Estimating daily global solar radiation by day of the year in six cities located in the Yucatán Peninsula, Mexico.

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Highlights

Day of the year-based (DYB) models were used to predict daily solar radiation.

Day of the year is the sole input to the DYB models assessed.

A new Gaussian day of the year-based model is proposed.

The proposed model estimates daily solar radiation with acceptable accuracy.

ABSTRACT

Prediction of daily global solar radiation by using day of the year is particularly attractive because this parameter is not dependent on the input of meteorological parameters. In this study, four existing day of the year-based (DYB) models were evaluated and a new empirical DYB model was developed for estimating daily global solar radiation on a horizontal surface for six automatic weather stations of Yucatán Peninsula, Mexico. The performance of the models was assessed with 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). The results show that the new proposed Gaussian DYB model estimates daily solar radiation better than other DYB models. Furthermore, a seasonal analysis shows that the model has good performance in all seasons, including in the rainy season. The results also suggest that the new model can be useful for highly variable climate conditions.

Keywords: global solar radiation, day of year, empirical models, Mexico

1. Introduction

Solar energy is one of the most important renewable and inexhaustible energy resources. It is also one of the cleanest energy resources that does not compromise or add to global warming. Because of its abundance, solar energy can play a prominent role in our energy future and reduce dependency on fossil fuel. Mexico is in an ideal position for the application of solar technologies because of its favorable geographic location in the northern hemisphere between latitudes 14°32' and 32°43' (Riveros-Rosas et al., 2015). With an area of nearly 2 million square kilometers, México is one of the five most attractive countries in the world for investment in photovoltaic (PV) solar power projects (Alemán-Nava et al., 2014). Therefore, broader utilization of solar energy will contribute to the development of Mexico's renewable energy sector and reduction of greenhouse gas emissions (Hernández-Escobedo et al., 2015).

The enormous solar potential of the Mexican states along the Gulf of Mexico has been corroborated by Hernández-Escobedo et al. (2015). The highest values of radiation occur in the spring and summer in the northern and northwestern regions of Mexico. The Yucatán Peninsula in Mexico in particular has an enormous opportunity for the utilization of solar water heaters as the main fuel for cooking and heating water. Such applications would save energy by avoiding burning liquefied petroleum gas or natural gas (Rosas-Flores et al., 2016).

Good daily global radiation data are necessary for design and evaluation of solar technologies such as photovoltaic and thermal systems. Several maps and tables of solar radiation over Mexico have been published by different authors that provide monthly and annual averages of solar radiation. However, understanding daily variations of solar radiation is important for assessing the renewable energy produced by solar energy. Riveros-Rosas et al. (2015) analyzed the solar radiation database of the Mexican National Weather Service and evaluated the daily global solar radiation for 36 select ground stations and compared the data to satellite-derived data for Mexico from the National Renewable Energy Laboratory's (NREL) Climatological Solar Radiation model. He estimated an average daily irradiation of 20 MJ/m²/day for Mexico, but noted that obtaining more conclusive results requires a larger amount of reliable solarimetric data over Mexico (Riveros-Rosas et al., 2015).

Solar radiation data for a particular geographical location is important not only for the design of solar energy systems, but also for agricultural and biological research studies and architecture (Boukelia et al., 2014; El-Sebai et al., 2016). However, in many cases necessary solar radiation data are not readily available due to the cost and difficulty of maintenance and calibration of the measuring equipment (Hunt et al., 1998). In general, only a few meteorological stations measure solar radiation. In the Yucatán Peninsula, around 70 automatic weather stations record solar radiation, and approximately 85% of these stations have erroneous measurements or missing data due to the lack of maintenance or calibration of solar radiation sensors.

In the absence of reliable solar radiation data, it is necessary to develop methods to estimate solar radiation by using more readily available data (Almorox et al., 2011). Many models have been developed to estimate global solar radiation based on various meteorological and geographical parameters such as maximum and minimum air temperature, sunshine duration, cloud cover, relative humidity, vapor pressure and precipitation (Besharat et al., 2013; Li et al., 2010; Yao et al., 2014; Quej et al., 2016). In addition to predicting global solar radiation as accurately as possible, such empirical approaches should also have uncomplicated functional forms with limited and readily available inputs. Recently, some studies have been aimed at developing and establishing simple models to estimate global solar radiation without meteorological data using the day of the year as the sole independent parameter, hereinafter referred as day of the year-based (DYB) models (Khorasanizadeh et al., 2014).

Al-Salaymeh (2006) proposed four correlation formulas of DYB models to predict daily global solar radiation on horizontal surfaces of Amman City in Jordan, with the best results obtained from a sine wave model. Bulut and Büyükalaca (2007) developed a DYB model for simulating daily global solar radiation in Istanbul, Turkey by using long-term data with a sine wave formulation. The model was tested for 68 locations in Turkey and the results had good fit for the measured data. Kaplanis and Kaplani (2007) developed a cosine wave DYB model to estimate daily global solar radiation in six climate zones of Greece. They found that the model predicts values of daily global solar radiation for those climate zones with high accuracy, with correlation coefficients for all cases being higher than

0.996. Li et al. (2010) proposed a new DYB equation using a hybrid sine and cosine wave formula to estimate daily global solar radiation in China. The predictions from the new equation were compared with three existing DYB models. Statistical results indicated that the new method provides better estimation and has good adaptability to highly variable weather conditions. Results from this model were site-dependent with a mean correlation coefficient of 0.937. This model can be used for estimating daily values of global solar radiation with higher accuracy. Zang et al. (2012) developed a new hybrid sine and cosine wave DYB formulation that performed best for estimation of global solar radiation for six climatic zones of China. Khorasanizadeh and Mohammadi (2013) conducted a study to estimate daily global solar radiation using DYB models in four cities situated in sunny regions of Iran and found that the hybrid sine and cosine wave and the 4th order polynomial models had better performance. The authors conclude that because DYB models are not dependent on any meteorological data, they can be utilized to estimate daily global solar radiation in regions where meteorological data do not exist. Khorasanizadeh et al. (2014) conducted a study in Birjand, Iran to compare DYB models and empirical temperature and sunshine duration based equations in the estimation of solar radiation. In general, their results revealed that DYB models can be easily utilized for estimating solar radiation in the study area and its neighboring regions with similar climates. More recently, Kaplanis et al. (2016) proposed a universal DYB model for the prediction of daily solar global radiation. The model uses a two cosine function and is applicable in both the Northern and Southern Hemispheres. Results show that the model proposed by Kaplanis et al. (2016) performs well for most latitudes between 0º and 71º in the Northern and

Southern Hemispheres and for most longitudes around the globe.

There is limited availability of weather stations with daily solar radiation data in the Yucatán Peninsula, so the use of a DYB model may be useful for estimating daily solar radiation in this region. Thus, the main objective of this study is to examine four DYB models for their suitability for estimating daily solar radiation for the Yucatán Peninsula. If none of these models are suitable, a proposed new DYB model is also tested for generating daily global solar radiation data in six cities of the Yucatán Peninsula, México.

2. Data and Methodology

2.1. Study area

The study region is located in the east of Mexico in an area known as Yucatán Peninsula. Fig.1 shows the geographical location of the study region as well as the locations of the automatic weather stations used in this study. Daily total global solar radiation data from the six automatic weather stations distributed across the Yucatán Peninsula were provided by the Mexican National Meteorological Service (SMN; Servicio Meteorológico Nacional) and Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP) for use in this study. Table 1 shows the geographical locations of the stations.

The Yucatán Peninsula is located between 19°40’ and 21°37’ N and 87°30’ and 90°26’W and is surrounded by the Caribbean Sea and the Gulf of Mexico. The majority of the Yucatán Peninsula lies below an elevation of 50 m above mean sea level. The peninsula extends over an area of 142,210 km^2. According to the Köppen system (Peel et al., 2007), the climate of this region is tropical savanna (Aw). Annual mean temperature ranges from 25.8 to 26.3 °C and precipitation occurs in summer and autumn with a gradient from relatively dry in the northwest (600 mm/year) to more humid towards the southeast (1400 mm/year).

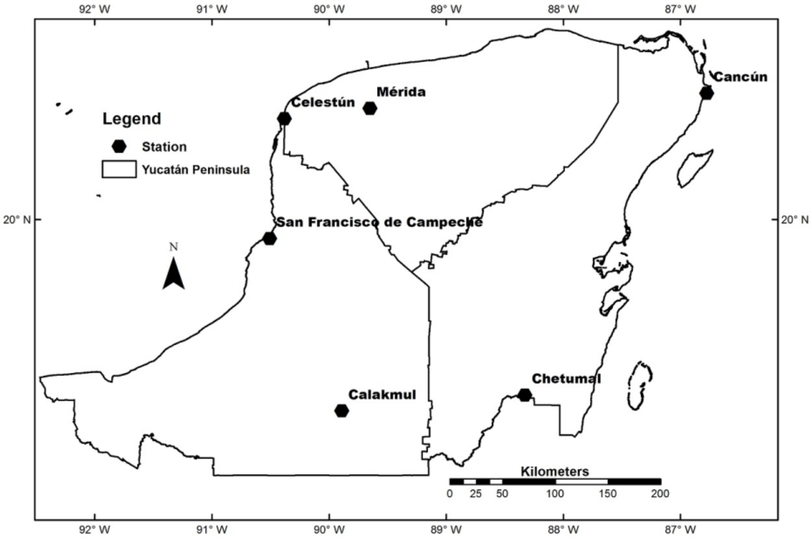

Fig.1. Distribution of the selected stations in the Yucatán Peninsula.

2.2 Missing data analysis

The database provided by the SMN and INIFAP was analyzed to find incorrect or missing values that were mainly associated with the malfunction of instruments. To overcome the problem of missing and erroneous data, the following procedure was implemented:

1. To find erroneous values of global solar radiation, the daily sky clearness index (K_T) was applied as an indicator of sky condition (i.e., degree of cloudiness). K_T is calculated as the ratio of measured daily global solar radiation intensity to the daily extraterrestrial solar radiation on a horizontal surface (Badescu, 2014). The upper and lower limits for K_T represent a clear sky and completely cloudy sky, respectively. Values of 0.015 and 1.00 as lower and upper thresholds of K_T, respectively, are recommended by Jian (2009) and Khorasanizadeh et al. (2013). For this reason, data were eliminated if the values of the daily sky clearness index were outside the range of $0.015 < K_T < 1.00$ (unitless).
2. If there were less than five consecutive missing or incorrect values in a month, interpolation was used to fill in missing values or replace incorrect values. If there were more than 5 consecutive days of missing or incorrect values in a month, data for the entire month were deleted.

An average daily global solar radiation was obtained for each day of the year from the total data series over all years, and all further computations were based on these average daily values.

2.3. Models for estimating daily solar radiation

Four existing and one proposed DYB model to predict daily solar radiation (*H*) on a horizontal surface are described below. Previous applications of the four existing models are described in Section 1 above (Al-Salaymeh, 2006; Bulut and Büyükalaca, 2007; Kaplanis and Kaplani, 2007; Li et al., 2010). Daily global solar radiation is a yearly quasi-periodic phenomenon due to seasonal effects. It is convenient to model daily values by the day of the year (n_{day}) (Li et al., 2010). Curve fitting, statistical analysis and determination of the regression coefficients of selected radiation models were performed with CurveExpert Professional 2.0 software.

2.3.1 Model (1)

Bulut and Büyükalaca (2007) presented a simple model using a sine wave formula to estimate global solar radiation (Eq. 1). The model was based on a trigonometric function that has only one independent parameter.

$$H = a + b \cdot \left| sin\left[\frac{\pi}{365} . (n_{day} + 5)\right]\right|^{1.5} \tag{1}$$

2.3.2 Model (2)

Kaplanis and Kaplani (2007) developed a cosine wave equation (Eq. 2) to estimate daily global solar radiation over the six climatic zones in Greece.

$$H = a + b \cdot cos\left(\frac{2\pi}{364} \cdot \ n_{day} + c\right) \tag{2}$$

2.3.3 Model (3)

Al-Salaymeh (2006) proposed a sine wave model (Eq. 3) to estimate daily global solar radiation in Amman, Jordan.

$$H = a + b \cdot \sin\left(\frac{2\pi}{c} \cdot \ n_{day} + d\right) \tag{3}$$

2.3.4 Model (4)

Li et al. (2010) proposed a sine and cosine wave equation (Eq. 4) for 79 meteorological stations across China. The model was applied by Zhang et al. (2012) and Khorasanizadeh and Mohammadi (2013).

$$H = a + b \cdot \ \sin\left(\frac{2\pi c}{365} n_{day} + d\right) + e \cdot cos\left(\frac{2\pi f}{365} n_{day} + g\right) \tag{4}$$

2.3.5 Model (5)

Al-Salaymeh (2006) used a single Gaussian function to predict daily global solar radiation in Amman city (Jordan). This function generates a graph characteristically symmetrical and bell-shaped, where its parameters define the position and shape of the curve. For the Yucatán Peninsula, the bell curve was not adjusted to the weather conditions during the rainy season. However, by making use of a sum of two Gaussian functions, the curve fit well (Fig. 2). Thus, a new DYB model based on a sum of two Gaussian correlation formulas (Eq. 5) is proposed to estimate daily global solar radiation on a horizontal surface. The model was developed using non-linear regression techniques.

$$H = a + b\,exp\left[-0.5\left(\frac{n_{day}-c}{d}\right)^2\right] + e\;exp\left[-0.5\left(\frac{n_{day}-f}{g}\right)^2\right] \tag{5}$$

where H is the daily global solar radiation on a horizontal surface [MJ/m^2·day]; n_{day} is the number of the day starting from January 1. For the 1st of January, n_{day}=1, and for 31st of December, n_{day}=365. a, b, c, d, e, f and g are empirical coefficients that should be determined for each site.

Model coefficients of Eqs. 1-5 were fit in each case by using nonlinear regression according to the Marquardt-Levenberg method in CurveExpert software (http://www.curveexpert.net/).

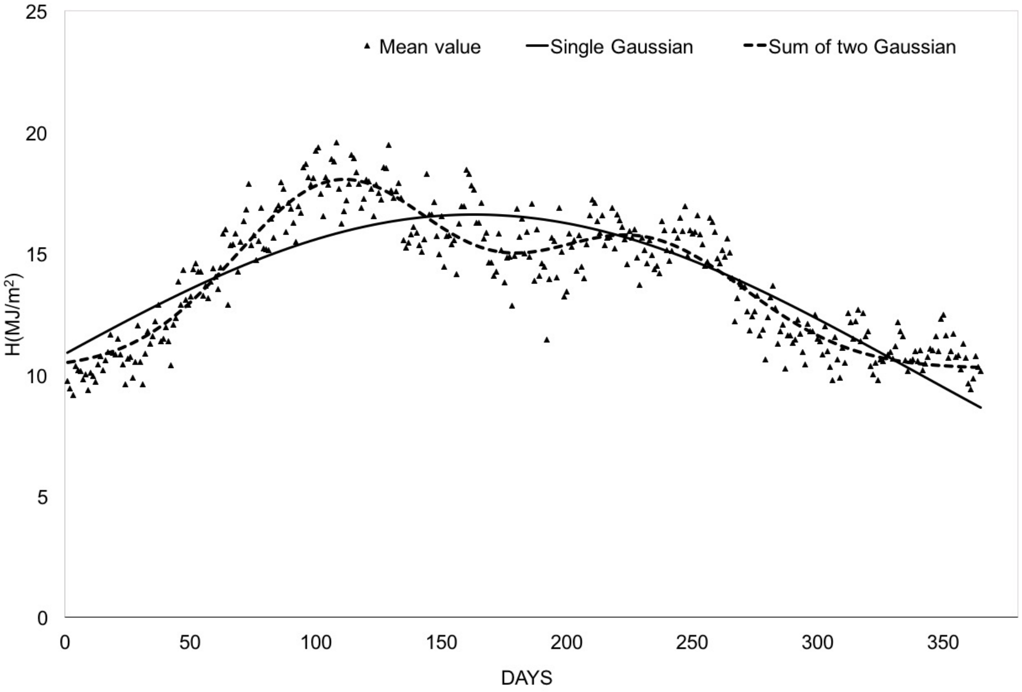

Fig. 2. Typical variation of daily global solar radiation in Yucatán Peninsula (triangles), and curves generated by the single Gaussian function and sum of two Gaussian correlation formulas.

Table 1

Geographical location of the meteorological stations.

Station name	Longitude (°W)	Latitude (°N)	Elevation (m)
Calakmul	-89.8925	18.365	28
Cancún	-86.7758	21.075	8
Celestún	-90.3831	20.858	10
Chetumal	-88.3278	18.5005	14

Mérida	-89.6517	20.9463	18
San Francisco de Campeche	-90.5072	19.8361	11

3. Performance evaluations

Model performance was evaluated with metrics that included **mean percentage error (MPE; Eq. 6), mean absolute percentage error (MAPE; Eq. 7), root mean squared error (RMSE; Eq. 8), mean absolute bias error (MABE; Eq. 9), mean bias error (MBE; Eq. 10), and coefficient of determination (R^2; Eq. 11). These performance metrics were calculated for each model for each automatic weather station.** These metrics are the most widely used by researchers to evaluate the performance of global solar radiation models (Teke et al., 2015).

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_c - H_m}{H_m}\right) x\ 100 \qquad \% \qquad (6)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{H_c - H_m}{H_m}\right| x\ 100 \qquad \% \qquad (7)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_c - H_m)^2} \qquad MJm^{-2}day^{-1} \qquad (8)$$

$$MABE = \frac{1}{n}\sum_{i=1}^{n}|H_c - H_m| \qquad \text{MJm}^{-2}\text{day}^{-1} \qquad (9)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_c - H_m) \qquad \text{MJm}^{-2}\text{day}^{-1} \qquad (10)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(H_c - H_{c,avg}\right)\left(H_m - H_{m,avg}\right)\right]^2}{\sum_{i=1}^{n}\left(H_c - H_{c,avg}\right)^2 \sum_{i=1}^{n}\left(H_m - H_{m,avg}\right)^2} \qquad \text{unitless.} \qquad (11)$$

where n is number of the readings, H_m is measured solar radiation, $H_{m,avg}$ is average of the measured solar radiation values, H_c is calculated solar radiation, and $H_{c,avg}$ is the average of the calculated solar radiation values.

Statistical errors and coefficient of determination were also calculated to determine whether model results significantly deviated from the observed data. Smaller values of MPE, MAPE, RMSE, MABE, and MBE indicate better approximations of observed data. An R^2 value of 1 indicates perfect representation of trends in observed data by calculated values.

4. Results and discussion

4.1. Overall model performance

Table 2 shows the performance metrics of the different models in each location. As can be seen, among the DYB models, Model 5 had the best performance for all locations according to overall performance metrics (i.e., average performance metrics for all locations: R^2=0.868, RMSE=1.191 MJ m^{-2} day^{-1}, MBE=0.006 MJ m^{-2} day^{-1}, MABE=0.928 MJ m^{-2} day^{-1}, MPE=-0.385 % and MAPE=5.09 %). Model 4 had the second best overall performance (R^2=0.850, RMSE=1.273 MJ m^{-2} day^{-1}, MBE=0.005 MJ m^{-2} day^{-1}, MABE=0.982 MJ m^{-2} day^{-1}, MPE=-0.429 % and MAPE=5.377 %). Models 1 and 2 had the worst performance when assessed by the statistical indices. In terms of R^2 and RMSE indices, the locations with the best and worst values are San Francisco de Campeche (0.892 and 1.036 MJ m^{-2} day^{-1}, respectively) and Mérida (0.831- 1.449 MJ m^{-2} day^{-1}, respectively). The nonlinear regression coefficients of the models are presented in Table 3.

Table 2

Performance metrics of the five empirical models in six selected cities in Yucatán Peninsula, México. The model with the best performance for each location is shown in italics.

Location	**Model**	**R^2**	**RMSE** (MJm^{-2}d^{-1})	**MBE** (MJm^{-2}d^{-1})	**MABE** (MJm^{-2}d^{-1})	**MPE** (%)	**MAPE** (%)

Calakmul	1	0.633	1.607	0.000	1.274	-1.293	9.019
	2	0.713	1.423	0.000	1.140	-1.066	8.196
	3	0.700	1.454	0.012	1.194	-0.932	8.789
	4	0.856	1.007	0.000	0.802	-0.511	5.861
	5	*0.863*	*0.984*	*0.000*	*0.777*	*-0.509*	*5.660*
Cancún	1	0.778	1.757	0.038	1.359	-0.628	7.150
	2	0.795	2.051	-1.144	1.573	-7.286	9.174
	3	0.824	1.560	0.006	1.225	-0.600	6.605
	4	0.843	1.475	0.034	1.099	-0.335	5.822
	5	*0.880*	*1.292*	*0.000*	*1.003*	*-0.469*	*5.366*
Celestún	1	0.697	1.816	0.000	1.462	-0.798	7.074
	2	0.772	1.578	0.000	1.278	-0.642	6.319
	3	0.802	1.470	0.003	1.184	-0.453	5.855
	4	0.869	1.195	0.000	0.932	-0.335	4.626
	5	*0.884*	*1.122*	*0.000*	*0.877*	*-0.308*	*4.345*
Chetumal	1	0.553	2.197	0.000	1.772	-1.214	8.874
	2	0.682	1.853	0.000	1.502	-0.906	7.685
	3	0.703	1.793	0.009	1.450	-0.699	7.387
	4	0.823	1.383	0.000	1.094	-0.476	5.643
	5	*0.849*	*1.278*	*0.000*	*1.005*	*-0.426*	*5.165*
Mérida	1	0.714	1.946	0.000	1.511	-1.070	8.011
	2	0.767	1.756	0.000	1.339	-0.918	7.137
	3	0.784	1.693	0.011	1.301	-0.652	6.965
	4	0.820	1.545	0.000	1.178	-0.644	6.264
	5	*0.831*	*1.499*	*0.038*	*1.159*	*-0.350*	*6.167*
San Francisco de Campeche	1	0.761	1.573	0.037	1.212	-0.188	5.978
	2	0.785	1.459	0.000	1.148	-0.601	5.866
	3	0.827	1.310	0.001	1.001	-0.412	5.096
	4	0.892	1.036	0.000	0.785	-0.274	4.049
	5	*0.904*	*0.975*	*0.000*	*0.751*	*-0.250*	*3.857*

Table 3

Regression coefficients for the selected models in six cities of Yucatán Peninsula, México.

Location	Model	a	b	c	d	e	f	g
Calakmul	1	10.565	6.235					
	2	14.041	3.167	-15.217				
	3	16.620	163.039	-176.730				

	4	14.442	1.632	-2.206	42.746	-2.872	1.137	0.173
	5	10.269	7.633	109.048	41.191	5.355	226.989	43.932
Cancún	1	13.766	9.867					
	2	20.450	4.370	-9.080				
	3	23.290	166.670	166.260				
	4	2.229	27.692	0.258	12.199	-20.202	-0.436	9.684
	5	13.344	8.625	97.143	40.092	9.407	211.286	55.796
Celestún	1	16.207	8.133					
	2	20.743	4.097	3.615				
	3	24.108	160.381	189.166				
	4	20.838	1.505	2.042	-1.396	4.008	1.022	3.569
	5	15.321	8.901	99.822	43.203	7.515	217.625	54.421
Chetumal	1	15.903	7.217					
	2	19.927	3.839	-2.538				
	3	22.990	154.560	196.260				
	4	20.108	-1.827	2.098	-4.658	-3.650	1.040	6.811
	5	15.158	9.502	101.605	41.624	6.601	222.054	45.593
Mérida	1	14.237	9.072					
	2	19.296	4.503	-9.015				
	3	23.040	162.540	172.197				
	4	19.230	-1.081	2.131	-4.781	-4.403	0.972	6.786
	5	13.719	8.396	99.369	42.394	8.296	210.814	55.348
San Francisco de Campeche	1	15.040	9.050					
	2	20.123	3.939	-9.050				
	3	23.431	165.999	186.465				
	4	20.351	-1.674	1.990	-4.439	-3.908	1.075	6.456
	5	14.533	8.421	100.561	43.291	7.720	220.373	58.924

Fig. 3 shows the long term daily measured global solar radiation data, the measured mean daily values and Model 5 predictions for the six locations on the Yucatán Peninsula. It is evident that the deviation between the measured and calculated values is very small. As expected, the maximum global solar radiation occurs in all cases in months with maximum daylight hours (i.e., May, June, July and August). In contrast, solar radiation is lower in December and January. During winter, the daily global solar radiation reaches the Earth surface at a greater angle, which significantly reduces the energy per unit area and the energy distribution on a horizontal surface. During summer months, the sun’s path at noon is near the zenith and thus, the solar radiation is greater.

Due to the seasonal variation of the daily global solar radiation throughout the year, the largest amounts of solar radiation reach most of the Yucatán Peninsula from April to September, with maximum values in April and August. The daily global solar radiation in June is lower compared to that in April and May, likely due to the rainy season that occurs between June and October. During the rainy season, the global solar radiation is strongly modulated by clouds and absorption of the atmospheric water vapor (Galindo et al., 1991; Stephens et al., 2012).

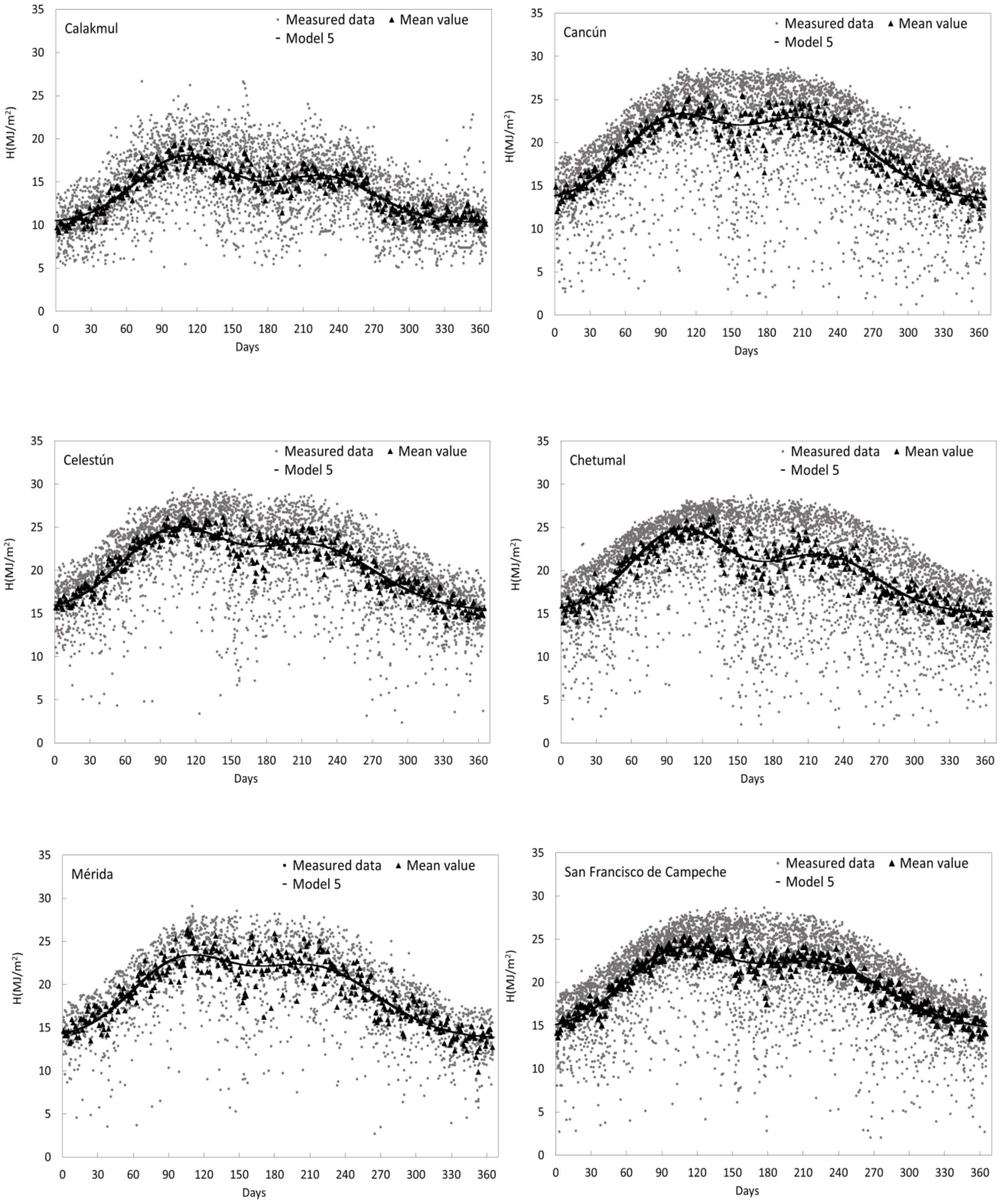

Fig. 3. Comparison between daily measured global solar radiation data (measured and daily mean of long-term measured data) and values estimated by proposed Model 5 for six locations on the Yucatán Peninsula.

4.2. Seasonal analysis of Model 5

To investigate the performance of the best-performing model (Model 5) in different seasons, the standard meteorological season scheme of Trenberth (1983) was applied (i.e., winter is defined as December, January, and February; spring is March, April, and May; summer is June, July and August; and autumn is September, October and November). Trenberth (1983) analyzed the first harmonic of solar radiation at the top of the atmosphere and its relationship to surface temperature to show that use of the standard meteorological season scheme is more appropriate than the astronomical season scheme over the continental regions of the Northern Hemisphere. The RMSE, MBE and MAPE indicators are used to assess statistical model errors during seasons. These statistical errors are presented in Table 4. In general, the model performed best in the winter season, with RMSE values that range between 0.795 and 1.113 $MJm^{-2}day^{-1}$. Model performance was lowest during summer with RMSE values ranging between 1.154 and 1.944 $MJm^{-2}day^{-1}$. This low performance is likely related to low values of solar radiation caused by precipitation events during the summer season. Reduced model performance is also observed during the autumn season, mainly during the months of September and October. Moreover, the model tends to slightly overestimate values of solar radiation throughout autumn with a range in MBE of 1.624 to 3.173 $MJm^{-2}day^{-1}$. The MAPE measures the size of the error in percentage terms, with preferred values between ±10% (Li et al., 2010; Khorasanizadeh and Mohammadi.,2013). In general, seasonal MAPE values are in the desired range for all locations. During the summer and autumn, the MAPE values are slightly larger than during the spring. In general, Model 5 estimates solar radiation with good performance, but performance varies by season.

Table 4

RMSE, MBE and MAPE values obtained with Model 5 during the standard meteorological season.

Location	Winter	Spring	Summer	Autumn
Calakmul				
RMSE ($MJm^{-2}day^{-1}$)	0.795	0.984	1.154	0.958
MBE ($MJm^{-2}day^{-1}$)	0.032	0.064	-0.002	1.667
MAPE (%)	5.610	4.886	5.854	6.194
Cancún				
RMSE ($MJm^{-2}day^{-1}$)	0.948	1.153	1.683	1.264
MBE ($MJm^{-2}day^{-1}$)	-0.001	-0.047	0.030	2.731
MAPE (%)	5.110	4.111	6.055	6.193
Celestún				
RMSE ($MJm^{-2}day^{-1}$)	0.867	0.888	1.457	1.168
MBE ($MJm^{-2}day^{-1}$)	0.022	-0.092	0.077	2.336
MAPE (%)	4.145	2.889	5.247	5.102
Chetumal				
RMSE ($MJm^{-2}day^{-1}$)	0.994	1.270	1.609	1.282
MBE ($MJm^{-2}day^{-1}$)	0.196	0.194	0.167	2.857
MAPE (%)	4.919	4.246	6.153	5.989
Mérida				
RMSE ($MJm^{-2}day^{-1}$)	1.113	1.363	1.944	1.426
MBE ($MJm^{-2}day^{-1}$)	0.054	-0.025	0.023	3.173
MAPE (%)	5.934	5.001	6.974	6.586
San Francisco de Campeche				
RMSE ($MJm^{-2}day^{-1}$)	0.872	0.792	1.236	0.938
MBE ($MJm^{-2}day^{-1}$)	0.016	-0.069	0.037	1.624
MAPE (%)	4.541	2.849	4.277	3.776

5. Conclusions

In Yucatán Peninsula, many areas of agricultural importance have no solar radiation records, and the lack of solar radiation data restricts the design of photovoltaic and irrigation systems, both of which are fundamental aspects for economic development and sustainable use of natural resources. Recently, Quej et al. (2016) calibrated 13 empirical models to estimate daily solar radiation in six sites of Yucatán Peninsula, However, these models require several input parameters such as minimum air temperature, maximum air temperature, precipitation and relative humidity. There are many regions in the Yucatán Peninsula where there are no weather stations, so such input parameters are not available. In this context, the use of DYB models to estimate solar radiation provides an effective alternative to estimate daily solar radiation. In this study, four DYB models from the literature and a newly developed model that estimate daily global solar radiation over the Yucatán Peninsula were evaluated. The overall result of this investigation indicated that the new model, in which a sum of two Gaussian correlation formulas was used, performed best for six locations on the Yucatán Peninsula. Moreover, according to seasonal analysis, despite the existence of rain events or persistent cloud cover during the summer and autumn, daily solar radiation was estimated with acceptable accuracy with only day of the year as an input parameter.

The newly developed model is very simple, effective and reliable, and does not require any meteorological data. Hence, this proposed model can be utilized to estimate daily horizontal global solar radiation throughout the year in areas where the solar radiation data and other meteorological data are not readily available. This model can therefore make a considerable contribution to solar radiation-related scientific studies and engineering applications in Yucatán Peninsula, Mexico, and similar approaches may be appropriate in other areas worldwide. One of the main disadvantages of these models is that they are highly site-dependent, so the equation must be calibrated if used in another region. Finally, future studies could be focused on developing a spatial database of daily global solar radiation with the proposed model.

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Captions for Tables:

Table 1. Geographical location of the meteorological stations.

Table 2. Performance metrics of the five empirical models in six selected cities in Yucatán Peninsula, México. The model with the best performance for each location is shown in italics.

Table 3. Regression coefficients for the selected models in six cities of Yucatán Peninsula, México.

Table 4. RMSE, MBE and MAPE values obtained with Model 5 during the standard meteorological season.