EXPLOITING SURFACE ALBEDO PRODUCTS: EXAMPLES OF ANTICIPATED DOWNSTREAM APPLICATIONS FROM THE GLOBALBEDO PROJECT.

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ABSTRACT

ESA has recently initiated the GlobAlbedo project aiming at the production of surface albedo products at global scale generated from a synergistic approach involving long time series of data acquired by sensors on board ENVISAT as well as some precursors such as Along Track Scanning Radiometer (ATSR) launched in the context of the Earth Observation Program. When available in a couple of years, these time-series of surface albedo products might be exploited further to retrieve a consistent ensemble of land surface variables characterizing the terrestrial surfaces (such as the effective LAI and the albedo of the vegetation background) as well as to assess a meaningful partitioning of the solar fluxes between the soil, vegetation and atmosphere layers, along multiple years and over large geographical regions.

We present and discuss results from the application of an inversion package designed to assimilate surface albedo products into a state of the art radiation transfer scheme. This method implements the adjoint and Hessian codes, generated using automatic differentiation techniques, of a cost function accounting for 1) the deviation from the prior knowledge on the model parameter values and, 2) the misfit between the remote sensing products and the model calculations. Uncertainties associated with the products, models and priors are specified via relevant prior covariance matrices. The inversion method provides an estimate of the posterior covariance matrix on the model parameters which is further exploited to evaluate, in turn, the posterior probability density functions of the radiant fluxes simulated by the radiation transfer model, including those that are not measured, e.g., the fraction of solar radiation absorbed in the ground. Global scale applications presented here are performed using the MODIS broadband surface albedo products. Our results illustrate the capability of this inversion package to retrieve efficiently a panoply of land surface variables, including some Essential Climate Variables, in a consistent manner and with documented accuracy.

Key words: Surface albedo; two-stream model; Adjoint and Hessian codes.

1. INTRODUCTION

The accurate knowledge of the land processes controlling distribution and partition of solar radiant flux between the vegetation and the underneath soil layer is required to improve simulations of the soil-vegetation-atmosphere exchanges at various space and time scales of interest for climate, numerical weather prediction as well as carbon cycle models (e.g. Pitman, 2003). Global multi-annual time series of some of these radiant fluxes, such as broadband surface albedos have become available from various institutions. ESA has recently initiated the GlobAlbedo project aiming at the production of long term time-series of surface albedo products at global scale generated from a synergistic approach involving long time series of data acquired by sensors on board ENVISAT as well as some precursors such as Along Track Scanning Radiometer (ATSR) launched in the context of the Earth Observation Program.

In the mean time, efforts have been made to improve the performance (notably with respect to their accuracy, capability, and software implementation as well) of the plane-parallel, so called two-stream, radiation transfer schemes currently implemented in host models (e.g. Pinty et al., 2006). This class of model is able to simulate accurately, that is within a few percent, the domain-averaged scattered, transmitted and absorbed fluxes related to most geophysical systems, irrespective of their intrinsic internal variability in the 3-D space, provided that effective instead of true model parameters are adopted. In the case of the Leaf Area Index (LAI), for instance, the effective value is associated with the interception of the direct radiation and is thus related to the direct transmission via the classical exponential decay as would occur in a turbid plane-parallel medium.

In order to fully exploit the available surface albedo products derived from remote sensing, it is first necessary to retrieve these effective values of the two-stream model parameters. This step is mandatory for ensuring the physical consistency between the measured fluxes and the dimensionality of the model used to estimate the model parameters, *i.e.*, the same class of model have to be used in inverse (to exploit remote sensing data) and forward (to simulate fluxes) mode. Pinty et al. (2007) have devised and documented the performance of such a retrieval procedure, hereafter referred to as the Joint Research Centre Two-stream Inversion Package (JRC-TIP). This procedure delivers a Gaussian approximation of the Probability Density Functions (PDFs) of the retrieved model parameter values together with a posterior covariance matrix. This information enables us to estimate the radiant fluxes simulated by the two-stream model, including those that are not part of the measurement set, *e.g.* the fraction of radiation absorbed in the ground.

We present results from the application of an inversion method conducted using MODIS derived broadband visible and near-infrared surface albedo products. The detailed analyses of the retrieval uncertainties highlight the central role and contribution of the LAI, the main process parameter to interpret radiation transfer observations over vegetated surfaces. Through a series of selected examples, the inverse procedure implemented in the JRC-TIP is shown to be robust, reliable and compliant with large scale processing requirements. Furthermore, this package ensures the physical consistency between the set of observations, the two-stream model parameters and radiation fluxes. It also documents the retrieval of model process parameters and radiant fluxes with associated uncertainties. The knowledge gained from the availability of remote sensing surface albedo products can be expressed in quantitative terms using a simple metric. This metric helps identify the geographical locations and periods of the year where the remote sensing products fail in reducing the uncertainty on the process model parameters as can be specified from current knowledge.

Once they become available, ESA Globalbedo products can be exploited as well using the JRC-TIP. Our current results illustrate the capability of this inversion package to retrieve efficiently a panoply of land surface variables, including some Essential Climate Variables, in a consistent manner and with documented accuracy as required by the Global Carbon Observing System implementation plan and envisaged in the ESA Climate Change Initiative.

2. OUTLINE OF THE JRC-TIP

2.1. Formulation of the inverse problem

The Joint Research Centre Two-stream Inversion Package (JRC-TIP), has been described in detail and its performance assessed in previous studies (Pinty et al., 2007, 2008; Lavergne et al., 2006; Clerici et al., 2010; Voßbeck et al., 2009). It is based on a generic formulation of the inverse problem such that the optimal solutions result from the minimization of a cost function $J(\mathbf{X})$. The latter balances the mismatch between the albedo 1) measured $\mathbf{d}$ (by MODIS visible and near-infrared broadband white sky surface albedos) and modeled (using the two-stream model $M(\mathbf{X})$ described in Pinty et al. (2006)) surface albedo with associated uncertainties specified in the covariance matrix $\mathbf{C_d}$ and 2) the deviation of the model parameters $\mathbf{X}$ from their prior PDF values represented by the maximum likelihood estimator $\mathbf{X_{prior}}$ and covariance matrix $\mathbf{C_{X_{prior}}}$. The solutions are given as a Gaussian approximation of the multidimensional PDFs of the model parameters together with a covariance matrix $\mathbf{C_{X_{post}}}$ documenting the uncertainties associated with these solutions.

The cost function $J(\mathbf{X})$ is thus expressed as follows:

$$J(\mathbf{X}) = \frac{1}{2}\left[\Big(M(\mathbf{X}) - \mathbf{d}\Big)^T \mathbf{C_d^{-1}} \Big(M(\mathbf{X}) - \mathbf{d}\Big) + \Big(\mathbf{X} - \mathbf{X}_{prior}\Big)^T \mathbf{C_{X_{prior}}^{-1}} \Big(\mathbf{X} - \mathbf{X}_{prior}\Big)\right] \quad (1)$$

The JRC-TIP implements a minimization scheme which exploits the adjoint, tangent linear and Hessian codes of $J(\mathbf{X})$ generated by the compiler tool Transformation in C++ (TAC++) (Voßbeck et al., 2008) available from FastOpt (`http://www.FastOpt.com/`). It delivers PDFs of the two-stream model parameters $\mathbf{X_{post}}$ as well as the radiation fluxes, *i.e.*, scattered, transmitted and absorbed by the vegetation layer and its background, simulated forward by the two-stream model. The uncertainty ranges of the estimated model parameters are propagated towards the radiation fluxes via the two-stream model first derivatives (Voßbeck et al., 2009).

2.2. Two-stream model parameters

The effective variables entering the two-stream model are, a spectrally invariant quantity, namely the Leaf Area Index (LAI) and, spectrally dependent parameters including 1) the true (by contrast to effective) albedo of the background $r_g(\lambda)$ 2) the effective single scattering albedo of elementary vegetation volumes, including leaves and branches, denoted $\omega_l(\lambda) = r_l(\lambda) + t_l(\lambda)$ where $r_l(\lambda)$ and $t_l(\lambda)$ refer to the effective reflectance and transmittance factors, respectively, and 3) the ratio $d_l(\lambda) = r_l(\lambda)/t_l(\lambda)$ which specifies the preferential forward or backward direction of scattering in the canopy layer.

The effective LAI value expresses the capability of the vegetation layer to intercept direct radiation, and is thus associated with the probability distribution function of the canopy gaps. This quantity is generally measured in the field with standard optical devices. Accordingly, the two main parameters controlling the flux partitioning, i.e., the effective LAI and the true background albedo, can be, in principle, estimated from in-situ measurements and this offers a practical means to evaluate the quality of the retrievals delivered by the inversion procedure.

2.3. Prior values

The strategy adopted in the present investigation is such that the prior values on the parameters characterizing the vegetation layer are time and space invariant, *i.e.*, they are not specified as a function of land cover and/or seasons. Moreover, the effective LAI, which is largely unknown and quite variable, is specified with a very large uncertainty allowing the inversion procedure to explore any physically realistic value. The mean values $\mathbf{X_{prior}}$ and associated standard deviations $\sigma_{\mathbf{X_{prior}}}$ used to set the diagonal of the prior covariance matrix $\mathbf{C}_{\mathbf{X_{prior}}}$ at the broadband visible and near-infrared spectral domains, respectively are provided in Table 1 (remaining entries in $\mathbf{C}_{\mathbf{X_{prior}}}$, not specified in Table 1, are zero). They are the same as those adopted in earlier studies (e.g. Pinty et al., 2008, Tab. 2 and Fig. 1) and are duplicated here for the sake of convenience. These values have been selected on the basis of model-based investigations and detailed time series analysis in previous investigations (Pinty et al., 2004, 2007; Lavergne et al., 2006).

2.4. Surface albedo dataset

The present investigation is based on an analysis of visible (0.3–0.7 μm) and near-infrared (0.7–3.0 μm) broadband white sky albedo values (Schaaf et al., 2002) (calculated under the assumption of an isotropic illumination of the surface) available at global scale from MODIS collection V005 products (MCD43B3) at 1 km (0.01°) spatial resolution for successive 16-day periods of year 2005 (`https://lpdaac.usgs.gov/`). The MODIS snow indicator associated with the 16-day composite MODIS surface albedo product has been used here to identify snow events and switch the prior background values as appropriate. Albedo values associated with quality flags 0 (best quality) and 1 (good quality) (MCD43B2) at the same (1 km) spatial resolution, were considered.

All retrievals discussed here are based on the specification, in the covariance matrix $\mathbf{C}_d$, of relative uncertainty values of 5% and 7% attributed to products with flag values 0 and 1, respectively (a lower limit for the absolute uncertainty value was set at 2.5 10^{-3}) and no correlation among uncertainties is assumed.

Table 1. Mean values $\mathbf{X}_{prior}$ and associated standard deviations $\sigma_{X_{prior}}$ used to set the diagonal of the prior covariance matrix $\mathbf{C}_{X_{prior}}$. λ_1 and λ_2 correspond to the broadband visible and near-infrared spectral domains, respectively. $\omega_l(\lambda_{1,2})$, $d_l(\lambda_{1,2})$ and $r_g(\lambda_{1,2})$ refer to the single scattering albedo, asymmetry factor and background albedo, respectively.

Variable	$\mathbf{X}_{prior}$	$\sigma_{\mathbf{X_{prior}}}$
LAI	1.5000	5.0
$\omega_l(\lambda_1)$	0.1700	0.1200
$d_l(\lambda_1)$	1.0000	0.7000
$r_g(\lambda_1)$	0.1000 [1] and 0.50 [2]	0.0959 [1] and 0.346 [2]
$\omega_l(\lambda_2)$	0.7000	0.1500
$d_l(\lambda_2)$	2.0000	1.5000
$r_g(\lambda_2)$	0.1800 [1] and 0.350 [2]	0.2000 [1] and 0.25 [2]

[1(2)] Values adopted for the bare soil (snow) case with a correlation factor of 0.8862 (0.8670) set in $\mathbf{C}_{X_{prior}}$.

3. RESULTS

The JRC-TIP generates a large amount of information in the form of PDFs about the two-stream model parameters (Pinty et al., 2010a) and the partitioning of the radiant fluxes (Pinty et al., 2010b) for each 1 km processed pixel of every successive 16-day periods. We show here a few selected examples to illustrate the performance of the package using mainly the mean retrieved values and the associated one-sigma PDF $\sigma_{\mathbf{X_{post}}}$ values extracted from the diagonal of the covariance matrix $\mathbf{C}_{\mathbf{X_{post}}}$.

3.1. Two-stream model parameters

The two-stream model parameter values can be observed together in a Red, Green, Blue (RGB) color composite image. Fig. 1 gives an illustration of such a color composite where the Red, Green and Blue layers are coding the near-infrared background albedo in the range [0., 0.5], the LAI in the range [0., 2.7] and the vegetation single scattering albedo in the range [0., 0.7], respectively. These maps refer to three 16-day periods representative of typical situations during the North Hemisphere early Spring (March 06-21) (top panel), Summer (June 10-25) (middle panel) and Autumn (October 16-31) (bottom panel), 2005, respectively. The combinations of tones mirror a range of highly contrasted geophysical situations. These maps exhibit broad patterns in relation with well-known land cover features. High LAI values (green tones) occurring in the Northern Hemisphere during summer relate mainly to agricultural activities and broadleaf forests, *e.g.*, over United States, Europe and China, or are associated with dense evergreen forests over equatorial regions. The apparent darkening and bluish trend of the boreal zones in Autumn especially over Canada underscores the occurrence of land surfaces characterized by relatively low LAI values coupled with dark background conditions. Warm and cold desertic regions (red tones) are also well-depicted.

All these well-established spatio-temporal patterns illustrate the performance of the JRC-TIP that operates on a pixel by pixel basis without any prior information on the land cover type. This nicely complements earlier results showing the temporal consistency of high resolution time series that was obtained without prior correlation in the time domain, *i.e.*, no time-dependent relationship is specified in the cost function (Pinty et al., 2008). It is noteworthy that the observed geographical and seasonal patterns directly result from the contribution of the observations since the priors do not contain space and time dependent constraints, *i.e.*, a similar RGB composite based on the priors would generate a monochromatic map.

3.2. Partitioning of the radiant fluxes

The estimation of the fraction of solar radiation that is absorbed by, transmitted through and scattered by the vegetation and its underlying background relies on the retrieval of the two-stream model parameters discussed above. An illustration of the results of this partitioning is given in Fig. 2 in the specific case of measurements available for the 13-28 August, 2005 16-day period in the broadband visible (or Photosythetically Active Radiation) domain. The reconstructed albedo products (top panel) exhibit a large variability due to the strong constrast between densely vegetated surfaces that absorb PAR very efficiently and warm (such as Sahara) and cold (Greenland) regions associated with very high albedo values. These albedo values are basically indiscernible from the MODIS input values to the JRC-TIP since the uncertainties (one-sigma values) of the reconstructed albedos fall well within the expected uncertainty range of the measurements in both the visible and near-infrared domains, *i.e.*, 5% (7%) for high quality (good quality) flag conditions. The midle panel displays the fraction of absorbed radiation in the vegetation layer that is thus similar to the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). The global patterns of FAPAR are close to those exhibited by the LAI (see Fig. 1) which is the main process parameter controlling absorption. The fraction absorbed in the background (bottom panel) remains rather limited over regions with high LAI values, *e.g.*, dense forests and agricultural crops. Over regions exhibiting very low LAI values, *e.g.*, cold and warm deserts, this absorbed fraction is essentially controlled by the surface albedo which may also show some spatial heterogeneity, for instance in Greenland or the Sahara. The latter regions differ significantly with respect to the absorbed fraction in the visible domain due to large differences (almost a factor of 2) in their visible spectral albedo values. More contrasted situations are found with the occurrence of snow packs during winter and early Spring season of the Northern hemisphere (Pinty et al., 2010b).

4. CONCLUSION

The present application has confirmed the robustness and reliability of the JRC-TIP as well as the pertinence of high quality surface albedo products such as the broadband white sky MODIS albedos. This procedure does not require implementing a back up solution given that a rather small fraction of the observations (about 0.5%) could not be interpreted and were flagged as not physically valid (or dubious) solutions, at 1 km resolution over the entire globe and over a full year. It was shown that key model process parameters such as effective LAI and associated radiation fluxes such as FAPAR can be inferred to a reasonable accuracy on the basis of the surface albedo quantities highly integrated in the spectral and angular dimensions. The current application has been conducted using MODIS products but quite similar results are expected at global scale from other data albedo sets such as derived from the Globalbedo project. It is worthwhile emphasizing that our inversion package fullfils the stringent requirements imposed by operational processing such as, reliability, robustness and computer efficiency.

The retrieved model parameters as well as associated the radiant fluxes were shown to be compatible with well-known land cover patterns and vegetation phenology. This spatio-temporal consistency exhibited by the retrieved fields is of particular interest given that the prior values on the model parameters are space- and time-invariant, *e.g.*, they are not specified as a function of land cover type and/or vegetation phenological states, though the background prior values are adjusted to account for the occurrence of snow.

The ensemble of fluxes shown here represents a rather complete information for both regional and global scale investigations of the water and carbon cycles, though only a small part could be shown and discussed in the present contribution. A definite asset of the JRC-TIP is to also deliver information on the radiation absorbed by the background that can provide relevant constraints on some land surface processes. The JRC-TIP outputs include for each valid pixel the PDFs of the two-stream model parameters and simulated fluxes with covariance matrices storing the associated uncertainties. This information is expected to fit the requirements for providing an advanced set of surface boundary conditions in regional and global scale studies of the water, carbon and more generally the energy cycle.

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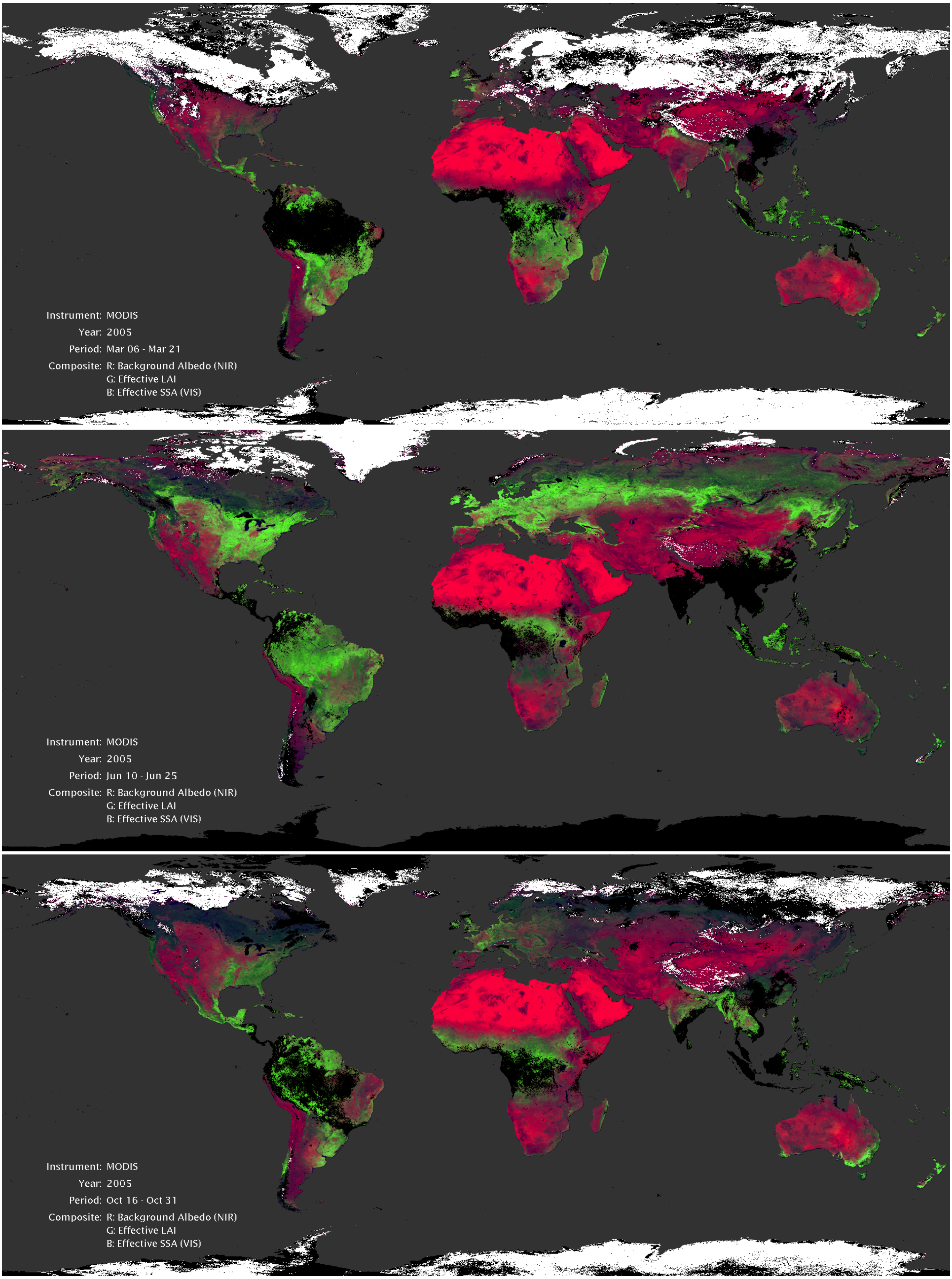

Figure 1. Red, Green and Blue (RGB) representation of model parameters retrieved for the March 06-21 (top panel), June 10-25 (middle panel) and October 16-31 (bottom panel), 2005 16-day periods, respectively. The red, green and blue layers are coding the near-infrared background albedo in the range [0., 0.5], the LAI in the range [0., 2.7] and the vegetation single scattering albedo in the range [0., 0.7], respectively. The black points represent the grid cells where no input albedo product is available from MODIS. Grid cells with a majority of snow occurrence instances during each 16-day periods are displayed in white.

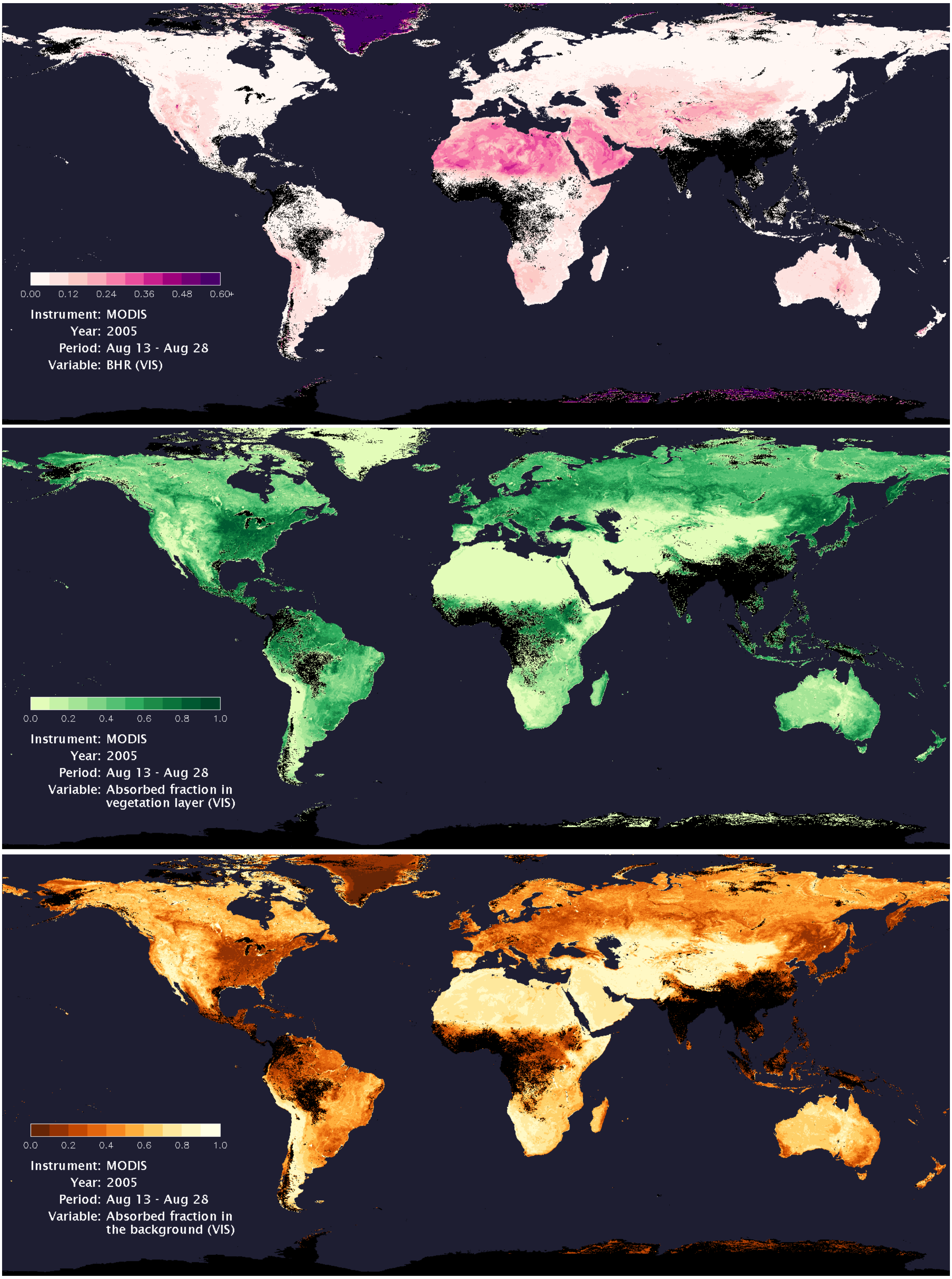

Figure 2. Partition of radiant fluxes in the broadband visible domain between the mean values of the fraction 1) scattered at the top of the vegetation - surface albedo - (top panel), 2) absorbed in the vegetation layer - FAPAR - (middle panel) and 3) absorbed in the ground layer (bottom panel). Maps are derived from the analysis of the 13-28 August, 2005 16-day period. The black points represent the grid cells where no input albedo product is available from MODIS.