Land surface VIS/NIR BRDF module for RTTOV-11: Model and Validation against SEVIRI Land SAF Albedo product

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Abstract

This proceeding describes the scientific approach and a preliminary validation of the visible and near infrared land Bidirectional Reflectance Distribution Function (BRDF) module for RTTOV version 11. The module provides global (at a spatial resolution of 0.1°) and monthly means land surface BRDF for any instrument with channel's central wavelength between 0.4 and 2.5 μm. It is based on a reconstructed hyperspectral BRDF from the seven channels of the operational global MODIS 16-days BRDF kernel-driven product MCD43C1 and a principal component analysis (PCA) regression method applied on the USGS hyperspectral measurements version 6 database for soils and vegetation surfaces. The module adopts a methodology similar with the UWiremis infrared land surface emissivity module developed for RTTOV. A preliminary validation of the BRDF against the SEVIRI Land SAF albedo product show a good correlation of the RTTOV module when applied on three SEVIRI visible and near infrared channels.

Introduction

In the next version of RTTOV (version 11) there will be a possibility for the users to simulate clear-sky satellite observations in the visible and in the near infrared spectral regions. In clear-sky situations over land, the major contribution to the signal simulated at the top of atmosphere comes from the surface. As for thermal or microwave spectral regions, the surface optical properties exhibit strong spectral signatures based on the surface type. Furthermore, in the visible and near infrared spectral regions, the surface optical properties also exhibit a strong geometrical dependency, which depend on the solar and on the satellite directions. To describe the spectral and the geometrical dependences of the surface, the surface optical properties are represented by the Bidirectional Reflectance Distribution Function (BRDF). Additionally, the surface optical properties of vegetation-covered area present a non-negligible seasonal dependency. In order to take into consideration the spectral, geometrical and temporal dependencies of the BRDF in visible and near infrared regions over land to provide a good BRDF estimate for RTTOV, we used a combination of hyperspectral reflectance laboratory measurements to take into account the spectral variability of land surface's reflectivity, and of global and seasonal satellite-based measurements of the BRDF to take into account both surface type and geometrical and seasonal variabilities of the surface optical properties. The methodology was developed in a similar way as it has been done for the RTTOV UWiremis infrared land surface emissivity module (Borbas and Ruston 2010). Here, the hyperspectral laboratory measurements database from the United States Geological Survey (USGS) has been used as well as the BRDF retrieval product from the MODIS Land team. The MODIS MCD43C1 product provide three parameters that allow the full description of the BRDF at 7 visible and near infrared bands bands (at 0.470 µm, 0.555 µm, 0.659 µm, 0.865 µm, 1.24 µm, 1.64 µm and 2.13 µm). The latter wavelengths of the MODIS bands have been chosen as hinge points for a Principal Component Analysis (PCA) on the hyperspectral laboratory measurements database. Then the MODIS measurements allow to constrain the reconstruction of a BRDF spectra that are used next to interpolate the BRDF of any instrument with central wavelengths in the visible and near infrared. The study is organized as follows. Section 2 present the USGS laboratory spectra selected for visible and near infrared spectral regions, i.e. between 0.4 and 2.5 µm. Section 3 gives a short description of the PCA analysis as well as the comparison between the laboratory measurements and their reconstructed spectra. Section 4 provides the mathematical relation between the MODIS product parameters and the BRDF. Section 5 gives details of the resampling of the original global MODIS 16-days BRDF dataset at 0.05° spatial resolution to a coarser global monthly means at 0.1° spatial resolution, as well as the development of a simplified quality mask for RTTOV. In Section 6, we performed a preliminary evaluation of the RTTOV BRDF module by comparing monthly mean RTTOV Black-Sky Albedo (BSA) values with one day of Land SAF SEVIRI albedo product in the three visible and near infrared SEVIRI bands (at 0.6 µm, 0.8 µm and 1.6 µm). Conclusion and perspectives are given in Section 7.

The USGS spectral library

The USGS spectral library version 6 is freely available at http://speclab.cr.usgs.gov/spectral-lib.html. It is a compilation of over 1300 hyperspectral reflectance spectra measured in laboratory, field campaigns or aircraft-based instrumentations of natural and man-made materials (Clark et al. 2007) that cover ultraviolet to mid infrared spectral regions (from 0.2 to 150 µm) at different spectral resolution between 0.002 and 0.03 µm. The database covers six classes of surface type (mineral, soil, coating, water, man-made and vegetation). The spectral region of each laboratory spectra differs by surface types. For the purpose of its application to RTTOV for land surface in visible and NIR spectral domains, we selected all spectra that cover the range between 0.4 to 2.5 µm for soil and vegetation surface types. Based on the overall database, the spectral range criterion and some visual inspection of the spectra quality, we selected a total number of spectra of 126 (100 spectra for soils and 26 spectra for vegetation). Fig. 1 shows the spectral variation of the reflectance for soil (Fig. 1a) and vegetation (Fig. 1b) surface types.

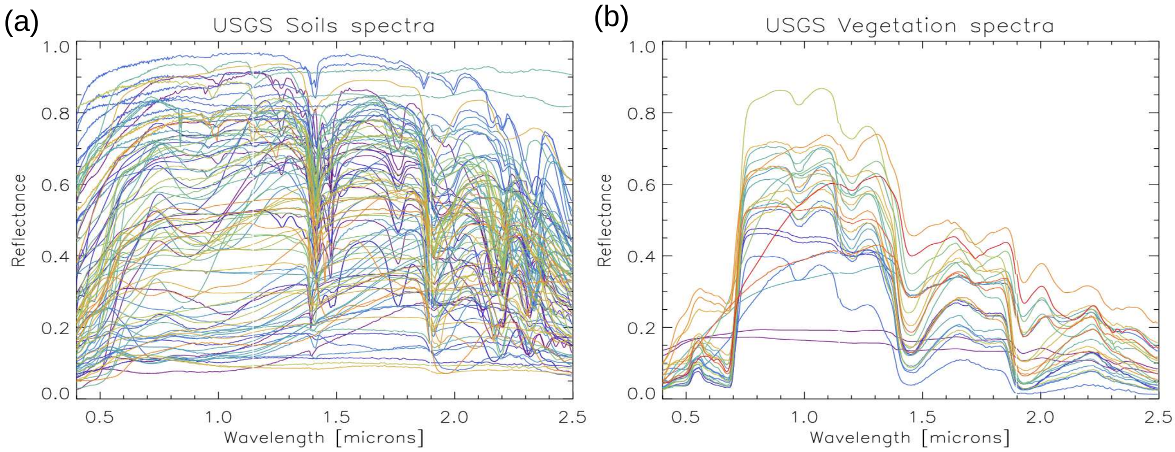

Fig. 1: The selected USGS spectra for soil (a) and vegetation (b) surface types.

The spectral resolution of the selected 126 spectra has been uniformed to 0.01 μm leading to 2101 spectral points for each spectrum.

The Principal Component Analysis (PCA) on the selected laboratory spectra

The first Principal Components (PCs or eigenvectors) of 126 selected laboratory spectra with wavelength resolution of 0.01 μm, were regressed against 7 hinge points corresponding to the central wavelength of MODIS. Fig. 2 illustrates the 126 laboratory spectra (Fig. 2a) and the reconstructed ones using 6 PCs (Fig. 2b). The number of 6 PCs was found to be most optimal by giving the best agreement between the original laboratory measurements and reconstructed spectra. This number was used hereafter in this study and was coded as default value in the RTTOV BRDF module.

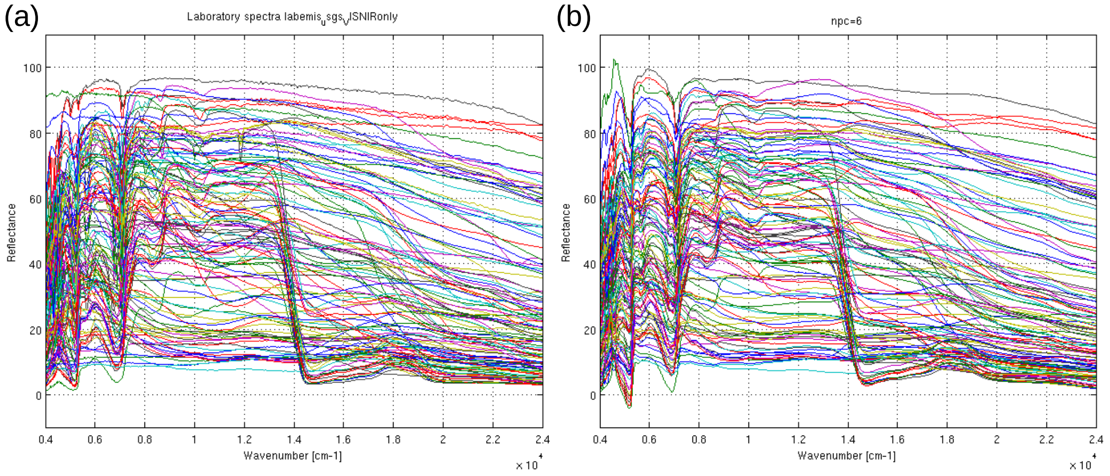

Fig. 2: The 126 selected USGS laboratory spectra (a) and their reconstructed spectra using 6 PCs (b).

The MODIS BRDF kernel-driven product

The MODIS BRDF kernel-driven product (named MCD43C1) is based on a 16 day period of acquisition and is provided globally at 0.05° spatial resolution. This product makes use of both Terra and Aqua satellites. The Collection 5 version is freely available at the following address: https://lpdaac.usgs.gov/products/modis_products_table/brdf_albedo_model_parameters/16_day_l3_0_05deg_cmg/mcd43c1. The product contains three BRDF kernel model parameters (f_{iso}, f_{vol} and f_{geo}) for the full description of the BRDF at 7 MODIS bands as well as quality flags. The BRDF is calculated by using the semi empirical linear model of Ross-Li (Lucht et al. 2000) that is given by:

$$BRDF(\theta_{sat},\theta_{sol},\Delta\phi,\lambda) = f_{iso}(\lambda) + f_{vol}(\lambda)K_{vol}(\theta_{sat},\theta_{sol},\Delta\phi) + f_{geo}(\lambda)K_{geo}(\theta_{sat},\theta_{sol},\Delta\phi), \quad (1)$$

where θ_{sol}, θ_{sat} and $\Delta\phi$ are the solar zenith angle, the satellite zenith angle and the azimuth difference between satellite and solar directions, respectively. λ is the wavelength. The first BRDF kernel model parameter f_{iso} is due to isotropic scattering. The second BRDF kernel model parameter f_{vol} is due to radiative transfer-type volumetric as from horizontally homogeneous leaf canopies. The third BRDF kernel model parameter f_{geo} is due to geometric-optical surface scattering as from scenes containing 3-D objects that cast shadows and are mutually obscured from view at off-nadir angles. The BRDF model kernel K_{vol} is given by:

$$K_{vol}(\theta_{sol},\theta_{sat},\Delta\phi)=\frac{(\pi/2-\Theta)\cos\Theta+\sin\Theta}{\cos\theta_{sol}+\cos\theta_{sat}}-\frac{\pi}{4}, \tag{2}$$

where $\cos\Theta=\cos\theta_{sol}\cos\theta_{sat}+\sin\theta_{sol}\sin\theta_{sat}\cos\Delta\phi$ and Θ is the scattering angle. The BRDF model kernel K_{geo} is given by:

$$K_{geo}(\theta_{sol},\theta_{sat},\Delta\phi)=\mathrm{O}(\theta_{sol},\theta_{sat},\Delta\phi)-\sec\theta_{sol}-\sec\theta_{sat}+\frac{1}{2}(1+\cos\Theta), \tag{3}$$

where

$$\mathrm{O}(\theta_{sol},\theta_{sat},\Delta\phi)=\frac{1}{\pi}(t-\sin t\cos t)(\sec\theta_{sol}+\sec\theta_{sat}), \tag{4}$$

with

$$\cos t=\frac{2\sqrt{D^2+(\tan\theta_{sat}\tan\theta_{sol}\sin\Delta\phi)^2}}{\sec\theta_{sol}+\sec\theta_{sat}}, \tag{5}$$

and with

$$D=\sqrt{\tan^2\theta_{sat}+\tan^2\theta_{sol}-2\tan\theta_{sat}\tan\theta_{sol}\cos\Delta\phi}. \tag{6}$$

Resampling the MODIS dataset to get a monthly BRDF and an associated quality index

The RTTOV BRDF module provides an atlas of monthly mean BRDF values on a fixed 0.1° spatial resolution. For that, we reassembled the original MODIS MCD43C1 BRDF kernel-driven product based on best pixels selected from a simplified mask that is rested itself on the original MODIS MCD43C1 quality flag. The methodology was done in two steps: (1) a spatial averaging and (2) a temporal averaging. The first step (i.e. the spatial averaging) is applied for each original MODIS MCD43C1 product (i.e., for a 16 days period). We used the original MODIS flags in order to get a simplified flag at a coarser spatial resolution (from original pixel at 0.05° to final pixel at 0.1°, so on a 4 by 4 original pixels basis). The second step (i.e. the temporal averaging) leans on the simplified flag obtained at the first step and on the selection of the best final pixel over the 16-days regridded MODIS data within a month. The two steps are described hereafter.

The first step makes use of three original MODIS MCD43C1 quality flags. The first one is the MODIS BRDF quality flag (called hereafter *sq*) that have 5 different values:

- *sq*=0 for best quality retrieval, i.e. for 75% or more with best full inversions,
- *sq*=1 for good quality retrieval, i.e. for 75% or more with full inversions,
- *sq*=2 for mixed retrieval, i.e. for 75% or less full inversions and 25% or less filled values,
- *sq*=3 for all magnitude inversions or 50% or less filled values,
- *sq*=4 for 50% or more filled values.

The two other MODIS BRDF flags are named as “Percent inputs” (that gives the percentage of inputs between 0 and 100 % and called hereafter *sp*) and “Percent snow” (that gives the percentage of snow between 0 and 100 % and called hereafter *sps*). From these three information, we developed a simplified flag on the regridded 16-day product (i.e. on each 4 by 4 original pixel at 0.05° within one final pixel at 0.1°) with different iterative tests. If the first test is validated, then a flag number is associated. If not, the second test is done, and so on…Table 1 describes the different tests and associated flag numbers. For each test, if at least one original pixel is found within the final pixel, the flag number is associated. The final value of the three BRDF kernel model parameters *f* is calculated by the value of the best original pixel or by the mean value if more than one original pixels validating the test are found.

Table 1: Test criterion for the flag number of the RTTOV simplified mask.

Test order	Flag number	Criterion			Description
		sq	*sp*	*sps*	
1	1	0-1	≥ 80%	0%	No snow, best and good quality for 80% inputs or more
2	2	0-1	≥ 80%	100%	Snow, best and good quality for 80% inputs or more
3	3	2-3	≥ 80%	0%	No snow, medium quality for 80% inputs or more
4	4	2-3	≥ 80%	100%	Snow, medium quality for 80% inputs or more
5	5	< 4	< 80%	≠0% or ≠100%	Remaining pixels, bad quality
6	6	4	0–100%	0–100%	Filled values, bad quality

In the second step, the flag numbers and the values of three BRDF kernel model parameters *f* are used to calculated a monthly simplified mask and the monthly means of *f* by using all original MODIS products within a month. For that, we searched for the best final pixel within a month, following:

- Mask = 0 for water surface,
- Mask = 1 if at least one final pixel with flag=1 is found,
- Mask = 2 if at least one final pixel with flag=3 is found,
- Mask = 3 if at least one final pixel with flag=6 is found,
- Mask = 4 if at least one final pixel with flag=2 or simplified flag=4 is found,
- Mask = 5 if at least one final pixel with flag=5 is found,
- Mask = 6 if no BRDF data (following the land/sea mask from UWIR emissivity atlases).

By this way, we kept only the best information from original MODIS MCD43C1 product into the final RTTOV BRDF atlas. If more than one final pixel are found within a month, we calculated a new mean of the three BRDF kernel model parameters *f*. Fig. 3 shows the monthly RTTOV BRDF mask for January 2007 (Fig. 3a), April 2007 (Fig. 3b), July 2007 (Fig. 3c) and October 2007 (Fig. 3d). Night persistent areas in high latitude or cloudy persistent areas (like in India in July, see Fig. 3c) are classified as no data. Antarctic and Artic areas, as well as snow-covered areas in winter season are well classified. Areas permanently classified as medium like in the north part of South America, in middle Africa or in Asia are explained by the difficulty to retrieve BRDF in presence of strong aerosols loading or cloud contamination.

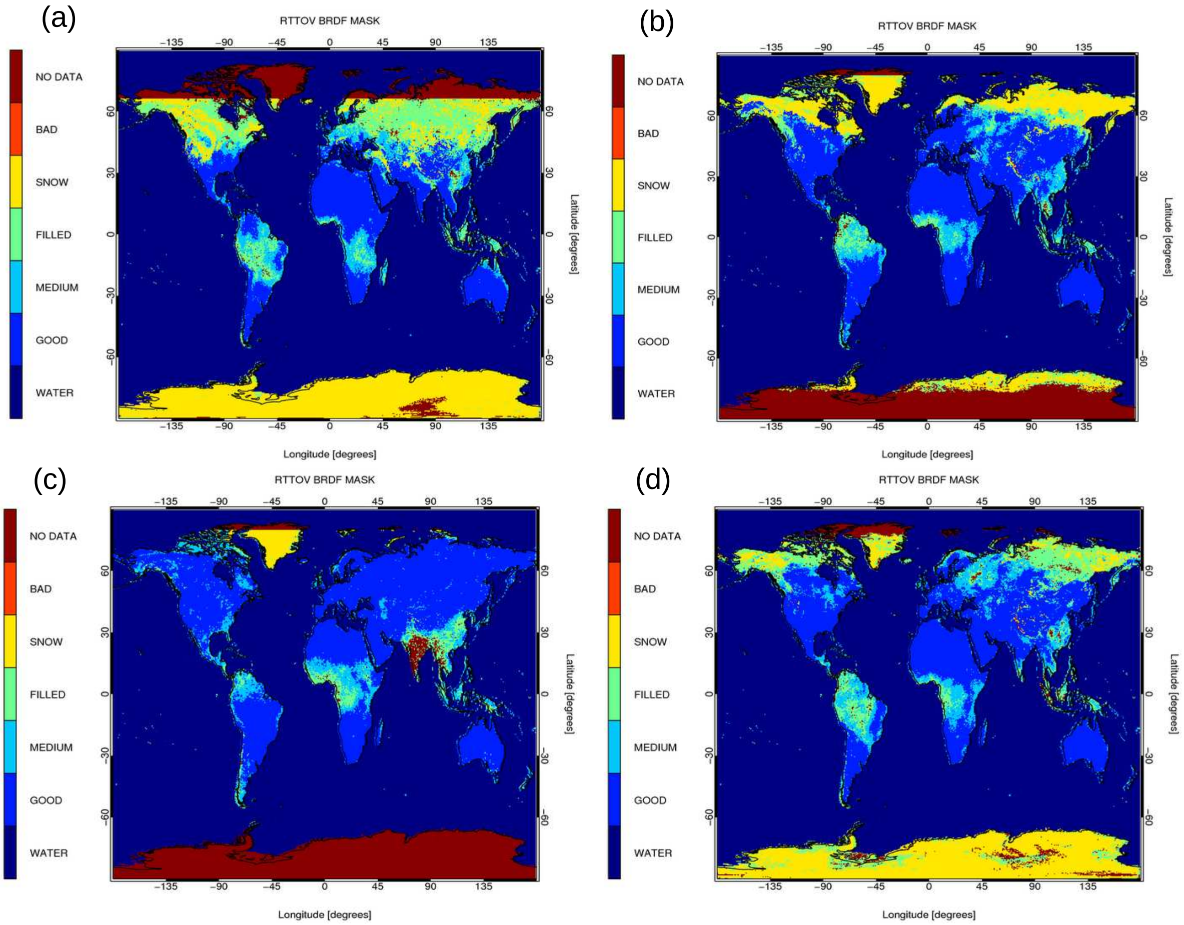

Fig. 3: RTTOV BRDF atlas mask for 2007: January (a), April (b), July (c) and October (d).

Validation of the RTTOV BRDF atlas with the Land SAF Black-Sky Albedo product

For any given location (in latitude and longitude), month, geometry and instrument channel's central wavelength, the RTTOV-11 BRDF module provides the BRDF estimate and the associated quality index that is extracted from the original MODIS quality flags. For the validation of the RTTOV BRDF module, we used SEVIRI Land SAF product for the 25th August 2011 averaged at 0.1° spatial resolution from the SEVIRI original spatial resolution. We were not able to validate directly the BRDF since the BRDF is not an operational product from the Land SAF team. We used the SEVIRI Land SAF Directional Hemispherical Reflectance or Black-Sky Albedo (BSA) product. The Land SAF Land Surface Albedo product is documented at the Land SAF website (http://landsaf.meteo.pt). The RTTOV BSA α_{bs} is calculated from the MODIS BRDF kernel-driven product and is given by the following equation (Lucht et al. 2000):

$$\begin{aligned}\alpha_{bs}(\theta_{sat},\lambda) &= f_{iso}(\lambda)(g_{0iso}+g_{1iso}\theta_{sat}^{2}+g_{2iso}\theta_{sat}^{3})\\ &+ f_{vol}(\lambda)(g_{0vol}+g_{1vol}\theta_{sat}^{2}+g_{2vol}\theta_{sat}^{3})\\ &+ f_{iso}(\lambda)(g_{0geo}+g_{1geo}\theta_{sat}^{2}+g_{2geo}\theta_{sat}^{3})\end{aligned}, \qquad (7)$$

where the different g coefficients are given in Table 2.

Table 2: Coefficients *g* for the calculation of the BSA.

g	Isotropic	Volumetric	Geometric
0	1.0	-0.007574	-1.284909
1	0.0	-0.070987	-0.166314
2	0.0	0.307588	0.041840

In Fig. 4 is depicted the monthly mean RTTOV Black-Sky Albedo for August 2011 in SEVIRI channel 1 at 0.6 µm (Fig. 4a) and the SEVIRI channel 1 Land SAF BSA product averaged on a 0.1° grid (Fig. 4b).

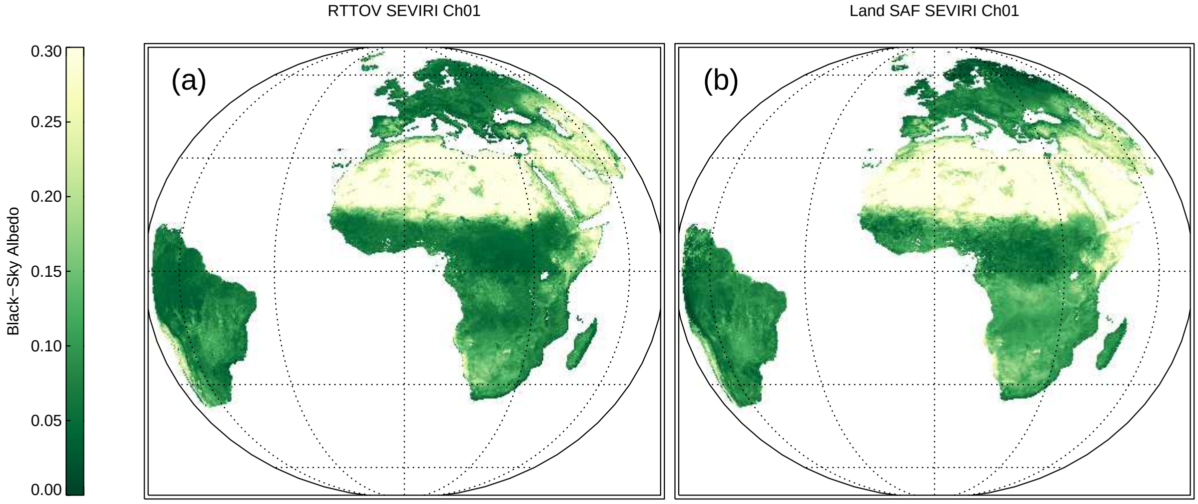

Fig. 4: Monthly mean RTTOV BSA for August 2011 in SEVIRI channel 1 at 0.6 µm (a) and SEVIRI channel 1 Land SAF BSA product for the 25th August 2011 (b).

Vegetation covered areas (with lower albedo) as well as desert areas (with higher albedo) are well retrieved from the monthly mean RTTOV BRDF values as compared with Land SAF product. However, RTTOV seems to slightly underestimate the albedo, especially over Central Africa. In Fig. 5a is depicted the monthly mean RTTOV BRDF mask for August 2011.

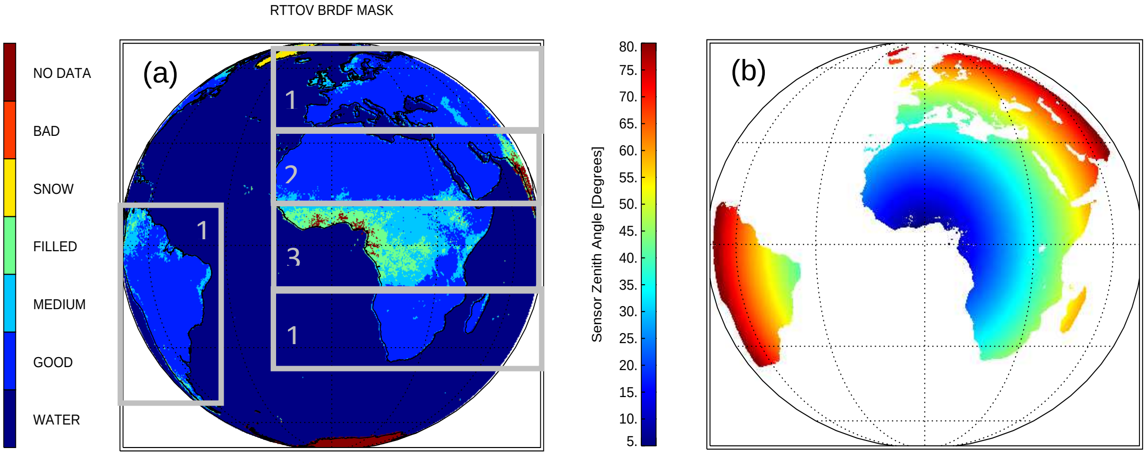

Fig. 5: Monthly mean RTTOV BRDF mask for SEVIRI-like observation in August 2011 (a). SEVIRI sensor zenith angle of the 25th August 2011 (b).

The quality index reveal that the quality of the MODIS BRDF retrieval is reduced in Central Africa. This might be explained by lower quality of the MODIS BRDF retrieval in the presence of aerosols and/or persistent clouds. To take into account this effect and to differentiate surface types in the interpretation of the results, we then separated the SEVIRI full disk into three parts as represented in grey box in Fig. 5a, i.e.:

1. Vegetated areas in Europe, South Africa and South America with good quality index.
2. Desert areas in Northern Africa and Middle-East with good quality index.
3. Vegetated areas in Central Africa with mainly medium and filled quality index.

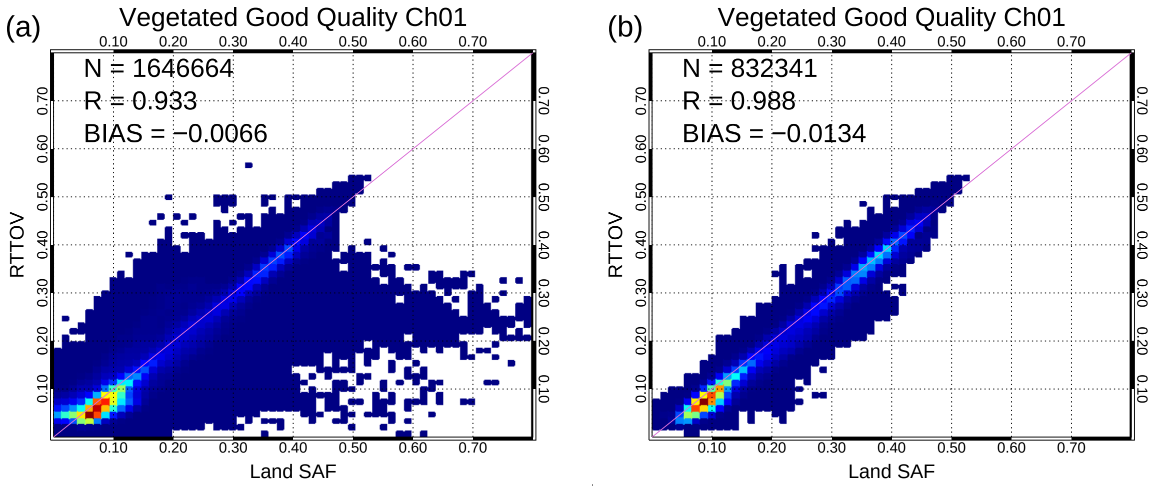

Fig. 6. Scatterplot between RTTOV and Land SAF BSA for SEVIRI channel 1 on vegetated areas with good quality retrieval (a). Same result when sensor zenith angle < 60°(b).

The scatterplot between RTTOV BSA and Land SAF BSA from Fig. 4 depicted in Fig. 6a shows a good correlation between RTTOV and Land SAF with a correlation coefficient of 0.933 but the scatterplot shows also a lot of outliers. These outliers might be explained by the difference in angular sampling between MODIS and SEVIRI, that is more critical for SEVIRI at the edge of the disk. By removing data for satellite zenith angle greater than 60° (see Fig. 5b) the outliers are removed (Fig. 6b) and the correlation coefficient increase to 0.988. However, we can see that a small negative bias of –0.013 is obtained in channel 1.

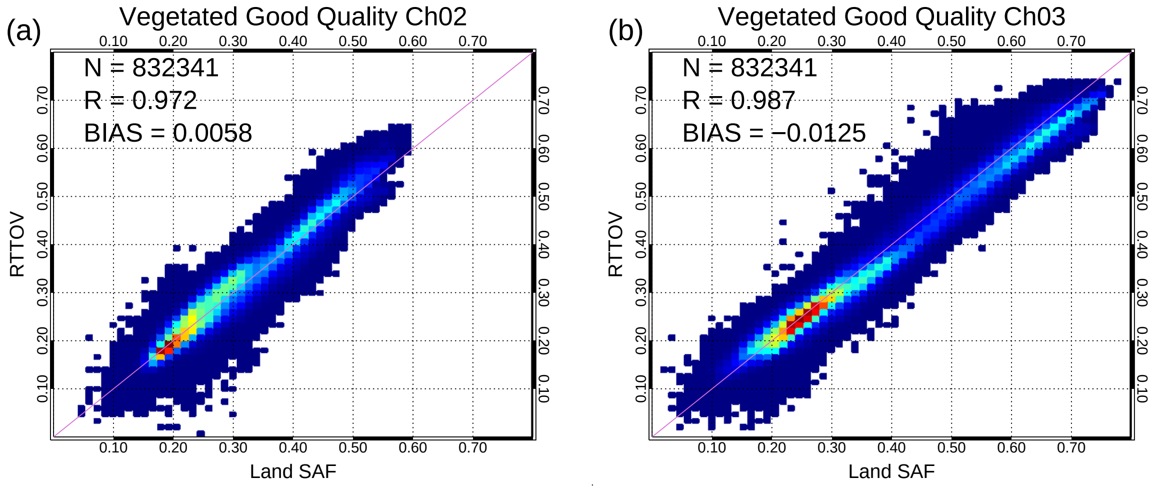

Fig. 7: (a) Same as Fig. 6b for channel 2 (at 0.8 μm). (b) Same as Fig. 6b for channel 3 (at 1.6 μm).

Scatterplots for channel 2 (at 0.8 µm) and for channel 3 (at 1.6 µm) over vegetated areas for good quality retrieval are depicted in Figs. 7a and 7b, respectively. The threshold on the satellite zenith angle have been used. Correlation coefficients are found to be 0.972 and 0.987 for channel 2 and 3, respectively with almost no bias in channel 2 and similar underestimation from RTTOV in channel 3 as compared with channel 1.

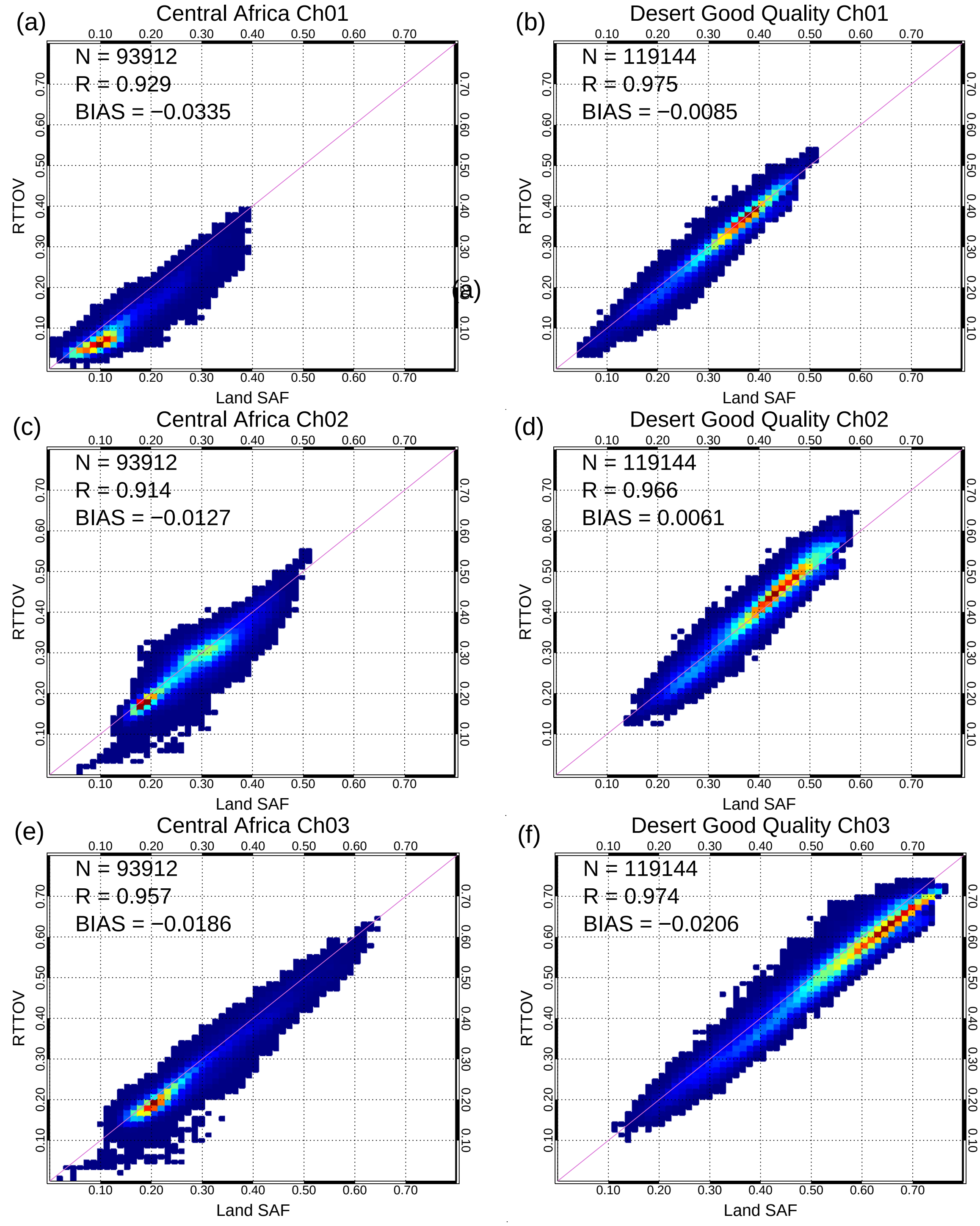

Fig. 8. Scatterplots between RTTOV and Land SAF BSA for SEVIRI in Central Africa for channel 1 (a), channel 2 (c) and channel 3 (e). Same results for desert areas for channel 1 (b), channel 2 (d) and channel 3 (f).

In the panel of Fig. 8 are depicted the results for Central Africa for channels 1, 2 and 3 (Figs. 8a, 8c and 8e, respectively), and for desert areas for channels 1, 2 and 3 (Figs. 8b, 8d and 8f, respectively) . Here again, the satellite zenith angle threshold have been used. For Central Africa, i.e. for vegetated areas with medium quality BRDF retrieval, the correlation coefficients are slightly reduced in all channels as compared with vegetated areas with good quality retrievals. Correlation coefficients are going from 0.97 to 0.91 for channel 1 (compare Figs. 7a and 8c) and from 0.99 to 0.96 in channel 3 (compare Figs. 7b and 8e). Furthermore, RTTOV underestimations are also increased to 0.033 (Fig. 8a), 0.013 (Fig. 8c) and 0.019 (Fig. 8e) for channels 1 to 3, respectively. For desert areas, correlations coefficient are as good as for vegetated areas with good quality retrieval, i.e. R > 0.97. However, a larger underestimation of the RTTOV albedo is found in channel 3 of 0.02 (Fig. 8f). Finally, we found a good consistency of the RTTOV albedo as compared with the Land SAF product

Conclusion

A BRDF model for land surfaces has been developed for RTTOV-11. It is based on a combination of USGS laboratory hyperspectral measurements of soil and vegetation surfaces and the MODIS BRDF kernel parameters products. This model allows the calculation of the BRDF for any instrument with channels between 0.4 and 2.5 mm. The model provides a global and monthly mean BRDF at 0.1° spatial resolution. It also provides a quality index of the BRDF. Comparison with one global SEVIRI Land SAF product show a good consistency between black-sky albedo with correlation coefficients greater than 0.9 for both vegetated and desert areas. It is found that RTTOV-11 BRDF model tends to underestimate the albedo in channels 1 and 3 and slightly overestimate in channel 2. Differences are found to be more important in areas where the presence of aerosols and/or persistent clouds reduce the quality of the MODIS BRDF retrieval and/or the SEVIRI Land SAF product. Further improvements will be included in the module as providing a standard deviation of the BRDF and providing a lower quality BRDF in areas with currently no data is available (as for example over India, see Fig. 3, bottom-left). For stronger validation, seasonal variability will be investigated by using more SEVIRI data as for example the 10-day Land SAF product over a year.

References

Clark, R.N., G.A. Swayze, R. Wise, E. Livo, T. Hoefen, R. Kokaly and S.J. Sutley, 2007: USGS digital spectral library splib06a, U.S. Geological Survey, Digital Data Series 231. Available at http://speclab.cr.usgs.gov/spectral.lib06/ds231/.

Borbas, E.A., and B.C. Ruston, 2010: The RTTOV UWiremis IR land surface emissivity module, Report NWPSAF-MO-VS-042, 24 pp.

Lucht, W., C.B. Schaaf, and A.H. Strahler, 2000: An Algorithm for the retrieval of albedo from space using semiempirical BRDF models, *IEEE Trans. Geo. Rem. Sens.*, **38**, 977-998.