Angular Normalization of Satellite Observations of Sun-induced Chlorophyll Fluorescence as an Improved Proxy of Vegetation Productivity

Jing M. Chen[1,2], Liming He[1], Shuren Chou[2], Gang Mo[1], Joanna Joiner[3], Hua Yu[2], Yongguang Zhang[2], Weimin Ju[2], and Ze Wang[1]

[1]Department of Geography University of Toronto, Canada
[2]International Institute of Earth System Science Nanjing University, China
[3]NASA Goddard Space Flight Center

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University of Toronto

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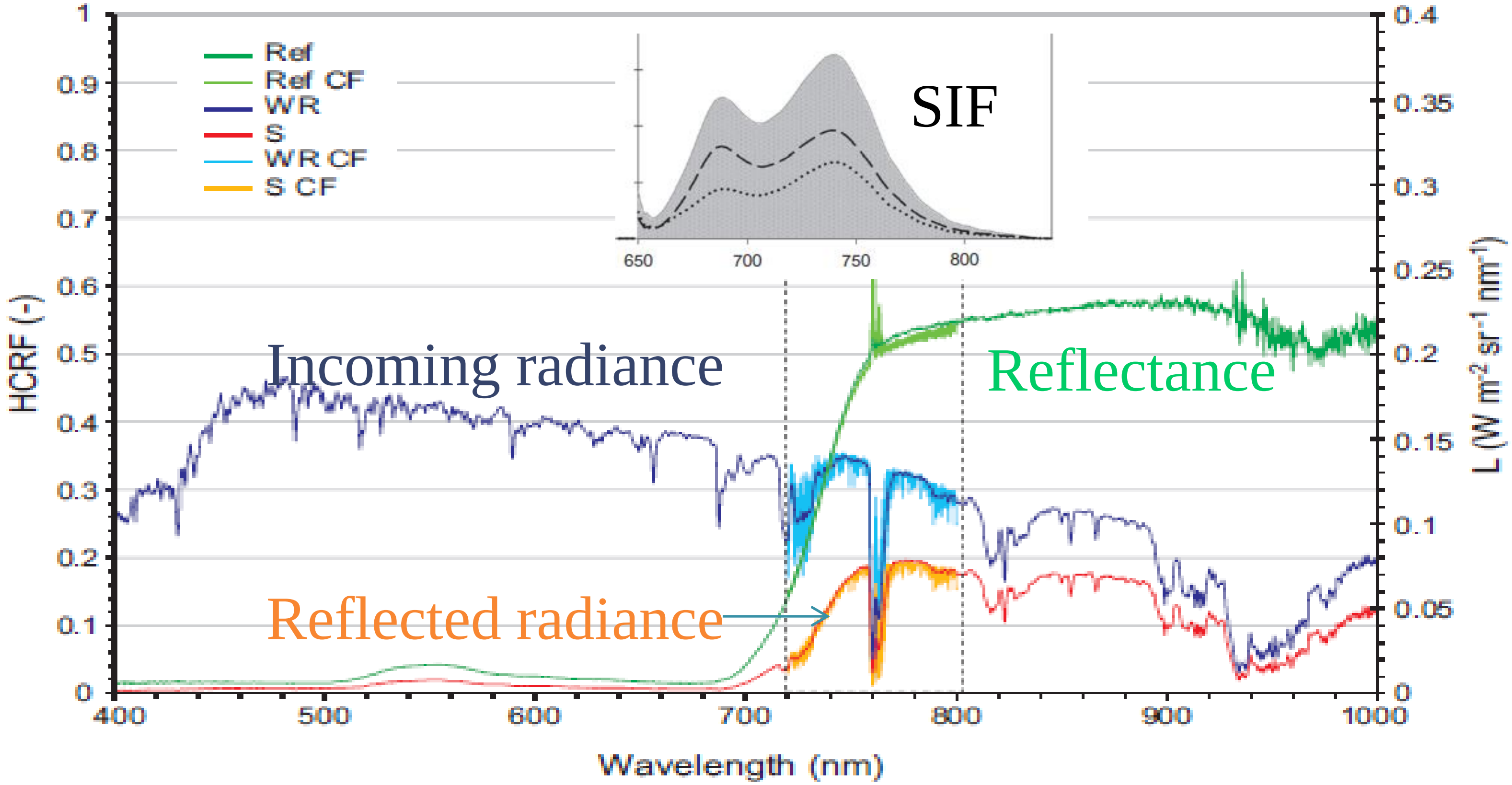
What is Sun-induced Chl Fluorescence (SIF)?

Part (~1%) of photosynthetically active radiation absorbed by leaf chlorophyll is emitted in longer wavelengths as SIF.



Colombo et al., 2016, *Annali Di Botanica*

Satellite Sensors That Measure SIF

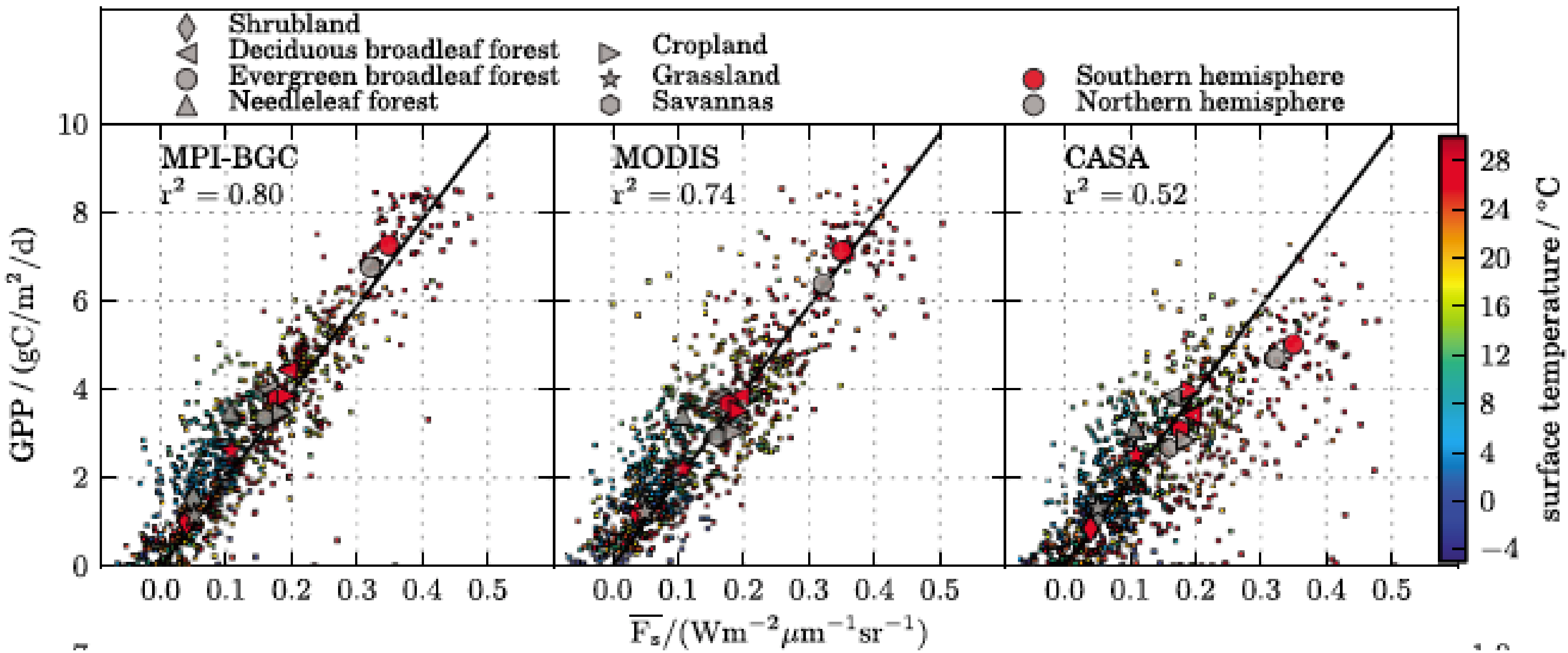
Launch: July 2014
Footprint: 1.29 km × 2.25 km
Cross-Track: <±1°

Launch: January 2009
Footprint: 10.5 km
Cross-Track: ±35°

Launch: October 2006
Footprint: 80 × 40 km
Cross-Track: ±54°

Correlation Between Chlorophyll Fluorescence and GPP

GOSAT, 2009, Annual Total, Spatial Correlation

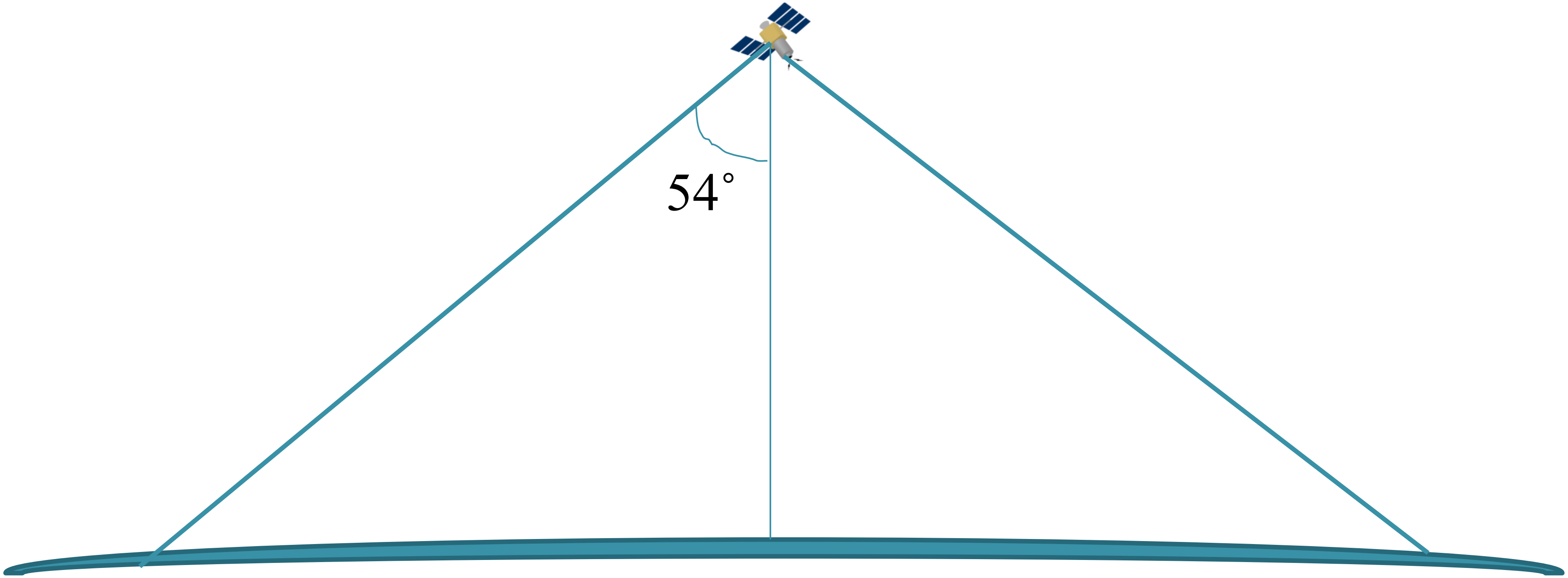


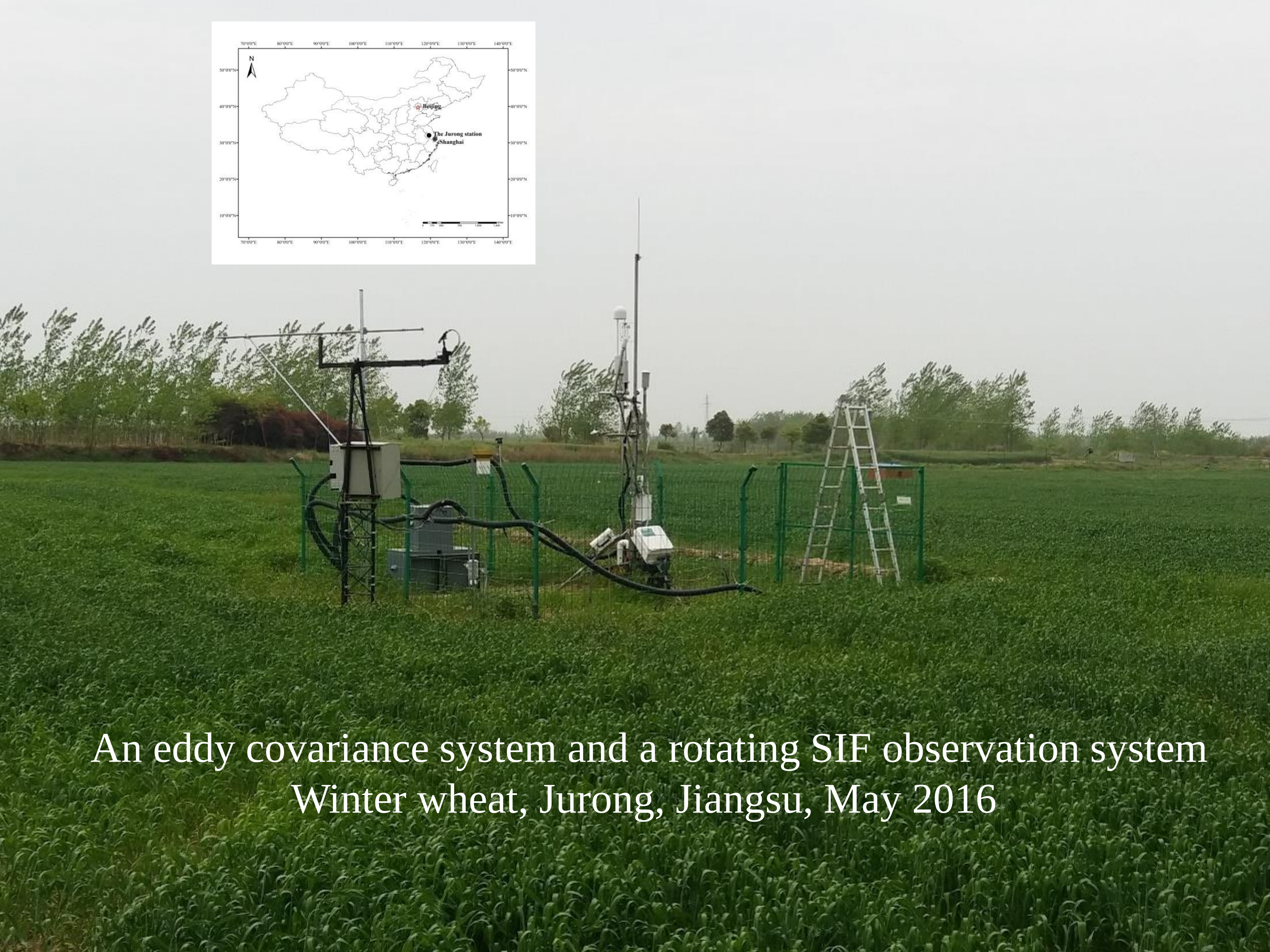
$$\overline{F_s} = F_s / \cos(SZA(t_0)) \cdot \int_{t=t_0}^{t=t_0+1} \cos(SZA(t))dt$$

Frankenberg et al. 2011, *GRL*

Questions

1. **Should we be concerned about the BRDF of SIF measurements?**

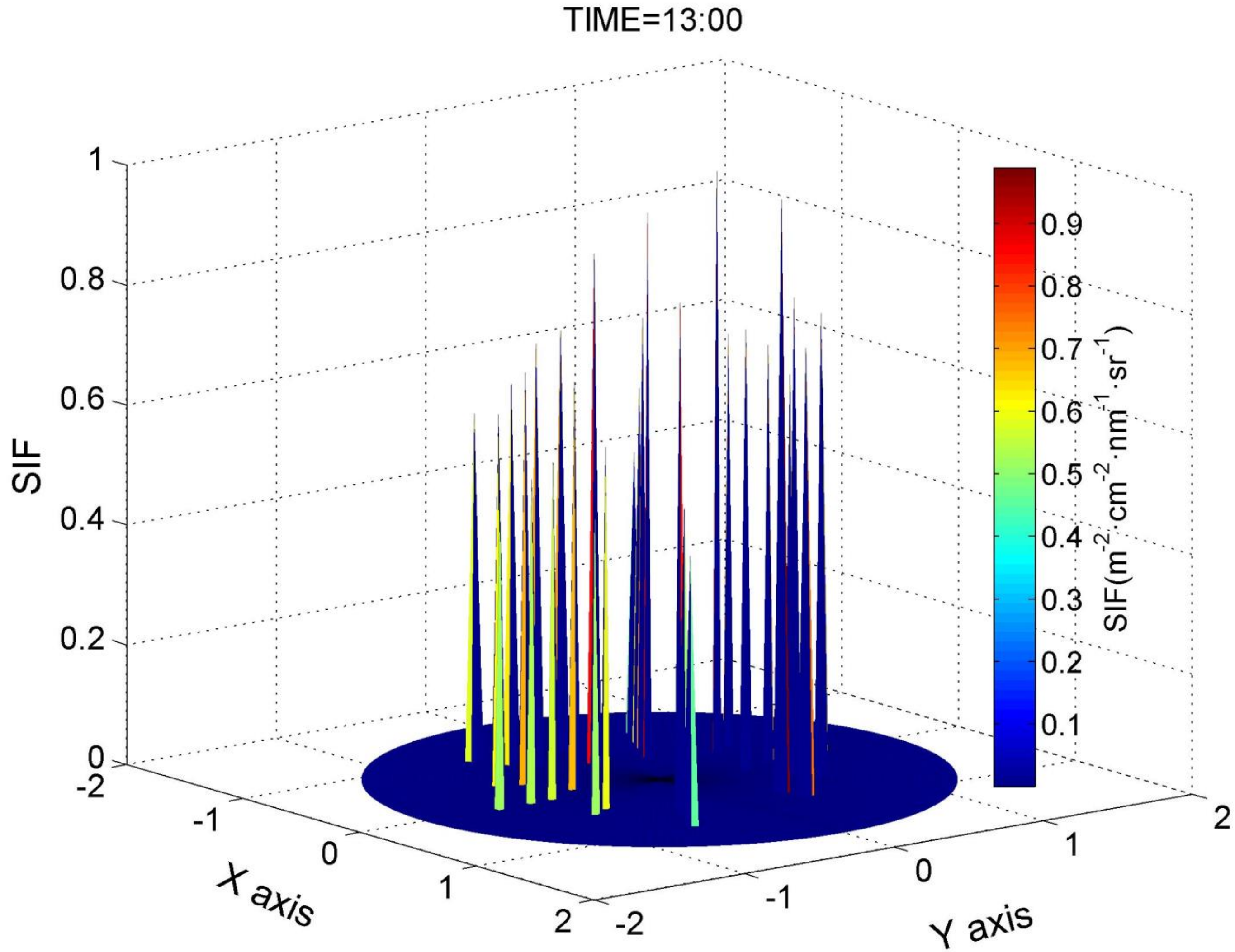




An eddy covariance system and a rotating SIF observation system
Winter wheat, Jurong, Jiangsu, May 2016

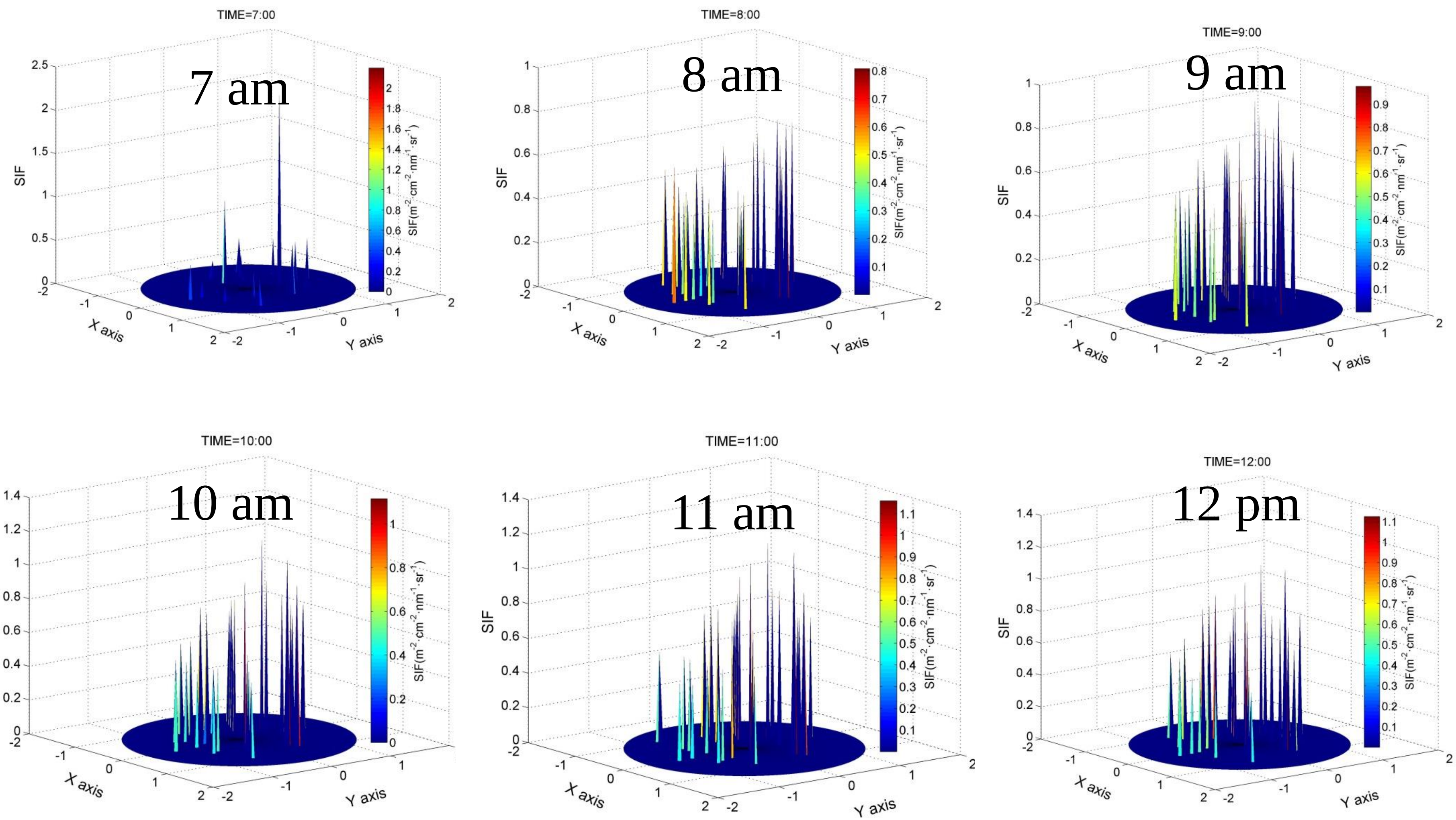
Multi-angle Observations of SIF_{687}

Winter Wheat, Jurong, Jiangsu, China, May 17, 2016



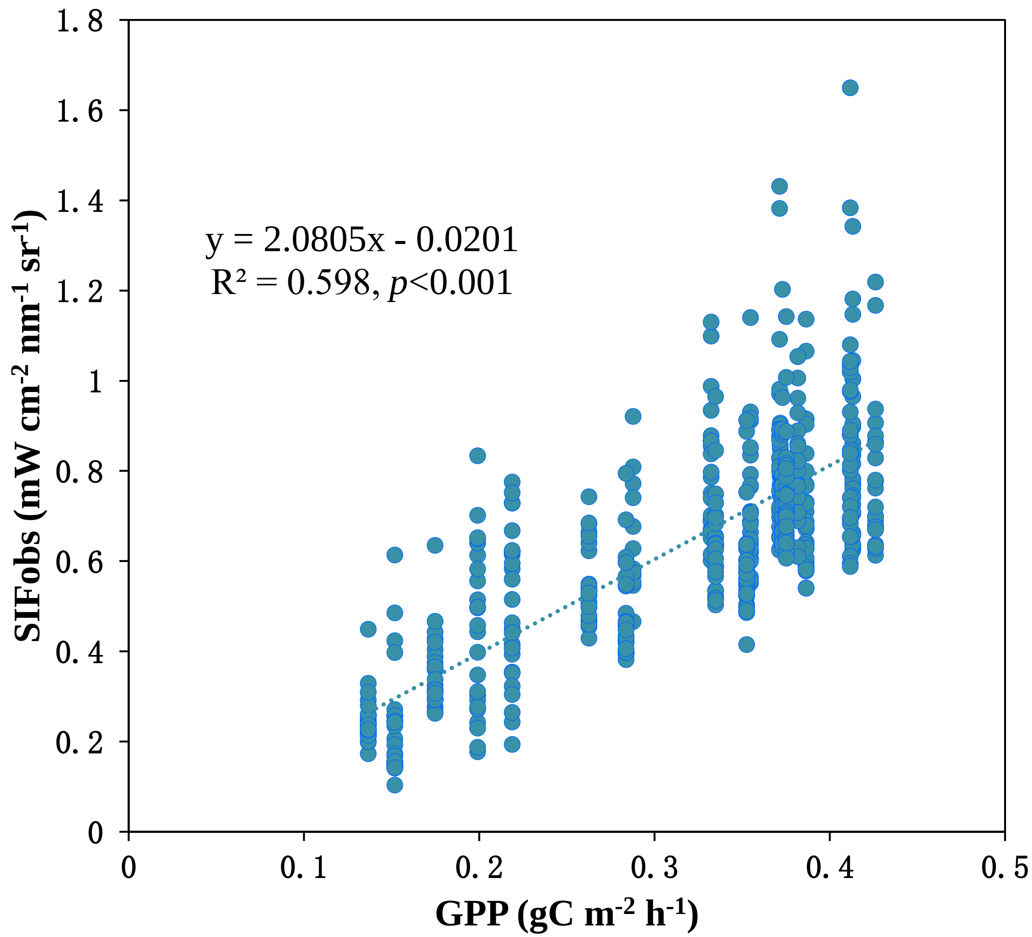
Multi-angle Observations of SIF_{687}

Winter Wheat, Jurong, Jiangsu, China, May 17, 2016



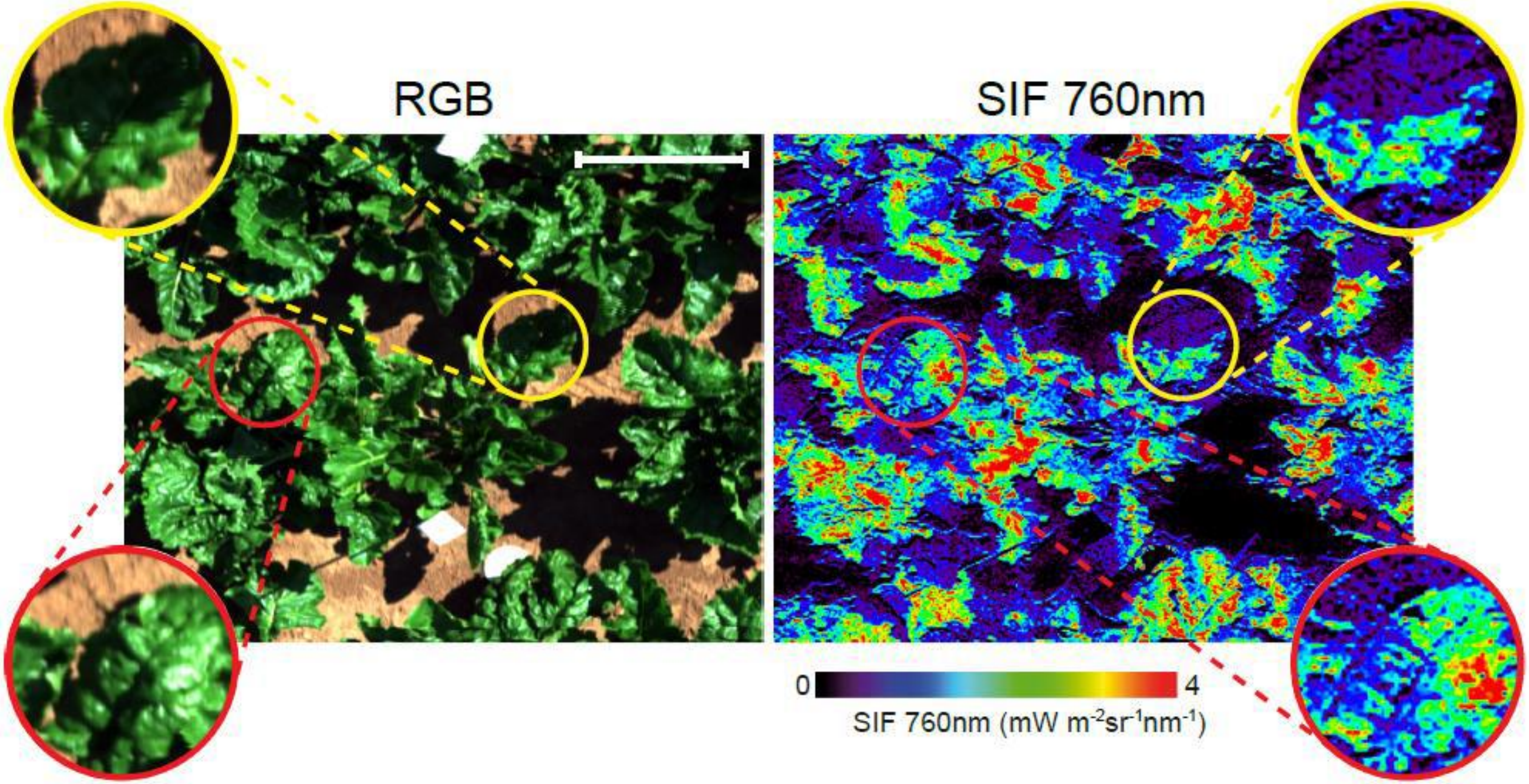
Multi-angle Observations of SIF_{687} vs. GPP

Winter Wheat, Jurong, Jiangsu, China, May 16, 2016



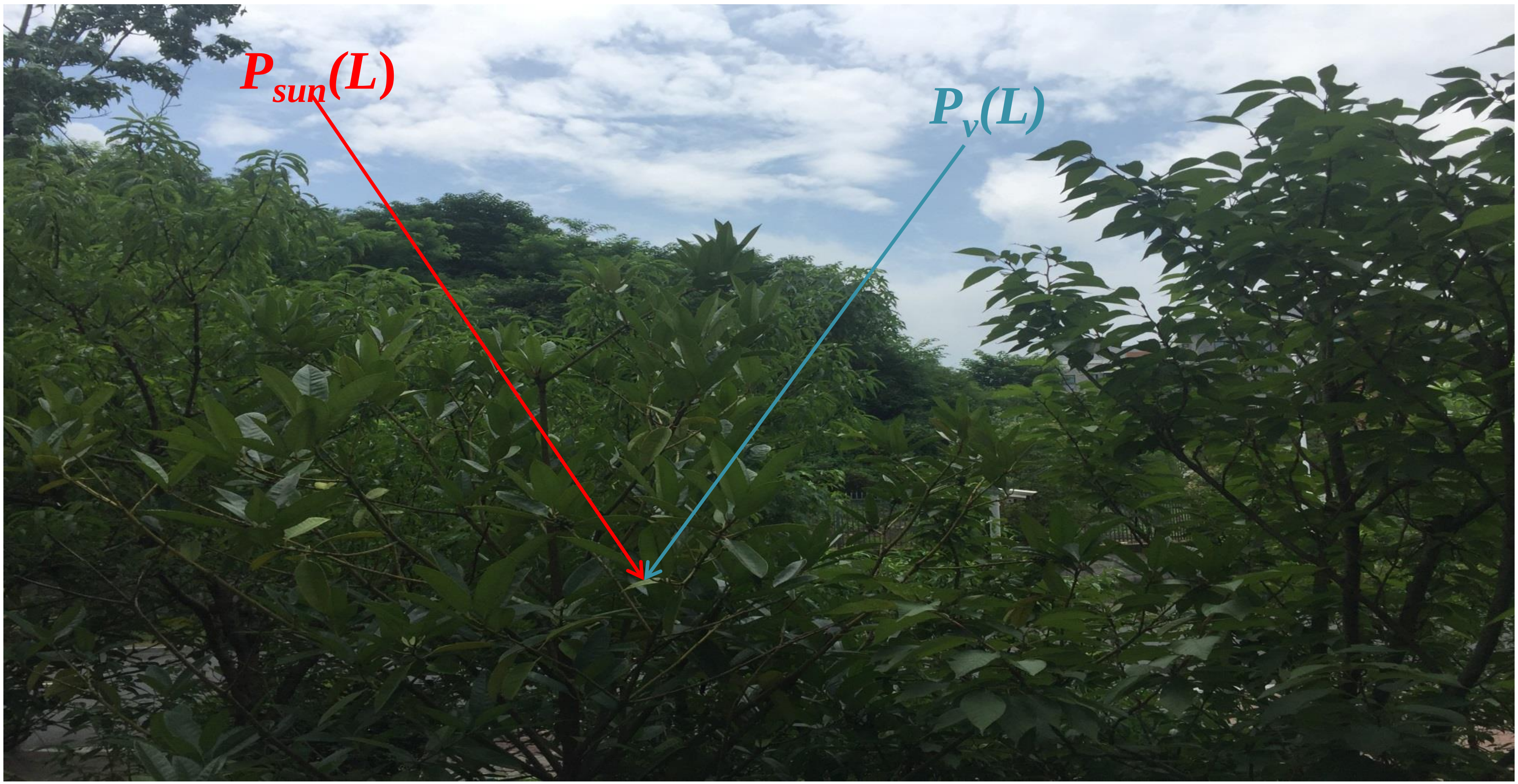
SIF at the Canopy Level

$$SIF(\theta_v, \theta_s, \phi, t) = P_{sun}(\theta_v, \theta_s, \phi) \times SIF_{sun}(t) + P_{sh}(\theta_v, \theta_s, \phi) \times SIF_{sh}(t)$$



Pinto et al., 2016, PCE

Probability of Observing a Sunlit Leaf



Probability of Observing Sunlit Leaves

$P_{sun,v}(L)$: Probability of observing sunlit leaves at the accumulated LAI (L),

$P_{sun}(L)$: Probability of illuminating a leaf at L,

$P_v(L)$: Probability of seeing a leaf at L

$$P_{sun,v}(L) = P_{sun}(L)\, P_v(L)$$

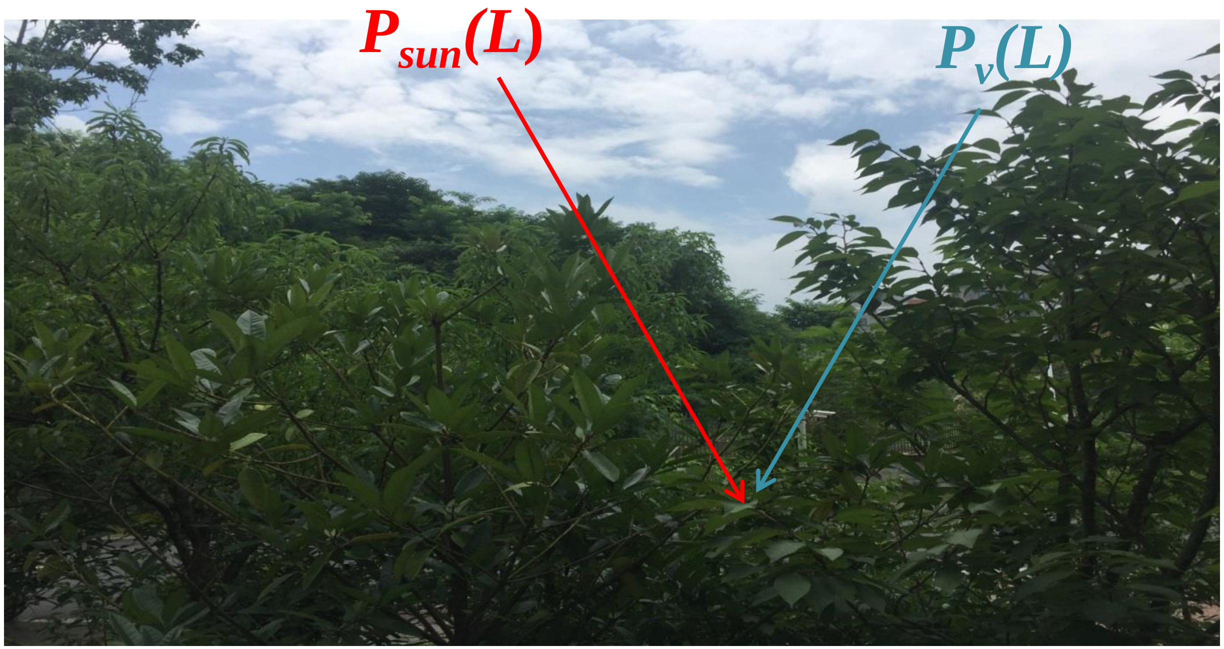
If these two probabilities are independent of each other, i.e., the solar beam and the view line reach the same leaf through different gaps in the canopy. Otherwise, a hotspot function needs to be used.

Probability of Observing Sunlit Leaves

$$L_{sun\_v} = \int_0^h \underbrace{\exp\left[-\frac{0.5}{\mu_s}\cdot\frac{L\Omega}{h}\cdot(h-z)\right]}_{P_{sun}(L)}\cdot\frac{L\Omega}{h}\cdot\underbrace{\exp\left[-\frac{0.5}{\mu_v}\cdot\frac{L\Omega}{h}\cdot(h-z)\right]}_{P_v(L)}dz$$

$$= 2\cdot\frac{\mu_s\mu_v}{\mu_s+\mu_v}\left\{1-\exp\left[-\left(\frac{1}{\mu_s}+\frac{1}{\mu_v}\right)\cdot\frac{L\Omega}{2}\right]\right\}$$

$$\mu_s = \cos\theta_s$$
$$\mu_v = \cos\theta_v$$



Observed SIF is the Sum of the SIF Emissions from Sunlit and Shaded Leaves and Enhancement due to Multiple Scattering

$$SIF_{740} = SIF_s \cdot L'_{sun\_v} + SIF_{sh} \cdot L'_{sh\_v} + \alpha \cdot SIF_s \cdot L_v$$

Sunlit + Shaded + Multiple Scattering

SIF per unit sunlit leaf area:

$$SIF_s = SIF_{740} / \left(L'_{sun\_v} + L'_{sh\_v} / \beta + L_v \cdot \alpha \right)$$

SIF at the hotspot:

$$SIF_h = SIF_{740} \cdot L_{sun} / \left(L'_{sun\_v} + L'_{sh\_v} / \beta + L_v \cdot \alpha \right)$$

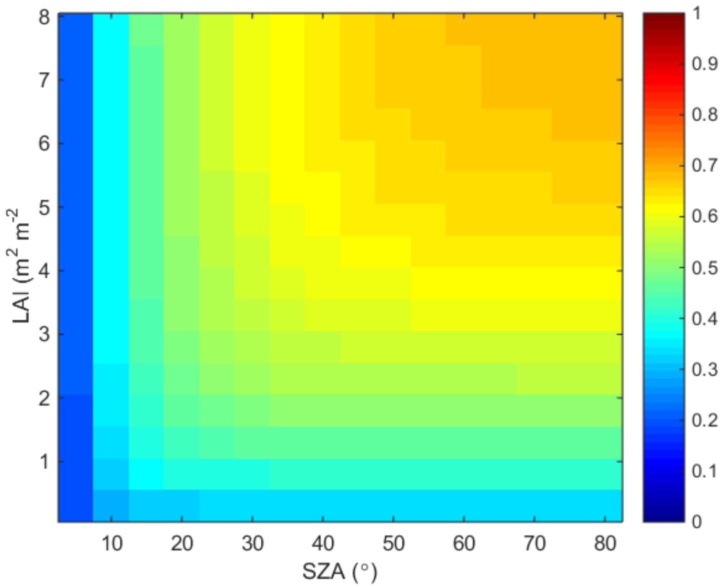
He, Chen et al. (2017, GRL)

Hot Spot Correction to the Probability of Observing Sunlit Leaves

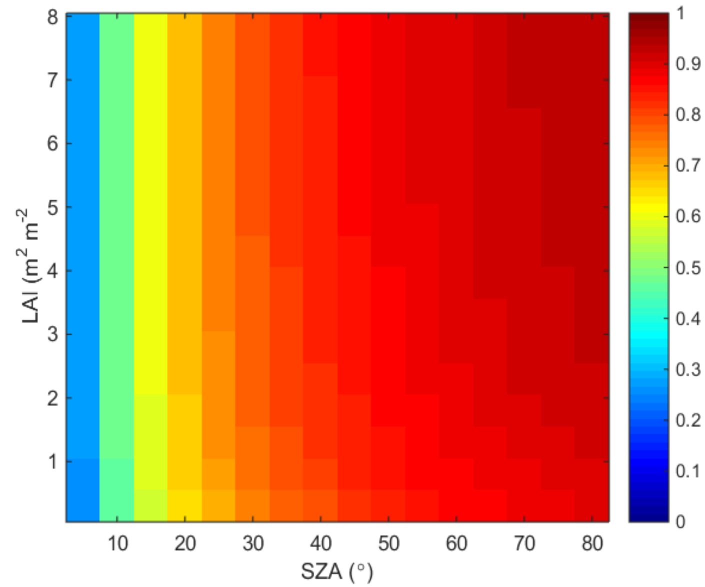
$$L'_{sun\_v} = L_{sun\_v} + \left[L_{sun} - L_{sun\_v} \right] F(\xi)$$

Ratio of the SIF Emissions from Leaves Trapped in the Canopy

Sunlit Leaves



Shaded Leaves



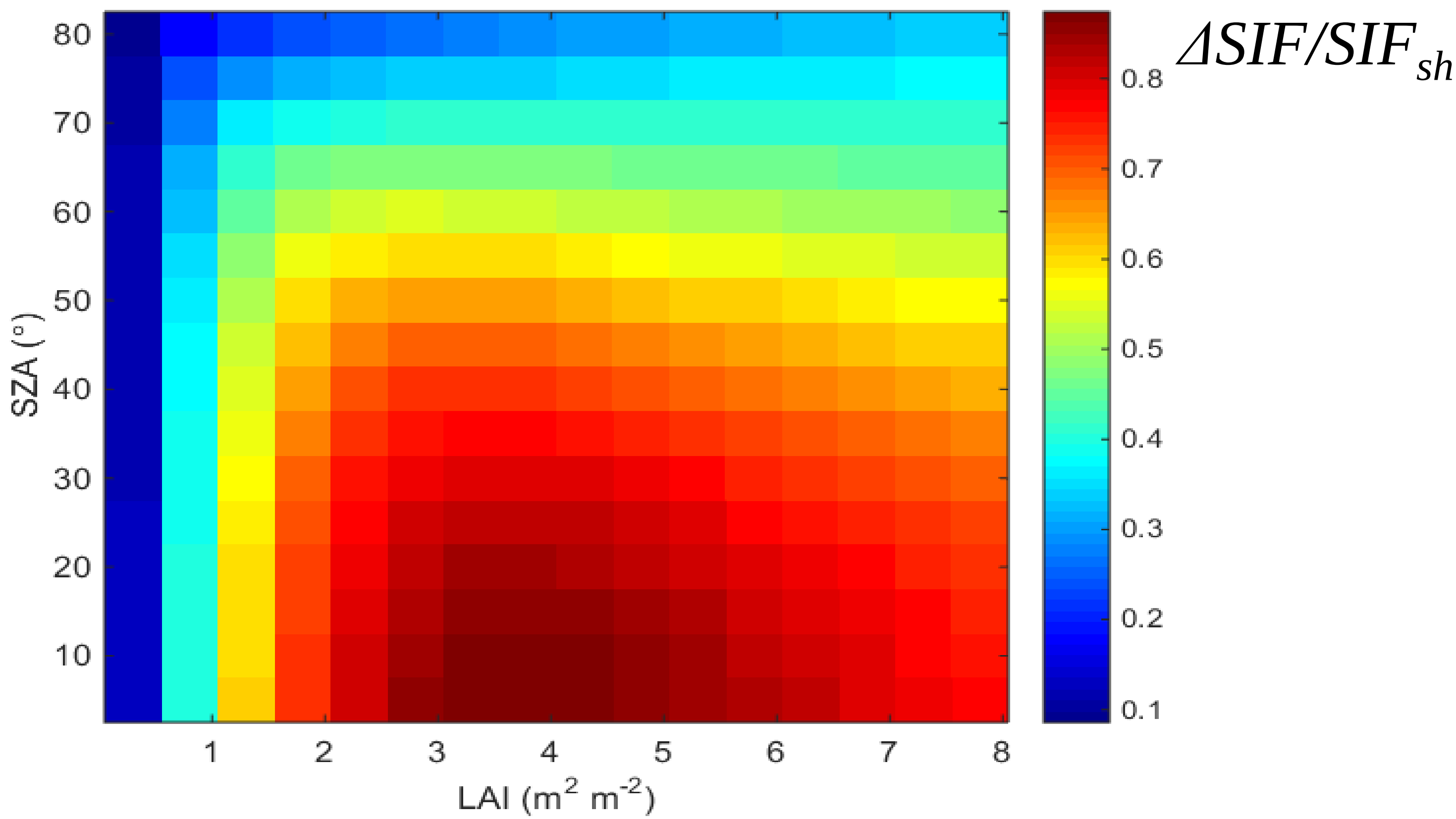
$$SIF_{sun}\cdot\int_0^h\left(1-P_c\left(\frac{L\Omega}{h}\cdot(h-z)\right)\right)\cdot\exp\left[-\frac{0.5}{\mu_s}\cdot\frac{L\Omega}{h}\cdot(h-z)\right]\cdot\frac{L\Omega}{h}dz$$

$$SIF_{sh}\cdot\int_0^h\left(1-P_c\left(\frac{L\Omega}{h}\cdot(h-z)\right)\right)\cdot\left(1-\exp\left[-\frac{0.5}{\mu_s}\cdot\frac{L\Omega}{h}\cdot(h-z)\right]\cdot\right)\frac{L\Omega}{h}dz$$

Enhancement of SIF by Multiple-scattering (MS) for a Shaded Leaf

Assuming that the SIF from a shaded leaf is one unit without MS, the MS contributes 0.1 to 0.87 unit of SIF for different LAIs and solar zenith angles.

$$\alpha = \Delta SIF / SIF_{sun}$$



Total Canopy SIF after Angular Normalization

$$SIF_t = SIF_h + SIF_{sh} \cdot \left(L - L_{sun} \right)$$

Leaf-level Photosynthesis Model

Farquhar's Enzyne-Kinetic Model

$$W_c = V_m \frac{C_i - \Gamma}{C_i + K}$$

$$W_j = J \frac{C_i - \Gamma}{4.5C_i + 10.5\Gamma}$$

$$GPP = \min(W_c, W_j) - R_d$$

Sunlit Leaf

Shaded Leaf

W_c and W_j are temperature/nutrient-limited and light-limited gross photosynthesis rates

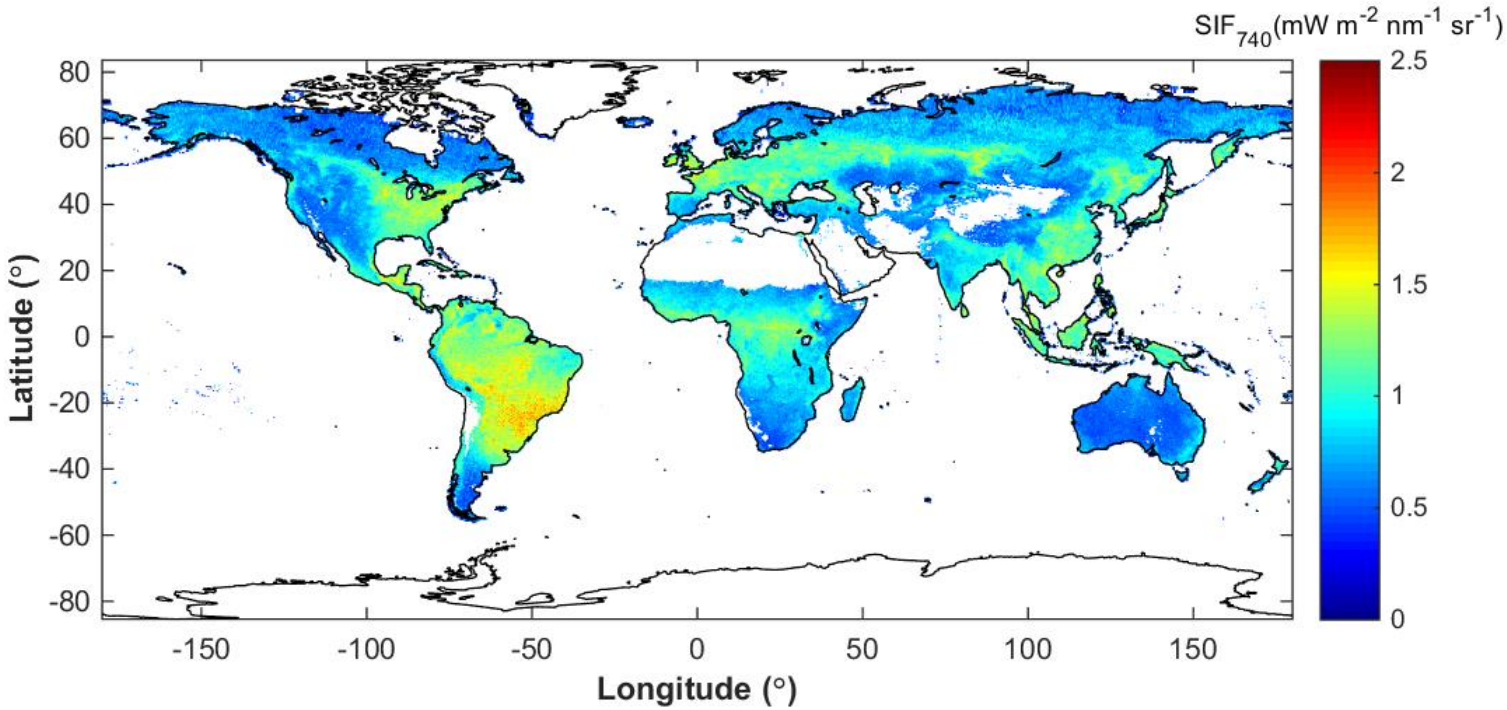
SIF and GPP at the Canopy Level

$$SIF_t = SIF_h + SIF_{sh} \cdot \left(L - L_{sun}\right)$$

$$GPP = L_{sun}GPP_{sun} + GPP_{sh}(L - L_{sun})$$

Chlorophyll Fluorescence Distribution

(GOME-2, 2010, Annual Average, 1° Resolution)



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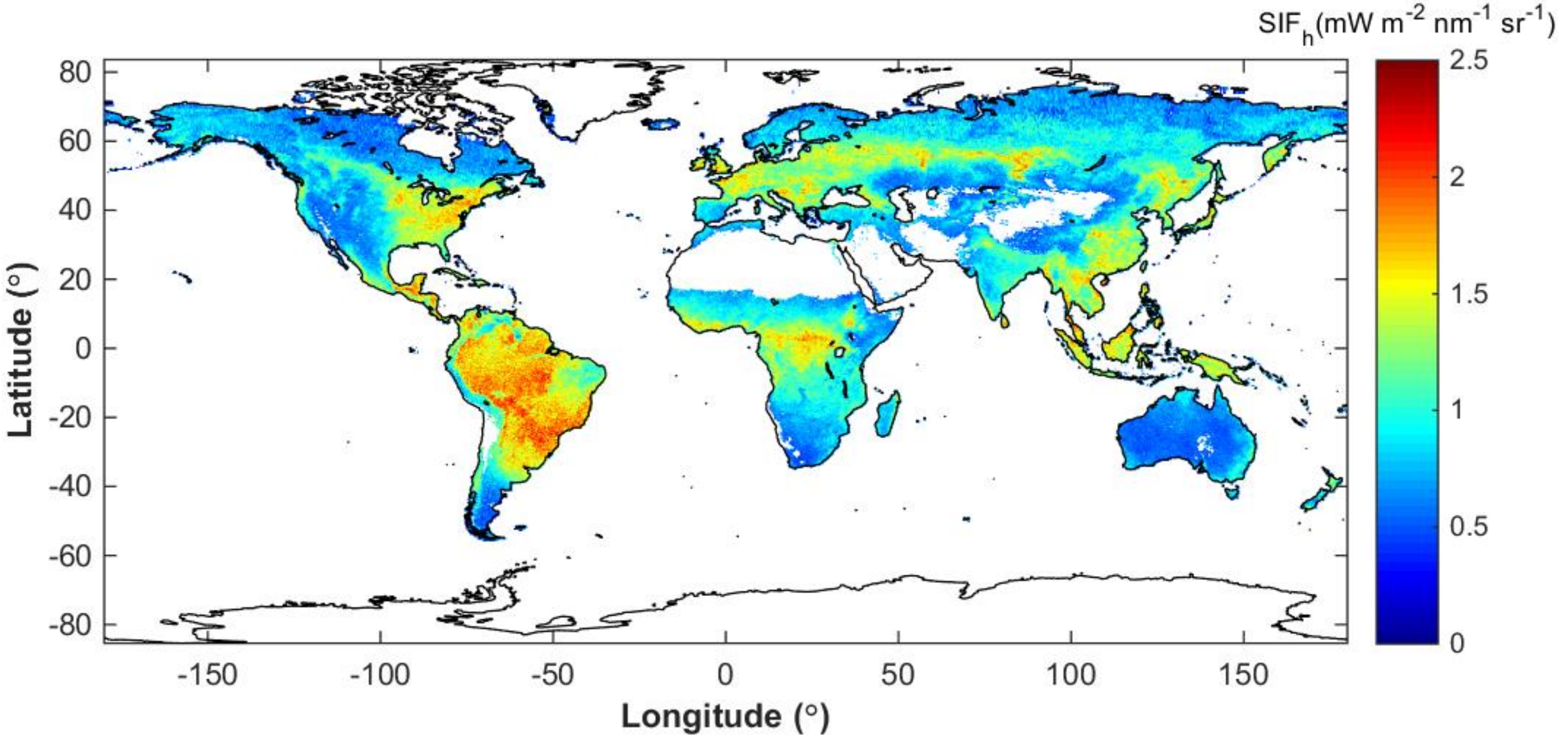
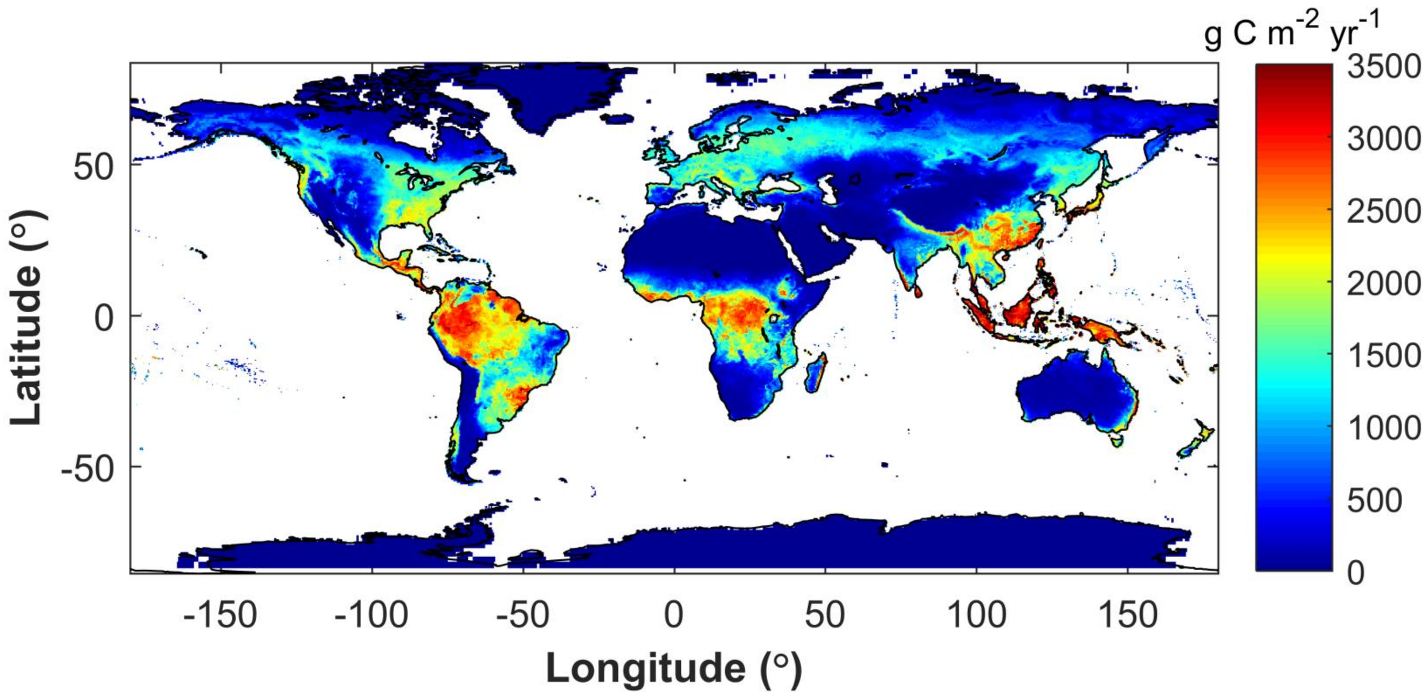
Daily Average: $\overline{F_s} = F_s / \cos(SZA(t_0)) \cdot \int_{t=t_0}^{t=t_0+1} \cos(SZA(t))dt$

Chlorophyll Fluorescence at Hotspot

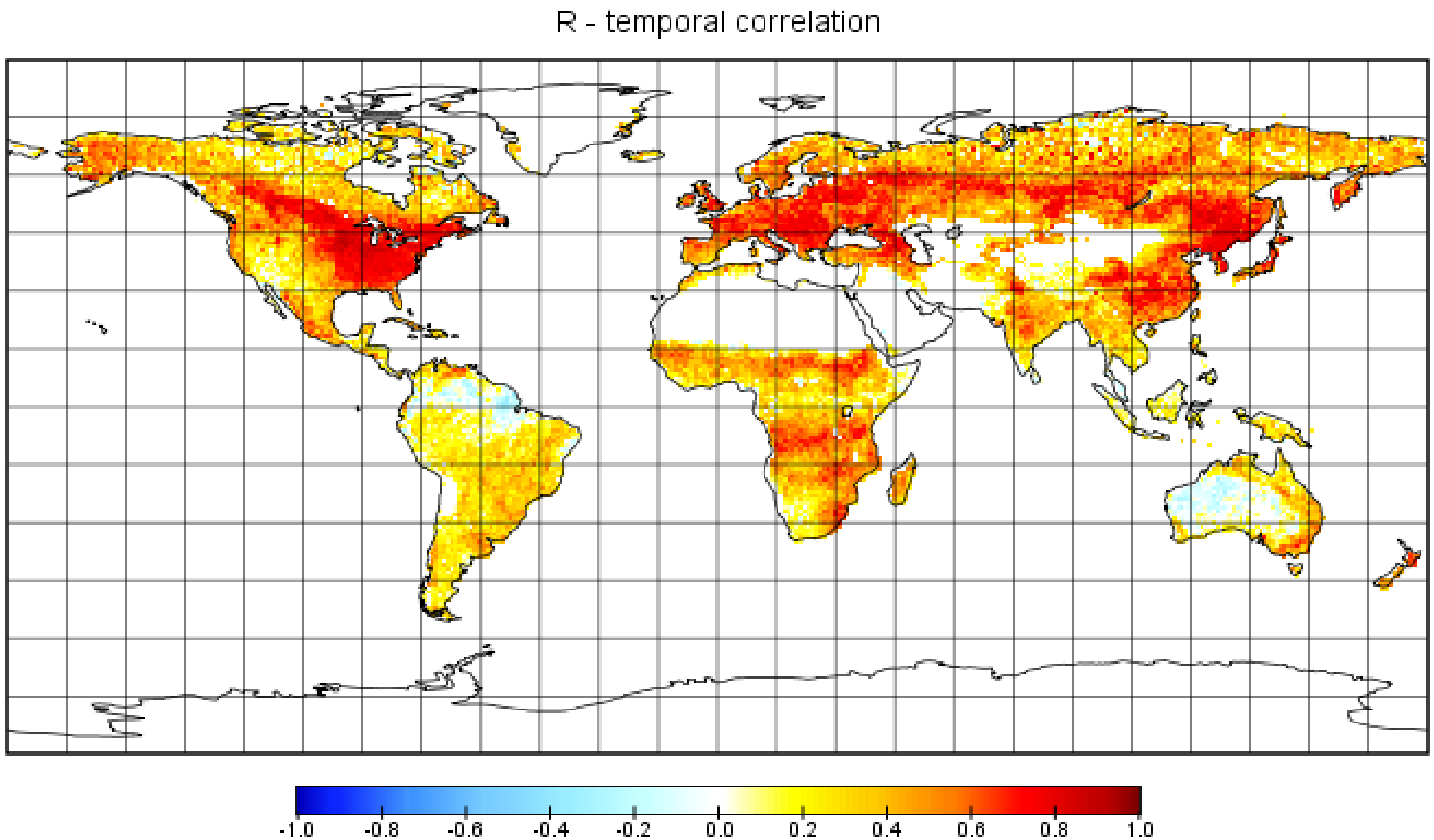
(GOME-2, 2010, Annual Average, 1° Resolution)



Global GPP Distribution
(Two-leaf model BEPS, 2010, 1° Resolution)



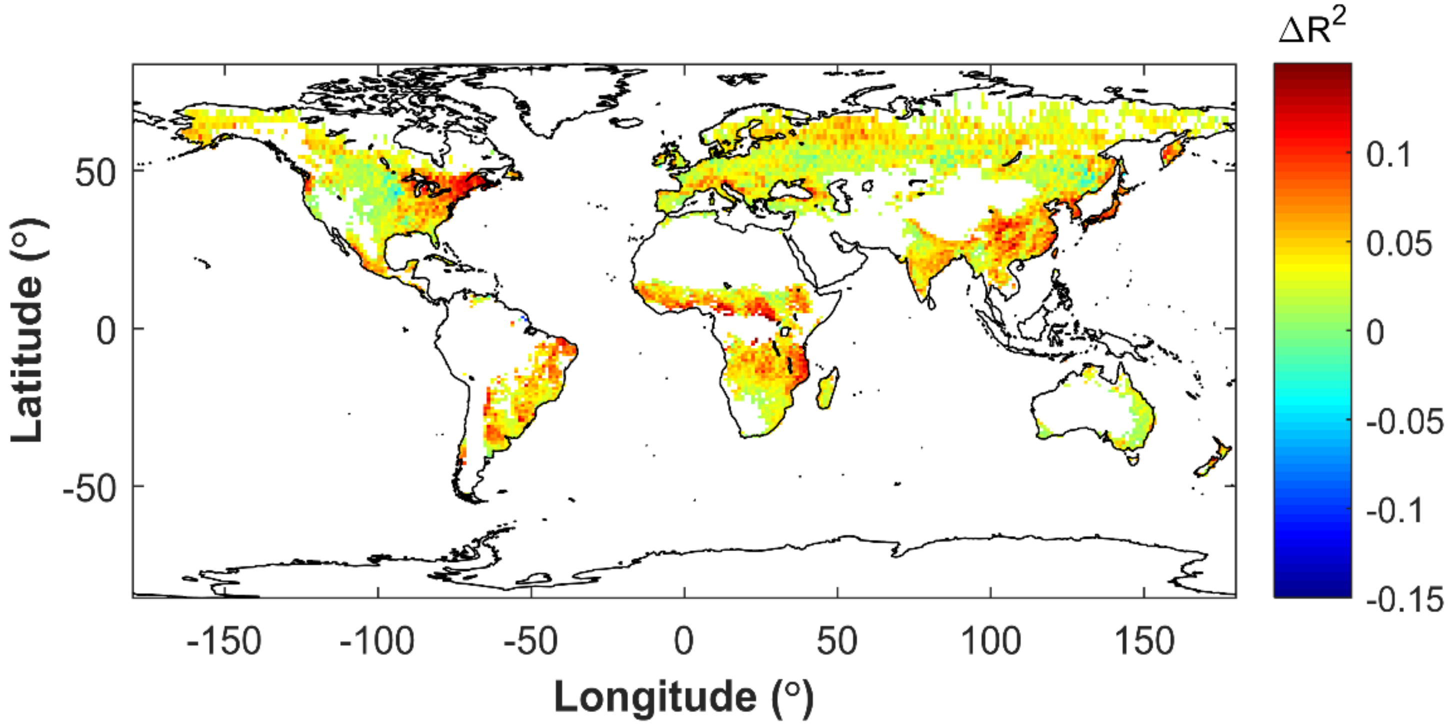
Temporal Correlation Between SIF and GPP
(GPP from BEPS, SIF from GONE-2, 2010, 1° Resolution)



Correlation coefficient (r)

Using original daily GONE-2 data and choosing the largest normalized daily SIF values in 10-day intervals to correlate with 10-day total GPP values over one year

Improvement of SIF after its Angular Normalization as a Proxy of GPP



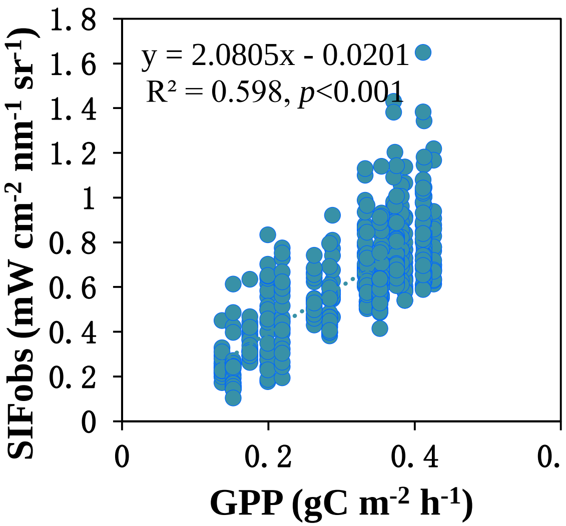
The differences of R^2 (ΔR^2) between SIF_t vs. total GPP and SIF_{740} vs. GPP, for pixels with $p<0.001$ in 2007-2015.

Positive values indicate improved correlation after the angular normalization.

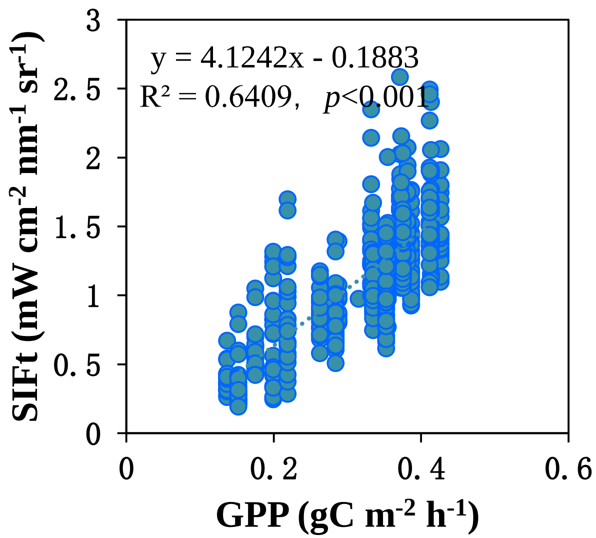
He, Chen et al. (2017, GRL)

Multi-angle Observations of SIF_{687} vs. GPP

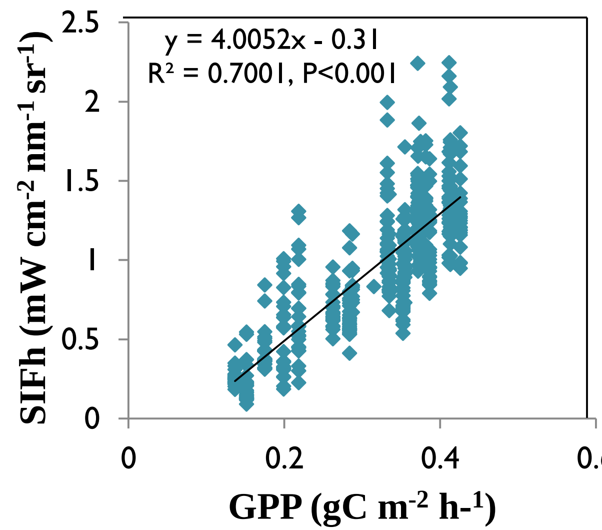
Winter Wheat, Jurong, Jiangsu, China, May 17, 2016



Before Angular Normalization



After Angular Normalization



Correlation with Hotspot SIF only

Summary

- So far limited field measurements of sun-induced chlorophyll fluorescence (SIF) over a rice field show large variations with view and sun angles;
- Separating the measured total SIF into sunlit and shaded components and re-computing the total SIF emission as the sum of these components is an effective way to normalize multi-angle SIF measurements;
- Applying the angular normalization scheme to GOME-2, we found that the coefficient of determination (r^2) is improved by up to 15% between normalized SIF and modelled GPP from the case without normalization. Most improvements are found in forests and shrubs where vegetation structure is distinct.

Acknowledgement:
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