Author responses to comments RC1

MS title: Process-based Modeling of Solar-induced Chlorophyll Fluorescence with VISIT-SIF version 1.0 (egusphere-2024-1542)

We sincerely thank the topic editor, Sato, reviewer1 and reviewer2 for their careful reviews and comments.

Below, we provided our responses to the review comments. The review comments are highlighted in orange, and our replies are kept in black.

Miyauchi et al describe the VISIT-SIF model for simulation of satellite SIF observations. The model was used to simulate GOSAT SIF measurements, and good results were obtained. The incorporation of SIF simulation in LSMs like VISIT provides opportunities to constrain and improve LSMs using data assimilation, and the proposed VISIT SIF model has the advantage of being capable of simulations with various viewing angles, which is not possible in many current models. However, I have several concerns as listed below. The manuscript has the potential for publication in GMD after revision.

Major comments:

1. The comparison between the VISIT-SIF model and the SIF simulations in other LSMs could be more accurate and more in-depth. And the advantages and unique features of VISIT-SIF can be emphasized more (Also see comment 2).

Reply1: We sincerely appreciate your valuable feedback and suggestions for our manuscript. As you suggested, the comparison with other models is important for emphasizing the advantages and unique features of this model. I revised the introduction as follows. And, as the comparison with other models' approach, we added the comparison simulation using observation angles with that using fixed angles in Appendix D.

L76-82:

"In general, strict representation of radiation transfer process is required to simulate satellite SIF retrievals, especially for the satellites having off-nadir observation angles due to their complicated geometric relationships among the incidence angle of the emission to the sensor, solar azimuth, and

orientation of leaves (Zhang and Zhang, 2023). But at the same time, the resolution of satellite images has kept increasing (e.g., Vicent et al., 2016), and implementation of RTMs for the observations are computationally expensive and prohibitively time-consuming. Hence, a simplified framework of avoiding direct calculation of RTMs can be an alternative and practical approach to simulate efficiently the satellite SIF retrievals."

L85-86:

"The implementation of our approach allows for easy extension to other satellite SIF retrievals."

The statement that no model can simulate GOSAT SIF (L68) is not true according to my knowledge. Lee et al (2015) and Norton et al (2018) have specifically evaluated simulations with GOSAT or used GOSAT for data assimilation. Actually, I believe most current models (listed in Table 1 in Li et al, 2022) can be used to simulate GOSAT SIF. Instead, stating the advantage of VISIT-SIF on simulating SIF observed at different angles here could be helpful.

Lee, J. E., Berry, J. A., van der Tol, C., Yang, X., Guanter, L., Damm, A., ... & Frankenberg, C. (2015). Simulations of chlorophyll fluorescence incorporated into the Community L and Model version 4. Global change biology, 21(9), 3469-3477.

Norton, A. J., Rayner, P. J., Koffi, E. N., & Scholze, M. (2018). Assimilating solar-induced chlorophyll fluorescence into the terrestrial biosphere model BETHY-SCOPE v1. 0: model description and information content. Geoscientific Model Development, 11(4), 1517-1536.

Li, R., Lombardozzi, D., Shi, M., Frankenberg, C., Parazoo, N. C., Köhler, P., ... & Yang, X. (2022). Representation of leaf-to-canopy radiative transfer processes improves simulation of far-red solar-induced chlorophyll fluorescence in the community land model version 5. Journal of advances in modeling earth systems, 14(3), e2021MS002747.

Reply2: We removed the phrase "no model" from the sentence as follow. As you pointed out, there are some models with the potential to simulate GOSAT SIF. In our submitted manuscript, we intended to argue that SIF simulations with different angles using point-based satellite information have not been conducted. However, the sentence was confusing.
We agreed with your suggestion about simulation using different angles and revised our manuscript (same as reply 1).

L72-73:

"GOSAT has been operated since the launch in January 2009, and of which SIF retrievals have the longest observation record of any single satellite sensor."

<u>Reply3</u>: For the advantage of the VISIT-SIF, same as the reply to the comment 1. The additional analysis using SCOPE was shown in reply5.

<u>Reply4</u>: We agree that the evaluation of LUT is necessary, as you mentioned. We added the following sentence and the figure evaluating the input variables and LUT in the Appendix B.

Appendix B: The evaluation of $r_{oz/sz}$ and r_{sd} in LUT and SCOPE
As a preliminary validation for the input parameters in SCOPE, the impact of $r_{oz/sz}$ and r_{sd} on F in Eq. (1) when changing each input parameter in Table A1 was examined (Fig. B1). The impact on F was estimated using SCOPE as the difference of $r_{oz/sz}$ and $1+r_{sd}$ in Eq. (1) and (2) compared to reference values ($r_{oz/sz}$ = 0.5 and $1+r_{sd}$ = 1.12). $r_{oz/sz}$ increases when SZ and OZ are close to each other, approaching a value of 1. As an exception, $r_{oz/sz}$ can exceed 1 when SZ is close to nadir, the OZ is lower value than SZ, and the LAI is lower than 2. The value of r_{sd} is 0.11 ± 0.05, and it becomes 0 when OZ and SZ are identical. The reference values were determined from LUT by fixing OZ to 0 (nadir) and setting the parameters (LAI = 5, SRAD = 800 w m^{-2}, SZ = 30°) close to the average values in region 39. Since OZ, SZ and LAI have a significant impact on SIF calculation, they were selected as input parameters for Eqs. (15) and (16). Under the nadir-based condition, AZ had no influence on F. However, the angle between the solar incident direction and the observation direction, determined by SZ, OZ and AZ have a complex impact on $r_{oz/sz}$ and r_{sd}, selecting AZ as an input parameter. SRAD is a fundamental input variable for radiative transfer calculations and was applied in the LUT to align the light environment with VISIT. Variables such as w, H_c, and C_{ab} have a relatively large effect on SIF calculations; however, since they are not computed within VISIT, fixed values were applied to them. SRAD is a fundamental input variable for radiative transfer calculations and was applied in the LUT to align the light environment with VISIT, although it caused only a small change in $r_{oz/sz}$ and r_{sd}.

The variables such as w, H_c, and C_{ab} have a relatively large impact on SIF calculations, however, since they are not computed within VISIT, fixed values were applied to them. LID also has a significant impact, but since there is no reasonable method for setting LID in global calculations for VISIT, it was fixed at Spherical. LID also has a significant impact, but since there is no reasonable method for setting LID in global calculations for VISIT, it was fixed to spherical. The impact of other parameters fell within ±3% and they were not selected as input parameters.

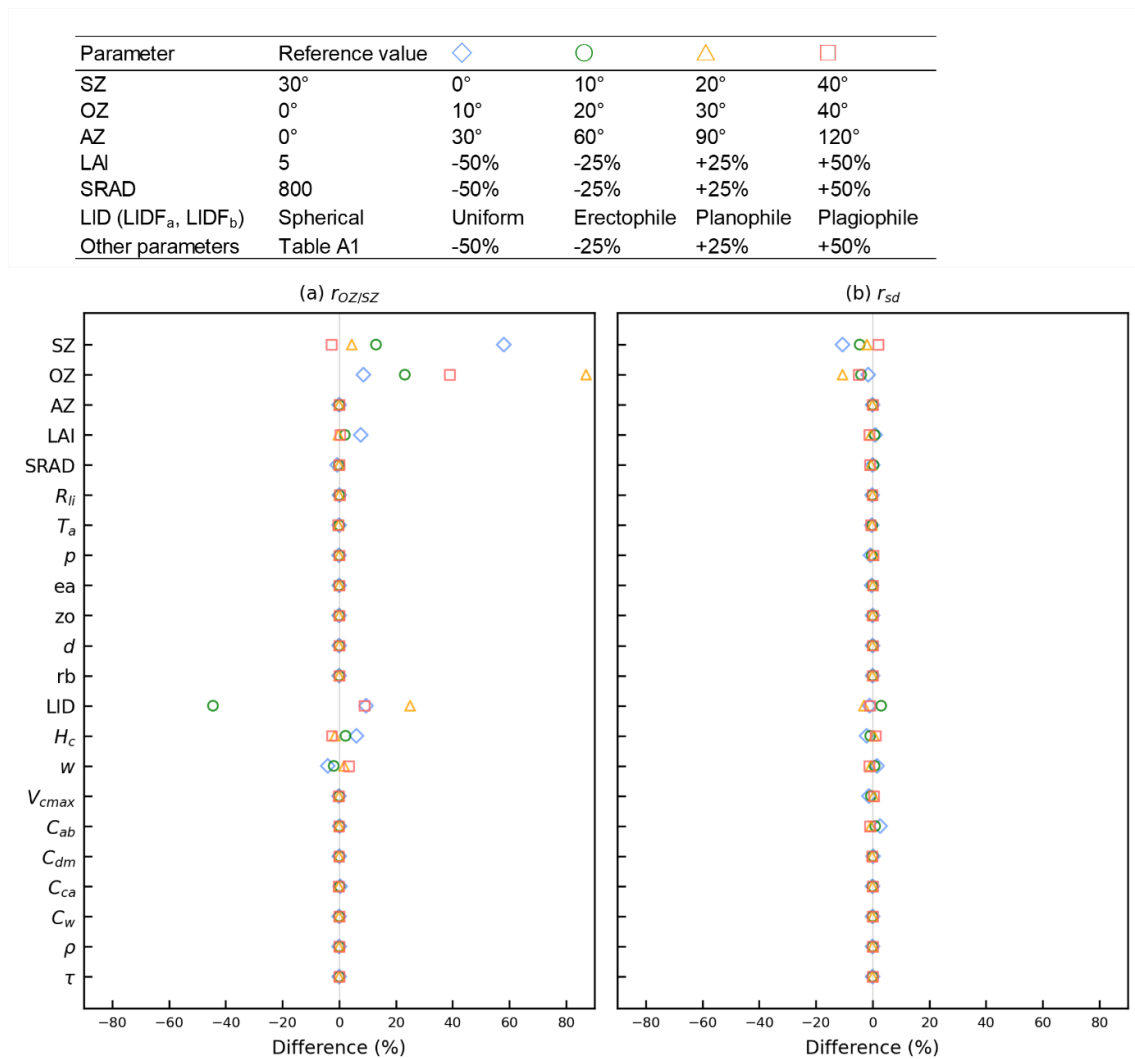| Parameter	Reference value	◇	◯	△	□
SZ	30°	0°	10°	20°	40°
OZ	0°	10°	20°	30°	40°
AZ	0°	30°	60°	90°	120°
LAI	5	-50%	-25%	+25%	+50%
SRAD	800	-50%	-25%	+25%	+50%
LID (LIDF$_a$, LIDF$_b$)	Spherical	Uniform	Erectophile	Planophile	Plagiophile
Other parameters	Table A1	-50%	-25%	+25%	+50%

Figure B1. The impact of $r_{oz/sz}$ and r_{sd} on SIF calculations (F in Eq. (1)) when changing each input parameter in Table A1. The impact was estimated using SCOPE by changing input parameters as shown in the upper table. The difference of 0 indicates that the simulation results from LUT and SCOPE are identical when parameters that are not used in LUT.

The evaluation of the geometry effect in Figure 3 looks a bit weird to me. The issue with most current models is that they only simulate for the nadir direction. I suggest also comparing the simulations with a scenario assuming nadir viewing angle.

Reply5: As you mentioned, many models calculated the nadir SIF, and we believe that our SIF calculation according to observation angles with nadir SIF would be meaningful. We added the comparison with the nadir SIF as additional information about the effect of considering observation angles in Appendix D.

Appendix D: Comparison of SIF simulated using observation angles and fixed angles.
We compared the SIF simulated using observation angles and nadir angles (OZ=0) (Fig. D1). Although some models employ approaches to calculate SIF considering the observation direction, SIF simulations and validations are conducted with the angle fixed to the nadir direction for comparison with OCO-2 SIF (Bacour et al., 2019; Li et al., 2022). Simulations using observation angles and nadir angles showed a bias, with SIF in nadir direction differing from SIF in observation direction by a maximum of +63% and a minimum of -27%. The fixation or omission of observation angles introduces uncertainties in SIF calculations; therefore, for satellites such GOSAT with varying observation angles, it is essential to appropriately account for geometric effects to ensure accurate simulations and analyses.
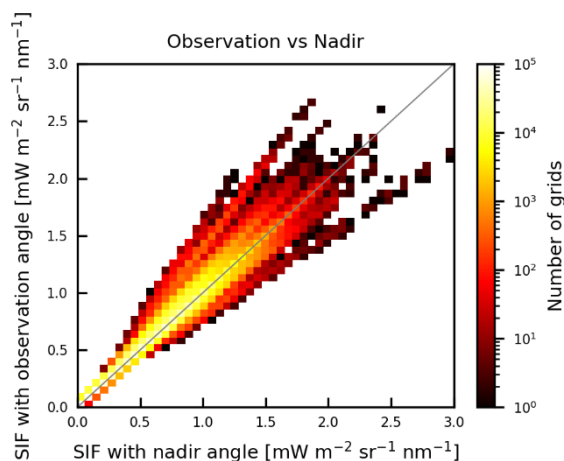

Figure D1. Comparison of SIF simulated by using observation angle and nadir angle. The scatter plot represents SIF at each observation point from 2009 to 2015.

3. I have a few concerns regarding the method:

a. The fluorescence yield at the leaf level and the photosystem level seem confused in the SIF model. Eq.2 requires leaf-level fluorescence yield, while Eq.3 provides photosystem-level fluorescence yield. Only part of photosystem-level fluorescence escapes the leaf as some are absorbed within leaf (Porcar-Castell et al, 2021). Using photosystem-level fluorescence yield as a leaf-level parameter would lead to bias in the simulation. Various approaches have been used to address this issue in other models, for example, see Lee et al, (2015) and Li et al, (2022).

Porcar-Castell, A., Malenovský, Z., Magney, T., Van Wittenberghe, S., Fernández-Marín, B., Maignan, F., ... & Logan, B. (2021). Chlorophyll a fluorescence illuminates a path connecting plant molecular biology to Earth-system science. Nature plants, 7(8), 998-1009.

Lee, J. E., Berry, J. A., van der Tol, C., Yang, X., Guanter, L., Damm, A., ... & Frankenberg, C. (2015). Simulations of chlorophyll fluorescence incorporated into the Community L and Model version 4. Global change biology, 21(9), 3469-3477.

Li, R., Lombardozzi, D., Shi, M., Frankenberg, C., Parazoo, N. C., Köhler, P., ... & Yang, X. (2022). Representation of leaf-to-canopy radiative transfer processes improves simulation of far-red solar-induced chlorophyll fluorescence in the community land model version 5. Journal of advances in modeling earth systems, 14(3), e2021MS002747.

Reply6: As you pointed out, the approach of converting the fluorescence yield at the photosystem-level to the leaf level is important. In our study, we used SCOPE in a simplified manner to calculate $r_{oz/sz}$, r_{sd}, f_u, and r_{756}, and compute canopy-level SIF considering the radiative transfer process. However, we have not accounted for internal reabsorption within a single leaf. Reabsorption by chlorophyll is only considered in the calculation of r_{756}. Therefore, VISIT-SIF has uncertainty in the fluorescence emission at the leaf level. The conversion from photosystem level to leaf level fluorescence yield remains is a challenge for our future model improvements. Regarding these points, we revised the manuscript as follows:

L154-156(method):
"The variable can be used to estimate canopy-level fluorescence by considering radiative transfer processes within the canopy layers; however, reabsorption at single-leaf-level in fluorescence yield was not reflected."

L399-405(discussion):
"By using SCOPE in a simplified manner, the radiative transfer process between canopy layers to calculate SIF in arbitrary observation direction can be computed; however, the uncertainty remains in the calculation of chlorophyll fluorescence yield at leaf- and canopy-level. While the reabsorption by chlorophyll was considered in the calculation of r_{756}, the internal reabsorption at the single leaf level was not directly considered in the fluorescence yield in Eq. (2). Li et al. (2022) used the simplified

scattering fluorescence coefficient in SCOPE, which estimates the chlorophyll fluorescence from the excitation light, to convert the fluorescence yield at the photosystem level to the leaf level. However, since VISIT-SIF and SCOPE differ in the model structure of canopy layers and spectral calculations, a conversion approach for fluorescence yield at leaf level has not been implemented in VISIT-SIF. The conversion of fluorescence yield from photosystem level to leaf-level is a challenge for future improvements of VISIT-SIF."

b. L131: I suggest providing some details on how VISIT simulates APAR, it is confusing to me why that can be considered APARsun.

Reply7: We added the sentence about $APAR_{sun}$ calculation as bellow.

L147-152:
"Here, APAR is the photosynthetically active radiation absorbed by canopy, which is the product of canopy-top irradiance, canopy reflectance, LAI and an attenuation coefficient that is a function of biome type and solar angle (Ito and Oikawa, 2002). $APAR_{sun}$ consists of the absorbed beam, diffuse, and scattered beam with the sunlit layer based on Farquhar model (de Pury and Farquhar 1997). Under the assumption that VISIT simulates biochemical processes occurring within sunlit leaves where the viewing angle coincides with the sun zenith angle, we adopted $APAR_{sun}$ in Eq. (2)."

c. L132: How is fu derived?

Reply8: f_u was calculated as the average fraction of upward chlorophyll fluorescence to tatal emitted chlorophyll fluorescence from photosystem across the 60 canopy layers in SCOPE. We revised the sentences related to f_u as shown in reply6.

L152-157:
"The variable f_u represents the fraction of the SIF emitted in the upward direction to that in both the upward and downward directions at the canopy-level. It was obtained as the average fraction across the 60 canopy layers by operating the SCOPE model. The variable can be used to estimate canopy-level fluorescence by considering radiative transfer processes within the canopy layers; however, reabsorption at single leaf level in fluorescence yield was not reflected. In addition, Equation (2) describes indirect incorporation of VISIT and SCOPE by multiplying $\Phi_{F,sun}$, $r_{oz/sz}$ and f_u."

Reply9: We revised as follows.

L20-21:

We also found that the mean seasonal variability in the simulated SIFs was closely consistent with the GOSAT SIF retrievals at the subcontinental scale.

L43:

in the oxygen absorption bands between 756 and 759 nm (Oshio et al., 2019) and between 734 and 758 nm (Joiner et al., 2013)

Others:

1. We added the caption for Fig. 5c.
2. We had revised the Eq.14 due to a mistake in unit.