Remote Sensing of Environment 142 (2014) 141–154

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Intercomparison of fraction of absorbed photosynthetically active radiation products derived from satellite data over Europe

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ARTICLE INFO

Article history:
Received 25 March 2013
Received in revised form 2 December 2013
Accepted 4 December 2013
Available online 27 December 2013

Keywords:
Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)
Europe
MODIS
JRC-TIP
MGVI
Intercomparison
Flux tower
Triple collocation

ABSTRACT

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is recognized as an essential climate variable (ECVs), playing a critical role in the estimation of the global energy and carbon balance. With multiple space-borne remote sensing FAPAR global products available from several sources the need for continual comparison and validation has become imperative. In this study, the performance of three global FAPAR algorithms (JRC-TIP, ESA/JRC MGVI and Boston University FAPAR) was evaluated over Europe for the year 2011. Results show an overall agreement among FAPAR products on sites having high and low FAPAR values, except for the north-eastern region of Europe characterized by boreal forest and the transition region with tundra biomes, where the Boston product exceeds values in other products by up to 0.5. Differences in FAPAR estimates over forest biomes suggest that assumptions on structure and optical properties of land surfaces in the different radiative transfer models play an important role in remote-sensing-derived FAPAR products. Uncertainty assessments were carried out using both quality indicators as proposed by the individual product teams as well as independent theoretical uncertainty estimates obtained with the triple collocation error model. The former revealed consistent spatial patterns but large differences in magnitudes (up to 0.1) with systematically lower uncertainties for the Boston product. The latter instead suggests similar uncertainty ranges among the three products. Finally, a comparison with ground estimates for the 2009–2011 period over four European flux tower sites showed consistent, plausible seasonal variations of remote-sensing-derived FAPAR products. Findings suggest that differences in absolute values and inconsistency in uncertainty representation among FAPAR products are still considerable. Standardization frameworks quantifying the impact of different radiative transfer formulations on the estimation of biophysical variables, independent uncertainty estimation methods and well-defined ground measurement protocols need to be put in place before FAPAR products can be reliably fed into existing biogeochemical process models.

1. Introduction

Consensus within the scientific community has formed on the need for improved knowledge on the carbon cycle, its variability, and its future state (Cihlar et al., 2002). Rising CO_2 content in the atmosphere, its effect on climate, and the associated role of terrestrial ecosystems in mitigating the impact of climate change are critical issues in understanding the global carbon cycle (Falkowski et al., 2000; Reichstein et al., 2013). Among all of the developed methods to estimate carbon fluxes, only space-borne remote sensing observations provide globally consistent, highly spatially and temporally resolved observations of a suite of land surface variables affecting carbon exchange. These variables can then be ingested in biogeochemical process models to be converted into fluxes (McCallum et al., 2009).

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) has been recognized by the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS) as one of the fundamental essential climate variables (ECVs), playing a critical role in the energy balance of ecosystems and in the estimation of the carbon balance (GTOS, 2008). FAPAR is generally defined as the fraction of Photosynthetically Active Radiation (PAR) absorbed by vegetation, where PAR is the solar radiation reaching the vegetation in the wavelength region 0.4–0.7 μm (Gower, Kucharik, & Norman, 1999). FAPAR is thus directly related to photosynthesis and is one of the few variables linking ecosystem function and structure (Asner, Wessman, & Archer, 1998). FAPAR products can either be used as an input to diagnostic terrestrial carbon models, such as Production Efficiency Models (PEMs) which calculate Gross and Net Primary Productivity (GPP/NPP) (Prince

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0034-4257/$ – see front matter
http://dx.doi.org/10.1016/j.rse.2013.12.005

& Goward, 1995; Running et al., 2004), or may serve as additional constraints during assimilation processes in more sophisticated schemes (Rayner et al., 2005). Therefore, the choice and accuracy of FAPAR data used will have a significant impact on the fluxes estimated by these models (McCallum et al., 2009). Furthermore, time series of FAPAR can be used to help monitor vegetation state and environmental indicators, drought events (Gobron et al., 2005), land degradation (Senna, Costa, & Shimabukuro, 2005), phenology (Gonsamo, Chen, Price, Kurz, & Wu, 2012; Huemmrich, Privette, Mukelabai, Myneni, & Knyazikhin, 2005; Verstraete et al., 2008) and biodiversity (Coops, Wulder, Duro, Han, & Berry, 2008).

Typically, FAPAR is estimated from physically based models describing the transfer of solar radiation in plant canopies and using remote sensing observations as input (Gobron & Verstraete, 2009). Alternatively, empirical relationships with vegetation indices based on field measurements are exploited usually in combination with concurrently acquired satellite images (Fensholt, Sandholt, & Rasmussen, 2004). The in situ validation of FAPAR products remains incomplete or inhomogeneous. PAR is monitored as part of the standard protocol at a variety of ecological and radiation research sites, e.g., FLUXNET (Baldocchi et al., 2001), the Long Term Ecological Research (LTER) Network (Baker et al., 2000), and the Surface Radiation (SURFRAD) Network (Augustine, DeLuisi, & Long, 2000). However, very few sites are equipped to perform the necessary measurements to derive canopy-scale FAPAR needed for the validation of space-borne remote sensing products (Gobron & Verstraete, 2009).

Capitalizing on the available space-borne remote sensing data, space agencies and other institutional providers have begun generating and delivering various FAPAR products at different temporal and spatial resolutions. Over ten years of space-derived FAPAR data are now available from different sources (CEOS-LPV). The evaluation of these different FAPAR datasets in terms of their uncertainty, convergence and ultimately usability in process models, is seen as a critical task (Seixas, Carvalhais, Nunes, & Benali, 2009). The few studies undertaken to date, restricted to specific products and spatio-temporal extents, suggest that important differences exist between datasets and should be investigated further (Gobron et al., 2007; Martínez, Camacho, Verger, García-Haro, & Gilabert, 2013; McCallum et al., 2010; Meroni et al., 2012; Seixas et al., 2009; Weiss, Baret, Garrigues, & Lacaze, 2007).

The objective of this paper is to undertake a detailed intercomparison and quality assessment of three global FAPAR products: (i) the JRC-TIP (Joint Research Centre Two-stream Inversion Package) FAPAR derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) (Pinty, Clerici, et al., 2011), (ii) the European Space Agency (ESA) JRC FAPAR obtained using the MEdium Resolution Imaging Spectrometer (MERIS) Global Vegetation Index (MGVI) (Gobron, Pinty, Verstraete, & Govaerts, 1999), and (iii) the Boston University FAPAR derived from MODIS (Knyazikhin, Martonchik, Myneni, Diner, & Running, 1998). This analysis is meant to serve as a starting point for upcoming validation activities proposed by the Land Product Validation (LPV) subgroup (http://lpvs.gsfc.nasa.gov) of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) for validation of moderate and coarse remote sensing products (Morisette et al., 2006). It included (i) an intercomparison among datasets across Europe for specific biome types for the year 2011; and (ii) a multitemporal comparison between the space-borne remote sensing products and ground-based estimates over selected European flux tower sites from 2009 to 2011. Products were further evaluated based on uncertainty information provided by the respective product teams and an independent theoretical uncertainty estimation method.

2. Data

Selection of the FAPAR products was based on their availability at a spatial and temporal coverage relevant for biogeochemical process models. Assimilation products resulting from the integration of multiple datasets (e.g., geoland2/BioPar (Meroni et al., 2012; Verger, Baret, & Weiss, 2008)) were not considered due to the difficulty to derive consistent uncertainty information for these products. This restricted the choice to three global operational products. Table 1 summarizes the characteristics of the FAPAR products, while their individual components and processing schemes are discussed in detail in the following paragraphs. We refer to the JRC-TIP FAPAR product as TIP, to the ESA/JRC MGVI product as MGVI and to the Boston University FAPAR product by using the official MODIS product catalog abbreviation, MCD (https://lpdaac.usgs.gov/products/modis_products_table/mcd15a2).

2.1. JRC-TIP

The JRC-TIP algorithm can compute FAPAR under direct, diffuse or direct plus diffuse illumination assuming any sort of optical properties for the canopy. For this study datasets obtained assuming a green canopy under diffuse illumination were chosen. The main input to the algorithm are MODIS broadband VIS (visible) and NIR (near-infrared) white sky albedo products (MCD43B3) provided at 0.01° (~1 km) spatial resolution for successive 16-day periods from combined Terra-Aqua datasets. The radiation transfer model is the two-stream model developed by Pinty et al. (2006) which simulates the partitioning of the solar fluxes based on a one-dimensional approach.

In the first step, the model inversion, the state variables are estimated from the observed scattered fluxes at the top of the canopy, i.e., the MODIS broadband visible and NIR white sky albedos. The set of state variables entering the two-stream model are a spectrally invariant quantity, namely the effective Leaf Area Index (LAI) and spectrally dependent parameters including i) the true albedo of the background, ii) the effective (by contrast to true) vegetation single scattering albedo, and iii) the direction (forward or backward) of scattering in the canopy layer with respect to the source of illumination. Prior values are assigned to these variables using Probability Density Functions (PDFs), to solve the underdetermined inverse problem. The effective LAI is specified with a large uncertainty (wide PDF) allowing the inversion procedure to explore any physically realistic value. This first step provides the posterior PDFs of the model state variables, including the effective LAI values (Pinty et al., 2006; Pinty et al., 2007). In the second step, the model can be used in forward mode to estimate the PDFs of all radiant fluxes, i.e., the reflected, transmitted and absorbed fluxes in the vegetation and background layers (Pinty, Andredakis, et al., 2011). A cost function is used to balance (1) the deviation from the a priori knowledge on the model state variables values and (2) the misfit between the observed remote sensing fluxes and the two-stream model simulations.

It should be noted that the prior values of the state variables are time and space invariant and not specified as a function of land cover and/or season. An exception is given by the prior PDF of the background albedo, which changes with the presence of snow, based on a MODIS snow flag. The inversion can be operated under a variety of conditions including those associated with a standard and green leaf scenario. The former refers to the general case with limited a priori knowledge (wide PDFs), while the latter scenario imposes much more constraining reflectance and transmittance factor values corresponding to typical green leaf properties. The green leaf scenario translates into a narrow PDF of the effective single scattering albedo of the canopy. As a result the green leaf scenario, which was chosen in this study, is characterized by lower retrieval uncertainties as compared to the standard scenario. No backup algorithm exists and in the cases (<0.5%) where the remote sensing observations cannot be reliably interpreted by the JRC-TIP algorithm values are flagged as non-physically valid pixels. JRC-TIP delivers a series of output files with a spatial resolution of 0.01° (~1 km) (same as the input albedos) every 16 days including radiant fluxes and LAI (Pinty, Clerici, et al., 2011).