Mapping High-Resolution Incident Photosynthetically Active Radiation over Land from Polar-Orbiting and Geostationary Satellite Data

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Incident photosynthetically active radiation (PAR) is required by almost all terrestrial ecosystem models and many other applications. The current PAR products that are developed for climate studies have much coarser spatial resolution and higher temporal resolution and are not suitable for land applications. This article reviews state-of-the-art methods for mapping land spatial-resolution incident PAR from both polar-orbiting and geostationary satellite observations.

Introduction

PAR is the total incoming solar radiation in the visible spectrum (400-700 nm) that corresponds with the range of light visible to the human eye. Since it strongly depends on the solar zenith angle and the cloud and aerosol properties, incident PAR shows the distinct temporal and spatial patterns.

Only PAR of the total solar radiation can be absorbed and converted to biomass by green vegetation through photosynthesis. Many ecosystem models calculate biomass accumulation linearly proportional to incident PAR. Different terrestrial ecosystem models, including models of terrestrial biogeochemistry, global vegetation biogeography, dynamic vegetation and land-atmosphere exchange processes have been developed for the function and dynamic nature of ecosystems, along with their role in the global carbon, nutrition, and water cycles. Almost all of these models contain the physiological processes involved in photosynthesis and stomatal regulation that control the exchange of water vapor and carbon dioxide between vegetation canopies and the atmosphere. Incident PAR is a critical variable to initiate, calibrate and validate these models.

Mapping incident PAR and insolation (total downward solar radiation) is also greatly valuable for understanding water and energy cycles and how they are affected by climate change. Other application areas include agricultural productivity and sustainability, ecological forecasting, energy management, public health, and water management. The user community that needs PAR/insolation include hydrologists/ecologists for characterizing surface fluxes, managing water and carbon resources; agronomists for monitoring crops, estimating water requirements and predicting yields at farm to continental scales; federal agencies involved in water resource allocation, crop yield assessment and drought monitoring; and urban and regional planners for mitigating heat island effects.

A worldwide observation network for measuring incident PAR is not yet established and the only practical means of obtaining incident PAR at spatial and temporal resolutions appropriate for most modeling applications is through remote sensing. Frouin and Pinker (1995) reviewed earlier methods for estimating incident PAR from the International Satellite Cloud Climatology Project (ISCCP) and Total Ozone Mapping Spectrometer (TOMS) observations. In general, there are roughly two types of algorithms for calculating incident PAR. *The first approach* (see Figure 1a) is to use retrieved cloud and other atmospheric parameters from different sources, with measured top-of-atmosphere (TOA) radiance/flux acting as a constraint. The Clouds and the Earth's Radiant Energy System (CERES) algorithm uses the cloud and aerosol information from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and TOA broadband fluxes as a constraint, to produce both insolation and PAR at the spatial resolution of 25 km with the instantaneous sensor footprint (the gridded product has the spatial resolution of 140 km). The Global Energy and Water Cycle Experiment (GEWEX) surface radiation budget (SRB) Release 2 product with a spatial resolution of 1° by 1° and high temporal resolutions mainly from GOES data is also based on this method. The ISCCP produces a new 18-year (1983-2000) global radiative flux data product called ISCCP FD every three hours on a 280 km equal-area global grid. ISCCP FD is calculated using a radiative transfer model from the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM). Atmosphere and surface properties are obtained primarily from TIROS Operational Vertical Sounding (TOVS) data.

The second approach (Figure 1b) is to establish the relationship between the TOA radiance and surface incident PAR based on an atmospheric radiative transfer model. This method was first applied to analyze Earth Radiation Budget Experiment (ERBE) data. Liang *et al*. (2006b) generated the PAR and insolation products at 1 km from MODIS data directly using this approach.

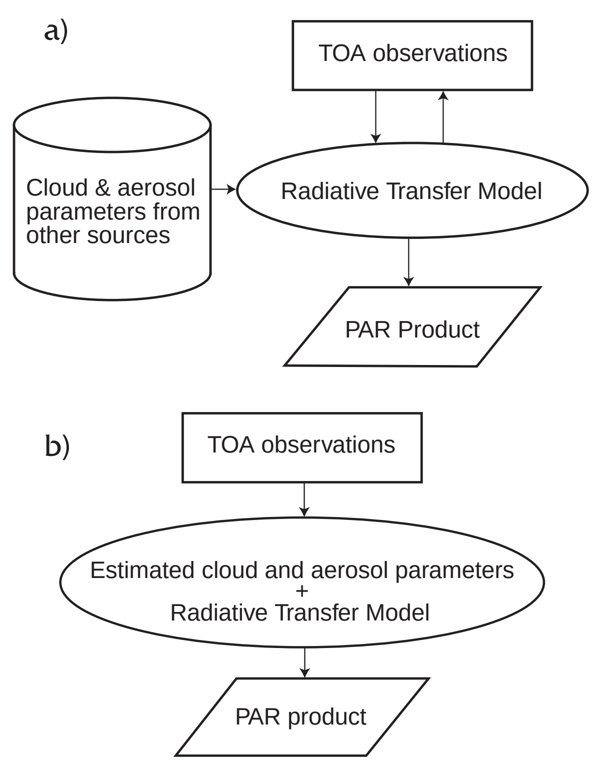

Figure1. Illustration of two methods for estimating incident PAR from satellite observations.

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The requirements of PAR products vary depending on the science question. Climate studies require coarser spatial resolutions (e.g. >1° by 1°) and higher temporal resolutions (e.g., 3 hours and daily). Higher spatial resolution is greatly desirable for land applications (e.g., ecosystem and hydrology). The MODIS science team (Running *et al.*, 2004) is currently generating the official MODIS 1 km global terrestrial GPP and NPP products with the Data Assimilation Office (DAO) shortwave radiation product at 1° by 1.5° resolution as an input. The GLO-PEM model (GLObal Productivity Estimation Model) (Prince and Goward, 1995) calculates the NPP using the fPAR product from the Advanced Very High-Resolution Radiometer (AVHRR) and the TOMS incident PAR product. The TOMS incident PAR product consists of monthly average estimates, at a spatial resolution of 1° by 1° from 66° North to 66° South latitude, and is not available after 1989. In addition to concern for the coarse spatial resolution, the monthly average PAR compromises the accuracy of the modeling because significant variation of PAR may occur over the span of a day. To mitigate this problem, the monthly average PAR is interpolated to generate a 10-day average. Returning to the problem of the PAR product spatial resolution, Prince (1995) found that PAR accuracy is not satisfactory at the 1° by 1° spatial resolution and concluded that 1 km incident PAR data is desperately needed. The spatial resolution of the MODIS data hydrological product (Nishida *et al.*, 2003) is also 1 km, but the meteorological forcing data currently available is quite coarse. In addition, Berg *et al.* (2005) pointed out that bias to many of the reanalysis fields limits their use for hydrological modeling.

Zhao *et al.* (2006) recently examined the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA-40) and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis by comparing these meteorological reanalysis data with weather station observations. They found that the biases in meteorological input data can introduce substantial error into MODIS GPP and NPP estimates, and emphasized the need for a more accurate incident solar radiation product. This product requires a 1 km spatial resolution and an 8-day temporal resolution to support MODIS GPP/NPP production.

Another issue for land applications is the separation of direct and diffuse PAR radiation. The volume of shade within vegetation canopies is reduced by more than an order of magnitude on cloudy and/or very hazy days compared to clear, sunny days because of an increase in the diffuse fraction of the solar radiance. Gu *et al.* (2002) found that diffuse radiation results in higher light use efficiencies by plant canopies and that diffuse radiation is much less likely to cause canopy photosynthetic saturation. In addition, the advantages of diffuse radiation over direct radiation increase with radiation level. Wang *et al.* (2007b) found that both light-use efficiency (the ratio of carbon uptake to absorbed PAR) and evaporative fraction (the ratio of evapotranspiration to available energy) distinctively increase with the ratio of diffuse to total incident solar radiation. These findings call for different treatments of diffuse and direct radiation in models of global primary production, and studies of the roles of clouds and aerosols in global carbon cycle. In fact, many land surface process models, such as SiB2 (Version 2 of the Simple Biosphere model) and Common (Community) Land Model (CLM), separate direct and diffuse solar radiation. However, none of the existing PAR products do so.

NASA established a Land Measurements Team to address the observational needs of its land-oriented science Focus Areas. One of the responsibilities of this team is to define the requirements and provide stewardship for a number of science-quality time-series data records, called "Earth System Data Records" (ESDR). As a first step in the process of developing the ESDRs, white papers on candidate products are developed in consultation with other members of the data producer community. Incident PAR is one of the candidate products and its white paper is available in the internet (Liang *et al.*, 2006a).

The operational weather satellite system is composed of two types of satellites: geostationary operational environmental satellites for short-range warning and "now-casting", and polar-orbiting satellites for longer-term forecasting. Both polar-orbiting and geostationary satellite data are used for mapping incident PAR. The objective of this article is to summarize the state-of-the-art methods on this topic with the emphasis on our own research.

PAR Estimation from Polar Orbiting Satellite Data

Sun-synchronous, near-earth satellite orbits (lower than 1000 km) are polar, and the inclination and altitude is such that a satellite always passes over a given site at the same local time. Therefore, the solar illumination seen by the satellite is constant for each site. Many satellites which make use of solar radiation for imaging use such sun-synchronous orbits. The sensors onboard these satellites acquire data over different areas of the earth at relatively infrequent intervals and have extensive applications to the land community, including AVHRR, MODIS, Medium Resolution Imaging Spectrometer (MERIS), Seaviewing Wide Field-of-View Sensor (SeaWIFS), Global Land Imager (GLI) and Visible/Infrared Imager/Radiometer Suite (VIIRS).

Estimation of instantaneous PAR

The standard MODIS high-level land products generated by NASA include surface reflectance and aerosol/cloud optical depth that can be used for calculating incident PAR (e.g., Van Laake and Sanchez-Azofeifa, 2004). However, some of the instrument algorithms for producing these land products are not well developed currently. For example, the aerosol optical depth product over land has many gaps (no retrieval) and is only available for densely vegetated surfaces (Liang *et al.*, 2006c). The cloud mask and other cloud products also need to be improved. Moreover, the MODIS atmospheric products have much coarser spatial resolution (~10 km) than surface reflectance. These products are not routinely available for AVHRR and other sensors. Therefore, the methods that reply on high-level atmospheric and surface products is generally not suitable for estimating incident PAR from polar orbiting data at a 1 km spatial resolution.

Liang *et al.* (2006b) developed a new method to map incident PAR (both direct and diffuse) from MODIS data. It first estimates surface reflectance from multi-temporal imagery and then PAR flux for each image. The basic procedure is composed of two steps: 1) determine the surface reflectance from the "clearest" observations during a temporal window, and 2) calculate incident PAR from the surface reflectance and TOA radiance/reflectance using the look-up table (LUT) approach. This new method differs from other methods in that surface reflectance and atmospheric properties are implicitly estimated simultaneously from the imagery itself.

The new PAR algorithm is validated using ground measurements at six FLUXNET sites (Fort Peck, Montana; Lost Creek, Wisconsin; Oak Ridge, Tennessee; Walker Branch, Tennessee; Santa Rem, Brazil; and Black Hills, South Dakoda) from 2002-2004. The validation results are shown in Figure 2 and their statistics in Table 1.

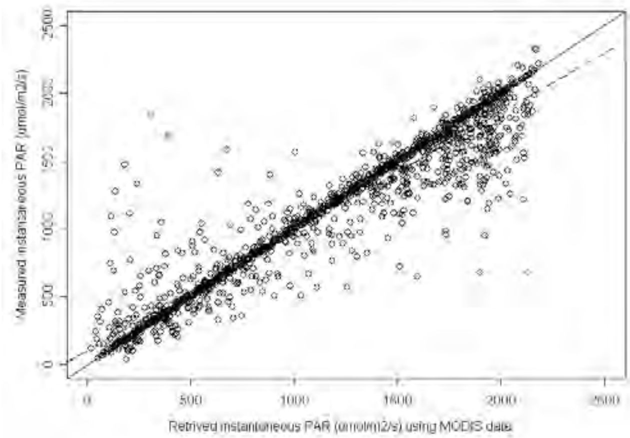

Figure 2. Validation of MODIS-derived instantaneous PAR data at six FLUXNET sites. The solid line is the 1:1 line, the dashed line is the best fit line based on least squares regression. Table 1 provides the statistics for the best fit line.

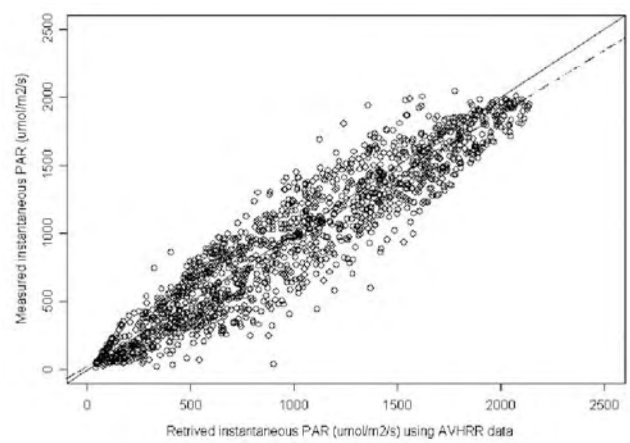

Figure 3. Validation of the AVHRR-derived instantaneous PAR data at the three FLUXNET sites. The solid line is the 1:1 line and the dashed line is the best fit line based on least squares regression. Table 1 provides the statistics for the best fit line.

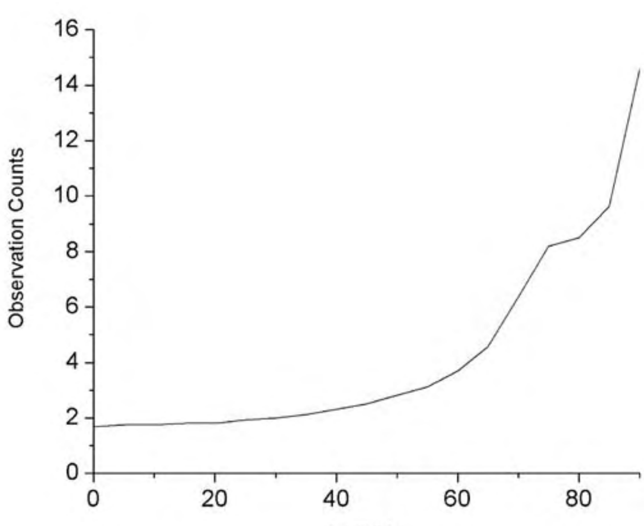

Figure 4. The average overpass counts of MODIS from both Terra and Aqua satellites over a time period of 12 hours as the function of latitude.

Table 1. Statistical summary of validation results of instantaneous PAR estimated using MODIS, AVHRR, and GOES. N is number of samples.

	MODIS	**GOES**	**AVHRR**
R^2	0.9011	0.9131	0.8788
Slope	0.8771	1.0327	0.9272
Intercept	103.9378	-28.0842	25.2575
Bias	32.4876	-6.0201	47.50
RMSE	194.815	161.130	195.478
Relative Error (%)	11.763	16.207	31.85
RMSE/Average (%)	17.494	15.33	20.527
N	1496	1775	1529

This method is being used for generating the incident PAR product from MODIS over North America for supporting the North America Carbon Program (NACP).

Liu *et al*. (2007) extended this method by using MODIS surface reflectance product (MOD09/MYD09). This method generates the normalized land surface reflectance from MODIS MOD09/MYD09 and MOD43/ MCD43 products using BRDF-correction and time-series interpolation to remove cloud or noise pixels. The measurement data from the Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFLUX) and meteorological stations were used to validate this method. This approach is used to map incident PAR over China, although more work is needed to evaluate its full potential.

Zheng (2007) used a similar algorithm to map incident PAR from AVHRR data. Because terrestrial ecosystem modeling and monitoring require long-term PAR data for model initiation, parameterization, and validation, the 20-plus years of continuous observations from AVHRR are extremely valuable. Although AVHRR has only one visible band, the retrieved PAR accuracy is comparable to the MODIS PAR product based on validation results. The validation results using the ground measurements at three FLUXNET sites (Metolius in Oregon, Park Falls in Tennessee, and Walker Branch in Wisconsin) are shown in Figure 3 and Table 1. The estimated and measured PAR values for all three sites are from January to March, 1996.

The key concept of this new algorithm is the use of multi-temporal signatures of remote sensing data. Because the basic requirement of this method is the high temporal resolution, it potentially can be used for many different polar-orbiting sensors, such as MERIS, SeaWiFS, GLI and VIIRS.

Temporal scaling

Instantaneous PAR is very useful for NPP and other ecosystem models, but many models require a daily time step and thus the daily PAR product is more desirable. Attempts were made to estimate daily radiation fluxes from discrete remote sensing observations (Van Laake and Sanchez-Azofeifa, 2005). Some methods only work under clear sky conditions because they employ a simple sinusoidal curve to retrieve variable diurnal net radiation. Van Laake and Sanchez-Azofeifa (2005) linearly interpolated atmospheric parameters to calculate instantaneous PAR in 30-minute intervals and then integrate daily PAR. However, this method cannot be used in our case because PAR has a strong diurnal variation that cannot be linearly interpolated from instantaneous PAR values. Liang *et al*. (2006b) used a simple linear regression to predict the daily average PAR from instantaneous values, but this approach is also crude.

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Wang *et al.* (2007a) presents an adjusted sinusoidal algorithm for integrating instantaneous PAR values from MODIS data to produce the daily-integrated PAR product. MODIS acquires data from both Terra and Aqua satellites, and the average number of overpasses as a function of latitude is shown in Figure 4. Validation results demonstrate that MODIS data alone adequately captures the diurnal variations of incident PAR at high latitudes where the number of MODIS overpasses is large. This approach is being used to generate the MODIS daily PAR product. The cover page of this journal issue shows an example of this. Zheng (2007) also applied the adjusted sinusoidal algorithm to calculate AVHRR daily PAR.

PAR Estimation from GOES Data

Satellites designed to monitor spatial and temporal variations of the dynamic atmospheric system for accurate weather and climate prediction typically operate in geostationary orbits. Geostationary satellites are positioned at an exact height above the Earth (about 36000 km). The satellites rotate above the Earth at the same speed as the Earth rotates around its axis, in effect remaining stationary above a point on the Earth (normally directly over the equator). Because the satellites remain stationary, they are ideal for remote imaging because their sensors can repeatedly scan the same area on the Earth's surface.

Currently there are five or six satellites positioned at regular intervals around the equator so that the entire earth is covered. The main satellites include Meteosat, positioned above Europe/Africa (approx 0° Longitude); GOES-EAST, positioned over USA/South America (75° West), GOES-WEST, positioned over the Pacific (135° West), GMS, positioned over Japan/Australia (140° East); and IODC, positioned at (63° East) for Indian Ocean Data Coverage. China operates the Feng-Yun geostationary satellites, FY-2C at 105°E and FY-2D at 86.5°E.

The United States operates the Geostationary Operational Environmental Satellite (GOES) system to maintain a continuous data stream from two GOES satellites, currently GOES-10 and GOES-12. GOES-12 imager's visible channel (0.55-0.72 μm) has a nominal spatial resolution of 1 km by 1 km at nadir and data acquired at 30-minute intervals. The spatial resolution of GOES images decreases at high latitudes.

The magnitude of PAR changes over the course of a day because of changing solar zenith angle and atmospheric conditions. The high temporal resolution of geostationary satellites is an advantage in capturing the PAR diurnal variation, compared to polar orbiting satellites, which usually take few observations at a given place per day. Geostationary satellites have long been used to estimate surface solar insolation and PAR. Zheng *et al.* (2007) extend the MODIS PAR algorithm (Liang *et al.*, 2006b) to GOES data. The GOES algorithm is an improvement over the MODIS algorithm in two important respects. First, the GOES algorithm accounts for the surface bidirectional reflectance using a semi-empirical BRDF model while MODIS PAR assumes that all surfaces are Lambertian. Second, this new GOES PAR algorithm utilizes spatial relationships to exclude possible cloud shadowed pixels, while the MODIS method relies exclusively on temporal relationships for cloud shadow exclusion.

Most PAR algorithms do not correct for topography. For example, Winslow *et al.* (2001) found that the ISCCP-PL PAR product in mountainous regions under-estimated PAR compared to the results of long-term radiation climate studies. This is particularly relevant for carbon cycle modeling when the spatial resolution increases because many mountainous regions are forested. The algorithm that maps PAR from GOES (Zheng, *et al.*, 2007) incorporates a topographic correction. The GOES algorithm corrects for: (1) the direct component of PAR based on angular effect, (2) the diffuse component for sky openness, and (3) the reflected direct and diffuse PAR flux from neighboring terrains. The validation results using the ground measurements at four FLUXNET sites (Canaan Valley in West Virginia, Lost Creek and Willow Creek in Wisconsin, and Metolius in Oregon) from days 191 to 198, 2004 are shown in Figure 5 and Table 1.

In a recent study, Wang *et al.* (2007c) further improved the algorithm to estimate both incident PAR and land surface broadband albedo simultaneously. They particularly address the PAR estimation over snow surfaces and incorporate the surface elevation in the LUT. The validation results demonstrate that the accuracy of retrieved incident PAR improves and the retrieved land surface albedo is as accurate as the MODIS albedo product.

Summary

Incident PAR is needed to address a variety of scientific questions in the fields of solar energy, climate change, and agriculture and as input in hydrologic and biogeophysical models. This article summarizes various algorithms that estimate incident PAR from both polar-orbiting and geostationary satellite observations. However, high resolution PAR over land currently is not a standard satellite product. We generated this product over North America and China.

Integration of multiple polar-orbiting satellite observations enables us to provide the high-accuracy daily-integrated PAR product required by most models and applications. This study also demonstrates that when relying only on one or two polar-orbiting satellites, the best strategy may be to combine polar-orbiting satellite data with geostationary satellite data in the same way that polar orbiting data are used to map PAR at high latitudes and geostationary satellite data at low latitudes.

Acknowledgements

This study is partially funded by NASA grants NNG05GD10G and NAG512892. R. Liu is supported in part by the National Natural Science Foundation from China (40471098). The MODIS, AVHRR, AND GOES PAR products over North America are available to the public. Contact the first author if you are interested in these products.

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