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Geoscientific Model Development Discussions

Interactive comment on "FLiES-SIF ver. 1.0: Three-dimensional radiative transfer model for estimating solar induced fluorescence" *by* Yuma Sakai et al.

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Dear Reviewer #1,

Thank you very much for your comments on our manuscript and your sincere efforts in constructing a decision report. The comments and suggestions made by you have been very useful in improving our manuscript. We have revised the manuscript following careful consideration of your comments. In the revised manuscript, rewritten and additional sentences are indicated in red and blue, respectively. We hope the revised manuscript is now suitable for publication in Geoscientific Model Development. We look forward to your favorable consideration. Our responses to your individual com-

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ments and questions are given below.

Very sincerely

Yuma Sakai

[Comment] My first concern is the comparison of the new FLiES-SIF 3D model to some field data, C1 at least to some other model simulations, such as DART. I knew some groups are doing bi- directional SIF measurements in the field. These data may be used to validate the new model to some extent. Also, the comparison to DART would also give some hints on the performances of FLiES-SIF. [Response] Thank you for pointing out. We have added the new section to require your suggestion (see Sect. 3.2 on page 14). [Comment] Meanwhile, in the section of Introduction, it seems that there are missing in some new advances and recent publications on how canopy structure impacts the top-of-canopy SIF during the last two years. The authors may consider including them. [Response] Thank you for pointing out. We have added the new reference information (Line 52 on page 2). Several points: [Comments] 1. L58: The expression of “At present, the Discrete. . .is the only available 3D model” is not clear. Is the DART model the only available 3D model to simulate SIF or other processes? As far as I know, there are other models that can simulate SIF, such as FluorFLIM (Zarco-Tejada et al, 2013), FluorFLIGHT (Hernández-Clemente et al., 2017). Are these not 3D models? References: Hernández-Clemente R, North P R J, Hornero A and Zarco-Tejada P J. 2017. Assessing the effects of forest health on sun-induced chlorophyll fluorescence using the FluorFLIGHT 3-D radiative transfer model to account for forest structure. Remote Sensing of Environment 193: 165-179.[doi:10.1016/j.rse.2017.02.012]. Zarco-Tejada, P., Suárez, L., & Gonzalez-dugo, V. (2013). Spatial Resolution Effects on Chlorophyll Fluorescence Retrieval in a Heterogeneous Canopy Using Hyperspectral Imagery and Radiative Transfer Simulation. IEEE Geoscience and Remote Sensing Letters, 10, 937-941. doi:10.1109/LGRS.2013.2252877 [Response] Thank you for pointing us in the direction of these studies. We have read these articles and added the reference information on Line 63 (page 3).

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[Comments] 2. It is not clear how to calculate APARC in Eq. (2)? Please add some information of the method. [Response] In the previous manuscript, the method of computing APARc was not described in detail (Lines 100–101 in the previous manuscript). APARc is independently computed by the FLiES-SIF APAR computation module, which is basically the same as the numerical scheme used in FLiES version 2.4 (Kobayashi, Hideki. (2019, August 6), Zenodo. http://doi.org/10.5281/zenodo.3586814). In the revised manuscript, we have added a detailed description of the model framework (e.g., Fig. 1 and Sect. 2.1 in the revised manuscript) and explain how to compute APARc in Sect. 2.1.3 (Lines 130–146). A flowchart of the simulation process is given in the new Fig. 1(b). In summary, APARc is computed by the radiative transfer computation in the broad PAR domain (400–700 nm) before the spectral SIF radiance is simulated. This APARc is used to re-scale the SIF radiance under the actual APAR conditions.

[Comments] 3. According to the phase function for SIF emissions in Eq. (12), SIF emissions are calculated from the adaxial and abaxial sides of a leaf separately, which indicates hemi-sphere integration. But in Eq. (4), the normalization factor is 4π. Should it be 4π or 2π? [Response] Thank you for pointing out this mistake. The correct normalization factor in Eq. (5) (page 8 in revised manuscript) is 2π. We have modified this equation. We checked all other equations carefully and found that they were correct. In addition, the source code was correctly described. Thus, this error would not have affected the simulation results.

[Comments] 4. Eq. (10) demonstrated the leaf-level SIF emission. Since you have already used a leaf level SIF model (FluoMODleaf) to derive the fraction of SIF emission from adaxial and abaxial side of leaves, I am curious why don't you use this model to simulate SIF emissions at leaf level? [Response] In our modeling, we use the FluorMODleaf model to derive the fraction of SIF emissions from the adaxial and abaxial sides of leaves (in the emission phase function) and the spectral composition of SIF, i.e., the factor fs in Eq. (11) (Eq. (10) in the previous manuscript). The broadband fluorescence energy is determined from APAR and the SIF yield computed by the model of Tol et al. (2014) and Farquhar's model (Farquhar et al., 1980). This enables us to couple the leaf traits (Vcmax, Jmax) and leaf physiological responses to environmental conditions (temperature, humidity, pCO2). Our approach is similar to that of the SCOPE model (Tol et al., 2009). In the revised manuscript, we have added a description of how we use FluorMODleaf and how we combine the leaf physiology module with the radiative transfer module (see Sect. 2.1.5 on page 6).

"To simulate the spectral SIF, the spectral composition of SIF must be known. Our approach is similar to that used in the SCOPE model (Tol et al., 2009). We derived the spectral composition from the FluorMODleaf model (Zarco-Tejada et al., 2006; Pedrós et al., 2010). The calculated leaf-level spectral SIF radiance variations given by FluorMODleaf were normalized to determine the fraction of SIF at wavelength , λ, fs (mW m$-$2 sr$-$1), with respect to the broadband (W m$-$2). That is, we only used the fraction of spectral composition from the FluorMODleaf model. The radiance was then determined from APAR andφf , which varies with environmental conditions and leaf traits such as the maximum carboxylation capacity, Vcmax, used in the photosynthesis model." (Lines 182-188 on page 6)

[Comments] 5. To reduce time, the simulation of SIF direct emission (Eq. (5)) and APARL (Eq. (11)) both follow the Beer-law instead of using the backward ray tracing method. Regarding to the simulations, are there a large differences between the two methods? The assumption of a homogeneous layer should be made to apply the Beer-law attenuation. Does that indicate the model is not a real "3D" model in the conventional sense? [Response] The attenuation function in Eqs. (6) and (12) (Eqs. (5) and (11) in the previous manuscript) are the same. FLiES-SIF is a 3D model in which individual trees are explicitly defined in a certain landscape. To clarify the 3D feature of the attenuation function, we modified Eq. (6) (Eq. (5) in the previous manuscript) as follows:

expâĄą(-τ_σ)=exp(-$\sum$_iu_$i\gamma$_i G_(σ,i) s_i ãĂŮ) where the optical thickness $\tau\sigma$ is computed as the sum of light paths of the ith tree from the emission point to the view direction. The same analogy can be applied to Eq. (12) (Eq. (11) in the previous manuscript). We have modified the descriptions of these equations as follows: "where ui, si, Gσ,i, and γi are the leaf area density, path length, mean leaf projection area, and clumping index of the ith tree. They are aggregated over the trees located in the light path between the emission point to the top of canopy in the view direction, respectively." (Lines 234– 236 on page 8) [Comments] 6. How do you calculate the scattering parameter wi,j in Eq. (14)? [Response] As described in the manuscript, wi,j is the weight of a photon with an initial weight of w0 (Eq. 11). wi,j is computed by multiplying the photon weight of the previous scattering order by wSIF (=rSIF + tSIF).

[Comments]7. Please add the description of the parameter GS in Eq. (16). [Response] We have added a description of GS. This is the mean leaf projection area, as defined in Eq. (7). (Line 320 on page 12)

[Comments]8. The authors have simulated the broadband SIF and considered the multi-scattering effect in the near-infrared spectral domain. Have you considered the re-absorption effect of SIF in the red spectral range? [Response] The current FLiES-SIF model takes the re-absorption effect of the emitted SIF into account. In the photon tracing, when the emitted fluorescence light hits other leaves, it is absorbed or scattered. In the red spectral domain, because the chlorophyll absorption is high, the leaf reflectance and transmittance are lower than in the near-infrared domain and more fluorescence light is absorbed. This process is considered in the variable weighting of the photons, wi,j, in Eq. (15). In the revised manuscript, we have added a new Sect. 2.1 to introduce the overall framework. The scattering and re-absorption processes in the FLiES-SIF model are now described as follows:

"The scattering and re-absorption of emitted fluorescence light must also be considered to identify the relationship between the fluorescence emitted by the chloroplasts and the top-of-canopy outgoing fluorescence 100 radiance (Porcar-Castell et al., 2014).

Several recent studies have worked on the quantification of the impact and modeling of scattering and absorption effects from the leaf scale (e.g., Agati et al. (1993); van der Tol et al. (2019)) to the canopy scale (e.g., Romero et al. (2018)). Multiple scatterings and re-absorption among leaves, trunks, and soil background can be numerically simulated using unbiased and efficient approaches (Kobayashi and Iwabuchi, 2008)." (Lines 98–103 on page 4)

[Comments]9. Figure 3: The arrows in Fig 3. did not point the voxels clearly. [Response] Thank you for pointing out this issue. We have corrected Fig. 3 (Page 28).

[Comments]10. To exhibit the variation of SIF with wavelengths clearly, it would be good for the Fig 8. and Fig 9. to be transformed into three-dimensional images. [Response] Thank you for this suggestion. These figures have been transformed to 3D images (Fig. 9 on page 33).

[Comments]11. L178: replace "The SIF radiance emitted..." by "The scattered SIF radiance emitted. . .". [Response] Thank you for this suggestion. This has been modified accordingly. (Line 289 on page 10)

[Comments]12. L315: replace "contribute" by "contributes". [Response] Thank you for pointing out this error. This has been corrected. (Line 431 on page 15)

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