Forward modelling of Solar Induced Fluorescence from JULES

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• SIF provides a potentially independent measure of the photosynthetic flux of carbon (GPP) at large scales.

• Understanding how GPP behaves in response to climate and elevated CO₂ is critical to understanding climate change and feedbacks with the carbon cycle.
SIF-model comparison strategy

Two options:

1. Assume simple SIF-GPP relationship
   a) Typically $GPP = k \times SIF$
   b) Generally relies on model assumptions to define $k$

2. Forward model SIF
   a) Can treat full physics problem
   b) Ensures model consistency
   c) Requires new model operators

NCEO GOSAT SIF

- Part of the NCEO Leicester Full Physics Retrieval algorithm for XCO$_2$
- Retrieves SIF at 772nm and 755nm at S and P polarisations.
SIF vs GPP

\[
\begin{align*}
\text{DJF} & : R^2 = 0.908, \quad \beta = 20.67 \pm 0.42 \\
\text{MAM} & : R^2 = 0.917, \quad \beta = 24.30 \pm 0.45 \\
\text{JJA} & : R^2 = 0.885, \quad \beta = 21.01 \pm 0.46 \\
\text{SON} & : R^2 = 0.884, \quad \beta = 23.99 \pm 0.53
\end{align*}
\]
Leaf scale SIF model

• Following van der Tol et al. (2014), quantum SIF yield:

\[ \varphi_{Ft,n} = \left[ 1 - \frac{J_n}{APAR_n} \right] \varphi_{F'm,n} \]

• Where \( J_n \) is the rate of electron transport (calculated by JULES) and \( \varphi_{F'm,n} \) is the maximum SIF yield.

• Assuming isotropic emission SIF in layer \( n \) is given by:

\[ S_n = 0.5 \times \varphi_{Ft,n} \times APAR_n \]
Two-stream canopy scale SIF model

- Layer optical properties from Meador and Weaver (1980):

\[ R = \frac{\gamma_2 (1 - e^{-2\delta \tau})}{\delta + \gamma_1 + (\delta - \gamma_1)e^{-2\delta \tau}}, T = \frac{2\delta e^{-\delta \tau}}{\delta + \gamma_1 + (\delta - \gamma_1)e^{-2\delta \tau}}, \delta = \sqrt{\gamma_1^2 - \gamma_2^2} \]

- Canopy SIF solution from adding method:

\[ \text{SIF} = \sum_{n=1}^{N} S_n T_{n-\frac{1}{2}} \left( 1 + R_{N-n+\frac{1}{2}} \right) \left( 1 + \frac{R_{n-\frac{1}{2}} R_{N-n+\frac{1}{2}}}{1 - R_{n-\frac{1}{2}} R_{N-n+\frac{1}{2}}} \right) \]
Consistency with JULES canopy RT

- JULES uses the Sellers (1985) model to compute canopy absorption and albedo
  - SIF model can also compute these properties
- Careful selection of $\gamma_n$ yields a solution that is numerically equivalent to Sellers
  - RMSD in the order $10^{-17}$
- Resulting RT model is physically consistent with scattering processes in the JULES model

Within canopy fluxes computed from the SIF model and JULES RT
SIF canopy model

• Treats all orders of scattering
• Emission assumed to come from the centre of each layer
• Predicts the outgoing hemispheric flux
Current implementation in JULES

• Modify JULES to output per-canopy layer variables:
  • GPP, APAR
  • Generates large output files

• Run SIF model “off-line” from main JULES run
  • Efficient way of experimenting with the SIF model

• Needs one additional variable from JULES...
JULES water stress model

• JULES represents impact of stress on GPP using a piecewise linear model
  • Similar to other global land surface models!
• Modifies GPP *after* the calculations of the Farquhar model
• Consequently approach taken in SIF model is to scale SIF by the same stress factor
July 2016

SIF (mW m\(^{-2}\).sr\(^{-1}\).nm\(^{-1}\))
January 2016

April 2016

July 2016

October 2016

SIF (mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$)
Canopy layer contributions to SIF

- Strong diurnal cycle aligned with APAR
- 90% of canopy exiting SIF from top 2 layers
Harvard forest SIF observations

Field campaigns

• Measuring SIF in greenhouses:
  • 3× temperature treatments
  • 2× CO₂ treatments
• Semi-permanent SIF spectrometer going up at Alice Holt later this year
• Collaborating with BiFor team
Conclusions

• Fully mechanistic SIF model developed for UK land model, JULES

• Currently in the process of testing against EO and in-situ observations

• Next steps:
  • NPQ model
  • Stress model
  • Directional signal
Testing model hypotheses about GPP

JULES - UKESM Land Surface Model

- Can be run “online” in a climate model or forced by observed meteorology
- Spatial and temporal resolution defined by forcing
- In this presentation:
  - WFDEI meteorology
  - 3hr time step
  - $0.5^\circ \times 0.5^\circ$ grid
- Farquhar equations for GPP
Predicted diurnal cycle

● = Morning

○ = Afternoon