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ESTIMATION OF GLOBAL SOLAR RADIATION IN VENEZUELA

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SUMMARY

A new relationship between sunshine duration and solar radiation was investigated through the analysis of data on monthly global solar radiation and hours of bright sunshine for eleven meteorological stations in Venezuela during the period 1964-1993. Linear regression was used to fit the Angström-Prescott equation. Estimated values were compared with measured values in terms of root mean square error, mean bias error, mean absolute bias error, mean percentage error, and mean absolute percentage error. It is recommended that the t-statistic be used in conjunction with a set of error statistical parameters to more reliably assess a model's performance. All the models fitted the data adequately and can be used to estimate monthly mean solar global radiation from sunshine hours. The Angström-Prescott's correlation obtained for the eleven cities can be used for estimating global solar radiation in Venezuela where only sunshine hours data were available.

Introduction

Knowledge of the local global solar radiation is required by most of the models that simulate crop growth. It is also essential for many applications, including architectural and solar energy systems design, and evapotranspiration estimates. The global solar radiation on horizontal surface at the location of interest is the most critical input parameter employed in the design and prediction of the performance of a solar energy device (Hussain *et al.*, 1999). Official studies (Contreras *et al.*, 2006) indicate that there is great potential for alternative energies in Venezuela, where solar energy could solve part of energy demand problem. Furthermore, as the energy source for photosynthesis and evapotranspiration, solar radiation is an important input to crop growth models (Allen *et al.*, 1998). Boisvert (1990) reported that the error introduced by the estimate of global radiation used in the evapotranspiration from Penman's method would be approximately the same as for the estimate of radiation. In spite of the importance of solar radiation measurements, these data are not available due to the operational difficulty in taking direct measurements and, hence, must be estimated. Venezuela has a variety of climates and is located in a region where the potential of global solar radiation in applications and agriculture are considerably high.

The empirical models can be roughly classified into three categories: a) sunshine-based models, b) cloud-based models, and c) meteorological data-based models (Almorox and Hontoria, 2004; Menges *et al.*, 2006; Yang *et al.*, 2006). The Angström-Prescott models are sunshine-based and have been widely applied to estimate global solar radiation. A well calibrated Angström-Prescott model is usually more accurate than a temperature based

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ESTIMACIÓN DE LA RADIACIÓN SOLAR GLOBAL EN VENEZUELA

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RESUMEN

Una nueva relación entre la duración de la insolación y la radiación solar global se estudia a través del análisis de datos de radiación solar global y horas de sol de once estaciones meteorológicas de Venezuela en el período 1964-1993. Se usó el método de la regresión lineal para estimar la ecuación de Angström-Prescott. Los valores estimados fueron comparados con las mediciones usando los estadísticos error cuadrático medio RMSE, los errores de sesgo MBE y MABE; los errores porcentual medio MPE, y porcentual absoluto medio MAPE. Se recomienda también el uso del estadístico t en conjunción con todos esos errores estadísticos para una mejor validación del modelo. Todos los modelos analizados estiman los datos de forma adecuada y pueden ser empleados en la estimación de la radiación global solar a partir de los datos de insolación. El método de Angström-Prescott puede ser usado para estimar la radiación solar en Venezuela cuando se dispone de los datos de insolación únicamente.

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RESUMO

Uma nova relação entre a duração da insolação e a radiação solar global estuadia-se por meio do análise dos dados de radiação solar global e horas de sol de onze estações meteorológicas da Venezuela usando a série 1964-1993. Se usou o método da regressão linear para estimar a equação de Angström-Prescott. Os valores estimados se compararam com os medidos usando os estatísticos erro quadrático meio RMSE, os erros de sesgo MBE e MABE; os erros percentual meio MPE, e percentual absoluto meio MAPE. Se recomendou também o uso do estatístico t em conjunção com todos esses erros estatísticos para uma melhor validação do modelo. Todos os modelos analisados estimam os dados de uma forma adequada e podem ser usados na estimativa da radiação global solar a partir dos dados de insolação. O método de Angström-Prescott pode usarse para estimar a radiação solar com dados de insolação na Venezuela.

model and a cloud based model (Iziomon and Mayer, 2001; Trnka *et al.*, 2005). The model has gained much popularity over the years. A number of studies have focused on tuning the empirical constants, and show that the parameters can be quite distinct in different regions. The applicability of these methods remains geographically limited and thus the model parameters have to be calibrated locally (Martínez-Lozano *et al.*, 1984; Gueymard *et al.*, 1995).

Several empirical models have been developed to calculate global solar radiation using various parameters. The parameters used as inputs in the calculations include sunshine duration, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitable water, albedo, atmospheric pressure, cloudiness and evaporation. The most commonly used parameter for estimating global solar radiation is sunshine duration; can be easily and reliably measured, and data are widely available. The first author who employed a linear relationship between global radiation and sunshine duration was Angström (1924):

$$H/H_c = k + (1- k)\ (n/N)$$

where H: amount of global radiation; H_c: global radiation under a real atmosphere in completely clear days; k: empirical constant, determined by Angström as k= 0,25 from Stockholm data; n: number of hours measured by a sunshine recorder; and N: maximum possible number of hours of sunshine. The modified version of the Angstrom's correlation has been the most convenient and widely used correlation for estimating the global radiation (Prescott, 1940):

$$H/H_0 = a + b\ (n/N) \qquad (1)$$

where H_0: extraterrestrial solar radiation on a horizontal surface ($MJ\cdot m^{-2}\cdot day^{-1}$), and a and b: empirically determined regression constants. These constants can assume a wide range of values depending on the location considered, and can be inferred from correlations established at neighboring locations. For example, when using the FAO 56 Penman estimation method (Allen ., 1998), use of Angström values calibration is recommended. In a general sense it may be said that the factors influencing a and b are (Almorox *et al.*, 2005): latitude, height of the station, reflection coefficient of the surface, mean solar altitude, water vapor concentration, natural or artificial pollution concentration.

The object of the present paper is to develop an improved Angström-Prescott estimation for the prediction of monthly average global radiation on a horizontal surface from sunshine duration in various locations in Venezuela.

Models and data

In order to obtain sets of regression constants with data available in Venezuela, measured data of monthly mean of global solar radiation and sunshine duration corresponding to the period between 1964 and 1993 was employed. The data were obtained from the World Radiation Data Centre (WRDC, http://wrdc-mgo.nrel.gov/) from eleven meteorological stations across Venezuela, given in Table I.

Daily extraterrestrial radiation on a horizontal surface H_0 can be calculated as a function of the solar constant (I_{sc}), the latitude of the site (λ), the eccentricity correction factor of the Earth's orbit (E_0), the solar declination (δ) and the mean sunrise hour angle (w_s); using the equation

$$H_0 = (1/\pi) I_{sc}\cdot E_0 (\cos\lambda\cdot\cos\delta\cdot\sin w_s + (\pi/180)\sin\lambda\cdot\sin\delta\cdot w_s)\ MJ\cdot m^{-2}\cdot day^{-1}$$

TABLE I
GEOGRAPHICAL LOCATION OF THE METEOROLOGICAL STATIONS USED IN THIS STUDY

Station name	Longitude (W)	Latitude (N)	Altitude (m)
Coro	69.68°	11.42°	16
Maracaibo	71.73°	10.57°	66
Barquisimeto	69.32°	10.07°	613
Maracay	67.65°	10.25°	436
Caracas (La Carlota)	66.88°	10.50°	835
Barcelona	64.68°	10.12°	7
Merida	71.18°	8.60°	1479
Ciudad Bolivar	63.55°	8.15°	43
S. Fernando de Apure	67.42°	7.90°	47
Tumeremo	61.45°	7.30°	180
Puerto Ayacucho	67.5°	5.60°	73

Source: WRDC

I_{sc} is the amount of energy received at the top of the Earth's atmosphere measured at an average distance between the Earth and the Sun on a surface oriented perpendicular to the Sun. The generally accepted solar constant of 118.108MJ·m^{-2}·day^{-1} is a satellite-measured yearly average. The solar declination in degrees can be computed from the Spencer formula (Spencer, 1971):

$$\delta=(180/\pi)(0.006918-0.399912\cos\Gamma+0.070257\sin\Gamma-0.006758\cos2\Gamma+0.000907\sin2\Gamma-0.002697\cos3\Gamma+0.00148\sin3\Gamma)$$

where the day angle Γ (radians) is given by

$$\Gamma = 2\pi(n_{day}-1)/365$$

where n_{day} is the number of the Julian day of the year, starting from the first of January. The eccentricity correction factor is calculated by the expression (Spencer, 1971)

$$E_0 = 1.00011+0.034221\cos\Gamma+0.00128\sin\Gamma+0.000719\cos2\Gamma+0.000077\sin2\Gamma$$

and the geometric mean sunrise hour angle on a horizontal surface, or theoretical sunrise/sunset w_s, can be calculated in degrees from

$$w_s = \cos-1\ [(-\sin\lambda\cdot\sin\delta)/(\cos\lambda\cdot\cos\delta)]$$

For a given month, the maximum possible sunshine duration can be calculated as

$$N= w_s/7.5$$

Methods of analysis

Coefficient values were calculated from regression analysis between H/H_o and n/N for a long period and for each month. This method is considered by Tadros (2000) as the best for predicting global solar radiation. Yorukoglu and Celik (2006) concluded that the statistical analysis should be based on the ratio of solar radiation to extraterrestrial solar radiation *vs* the ratio of sunshine duration to day length.

The performance of the models was evaluated on the basis of the statistical measures like root mean square error (RMSE), mean bias error (MBE), mean absolute bias error (MABE), mean percentage error (MPE), and mean absolute percentage error (MAPE). These tests are the ones that are most commonly applied in comparing the models of solar radiation estimations (Ampratwum and Dorvlo, 1990; Hussain *et al.*, 1999; Rehman, 1999; Ertekin and Yaldiz, 2000; Tadros, 2000; Toğrul *et al.*, 2000; Sabziparvar *et al.*, 2007).

$$di=(1/H_{io})(H_{im}-H_{ic})$$
$$RMSE=[\Sigma(d_i)^2/N_{obs}]^{0.5}$$
$$MBE=\Sigma(d_i)/N_{obs}$$
$$MABE=\Sigma(|d_i|)/N_{obs}$$
$$MPE=1/N_{obs}\Sigma100[(H_{im}-H_{ic})/H_{im}]$$
$$MAPE=1/N_{obs}\Sigma100\cdot[|(H_{im}-H_{ic})/H_{im}|]$$

where d_i: difference between the measured and calculated ratios H_m/H_0-H_c/H_0, N_{obs}: number of data pairs, H_{im}: measured solar radiation, H_{ic}: calculated solar radiation, and H_{io}: extraterrestrial solar radiation.

The RMSE provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the deviation between the calculated and measured values. The smaller the value, the better the model performs, but a few large errors in the sum can produce a significant increase in the indicator. The values of the MBE represent the systematic error or bias, while the RMSE is a non-systematic error. A positive value of MBE shows an over-estimate while a negative value represents an under-estimate by the model. The MABE gives the absolute value of bias error and is a measure of the goodness of the correlation. The MPE is an overall measure of forecast bias, computed from the actual differences between a series of forecasts and actual data points observed; each difference being expressed as a percentage of each observed data point, then summed and averaged. The MAPE is an overall measure of forecast accuracy, computed from the absolute differences between a series of forecasts and actual data observed; each absolute difference is expressed as a percentage of each actual data, then summed and averaged. The MBE and MPE offer information regarding overestimation or underestimation of estimated data; low values of these mean errors are desirable, though it should be noted that overestimation of an individual data element will cancel underestimation in a separate observation.

However, these estimated errors provide reasonable criteria to compare models but do not objectively indicate whether a model's estimates are statistically significant. The t-statistic allows models to be compared and at the same time it indicates whether or not a model's estimate is statistically significant at a particular confidence level (Stone, 1993; Jacovides and Kontoyiannis, 1995; Toğrul *et al.*, 2000). The *t*-statistic is defined as

$$t=[(N_{obs}-1)MBE^2/(RMSE^2-MBE^2)]^{0.5}$$

Results and Discussion

According to the statistical test results, it can be seen that all the regression equations gave good results. Table II shows the values of the Angström model parameters, the statistical parameters calculated using the models are presented in Table III.

It is evident from Table II that the values of a and b are subjected to a very large variability. In the developed models, the values of the constant

TABLE II
REGRESSION COEFFICIENTS OF EQ. (1) FOR EACH STATION

Station name	a	b
Coro	0.338	0.350
Maracaibo	0.253	0.263
Barquisimeto	0.260	0.376
Maracay	0.297	0.291
Caracas (La Carlota)	0.315	0.226
Barcelona	0.283	0.296
Merida	0.300	0.343
Ciudad Bolivar	0.302	0.256
S. Fernando de Apure	0.308	0.279
Tumeremo	0.269	0.352
Puerto Ayacucho	0.289	0.215
All stations	0.263	0.344

TABLE III
RESULTS FOR T-STATISTIC AND EXPLORED ERRORS

Station name	t-statistic *	RMSE	MBE	MABE	MPE	MAPE
Coro	0.000205	0.0321	0.000000	0.0244	-0.3166	4.2741
Maracaibo	0.000248	0.0313	0.000000	0.0238	-0.6243	5.9553
Barquisimeto	0.000091	0.0502	0.000000	0.0424	-1.0325	8.6737
Maracay	0.000358	0.0341	0.000001	0.0263	-0.4992	5.4417
Caracas (La Carlota)	0.000117	0.0317	0.000000	0.0256	-0.5400	5.9140
Barcelona	0.000223	0.0269	0.000000	0.0199	-0.3056	4.1159
Merida	0.000265	0.0257	0.000000	0.0196	-0.2616	3.9600
Ciudad Bolivar	0.000028	0.0273	0.000000	0.0212	-0.3391	4.5405
S. Fernando de Apure	0.000030	0.0539	0.000000	0.0468	-1.2903	9.8638
Tumeremo	0.000037	0.0377	0.000000	0.0287	-0.6759	6.3727
Puerto Ayacucho	0.000246	0.0344	-0.000001	0.0291	-0.7259	7.2791
All stations	0.000597	0.0517	0.000001	0.0410	-1.1738	8.7260

* $t_{critical}$ at 5%=1.96.
RMSE: root mean-square error, MBE: mean bias error, MABE: mean absolute bias error, MPE: mean percentage error, and MAPE: mean absolute percentage error.

a varies from 0.253 to 0.338, while the Angström-Prescott coefficient b varies from 0.215 to 0.376. The overall mean and deviation of the eleven values of a, b, and a+b were, respectively, 0.292 ±0.045; 0.295 ±0.080; and 0.587 ±0.100.

For the estimation of monthly mean daily global solar radiation, the best performance based on RMSE, MABE, MPE and MAPE was achieved for the stations of Merida, Barcelona and Coro. The results were worse for S. Fernando, Barquisimeto, Puerto Ayacucho and Tumeremo. The comparison between the different models according to the t value shows that for all the stations, the calculated t values were less than the critical t value. These results show that the equations have statistical significance for all the stations (Table III).

Utilizing a combination of eleven stations in Venezuela, it has been shown that the global solar radiation across the country can be related with the relative sunshine duration. According to the results, the linear annual equation is recommended for the estimation of monthly average daily global solar radiation in areas where the radiation data is missing or unavailable. Its form is

$$H/H_o = 0.26+0.34(n/N) \quad (2)$$

The present work will help advance the state of knowledge of global solar radiation to the point where it has applications in the estimation of evapotranspiration and crop growth models.

Conclusion

Solar radiation data is essential to the work of energy planners, engineers and agricultural scientists. Based on data at eleven stations in Venezuela, the Angström-Prescott equation was obtained and the corresponding empirical coefficients are given for each station (Table II). The results show that these Angström-Prescott coefficients are site-dependent, and showed good agreement. As the global solar radiation data are not available for most areas in Venezuela, a countrywide general equation was developed on the basis of the information at eleven stations. This equation (2) can be used to estimate the monthly average daily global solar radiation in Venezuela.

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