A SIMPLE PHYSICAL MODEL TO ESTIMATE GLOBAL SOLAR RADIATION IN THE CENTRAL ZONE OF CHILE

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Abstract

Global solar radiation at surface is the result of a complex interaction of energy between the atmosphere an the surface. Recently, several progress have been made towards the creation of accurate, physically-based solar radiations formulations that can model this interactions over complex terrain. A simple global solar radiation model was developed for the Central Zone of Chile, being fully integrated within a geographic information system (Idrisi) and based on a digital elevation model (DEM). Key features are (i) the determination of atmospheric transmissivity from measured meteorological data, (ii) modeling of the direct and diffuse component of solar radiation, and (iii) the consideration of cloud coverage. In this study, the developed model was used to estimate the spatial distribution of incoming monthly potential global solar radiation for the work area. These results are better than those obtained by classical interpolators, and still better if the process is run on the complex terrain areas. Finally the potential application of this method is discussed.

INTRODUCTION

Solar energy is an important renewable energy source for the country, both in the generation of PV electricity and as heat. Therefore, it is necessary to quantify the solar potential of an area, but the achieving of this goal requires first an adequate estimation of solar radiation incident on the Earth's surface. Generally, the spatial variability of solar radiation is determined by the interplay of chronological, geographical, atmospheric and surface conditions (Breitkreuz et al., 2007). However, there are simple geometric formulas that allow a relatively reliable estimation, so the spatial modeling of this variable is crucial to quantify the availability of energy per area unit for its potential use.

The solar radiation modeling has shown significant progress in recent decades, reaching at present integration in geographic information systems that allow quantification at its spatial distribution. There is a range of estimation methods, the firsts uses formulations that seek empirical parameterization of the local physical conditions, using measurements in this field, from which quantitatively describes the optical characteristics of the air by simple equations and attenuation of solar radiation on the surface (Angstrom, 1924, Liu and Jordan, 1960; Erbs et al., 1982, Iqbal, 1983). More current methods uses complex models of radiative transfer in the atmosphere, usually implemented in numerical weather forecast models such as MM5 (Dudhia 1993, Grell et al., 1995), HIRLAM (Undén et al., 2002) or WRF. (Michalak et al., 2005).

In this paper, a simple method to estimate solar radiation in central Chile was developed. This model is based on the classical equations for estimating the global radiation, but also introduces the effects of the atmosphere and topography (Iqbal, 1983).

MATERIALS AND METHODS

Study area and meteorological data

The area of study corresponds to central Chile, located between 32 and 40 degrees south latitude, covering the regions of Valparaíso, Metropolitana, del Libertador Bernardo O'Higgins, del Maule, del Bio-Bio and de la Araucanía, as shown in Figure 1. This area of study gathers the highest population density in the country and has favorable geographic and climatic conditions that allow the development of the major national productive sectors.

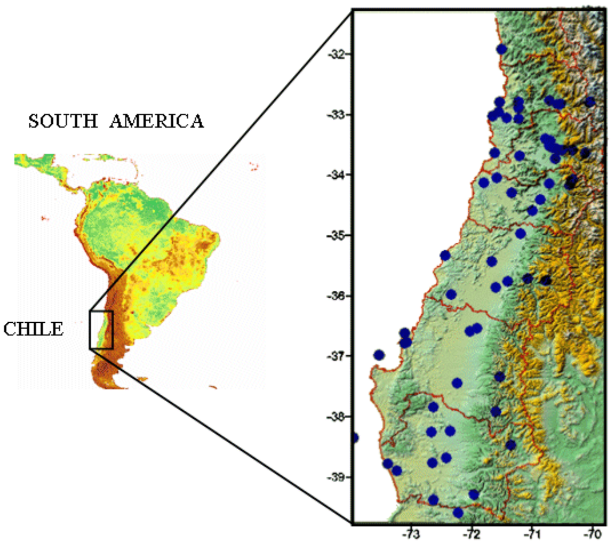


Figure 1.- Area of study, corresponding to the regions of Valparaíso, Metropolitana, del Libertador Bernardo O'Higgins, del Maule, del Bio-Bio and de La Araucanía. Blue points represent the meteorological stations used in the present work.

The meteorological database was constructed from climatological data network of meteorological stations belonging to the Chilean Meteorological Direction (DMC), Water General Direction (DGA), National Institute of Agricultural Research (INIA) and information available in previous studies. In total, 60 stations were collected, leaving the 10% of them to be used in the validation process.

Theoretical model of solar radiation

Solar energy comes in the form of radiative flow determines the surface energy balance, the water cycle and ocean and atmospheric circulation. These processes are used by different ecosystems through the processes of terrestrial life. The calculations of solar radiation reaching the Earth's surface depend of spherical trigonometry relations between the sun and the Earth, and the Earth's orbit around the sun.

The calculation of the radiation flow received in a horizontal surface of the land requires azimuthal angles and zenith during every instant in the evaluation of the solar flux. The total daily solar radiation (H_0) for a horizontal surface, is given by

$$H_o = \int_{Sunrise}^{Sunset} I_o(t)\, dt \qquad (1)$$

where

$$I_o(t) = I_{sc} E_o \left[Sin(\delta) Sin(\phi) + Cos(\delta) Cos(\phi) Cos(w) \right] \qquad (2)$$

where ϕ is the latitude of an specific place. The result of this integral (1) from equation (2) is

$$I_o(t) = \frac{24}{\pi} I_{sc} E_o Cos(\phi) Cos(\delta) \left[Sin(w_s) - \frac{\pi}{180} w_s Cos(w_s) \right] \qquad (3)$$

where Isc is the solar constant (1367 Watt/m^2), w_s given by

$$Cos(w_s) = -Tan(\phi) Tan(\delta) \qquad (4)$$

δ is the solar declination, is given by

$$\delta = \left(\frac{180}{\pi} \right) (0.006918 - 0.399912 Cos(\Gamma) + 0.070257 Sin(\Gamma) - 0.006758 Cos(2\Gamma) + 0.000907 Sin(2\Gamma - 0.002697 Cos(3\Gamma) + 0.00148 Sin(3\Gamma)) \qquad (5)$$

E_0 is the correction factor for the position of the earth in its orbit, with

$$E_0 = 1.000110 + 0.034221 Cos(\Gamma) + 0.001280 Sin(\Gamma) + 0.000719 Cos(2\Gamma) + 0.000077 Sin(2\Gamma) \qquad (6)$$

where Γ is given by

$$\Gamma = \frac{2\pi(d_n - 1)}{365} \qquad (7)$$

and d_n is the julian day.

The main characteristic of a randomly oriented surface is that the magnitude of the azimuth of the surface is greater or less than zero. Accordingly, for a given geographical position, in the absence of the Earth's atmosphere, trigonometric relationships between the Sun and a surface oriented in any arbitrary direction respect to the local meridian on Earth are given by

$$Cos(\theta_a) = Cos(\beta)\cdot Cos(\theta_z) + Sin(\beta)\cdot Sin(\theta_z)\cdot Cos(\psi - \gamma) \qquad (8)$$

where θ_a represents the angle of incidence measured in degrees for an arbitrarily oriented surface, δ is the solar declination in degrees, ϕ is the latitude of the geographical location measured in degrees, β is the slope of the area measured in degrees, γ represents the azimuth of the surface measured in degrees, θ_z is the angle measured in degrees to a horizontal surface, and ψ is the solar azimuth measured in degrees for an horizontal surface (figure 2).

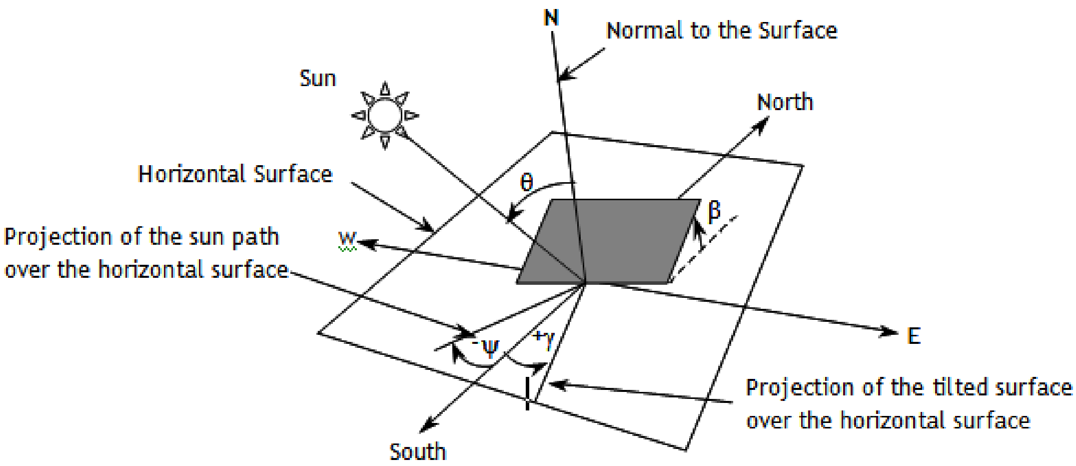


Figure 2.- Position of the sun on an arbitrarily inclined surface respect to the equator, and the geometric parameters that describes it.

The radiation is estimated according to the relationship that exists with cloud cover, and giveb by

$$\frac{R_g}{R_{hs}} = f(C\%) \qquad (9)$$

where f (C%) is a function that depends on cloud cover. In central Chile has been found that this relation is (Morales et al., 2003)

$$f(C\%) = \frac{1}{1.66351 + 0,03513\cdot C^{1.8752}} \qquad (10)$$

To estimate the daily cloud covering as a function of the latitude, it was considered that that depends principally on the position of the Pacific's Anticyclone Center (PAC). For daily modeling, Maximum Pressure Location in Chile (MPL) was used as a climate descriptor. MPL shows a good correlation with cloudiness. For a calibration between the cloud and the MPL, a linear relation was proposed (Parra y Morales, 1994)

$$C\%(i) = A(\phi,\nu) + B(\phi,\nu)\left[LPM(i) - \phi\right] \qquad (11)$$

where C% (i) is the monthly average percentage of cloud cover, ν is the longitude of the place and i represents the month of the year. To find the values of A(ϕ,ν) and B(ϕ,ν), is necessary to processed monthly average data of cloudiness and LPM. The result of this relationship is

$$A(\phi,\nu) = 1.20259018 + 6.05996626 \cdot |\phi| - 1.02434364 \cdot |\phi|^2 + 9.09001061 \cdot |\nu| - 0.33397432 \cdot |\nu|^2 + 0.87460789 \cdot |\phi| \cdot |\nu| \qquad (12)$$

$$B(\phi,\nu) = 0.90967134 - 0.9902772 \cdot |\phi| + 0.17846685 \cdot |\phi|^2 - 2.02486866 \cdot |\nu| + 0.07295242 \cdot |\nu|^2 - 0.17925801 \cdot |\phi| \cdot |\nu| \qquad (13)$$

with a coefficient of determination of 0.8 and p <0.01. Using spline interpolation method between the months of year, the daily cloudiness was estimated from equation (11).

Collares-Pereira and Rabl (1979) utilized pyrheliometer data to find a analytical form to estimate the diffuse radiation, given by

$$\frac{Rglobal}{Rdiffuse} = \begin{cases} 0.99 & f \le 0.17 \\ 1.188 - 1.272f + 9.473f^2 - 21.856f^3 + 14.648f^4 & 0.17 \le f \le 0.8 \\ 0.115 & f > 0.8 \end{cases} \qquad (14)$$

Finally, the global solar radiation on an arbitrarily oriented surface is given by

$$Rg = (R_{direct} - R_{diffuse}) + 0.5 \cdot R_{diffuse} \cdot \left(1 + Cos(\beta)\right) + 0.5 \cdot \alpha \cdot R_{horizontal} \cdot \left(1 - Cos(\beta)\right) \qquad (15)$$

Where Rdirect is direct radiation, Rdiff is diffuse radiation, α is the surface albedo, and β is the slope of the surface.

Digital elevation model

To learn the effect of topography on solar radiation is necessary to calculate the main topographical characteristics of central Chile, as are the altitude, slope and exposure. In this case, the use of a Digital Elevation Model (DEM) called GTOPO30, which has a resolution of one kilometer (United States Geological Survey, 2004), was proposed. This database allows the representiation of elevation changes that presents the topography along the studied area, and from this database calculates the change in solar radiation.

RESULTS AND DISCUSSION

In central Chile, the synoptic time scale is governed by the spatial interactions that occur moment to moment between the major meteorological centers of action: the Pacific Anticyclone (AP), Coastal Low (BC) and what is called Profundization of the Low Coastal (PBC). Located at a further south latitude of the AP, a wedge of high pressure penetrates into the continent by the coastline and divides the national territory into three different weather regions. Belonging to the wedge, the LPM is defined as the place (latitudinal) of maximum pressure in Chile, leaving the BP at South and the BC or PBC at North (Parra and Saavedra, 1993); then, any point in the area of study is climatologically characterized by the distance to the LPM during the year. In this way, the cloudiness can be estimated as the monthly average value from equation (11).

From the measured values of meteorological stations in Chile, a database for the cloud cover and solar radiation was build. Using the equations (11) to (13) the average monthly cloud cover for the entire study area was calculated, and the monthly averages matrix of these values were constructed. LPM values used are shown in Figure 3 as average per month (MOY is month of year).

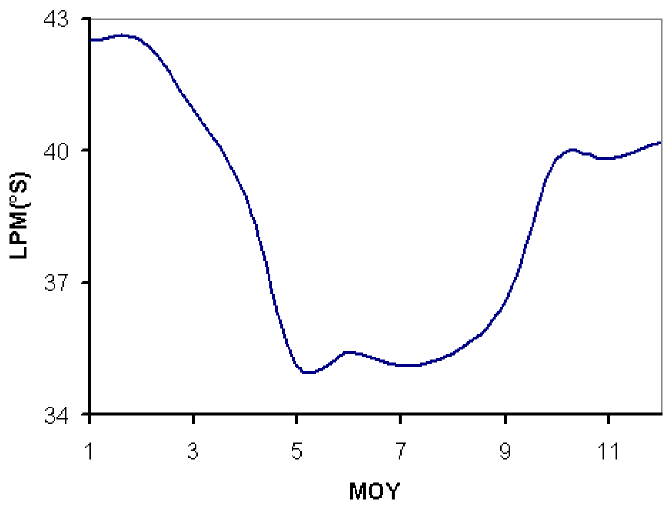
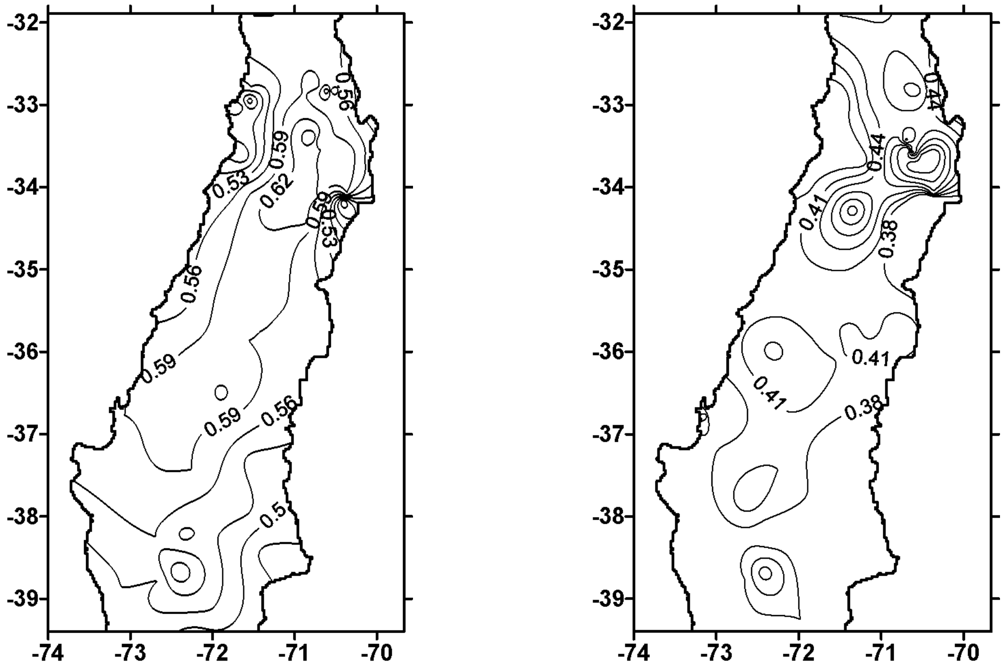
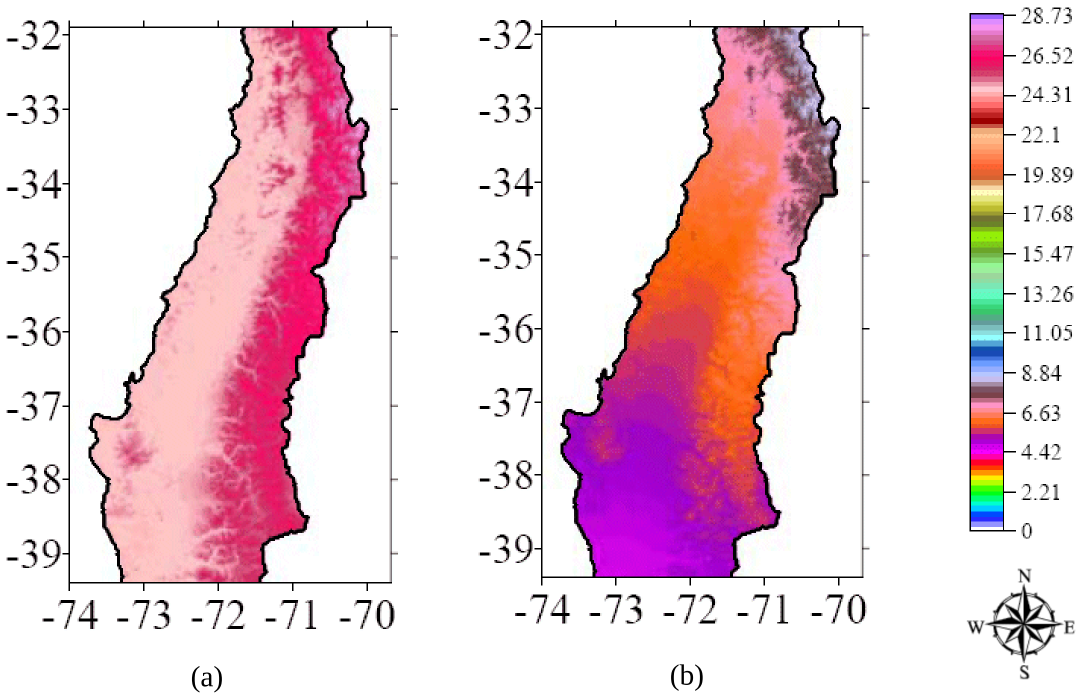


Figure 3.- Monthly mean values of the Maximum Pressure Place (LPM) in Chile.



(a) (b)

Figure 4.- Spatial distribution of monthly average values of the transparency coefficient of the atmosphere for months (a) January and (b) July.



(a) (b)

Figure 5.- Radiación solar global en superficie media mensual para los meses de (a) enero y (b) julio, en MJ m^{-2} $día^{-1}$.

The monthly cloud cover average is estimated from equation (10) and for each month of the year, values that are stored in an array. Figure 4, for example, shows the spatial distribution of monthly average values of the transparency coefficient of the atmosphere for months (a) January and (b) July.

Using the equations 1 to 15 and the programming tools provided by the QBasic program, a mathematical simulation model capable of representing the spatial distribution of monthly average global solar radiation over the entire area in central Chile matrix or raster format was developed. Figure 5 shows the matrix obtained for the months of January and July that represents the spatial distribution of monthly average global solar irradiation on the central zone of Chile, whose values are expressed in [MJ m^{-2} day^{-1}].

CONCLUSIONS

From the background provided by the meteorological stations, it is possible to visualize that the spatial and time variability of the coefficient of transparency of the atmosphere is complex. However, it is also noted that despite this complexity the parameter shows a longitudinal and latitudinal tendency. This is reflected in the relations obtained from the temperature variations and cloud cover. The estimation of the transparency coefficient can be obtained with reasonable accuracy, with errors of 5%, based on values of cloud cover in eighths and maximum pressure values in Chile.

The simple model, programmed in QBasic, quantifies the availability of solar energy on the Central Zone of Chile, but its calculation is associated with astronomical, trigonometrical and topographical factors. However, this model has built a widespread tool for calculation on the area under study, through which the estimation of the monthly average values of global solar radiation on an arbitrarily oriented surface also considering the atmospheric factors can be achieved. Indeed, by introducing the calculation of the transparency coefficient, the direct and diffuse solar radiation on a horizontal surface into this routine, it was possible to estimate the monthly average global solar radiation on a surface for the Central Zone of Chile with a reasonable accuracy and errors less than 10%. The proposed model proves to be a useful tool for the generation of a solar radiation spatial database, integrated into a geographic information system, based on simple algorithms and accessible to all users.

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