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Empirical models for estimating daily global solar radiation in Yucatán Peninsula, Mexico

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ABSTRACT

This paper evaluates the accuracy and applicability of thirteen empirical global solar radiation models for warm subhumid regions that use daily meteorological data at six stations in Mexico (Yucatán Peninsula). One of the models investigated is a new empirical model developed for estimation of daily global solar radiation from a horizontal surface. The models were evaluated using root mean squared error (*RMSE*), mean bias error (*MBE*), mean percentage error (*MPE*), mean absolute percentage error (*MAPE*), mean absolute bias error (*MABE*) and coefficient of determination (R^2). Results show that the newly developed model performs best for all stations; models based on temperature, rainfall and air humidity performed better than models that used temperature data only. If only temperature data are available for estimation of global solar radiation, the Bristow and Campbell model had the best results. The new proposed model can be used in hydrologic and agricultural studies to estimate global solar radiation in warm subhumid regions when temperature, precipitation and humidity data are available.

1. Introduction

Daily global solar radiation (*H*) is an important variable for a wide range of applications in areas such as meteorology, climatology, hydrology, crop simulation models and estimation of crop evapotranspiration. *H* is the most important source of renewable energy on the planet. Reliable estimation of *H* is of fundamental importance for applications such as efficient determination of irrigation water needs and potential yield of crops [1–3].

Despite the recognized importance of solar radiation data, such data are directly recorded in only a few meteorological stations, especially in developing countries. Spatial coverage of meteorological stations that record solar radiation in many developing regions is inadequate and sparse. For example, in the Yucatán Peninsula in Mexico, the ratio of stations measuring *H* to those measuring temperature and precipitation is 1:160. Moreover, most of these stations have erroneous measurements or missing data due to the lack of maintenance or calibration of the solar radiation sensors [4,5].

Because of the lack of reliable solar radiation data, researchers have developed a large number of methods to estimate *H* from other available meteorological variables. These methods are based on empirical modeling related to variables such as temperature [6–11], sunshine duration [12–17], rainfall [18–22], cloudiness [23–25], elevation [26–28], humidity [2,21,24,29–31] and latitude [32,33]. Several studies have shown that the best performing models use sunshine duration data, followed by those utilizing cloudiness and then temperature data [34,35]. However, sunshine and cloudiness data are not available at most meteorological stations. Thus, if temperature-based models can be used with sufficient reliability, solar radiation estimates could be available at more locations provided the empirical parameters are calibrated for each specific location [2]. Also, several studies have demonstrated that adding rainfall data to temperature-based models results in increased performance [19,21,22,36].

In this paper, we analyzed the possibility of reliably estimating daily global solar radiation from available meteorological and geographical data. The objectives of this study were to evaluate the accuracy and applicability of eight empirical models that utilize only daily air temperature, four models that use available meteorological records such as precipitation, humidity and temperature, and finally, to develop a new model that utilizes temperature, rainfall and mean relative humidity for estimating *H* in Yucatán Peninsula, Mexico.

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Nomenclature

$a-g$	regression coefficients
H	daily global solar radiation (MJ m^{-2} day^{-1})
Ho	daily extraterrestrial radiation (MJ m^{-2} day^{-1})
T_{max}	daily maximum temperature (°C)
T_{min}	daily minimum temperature (°C)
T_{avg}	daily average temperature (°C)
$f(T_{avg})$	function based on the daily mean temperature (°C)
Dl	function correcting the effect of site differences in day length
P_a	atmospheric pressure (kPa)
P_o	standard pressure (kPa)
Z	site elevation (m)
T_{mean}	mean annual temperature (°C)
H_{day}	half-day length (radians)
$ICSKY$	corrected clear-sky solar irradiation
Is	clear-day solar radiation (MJ m^{-2} day^{-1})
T	transmissibility coefficient for the Mahmood–Hubbard model
LD	longest day of year (h)
DOY	day of year, starting 1 January
$e_s(T_{min})$	saturation vapor pressure at temperature T_{min} (kPa)
$e_s(T_{max})$	saturation vapor pressure at temperature T_{max} (kPa)
P	daily total rainfall (mm)
$j-1, j, j+1$	previous, current and next day
RT	transformed rainfall, using $P > 0$, $RT = 1$; $P = 0$, $RT = 0$
D	daily averaged saturation deficit (kPa)
RH	daily average relative humidity (%)
I_{sc}	solar constant (118.108 MJ m^{-2} day^{-1})
E_0	eccentricity correction factor of the Earth's orbit
ω_s	sunset hour angle (degrees)

Greek letters

ΔT	daily temperature difference (°C)
τ_{cf}	atmospheric transmittance of the cloud-free atmosphere
τ_o	transmittance of clean dry air
τ_a	transmittance affected by atmospheric aerosols and ozone
τ_v	transmittance affected by atmospheric water vapor
ϕ	site latitude (degrees)
Γ	day angle (radians)
δ	solar declination (degrees)
Π	number Pi

2. Materials and methods

2.1. Study area

The Yucatán Peninsula is located between 19°40′ and 21°37′N, and 87°30′ and 90°26′W, in east Mexico. The region covers an area of 142,210 km^2 and is surrounded by the Caribbean Sea and the Gulf of Mexico. The majority of the Yucatán Peninsula lies at 50 m below mean sea level. Daily global solar radiation data were provided by the National Meteorological Service (SMN) and the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) from six agro-meteorological stations spatially distributed across the Yucatán Peninsula. Table 1 shows the geographical location of the stations as well as the time periods for the data used to evaluate and establish the models.

The climate of the Yucatán Peninsula is warm subhumid (Aw) according to the Köppen system [37], with a rainy summer and dry winter. Annual mean temperature ranges from 25.8 to 26.3 °C and precipitation ranges from a minimum in the northwest of 600 mm/year to higher quantities toward the southeast (1400 mm/year).

2.2. Missing data analysis

Erroneous and missing readings exist in the database mainly due to instrument malfunctions. The following procedure was implemented to address missing or erroneous data [38,39]: (a) if the daily clearness indices were outside the range of 0.015–1, the data were considered erroneous and deleted; (b) missing or incorrect values for more than 5 days in a month were deleted completely; and (c) if less than five consecutive missing or incorrect values were found within one month, interpolation was used to fill in missing or replace incorrect values. Overall, deleted and missing data accounted for approximately 2.3% of the database and were replaced with estimated values by interpolation.

Table 1
Geographic information and time frame of the database from 6 stations in Yucatán Peninsula.

Station	Longitude (°W)	Latitude (°N)	Altitude (m)	Time period
Calakmul	−89.8925	18.3650	28	2003–2014
Campeche	−90.5072	19.8361	11	2001–2014
Celestún	−90.3831	20.8580	10	2000–2014
Efraín Hernández	−89.8925	18.1935	90	2006–2014
Mérida	−89.6517	20.9463	18	2000–2006
Tantakín	−89.0472	20.0303	30	2003–2011

2.3. Models for estimation of solar radiation

A number of methods that use empirical relationships to estimate the global solar radiation from commonly measured meteorological variables have been developed in the past. Eight of these empirical models that estimate H from temperature, three that use temperature and rainfall data to estimate H, and one that utilizes temperature, rainfall and relative humidity data to estimate H were selected for testing. Selection of the models considered availability of records, extensiveness of use, previous performance, simplicity, and the current state of model development. In addition, a new model was developed that requires rainfall data, temperature and relative humidity (Table 2).

2.3.1. Estimation of extraterrestrial radiation, Ho

Daily total extraterrestrial radiation (Ho) is included in several of the relationships investigated. Ho is calculated from a solar constant, an eccentricity correction factor of the Earth's orbit (E_0), site latitude (ϕ), day of the year (DOY), and solar angle (δ), using standard geometric procedures according to Eqs. (1)–(5) [2,40]:

$$Ho = (1/\pi) I_{sc} E_0 (\cos\phi\cos\delta\sin\omega_s + (\pi/180)\sin\phi\sin\delta\omega_s) \quad (1)$$

$$E_0 = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos(2\Gamma) + 0.000077\sin(2\Gamma) \quad (2)$$

$$\delta = (180/\pi)\cdot(0.006918 - 0.399912\cos\Gamma + 0.070257\sin\Gamma - 0.006758\cos 2\Gamma + 0.000907\sin 2\Gamma - 0.002697\cos 3\Gamma + 0.00148\sin 3\Gamma) \quad (3)$$

$$\Gamma = 2\pi(DOY - 1)/365 \quad (4)$$

$$\omega_s = \cos^{-1}[(-\sin\phi\sin\delta)/(\cos\phi\cos\delta)] \quad (5)$$