Remote Sensing of Environment 165 (2015) 14–26

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

A method for estimating hourly photosynthetically active radiation (PAR) in China by combining geostationary and polar-orbiting satellite data

Li Li [a,b], Xiaozhou Xin [a,*], Hailong Zhang [a], Jiangfeng Yu [a], Qinhuo Liu [a,c], Shanshan Yu [a], Jianguang Wen [a]

[a] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[b] RS and GIS Institute of Peking University, Beijing 100871, China
[c] Joint Center for Global Change Studies (JCGCS), Beijing 100875, China

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 13 March 2015
Accepted 31 March 2015
Available online xxxx

Keywords:
PAR estimation
MTSAT
MODIS
6SV
SBDART
Look-up table

ABSTRACT

Photosynthetically active radiation (PAR) is an important parameter in ecosystem and land surface models. PAR represents the amount of solar radiation in the spectral range of 400–700 nm that travels through the atmosphere to the top of the vegetation canopy. In recent years, various methods using different input data to estimate PAR and produce different PAR products have been developed. However, most of the algorithms used in these state-of-the-art studies have not fully compensated for the low spatial and temporal resolution of the data, which affects the accuracy of the PAR estimates. In this study, we have developed a method for estimating hourly PAR based on a combination of geostationary and polar-orbiting satellite data. The Multifunctional Transport Satellite (MTSAT) was selected to retrieve cloud optical depth (COD) with a higher spatial resolution, and the polar orbit satellite data of the Moderate Resolution Imaging Spectroradiometer (MODIS) products were used to derive surface parameters based on multispectral characteristics. A look-up table was established by the Second Simulation of a Satellite Signal in the Solar Spectrum-Vector (6SV) model and the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model consisting the following parameters: solar zenith angle, total water vapor, total ozone column, aerosol optical depth (AOD), COD, surface elevation, surface albedo and PAR. The instantaneous PAR was linearly interpolated from the input data for the selected parameters and the look-up table. The root mean square error (RMSE) between the estimated and observed instantaneous PAR at the Huailai station was 45.72 W/m^2 for all sky conditions. The RMSE between the estimated and observed daily PAR at the meteorological stations was 17% in the eastern regions of China. The mean bias error (MBE) was between −2.83 and 32.43 W/m^2 for the Tibetan Plateau. These results indicated that the proposed method can significantly improve the accuracy of PAR estimates and can be used to produce PAR products with high spatial and temporal resolution. However, the method requires further improvement, especially with respect to cloudy conditions.

1. Introduction

Photosynthetically active radiation (PAR) is the solar radiation within the spectral range of 400–700 nm. This radiation can be absorbed by photosynthetic organisms, such as plants, and is used in the process of photosynthesis. Photosynthesis is a basic process involved in plant growth and contributes to regional and global climate change. Therefore, PAR plays an important role in many ecosystem models and in the third-generation land surface model. Most (approximately 97.50%) energy from solar radiation is at wavelengths of between approximately 0.31 and 5.60 μm, including visible light (43.50%) and the near-infrared spectrum (36.80%). Under clear sky conditions, the attenuation of solar radiation in the atmosphere consists of three main components: the absorption and scattering by aerosols in the broadband, ozone in the visible band and water vapor in the near-infrared band; Rayleigh scattering; and Mie scattering (including cloud reflection). Under cloudy conditions, the influence of the atmosphere is much more complex than under clear conditions due to the strong temporal and spatial variation of cloud cover and three-dimensional cloud characteristics.

The PAR at the top of the canopy can be calculated using the incoming PAR at the top of the atmosphere and the transmittance of the atmosphere. Theoretically, PAR is expressed as follows:

$$\mathrm{PAR} = \eta \times Q,$$

where η is the ratio of PAR to the solar shortwave radiation and Q is the solar shortwave radiation. Moon (1940) found that the ratio of PAR to solar radiation was approximately 0.44. McCree (1966) found that this ratio could change under varying weather conditions. On clear sky, the

---

* Corresponding author.
E-mail address: xin_xzh@163.com (X. Xin).

http://dx.doi.org/10.1016/j.rse.2015.03.034
0034-4257/© 2015 Elsevier Inc. All rights reserved.

ratio ranged from approximately 0.47 to 0.52, and on cloudy sky, the range was 0.50–0.58. 0.50 is used as the ratio of PAR in the Carnegie–Ames–Stanford Approach (CASA) model (Potter et al., 1993). Li (2010) examined the value of η at the Huailai experimental site in Hebei Province, China, using observations of PAR and solar radiation and found that η is approximately 0.38 and depending on atmospheric conditions.

Generally, there are two methods for the estimation of PAR: direct methods and indirect methods. The direct methods include semi-empirical methods, radiation transfer parameterization methods and look-up table (LUT) methods, and PAR is estimated using the relationships between the atmospheric parameters or meteorological variables. The semi-empirical models establish a statistical relationship between satellite images and surface radiation observations rather than accounting for specific atmospheric conditions and composition. To obtain the PAR, the Heliosat model established a statistical relationship between sensor visible band data and surface shortwave radiation using a cloud cover index based on a regression of the surface shortwave radiation (Cano et al., 1986). Radiative transfer parameterization methods use relatively simple radiative transfer models. The various parameters that affect radiative transfer are quantified based on actual atmospheric conditions at the time that the satellite is overhead. Leckner developed the first simple parametric model based on the theory of radiative transfer (Leckner, 1978). Subsequently, BIRD (SPCTRAL2) (Bird & Riordan, 1986), CPCR2 (Gueymard, 1989), SMARTS (Gueymard, 1994) and other parameterization models were developed. These models can be divided into two categories based on spectral resolution: broadband models and spectral models. Singh, Raman, Dwivedi, and Nayak (2008) inversed instantaneous PAR with the BIRD model based on IRS P4 ocean color remote-sensing monitoring satellite data. The results were compared with field-measured PAR data from two seasons, and the RMSE was 21.28 W/m^2. Alados, Foyo-Moreno, Olmo, Alados-Arboledas, and Grupo de Fisica dé la Atmosfera (2002) used the SPCTRAL2 model and SMARTS2 model to estimate PAR with different aerosol types. When compared with ground-based measurements from two Spanish observation sites, the RMSE for the SMARTS2 model was 5.30–11% and the RMSE for the SPCTRAL2 was 6.4–12.8%. The authors found that the different aerosol types largely determined the PAR estimations. With the development of remote-sensing technology, the inversion of PAR using satellite data has received increasing attention in recent years. Frouin and Pinker (1995) modified Gautier's algorithm to estimate solar radiation and replaced the total solar radiation band with the PAR band (Gautier, Diak, & Masse, 1980). The remaining parameters were derived from remote-sensing satellite data in the visible and near-infrared bands. Pinker and Laszlo (1992) estimated global PAR using a method developed from Pinker and Ewing's broadband solar radiation flux estimation, which used forward radiative transfer model (RTM) simulations to obtain the relationship between atmospheric transmittance and broadband reflectance at the top of the atmosphere (Pinker & Ewing, 1985). Chen, Gao, Yang, Liu, Gu, and Tian (2008) added multiple atmosphere-surface reflections and aerosol parameters to the underlying ocean surface in the MODIS ocean PAR products model. Using this modified model, the PAR under clear sky conditions was estimated. The RMSE was 20.59 W/m^2 compared with ground observations. To improve the computational efficiency of PAR estimations, several methods based on the radiative transfer model have been developed. Liu, Liang, He, Liu, and Zheng (2008) showed that the top-of-atmosphere (TOA) radiance depends on the surface reflectance and the atmospheric properties that largely determine incident PAR. Therefore, these authors first estimated surface reflectance. This approach assumes known aerosol properties for the observations, with minimized blue reflectance for the temporal window of each pixel. Their inverted surface reflectance was then interpolated to determine the surface reflectance of the other observations. The second step was to calculate PAR by matching the computed TOA reflectance from the LUT with the TOA values from the satellite observations. The RMSE of the estimated instantaneous PAR from three flux sites yielded is 194.82 $\mu mol/m^2/s$ (17.50%).

Most parameterized models can only estimate PAR under clear conditions, but cloud is an important factor affecting the amount of PAR that reaches the surface. Therefore, the accuracy of PAR estimations for cloudy sky conditions determine the accuracy of daily PAR. A pre-calculated PAR for clear sky with cloud transmittance is the commonly used method. Cloud transmittance is generally determined by the cloud amount and cloud type (Atwater & Ball, 1981; Davies & McKay, 1989; DeGaetano, Eggleston, & Knapp, 1995). There are many PAR products derived from different satellite sensors. The TOMS PAR product covers a range from 66°N to 66°S with 1 × 1° pixel resolution. TOMS is a monthly mean PAR product (Eck & Dye, 1991). NASA provides a MODIS ocean PAR product (MOD22) with a spatial resolution of 1 km. MOD22 consists both daily integrated and instantaneous PAR products (Carder, Chen, & Hawes, 1999). NASA is also funding research for a MODIS land PAR product.

Most of the above models do not estimate direct and diffuse radiation separately. However, the direct radiation as a proportion of total radiation is an important parameter in many studies, such as the researches that focused on surface albedo and the fraction of photosynthetically active radiation (FPAR). A model that estimates direct and diffuse radiation separately can be used to obtain the proportion of direct radiation in the total radiation.

For moderate resolution PAR estimation, many algorithms do not take into account the effects of topography. The effects of terrain should not be ignored at fine spatial resolution. First, topography can directly affect the length of the radiative transfer path through the atmosphere, thereby affecting radiation transmittance. Second, topography also affects the solar elevation angle and the atmospheric profile. Both factors are sensitive parameters in the determination of PAR.

The spatial and temporal resolution of the above-noted PAR products is very low. Gerenally, the daily PAR is accumulated by the instantaneous satellite images. However, due to frequent changes of daily cloud cover, using one or two instantaneous values to fit a daily model will inevitably cause over- or underestimation.

In this study, the LUT of PAR was first created offline under different weather conditions from an RTM. Then, the atmosphere parameters were calculated from the remote-sensing data, the PAR was derived using the look-up tables. To improve the current shortcomings of PAR algorithms and products, a new method that combines geostationary and polar orbital satellite data to improve the temporal resolution of the PAR product is presented. MTSAT geostationary and MODIS polar orbital satellite data were used to estimate instantaneous and hourly PAR for the entire geographical area of China. Finally, we used ground observations to verify the accuracy of the method.

2. Theory and methods

Carder, Chen, and Hawes (1999) divided downward solar irradiance into two components:

$$E_d(\lambda) = E_{dd}(\lambda) + E_{ds}(\lambda), \tag{1}$$

where $E_{dd}(\lambda)$ is the direct light flux and $E_{ds}(\lambda)$ is the diffuse light flux. $E_{dd}(\lambda)$ is calculated as

$$E_{dd}(\lambda) = E_0(\lambda)\cos(\theta)T_r(\lambda)T_{oz}(\lambda)T_0(\lambda)T_w(\lambda)T_a(\lambda), \tag{2}$$

where $E_0(\lambda)$ is the mean extraterrestrial irradiance corrected by the Earth–sun distance and orbital eccentricity, θ is the solar zenith angle and T is the transmittance after absorption and/or scattering by various atmospheric components, including r, oz, o, w and a, which