Interactive comment on "Investigating the usefulness of satellite derived fluorescence data in inferring gross primary productivity within the carbon cycle data assimilation system" by E. N. Koffi et al.

General comments

We thank the 3 reviewers for their constructive comments, which undoubtedly improve the clarity of the manuscript. In what follows, we first describe the main objectives of the project with an emphasis on the specific work presented in the paper. We then summarize the main findings. Finally, we reply to the major criticisms of the reviewers. For the specific comments, our responses are given after the comments of each reviewer.

Our ultimate goal is to use the solar induced fluorescence (SIF) observed by satellite to constrain the gross primary productivity (GPP) within the Carbon-Cycle Data assimilation System (CCDAS) framework. We ingest SIF measurements into the CCDAS built around the Soil Canopy Observations, Photometry and Energy fluxes (SCOPE) model. The formulations of both the GPP and SIF in SCOPE utilize the maximum carboxylation rate V_{cmax}, which is expected to mediate information from SIF to GPP within the CCDAS. This specific work mainly investigates the sensitivity of both SIF and GPP to the environmental conditions (mainly the short wave radiation R_{in} and the integrated absorbed photosynthetically active radiation aPAR) and the biochemical parameters of the SCOPE model (mainly V_{cmax} and the leaf chlorophyll concentration C_{ab}), with a focus on V_{cmax}. The tests are performed along with various values of the leaf area index (LAI) and for both C3 and C4 vegetation types. In addition, we examine the sensitivity of both GPP and SIF to aPAR, which integrates both the LAI and the incoming radiation. The paper starts by an assessment of these sensitivities by using the model SCOPE alone. Then, the CCDAS built around SCOPE is forced by monthly climate data to investigate the ability of the CCDAS to reproduce SIF measurements at the frequency 755 nm over 2009-2010 period.

In summary, the idealized tests with SCOPE standalone confirm the strong sensitivity of GPP to both V_{cmax} and aPAR (also to R_{in}). However, the current version of SCOPE model does not show any sensitivity of GPP to C_{ab}. Simulated SIF is insensitive to V_{cmax} under low light conditions and the sensitivity slightly increases under high light conditions, but it is strongly sensitive to both C_{ab} and aPAR (also to the incoming radiation). The built CCDAS simulates well the patterns of SIF suggesting that the combined model is able to ingest these measurements. Within the CCDAS SIF is sensitive to aPAR and C_{ab}, but it is insensitive to $V_{cmax.}$

The major criticisms of the submitted manuscript by the reviewers concern:

1) The weak sensitivity of SIF to V_{cmax} that contradicts the strong sensitivity reported in the study of Zhang et al. (2014)
2) The lack of the sensitivity of GPP to C_{ab} in the SCOPE model that contradicts the published positive relationship between the two variables
3) The lack of the comparison of SCOPE modelled GPP to observed GPP such as those from FLUXNET to illustrate the diurnal variations of SCOPE simulations
4) The lack of sensitivity of SIF to V_{cmax} within the CCDAS
5) The lack of clarity of the abstract

1. As already acknowledged in the discussions of the submitted version of the paper, to understand the differences between our results and those from Zhang et al. (2014), we carefully made detailed analysis by using the SCOPE model alone and SCOPE settings reported in Zhang et al. (2014). For the environmental input (temperature and short wave radiation), we used their values over a large range. Thus, we made simulations of SIF by using the C4 crop (here corn and soybean) with SIF retrieved at the frequency 740 nm. The tests are carried out by using the SCOPE model with the fluorescence model choice "0" (i.e., the parameter K_n is obtained by an empirical fit to Flexas'data; version 1.53 of SCOPE model). In detail, the relevant settings of SCOPE used in our study can be described as follows: the radiation varies from 1 to 1200 W/m^2; V_{cmax} varies from 1 to 350 μmol m^{-2} s^{-1}; temperature varies from 10^{o}C to 30^{o}C; C_{ab} values from 1 to 80 μg cm^{-2}. Several values of LAI (between 0.1 and 6) are also considered.

   The strongest sensitivity for SIF was found for a temperature input of 28^{o}C, a LAI of 6 (See Figure S41 in the Section S4 of the Supplementary material). This optimal simulation sensitivity does not reach the magnitude seen in Zhang et al. (2014). Using these inputs, SIF almost double between V_{cmax} values of 10 and 200 μmol m^{-2} s^{-1}, whereas Zhang et al. (2014) sees SIF increases by a factor greater than three (See Figure 3 in Zhang et al., 2014). Again, with the current version of SCOPE we are using, we do not find such a strong sensitivity of SIF to V_{cmax} as obtained from Zhang et al. (2014). Our results do show a weak sensitivity of SIF to V_{cmax} under low light condition and this sensitivity slightly increases with the increase of the radiation , but only for a large proportional increase of V_{cmax} (e.g., between 10 and 75μmol m^{-2} s^{-1}) related to the growing period of the crops (Figure S41 in the Supplementary material).

   In addition, we also investigated the sensitivity of SIF to both C_{ab} and LAI and as already reported in the paper, SIF is strongly sensitive to these two parameters (Figure S41 in the Supplementary material).

2. The version of SCOPE used in this study shows a very weak sensitivity of GPP to the chlorophyll content (C_{ab}), which is obtained only for small C_{ab}. Effectively, this contradicts established positive relationship between the two variables as reported in Fleischer (1935) and more recently in Gitelson et al. (2006). As already mentioned in the discussions of the submitted version of the manuscript, in the current version of the SCOPE model, C_{ab} and V_{cmax} are independent parameters, but in reality they are correlated. A nitrogen scheme as a more explicit link between C_{ab} and GPP may be required in the model. Moreover, as stated in van der Tol et al. (2014), the computation of the fluorescence yield Φ_{Fm} (Eq.2 in this paper) depends on the parameter K_n, which is unknown and there is no theoretical basis to constrain it. Thus, an empirical relationship of K_n is used to calculate Φ_{Fm}. In the current version of the model SCOPE, there are two parameterizations of K_n. In this paper, we use the parameterization of K_n from a Flexas' dataset that includes drought stress, as noted within the model. Nevertheless, we have tested the other parameterization and large differences are found from their SIF output. Consequently, more research is needed to consolidate SIF modeling in SCOPE biochemistry model as there can be a notable effect of different models for K_n on the photosystem yields and subsequent sensitivity of SIF.

These comments are now used in the discussions at the relevant part.

3. The photosynthesis equations within SCOPE are in common use within the land-surface modeling community. They are based upon Farquhar et al. (1980) and Collatz et al. (1992) photosynthesis models for C3 and C4 plants respectively (see van der Tol et al., 2009). SIF calculations are performed after the calculation of photosynthetic yield in the biochemical module. Thus we may assume these photosynthesis equations have been tested extensively in the past. Additionally, any comparison of SCOPE GPP to observed (e.g. fluxnet) would likely require an in depth analysis of the canopy radiative transfer and other "new" aspects of the model which is outside the aims of the current study.

   Nevertheless, we have now made SCOPE simulations using temperature and incoming short wave radiation observed at two FLUXNET stations: Hyytiala (acronym FI-Hyy, longitude/latitude of $24.295^o/61.847^o$) and Roccarespampani 1 (acronym IT-Ro1 $11.93^o/42.408^o$). The FLUXNET data is described in e.g., Baldocchi (2003) and Papale et al. (2006) with the dedicated website from: http://www.fluxnet.ornl.gov. Unfortunately, we do not have any observed LAI data at these selected stations. We have then used the monthly LAIs of the biosphere model BETHY, which are relevant for the vegetation of the FLUXNET station. Note that we used these BETHY LAIs in the CCDAS built around SCOPE in this study. For this exercise, we keep constant the V_{cmax}. The modelled GPPs are compared against the FLUXNET ones. Note also that these stations have no observed SIF.

   As an illustration of the diurnal variations of both the simulated and observed GPP together with the input variables and also the simulated SIF at the station Hyytiala are shown in Figure 4 in the revised version of the paper. This new Figure replaces the one in the submitted version of the paper (i.e., diurnal variations at Cabauw). Overall, results obtained from these two stations clearly show that SCOPE model can nicely reproduce the diurnal observed GPP with meaningful choices of both LAI and V_{cmax} values (See Figure 4 in the revised version of the paper and also Figure S21 in the Supplementary material).

   The seasonal variations of these quantities are computed for some years at each of the two selected sites and shown in Figures S22 and S23. The model reproduces quite well the observed GPP. However, the simulated SCOPE GPP peak over a year occurs earlier (within 1-2 months) than observed ones. This result is maybe caused by both LAI and V_{cmax} of BETHY which seem apparently large during the growing season of the vegetation at these sites. Note that in these simulations, the LAIs are kept constant during a whole month and V_{cmax} is set constant for each BETHY PFT. The results of these preliminary analyses can be then reinforced by using e.g., the satellite MODIS weekly LAI data relevant for these stations.

   Since the detailed evaluation of the SCOPE GPP is beyond the scope of this study, we do not repeat the exercise for either other FLUXNET stations or compute any metrics that quantify the performance of the model in reproducing GPP. These preliminary analyses reinforce our aim to use the CCDAS to optimize the V_{cmax} given the climate data (including meteo, LAI). Indeed, the differences between SCOPE modelled GPP and FLUXNET one depend on both LAI and V_{cmax}.

4. The reviewer #4 argues that the lack of the sensitivity of SIF to V_{cmax} in the CCDAS is mainly due to the fact that the simulations are performed under low light conditions. As an illustration of the effect of incoming radiation on the SIF to V_{cmax} sensitivity, we show the SIF-V_{cmax} relationship under six radiation conditions ranging from 10 to 1200 Wm^{-2}, with a chlorophyll content of 40 ug cm^{-2} and LAI of 3 (See Section 1 of Supplementary material Figure S12). This shows that even under very high radiation conditions the sensitivity may still be considered low to moderate. We have examined in detailed the values of the short wave radiation (R_{in}) used in the CCDAS simulations. We derived the mean, median, and quartiles together with the minimum and maximum values of these R_{in} at global and regional (North Hemisphere, Tropics, and South Hemisphere) scales (See Figure S31 in the Section S3 of the Supplementary material for details). Overall, R_{in} values used in the CCDAS are mostly under moderate light conditions (around 400-600 W/m^2), but at some pixels R_{in} values can be larger than 800 W/m^2. Also, as described in the Section 3.2 of the paper, the CCDAS simulates hourly SIF and GPP for one representative day in a month. We do that because the computation of fluorescence SIF is time demanding. We then compute both SIF and GPP only at 12 h local time, i.e., around the time of their peaks during a sunny day. Thus, in accordance with the idealized tests, these light conditions used to force the CCDAS can explain only a small part of the lack of sensitivity of SIF to $_{Vcmax}$. The range of V_{cmax} used in the CCDAS does explain the great part of the lack of the sensitivity. Indeed, as clearly shown in Figure 3 of the paper (also Figure S13 in the Supplementary material) dealing with the sensitivity of simulated SIF to V_{cmax} for various R_{in} values, even under high light conditions (i.e., R_{in}> 600 W/m^2), the sensitivity of SIF to V_{cmax} is still low between two consecutive V_{cmax} values. As an example, at R_{in} value of 800 W/m^2, we see little difference in SIF between V_{cmax} 75 and 125 μmol m^{-2} s^{-1}. The largest difference in SIF of about 1 W m^{-2} μm^{-1} sr^{-1} is found for V_{cmax} between 10 and 250 μmol m^{-2} s^{-1}. Such a rapid increase of V_{cmax} may occur only during the growing season. Thus, except during the growing period of the vegetation, simulated SIF is insensitive to $V_{cmax.}$

   Moreover, the SCOPE simulations using FLUXNET data for high light conditions do not also show any sensitivity of SIF to V_{cmax} (see Figure 4 of the revised paper and other results described in the Section S2 of the Supplementary material).

   In conclusion, we still think that SCOPE SIF is not enough sensitive to V_{cmax} in its current version. Hence, we do not amend our conclusions about the sensitivity of SCOPE SIF to V_{cmax}.

5. The abstract has been revised as follows:

   We investigate the utility of satellite measurements of solar induced chlorophyll fluorescence (SIF) in constraining gross primary productivity (GPP). We ingest SIF measurements at the frequency 755 nm into the Carbon-Cycle Data Assimilation System (CCDAS) which has been augmented by the fluorescence component of the Soil Canopy

Observation, Photochemistry and Energy fluxes (SCOPE) model. The usefulness of SIF to constrain GPP is then investigated along with the assessment of the sensitivity of both SIF and GPP to the carboxylation capacity (V_{cmax}) and the chlorophyll content (C_{ab}) for different plant functional types (PFTs) subjected to various environmental conditions. Since the relationships between V_{cmax} and both SIF and GPP are subtle, we first perform sensitivity tests through idealized experiments by using the SCOPE model alone. Then, we investigate the ability of the built CCDAS to reproduce SIF measurements obtained over 2009-2010 period.

Idealized sensitivity tests of SCOPE show that GPP is strongly sensitive to V_{cmax} and the incoming radiation, while SIF exhibits a strong sensitivity to C_{ab} and incoming radiation. The sensitivity of SIF to V_{cmax} is low, but does show a slight increase with increasing radiation and within the range of V_{cmax} expected during the growing season where a rapid increase productivity from low V_{cmax} values can occur.

CCDAS simulates well the patterns of satellite measured SIF suggesting the combined model is capable of ingesting the data. CCDAS supports the idealized sensitivity tests of SCOPE, with SIF exhibiting sensitivity to C_{ab} and incoming radiation, both of which are treated as perfectly known in previous CCDAS versions. Effective use of SIF measurements in future will require careful consideration of these factors, as well as development of the link between SIF and GPP within SCOPE.

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Interactive comment on “Investigating the usefulness of satellite derived fluorescence data in inferring gross primary productivity within the carbon cycle data assimilation system” by E. N. Koffi et al.

Anonymous Referee #1
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In what follows, the comments of the reviewer are in italic and our reply in normal face.

General comments

The opportunity of using solar induced fluorescence (SIF) data obtained from satellites opens new perspectives in the study of vegetation-atmosphere interaction. In fact, differently from reflectance, fluorescence is produced by plants as direct result of their biological activity, so it has the potential of being a direct measure of photosynthesis. The efforts aimed at implementing SIF data into biogeochemical modeling have therefore a great potential in global carbon cycle studies. The CCDAS model used in the present work by Koffi and colleagues, with his prognostic capabilities, is apparently an adequate tool for testing SIF data potential.

In the current study, the Authors tried to implement into CCDAS a module coming from another model, SCOPE, and to derive fluorescence and gross primary productivity at regional and global scale, essentially moving from absorbed photosynthetically active radiation (aPAR) data and chlorophyll content information.

Results are realistic in terms of modelled GPP and SIF, but is worth mentioning that both variables are linked with aPAR, so it is not clear what is the real improvement coming from of the current modeling effort. It seems to me instead, that equifinality exists between fluorescence and aPAR (and possibly also with chlorophyll content and Vcmax). I’m possibly biased toward data-oriented semi-empirical models, but I would find more interesting to see model outputs obtained using SIF measured data as an input, possibility mentioned at the end of the paper.
Unfortunately the problem isn't equifinality. Equifinality occurs when many different values of the target variables project onto the same value of the observable. In that case there is information on the target variables available from the observations but it is not independent information on each target variable. If there is little sensitivity of an observable to a target variable we cannot extract much information from the observations, even if the observable is a function of only that variable. The more general question of model structure is an interesting one. Put bluntly we can ask "Is SCOPE a good model?" That's a model evaluation question. It must be addressed but not here.

There are also aspects not fully convincing in the model output, like the relation between chlorophyll content and GPP (Fig. 2d), apparently contradicting the well established positive relationship between the two variables (Fleischer, 1935). This is acknowledged at the end of the paper, where a potential effect of Nitrogen content is also invoked, but highlights anyway the limits of the current modeling exercise.
We reply to this in the item 2) of our general comments

What I find to be missing, in order to properly evaluate the results from the current modeling activity, is an independent testing of the results in terms of modelled GPP. Since thousand of site-years of GPP data are available from the FLUXNET database, I strongly recommend to perform model-data comparison in a revised version of the paper, instead of using a single period of a FLUXNET site (probably Cabauw, NL, 2006) in which GPP data were not available, as in the current version of the paper.
We have made SCOPE simulations by using meteorological data (here temperature and incoming short wave radiation) observed at two FLUXNET stations: Hyytiala (acronym FI-Hyy, longitude/latitude of 24.295°/61.847°) and Roccarespampani1 (acronym IT-Ro1 11.93°/42.408°). The diurnal variations of both the simulated and observed GPP together with the input variables and also the simulated SIF at the station Hyytiala during summertime are shown in Figure 4, which replaces the one in the submitted version of the paper (i.e., diurnal variations at Cabauw). For details, see item 3) in our general comments.

Specific comments

The abstract is extremely short and not very informative: which are the main findings from the current study?
The abstract has been revised (see our general comments)

Page (P) 708, Line (L) 16-18. The term 'system' is repeated three times, probably with different meanings. As a result, the sentences are somewhat hermetic.
The sentences have been clarfied.

P708 L21: 'Recent work have': Please check grammar. It is p709 L21
OK. Done

P709 L24, P710 L2: 'data are', 'data is': Please be consistent.
OK. We correct with "data is"

P710 L1: The CCDAS model is clearly presented in Scholze et al., 2007, while here information on its structure is missing. I prefer self-standing papers, so I recommend a short overview of that model also here.
The main components of the CCDAS were already defined in the introduction and now clarified when describing the CCDAS built around BETHY. Also, the work of Scholze et al. (2007) has been cited in this paragraph. We still think that enough information is given in the paper for the description of the CCDAS which prevents to lengthen it. For more details, the readers may report to the cited works.

P711L27: 'The vegetation is characterized by different values of the leaf area index (LAI).' I guess the Authors refer to the parameter vector representing vegetation.
We are talking about the idealized tests when using the SCOPE model alone. Thus, the different values of the leaf area index (LAI) concern the single values used in the sensitivity tests as shown in Figure 2. This has been clarified in the text by adding that these LAI values are for the idealized tests

P713L1: 'from absorbed fluxes': which kind of fluxes?
Replaced by "radiative fluxes"

P716L7: '13 plant functional types (PFT) based on Wilson and Henderson-Sellers (1985)': Unfortunately, these 13 plant functional types are not defined elsewhere in the text, and in the mentioned paper from Wilson and Henderson-Sellers a total of 80 land cover classes and 8 grouped land cover classes were defined.
In fact these 13 PFTs are defined in Table 1. This is clarified by quoting the Table 1 in this sentence

P718: 'vapour pressure'. It is not clear to me which kind of information the Authors try to capture from vapour pressure information. In plant physiology it is well established a linkage between the vapour pressure deficit (dew point water vapour pressure observed vapour pressure) and stomatal conductance and also GPP (e.g. Duursma et al., 2014), but I'm not aware of a direct link between plant physiological responses and air water pressure. The same at P723L7 and in Fig. 4a.
It is effectively misleading. We are talking about the air vapour pressure at leaf level used to compute the internal CO_2 concentration of the leaf in the biochemical model. This has been clarified where needed.

P722L7: Since aPAR appears to be a key variable in this modelling, it is not clear to me why the authors do not show it in the graphs.
This comment concerns the graphs in Figure 2. Effectively, we do not show the aPAR on this Figure because we have the intent here to examine the sensitivity of both GPP and Fs to input data. As already reported in the submitted version of the paper, we also produced the graphs with aPAR. The graphs with aPAR are now given in the Supplementary material (See Section S1).

P725 L20-21: 'regional: : :regions'? Please correct.
The sentence is reformulated as "Correlations are computed at global and regional (southern hemisphere, tropics, and southern hemisphere) scales and over the studied period"

P729L19-20: 'Any model seeking to use Fs should therefore account for chlorophyll concentration.' I think that the Authors are doing a merely inductive reasoning while making this statement. They tested a single model only, indeed.
The sentence is replaced by "This study also shows that the use of Fs measurement in the model should account for chlorophyll concentration".

P 731L15-16: 'We have seen a strong linear relationship between the fluorescence Fs and aPAR.' Is this an observational result or a modeling result?
Both. As an example, the results in Figure 6 show a strong correlation between modelled Fs and aPAR and a good correlation between measured Fs and aPAR from the CCDAS simulations. The sentence is then reformulated as "We have seen a good linear relationship between the fluorescence Fs and aPAR"

Figure 4. Looking at the main x axis and at the represented daily patterns, it seems that both GPP and fluorescence have a peak at midnight in the second day of the time series. It looks strange.
This Figure is replaced by a new Figure (see our comments above).

Captions of Fig. 5 are really unclear, consider rewriting.
The captions have been clarified.

Figure 6 is difficult to be understood, since the colours representing the different PFTs are not defined.
This has been clarified.

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