

## ***Interactive comment on “Filling-in of far-red and near-Infrared solar lines by terrestrial and atmospheric effects: simulations and space-based observations from SCIAMACHY and GOSAT” by J. Joiner et al.***

**J. Joiner et al.**

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**We thank Dr. Guanter for his careful review of the manuscript. For convenience, we include his full review here and respond to his comments in bold below.**

The authors build on previous work on the exploitation of satellite measurements in solar Fraunhofer lines for the retrieval of non-solar electromagnetic signals (as opposed to reflected solar radiation). The basic idea is that surface or atmospheric emitted signals superpose to solar-reflected radiation at the TOA in an additive way, which

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makes both emitted and reflected signals can be decoupled by the modeling of the fractional depth of solar lines. In a previous work, the same authors demonstrated the feasibility of using this concept for the retrieval of terrestrial chlorophyll fluorescence (Fs) from GOSAT-FTS measurements in the Fraunhofer line in 770.1 nm (Joiner et al., Biogeosciences, 2011).

In this new manuscript, they extend this approach to a Fraunhofer line in 866 nm which is sufficiently resolved by SCIAMACHY coarser resolution measurements. The authors find an additive signal in 866 nm which correlates spatially with vegetated areas as indicated by satellite-based vegetation indices and with GOSAT-based Fs. Despite only a very low Fs signal could happen at that wavelength (most of the Fs emission is expected to happen in the 650–800 nm range, with a steep decrease towards the edges of this interval), it can be speculated it is the most likely reason to explain the observed in-filling of the 866 nm line. As a secondary objective, the authors report on the improvements performed on their GOSAT Fs retrieval scheme, which now includes a time-dependent set of reference spectra to model Fs in-filling.

The manuscript tackles a rapidly rising field of research, to which the authors have considerably contributed. The methodology and sensitivity analyses proposed for the retrieval of in-filling signals in 866 nm seem sound, and the results strengthen the confidence on the feasibility of Fs retrieval from space. Although I consider some points concerning the introduction, methodology and results must be addressed (see comments below), I recommend the manuscript for publication in AMT. The following comments and suggestions might help to improve the manuscript.

**We thank Dr. Guanter, whose pioneering work broke ground in satellite fluorescence measurements, for these encouraging comments and for the suggestions that help to improve the manuscript. Please see our responses below.**

1. Statement of the problem: Almost no experimental evidence supports the existence of a non-negligible Fs signal for wavelengths >850 nm, where any Fs ap-

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pears to be below the NEdL of standard lab and field instruments. The possibility of a measurable Fs signal of  $\sim 0.1\text{--}0.2\text{mW/m}^2/\text{sr/nm}$  under natural illumination conditions and the leaf-level is discussed in Section 2, without a clear conclusion as to whether those Fs levels in 866 nm are realistic for the SCIAMACHY spatial and temporal scales. The authors choose then a conservation position and only refer in the remaining of the paper to the detection of a general in-filling signal, "chlorophyll-a fluorescence being a plausible candidate".

Some points concerning this:

- Sections 1-Introduction and 2-Laboratory measurements are solely dealing with the description of the Fs signal and its detection from space. This does not seem to be consistent with the rest of paper, which only proposes Fs as one of several possible candidates for the observed in-filling. "we make no assumption about the source of the additive signal" is stated in Section 4.1. Fs is not mentioned in the title either. It is appreciated that the authors do not want to over-sell the point of Fs measurement in 866 nm in view of the mentioned concerns about the signal levels. But the introduction does not seem to show this, which is confusing to the reader at the first glance. Please, consider to rewrite some parts of the text according to this.

**We have revised the abstract, introduction, and Sect. 2 to be more consistent with each other as well as with the foci and flow of the rest of the paper. Also, see response to comments below such as adding "fluorescence" to the title. These changes clearly place emphasis on the fact that we are examining the filling-in of NIR solar lines with the primary objective of showing that the Ca II line filling is consistent (at least in part) with emission expected from vegetation fluorescence. We also changed the wording of the statements regarding "no assumption about the source of the additive signal". In Sect. 4.1, the statement now reads "Note that the above results hold for any type of additive signal including fluorescence from sources in**

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**vegetation or minerals," and later describe  $\overline{F}$  simply as "a generic additive signal".**

- Concerning section 2, I feel it is crucial for this work to make as much a solid statement about Fs emission in  $\text{wvl} > 850\text{nm}$  as possible. Although it is understood that it might be rather difficult to find experimental evidence on this, the paper might greatly benefit from extending section 2 with more information, references and discussion. In particular, some lines about the effect on Fs levels of morning rather than afternoon illumination (SCIAMACHY and GOSAT, respectively) would be important. The title "Laboratory measurements" could be extended to include fluorescence.

**We have added "fluorescence" to the section title as suggested. The new title is "Laboratory measurements of fluorescence at wavelengths  $> 850\text{ nm}$ ". We were unable to find additional references describing fluorescence measurements beyond 800 nm. We added the following sentences: "Laboratory instruments using light-induced pulses have focused on the red and far-red fluorescence emission peaks and not the far-red/NIR emission tail in diagnostic measurements. This is true for laser-induced lab and field measurements as well. Detectors are typically chosen to be affordable and are therefore usually limited in spectral range. Consequently, very little information is available on the NIR tail region beyond about 800 nm."**

**We also added more text to this section, specifically discussing a reference that describes diurnal measurements: "They (Amoros-Lopez et al., 2008) also measured a diurnal cycle of fluorescence for wavelengths up to 800 nm using artificial illumination in a setup similar to that described above. Their results show very little difference in fluorescence measured at 10:00 (close to the SCIAMACHY local overpass time) and 12:00 (closer to the GOSAT local overpass time) for wavelengths between 770 and 800 nm." Fluorescence at 14:00 was slightly lower (by  $\sim 15\%$ ) as compared with noon.**

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On the other hand, the relatively important updates of the older GOSAT Fs retrieval approach by Joiner et al (2011) are not mentioned in the introduction. Considering this is not a negligible point of this manuscript, a brief discussion of this (e.g. why the approach needed to be updated) could be added to the statement of the problem.

**We agree that the updates to the initial GOSAT results are an important part of the paper. We had stated in the introduction, “Here, we build on that (previous) work by developing methodology to correct for instrumental artifacts that produce false filling-in signals that can bias fluorescence retrievals.” More discussion on this point is given in the later sections. We have added discussion of this point in the introduction as suggested: “The methodology is applied to both SCIAMACHY and GOSAT data and is generalizable to other instruments. This methodology improves upon the accuracy of the results reported in the initial study of Joiner et al. (2011) and enables the use of more data as compared with the approach of Frankenberg et al. (2011) thereby potentially improving the fidelity of GOSAT data.”**

## 2. Methodology

- As in Joiner et al (2011), Fs retrieval is performed over narrow spectral fitting windows ( $\sim 0.35\text{nm}$ ) containing one single Fraunhofer line. However, as discussed by Frankenberg et al (2011), the use of wider spectral windows with several lines (e.g. 756-759nm and 769-774nm) should lead to a much lower sensitivity to noise, which is the main error source in GOSAT retrievals. Why is the retrieval approach not making use of wider fitting windows, at least for GOSAT? There seems to be nothing in the current narrow-window approach which prevents it to be extended to wider windows. The reason to keep using those narrow fitting windows should be discussed in the manuscript, maybe including simulations of single-retrieval 1-sigma error for the narrow and wide fitting windows.

**As the scope of this paper is already quite large, we prefer to leave to a fu-**

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ture study the investigation of the intricacies of using different fitting windows. We revised the text on this point and now state “Our fitting windows are similar to *though more narrow* than those used by Frankenberg et al (2011).” We also added to the revised version “While the use of broader fitting windows that include more Fraunhofer lines may potentially improve the signal-to-noise ratio of the retrievals, it may also require the retrieval of additional parameters such as those that account for the wavelength dependence of reflectivity and fluorescence. We have chosen here a conservative approach that utilizes narrow windows that contain the strongest Fraunhofers lines, although the approach can be extended to wider fitting windows. Further optimization of fitting windows is beyond the scope of this work but may be the focus of a future study.”

Apart from this, please give an explanation of where the 0.696 scaling factor (3 decimal places?) comes from.

**Upon further consideration, it is not clear given the GOSAT signal-to-noise ratio that a single value of scaling is appropriate. Our revised version does not scale and add results from the two GOSAT fitting windows, but instead shows results from those windows separately. This does not change any of the major findings. Please see updated figures below.**

- No much information is actually given on uncertainties in section 5.7, which might be particularly relevant for the new retrievals with SCIAMACHY. For example, on single- retrieval errors. Could this be added to the text? In particular, what is the random error in Fs due to noise? How many retrievals are normally available for each  $0.5^\circ$  cell of the SCIAMACHY maps, and how is this affecting the standard error?

**As stated, we believe the systematic errors to have a significant impact on retrievals of the additive signal. And as it is difficult if not impossible to estimate the magnitude of the systematic errors and how well our approach**

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corrects them, we did not provide error estimates in the discussion paper, but rather indicated the variability in the derived signals. However, we added to the revised manuscript estimated errors based on the assumption of random noise:

“Here, we similarly compute errors for SCIAMACHY retrievals using the same assumptions. As discussed in Joiner et al. (2011), errors in scaled-F are proportional to  $R / \text{SNR}$ , and the relative error in terms of fraction of radiance is inversely proportional to SNR. For SNR=1000, which is consistent with radiance residuals, we obtain a relative error of 0.3%. For R=0.2 and 0.4, we obtained scaled-F errors of 0.37 and 0.75, respectively. Standard deviations in monthly scaled-F retrievals within gridboxes of  $0.5^\circ \times 0.5^\circ$  are roughly consistent with these expected errors as shown in App. C.”

Furthermore, we added the following regarding the number of retrievals available for the gridded data: “The number of observations in a  $0.5^\circ \times 0.5^\circ$  gridbox in a month varies from 0 to  $\sim 12$ . For the 8 year climatological monthly averages, the number of points in a gridbox thus ranges from 0 to about 100. Therefore, for gridboxes with relatively large numbers of observations, the standard error for the climatological monthly mean can be approximately an order of magnitude less than the standard deviations. Sample global maps of these statistical parameters are shown for January and July in App. C. We note that these values may still underestimate errors in the derived absolute values of  $\bar{F}$  and scaled-F and that theoretical error calculations based on the assumption of random, Gaussian errors may be considered only as a lower limit.” Please see new figures below.

It is also mentioned that both SCIAMACHY channel 4 and 5 are used. How are retrievals from each channel combined in the final scaled-F product? Is the same 1-sigma uncertainty to be expected from each channel?

**We are sorry to have caused confusion. We use only channel 5 in the re-**

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**trieval. This is now clearly stated in a revised version.**

Also, please give more information on the effect of the South Atlantic anomaly (SAA) (?) on the measurements.

**We thought it important to at least mention the potential of the SAA to cause problems in the retrievals. However, we see no definitive evidence of such problems. We now state in the manuscript, “However, we find no clear evidence of the effects of the SAA on our results.”**

3. The Results section might be too short with respect to the rest of the manuscript. Some potential extensions/modifications could be: - Updated GOSAT retrievals: the use of time-dependent reference spectra accounting for both instrument degradation and zero-level offsets are expected to greatly improve the results with respect to those in Joiner et al (2011). Given the fact that that pioneering work has become a reference in these emerging field, it might be useful to discuss in this manuscript why that approach had to be improved, and what the impact of these changes is on the results presented in Joiner et al. (2011). In particular, the  $F_s$  levels in Figs.8-9 (scaled at 770nm) are higher than those described by Frankenberg et al (2011) (scaled at 755nm) and lately by Guanter et al (2012, RSE in press), and there is some trace of non-negligible negative values over some desert areas. Please, add some discussion along this direction.

**The reason for the discrepancy between our GOSAT results and those of Frankenberg et al. (2011) and Guanter et al. (2012) appears to be that in the discussion paper we added the results of the 2 polarizations, whereas Guanter et al. (2012) average the data and Frankenberg et al. (2011) used only a single polarization. When this is taken into account as well as other factors such as that Frankenberg et al. (2011) show mostly annual averages of absolute  $F_s$  (Guanter shows absolute  $F_s$  as well) and we show monthly means and scaled-F rather than absolute  $F_s$  (which is appropriate when comparing with EVI as we do in these figures), our results are quite**

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comparable to the other results mentioned above. We now show scaled-F derived by averaging the polarizations and make this clear in the revised manuscript. We added “We note small differences in absolute values obtained with the two polarizations.” We added in the results section “GOSAT results are comparable in magnitude show similar spatial/temporal characteristics as compared with those of Frankenberg et al. (2011) and Guanter et al. (2012).”

The reasons for improving the approaches of Joiner et al. (2011) as well as Frankenberg et al. (2012) are now stated in the introduction (see response to comment above). Additional discussion was given in Sect. 5.7 including how the results changed as compared with Joiner et al. (2011). As it is always the case that an initial retrieval/result, especially one from a new satellite instrument, is iteratively improved upon in subsequent works, and as this issue was mentioned multiple times in Guanter et al. (2012), we do not further belabor the point.

We added an additional filter that removed anomalously high values of filling-in around coastlines that we believe is due to the SCIAMACHY memory effect (see response to reviewer 2). Additional discussion on this point is now given and text in the previous version that only speculated as to the cause has been removed. All SCIAMACHY results were regenerated with the new filter applied. As this filter significantly decreases the number of retrievals around coastlines, we moved some of the boxes in Fig. 10 away from coasts.

Regarding non-negligible negative values over some desert areas, we added, “We also note some negative filling-in values over these regions that have high radiances values. The memory effect of SCIAMACHY may contribute to these features as radiances at 866 nm show sometimes large gradients over these areas and our filtering scheme may not have com-

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pleted removed all affected pixels. The SCIAMACHY memory effect may also affect the reference spectra, particularly for high values of radiance that correspond to the bright cloudy data over ocean.

- Assuming the retrieved scaled-F signal can be interpreted as fluorescence, it would be very interesting to see long temporal series of scaled-F from the SCIAMACHY product over e.g. the regions of interest in Fig 11. It could also help to discard instrumental effects on the in-filling signal (e.g. instrument degradation).

We have added a figure showing longer time series to illustrate that the effects of instrument degradation are not obvious in the time series in App. C: “For reference, Figure 14 shows the entire time series of monthly-mean scaled-F for 3 of the boxes shown in Fig. 10 where there is a significant seasonal cycle. Inter-annual variability is seen in these data. Evidence of long-term trends due to either geophysical changes or calibration drift is not obvious. Future studies will focus on determining whether the inter-annual variations shown can be related to geophysical parameters such as environmental stress on vegetation. Because the systematic errors that we attempt to correct for can represent a large fraction of the observed additive signal, we do not rule out the possibility that at least some of the inter-annual variations are due to uncorrected systematic errors. That is why we focus on climatological averages in this work.”

- It would be helpful for the GOSAT community to see plots of the temporal dependence of the GOSAT reference spectra referred to in section 5.3.

We have added a figure and short discussion to an additional appendix (B) showing the temporal dependence of the filling-in from cloudy ocean spectra as well a rough latitudinal dependence: “Here, we show temporal and latitudinal variations in the false filling-in caused primarily by the zero-level offset problem in GOSAT data. Figure 12 shows filling-in as a function of normalized radiance binned at intervals of 0.05. We compute the filling-in

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for diagnostic purposes only; it is more straight-forward to interpret and compare with previous works than reference spectra. The overall dependence of filling-in on (normalized) radiance is similar to the dependence derived using data over Antarctica by Frankenberg et al. (2012). However, here we show that the filling-in at low to moderate radiances for both polarizations varies with both time and latitude.”

- Fig. 12-6. High levels of SCIAMACHY scaled-F are shown in June, when EVI is lower than 0.3. This seems unfeasible, and suggests effects other than fluorescence are accounting for the reported in-filling, at least over the India site. Please, comment.

**We do not have an solid explanation for this and that is actually why we chose to highlight this region in the seasonal cycle figure including discussion. We hope that our results will initiate further laboratory as well as field studies in this area. We added “The differences between scaled-F and EVI shown here remain unexplained; it is hoped that future studies will focus on this area to discern whether these differences stem from algorithmic/instrumental artifacts or a geophysical effect.”**

- Figs.9-10: - I think 9 10 could be merged into one single figure showing 4 months, either the central months of each season or the seasonal means. Not much extra information seems to be added by the 12 months.

**We have merged these into a single figure showing 6 months (every other month). This is a compromise to show a good progression of the additive signal and lend more weight to the hypothesis that fluorescence is a significant or primary contributor to the additive signal. See new figure below.**

- TOA radiance instead of reflectance should be displayed if this is to show a potential correlation between Fs retrievals and instrumental effects, as at-sensor radiance would be the parameter driving potential instrument-related in-filling.

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**We have incorporated your suggestion into the revised figure. Overall the spatial variations of radiance do not look very different as compared with those of reflectance; the main difference is of course the north to south gradient produced by the cosine solar zenith angle effect.**

4. Other comments: - Title: 'far-red' could be omitted (near-infrared sufficient for 755-866nm?), whereas it could be considered to add 'fluorescence' as a key-word despite the "conservative" position chosen with respect to the nature of the detected F signal.

**As suggested, we have added “fluorescence” to the title. Because the title is a bit wordy, we removed ‘far-red’. The reason we had used this term is that in the fluorescence community the wavelengths around 740 nm are commonly referred to as far-red. But in the atmospheric community, these wavelengths would also be considered as part of the near-IR.**

- @AMTD Editorial office: the dates of manuscript receive and acceptance in AMTD must be wrong (2011 rather than 2010)

**Thank you for pointing out the error. This will be corrected in a revised version.**

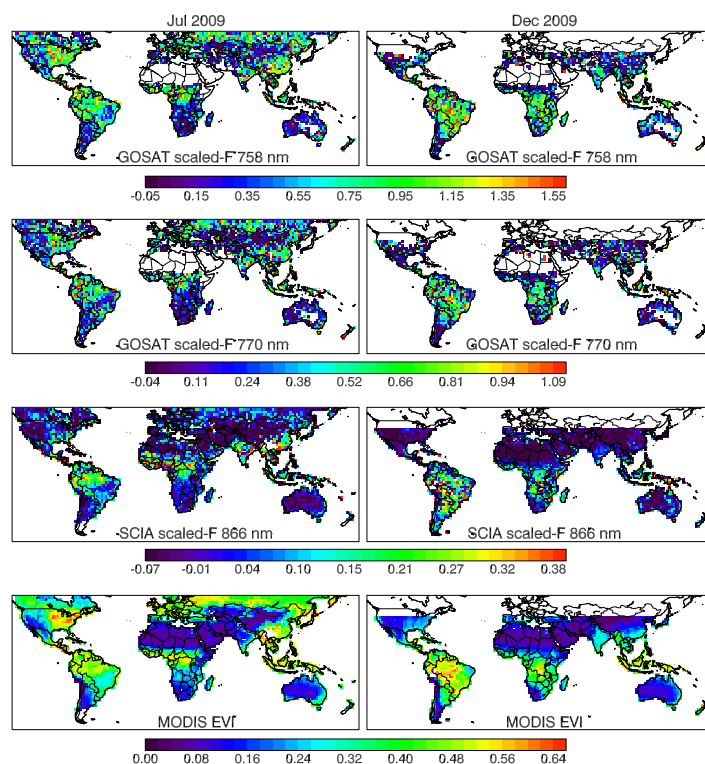
**Finally, we added several references to your recent paper (that you listed as “in press”) but is now published. We also added a paragraph in App. C and a figure showing dependence of the additive signal on viewing geometry. For the record, we found that GOSAT results depended on the QC filter criteria applied and given the relatively short observing record were not robust. Therefore, we focus on the SCIAMACHY results that show significant angular dependences in some regions: “Finally, we note that there is a dependence of the SCIAMACHY retrieved additive signal on viewing geometry. Figure 15 shows scaled-F retrieved on the east and west sides of the SCIAMACHY swath, the difference between the two, and the east to west side swath difference of radiance for the July climatology.**

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The scaled-F angular dependence shows some similarities to that of radiance, but also shows some differences. Guanter et al. (2012) also report on viewing-angle dependence of retrieved fluorescence from GOSAT. These dependences may be related to differences in the amounts of absorbed PAR and fluorescence escaping the canopy for different viewing geometries, related to leaf orientation and canopy effects. The results shown here are preliminary; further examination of these effects will be the topic of future studies.”

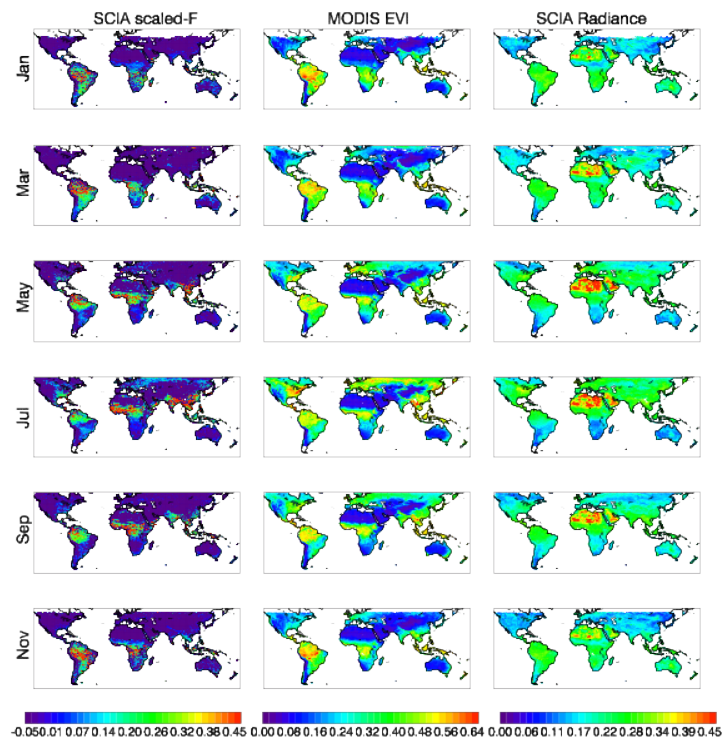
Interactive comment on Atmos. Meas. Tech. Discuss., 5, 163, 2012.

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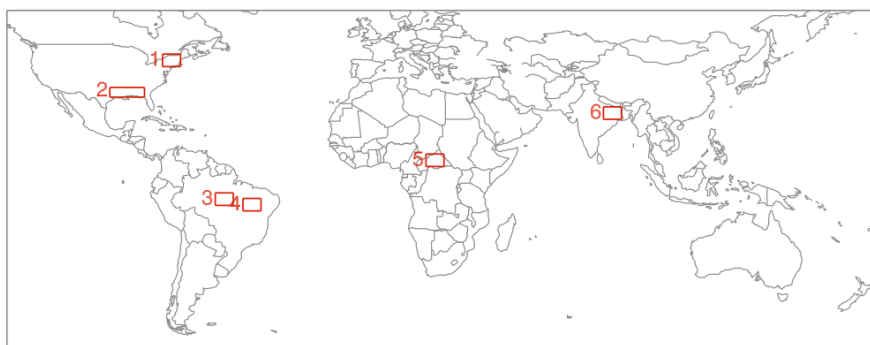
**Fig. 1.** Revised Figure 8 showing GOSAT 758 and 770 nm results separately and with new filter applied to SCIAMACHY retrievals of scaled-F.

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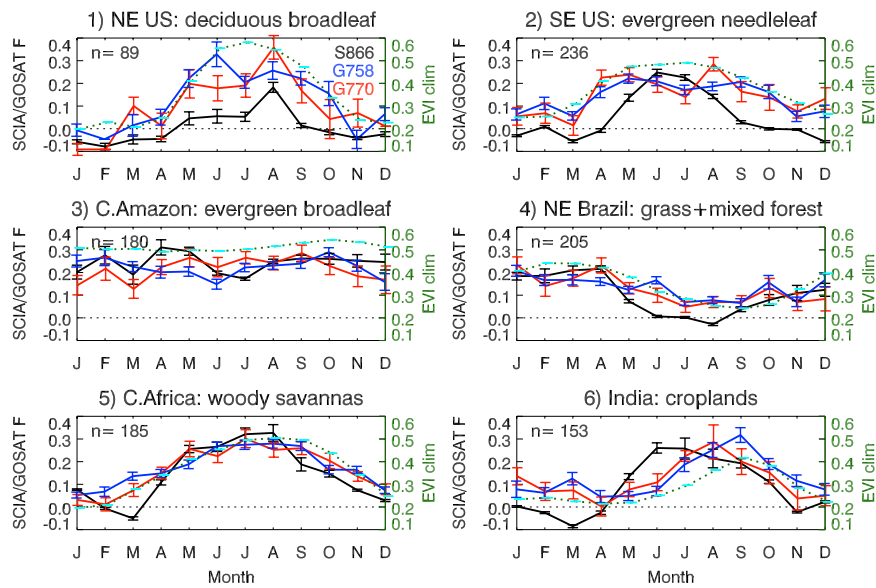
**Fig. 2.** Revised Figure 9 showing every other month, SCIAMACHY results revised using new filter to mitigate problems around coastlines

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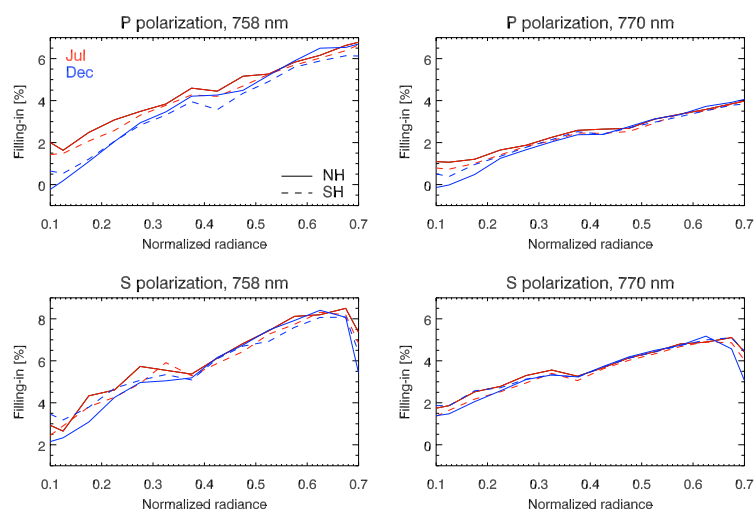
**Fig. 3.** Revised figure slightly modifying some regions (moved away from coastlines)

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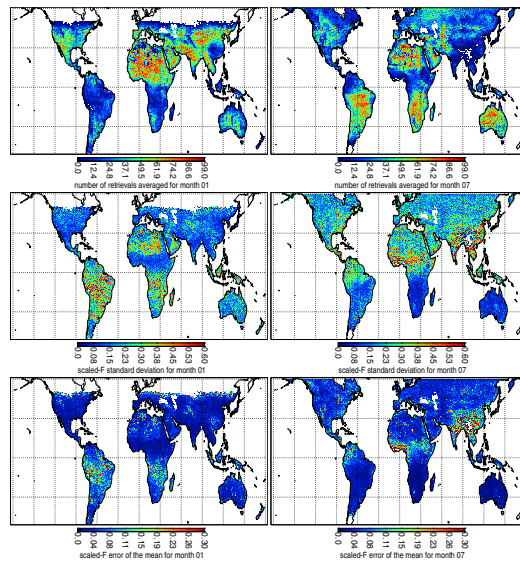
**Fig. 4.** Revised figure showing GOSAT 758 and 770 nm results separately and with new filter applied to SCIAMACHY retrievals of scaled-F for modified regions

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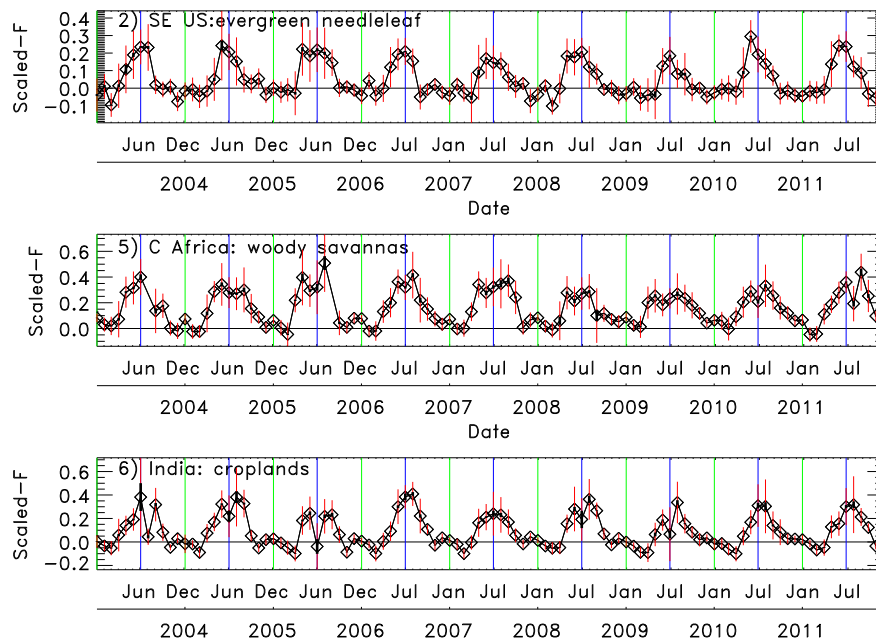
**Fig. 5.** Additional figure showing filling-in derived over cloudy ocean fields-of-view as a function of normalized radiance.

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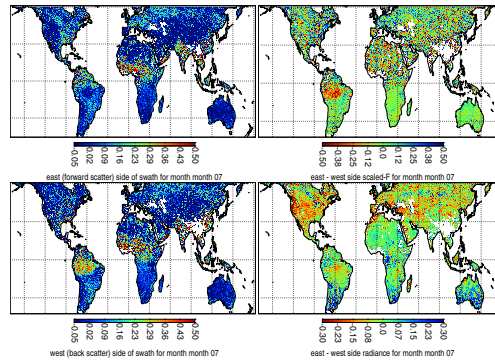
**Fig. 6.** Additional figure showing statistical parameters for monthly mean SCIAMACHY scaled-F for January (left panels) and July (right panels). Figure will be enlarged in final copy.

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**Fig. 7.** Additional figure showing monthly mean scaled-F as derived from SCIAMACHY versus time over the period Jan. 2003 – Dec. 2011 for 3 of the boxes shown in Fig. 3 as indicated.

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**Fig. 8.** Additional figure showing scaled-F and radiance differences from east and west sides of the SCIAMACHY swath. Figures will be enlarged in final copy.