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Simple Algorithm for Estimation of Photosynthetically Active Radiation (PAR) Using Satellite Data

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Abstract

A simple algorithm for estimation of Photosynthetically Active Radiation (PAR) with satellite data is developed. The algorithm, which is based on a simple radiative transfer scheme, requires only one spectral channel (red) of a satellite. The algorithm was tested with satellite data taken by Terra/MODIS and Aqua/MODIS. The relative error of daily total PAR estimated by this algorithm was 27%. It can provide PAR maps with a resolution as fine as 250 m, with which the topographic influence on the PAR distribution (due to local clouds) is clearly seen.

1. Introduction

Solar radiation is one of the most important component in the land-surface process. It provides the energy which drives meteorological, hydrological, and ecological processes. Among the solar radiation, photosynthetically active radiation (PAR) is the fraction with wavelength between 0.4 μm and 0.7 μm. Plants can use PAR for their photosynthesis. Therefore, to estimate agricultural and forest productivity, accurate data about PAR are desired.

In order to estimate PAR which reaches the ground, the loss of PAR by reflection and absorption by atmosphere must be considered. This atmospheric disturbance, especially due to clouds, show large variability in space and time, hence estimation of PAR depends on accurate observation of the distribution of the atmospheric condition. Satellite remote sensing can be a solution to this requirement because a satellite can observe atmosphere with regular temporal intervals. In fact, some studies (van Laake and Sanchez-Azofeifa 2005; Liang et al. 2006; Frouin and Murakami 2007) realized estimation of PAR with satellite optical sensors (e.g., MODIS).

However, these existing methods employ complicated radiative transfer models dealing with scattering processes of the radiation by various types of particles. Therefore, they require satellite datasets with enough quality of enough number of spectral bands. This requirement reduces choices of satellite data. Sometimes it can be met with expense of spatial resolution. For example, the PAR product derived by van Laake and Sanchez-Azofeifa (2005) is nominally 1 km resolution but it highly depends on the aerosol data of 10 km resolution.

In this study, I propose a simple algorithm to estimate PAR with satellite data as small requirement as possible. By taking this algorithm the spatial resolution of 250 m can be targeted.

2. Method

2.1 Algorithm and theoretical background

Let I_0, A, R_A, and R_G be incoming PAR flux (in photon flux density) at the top of atmosphere, absorption of PAR in the atmosphere (including aerosols and clouds), reflectance of PAR at the top of atmosphere, and reflectance of PAR on the ground, respectively. The incoming PAR on the ground can be represented as TI_0, where, T is a variable depending on atmospheric condition and ground surface. The meanings of T is similar to the atmospheric transmittance but they are not identical because T depends on multiple reflections between the atmosphere and the ground. Meanwhile, PAR which leaves the earth to the space is $R_A I_0$. PAR which is absorbed on the ground is $T\,(1-R_G)\,I_0$. Then the conservation of energy leads to the following equation:

$$I_0 = R_A I_0 + T\,(1-R_G)\,I_0 + A. \tag{1}$$

The absorption in the atmosphere is assumed to occupy a constant fraction of the incoming PAR, namely, aI_0. Absorption by cloud particles was neglected, because the single scatter co-albedo of cloud particles (5 μm~10 μm) in the PAR region is mostly zero (less than 10^{-5}; e.g., Petty 2006). Then the absorption in the atmosphere is represented as:

$$A = aI_0. \tag{2}$$

We assumed the value of a to be 0.1 (see Appendix). Substituting Eq. (2) to Eq. (1) yields the following equation:

$$T = \frac{1 - R_A - a}{1 - R_G}. \tag{3}$$

Satellite data (without atmospheric correction) give R_A.

In principle, R_G should be estimated from atmospherically corrected satellite data. However, in this study, the influence of atmospheric correction is assumed to be negligible, hence the atmospheric correction is skipped. In order to mitigate errors due to this simplification, it is necessary to use a spectral band on which the atmospheric effect is less influential, hence I chose to use a longer end of the PAR spectrum (red). Then cloud-free red-band satellite data (after the cloud-screening composite) give R_G. Other influential factors, such as bi-directional reflectance factors (BRF), are also neglected.

Astronomical calculation gives I_0. By multiplying T derived by Eq. (3) with I_0, the estimation of PAR completes.

2.2 Data and analysis

I implemented the aforementioned algorithm with instantaneous data taken by two satellite sensors: Terra/MODIS and Aqua/MODIS of NASA. For estimation of R_A, I used the band 1 (red) data of so called "level 1B" products (MOD02QKM; 250 m resolution), which are

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reflectance at the top of atmosphere with radiometric correction but without atmospheric correction. For each day and each pixel, at least two R_A data exist because Terra satellite makes observation every morning and Aqua satellite makes observation every afternoon.

I estimated R_G by taking monthly minimum R_A at each pixel. Therefore, the interval of R_G data is monthly. I used it for daily analysis, assuming the day-to-day variability of R_G was small. This assumption may have caused error when the ground surface condition rapidly changed, such as snowfall and snow melt.

With those data and Eq. (3), I estimated instantaneous T value at each pixel on the satellite data. Then I averaged T value at each pixel within a day. On the other hand, I estimated daily total I_0 value at each pixel from the solar radiation spectrum (Thuillier et al. 2003), distance between sun and earth, and the incident angle (solar zenith angle). By multiplying the daily-averaged T value and the daily total I_0 value, I estimated daily total PAR at each pixel.

The target period is DOY 124 to DOY 365, 2004. The target area is central Japan including Chubu and Kanto region.

2.3 Ground truth

I compared the estimated PAR to PAR data observed on two ground sites: Takayama (137.4231 E, 36.1462 N; 1420 m a.s.l.) and Mase (140.0272 E, 36.0536 N; 12 m a.s.l.), both of which are AsiaFlux sites. On each site the PAR was measured with silicon photo-diode sensors (Koito IKS-27 and Li-Cor LI-190) and recorded with 5-min (Takayama) or 30-min (Mase) interval. I calculated daily total PAR.

3. Results

The estimated PAR showed seasonal and day-to-day changes similar to the ground observation at the two sites (Fig. 1). By trusting the ground observation, I assessed the error in PAR estimated with satellite data as follows: The root-mean-square error (RMSE) was 7.4 mol/m^2/day (relative error: 27%), with correlation coefficient of 0.94 (n = 478; Fig. 2). The regression equation between ground observation (x) and satellite estimation (y) was $y = 1.11x - 0.50$.

4. Discussion

The magnitude of relative error (27%) in this algorithm is fairly larger than the relative error of 5–8% in detailed algorithm by Van Laake and Sanchez-Azfeifa (2005). It may be partly due to the simplification of radiative transfer process. Another possible error source is, as Laake and Sanchez-Azfeifa (2005) pointed out, the higher solar zenith angle in this study due to higher latitude than their target area (tropics).

The accuracy can be improved by adjustment of the parameter a, if necessary. In fact, adjustment of a to 0.17 improved the agreement with ground truth (RMSE = 6.2 mol/m^2/day). It means the value 0.1 for a is possibly an undershoot. The possible reason for this error is a seasonal change of the transmittance, discrepancy of spectral bands, representativity of the ground data etc.

In order to assess the influence of using only the red band data, I performed the analysis with MODIS band 3 (blue) and band 4 (green) instead of the band 1 (red). As a result, RMSE of estimated PAR against the ground truth were 6.6 mol/m^2/day (for the case of band 3) and 7.0 mol/m^2/day (for the case of band 4). This result suggests the selection of the spectral band within the PAR region has only a small or moderate influence.

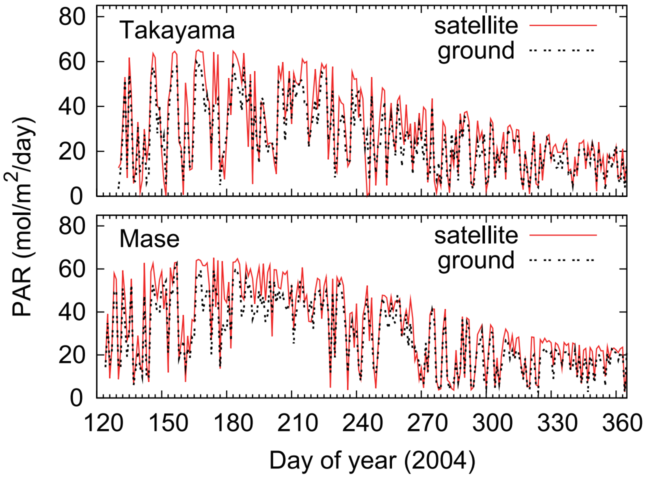

Fig. 1. Temporal changes of satellite estimation and ground observation of daily PAR.

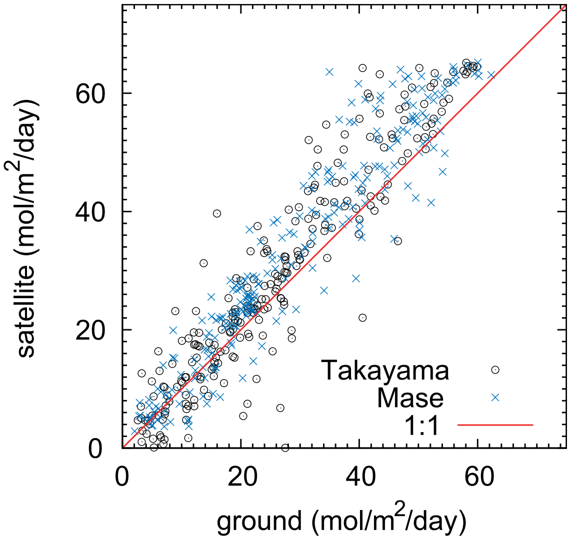

Fig. 2. Comparison of satellite estimation and ground observation of daily PAR.

In order to assess the influence of skipping the atmospheric correction, I performed the analysis with atmospherically corrected data (MOD09GQK) in deriving the R_G value. The resultant RMSE was 6.7 mol/m^2/day.

The validity of this simple algorithm has not been guaranteed in different circumstances, such as different climatic zones (arid, boreal, tropics, etc.), different load of aerosols with various characteristics (dusts from yellow sands or forest fire), and so forth. Therefore, further effort on the validation works is called for. For example, validation using the ground PAR data taken by SkyNet and FluxNet, is desirable. Test of this algorithm with other satellites is also desirable. These are the next step of this study.

This algorithm provides PAR with spatial resolution of 250 m. Such a fine resolution is critically important for ecology or land surface process study, because the

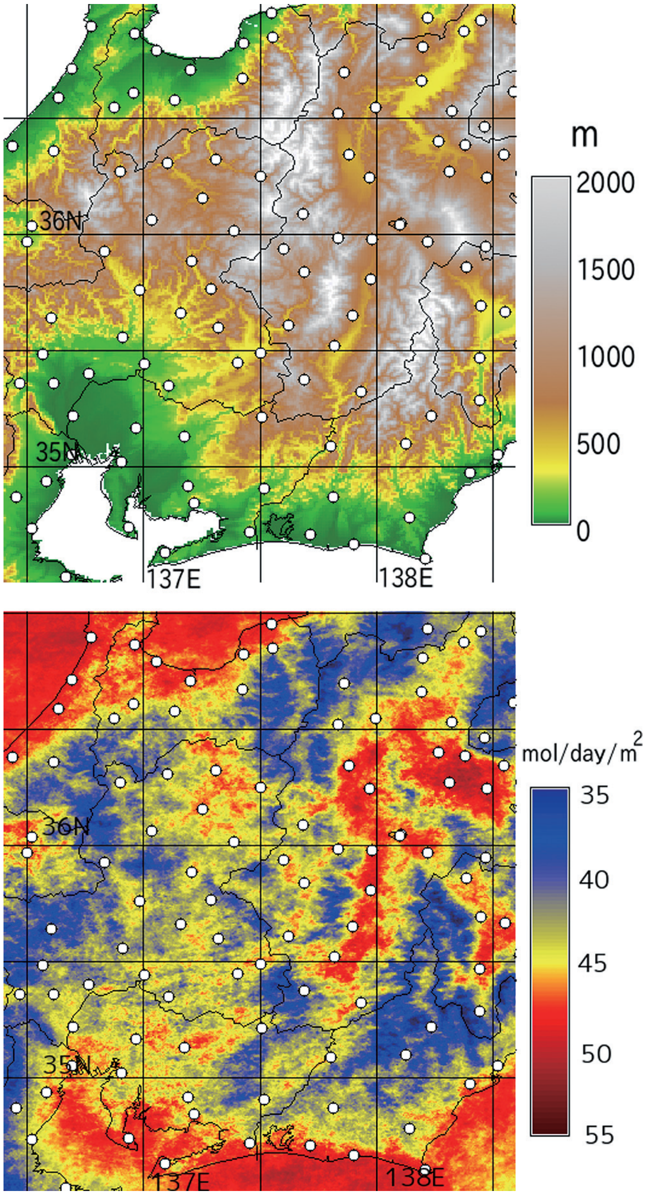

Fig. 3. Topography (top) and average daily PAR in summer (bottom) in the central mountains in Japan. The mean daily PAR through DOY 211 to DOY 240, 2004, was estimated from satellite data and averaged. White circles indicate the location of JMA/AMeDAS observation sites. Note the interval of the grid is 0.5 degree, corresponding to a distance of about 50 km.

influence of local clouds in response to topography, namely, cloudy in mountains and sunny in lowlands, is obviously seen with this scale (Fig. 3). In contrast, it is difficult to estimate PAR distribution in such high resolution and reliability by a ground observation network. For example, the resolution of observation sites of AMeDAS (Automated Meteorological Data Acquisition System) of Japan Meteorological Agency is about 20 km (Fig. 3). Besides, these sites tend to locate in lowlands for capability of maintenance. Therefore, it is impossible to represent the topographic influence by simple interpolation of these sites.

Appendix

Determination of parameter a

From the Eq. (3), the following equation can be obtained:

$$a = 1 - R_A - T\,(1 - R_G). \tag{4}$$

I estimated values of R_A, T, and R_G by a radiative transfer calculation (Aoki et al. 1999) with the following conditions. Atmosphere model: clear sky in mid-latitude summer (Anderson et al. 1986); aerosol model: OPAC Continental Average model (Hess et al. 1998) with aerosol optical thickness (at 0.5 μm) of 0.2 (annual average at Ryori station during 2004–2005. JMA 2008); ground condition for albedo: wheat field (Liou 2002); wavelength: between 0.6375 μm and 0.6625 μm. As a result, the a value estimated by Eq. (4) varied between 0.07 and 0.14, depending on solar zenith angle between 6 degree and 63 degree. Taking the middle of this range, I assumed a to be 0.1.

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