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 $\mu mol\ m^{-2}\ s^{-1}$; temperature varies from 10^oC to 30^oC; C_{ab} values from 1 to 80 $\mu g\ cm^{-2}$. 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^oC, 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 $\mu mol\ m^{-2}\ s^{-1}$, 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 75$\mu mol\ m^{-2}\ s^{-1}$) 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.

References

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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 #4
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In what follows, the comments of the reviewer are in italic and our reply in normal face.

The present study attempts to evaluate the usefulness of space-borne measurements of solar-induced fluorescence (SIF) data in constraining GPP within a Carbon Cycle Data Assimilation System (CCDAS). The recent available satellite SIF data has provided a new perspective on monitoring broad-scale vegetation photosynthesis as chlorophyll fluorescence is central to photosynthesis. In the current study, the authors used CCDAS as an additional tool to investigate the potential of SIF as a complementary to some recent work. The results are quite meaningful. However, there are some major issues which are needed to be addressed.

General comments

In this study, they found that fluorescence is not sensitive to the key parameter (Vcmax) of a coupled photosynthesis-fluorescence model, which directly contradicts with a recent work by Zhang et al. (2014) as they stated in their conclusion. They also found that fluorescence is more sensitive to chlorophyll concentration (Cab) but GPP not. These findings also contradict with the results from FLEX/Sentinel-3 Tandem Mission Photosynthesis Study – FINAL REPORT (Mohammed et al., 2014) in which they showed that fluorescence is more sensitive to Vcmax than Cab both for C3 and C4 plants.
Effectively, the sensitivities reported in Mohammed et al. (2014) show that SIF is more sensitive to V_{cmax} than C_{ab} mostly at the frequency 687 nm and these sensitivities seem depend on the range of the V_{cmax} and C_{ab} values used for the computation of these sensitivities (Pages 79-80 of the report). We have simulated SIF at the frequency 687 nm and effectively SIF is more sensitive to V_{cmax} than C_{ab} over the range of C_{ab} and V_{cmax} used in their study. When simulating at the frequency 687 nm, SIF is found to be more sensitive to C_{ab} for only very low C_{ab} values ($< 10\ \mu g\ cm^{-2}$), while SIF is strongly sensitive to V_{cmax} over a large range of V_{cmax} values. Hence, the results from Mohammed et al. (2014) do not contradict our results, but the differences between the two conclusions clearly illustrate the need to specify the settings of SCOPE when making comparison with other studies.

The reason for such a difference between the current study and Zhang et al. (2014), in my opinion, is due to the following:
(1) Under light saturation conditions (high light illuminations), plants photosynthesis is limited by Rubsico maximum carboxylation rate (Vcmax) in the Faquahar et al. model, and hence for fluorescence in the model. In the Figure 2a of their study, the authors show the sensitivity of SIF to Vcmax at an incoming radiation level of 500 W/m2 (Rin). In the study of Zhang et al. (2014), they focused the analysis during the growing season at crop sites. The Rin in these crop sites (e.g., Mead sites) can be more than 900 W/m2 (generally larger than 700) around noon during July and August. Hence, the radiation level in the current study may be too low as they stated in

their manuscript in P726, Line 3-4. This level of radiation may be still in light-limited conditions for plants. In the study of Zhang et al. (2014), they also pointed out that the sensitivity of SIF to Vcmax is not high during the early or late growing season.

This is the most important factor why the simulated Fs is not sensitive to Vcmax. As stated in the study of van der Tol, et al., (2015), ' When light is in excess or stress develops there is a reduction in the fluorescence yield and the slope of the dependence of SIF on light intensity declines. This is the basis for inversions to obtain Vcmo [Zhang et al., 2014]. With increasing stress or reductions in Vcmax at constant light (as would occur with repeated sun synchronous satellite observations), SIF would be observed to decrease. The extent of this decrease may depend on the severity and type of stress.'.

(2) The study of Zhang et al. (2014) focused on the cropland, especially for C4 crop (corn). The authors need to mention this when making the comparisons.
(3) The current study used monthly observed climate data including incident radiation to drive SCOPE which gave smaller radiation values as they mentioned. While Zhang et al. (2014) used field instantaneous meteorological and other measurements (e.g., LAI etc) which represent more actual conditions. As they stated in P731 Line 1-3, if they optimally chose temperature and LAI, they could reproduced a sensitivity about 2/3 that shown in Zhang et al. (2014). This means that the data set they used to drive SCOPE has given some uncertainties for the sensitivity analysis. This raised the concern whether they can used mean monthly observed data for SCOPE since it need instantaneous driver especially for radiation. This should be discussed carefully.
Our responses are given in items 1) and 4) in our general comments

In summary, the authors need specify and mention the different conditions when they compare with other studies.
The different settings when comparing our results to those of Zhang et al. (2014) are now given in a new Table (Table 2). Otherwise, the settings are specified in the legends of the figures.

The Abstract is not clear at the current stage. They should clearly state their main findings.
Their Fig.3a is similar to the Figure 12 (lower left) in the study of van der Tol, et al.,(2015), but with lower sensitivity of Fs to Vcmax. This needs to be discussed and explained.
The analysis presented in van der Tol et al. (2014) (Figure 12) deals with fluorescence flux at leaf level, while SIF in Figure 3 is computed at the canopy level, as described in the Section 2.1.1 of the paper. In fact, van der Tol et al. (2014) argued that "*in the canopy, leaf illumination is variable among leaves, and the relationship after aggregating over all leaves may differ from what we presented here* (i.e. in their Figure 12)". That is exactly what we obtained in this study (e.g., Figure 3). Moreover, we do not use the same K_n model when computing the fluorescence yield (see item 2) in our general comments for more details)

For the diurnal simulations, they could use other FluxNet sites to make the comparison with the SIF and GPP measurements. This would make the diurnal simulations more meaningful.
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 $24.295^o/61.847^o$) and Roccarespampani1 (acronym IT-Ro1 $11.93^o/42.408^o$). 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.

LAI is a more important parameter for both SIF and GPP simulations. In the sensitivity analysis in 3.1, why don't they provide the sensitivity analysis for LAI?
The sensitivity analysis for LAI was already discussed in either the idealized tests (Figure 2) or the CCDAS simulations where the LAIs are provided at each grid cell of the model at global scale. Thus, in Figure 2 of the paper, the graphs are generated for several values of LAIs. As expected, both SIF and GPP are sensitive to LAI and this sensitivity slightly decreases for large LAI values (>4). Comments about these results were already mentioned in the submitted version of the paper in Section 4.1.1.

Specific & minor points (reference is made to page P and line L numbers):

P708 L7-8: Need specify the result is for low-light conditions within the CCDAS.
The short wave radiation values used in the CCDAS span large range representing low and high light conditions. Therefore, we do not mention this. See item 4) in our general comments for further details

P708 L14: The natural terrestrial carbon flux
OK. Done

P708 L14: This sentence is not clear.
The sentence has been clarified.

P709 L17: 'their estimates' means what?
Their GPP estimates. This has been clarified

P709 L18: '. . . larger GPP in the tropics .." compare to what?
Koffi et al. (2012) found larger GPP in the tropics compared to those inferred from satellite based up-scaling methods. This has been clarified.

P709 L21: '. . . plant fluorescence (hereafter Fs) . . .' . Please consider ' sun-induced fluorescence (SIF)' and revise through the manuscript.
SIF has been used to replace Fs through the manuscript as suggested.

P709 L24-25: ' They showed . . . GPP at the global scale'.
OK. Corrected as suggested.

P710 L3-4: Not really well understood, especially with the stead state fluorescence.
Need reference here.
The references are already given afterwards in the submitted version of the paper by quoting different studies about that.

P715 L14-15: Not summation of fluorescence yield Φft, but florescence flux.

OK. Corrected.

P716 L2: should be ' canopy radiative transfer'?
Yes. Corrected.

P717 L21-24: SCOPE need instantaneous driver, especially for radiation input, are the mean monthly observed climate data OK for the simulations?
Yes. See our general comments for the range of their values in item 4)

P719: Are the sensitivity running of SCOPE at hourly step?
Yes. 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. Thus, we compute both SIF and GPP only at 12 h local time, i.e., around the time of their peaks during a sunny day. Moreover, for the idealized tests, both SIF and GPP are computed at 12 h (see Section 3.1). This is now clarified.

P720 L19-21: I would say, C4 vegetation is more sensitive.
Yes, but not at this place. We say this after the sensitivity tests in the Section 4.12

P720-721: Need point out the sensitivity analysis is under light-limited conditions.
No. We made the tests first by using short wave radiation R_{in} of 500 W/m^2, then we examined the sensitivities of both SIF and GPP to R_{in} (Figure 2 of the paper). Furthermore, we investigated the sensitivities of SIF and GPP to V_{cmax} for various values of R_{in} (Figure 3)

P721 L25-28: This contradicts with well-known and many published studies. Need specify why.
Yes. This was already acknowledged in the discussions. Now, we mention this also in this part.

P723 L10-11: In my opinion, Vcmax impacts the values of SIF and GPP, but not their relationship.
The simulated SIF and GPP are strongly sensitive to aPAR. GPP is strongly dependent on V_{cmax} and this study shows that SIF is dependent to C_{ab}. Having a subtle relationship between these variables (i.e., SIF and GPP) via V_{cmax} or C_{ab} can help to transfer SIF information to GPP and vice versa. This is the basic element of the CCDAS since aPAR (or short wave radiation) are input variables to this system.

P724 L4-6: Should include negative retrievals of SIF.
We agree with reviewer that measured negative values of SIF are signal. However, the SCOPE model does not simulate such SIF negative values. Hence, considering the observed negative values of SIF will systematic bias the result. To avoid this, we only consider only positive measured SIF in the comparison.

P726 L3-4: How smaller is the Rin in the CCDAS than actual values? The radiation level determined the relationship between SIF and GPP, and their sensitivity to Vcmax.

See our general comments in item 4). The range the radiation used in the CCDAS is now given in the Section 3.2 and R_{in} are cover moderate light conditions and also in some cases high light conditions

P729 L16-18: should be ' . . . is unlikely to work within the CCDAS'.
OK. Done

P730 L18-19: You need mention that the work of Zhang et al. (2014) was at light saturation state for cropland.
OK. Done

P730 L19-20: How the 4 times differences come from? In their work of Zhang et al. (2014), they showed different sensitivity of SIF to Vcmax for different period of the growing season for the cropland. If you compared the sensitivity of SIF to Vcmax for the early growing season (e.g., early June) with that in the middle of growing season (e.g., July), there are also differences especially for C3 crop. Please also check the general comments.
See our general comments in item 1)

P731 L1-3: This is good point. Need discuss more.
See our general comments in item 1)

P732 L8-9: Need mention the illumination condition (light limited or light saturated).
No. See item 4 in our general comments