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A Hybrid Method for Evaluating Absorbed Solar Energy at the Surface Level Using Remote Sensing Data

Maxim A. Yakunin*
Altai state university,
Krasnoarmeiskiy, 90, Barnaul, 695049
Russia

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A new method to evaluate the solar energy absorbed by the surface using remote sensing data and the method of basic spectra is presented. The proposed method allows one to calculate parameters of radiation transferring in the atmosphere without being related to specific satellite instruments or areas.

Keywords: basic spectra method, remote sensing, transmittance, aerosol optical thickness, total precipitable water, absorbed solar energy.

Introduction

The amount of solar energy absorbed by the "atmosphere–surface" system is a key parameter in the problem of global climate change. The use of remote sensing satellite data is the most convenient way to establish monitoring of the radiation balance of the earth over vast areas. Current remote sensing systems provide high spatial resolution data and allow one to carry out monitoring over very big areas.

The majority of current models for evaluating the solar energy absorbed by the surface using satellite data are based on statistical processing of data from numerical simulations of atmosphere radiation transfer. One of such models is the model provided by Tang [1]. It uses MODIS/Terra spectroradiometer data for the top of the atmosphere (TOA) radiances to calculate then amount of solar energy W (W/m^2) absorbed at the surface level:

$$W = (\alpha' - \beta' r) E_0 \cos\theta_s / d^2, \tag{1}$$

where r is the TOA broadband albedo, θ_s is the solar zenith angle, E_0 is the TOA solar irradiance at one astronomical unit (1358 W/m^2), d is the distance from Earth to the sun in astronomical units. Coefficients α' and β' are

$$\alpha' = 1 - a_1\mu^{-1} - a + 2\mu^{-x} - (1 - \exp(-\mu))(a_3 + a_4 w^y)\mu^{-1}$$

$$\beta' = (1 + a_5 + a_6 ln(\mu) + a_7 w^z),$$

where a_i, x, y, z are constants for various types of surface, μ is the cosine of the solar zenith angle, w is the total precipitable water. MODIS/Terra spectral radiances ρ are used to calculate TOA broadband albedo r:

$$r = b_0 + \sum_{i=1}^{7} b_i \rho_i. \tag{2}$$

The main drawback of this and other similar models [2, 3] is the need for solving systems of equations which are obtained by fitting a large number of numerical simulation data. Due to that

*m.yakunin89@gmail.com

it is impossible to evaluate errors of each input parameter on every step of calculations [4]. Another significant disadvantage of the models is their dependency on specific satellite instruments or geographical areas.

A hybrid method to calculate the amount of absorbed solar energy (the range of wavelength is 0.3–2.4 μm) is presented in this paper. This method is based on spectral approach. It allows one to recover the spectral albedo (a) of the surface using outgoing radiance at TOA and to calculate the spectrum of radiation incident on the surface (E_s) with the use of spectral function of atmospheric transmittance with corresponding parameters. To solve these problems MODTRAN5.2.1 code is used to simulate interaction of solar radiation with "atmosphere–surface" system. The MODIS/Terra satellite data [5] is used as input data.

1. Calculation of the amount of absorbed solar energy using MODTRAN5.2.1 code

To evalute surface spectral albedo MODTRAN5.2.1 is used. At the first step radiance at TOA in wavelength range of MODIS i channel is calculated using MODIS spectral filter function with known atmospheric parameters and some particular surface albedo a [6]. After that calculated with MODTRAN radiance is compared with real radiances measured with MODIS. If they differ then albedo is changed. Thus, using method of chords, it is possible to determine albedo within required accuracy with few MODTRAN runs. In this work first 7 MODIS channels (459–2155 nm) are used. However, the proposed method does not have any restrictions to use any other channels or spectral bands. On the final step interpolating function based on calculated albedo in MODIS bands is constructed. The function is based on cubic splines. Calculations showed that such interpolating function gives good results for many types of natural surfaces (vegetation, grass, soils, water etc.)

MODTRAN is also used again to solve the problem of evaluating the energy that reaches the surface level. When surface spectral albedo and spectrum of incline energy at the surface level are known the spectrum of absorbed solar energy is calculated and then integrated over the required wavelength range.

To validate the method described above, the results of calculated absorbed solar energy at the surface are compared to data from SURFRAD — a network of surface stations which conduct monitoring of radiation balance. Three stations located in Boulder, Bondville and Desert Rock were chosen. Data for 25 days was used that represents summertime clear-sky conditions. For each of these days required MODIS data was used (MOD021km, MOD03, MOD04, MOD05, MOD35_L2). Only those satellite scenes were used in validation where the surface station was in the middle of the scene. This condition is necessary to avoid distortion of pixels at the scene corners due to the shape of Earth. Using geographical coordinates of stations required MODIS data were extracted from respective pixels. A total of 75 calculations of absorbed solar energy were made under various atmospheric conditions, scene geometry and surface types. It was found that the difference between amount of absorbed solar energy calculated with the proposed method and amount of absorbed energy measured by surface monitoring stations is not more than 2–6 %. Therefore, the proposed method allows one to obtain correct results.

2. Basic spectra method

The use of MODTRAN in real-time computations of absorbed solar energy on vast territories is difficult because of high computational cost for each pixel processing. To reduce calculation time it is necessary to replace MODTRAN calculations by calculations with simpler computational model. This model is based on mathematical model which properly describes processes of propagation and interaction of radiation with "atmosphere–surface" system.

In this paper we propose such mathematical model which uses basic spectra. Basic spectra are spectra of parameters of functions that describe processes of interaction of radiation with "atmosphere–surface" system. Basic spectra are determined for pre-specified particular conditions of observation and fixed atmospheric parameters. These spectra could be obtained from natural or numerical experiments. The required spectra needed to calculate energy for arbitrary values of atmospheric parameters and conditions of observation could be found in terms of basic spectra with the use of special conversion operators. These operators could be found using physical laws or simple approximations and conditions of observation.

By way of example let us consider the usage of the basic spectra method for evaluating the energy of radiation incident on the surface. It is one of the stages to evaluate the total absorbed solar energy.

The process of attenuation of the radiation during its transfer through the atmosphere can be described in terms of spectral transmittance function for certain atmospheric condition. Analysis of 2550 MODTRAN simulations of radiation transfer showed that two key parameters, namely, aerosol optical thickness (AOT) and total precipitable water exert primary control over the amount of energy traveled through the atmosphere (in clear-sky condition). These parameters could be found in MODIS products (MOD04 and MOD03, respectively). The other MODTRAN atmospheric parameters could be set to default values. With this assumption overall total errors are not more than 2 %. Fig. 1 shows the dependence of spectrum of upwelling radiation at TOA on atmospheric parameters.

The atmospheric transmittance spectrum for known AOT and total precipitable water can be used to calculate transmittance for random values of these atmospheric parameters using following conversion formula:

$$E_s = \int_{\lambda_1}^{\lambda_2} F_{sun} \cdot \widehat{W}\, T_{wv}|_\theta \cdot \widehat{A}\, T_{aer}|_\theta \cdot T_{atm}|_\theta \cdot \cos\theta d\lambda, \tag{3}$$

where F_{sun} is the spectrum of solar irradiance at TOA, T_{wv} is the water vapor transmittance for total precipitable water of 0.5 g/cm^2 and solar zenith angle (SZA) = 0°, T_{aer} is the aerosol transmittance for AOT = 0.1 and SZA = 0°, $\widehat{W}$ is the conversion operator of the basis spectrum T_{wv} to the spectrum with random value of total precipitable water, $\widehat{A}$ is the conversion operator of the basis spectrum T_{aer} to the spectrum with random value of AOT, T_{atm} is the atmospheric transmittance without water and aerosol contribution with SZA 0°, E_s is the amount of solar energy incident on surface, θ is the solar zenith angle.

The form of conversion operators of can be obtained using Beer's law:

$$T = e^{-c\frac{l_0}{\cos(\theta)}s(\lambda)}, \tag{4}$$

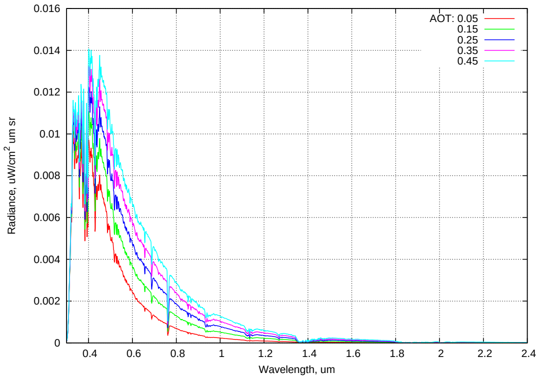
where c is the parameter that determines a concentration of the absorbing substance, l_0 is the thickness of atmospheric layer in meters, θ is the solar zenith angle, $s(\lambda)$ is the transmittance function. This function depends only slightly on concentration.

If c_0 and θ are parameters of the basic spectrum T_0 and c' and θ' are parameters of the required spectrum T' then

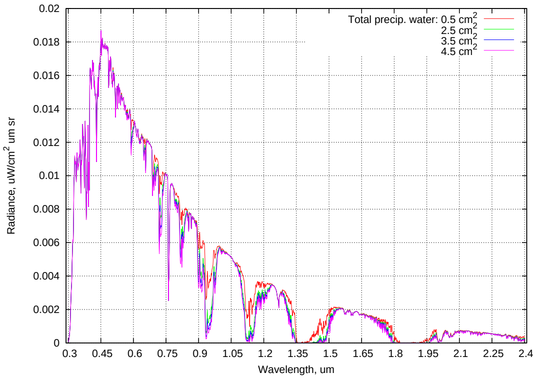
$$\left.\begin{aligned} T_0 &= e^{-c_0\frac{l_0}{\cos(\theta_0)}s(\lambda)} \\ T' &= e^{-c'\frac{l_0}{\cos(\theta')}s(\lambda)} \end{aligned}\right| => T' = e^{\frac{c'\cos(\theta_0)}{c_0\cos(\theta')}\ln T_0}.$$

Thus

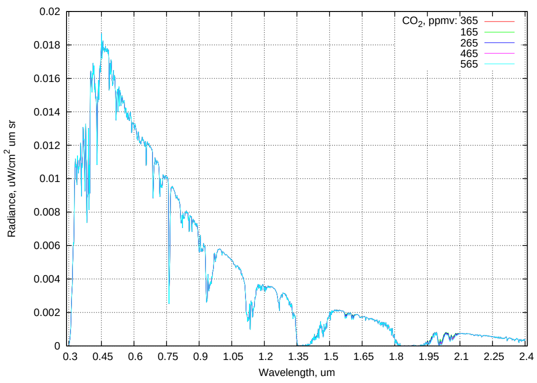
$$\widehat{W}T_0 = e^{\frac{c'\cos(\theta_0)}{c_0\cos(\theta')}\ln T_0}. \tag{5}$$



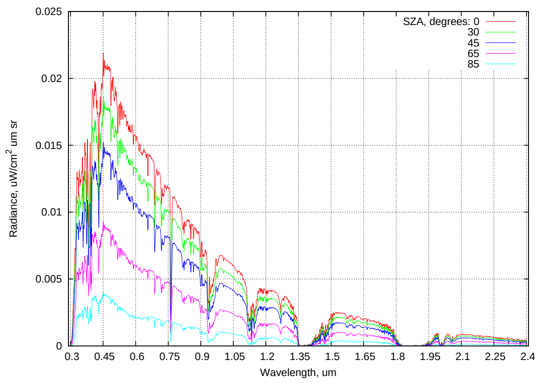
(a) AOT



(b) Total precipitable water



(c) CO_2



(d) SZA

Fig. 1. Dependence of TOA radiance on atomosheric parameters and observation conditions

Water transmittance spectra are showed in Fig. 2. These are basic spectrum ($w = 0.5\ g/cm^2$), required spectrum ($w = 1.572\ g/cm^2$), spectrum calculated with the use of basic spectra method and the spectrum simulated with MODTRAN ($w = 1.572\ g/cm^2$). This figure shows that the difference between calculated and simulated with MODTRAN spectra is less than 0.3 and it is located mostly in the range of abrupt change of the transmittance.

3. Validation

For validation of the proposed method the same set of data was taken that was used for calculation of absorbed solar energy with MODTRAN in Section 1.

Amount of the incident energy at the surface level in the geographical coordinates of SURFRAD stations was calculated by proposed method using MODIS spectroradiometer data of atmospheric condition and Sun-to-point-of-view geometry. Transmittance basic spectra and spectrum of solar irradiance at TOA were obtained using MODTRAN and then required spectra for each day were evaluated by proposed method. Then the amount of energy at the surface level was calculated for each of 75 days and compared with the value of energy measured by the station at the time when the satellite was above the station. The results of validation are summarized in Tab. 1. There are data from SURFRAD sites in 3 columns, amount of energy at the surface that has been calculated with the basic spectra method (BSM), their difference, and

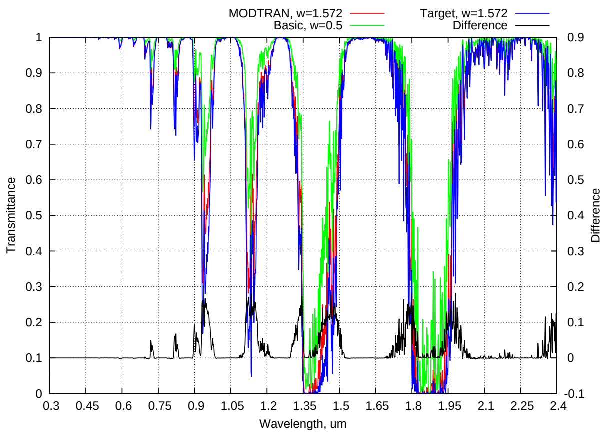


Fig. 2. Basic and required transmittance spectra

the relative errors. As one can see the average error is 4–5 %. It means that the basic spectra method is a reliable technique and it can be used in applied calculations.

Table 1. Results of validation

Bondville				Boulder				Desert Rock			
SURFRAD	BSM	Diff.	%	SURFRAD	BSM	Diff.	%	SURFRAD	BSM	Diff.	%
752.53	742.58	9.96	1.32	755.13	706.8	48.33	6.4	779.19	743.35	35.85	4.6
809.57	752.35	57.21	7.07	766.67	724.2	42.48	5.54	779.77	760.96	18.82	2.41
765.42	702.67	62.76	8.2	788.12	775.86	12.27	1.56	775.21	712.59	62.61	8.08
760.08	730.69	29.39	3.87	898.63	856.83	41.80	4.65	757.62	741.17	16.45	2.17
857.23	790.09	67.14	7.83	861.77	826.84	34.94	4.05	757.07	696.78	60.18	7.95
866.39	832.38	34.01	3.93	844.35	814.49	29.86	3.54	763.22	733.91	29.31	3.84
779.3	737.03	42.27	5.42	825.8	786.43	39.37	4.77	766.52	731.54	34.97	4.56
868.11	804.8	63.31	7.29	883.61	870.93	12.68	1.44	759.42	733.37	26.05	3.43
782.11	729.52	52.58	6.72	898.15	839.13	59.02	6.57	767.66	725.31	24.35	5.52
810.17	794.94	15.23	1.88	889.28	825.43	63.85	7.18	845.25	805.18	40.07	4.74
848.57	787.36	61.21	7.21	896.48	872.01	24.47	2.73	756.13	731.39	24.75	3.27
823.56	811.94	11.62	1.41	795.68	745.00	50.68	6.37	778.18	725.05	53.13	6.83
857.9	829.4	28.5	3.32	863.13	811.39	51.74	5.99	785.87	754.26	31.62	4.02
899.36	884.46	14.9	1.66	879.25	863.03	16.21	1.84	794.7	784.19	10.51	1.32
814.38	796.85	17.53	2.15	888.58	859.24	29.35	3.3	803.52	754.34	49.19	6.12
878.29	868.64	9.66	1.1	814.73	778.89	35.85	4.4	784.95	747.49	37.47	4.77
814.79	772.23	42.56	5.22	883.16	865.24	17.92	2.03	776.24	739.61	36.63	4.72
850.78	792.98	57.80	6.79	872.17	859.44	12.74	1.46	783.92	716.77	67.15	8.57
840.36	822.33	18.03	2.14	865.52	795.91	69.62	8.04	787.36	744.91	42.55	5.5
890.4	864.58	25.81	2.9	886.42	851.97	34.45	3.89	791.89	753.36	38.53	4.87
897.97	857.12	40.85	4.55	869.57	841.06	28.51	3.28	779.34	721.86	57.48	7.38
886.52	841.71	44.81	5.05	874.68	855.05	19.63	2.24	773.92	726.59	47.32	6.11
869.58	831.69	37.89	4.36	864.84	824.78	40.06	4.63	780.4	734.69	45.70	5.86
880.36	846.17	34.19	3.88	861.54	829.4	32.14	3.73	788.54	763.59	24.96	3.16
848.04	793.46	54.58	6.44	837.15	819.44	17.71	2.12	751.67	729.9	21.77	2.9
	Average:	37.35	4.47		Average:	34.63	4.07		Average:	38.22	4.9

Further study will be focused on application of the basic spectra method to evaluate the diffuse component of radiation and spectral albedo.

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Гибридная методика расчета количества поглощенной солнечной энергии на уровне подстилающей поверхности по данным спутникового мониторинга

Максим А. Якунин

Описана методика расчета количества поглощенной солнечной энергии на уровне подстилающей поверхности с использованием данных спутникового наблюдения на основе предложенного метода опорных спектров. Предложенный метод позволяет рассчитывать параметры распространяющегося в атмосфере излучения без привязки к определенным спутниковым приборам или территориям.

Ключевые слова: метод опорных функций, дистанционное зондирование Земли, коэффициент пропускания атмосферы, аэрозольная оптическая толщина, полное содержание водяного пара, поглощённая солнечная энергия.