k_P in laboratory studies.



Measurements of k_P and k_N were conducted on leaves during studies of CO_2 exchange. Under strong illumination (red points, left) feedback tends to keep k_P about constant. Thus, fluorescence from PSII and photosynthesis at the leaf scale change in parallel in high light. A contribution of fluorescence from PSI is also included in SIF. These have different but overlapping spectra. Ideally these should be quantified separately.

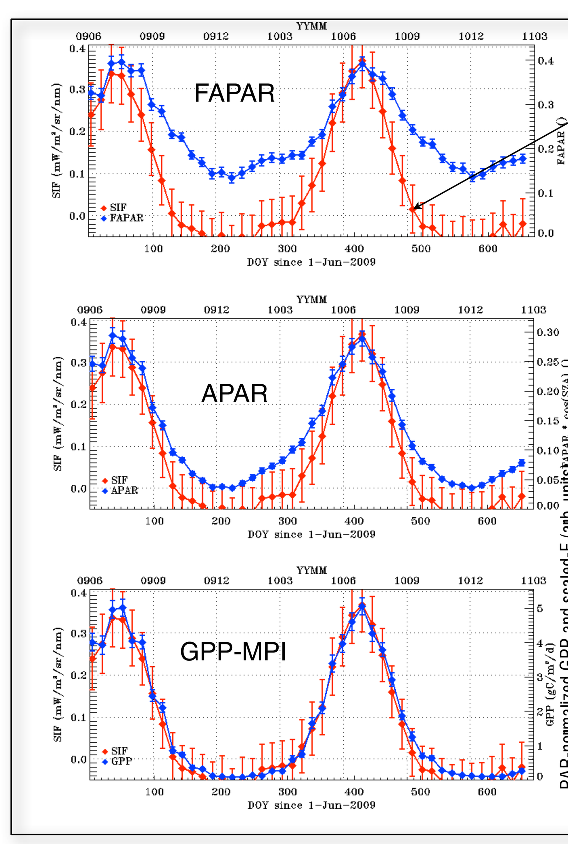
★ Studies of photosynthetic mechanisms support the use of satellite measured SIF as a proxy for GPP, but much more work is required to quantify the role of leaf biochemistry and canopy optics on the observed SIF. Inversion of SIF to obtain FPAR and V_{cmax} seems plausible. The ability to simulate SIF has been added to SIB3 and CLM4 enabling comparison of model output with satellite retrievals.

Water Stress



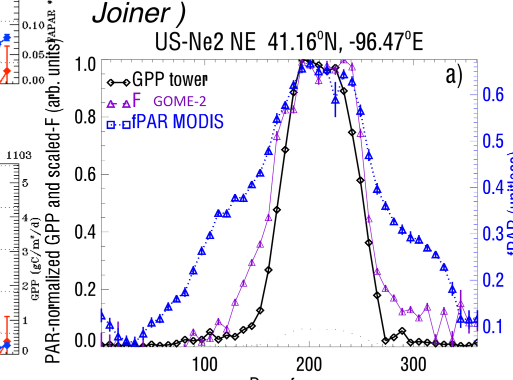
SIF monitored from above a rain-fed sorghum field before during and after a drought event. The slope of SIF vs PAR is ε_F. ε_F was high on day 214, had declined to half by day 243, and it is almost completely recovered 5 days later following a rain event. The PRI showed similar changes, but NDVI did not change. Photosynthesis was not measured but it probably declined during the drought. This is interpreted as an increase in non-photochemical quenching (k_N) due to drought stress. (from Daumard et al., 2009; see also a new paper, Lee et al. coming on-line in Proc. of the Royal Society, on May 1).

The Seasonal Cycle

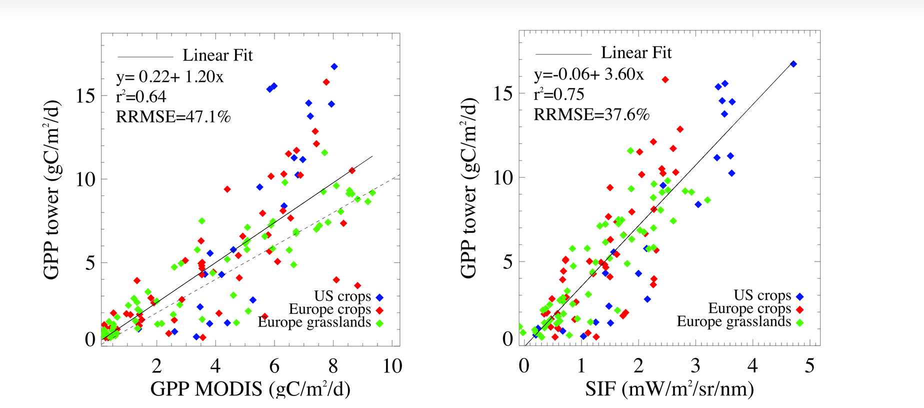


Left, Biweekly temporal profiles of SIF from GOSAT together with GPP, APAR, and FAPAR averaged for all vegetated areas at latitude >45°N (C. Frankenberg (unpublished).

Below, observed seasonal GPP (corn or soybeans) at a flux site (Mead, NE) compared with SIF (GOME-2) and fFPAR MODIS (J. Joiner)

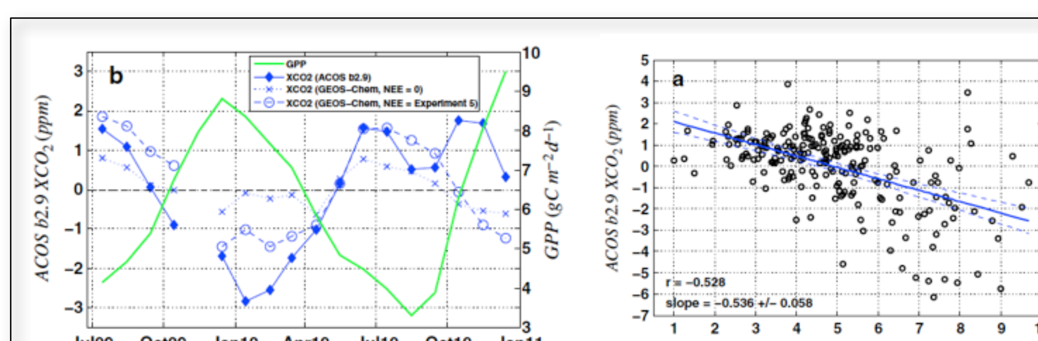


Photosynthetic Rate



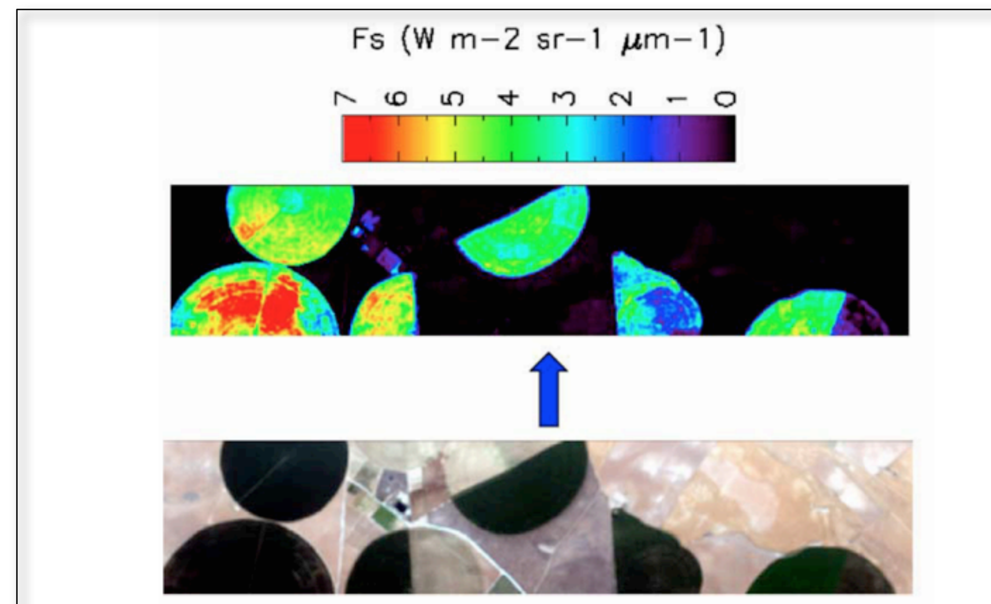
Tower fluxes indicate higher GPP in some regions than expected based on model output. Analysis of SIF from GOME-2 shows less scatter in comparison to the tower data and captures the higher GPP, perhaps indicating a path for model improvement (Luis Guanter in preparation).

GPP and CO_2 concentration



GOSAT measurements of column CO_2 over Amazonia correlate with GPP estimated from GOSAT SIF (Parazoo et al., 2013 GRL in press).

★ It appears that SIF measurements can provide useful feedback for models.



Composite and SIF images taken with the CASI sensor (Guanter et. al. 2007). The circles are center pivot irrigation plots. SIF measurements see only the vegetated surfaces, and their respective radiances. Thus, SIF can be summed linearly over heterogenous surfaces. This is more difficult to do with reflectance based vegetation indices. This is important because fluorescence retrievals have a large footprint (GOME-2 has a 40 x 80 km footprint; GOSAT 10 km).

Conclusions

★ SIF shows promise for improving the representation of photosynthesis and its role in Earth System models.

★ SIF captures changes in photosynthesis that are associated with changes in greenness **AND** changes that are associated with LUE. While models can do this, other information (*eg.* temperature, soil moisture, precipitation, canopy properties) is required.

★The satellites seem to be reporting on molecular events in the chloroplast membranes in the instrument footprint. This represents a unique opportunity to connect with scientists who work at the molecular scale.

★ There is still much to learn about the linkage of SIF to molecular mechanisms and to GPP - especially the optics of chloroplast to top of canopy scaling.

★ SIF retrievals (using Fraunhofer lines) are more robust to interferences from atmospheric scattering, thin clouds and spatial scaling issues than reflectance approaches.

★ New instrumentation capable of making comparable measurements to the satellites are needed for field research.

★ The Photochemical Reflectance Index appears to co-vary with SIF and this measurement can be synergistic.

★ See also Poster #13, Session 1-B, Tuesday afternoon.

Recent Publications

1.Daumard, F., Champagne, S., Fournier, A., Goulas, Y., Ounis, A., Hanocq, J. F., & Moya, I. (2010).. Geoscience and Remote Sensing, IEEE Transactions on, 48(9), 3358–3368. doi: 10.1109/TGRS.2010.2046420

2.Frankenberg, C., Butz, A., and Toon, G. C. (2011). Geophysical Research Letters, 38(3), L03801. doi:10.1029/2010GL045896.

3.Frankenberg, C., Fisher, J., Worden, J., Badgley, G., Saatchi, S., Lee, J.-E., et al. (2011).. Geophysical Research Letters, 38(17), L17706.

4.Frankenberg, C., O'Dell, C., Guanter, L., and McDuffie, J. (2012). Atmospheric Measurement Techniques, 5(8), 2081–2094. doi:10.5194/amt-5-2081-2012.

5.Genty, B., Briantais, J.-M., & Baker, N. R. (1989). BBA - General Subjects, 990(1), 87–92. doi:10.1016/S0304-4165(89)80016-9

6.Guanter, L., Alonso, L., Gómez-Chova, L., Amorós-López, J., Vila, J., & Moreno, J. (2007). GEOPHYSICAL RESEARCH LETTERS, 34(8), L08401. doi:10.1029/2007GL029289

7.Guanter, L., Frankenberg, C., Dudhia, A., Lewis, P. E., Gómez-Dans, J., Kuze, A., et al. (2012). Remote Sensing of Environment, 121, 236–251. doi:10.1016/j.rse.2012.02.006

8.Guanter, L., Rossini, M., Colombo, R., Meroni, M., Frankenberg, C., Lee, J.-E., and Joiner, J. (2013). Remote Sensing of Environment, 133, 52–61. doi:10.1016/j.rse.2013.01.017

9.Joiner, J., Yoshida, Y., Vasilkov, A. P., Yoshida, Y., Corp, L. A., and Middleton, E. M. (2011). Biogeosciences, 8(3), 637–651. doi:10.5194/bg-8-637-2011.

10.Joiner, J., Yoshida, Y., Vasilkov, A. P., Middleton, E. M., Campbell, P. K. E., Yoshida, Y., et al. (2012). Atmospheric Measurement Techniques, 5(4), 809–829. doi:10.5194/amt-5-809-2012.

11.Joiner, J., Guanter, L., Lindstrot, R., Voigt, M., Vasilkov, A. P., Middleton, E. M., et al. (2013). Atmospheric Measurement Techniques Discussions, 6(2), 3883–3930. doi:10.5194/amtd-6-3883-2013

12.Lee, J. E., Frankenberg, C., van der Tol, C., Berry, J., Guanter, L., Fisher, J., Boyce, K., Morrow, E., Asefi, S., Badgley, G., Saatchi, S. (in press). Proceedings of the Royal Society B.

13.Parazoo, N. C., Bowman, K., Frankenberg, C., Lee, J.-E., Fisher, J. B., Worden, J., et al. (2013). Geophysical Res. Lett., n/a–n/a. doi:10.1002/grl.50452