Estimating Photosynthetically Available Radiation at the Ocean Surface from ADEOS-II Global Imager Data

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A simple, yet efficient and fairly accurate algorithm is presented to estimate photosynthetically available radiation (PAR) at the ocean surface from Global Imager (GLI) data. The algorithm utilizes plane-parallel radiation-transfer theory and separates the effects of the clear atmosphere and clouds, i.e., the planetary atmosphere is modeled as a clear atmosphere positioned above a cloud layer. PAR is computed as the difference between the incident 400–700 nm solar flux at the top of the atmosphere (known) and the solar flux reflected back to space by the atmosphere and surface (derived from GLI radiance), taking atmospheric absorption into account. Knowledge of pixel composition is not required, eliminating the need for cloud screening and arbitrary assumptions about sub-pixel cloudiness. For each GLI pixel, clear or cloudy, a daily PAR estimate is obtained. Diurnal changes in cloudiness are taken into account statistically, using a regional diurnal albedo climatology based on 5 years of Earth Radiation Budget Satellite (ERBS) data. The algorithm results are verified against other satellite estimates of PAR, the National Centers for Environmental Prediction (NCEP) reanalysis product, and in-situ measurements from fixed buoys. Agreement is generally good between GLI and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) estimates, with root-mean-squared (rms) differences of 7.9 (22%), 4.6 (13%), and 2.7 (8%) Einstein/m$^2$/day on daily, weekly, and monthly time scales, and a bias of only 0.8–0.9 (about 2%) Einstein/m$^2$/day. The rms differences between GLI and Visible and Infrared Spin Scan Radiometer (VISSR) estimates and between GLI and NCEP estimates are smaller and larger, respectively, on monthly time scales, i.e., 3.0 (7%) and 5.0 (14%) Einstein/m$^2$/day, and biases are 1.1 (2%) and –0.2 (–1%) Einstein/m$^2$/day. The comparison with buoy data also shows good agreement, with rms inaccuracies of 10.2 (23%), 6.3 (14%), and 4.5 (10%) Einstein/m$^2$/day on daily, weekly, and monthly time scales, and slightly higher GLI values by about 1.0 (2%) Einstein/m$^2$/day. The good statistical performance makes the algorithm suitable for large-scale studies of aquatic photosynthesis.

1. Introduction

The solar energy available for photosynthesis, known as PAR, controls the growth of phytoplankton and, therefore, the development of crustaceans, fish, and other consumers. It ultimately regulates the composition and evolution of marine ecosystems. Knowing the distribution of PAR over the oceans, spatially and temporally, is critical to understanding bio-geo-chemical cycles of carbon, nutrients, and oxygen, and to address important climate and global change issues such as the fate of anthropogenic atmospheric carbon dioxide.

The spectral range of PAR contains wavelengths that intervene in the chemical reactions of photosynthesis, and was designated by the SCOR/UNESCO Working Group 15 as 350–700 nm (Tyler, 1966). For practical reasons (e.g., lack of measurements in the ultraviolet), 400–700 nm is often used in the definition of PAR. Neglecting the ultraviolet part is not dramatic, because ultraviolet light

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ductivity (Smith et al., 1997). In oligotrophic waters, however, ultraviolet light may penetrate deeper than green, yellow, and red light, and the percentage of ultraviolet light may reach 15% at the base of the euphotic layer. In coastal waters, on the other hand, neglecting ultraviolet light is inconsequential, because this light is quickly absorbed as it penetrates the surface, due to relatively high concentrations of particulate and dissolved matter. Furthermore, variations in near-ultraviolet light, unlike ultraviolet-B light, are not expected to significantly alter primary production efficiency.

Early maps of ocean primary productivity were based on sparse measurements (oxygen and radiocarbon determinations), extrapolated using information on the distribution of nutrients and light (Steeman-Nielsen and Jensen, 1957; Koblentz-Mishke et al., 1970; Berger et al., 1987). The influence of light was not explicitly taken into account, but crudely parameterized in the extrapolation scheme. As Berger (1989) pointed out, due to the lack of data “guesswork was unavoidable”. The situation changed dramatically with the advent of satellite ocean-color sensors. Starting in 1978 with the Coastal Zone Color Scanner (CZCS) aboard NIMBUS-7, these sensors provided the opportunity for a new global view of ocean productivity. The chlorophyll abundance recovered from satellite ocean color is well correlated with primary production. Global maps of seasonal and/or annual productivity based on satellite chlorophyll. Global maps of seasonal and/or annual productivity based on light-dependent models were reported in Longhurst et al. (1995), Antoine et al. (1996), and Behrenfeld and Falkowski (1997b). In the first two studies, surface PAR was estimated using a clear sky model corrected for cloudiness. The effect of clouds was parameterized as a function of fractional cloud cover, taken from surface reports (Hahn et al., 1987) or the International Satellite Cloud Climatology Project (ISCCP) database (Rossow et al., 1988). In the third study, the distribution of PAR was obtained from ISCCP (i.e., satellite-derived) fields of total surface solar irradiance (Bishop and Rossow, 1991).

On the one hand, visual cloud observations are inherently inaccurate and not directly related to atmospheric transparency. On the other hand, the relationship between total solar irradiance and PAR at the surface, which is fairly constant under clear skies (Baker and Frouin, 1987), may vary significantly under cloudy skies depending on liquid water content (Pinker and Laszlo, 1992). It is certainly more appropriate to derive surface PAR directly, and several satellite-based techniques have been developed for this purpose (see the review of Frouin and Pinker, 1995).

The satellite-based techniques for estimating surface PAR and total solar irradiance are applicable to a variety of sensors, in particular those aboard operational meteorological satellites. For primary productivity computations, however, it is advantageous to acquire both PAR and chlorophyll abundance from the same sensor. This can be achieved with ocean-color sensors, which, even though designed to retrieve chlorophyll abundance, are also sensitive to PAR (the more radiance reflected to space, the less PAR reaching the surface), provided they do not saturate over clouds. In that way, studies of ecosystem dynamics are facilitated.

In the present article, an algorithm is presented to estimate daily PAR at the ocean surface from ADEOS-II GLI data. The algorithm is evaluated by comparing results with other satellite estimates, the NCEP reanalysis product, and with in situ measurements from long-term fixed buoys at equatorial and tropical locations. Statistical performance is quantified on daily, weekly, and monthly time scales. The advantages and limitations of the algorithm are discussed, especially its inherent inability to fully capture diurnal variability of clouds. In view of requirements and performance, the adequacy of the algorithm for large-scale studies of photosynthesis is discussed, and recommendations are made for improving and extending the algorithm to various satellite ocean-color sensors.

2. Algorithm Description

The algorithm estimates daily (i.e., 24-hour averaged) PAR reaching the ocean surface from GLI data. PAR is defined as the quantum energy flux from the Sun in the spectral range 400–700 nm. It is expressed in Einstein/m²/day.

The PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be decoupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer. This approach was shown to be valid by Dedieu et al. (1987) and Frouin and Chertock (1992). The great strength of such a decoupled model is its simplicity. It is unnecessary to distinguish between clear and cloudy regions within a pixel, and this obviates the need for often-arbitrary assumptions about cloudiness distribution.

Under solar incidence $\theta_s$, the incoming solar flux at the top of the atmosphere, $E_0 \cos(\theta_s)$, is diminished by a factor $T_d T_a (1 - S_A)$ by the time it enters the cloud/surface layer. In this expression, $T_d$ is the clear sky diffuse...