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New mathematical approach to determine solar radiation for the southwestern coastline of Pakistan

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Abstract. Solar Energy is the energy of solar radiation carried by them in the form of heat and light. It can be converted into electricity. Solar potential depends on the site's atmosphere; the solar energy distribution depends on many factors, e.g., turbidity, cloud types, pollution levels, solar altitude, etc. We estimated solar radiation with the help of the Ashrae clear-sky model for three locations in Pakistan, namely Pasni, Gwadar, and Jiwani. As these locations are close to each other as compared to the distance between the sun and earth, therefore a slight change of latitude and longitude does not make any difference in the calculation of direct beam solar radiation (BSR), diffuse solar radiation (DSR), and global solar radiation (GSR). A modified formula for declination angle is also developed and presented. We also created two different models for Ashrae constants. The values of these constants are compared with the standard Ashrae Model. A good agreement is observed when we used these constants to calculate BSR, DSR, GSR, the Root mean square error (RMSE), Mean Absolute error (MABE), Mean Absolute percent error (MAPE), and chi-square (χ^2) values are in acceptance range, indicating the validity of the models.

Keywords: Ashrae constants; Ashrae model; global; hourly and diffused solar radiation; mathematical modeling; solar radiation

1. Introduction

Solar radiation analysis is essential for professionals and scientists working as architects, agriculturists, hydrologists, and solar engineers to know the exact knowledge of solar availability in different places Aras *et al*. (2006). In 1992, Abdalla and Al-Madani (1992) estimated solar radiation by a third-degree polynomial by taking a ratio of Hourly and Beam radiation. Environmental scientists highlighted the issue of global warming in the last three decades. Beside Global warming, the world is confronted with the problem of rapid depletion of fossil fuels. Both issues can be addressed if green energy sources are used as an alternative to conventional energy sources. Green energy sources include wind, biomass, tidal, hydropower, and solar power. Solar radiations are one of the essential components of a living organism; these are the heat and light radiations received by the earth from the sun. These radiations fall directly on the ground (direct solar beam radiations) and are received by the earth after reflection from clouds, pollutants, air

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molecules, water vapor, etc.; these are known as diffuse solar radiations. The sum of these two solar radiations is known as Global Solar Radiation Mousavi Maleki *et al*. (2017). People have been using solar photovoltaic technology to generate electricity in many places. The precise knowledge of the availability and variability of solar flux is needed in the complete utilization of the solar potential for generating electricity. Estimation of solar radiation methods has a history of more than 100 years. Various mathematical models were developed to estimate solar radiation. The most famous and conventional model is the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Model.

This model proposed three equations to calculate direct, diffuse, and global solar radiation, discussed in the discussion section. These equations employ three constants (Ashrae constants, A, B, and C); each has a set of 12 values for each month of a year. Ashrae clear sky model is a milestone in the history of solar radiation studies. Scientists have contributed to the understanding and utilizing solar radiation; some recent contributions are highlighted here. Fariba Basharat and her team developed a model for computing the average monthly daily radiation GSR on a horizontal surface for the city Yazd of Iran Besharat *et al*. (2013). Mao-Fen Li *et al*. developed a general model to calculate solar radiations with the help of environmental data from 63 sites. The models were classified as temperature and sunshine-based models. They used a k-means clustering algorithm to test the models and identified five solar radiation zones. They employed various statistical errors to check the model's validity Li *et al*. (2013). Milan Despotovic evaluated the performances of 101 models for solar radiation determination; they introduced global performance indicators to assess the performance of models Despotovic *et al*. (2015). Kazim Kaba employed a deep learning method to estimate solar radiation in 30 locations in Turkey. They used available data of environmental variables and extraterrestrial radiations for 34 stations. Their study used a six-year dataset to train and test the model Kaba *et al*. (2018). Physicist Colienne Demain evaluated the performance of 14 models which estimate solar radiation on tilted surfaces. The data was recorded Royal Meteorological Institute of Belgium; none of the models correctly estimates solar radiations for diverse atmospheric conditions and altitudes. They developed a model using the coupling of three models for various sky conditions and found that the same is good for shorter input data time intervals Demain *et al*. (2013). Badia Amrouche and Xavier Le Pivert presented a method to forecast daily global radiation using neural networks and spatial modeling. The methodology was tested for two locations in France; test results show that the methodology estimated global solar radiation with satisfactory accuracy Amrouche and Le Pivert (2014). Lunch Wang and his team predicted solar radiations using three methods: neural network and Regression analysis. They suggested improving the Bristow-Campbell solar radiation model based on factors influencing solar radiations Wang *et al*. (2016). Gasser E. Hassan *et al*. presented seventeen temperature-based models for estimating global solar radiations. They compared the results of these models with three models proposed by Annandale, Allen, and Goodin. They used 20 years of measured data from the case study location to develop the model and used ten different locations in Egypt for testing purposes. They found that the suggested models perform better than accurate sunshine-based models Hassan *et al*. (2016). Abdelaziz Rabehi compared different models for estimations of solar radiation; they assessed multi-layer perceptron and boosted the decision tree. They developed a model by combining these models with linear regression to estimate daily solar radiation, and they concluded, based on statistical errors, that the multi-layer model performs better Rabehi *et al*. (2020). Ümit Ağbulut predicted global solar radiation for four provinces of Turkey by employing four machine learning algorithms, namely, Artificial Neural Network (ANN), support vector machine, deep learning, kernel, and nearest neighbor. The model used input parameters cloud cover, daily minimum and maximum temperature, extraterrestrial radiation, and day lengths. They concluded that ANN is the best for predicting global solar radiation Ağbulut *et al*. (2021). Yu Feng and his team developed a machine learning model (particle swarm optimization and extreme learning machine) and predicted daily global solar radiation. They compared the results of global solar radiation with corresponding results obtained by five other machine learning models. They found that the proposed model estimates accurate values of solar radiation Feng *et al*. (2020). Rahul G. Makeda developed models to estimate global solar radiation with temperature, latitude, longitude, relative humidity, and sunshine hour as input parameters. They found that the five variables model was the best Makade *et al*. (2020). Aondoyila Kuhea and his mates developed a neural network model to estimate the global solar radiation of one of the cities of Nigeria. Their model uses a feed-forward back-propagation neural network, generalized regression neural network, and radial basis network function. They concluded that the model is the best for estimating global solar radiation at locations where no recording instrument is available Kuhe *et al*. (2021). In a Ghana study, solar radiation was measured using photovoltaic panels mounted on tilted surface, and the air temperature and sunshine were measured Quansah *et al*. (2014). Recently, in three states of Pakistan i.e., Sindh, Punjab, and Baluchistan about 25 meteorological centers were made to estimate solar radiation by various models for example Sunshine hour-based model Temperature based model, geographical-parameter based model cloud-based model and Meteorological parameters-based model this theory was investigated through photovoltaic meters but not checked through scientifically proven methods. In a piece of work Khalid and Zakaria (2016) revealed that, calculations of solar radiation using above mentioned model have good results for Baluchistan than Sindh and Punjab. Forecasting efficiency of the said model was estimated by mean predicated errors and by their inequality coefficient. Result also estimated for the accurate ways to estimate solar radiation in Pakistan by Geographical and Meteorological parameter-based model. A similar research was carried out in Erzurum, Turkey by Bakirci (2009) where the results for daily total solar radiation were calculated by integral of hourly distribution, the validity of the model was checked through mean bias error, t-statistics, and root means square error methods. Parishwad *et al*. (1997) A study concluded that an exponential (growth) curve could be fitted exactly to the ASHRAE Model to estimate hourly radiation because they were getting less diffused radiation. It increased beam radiations when they tried calculating solar radiations for 06 cities of Central India Jamil and Khan (2014). Their article estimated solar radiation for Agra on a clear day when cloudiness Means biased error mean error, and the t-statistics method to analyze the model's performance. The result has validated the ASHRAE clear sky model to calculate hourly radiation in Aligarh. The majority of Pakistan's coastline is in Baluchistan State; this region was part of Oman and handed over to Pakistan in 1949; it mainly has three seaports Gevini, Pasni, and Gwadar. this part has become of international importance after the announcement of CPEC (China Pakistan Economic corridor). This one road, one belt project will bring this country a 57 billion dollar investment. Out of Pakistan's 1050 km long coastline, 770 KM is of Baluchistan Pakistan (2016). Moreover, this southwestern coastline is enriched with tourist sites, beautiful beaches, and Mangroves forests. There are 7340 hectares of these forests. Many migratory birds come here from Northern Hemisphere for recreation and survival; it's an important corridor for breeding purposes for the endangered green turtle Khattak (2016).

Fig. 1 Location of southwestern Coastline of Pakistan (Jiwani, Gwadar, and Pasni)

2. Study area

That study area lies in South Asia, mainly the South part of the said region. This area is already facing problems related to water shortage, scarcity of Energy demands, and Environment pollutants Mansoor *et al*. (). But the study by Urooj and Ahmad (2017) showed that there is a lot of potentials to produce solar and wind energy in that region. The coastline of Pakistan is the central zone of this part; it is spread over 1050 km and is divided into two portions, Sindh state, and Baluchistan state. Baluchistan's coastal belt is potentially essential due to its newly constructed ports under China Pakistan Economic Corridor (CPEC). It is situated in the southwestern part of the country. Its seaward coastline is on the Arabian sea and spreads over 770 km. This region has an average annual temperature of 26.7°C and a mean rainfall of 220 mm; the average humidity is 67% Lashari and Khushk (2007). This region observes two summer seasons April, May, and September, October. From 1947 to 2005, a 4.7°C annual temperature increase was observed in this zone Sajjad *et al*. (2009).

Three sites in the Baluchistan province of Pakistan are considered in this study. All the sites are situated along the Arabian sea. As shown in Fig. 1, the latitudes and longitudes of the three locations are not much different. Therefore, all three sites are expected to have the same values of solar radiations, BSR, DSR, and GSR. Pasni is situated near the Makran coast. It is a medium-sized fishing port, Jiwani is located along the Gulf of Oman, and Gwadar is between Pasni and Jiwani. Gwadar is 59 kilometers from Jiwani, and the distance between Pasni and Gwadar is 116 kilometers. All three cities are in the Gwadar district and are situated in or near the subtropical desert biome; they have a hot arid climate.

3. Results and discussion

Three types of solar radiation are essential, direct or solar beam radiation (BSR), diffuse solar radiation (DSR), and global solar radiation (GSR). Direct solar radiation or hourly solar beam radiation is the radiation measured in the direction of solar radiation on a horizontal surface. Diffuse solar radiation is radiation that falls on earth after diffraction or remission by various atoms and molecules in the air, clouds, dust, etc. Global solar radiation is obtained by the sum of diffuse and direct solar radiation. The solar radiation received by the earth depends on atmospheric conditions and cloudiness. The ASHRAE equations calculate direct, diffuse, and global hourly solar radiation I_{bn}, I_d, and I, respectively.

$$\mathbf{I = I_{bn}cos\theta_z + I_d} \tag{1}$$

$$\mathbf{I_{bn} = Ae^{(-B/cos\theta_z)}} \tag{2}$$

$$\mathbf{I_d = CI_{bn}} \tag{3}$$

3.1 Ashrae constants

Direct or solar beam radiation can calculate global and diffuse radiations. Ashrae constants A, B, and C are apparent solar radiation constant, atmospheric extinction coefficient, and diffuse sky factor. The constant A has a power density dimension, and the constants B and C are dimensionless. These constants have different constants values for other months. The Ashrae constant 'C' measures the ratio of diffuse and direct solar beam radiations. The solar radiation is measured in the unit of solar beam intensity (W/m^2). The ASHRAE clear-sky model deals with the calculations of hourly solar radiation. The model helps in calculating BSR and DSR. Ashrae tabulated three sets of 12 values (one for each month from January to December) for each of the three constants A, B, and C. The variation in these constants' values reflects that humidity and turbidity vary throughout the year. The model was developed for a typical atmosphere with a dust particles density of 200 particles/cm^3 with a known ozone concentration.

The main objective of this study was to develop mathematical models to calculate these constants. One of the models (sine functions model) is based on trigonometric function and the second model (piecewise functions) gives these constants a polynomial of month number.

3.2 Model I

In this model, all three Ashrae constants (A, B, and C) are expressed as sine functions of month number (n); these constants are given in Eqs. (4)-(6). Table 1 compares Ashrae constants with the corresponding calculated constant by the method I. The difference in A values is less than one percent, the difference in B values is less than three percent, whereas the difference in C values is slightly oversized (7%). The method I give discounts closer to values given by Ashrae's clear sky model. To provide a visual comparison, in Figs. 2-4 calculated values of A, B, and C are plotted with the values of the Ashrae clear sky model.

$$\mathbf{A = 1160 + 76 * Sin(-0.54 * n + 64.71)} \tag{4}$$

$$\mathbf{B = 0.172 + 0.034 * Sin(0.54 * n - 1.98)} \tag{5}$$

$$\mathbf{C = 0.099 + 0.042 * Sin(0.62 * n - 2.44)} \tag{6}$$

3.3 Model II

In this model, piecewise functions for all three Ashrae constants (A, B, and C) are given as a function of month number (n); these functions are provided in Eqs. (7)-(9). Each function of A, B,

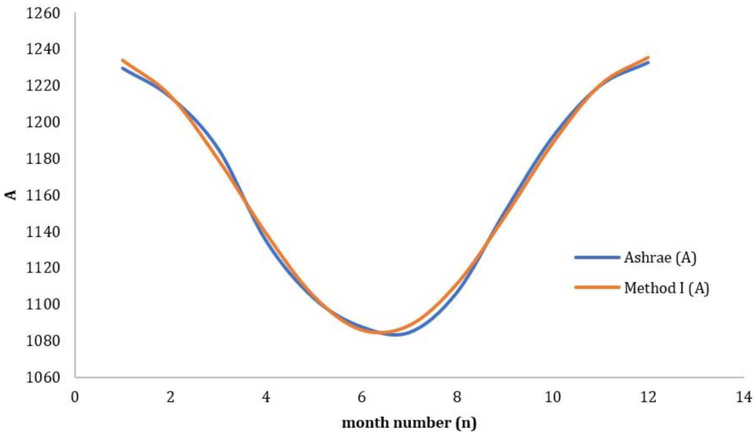


Fig. 2 Comparison of Ashrae constant A with Model I

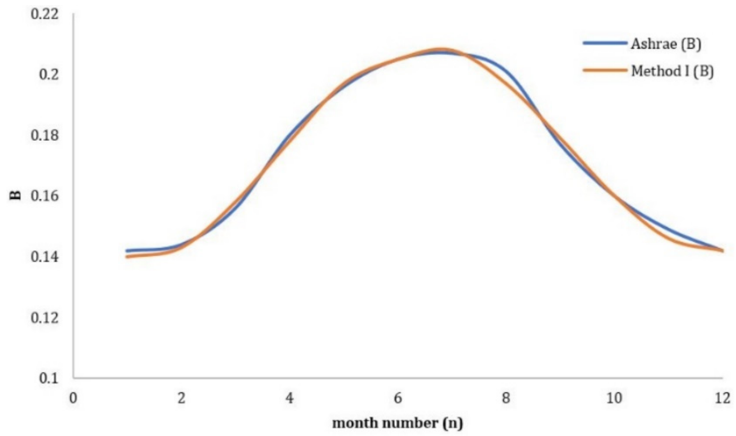


Fig. 3 Comparison of Ashrae constant B with Model I

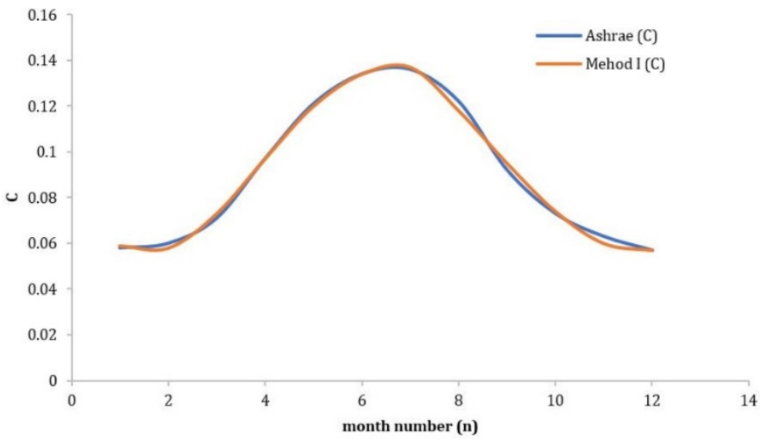


Fig. 4 Comparison of Ashrae constant C with Model I

Table 1 Ashrae constants A, B, and C by Ashrae clear sky and new models

Month #	A			B			C		
	Ashrae	**Model I**	**Model II**	**Ashrae**	**Model I**	**Model II**	**Ashrae**	**Model I**	**Model II**
1	1229.475	1228.875	1233.952	0.142	0.140	0.138	0.058	0.059	0.058
2	1213.713	1216.265	1216.265	0.144	0.143	0.145	0.060	0.058	0.060
3	1185.340	1181.137	1181.137	0.156	0.158	0.160	0.071	0.073	0.076
4	1134.900	1138.203	1138.203	0.180	0.178	0.178	0.097	0.097	0.101
5	1103.375	1102.174	1102.174	0.196	0.197	0.194	0.121	0.120	0.125
6	1087.613	1087.763	1087.763	0.205	0.205	0.204	0.134	0.134	0.139
7	1084.460	1083.698	1083.698	0.207	0.208	0.205	0.136	0.137	0.139
8	1106.528	1109.153	1109.153	0.201	0.197	0.196	0.122	0.118	0.123
9	1150.663	1148.794	1148.794	0.177	0.179	0.181	0.092	0.095	0.099
10	1191.645	1190.536	1190.536	0.160	0.160	0.163	0.073	0.074	0.075
11	1220.018	1222.295	1222.295	0.149	0.146	0.147	0.063	0.060	0.059
12	1232.628	1231.988	1231.988	0.142	0.142	0.139	0.057	0.057	0.059

and C has two pieces; the first one is for the first six months ($1 \leq n \leq 6$), and the second one is for the next six months ($7 \leq n \leq 12$). Table 1 compares Ashrae constants with the corresponding calculated constant by method II. The difference is that A and C values are less than one percent, and B values are less than three percent. The values of constants A, B, and C are in good agreement with the corresponding constants of the Ashrae clear sky model. Though each model finds acceptable values of the constants, method I give relatively better values in Figs. 5-7 calculated values, by model II, together with the Ashrae clear model values, are plotted. Figs. 5-7 also show that the calculated values are close to the values of the Ashrae clear model.

$$\mathbf{A} = \begin{cases} \mathbf{1204.254 + 48.139714n - 25.971143n^2 + 2.452n^3} & \mathbf{1 \leq n \leq 6} \\ \mathbf{2317.80338 - 465.62387n + 55.430262n^2 - 2.014055n^3} & \mathbf{7 \leq n \leq 12} \end{cases} \tag{7}$$

$$\mathbf{B} = \begin{cases} \mathbf{0.16333 - 0.03479n + 0.015008n^2 - 0.0013426n^3} & \mathbf{1 \leq n \leq 6} \\ \mathbf{-0.42077 + 0.233065n + -0.027397n^2 + 0.00099n^3} & \mathbf{7 \leq n \leq 12} \end{cases} \tag{8}$$

$$\mathbf{C} = \begin{cases} \mathbf{0.084333 - 0.0408677n + 0.016591n^2 - 0.0013982n^3} & \mathbf{1 \leq n \leq 6} \\ \mathbf{-0.26642 + 0.173657n - 0.0226627n^2 + 0.00087n^3} & \mathbf{7 \leq n \leq 12} \end{cases} \tag{9}$$

The calculation of BSR requires the values of $\cos\theta_z$, which are found with the help of day angle, latitude, and declination angle. The declination angle δ was defined by Spencer (1971) and is given by the following equation.

$$\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma)(180/\pi) \tag{10}$$

where Γ is the angle of corresponding day in radians, two other formulas which are commonly used are given in Iqbal (2012) and Cooper (1969).

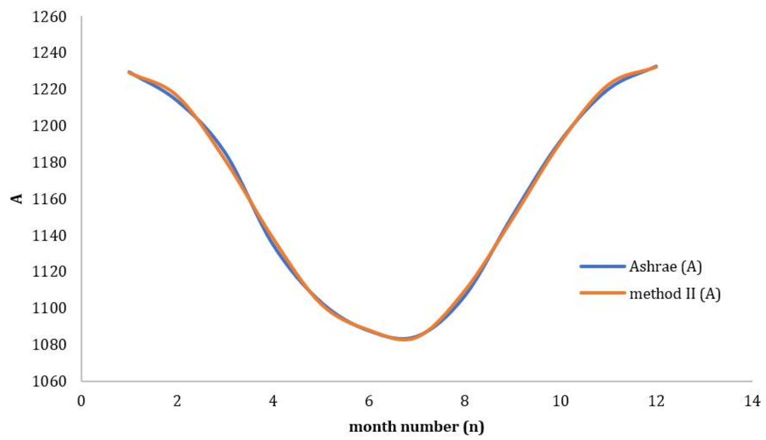


Fig. 5 Comparison of Ashrae constant A with Model II

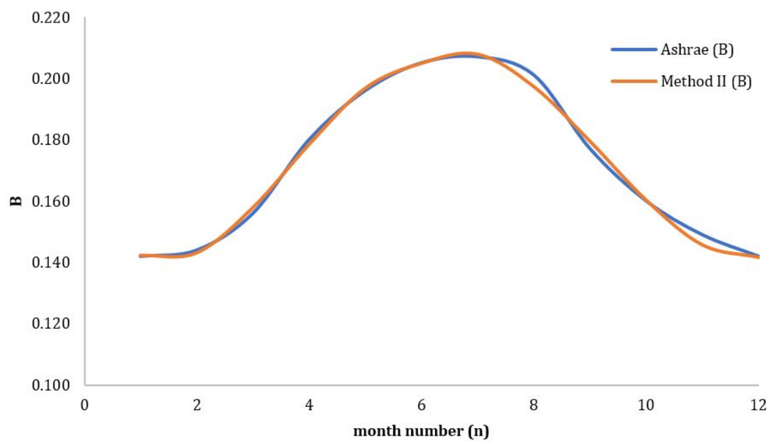


Fig. 6 Comparison of Ashrae constant B with Model II

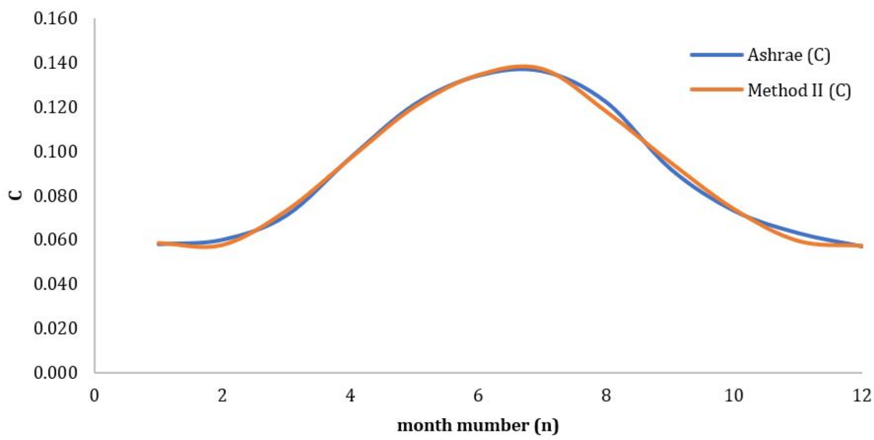


Fig. 7 Comparison of Ashrae constant C with Model II

$$\delta = sin^{-1}\left[0.4Sin\left(\frac{360}{365}(d_n - 82)\right)\right] \tag{11}$$

$$\delta = 23.45Sin\left(\frac{360}{365}(d_n - 284)\right) \tag{12}$$

We have used a modified version of the above formulas; the above formulas are in degrees, whereas the modified formula (see Eq. (4)) is in radians.

$$\delta = 23.44 * Sin(0.0169d_n - 1.368) \tag{13}$$

Where d_n is the day number, in Fig. 8, the declination is plotted against the day number (1 to 365), the graphs plotted by modified formula and Eq. (3) overlap entirely.

The solar radiations BSR, DSR, and GSR, have been calculated for the 21st day of each month from January to December for the Pasni, Jiwani, and Gwadar cities of Baluchistan, Pakistan. Figs. 9-11 gives BSR, DSR, and GSR for these three cities. In multiple bar charts, the blue bar shows Ashrae constants calculated by Ashrae clear sky model. The orange and green bars show the same calculated by a model I (sine function model) and model II (piecewise function), respectively. It is clear from graphs that solar fluxes for Pasni, Jiwani, and Gwadar for all three radiations are almost

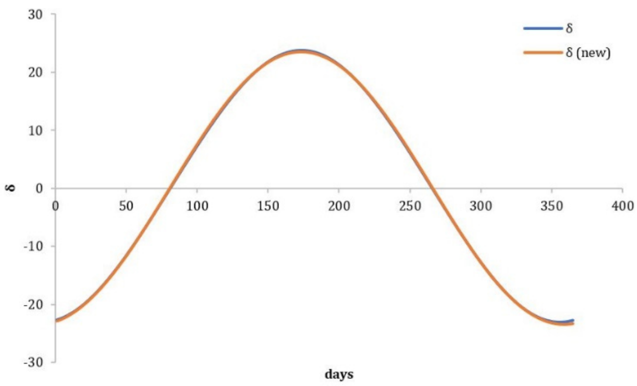
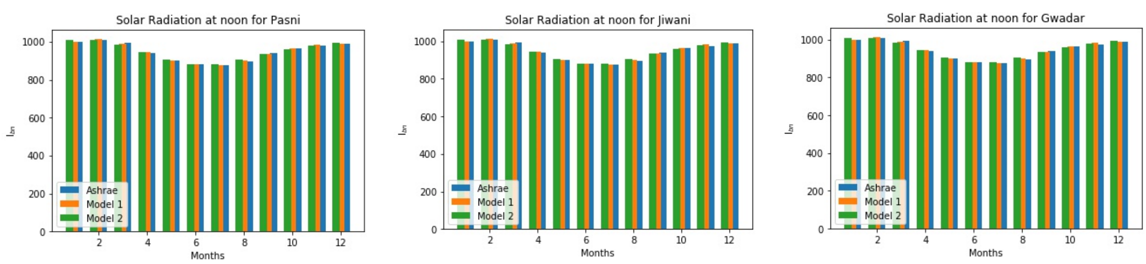
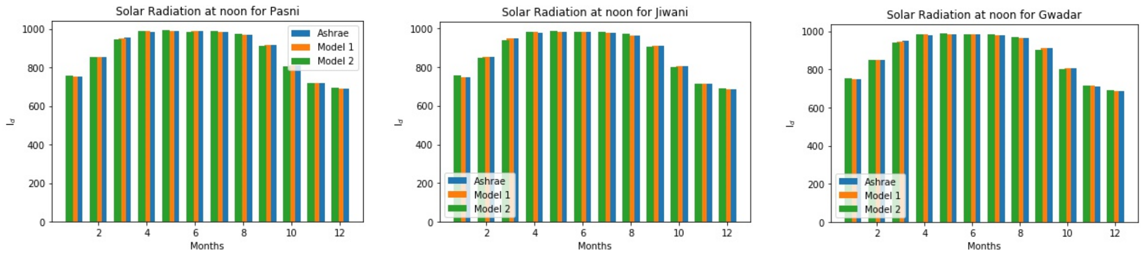


Fig. 8 Comparison of a new formula for declination angle with the existing formula



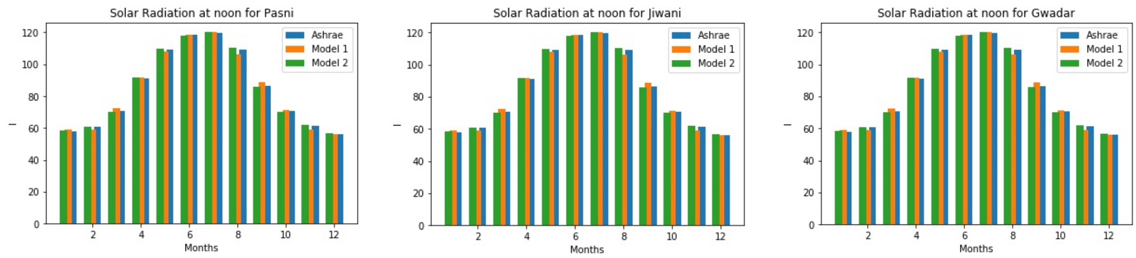
(a) (b) (c)

Fig. 9 Beam Solar radiations (BSR) for (a) Pasni; (b) Jiwani; and (c) Gwadar for the 21st day of January to December



(a) (b) (c)

Fig. 10 Diffuse Solar radiations (DSR) for (a) Pasni, (b) Jiwani, and (c) Gwadar from the 21st day of January to December



(a) (b) (c)

Fig. 11 Global Solar radiations (GSR) for (a) Pasni, (b) Jiwani, and (c) Gwadar for the 21st day of January to December

identical; the reason is the relative values of their latitudes and longitudes and the lesser distance between them compared to the distance between the sun and earth. Therefore, both models determine the same solar energy values as calculated by the Ashrae clear sky model.

4. Validation of results

To validate the results of BSR, DSR, and GSR calculations for the 21st day of each month by a new model, we calculated Root Mean Square Error, Mean Absolute Error, Mean Absolute Percent Error, and Chi-square statistic. Table 2 shows the values of RMSE, MABE, MAPE, and Chi-square statistics. Again, the pattern of statistical error for three cities, Pasni, Jiwani, and Gwadar, is the same. The maximum value of RMSE that occurs for BSR is less than 4 in model I and less than 6 in model II; the maximum value of MABE for DSR is less than three in model I, whereas it is less than 6 in model II. Likewise, the maximum value of MAPE occurs for DSR; it is less than 2 for model 1 and less than 0.6 for model II. Finally, the maximum value of Chi-square occurs for DSR in model I and BSR in model II, which are less than 0.4 and less than 0.6.

Table 2 Statistical errors in BSR, DSR, and GSR for Pasni, Gwadar, and Jiwani

		Methods							
		I	II	I	II	I	II	I	II
		RMSE		MABE		MAPE		Chi-Square	
Pasni	Ibn	3.6729	5.9925	2.9216	5.2951	0.3070	0.5550	0.1696	0.4486
	Id	1.5878	0.5142	1.2826	0.4517	1.6528	0.5550	0.3845	0.0372
	I	2.0877	5.4975	1.5429	4.8609	0.1675	0.5550	0.0554	0.4088
Gwadar	Ibn	3.6793	6.0019	2.9262	5.3036	0.3077	0.5564	0.1703	0.4504
	Id	1.5857	0.5149	1.2811	0.4524	1.6523	0.5564	0.3838	0.0374
	I	2.0810	5.4847	1.5383	4.8495	0.1677	0.5564	0.0552	0.4088
Jiwani	Ibn	3.6797	6.0015	2.9265	5.3034	0.3078	0.5564	0.1704	0.4504
	Id	1.5855	0.5149	1.2810	0.4524	1.6523	0.5564	0.3838	0.0374
	I	2.0798	5.4836	1.5375	4.8482	0.1678	0.5564	0.0552	0.4087

5. Conclusions

The solar radiations BSR, DSR, and GSR, have been calculated for three cities (Pasni, Jiwani, and Gwadar) of Baluchistan State of Pakistan with the help of two new models (trigonometric function model and piecewise function model) of Ashrae constants. The values of Ashrae constants calculated by new models have been compared with the Ashrae clear sky model. The comparison shows that both models determine values in the acceptance range. However, the first model is better. The new models were employed with the Ashrae clear sky model to calculate BSR, DSR, and GSR for the 21st day of each month. The standard statistical errors validate the performance of calculations by the models; Root Mean square error (RMSE), Mean Absolute error (MABE), Mean Absolute percent error (MAPE), and chi-square statistic (χ^2). These errors have been calculated as indirect, diffuse, and global solar radiation for three cities Pasni, Gwadar, and Jiwani. The errors are tabulated in Table 2; in all cases, the errors are less than the accepted range of 10%. If we compare the performance of models, it is clear from the table that the range of errors in the model I is less than that in model II; however, in both models, the errors are in the accepted range. A modified formula of declination angle (the angle between the line joining centers of Earth and Sun and the projection of this line on the equatorial plane) is presented. The formula of declination angle already in use is in degrees; the modified formula is in radians. The RMSE in modified values of declination angle is 0.2438. This shows that the modified formula determines values of angle of declination that are in good agreement with the corresponding known values.

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