On calculation of photosynthetically active radiation in estimation of carbon balance parameters of surface ecosystems

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Modified Monte Carlo algorithms are presented for calculating spectral fluxes of short-wave radiation for efficient computation of photosynthetically active radiation (PAR) in the clear-sky atmosphere, overcast, and broken clouds. A database is created for fast calculations of monthly mean PAR values for different geographic latitudes, months, and surface types, using satellite data on the cloud amount. The calculations are compared with ground data for BOREAS NSA (Canada).

Introduction

The photosynthetically active radiation (PAR, 400–700 nm) constitutes approximately 45% of the shortwave radiation reaching the Earth surface. In the process of photosynthesis, PAR is partially absorbed by plants, thus being one of the key characteristics of accumulation of carbon by ground ecosystems. Therefore, the energy parameters of PAR, determined at different time and space averaging, are initial data in practically all carbon transport models (see, e.g., Refs. 1–5). Together with other atmospheric parameters (the precipitation amount, atmospheric and soil temperatures, etc.), PAR is also used for estimation of carbon balance of forest ecosystems with the help of regression models based on direct measurements of CO_2 fluxes at different ground sites.[6,7]

For modeling carbon cycle on a global scale, it is necessary to know PAR levels and spatial and temporal PAR variations in different regions of the globe. During last decade, systematic measurements of PAR and other meteorological parameters are performed in FLUXNET network (http://daacsti.ornl.gov/FLUXNET/fluxnet.html), including some regional networks (AMERIFLUX, EUROFLUX). In Russia, a quite large array of measurements of the photosynthetically active radiation is accumulated in the Meteorological Observatory of the Moscow State University.[8,9] However, the possibilities of ground-based PAR measurements are limited geographically. Therefore, radiation codes, whose input parameters are data of satellite measurements of atmospheric parameters, primarily the cloud amount and the cloud optical depth, are of wide use in current PAR estimates.

Earlier, the Institute of Atmospheric Optics SB RAS has developed efficient Monte Carlo algorithms for calculation of spectral fluxes of the shortwave radiation for different atmospheric conditions: clear-sky atmosphere, overcast, and broken clouds.[10,11] In this paper we describe a modification of these algorithms designed for PAR determination from satellite data on the cloud amount, and compare calculation results with ground-based BOREAS NSA measurements (province Manitoba, Canada, 55.9°N, 98.5°W) of the AMERIFLUX network.

1. Atmosphere model

The plane-parallel model of atmosphere is specified as a set of N_{lay} horizontally homogeneous layers, each characterized by constant meteorological parameters (pressure, temperature), atmospheric gas concentration, and aerosol optical characteristics. Top-of-atmosphere (TOA) height $H_{\mathrm{atm}}^{\mathrm{top}}$ is assumed to be 100 km. Underlying surface is assumed to reflect the incident radiation according to Lambert law.

Aerosol model

Each jth layer, $j = 1, ..., N_{\mathrm{lay}}$, is assigned with an individual aerosol extinction coefficient, single scattering albedo, and scattering phase function at $\lambda_0 = 550$ nm. The spectral behavior of the optical characteristics and their vertical stratification correspond to the model recommended by World Climate Research Program (WCP).[12] The aerosol optical characteristics are calculated for reference wavelengths in accordance with Mie theory[13] and by linear interpolation for other λ values. Within each layer, Rayleigh scattering coefficients are also specified.[14]

Optical cloud model

For modeling clouds within a separated layer, we use a *statistically homogeneous* cloud model based on the Poisson point flux on straight lines.[15] Input model parameters were positions of cloud top

$H_{\rm cl}^{\rm top}$ and bottom $H_{\rm cl}^{\rm bot}$ boundaries, mean horizontal cloud size D (or the parameter $\gamma = H/D$, where $H = H_{\rm cl}^{\rm top} - H_{\rm cl}^{\rm bot}$ is the geometrical thickness of a cloud layer), as well as some optical characteristics, namely, the cloud extinction coefficient, single scattering albedo, and scattering phase function. The optical characteristics of liquid water clouds were calculated for a reference set of wavelengths assuming a wide particle size distribution[16]; optical characteristics at other wavelengths required in calculations were obtained using the linear interpolation.

2. Calculation technique

Integrated (within a spectral range 400–700 nm) fluxes of upward ($F_{\rm PAR}^{\uparrow}$) and downward ($F_{\rm PAR}^{\downarrow}$) solar radiation at the level z were calculated by formula

$$F_{\rm PAR}^{\uparrow(\downarrow)}(z) = \sum_{i=1}^{N} F_i^{(\uparrow)\downarrow}(z),\ \ F_i^{\uparrow(\downarrow)}(z) = \int\limits_{\lambda_i}^{\lambda_{i+1}} F^{\uparrow(\downarrow)}(z,\lambda)\,{\rm d}\lambda,$$

$$i = 1,\ ...,\ N,\ \lambda_1 = 400\ {\rm nm},\ \lambda_{N+1} = 700\ {\rm nm}, \qquad (1)$$

where N is the number of spectral intervals; $F^{\uparrow(\downarrow)}(z,\lambda)$ are spectral fluxes.

Within the ith spectral interval (λ_i, λ_{i+1}), optical characteristics of clouds and aerosol, as well as the Rayleigh scattering coefficients, were assumed to be constant. As was already noted, fluxes $F_i^{\uparrow(\downarrow)}(z)$ were calculated by the Monte Carlo algorithms: under conditions of clear-sky and horizontally homogeneous overcast we used the direct simulation method,[17] and in broken clouds – the algorithm suggested by Titov et al.[10] Photon trajectories in the atmosphere were modeled independently of the gas absorption.

The selective molecular absorption in each spectral interval $\Delta\lambda = (\lambda_i, \lambda_{i+1})$ was taken into account using transmission functions $T_{\Delta\lambda}(\Delta m^*)$, where Δm^* is the optical mass of absorbing gases accumulated along the photon trajectory. To determine $T_{\Delta\lambda}(\Delta m^*)$, we used approximation in the form of the linear combination of several exponentials (the k-distribution method).[11, 18] For instance, for direct component of the downward radiation, $T_{\Delta\lambda}(\Delta m^*)$ was represented as

$$T_{\Delta\lambda}(\Delta m^*) = \int\limits_{\lambda_i}^{\lambda_{i+1}} S(\lambda)\,T(\Delta m^*,\lambda)\,{\rm d}\lambda \Big/ S_{\Delta\lambda} =$$

$$= \sum_{l=1}^{L} C_l \exp\left(-m \int\limits_{0}^{H_{\rm atm}^{\rm top}} k(g_l,z)\,{\rm d}z\right), \qquad (2)$$

$$S_{\Delta\lambda} = \int\limits_{\lambda_i}^{\lambda_{i+1}} S(\lambda)\,{\rm d}\lambda.$$

Here, $S(\lambda)$ is the spectral solar constant;

$$T(\Delta m^*,\lambda) = \exp\left(-m \int\limits_{0}^{H_{\rm atm}^{\rm top}} \kappa_{\rm mol}(\lambda,z)\,{\rm d}z\right)$$

is the monochromatic transmission function of the Earth atmosphere; m is the atmosphere optical mass (in the direction to Sun); $\kappa_{\rm mol}(\lambda, z)$ is the molecular absorption coefficient at the wavelength λ and the height z above the earth surface; $k(g, z)$ is absorption coefficient in the space of cumulative frequencies g; g_l and C_l are nodes and coefficients of Gaussian quadratures; $\sum_{l=1}^{L} C_l = 1$.

In our calculations, $N = 3$, i.e., a 400–700 nm region was divided into 3 equal-size intervals: 400–500, 500–600, and 600–700 nm. Within each interval, optical characteristics of clouds, aerosol, and molecular scattering were assumed to be equal to their values at wavelengths corresponding to the interval center: 450, 550, and 650 nm. The surface albedo $A_{{\rm s},i}$ in the ith interval was calculated by the formula

$$A_{{\rm s},i} = \frac{\int\limits_{\lambda_i}^{\lambda_{i+1}} A_{\rm s}(\lambda)\,{\rm d}\lambda}{\lambda_{i+1} - \lambda_i},\quad i = 1,\ 2,\ 3.$$

Spectral values of the surface albedo $A_{\rm s}(\lambda)$ were taken from the model of Hook.[19]

The molecular absorption coefficients were calculated beforehand using the HITRAN-2000 database (http://www.hitran.com) and the continuum absorption model CKD2.4 (http://rtweb.aer.com). The number of Gaussian quadratures in Eq. (2) $L = 10$. Vertical profiles of the temperature, air pressure, and gas concentrations (H_2O, O_2, and O_3) were specified in accordance with the LOWTRAN7 model,[14] taking into account the season and geographic zone. Values of solar constant at the top of atmosphere correspond to those in Refs. 20 and 21.

To test the given approach for $F_{\rm PAR}^{\downarrow(\uparrow)}$ calculation, we compared vertical profiles of downward and upward PAR fluxes, obtained by the above-described method, with results of calculations by algorithms developed at the Russian Research Center Kurchatov Institute (RRC Kurchatov Institute). (The latters had been repeatedly tested in ground-based measurements of integrated solar fluxes.[22,23]) The calculated $F_{\rm PAR}^{\downarrow(\uparrow)}$ profiles under conditions of the clear-sky atmosphere of mid-latitude summer[14] and continental aerosol model[12] are presented in Table 1. It is seen that the maximal differences between PAR fluxes, calculated by the two independent algorithms, do not exceed 1.5 W/m^2.

Considering that the accuracy of RRC Kurchatov Institute calculations is estimated within 2–3 W/m^2, the obtained discrepancy can be regarded insignificant, and the described approach can be used for determination of the photosynthetically active radiation.

Table 1. Upward and downward PAR fluxes, W/m^2; mid-latitude summer,[14] continental aerosol,[12] solar zenith angle of 60°

z, km	$F^{\downarrow}_{\mathrm{PAR}}(z)$		$F^{\uparrow}_{\mathrm{PAR}}(z)$	
	RRC	IAO	RRC	IAO
0.0	199.585	198.109	12.826	12.549
0.2	202.878	201.543	14.924	14.737
0.5	207.722	206.676	17.919	17.922
1.0	215.691	215.081	22.700	22.946
2.0	223.619	223.483	27.329	27.789
3.0	234.572	234.842	34.057	34.732
5.0	239.787	240.004	38.126	38.799
10.0	248.829	249.118	45.245	46.016
15.0	253.714	254.454	48.588	49.768
20.0	256.856	257.635	49.784	51.166
25.0	259.965	260.695	50.108	51.509
50.0	265.226	265.626	50.110	51.404
100.0	265.345	265.753	50.127	51.418

3. Comparison of model calculations and experimental data

Most long-term and continuous measurements for study of carbon exchange in boreal forests were performed in the framework of International Project BOReal Ecosystem-Atmosphere Study (BOREAS). This project (http://www-eosdis.ornl.gov/BOREAS/bhs/BOREAS_Home.html) was directed towards studying specific features of interaction of boreal forests with atmosphere and assessing their role in the global carbon cycle. During the Project implementation, two sites were organized on the territory of Canada: Southern Study Area (SSA, 53.4–54.3°N, 104.2–106.3°W) and Northern Study Area (NSA, 55.4–56.2°N, 97.2–99.0°W). Measurements covered about half-hundred of parameters characterizing forest, soil, and atmosphere. To construct regression dependences relating CO_2 fluxes to atmospheric parameters, only some of them were used, the PAR flux measured at BOREAS NSA among them.

The BOREAS NSA data for the period from March 1994 to December 2003 were taken from the corresponding site of AMERIFLUX network (http://public.ornl.gov/ameriflux/) in the form of unified files, in which the measured quantities were half-hour averages. The PAR data ($\mu\mathrm{mol} \cdot \mathrm{photon} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$), with accounting for gaps, were recalculated into corresponding monthly mean values (W/m^2), which then were immediately used in regressions of the carbon balance of forested ecosystems.

The diurnally mean PAR value, calculated on the fifteenth day of the chosen month, was used as a model estimate of the monthly mean PAR value from satellite data. It was assumed that the cloud amount was unchanged during a day and equal to its monthly mean value retrieved from MODIS data (Modis/Terra Atmosphere Monthly Global Product, http://g0dup05u.ecs.nasa.gov/Giovanni//modis.MOD08_M3.shtml). As an example, Table 2 presents the monthly mean cloud amount n_0 over BOREAS NSA for 4 years.

Table 2. Monthly mean cloud amounts (%) over BOREAS NSA

Month	Year			
	2001	2002	2003	2004
1	81	83	84	90
2	58	64	74	82
3	70	57	74	58
4	46	57	58	54
5	61	51	40	57
6	48	42	54	63
7	52	66	45	58
8	63	69	55	71
9	58	86	77	64
10	90	87	82	85
11	81	87	81	71
12	75	84	77	71

In the calculations we assumed one-layer clouds and the height of the bottom boundary $H^{\mathrm{bot}}_{\mathrm{cl}}$ of 2 km. The mean horizontal cloud size D and the shape parameter γ determining the cloud top boundary $H^{\mathrm{top}}_{\mathrm{cl}}$ corresponded to data from Ref. 24. The cloud extinction coefficient σ_{cl} was chosen directly proportional to the cloud amount n_0 expressed in percent, that is

$$\sigma_{\mathrm{cl}} = 0.12 n_0. \tag{3}$$

Over a wide range of n_0 and solar zenith angles, formula (3) ensures a good agreement (at a mean discrepancy of about 5 W/m^2) between PAR values calculated by this algorithm and by the algorithm of RRC Kurchatov Institute. In these calculations, the broken clouds were represented as a random Gaussian field bounded below at some chosen level.[25] In its turn, the Gaussian model ensures a satisfactory agreement of calculations with data of ground- and satellite-based radiation measurements,[26–29] where cloud extinction coefficient is specified in the form

$$\sigma^{*}_{\mathrm{cl}} = 0.3 n_0 \tag{4}$$

Formulas (1) and (3) were used to calculate downward PAR fluxes for different combinations of reference values of the solar zenith angle, cloud amount, and surface albedo. The cosine of solar zenith angle and the cloud amount varied with steps 0.1 and 10%, respectively. The obtained calculation array and specially designed servicing software formed a database allowing one to rapidly calculate, based on the linear interpolation, monthly mean PAR values for arbitrarily chosen geographic coordinates, month of the year, and surface type. The database-calculated monthly mean PAR values were used in constructing the regression model intended for calculation of the monthly mean carbon balance NEE (Net Ecosystem Exchange) of Canadian and Siberian boreal forests.[7]

Figure 1 presents the measured and calculated monthly mean downward PAR values for BOREAS NSA in 2001–2003.

Figure 1 shows that calculations of $F^{\downarrow}_{\mathrm{PAR}}(z = 0)$ are close to measurements. Discrepancies have practically no effect on the accuracy of regression determination of the boreal forest NEE. Relatively large differences are observed for small PAR values corresponding to winter months, when sun elevations are low and photosynthesis in plants is absent because of low air temperatures.

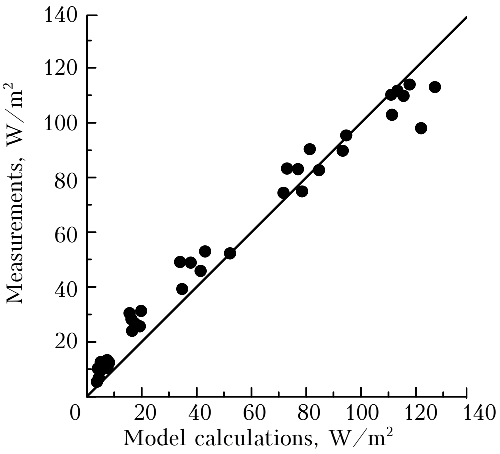

Fig. 1. Measured and modeled monthly mean downward PAR values for BOREAS NSA, 2001–2003.

Conclusion

This paper presents algorithms of PAR calculation for clear sky, overcast, and broken clouds. Spectral range 400–700 nm is divided into three equal-size intervals, where spectral variations of aerosol and cloud optical characteristics are neglected. Radiative characteristics are calculated by the Monte Carlo method; the transmission function of atmospheric gases is approximated by exponential series (*k*-distribution method). Molecular absorption coefficients are calculated with the use of the spectroscopic database HITRAN-2000, taking into account the specified profiles of meteorological parameters and atmospheric gas concentrations.

Using the developed algorithms, we performed a great amount of computations of reference PAR values and constructed a database for fast calculation of monthly mean PAR values for different geographic latitudes, months, and surface types. The model-derived and measured monthly mean PAR values in BOREAS NSA (Canada) in 2001–2003 well agree, which confirms that the developed approach provides for PAR estimates with an error not influencing the accuracy of regression estimates of CO_2 fluxes in boreal forests.

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