Estimation of Global Solar Radiation Flux Density in Brazil from a Single Measurement at Solar Noon

A.B. Pereira1; N.A. Villa Nova2; E. Galvani3

1Department of Soil Science and Agricultural Engineering, Universidade Estadual de Ponta Grossa, 84030-900 Ponta Grossa, PR, Brazil; e-mail of corresponding author: abelmont@uepg.br
2Department of Exact Sciences, Escola Superior de Agricultura 'Luiz de Queiroz'/Universidade de São Paulo, 13418-900 Piracicaba, SP, Brazil; e-mail: navnova@carpa.ciagri.usp.br
3Department of Geography, Laboratory of Climatology and Biogeography, Universidade de São Paulo, 01065-970 São Paulo, SP, Brazil; e-mail: emersongalvani@hotmail.com

(Received 22 July 2002; accepted in revised form 11 April 2003; published online 24 July 2003)

The calculated values of solar energy potential permit the evaluation of the maximum possible performance of energy capture systems. This is very important in engineering projects designed to make use of solar energy in its various forms, including capture by the biomass, photoelectricity for small potentials, direct capture by collectors, irrigation of crops, agricultural potential production, agroclimatic zoning and resources for varied thermodynamic cycles.

The aim of this study was to develop and appraise a mathematical model for evaluation of solar energy potential with radiometric data collected in the cities of Botucatu, Piracicaba and São Paulo, State of São Paulo, Brazil, as a function of a single measurement of solar irradiance at solar noon.

The performance of the estimation model of maximum energy input was examined using determination coefficients $R^2$ and Willmott’s index of agreement $d$ applied to estimated and observed data at the sites in study. A new way of estimating the $a$ and $b$ parameters of the Angström equation is proposed, which is irrespective of daily integrations and does not require a large number of radiometric measurements, one such measurement taken at solar noon being sufficient.

The results presented show that the proposed methodology was feasible for the evaluation of the Angström equation parameters, besides eliminating the multiple error sources produced by the conventional methodology, which is largely used in Brazil from data measured by bimetallic actinograph. The latter can present restrictions, such as lack of calibration, reading failures and integration errors of radiometric curves especially on cloudy days.

For the climatic conditions of the studied sites, it is concluded that it is possible to estimate accurately the maximum daily solar energy input. The estimation of the global irradiance by the proposed method generated values equivalent to those obtained using measurements of the duration of bright sunshine for Botucatu, SP and even more exact ones for Piracicaba, SP as well as values extremely close to the real conditions measured in São Paulo, capital, Brazil.

© 2003 Silsoe Research Institute. All rights reserved
Published by Elsevier Science Ltd

1. Introduction

Due to the potential world energy collapse, which is anticipated to occur with the foreseen ending of fossil fuels (petroleum, coal, gas) and also due to the high level of pollution and global climatic changes (Watson et al., 1990) associated with continued use of such fuels, research is turning more and more towards search for alternative resources. Among them, the use of solar energy stands out, since solar radiation is the primary source of all atmospheric phenomena and also of physical, chemical and biological processes observed in agricultural ecosystems.

Solar energy in Brazil is currently measured by the National Institute of Meteorology (INMET) as well as by other research institutions, using the Robitzsch
bimetallic actinograph. The number of more accurate radiometers in use, such as pyranometers and pyrheliometers, is insufficient in relation to needs. Reliable data from actinographs requires regular calibration and involves errors when integrating records measured especially on cloudy days. As the actual number of actinographs is also insufficient the extensive process of the evaluation of solar energy for irrigation, agricultural potential production, agroclimatic zoning, designing collectors for solar heaters and other photovoltaic equipment that depend on solar energy, net radiation balance, is still done by Campbell–Stokes sunshine records using the general model proposed by Prescott (1940) and diffused by Penman (1948).

Several researchers from all over the world have made use of the classical methodology of Angström to characterise the distribution regime of solar energy in their regions. Recently, Ramachanda and Subramanian (1997) employed such a methodology to estimate the global solar irradiance from a data set of 20 yr for Mangalore and of 25 yr for Goa, in India. Sahin and Sen (1998) proposed a simple method to estimate the Angström coefficients, which gave a significant relationship between global irradiance and duration of bright sunshine hours from a data set of 28 weather stations spread over Turkey. Variations of regional parameters of the Angström equation were obtained for the whole country.

Ampratwum and Dorvlo (1999) presented various mathematical models that include Angström–Black regression functions of linear, logarithmic, linear–logarithmic, quadratic and trigonometric types to estimate the global solar radiation density flux $Q_g$ from hours of bright sunshine in an arid region of Oman. Elagib and Mansell (2000) considered the establishment of monthly specific equations to estimate the solar energy input in Sudan, using data from 16 weather stations comprising sub-humid, semi-arid, arid and super-humid zones as a function of the dependence between $Q_g$ and other factors, such as latitude, altitude and insolation ratio. An analysis of many models found in the literature to determine the global solar radiation flux density demonstrated that the use of such models must be encouraged rather than the dissemination of radiometric network stations (Santos et al., 1983).

Although there is some outstanding national research on the construction and calibration of solar radiometers with a high degree of accuracy, such as pyranometers and pyrheliometers, evaluations of the availability of solar irradiance in Brazil are usually made using estimation equations based on measurements of the duration of bright sunshine hours. All technologies utilising solar energy require information on its potential and actual amount throughout the year at a given site. For this, a series of radiometric measurements is required. However, such series are rare and, when available, may be unreliable due to the lack of calibration equipment, reading failures and integration errors of radiometric curves especially on cloudy days. The difficulties relative to accuracy of the global solar radiation measured by actinograph can many times generate Angström coefficients $a$ and $b$, which are precarious estimated by the conventional methodology, resulting in significant errors of evaluation.

Faced with this problem, a model to estimate global irradiance potential throughout the year has been developed in this paper for Piracicaba, Botucatu and São Paulo, in the State of São Paulo, Brazil, with only

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a, b$</td>
<td>Angström coefficients, dimensionless</td>
</tr>
<tr>
<td>$c$</td>
<td>model performance index, dimensionless</td>
</tr>
<tr>
<td>$D_J$</td>
<td>number of days computed since the first of January up to the considered date, dimensionless</td>
</tr>
<tr>
<td>$d$</td>
<td>agreement index, dimensionless</td>
</tr>
<tr>
<td>$H$</td>
<td>semi-arc from the meridian crossing to the sunset, deg</td>
</tr>
<tr>
<td>$h$</td>
<td>diurnal semi-arc, rad</td>
</tr>
<tr>
<td>$J_0$</td>
<td>solar constant corresponding to 1367.42 W m$^{-2}$</td>
</tr>
<tr>
<td>$I_{12}$</td>
<td>maximum global radiation at solar noon on a horizontal surface, W m$^{-2}$</td>
</tr>
<tr>
<td>$n$</td>
<td>sample sizes, dimensionless</td>
</tr>
<tr>
<td>$Q_g$</td>
<td>daily global solar radiation flux density, MJ m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>$Q_{ge}$</td>
<td>daily solar energy potential calculated by the proposed method, MJ m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>$Q_{gm}$</td>
<td>daily maximum potential of global radiation measured by the pyranometer, MJ m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>daily extra-terrestrial radiation, kJ m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>coefficient of determination, dimensionless</td>
</tr>
<tr>
<td>$R$</td>
<td>coefficient of correlation, dimensionless</td>
</tr>
<tr>
<td>$r$</td>
<td>Earth–sun distance, expressed in terms of average distance, dimensionless</td>
</tr>
<tr>
<td>$T_r$</td>
<td>sunrise time, h</td>
</tr>
<tr>
<td>$T_s$</td>
<td>sunset time, h</td>
</tr>
<tr>
<td>$t$</td>
<td>time, h</td>
</tr>
<tr>
<td>$z_{12}$</td>
<td>zenithal angle at solar noon, deg</td>
</tr>
<tr>
<td>$\delta$</td>
<td>solar declination, deg</td>
</tr>
<tr>
<td>$\phi$</td>
<td>local latitude, deg</td>
</tr>
</tbody>
</table>
one radiometric measurement at solar noon as input. This approach, idealised by Villa Nova and Salati (1977) and tested against accurate pyranometer measurements at the studied sites, does not require extensive series of measurements dependent on daily integrations aimed at the calculation of global solar radiation flux density. In order to carry out a comparative analysis between the criterion of estimation of $Q_o$ based on Angström’s classical methodology and that defined by the monitoring of solar energy potential, the coefficients of $a$ and $b$ obtained by Ometto (1968) in Piracicaba, SP, and also by Tubelis et al. (1976) in Botucatu, SP, Brazil, were taken into account to assess the performance of the methodology so that it might be possible to recommend its utilisation at any locality or region.

2. Materials and methods

2.1. Data

The climate of Piracicaba city (22°43’S, 47°25’W Gr and 580 m) and the capital Sã o Paulo, (23°39’S, 46°37’W Gr and 800 m) according to the Köppen System is classified as Cwa or sub-tropical with rains in the summer and dry winter. The climate of Botucatu city (22°51’S, 48°26’W Gr and 786 m), in the State of Sã o Paulo, Brazil, is classified as Ca or rainy temperate, constantly wet and with hot summers. The number of hours of insolation was measured with a Campbell–Stokes sunshine recorder; the average vector beam $r$ was obtained from an Astronomic yearbook published in 1980 by the Geophysical and Astronomical Institute of the University of Sã o Paulo—IAG/USP (Astronomic yearbook, 1980); and the solar declination $\delta$ in degrees was defined by means of the following expression:

$$\delta = 23.45 \sin \left[ \frac{360}{365} (D_j - 80) \right]$$  (1)

where $D_j$ is the number of days computed since the first of January up to the considered date.

The extra-terrestrial radiation $Q_\infty$, expressed in kJ m$^{-2}$ day$^{-1}$, was calculated by the following equation:

$$Q_\infty = \frac{J_0}{r^2} \left[ h \sin \delta \sin \phi + \cos \delta \cos \phi \sin H \right]$$  (2)

$$H = \arccos \left[ -\tan \delta \tan \phi \right]$$  (3)

Where: $J_0$ is the solar constant corresponding to 1367-42 W m$^{-2}$ (Crommelynck & Fichot, 1997); $H$ is the semi-arc from the median crossing to the sunset in degrees; $h$, is the diurnal semi-arc in radians; and $\phi$ is the local latitude in degrees.

Global solar radiation $Q_o$ in MJ m$^{-2}$ day$^{-1}$ was measured by an Eppley pyranometer, model PSP, which was connected to a data logger. The maximum intensity of global solar irradiance $I_{12}$ in W m$^{-2}$ on cloudless days, at solar noon, was determined from pyranometer records for the selected days. These days were defined by the radiometric curve bell shaped for a characteristic clear day and selected by means of insolation rate values higher than 0.85.

2.2. Theory of the method

The methodology for calculating the potential of solar energy at a given site, for each period of the year is as follows.

Defining $J_0/r^2$ as the instantaneous value of the direct radiation normal to the solar beam, at the top of the atmosphere, the extra-terrestrial radiation for each solar energy flux density on a horizontal surface, during a day, at this same site, is given by integration with respect to time $t$:

$$Q_o = \int_{T_s}^{T_r} \left[ \frac{J_0}{r^2} \right] \cos z \, dt$$  (4)

Where $T_r$ and $T_s$ are the sunrise and sunset times respectively, and

$$\cos z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos H$$  (5)

The flux instantaneous density on a horizontal surface is $[J_0/r^2]^* \cos z$, $[J_0/r^2]^*$ being the value of diffuse and direct radiation, at soil level, transmitted through a number of optical masses of the atmosphere. Variables with an asterisk superscript have the same meaning as in Eqn (4) but correspondent to the solar radiation flux density that might reach the soil surface at a given instant.

Thus, the quotient $Q_a/Q_o$ is given by the following relationship:

$$\frac{Q_a}{Q_o} = \frac{\int_{T_r}^{T_s} \left[ \frac{J_0}{r^2} \right] \cos z \, dt}{\int_{T_r}^{T_s} \left[ \frac{J_0}{r^2} \right] \cos z \, dt}$$  (6)

Assuming that $[J_0/r^2]^*$ can be considered roughly constant during the day, it can be defined as

$$\frac{Q_a}{Q_o} = \frac{[J_0/r^2]^* \int_{T_r}^{T_s} \cos z \, dt}{\int_{T_r}^{T_s} [J_0/r^2] \cos z \, dt}$$  (7)

Cancelling the identical integrals gives

$$\frac{Q_a}{Q_o} = \frac{[J_0/r^2]^*}{[J_0/r^2]}$$  (8)

According to Lambert law, at solar noon

$$[J_0/r^2]^* = \frac{I_{12}}{\cos Z_{12}}$$  (9)

where $Z_{12}$ is the zenithal value at solar noon.
Considering that at solar noon \( H = 0 \):

\[
\cos z = \sin \delta \sin \varphi + \cos \delta \cos \varphi
\]  

(10)

Then

\[
Z_{12} = \delta - \varphi
\]

(11)

Thus,

\[
\cos Z_{12} = \cos(\delta - \varphi)
\]

(12)

Substituting Eqns (9) and (12) in Eqn (8) yields

\[
\frac{Q_d}{Q_o} = \frac{I_{12}/(\cos Z_{12})}{\left[J_0/r^2\right]}
\]

or

\[
\frac{Q_d}{Q_o} = \frac{I_{12}}{\left[J_0/r^2\right] \cos(\delta - \varphi)}
\]

(13)

With Eqn (13), the atmospheric transmissivity on cloudless days, defined by \( Q_d/Q_o \), can be estimated as a function of global radiation intensity at solar noon \( I_{12} \) and the astronomical parameters \( J_0/r^2 \), \( \delta \) and \( \varphi \).

The value of \( Q_d/Q_o \), determined this way, also expresses, according to Prescott’s equation (Martinez-Lozano, 1984), the sum of the parameters \( a \) and \( b \) on a cloudless day, since the insolation ratio in this condition is equal to 1 (theoretical value). Thus,

\[
\frac{Q_d}{Q_o} = a + b
\]

(14)

Consequently, the maximum potential of global radiation for a given day and site, \( Q_{gm} \) in MJ m\(^{-2}\) day\(^{-1}\), can be calculated by the following equation:

\[
Q_{gm} = \frac{Q_o \cdot I_{12}}{\left[J_0/r^2\right] \cos(\delta - \varphi)}
\]

(15)

### 2.3. Validation of the proposed methodology

For evaluating and validating the proposed method, it was necessary to obtain data from Eppley pyranometers, whose integration provided the true value of \( Q_{gm} \) (measured). Sets of data observed at Piracicaba, Botucatu and São Paulo were used for the periods June–December 1993, March–December 1995 and June–December 1994, respectively. With this data, it was possible to evaluate the estimate supplied by the methodology through the correlations between the measured \( Q_{gm} \) and estimated \( Q_{ge} \) global radiation. An independent series of data was considered to compare measured and estimated values in order to obtain a better confirmation and validation of the models for each site in study. The periods used for such a purpose at Piracicaba, Botucatu and São Paulo, respectively, were July–November 1996, June–December 1994 and April–July 1995.

### 2.4. Definition of angström coefficients by means of estimated solar radiation ratio

The latitudinal dependence of the coefficient \( a \) of the Angström–Prescott equation was found by Glover and McCulloch (1958) to be related to latitude \( \varphi \) by

\[
a = 0.29 \cos \varphi
\]

(16)

The coefficient \( b \) was calculated as the difference between estimated ratio \( Q_d/Q_o \) representing the sum of the coefficients \( a \) and \( b \) for cloudless day conditions, and the value of \( a \). Thus,

\[
b = \frac{Q_d}{Q_o} - 0.29 \cos \varphi
\]

(17)

The calculated values of the solar energy potential \( Q_{ge} \) by the proposed methodology were correlated with the measured values in Eppley pyranometers for the selected cloudless days. As the values of correlation and determination coefficients analysed separately can lead to interpretations not always suitable for the performance of the studied model, the agreement index \( d \) proposed by Willmott et al. (1985) was also used.

In this paper, a new index \( c \) proposed by Camargo and Sentelhas (1995) was also adopted to indicate the performance of the model, putting together the accuracy \( R \) and exactness \( d \) indices, being defined by the multiplication between both indices.

### 3. Results and discussion

The daily values of the available solar energy potential calculated by the proposed method \( Q_{ge} \) and measured by the pyranometer \( Q_{gm} \) were highly correlated, since the analysis shows that over 95% of the \( Q_{gm} \) variations can be explained by the calculated values. The linear regression equations for evaluation of the daily global irradiance potential, in MJ m\(^{-2}\) day\(^{-1}\), were the following at Piracicaba, Botucatu and São Paulo:

\[
Q_{gm} = 0.916 Q_{ge} + 0.396 \pm 0.99
\]

\[
Q_{gm} = 0.959 Q_{ge} - 0.07 \pm 0.47
\]

\[
Q_{gm} = 0.973 Q_{ge} - 0.584 \pm 0.32
\]

with values for the coefficient of determination \( R^2 \) of 0.95, 0.99 and 0.99 and sample sizes \( n \) of 42, 103 and 33, respectively.

The \( F \) value was highly significant, revealing a convincing correlation between the measured and estimated data of solar energy potential. The \( t \) test for the linear coefficient of the regression equation was not significant for Piracicaba and Botucatu cities, showing that the value of the linear coefficient is not statistically different from zero for both sites. However, such a test...
for São Paulo, was significant, showing therefore that the value of regression linear coefficient is statistically different from zero.

The coefficient of determination $R^2$ and correlation coefficient $R$ bring information about the degree of accuracy, but do not reveal the exactness of the model. The index of agreement $d$ proposed by Willmott et al. (1985) reveals a high level of exactness with a value of $d$ equal to 0.97, 0.99 and 0.98 for Piracicaba, Botucatu and São Paulo, respectively.

The index $c$ has assumed the values of 0.94, 0.98 and 0.97, respectively, for the studied sites, showing an excellent performance, according to the interpretation criterion of the performance of mathematical models presented by Camargo and Sentelhas (1995). The performance of such models, which proposes correction factors to estimate the solar energy potential, can be seen in Fig. 1. It is possible to verify that both accuracy, given by the trend line and the exactness demonstrated by the dispersion of the data around the fitted line of the estimates, were satisfactory. The values of $c$ were higher than 0.94, exceeding, however, values of $d$ considered as satisfactory, whose lower limit recommended by Robinson and Hubbard (1990) is of 0.75.

Figure 2 shows the performance of the models in comparison to an independent data series. The scatter is

---

![Graphs showing comparison between measured and estimated solar energy potential](image_url)

**Fig 1.** Comparison between global irradiance $Q_g$ measured by the Eppley pyranometer with the potential estimated by the proposed methodology at: (a) Piracicaba; (b) Botucatu and (c) São Paulo; — , linear regression line; $R^2$, coefficient of determination; $d$, Willmott’s index of agreement; $c$, model performance index

**Fig 2.** Comparison between measured and estimated solar energy potential, using an independent data series at: (a) Piracicaba; (b) Botucatu and (c) São Paulo; — , linear regression line; $R^2$, coefficient of determination
relatively small for the studied sites, confirming the viability of the proposed methodology. While results are site-specific, the present methodology is general and provides a climate-based definition for maximum possible daily global solar radiation as well as that proposed by Meek (1997). However, it is convenient to state here that there is no need to take into account all those parameters linked to atmospheric turbidity and sky cover conditions, because they are already included in each radiometric measurement taken at solar noon.

Although the hypothesis, which assumes $[J_0/r^2]^*$ is constant throughout the day, is not true, due to the fact that at elevated zenithal angles the long atmospheric path penetrated by the solar radiation beam, given by sec $z$, reduces the value of $[J_0/r^2]^*$, at these times the low value of cos $z$ results in a low $[J_0/r^2]^*\cos z$ product. For this reason, the model’s integration of $[J_0/r^2]^*\cos z$ leads to estimates close to the real values—a fact which gives a rational support for such an approximation considered in this study, as can be seen from Figs. 3 and 4 for Piracicaba and Botucatu, respectively. Such figures have been constructed plotting the hourly values of $[J_0/r^2]^*$, obtained by means of Eqn (9), as a function of time, since for each hour it has its corresponding zenithal angle.

Figure 5, based on the data set obtained by Pereira (1997) and published by Villa Nova and Pereira (1997), shows that estimated global irradiance based on the proposed theory was more exact for the climatic conditions of Piracicaba than when based on the conventional methodology. Although both methods showed high correlations, the scatter of the data around the 1:1 line for the proposed methodology was smaller than that obtained by the classical Angström theory. This was statistically confirmed in the agreement index $d$ and performance coefficient $c$, which were 0.98 and 0.95 for the proposed methodology, and 0.94 and 0.92 for the conventional methodology, respectively. The performance of coefficient $c$, therefore, revealed an excellent performance for the estimation models of global radiation.

Figure 6 shows that estimates based on the conventional methodology were more exact for the climatic conditions of Botucatu than those obtained from coefficients defined by the current theory. This can be explained, in part, by the fact that Botucatu is a

---

**Fig. 3. Comparison between hourly curves of global solar radiation flux density measured by the Eppley pyranometer (△) and estimated by the proposed methodology (■) at Botucatu on two dates: (a) 8 December 1994 and (b) 12 October 1994**

**Fig. 4. Comparison between hourly curves of global solar radiation flux density measured by the Eppley pyranometer (△) and estimated by the proposed methodology (■) at Piracicaba on two dates: (a) 28 November 1993 and (b) 28 August 1993**
mountainous region, which facilitates a prevailing formation of orographic clouds with a large thickness. Under such a situation, for a condition of insolation ratio approximately equal to zero, the value of coefficient $a$ will be lower than the one determined by the expression $0.29\cos\phi$. Thus, the highest values of such a coefficient will result in overestimates of the global solar radiation. However, in many situations, such as for climatic conditions of Piracicaba and São Paulo the approximation for the coefficient $a$ proposed by Glover and McCulloch (1958) provided extremely satisfactory results. Nevertheless, depending on local atmospheric conditions, the responses will be able to reveal the need for a thorough analysis on mathematical treatment of the parameter which reflects the value of radiation ratio $Q_g/Q_o$ when there is a total sky cover, i.e. for situations in which insolation ratio is approximately equal to zero. The statistical confirmation for this can be demonstrated by means of the following indices of agreement $d$ and performance $c$: 0.88 and 0.84 for the proposed methodology and 0.93 and 0.88 for the classical methodology, respectively. The variation observed on such statistical parameters does not point out differences that might justify a preferential utilisation of the classical methodology in Botucatu in relation to the current methodology, once the former requires daily integrations of a large data set.

Figure 7 shows that Angström’s coefficients values, $a$ and $b$, obtained by the methodology generated estimated values of global radiation extremely close to the measured ones in São Paulo. This can be confirmed through the values for $d$ and $c$, which were 0.98 and 0.95, respectively.

4. Conclusions

Accurate estimates of the maximum daily solar energy input were obtained as a function of only one measurement taken at solar noon.

The proposed methodology was efficient in rapidly estimating the parameters $a$ and $b$ of the Angström equation, eliminating the multiple error sources produced by conventional methodology.

The estimation criterion of global solar radiation based on the proposed theory generated values equivalent to those obtained by the classical methodology of Angström at Botucatu and even more exact ones for Piracicaba as well as values extremely close to the real conditions measured in São Paulo.
Linear regression line: $R^2 = 0.944$, $d = 0.981$

Fig. 7. Comparison between the global solar radiation flux density measured by the pyranometer and global irradiance estimated from Angström’s equation coefficients $a$ and $b$ determined by the proposed methodology at São Paulo: — , linear regression line; $R^2$, coefficient of determination; $d$, Willmott’s index of agreement

References


Camargo A P; Sentelhas P C (1995). Avaliação de modelos para estimativa da evapotranspiração potencial mensal em base diária para Campinas e Ribeirão Preto, SP. [Evaluation of models for estimating the monthly potential evapotranspiration in a daily basis for Campinas and Ribeirão Preto, SP, Brazil.] In: Congresso Brasileiro de Agrometeorologia, Vol. 7, Anais... Campina Grande, pp 415–417 (Summary in English)


Ometto J C (1968). Estudo sobre as relações entre radiação solar global, radiação líquida e duração do brilho solar. [Study about the relationships between global solar radiation, net radiation and duration of bright sunshine.] PhD Thesis, Escola Superior de Agricultura ‘Luiz de Queiroz’, Universidade de São Paulo, Piracicaba (Summary in English)

Penman H L (1948). Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society, 193, 120–145

Pereira A B (1997). Modelo de estimativa do potencial de energia solar à superfície. [Estimate model of the solar energy potential at surface.] PhD Thesis, Faculdade de Ciências Agronômicas de Botucatu, Universidade Estadual Paulista, Botucatu (Summary in English)


Santos R; André R G B; Volpe C A (1983). Estimation of the global solar radiation in Jaboticabal, SP, Brazil. Científica, 11, 31–39 (Summary in English)

Tubelis A; Nascimento F J L; Foloni L L; Fisher V A; Francischini W (1976). Estimation of the daily global solar radiation at Botucatu, SP, Brazil, from the daily duration of bright sunshine. Científica, 26, 53–60 (Summary in English)


Villa Nova N A; Pereira A B (1997). Avaliação do potencial de energia solar global no município de Piracicaba, SP, Brasil. [Evaluation of global solar energy potential at Piracicaba, SP, Brazil.] In: Congresso Brasileiro de Agrometeorologia, Vol. 10, Anais... Piracicaba, pp 413–415 (Summary in English)
