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

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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

**OCO-2**
- Launch: July 2014
- Footprint: 1.29 km × 2.25 km
- Cross-Track: <±1°

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

**GOME-2**
- Launch: October 2006
- Footprint: 80 × 40 km
- Cross-Track: ±54°
Correlation Between Chlorophyll Fluorescence and GPP

GOSAT, 2009, Annual Total, Spatial Correlation

Frankenberg et al. 2011, GRL

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

TIME=13:00
Multi-angle Observations of SIF$_{687}$

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

7 am

8 am

9 am

10 am

11 am

12 pm
Multi-angle Observations of SIF$_{687}$ vs. GPP
Winter Wheat, Jurong, Jiangsu, China, May 16, 2016

$y = 2.0805x - 0.0201$
$R^2 = 0.598, p<0.001$
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

\[ P_{\text{sun}}(L) \quad P_{\nu}(L) \]
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

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

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

\[ P_{\text{sun}}(L) = \mu_s = \cos \theta_s \]

\[ P_{\text{v}}(L) = \mu_v = \cos \theta_v \]
Observed SIF is the Sum of the SIF Emissions from Sunlit and Shaded Leaves and Enhancement due to Multiple Scattering

\[
SIF_{740} = SIF_s \cdot L'_{sun\_\nu} + SIF_{sh} \cdot L'_{sh\_\nu} + \alpha \cdot SIF_s \cdot L_v
\]

Sunlit + Shaded + Multiple Scattering

SIF per unit sunlit leaf area:

\[
SIF_s = \frac{SIF_{740}}{L'_{sun\_\nu} + L'_{sh\_\nu} / \beta + L_v \cdot \alpha}
\]

SIF at the hotspot:

\[
SIF_h = \frac{SIF_{740} \cdot L_{sun}}{L'_{sun\_\nu} + L'_{sh\_\nu} / \beta + L_v \cdot \alpha}
\]

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

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

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

\[ \alpha = \frac{\Delta SIF}{SIF_{sun}} \]
Total Canopy SIF after Angular Normalization

\[ SIF_t = SIF_h + SIF_{sh} \cdot (L - L_{sun}) \]
Farquhar’s Enzyne-Kinetic Model

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

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

\[ GPP = \min(W_c, W_j) - R_d \]

\( W_c \) and \( W_j \) are temperature/nutrient-limited and light-limited gross photosynthesis rates.
SIF and GPP at the Canopy Level

\[ SIF_t = SIF_h + SIF_{sh} \cdot (L - L_{sun}) \]

\[ GPP = L_{sun} GPP_{sun} + GPP_{sh} (L - L_{sun}) \]
Chlorophyll Fluorescence Distribution (GOME-2, 2010, Annual Average, 1° Resolution)

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.
The differences of $R^2$ ($\Delta R^2$) 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 $\text{SIF}_{687}$ vs. $\text{GPP}$

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

**Before Angular Normalization**

$$y = 2.0805x - 0.0201$$
$$R^2 = 0.598, p<0.001$$

**After Angular Normalization**

$$y = 4.1242x - 0.1883$$
$$R^2 = 0.6409, p<0.001$$

**Correlation with Hotspot SIF only**

$$y = 4.0052x - 0.31$$
$$R^2 = 0.7001, P<0.001$$
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.

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