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Physics and Chemistry of the Earth 30 (2005) 159–164
PHYSICS and CHEMISTRY of the EARTH
www.elsevier.com/locate/pce

The use of satellite measurements to estimate photosynthetically active radiation

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Accepted 24 August 2004
Available online 11 November 2004

Abstract

Photosynthetically active radiation (PAR) reaching the earth surface is a major parameter controlling many biological and physical processes related with the evolution of plant canopies, agricultural and environmental fields. Unfortunately PAR is not often measured and therefore must be estimated from other meteorological variables. Satellite measurements can provide PAR estimates over wide areas and with a high temporal frequency. These estimations can be used to estimate the agroclimatic potential of a location or as input data for different crop productivity models. In this paper we use a new method to estimate PAR using measurements from Meteosat. The satellite estimates are tested against ground measurements of PAR in Southern Spain.

Keywords: Global radiation; Photosynthetically active radiation; Cloud cover; Sunshine

1. Introduction

Incident photosynthetically active radiation (400–700 nm) is required to model photosynthesis of single plant leaves and plant communities. Unfortunately there are very few stations able to measure photosynthetically active radiation (PAR) and usually there is no data available in the region of interest. Several authors have estimated the photosynthetically active radiation from measurements of global solar radiation with good results (Alados et al., 2000). But sometimes there is no access to solar radiation data and this must also be estimated from other meteorological parameters. In this work we have developed a new model to estimate solar radiation under cloudy conditions and then combined it with a model able to estimate PAR from solar global radiation.

The evaluation of photosynthetically active solar potential for wide areas is also difficult because we do not know what the spatial variability of solar beam irradiance is (Gautier, 1982). If we could obtain an estimation of solar photosynthetically active solar irradiance from satellite images there would be much more information available as geostationary satellite data cover wide area and have an adequate temporal frequency (Broesamle et al., 2001).

When estimating solar global radiation from satellite images there have been mainly two approaches (Rizzi et al., 1980). On one side, several statistical relationships between the solar irradiance and others meteorological parameters have been developed (Beyer et al., 1996). These models usually estimate daily values of solar irradiance although some models have been developed for hourly values. On the other hand some models have been developed that take into account the physics involved in the interaction between solar radiation and the atmosphere (Gueymard, 1993). These models try to estimate

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1474-7065/$ - see front matter
doi:10.1016/j.pce.2004.08.029

Nomenclature

C	cloud cover
C_i	cloud cover for each layer
D	diffuse solar radiation
D_r	diffuse solar radiation due to Rayleigh scattering
D_a	diffuse solar radiation due to aerosols scattering
D_m	diffuse solar radiation due to multiple reflection processes between ground and sky
F_c	forward scattering factor
G	global solar radiation
I	beam solar radiation
I_0	extraterrestrial solar radiation
k_t	hemispherical broadband transmittance
m_a	optical air mass than can be computed form solar zenith angle
MBE	mean bias error
N	total number of hourly data
Q_p	photosynthetically active radiation
RMSE	root mean square error
S/S_0	sunshine duration
t_i	cloud transmittance for each layer
T_L	Linke turbidity factor
VIS	visibility estimation
w	water content
α	Angstrom exponent for the aerosol transmittance
β	Angstrom coefficient for the aerosol transmittance
δ_R	Rayleigh optical thickness
ρ_a	atmospheric reflectivity
ρ_c	cloud albedo
ρ_g	ground albedo
ρ	relative albedo
ρ_{clear}	relative albedo in clear conditions
ρ_{cloud}	relative albedo in cloudy conditions
θ_z	solar zenith angle
τ_o	ozone transmittance
τ_g	gas transmittance
τ_w	water transmittance
τ_r	Rayleigh transmittance
τ_a	aerosols transmittances

the physical extinction process using broadband transmission coefficients instead of spectral ones. To this end they consider a stratified atmosphere and they analyze different scattering and absorption processes. Scattering processes are caused by air molecules and aerosols and absorption processes are caused mainly by ozone, water vapor, oxygen and carbon dioxide.

In this work the model that we have used to estimate the solar direct irradiance estimates the global solar irradiance in cloudless conditions using a parametric model and then amends this estimation taking into account the effect of the cloud cover using an appropriate transmission function. The size of the cloud cover in the location of interest has been estimated using radiance measurement from satellite sensors.

Once we have estimated the global radiation the following step is to use these estimates as an input to a photosynthetically active radiation empirical model. To this end we have chosen a model proposed by Alados-Arboledas et al. (2000) and then compared the estimations with measurements of PAR from several meteorological stations.

2. Experimental data

For model computation and confirmation we used meteorological data collected during 1996 at a radiometric station located at the University of Almeria (36.83°N, 2.11°W). This station is placed in a seashore site on the Mediterranean coast of southeastern Spain and has a temperate climate.

The measurements include hourly values of global, diffuse, beam and photosynthetically active radiation, temperature and relative humidity. Horizontal solar diffuse and global irradiance were measured using a pair of CM-11 Kipp & Zonnen pyranometers, one with a polar axis shadow band and another without it. In all the stations photosynthetic active photon flux density has been measured by means of a LICOR model 190 SA quantum sensor. Data were recorded and averaged on a minute basis. Next, hourly averaged values were obtained for all variables. To avoid cosine response problems of the radiometric sensors, we have only used cases corresponding to solar zenith angles less than 85°. The diffuse irradiance measured by shadow band has been corrected using the model developed by Batlles et al. (1995). The measurements of temperature and relative humidity were registered by means of standard sensors. The direct irradiance was obtained from global and diffuse irradiance.

We also used hourly images obtained by Meteosat during 1996. The values of the pixels associated to the ground station were calculated averaging a matrix of 3×3 pixels around the location of the ground station.

3. Model description

We will first describe the parametric model used to estimate global solar irradiance in cloudless skies. Then we will introduce the effect of the clouds using the measurements of the Meteosat Satellite. Lastly we will estimate photosynthetically active radiation from the global solar estimates.

3.1. Clear skies global solar radiation estimation

The parametric model in this study compute broadband transmittances for the different atmospheric extinction processes. The use of these transmittances allows the computation of the direct beam component. For the diffuse component some approximations have been used in order to consider the complexity of scattering process. Finally, global irradiance is obtained by combination of the direct irradiance projected onto the horizontal surface and the diffuse horizontal irradiance.

$$G = I\cos\theta_z + D \tag{1}$$

In this article we have chosen a parametric model proposed by Iqbal (1983). This choice have been made as it is one of the models that estimate better the hourly global irradiance (Batlles et al., 2000). The ozone and water vapor transmittances are calculated by means of their respective absorptances following Lacis and Hansen (1974) and the Rayleigh and aerosol transmittances following Iqbal (1983). In this model the beam transmittances reads as follows:

$$I = 0.9751 I_0 \tau_r \tau_o \tau_g \tau_w \tau_a \tag{2}$$

where the factor 0.9751 shows that the spectral interval considered is 300–3000 nm. I_0 is the extraterrestrial irradiance at normal incidence, τ_o, τ_g, τ_w, τ_r and τ_a are the ozone, gas, water, Rayleigh and aerosols scattering transmittances, respectively.

The horizontal diffuse irradiance at ground level (D) is a combination of three individual components corresponding to the Rayleigh scattering (D_r), the aerosols scattering (D_a) and the multiple reflection processes between ground and sky (D_m):

$$D_r = \frac{0.79 I_0 \cos\theta_z \tau_o \tau_g \tau_w \tau_{aa} 0.5(1-\tau_r)}{(1 - m_a + m_a^{1.02})} \tag{3}$$

$$D_a = \frac{0.79 I_0 \cos\theta_z \tau_o \tau_g \tau_w \tau_{aa} F_c (1-\tau_{as})}{(1 - m_a + m_a^{1.02})} \tag{4}$$

$$D_m = \frac{(I\cos\theta_z + D_r + D_a)\rho_g\rho_a}{1-\rho_g\rho_a} \tag{5}$$

According to Gueymard (1993) aerosols are generally the main source of extinction in the atmosphere for clear sky conditions. There are several methods to calculate the aerosol transmittance depending on the kind of measurements available. Iqbal recommends the estimation of the aerosol transmittance from the visibility using the following formula (Mächler, 1983):

$$\tau_a = [0.97 - 1.265(\mathrm{Vis})^{-0.66}]^{m_a^{0.9}} \tag{6}$$

As visibility was not measured at our meteorological stations we estimated it using the relationship proposed by Mächler and Iqbal (1985):

$$\begin{aligned}\mathrm{VIS} = 147.994 - 1740.523[\beta x - (\beta^2 x^2 - 0.17\beta x \\ + 0.011758)^{0.5}]\end{aligned} \tag{7}$$

where

$$x = 0.55^{-\alpha} \tag{8}$$

α and β are the Angstrom turbidity parameters. We have used 1.3 as the value of α, a value widely accepted. β is calculated using the Linke turbidity factor T_L following the equation proposed by Dogniaux (also given in Page, 1986)

$$T_L = \left(\frac{85+\alpha}{39.5e^{-w} + 47.4} + 0.1\right) + (16 + 0.22w)\beta \tag{9}$$

where α is the solar elevation in degrees and w is the precipitable water content in cm.

The Linke turbidity factor T_L, is defined as the number of Rayleigh (an atmosphere clear of aerosols and without water vapor) required to produce a determined attenuation of direct radiation. This is calculated using the following equation:

$$T_L = \frac{1}{\delta_R m_a}\ln\frac{I_0}{I} \tag{10}$$

where I is the beam irradiance, I_0 is the extraterrestrial irradiance, m_a is the relative optical mass and δ_R is the Rayleigh optical thickness, obtained using Kasten's formula (Kasten, 1980). A complete description of the model is given in Iqbal (1983).

3.2. Cloud transmission scheme

According to Davies (1987) cloud layer models, are best suited in principle for estimating hourly irradiation since they are sensitive to changes in cloud layer amounts and allow cloud transmittance to vary with cloud type.

They have the general form:

$$G = G_0 \prod_{i=1}^{3} \frac{(1-C)}{1-\rho_g\rho_a} \tag{11}$$

where G_0 is a theoretical estimate of cloudless sky global irradiance by a clear sky model with the term of multiple scattering removed. C is the cloud amount. The denominator is a function of ground albedo, ρ_g, and atmospheric reflectivity for surface reflected irradiation, ρ_a, which incorporates multiple reflections between ground and atmosphere (Davies and McKay, 1989).

In this paper we have used a modification of this model using cloud cover estimations from Meteosat instead of ground measurements. To estimate the contribution of the cloud cover from satellite measurements we have used the fact that when there are clouds over a pixel, the signal received by the satellite sensor is bigger that the one received if there are no clouds.

We can use this fact to estimate the amount of cloud if we compare radiance values measured by the satellite with an estimation of the irradiance that would be measured in cloudless conditions.

To estimate global radiation we first estimate the cloud transmission function from radiance values measured by Meteosat The effect of the clouds on radiation was determined by a comparison of the relative albedo measured, ρ, with the relative albedo in cloudy and clear conditions, ρ_{cloudy} and ρ_{clear}. Using this measurements we will obtain the effective cloud cover, n, from the following expression:

$$n = \frac{\rho - \rho_{\mathrm{clear}}}{\rho_{\mathrm{cloudy}} - \rho_{\mathrm{clear}}} \tag{12}$$

Once we have estimated the effective cloud cover we can estimate the global solar irradiance from the following expression:

$$G = G_0 \frac{(1-n)}{1 - \rho_{\mathrm{s}} g \rho_{\mathrm{a}}} \tag{13}$$

The solar global irradiance estimated by the model decreases when the radiance measured by Meteosat increases. One important advantage of this model is that no regression or statistical fit was performed in the development of the model. Because of this, the model does not introduce local variables and could be used as it is in other locations.

3.2.1. Models performance

We have studied the performance of the model comparing estimated global irradiance values with ground measurements. The root square mean error ant the mean bias error of both models are shown in Table 1. Mean bias error shows the models' tendency and root mean bias error shows the models' short-term error. Errors are given as a percentage of the mean bias irradiances, which is 620 W/m^2.

Studying the results of the model it can be seen that the mean bias error is -2.2%, a relatively small deviation, though it shows that this model tends to underestimate global radiation values. The root mean square error of the model is 21.2%. Although the RMS is relatively high the quadratic error obtained is of the same order than those obtained when working with ground measurements of cloud cover (Gueymard, 1993).

Table 1
Statistical results of the global model

	MBE	RMSE
Solar global model	−2.2%	21.2%

One possible explanation of this behavior could result from the relationship of sunshine and cloud cover measurements with the position of the sun disk relative to the cloud patches, a very strong modulator of the irradiance field in the atmosphere, Wyser et al. (2002). Blumthaler et al. (1994) have shown that global irradiance shows a strong relationship with the relative position of the sun disk to the clouds, due to this relationship solar radiation measurements show pronounced short term variations under partially cloudy skies. The importance of these variations grows when the measurement interval decreases Choudhury (1982), so it is more relevant when estimating hourly values than when estimating daily values. This could explain that when we introduce this information using sunshine measurements, the model provides estimations with far lower quadratic errors (Rubio et al., 1999).

In Fig. 1, measured global irradiance vs. estimated global irradiance is shown. It can be seen that the model works correctly for global irradiance values over 500 W/m^2 but there are more error when the measured beam irradiance is under 500 W/m^2, values mostly associated with the existence of a cloud cover. It can be seen that most points are situated along the 1:1 line. The points that are situated over this line are cases where there is a partial cloud cover and the solar disk is hidden by the clouds. In this case beam irradiance is similar to that measured if the sky were completely covered by cloud but the satellite measures the size of the cloud cover and so, our model overestimates the solar beam irradiance.

The distribution of the residuals of the model in terms of the solar elevation is shown in Fig. 2. There is a strong correlation of the residuals with the solar elevation. For low solar elevation angles the model shows a strong tendency to underestimate, tendency that is reduced when the solar elevation angle increases. The

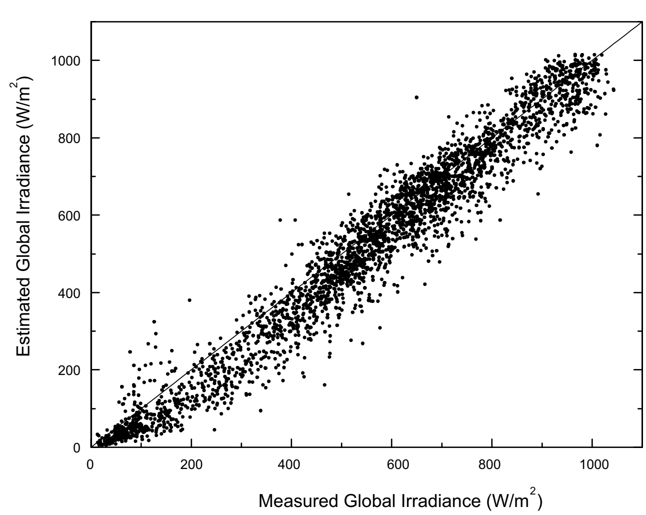

Fig. 1. Measured vs. estimated values of global solar radiation.

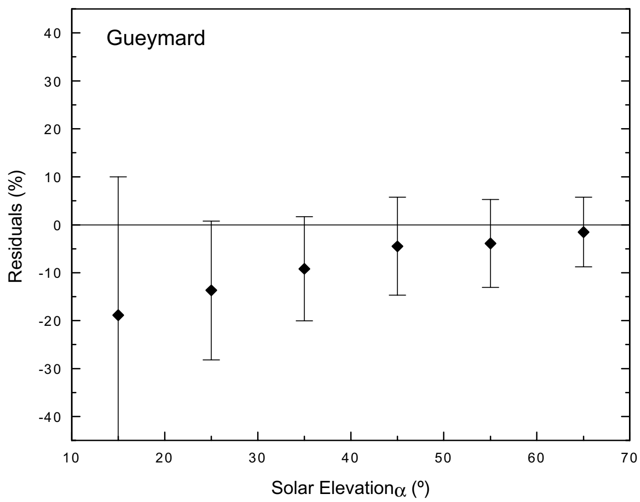

Fig. 2. Residuals of the model in terms of the solar elevation angle.

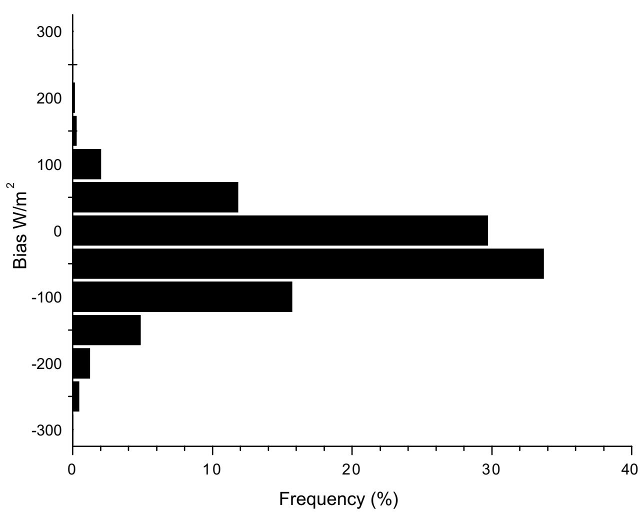

Fig. 3. Residual histogram of both models for the Spanish database.

source of the behaviour is found mainly in the estimation of the direct component of the solar radiation and is related to the presence of clouds close to the horizon.

Fig. 3 shows a histogram of the bias for each model. We can observe that the model shows a slight tendency to underestimate the measurements, this can be derived from the position of the mode of the distribution $-50\,\mathrm{W/m^2}$. The width of the distribution $150\,\mathrm{W/m^2}$ is consistent with the quadratic error obtained.

4. Photosynthetically active radiation estimation

Several authors have shown that when there is no PAR data available is possible to estimate it from global radiation measurements (Kasten and Czeplak, 1980). Once we have estimated the global radiation the following step is to use this estimate photosynthetically active radiation from the values of global solar radiation that have been estimated by the model. We have chosen an empirical model proposed by Alados-Arboledas et al. (2000) because it has been developed using Almeria's database and its performance has been compared to other models Lopez et al. (2001). This model estimates the hourly PAR from global irradiance, the clearness index, k_t and the solar zenith angle θ_z. According to Möttus et al. (2001) when estimating direct PAR in cloudless conditions the solar zenith angle is the most important factor, and the clearness index factor allows the model to take into account the effect of the clouds. The model reads as follows:

$$\frac{Q_p}{G} = 1.832 - 0.191 \ln kt + 0.099 \cos \theta_z \tag{14}$$

When we use the estimates of global radiation as input to the PAR model we obtained the results shown in Table 2. The first difference is the increase in the error of the estimation with a RMSE of 29% for the PAR estimations of the model. This could be expected as we are adding the errors of the broadband model to those of the PAR model. As the mean bias error obtained is 3%, the model has gone from underestimate global radiation values to overestimate PAR values. It is important to note that even with the increase in the error, the results obtained with the model are better than those obtained by other models that use sunshine or cloud cover measurements. We think that this model is a clear alternative to estimate photosynthetically active radiation when there is no global radiation measurements available.

Table 2
Statistical results of the PAR model

	MBE	RMSE
PAR model	3%	29%

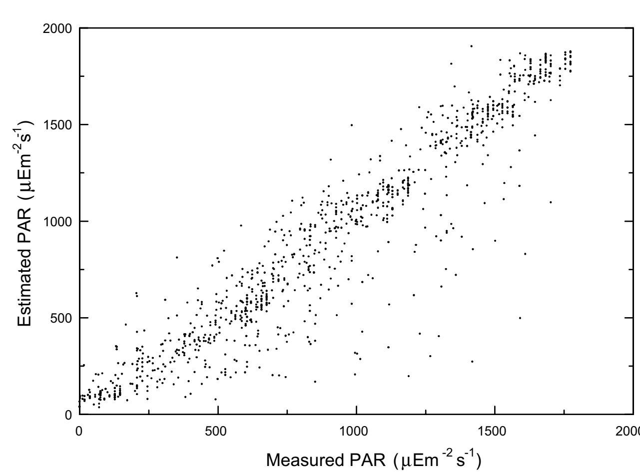

Fig. 4. Measured vs. estimated values of photosynthetically active radiation.

In Fig. 4, a scatter plot of estimated vs. measured photosynthetically active irradiance values is shown. The graph shows a greater spreading of the measurements than in the global solar radiation case, specially for lower values of the photosynthetically active radiation. But even with the greater spreading it can be seen that most points are situated along the 1:1 line.

5. Conclusions

In this work we have tested a model that estimate hourly values of photosynthetically active radiation using measurements from the Meteosat satellite. To this end we have developed a model capable to estimate global solar radiation under cloudy sky conditions using as input cloud cover estimates obtained from Meteosat.

This global solar radiation model has shown a MBE of −2.2% and a RMSE of 21%. Using the estimated values of global radiation we have proceeded to estimate the photosynthetically active radiation. The results obtained with this model are quite good as the RMSE is 29%, an error comparable to different models found in the literature.

Acknowledgement

This work was supported by the Ministerio de Ciencia y Tecnología through the research project (REN/2001)-3890-C02-01/CLI.

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