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Empirical model development for the estimation of clearness index using meteorological parameters

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Abstract: The clearness index is an indispensable parameter required for the design and analysis of solar energy systems. In the absence of measured values for a specific location, the clearness index can be estimated from other measured meteorological variables. In this study three meteorological parameters, sunshine hours, monthly mean values of the temperature difference (ΔT), and cloudiness, are used to develop empirical models for the estimation of clearness index. The empirical models are developed for five major cities in Pakistan (Karachi, Multan, Lahore, Islamabad, and Quetta). For empirical model development, long-term data (1991 to 2010) of monthly average clearness index, sunshine hours, average daily minimum and maximum temperatures, and cloudiness have been used. The accuracy of the models has been tested by statistical indicators that include mean percentage error (MPE), coefficient of determination (R^2), mean absolute relative error (MARE), mean bias error (MBE), and root mean square error (RMSE). The error analysis revealed that the proposed models are suitable for the estimation of the clearness index. It is also concluded that multiple regression models give better estimates of clearness index for all the stations ($0.80 \leq R^2 \leq 0.86$) compared to single parameter model and therefore are recommended. The study indicated that clear sky conditions prevail throughout the months at all the investigated sites ($0.58 \leq K_T \leq 0.68$), which is a good indicator for solar energy utilization. The statistical indicators also suggest that multilinear regression model M-3 gives a better representation of the climate system and using three parameters reduces the uncertainties in the developed model.

Key words: Clearness index, meteorological variables, cloudiness, sunshine hours, statistical evaluation

1. Introduction

Fast technological advancements, supportive government policies, and competitive costs of deployment result in tremendous increase in solar energy growth. Solar photovoltaic (PV) technology is a matured technology and is commercially acceptable globally. The cost of energy generation from solar PV sources has decreased drastically due to economy of scale. Global solar PV energy utilization has grown by about 45% since the year 2000 [1]. According to latest report [2], more than 97 GW of solar PV energy was added globally in 2017, bringing the global cumulative installed capacity to 400 GW, an increase of 32%. With respect to new PV

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capacity additions, China remained on top with 53 GW, while the USA and Japan ranked second and third with respective PV addition capacities of 11 GW and 7 GW.

Pakistan is among the countries that receive the world's highest solar insulation intensities during the year. It is estimated that approximately 1 kW/m^2 of solar energy is received across the country with an average sunshine duration of 6–8 h per day. The annual number of sunshine hours in Pakistan varies between 3000 and 3300 h. The total power generation capacity of Pakistan is 22,797 MW [2] while the estimated solar potential is 90,000 MW to 100,000 MW [1], which is about 4 to 5 times the present generation. The major power-contributing sources of electricity in the country are oil (36%) and gas (30%). Hydropower contributes 6600 MW to the total generation and is decreasing due to depleting water reservoir capacities. Nuclear power contributes 1321 MW (5.6%) of the total generation capacity. The annual national electricity demand is more than 18,000 MW and becomes more during peak demand in summer. The electricity shortfall during summer reaches about 4000 MW to 5000 MW [2], which is alarming. Solar energy is being utilized globally in many applications such as zero energy and sustainable villages [3], PV irrigation [4, 5], solar thermal systems [6], PV power plants for small loads [7, 8], grid-connected multi-megawatt-sized PV power plants [9, 10], solar cooling systems [11], solar water heating systems for industrial applications [12], PV water pumping [13, 14], PV energy for desert camping [15], and solar energy utilization and hybrid power systems for remote locations [16–22]. Solar energy is an abundant source of energy and can be utilized to address the global energy demands. Accurate estimation of solar energy availability in both spatial and time domains is essential for profitable utilization.

Estimation of solar potential of a site is an important indicator in order to assess the feasibility of setting up a solar energy-based electrical energy generation system. Various research groups are working in this area employing different estimation techniques for accurate estimation of solar energy resources. Easily available sunshine data are commonly used to obtain an estimate for global solar radiation by fitting Angstrom-–Prescott type models [23–25]. Other studies [26–30] for the estimation of global solar radiation used commonly measured weather parameters such as temperature, relative humidity, daily sea level pressure, daily vapor pressure, and sunshine duration as input. Temperature-based correlations have been applied for the estimation of global solar radiation in the absence of other meteorological parameters [31–33]. Artificial neural network (ANN) models are employed successfully for the estimation of global solar radiation [34, 35].

Mohandes and Rehman [36, 37] and Mohandes et al. [38] used ANNs for the development of solar radiation maps for Saudi Arabia and found good agreement between the estimated and measured values. Rehman and Mohandes [39], in another application, used the ANN method for splitting the GSR into direct and diffuse radiation for solar thermal applications and reported excellent performance of the method. Rehman and Ghori [40] used geostatistics for spatial estimation of GSR and found good agreement between the estimated and measured values. Empirical modeling techniques are also useful and easy to use as adopted by various authors [41–43].

In addition to solar potential estimations of sites, the assessment of variation of solar radiation in the temporal and spatial domains is also a subject of interest. Such variations are difficult to predict primarily because of the nonlinear nature of interactions in complex atmospheric conditions. In order to quantify the loss of solar radiation because of atmospheric conditions, a simple numerical approach is adopted. Physically clear and sunny conditions are characterized by a parameter known as the clearness index (K_T), having a value lying in the range between 0 and 1. A high value is related to clear sunny conditions and low values indicate cloudy conditions. The clearness index (K_T) is obtained by taking the ratio between total solar radiation and extraterrestrial radiation (H_0). Therefore, the clearness index (K_T) is an indicator of the degree of transparency of solar radiation through the atmosphere. It is a stochastic parameter and is a function of time of year, season, climatic conditions, and geographic location. Therefore, a reliable model of clearness index is essential to determine the atmospheric effects on solar radiation.

The diurnal and seasonal variations of hourly and daily clearness index values were studied to analyze the atmospheric conditions for tropical stations of Nigeria [44]. Kheradmanda et al. [45] presented an integrated ANN model for forecasting clearness index by taking into account environmental and meteorological parameters. The authors used long-term monthly data of 30 years to support their findings. Clearness index models also act as design tools to assess the performance of stand-alone PV systems. Dervishi and Mahdavi [46] used K_T values to determine the level of solar radiation availability of solar energy utilization systems. It also works as a design tool in characterizing the atmospheric conditions prevailing over a particular location in a specific time duration [47]. Waleed et al. [48] estimated mean monthly values of clearness index using different meteorological parameters to estimate clearness index. Mellit et al. [49] applied the ANFIS technique to predict clearness index for designing a photovoltaic system. Al-Lawati et al. [50] developed maps of clearness index values for Oman using a radial basis function for neural networks to estimate solar radiation. Their study was beneficial for the evaluation of the performance of solar energy conversion systems for the investigated region. Waewsak and Chancham [51] used monthly mean clearness index and normalized monthly sunshine duration data to estimate the monthly global solar radiation in Thailand using a regression technique. Hollands [52] utilized the clearness index to establish models for the estimation of diffused solar radiation and concluded that the model fit closely with the measured data. Firoz et al. [53] used sunshine hours and clearness index to develop two correlations for the estimation of monthly average daily diffuse solar radiation for Karachi, Pakistan.

In the present study, unilinear and multilinear parametric regression models are developed for the estimation of monthly average clearness index from the available meteorological data on sunshine hours, monthly mean values of the temperature difference (ΔT), and cloudiness for five meteorological stations in Pakistan. Estimated values have been evaluated by using statistical indicators to judge the suitability of the proposed models. Though the models are simple, their performances are excellent and very accurately describe the local climate conditions. The investigated sites comprise vast arid structures; therefore, direct normal irradiance (DNI) is an important aspect in terms of sunshine hours used in our model. It is important to reduce all uncertainties present in the solar parameter data for empirical modeling. This will ultimately result in better predictions of the computed model. Furthermore, by incorporating more input climate parameters, the reliability of the model increases. In the present paper long-term hourly data are used to model clearness index. Additionally, clearness index profiling is done for 5 cities of Pakistan: Karachi, Multan, Lahore, Islamabad, and Quetta.

2. Materials and methods

2.1. Climate data

In this work, the climatological data for sunshine hours, average daily minimum and maximum temperatures, cloudiness, and clearness index were acquired from the Pakistan Meteorological Department (PMD). The recorded data span a period of 20 years, i.e. from 1991 to 2010, for five stations; see Table 1 and Figure 1. Table 2 lists the monthly averaged clearness index (K_T), fraction of sunshine hours (n/N), cloudiness (C), and difference of maximum and minimum temperature (ΔT) for the all the sites under investigation. Figures 2–5 show the variations of monthly average values of clearness index (K_T), fraction of sunshine hours, cloudiness, and difference of minimum and maximum temperatures. Monthly mean daily values are obtained by averaging the data for the average day of each month. It is observed in Karachi that larger values of solar radiation and sunshine fractions occur in the months of October to January and the lowest in July (Table 2). At the rest of the locations, higher values occur during April to June and sometimes until July. However, the highest solar radiation intensities and sunshine durations are observed in Quetta compared to other stations reported in this study.

Table 1. Geographical positions of sites and duration of data used in the current study for the estimation of clearness index.

Station	Latitude (N)	Longitude (W)	Elevation (m)	Data record
Islamabad	33°37′N	73°5′E	508	1991 to 2010
Lahore	31°33′N	74°19′E	215	1991 to 2010
Quetta	30°15′N	66°53′E	1589	1991 to 2010
Multan	30°12′N	71°26′E	123	1991 to 2010
Karachi	24°48′N	66°59′E	4	1991 to 2010

Figure 1. Location of the meteorological stations used in the present study.

2.2. Clearness index

The clearness index provides information about the atmospheric conditions and is the ratio of the horizontal global solar radiation to extraterrestrial solar radiation. It is a dimensionless number lying in the range of (0, 1) indicating the amount of solar radiation penetrating through the atmosphere and striking the Earth's surface. Monthly clearness index is given by:

$$K_T = \frac{H}{H_o}, \tag{1}$$

Table 2. Measured values of clearness index, sunshine hours, cloudiness, and temperature difference (ΔT) for five stations.

Stations	Climate parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Karachi	H/H_o	0.647	0.569	0.584	0.591	0.573	0.567	0.464	0.458	0.552	0.651	0.674	0.669
	n/N	0.800	0.725	0.739	0.733	0.649	0.462	0.234	0.251	0.574	0.801	0.808	0.790
	C	0.257	0.233	0.254	0.201	0.238	0.445	0.699	0.703	0.417	0.126	0.147	0.235
	ΔT °C	14.900	14.400	15.200	11.800	9.000	7.100	6.600	5.700	7.500	13.600	15.300	14.900
Quetta	H/H_o	0.660	0.630	0.640	0.670	0.720	0.706	0.670	0.702	0.680	0.760	0.730	0.690
	n/N	0.626	0.628	0.698	0.637	0.844	0.726	0.747	0.809	0.828	0.913	0.848	0.777
	C	0.407	0.429	0.435	0.385	0.253	0.170	0.284	0.230	0.097	0.079	0.216	0.311
	ΔT °C	14.400	13.000	13.700	17.300	17.000	14.900	14.200	16.000	19.000	20.600	21.800	15.800
Multan	H/H_o	0.602	0.623	0.635	0.641	0.612	0.564	0.531	0.562	0.614	0.617	0.618	0.635
	n/N	0.625	0.558	0.696	0.706	0.687	0.615	0.627	0.684	0.729	0.781	0.737	0.683
	C	0.268	0.310	0.299	0.267	0.258	0.298	0.418	0.356	0.198	0.091	0.126	0.207
	ΔT °C	15.900	12.000	12.600	17.100	14.800	12.100	9.500	9.000	10.200	17.400	15.900	15.700
Lahore	H/H_o	0.592	0.621	0.619	0.677	0.665	0.640	0.590	0.624	0.632	0.707	0.719	0.766
	n/N	0.609	0.612	0.680	0.765	0.743	0.654	0.570	0.605	0.644	0.800	0.789	0.666
	C	0.376	0.402	0.400	0.347	0.267	0.251	0.454	0.463	0.272	0.106	0.178	0.293
	ΔT °C	12.5	8.90	10.0	13.10	12.70	10.20	8.40	7.70	8.40	12.70	12.60	11.80
Islamabad	H/H_o	0.551	0.658	0.670	0.690	0.740	0.760	0.675	0.645	0.680	0.710	0.720	0.660
	n/N	0.535	0.537	0.606	0.650	0.739	0.692	0.604	0.611	0.666	0.744	0.668	0.543
	C	0.441	0.504	0.508	0.502	0.461	0.433	0.581	0.568	0.353	0.203	0.265	0.384
	ΔT °C	10.700	13.500	14.700	17.100	16.400	15.400	10.200	9.000	11.200	17.400	15.900	12.000

where H (MJ m^{-2} day^{-1}) is the predicted monthly mean of daily global solar radiation on a horizontal surface and H_o (MJ m^{-2} day^{-1}) is the monthly mean extraterrestrial solar radiation on a horizontal surface. Values of the monthly average daily extraterrestrial radiation (H_o) are calculated from the models [54].

2.3. Empirical models' development

Climate models are mathematical representations of climate either use physical quantities based on underlying physical laws or, in the case that physical quantities are not available explicitly, parametric numerical data measured for the environment. In a broad sense, equations derived using physical laws are theoretical models of the climate system, whereas equations based on recorded data form an empirical model based on regression analysis. In regression analysis a model is developed by relating two or more independent variables to a dependent variable. The empirical models used in this research can be divided into three groups depending upon the number of input variables. The first group consists of a model based on one independent variable, which is sunshine duration fraction or sunshine hours; the second group uses ambient temperature difference; and the third group utilizes the three independent variables of sunshine hours, monthly mean values of temperature difference (ΔT), and cloudiness to estimate clearness index.

2.3.1. M-1: Sunshine duration-based models

The sunshine duration-based model includes one parameter: sunshine duration. The classical form of the Angstrom–-Prescott model (A–P model) [55, 56] is applied successfully to estimate the clearness index using

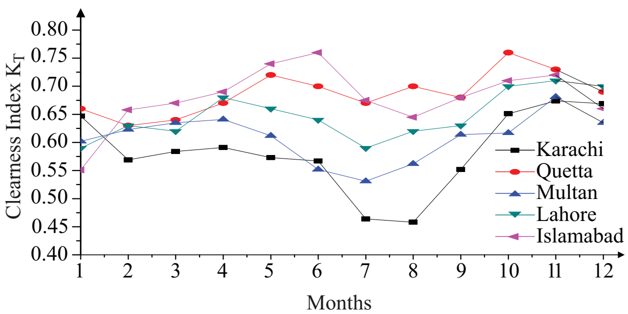

Figure 2. Monthly variation of clearness index over 20 years of data collection period.

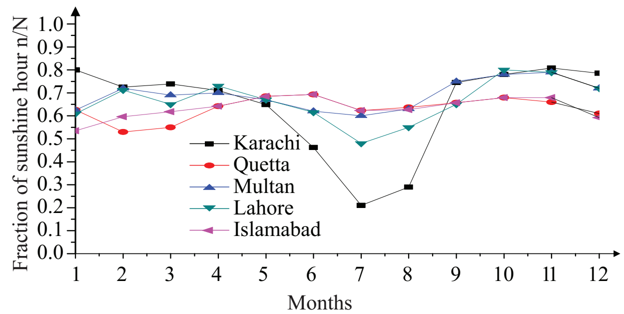

Figure 3. Monthly variation of sunshine duration over 20 years of data collection period.

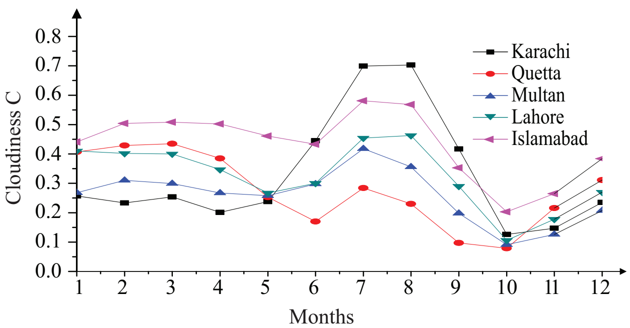

Figure 4. Monthly variation of cloudiness over 20 years of data collection period.

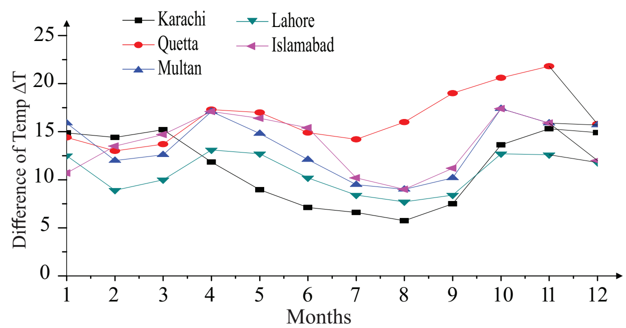

Figure 5. Monthly variation of difference of temperature over 20 years of data collection period.

the following relation:

$$K_T = \frac{H}{H_o} = a + b(\frac{n}{N}), \tag{2}$$

where a and b are regression coefficients and vary with location, n is the measured sunshine duration in hours, and N is the maximum possible day length.

2.3.2. M2: Air temperature-based models

In the case of unavailability of measured sunshine hours or other meteorological parameters, air temperature, which is widely available, is used to estimate K_T. Angstrom type regression models based on the difference between the mean value of the daily minimum (T_{min} °C) and daily maximum (T_{max} °C) temperatures are used in the following equation:

$$K_T = \frac{H}{H_o} = a + b(\Delta T), \tag{3}$$

where $\Delta T = T_{max} - T_{min}$.

2.3.3. M-3: Multiparameter-based regression models

Multiparameter regression models use a combination of two or more meteorological parameters for the estimation of clearness index. In the present study, the combination of sunshine duration fraction, difference of air temperature ($\Delta T = T_{max} - T_{min}$), and cloud cover is used to estimate K_T:

$$K_T = \frac{H}{H_o} = a + b(\frac{n}{N}) + cC + d\Delta T, \tag{4}$$

where *a*, *b*, *c*, and *d* are empirical constants determined using the measured meteorological data and *C* is cloud cover.

3. Statistical evaluation tools

The calculated values of K_T obtained from the empirical models are compared with the observed values. Statistical error parameters are used to judge the performance of each model. In this study, the reliability of the models has been tested using five different statistical indicators as described below:

$$R^2 = 1 - \left[\frac{\Sigma(K_{T,im} - K_{T,ic})^2}{\Sigma(K_{T,im} - K_{T,m,avg})^2}\right], \tag{5}$$

$$RMSE = \left[\frac{\Sigma(K_{T,im} - K_{T,ic})^2}{N_{obs}}\right]^{0.5}, \tag{6}$$

$$MBE = \Sigma\left[\frac{(K_{T,im} - K_{T,ic})}{N_{obs}}\right], \tag{7}$$

$$MPE = \frac{1}{N_{obs}}\Sigma 100 * \left[\frac{(K_{T,im} - K_{T,ic})}{K_{T,im}}\right], \tag{8}$$

$$MARE = \frac{1}{n}\Sigma\left|\frac{(K_{T,im} - K_{T,ic})}{K_{T,im}}\right|, \tag{9}$$

where $K_{T,im}$ and $K_{T,ic}$ are the *i*th observed and estimated values of clearness index. The average of the measured K_T values is represented by $K_{T,m,avg}$, while *n* is the number of observations. For better data modeling results, statistical error parameters should be close to zero, but R^2 should approach one. MBE and MPE provide information about over- and underestimation of estimated values.

4. Results and discussion

In this study, empirical models of clearness index are developed for five stations using fraction of sunshine hours, temperature difference ($\Delta T = T_{max} - T_{min}$), and cloudiness. Regression analysis is performed for the determination of model coefficients. The derived coefficients for all three categories of the empirical models are summarized in Table 3. The models are validated by comparing estimated and measured values of clearness index for all the cases in terms of MPE, R^2, RMSE, MBE, and MARE (see Table 4).

The ranges of R^2 and RMSE achieved in this study for all locations and models varied between 0.429 and 0.861 and between 0.0166 and 0.039, respectively. These values indicate that the performance of all models is not up to an acceptable level. Some models show overestimation (+VE MBE), while others show insignificant

Table 3. Regression coefficients for the five study sites.

Model parameters					
Sites	Models	a	b	c	d
Karachi	M-1	0.385	0.315	-	-
	M-2	0.41	0.015	-	-
	M-3	0.336	0.375	0.054	-0.001
Quetta	M-1	0.435	0.334	-	-
	M-2	0.514	0.011	-	-
	M-3	0.506	0.176	-0.066	0.004
Multan	M-1	0.201	0.586	-	-
	M-2	0.503	0.008	-	-
	M-3	0.594	-0.035	-0.13	0.005
Lahore	M-1	0.334	0.472	-	-
	M-2	0.5	0.011	-	-
	M-3	0.538	0.157	-0.165	0.005
Islamabad	M-1	0.316	0.575	-	-
	M-2	0.516	0.012	-	-
	M-3	0.26	0.485	0.079	0.006

Table 4. Statistical errors between observed and estimated clearness index values.

Sites	Models	R^2	MPE (%)	MBE	RMSE	MARE
Karachi	M-1	0.85	0.298	-8.80E-17	0.033	0.05
	M-2	0.682	0.478	-3.70E-17	0.038	0.061
	M-3	0.861	0.213	1.39E-17	0.028	0.04
Quetta	M-1	0.688	0.079	-4.60E-17	0.02	0.023
	M-2	0.631	0.1	-1.20E-16	0.022	0.029
	M-3	0.8	0.051	-1.70E-16	0.016	0.017
Multan	M-1	0.711	0.129	9.25E-18	0.022	0.03
	M-2	0.429	0.178	8.33E-17	0.031	0.044
	M-3	0.828	0.076	6.48E-17	0.017	0.022
Lahore	M-1	0.73	0.076	-1.90E-17	0.017	0.022
	M-2	0.461	0.211	9.25E-18	0.03	0.032
	M-3	0.759	0.092	1.02E-16	0.02	0.027
Islamabad	M-1	0.817	0.125	-7.40E-17	0.022	0.029
	M-2	0.433	0.36	-1.20E-16	0.039	0.047
	M-3	0.861	0.097	-1.10E-16	0.019	0.022

underestimation (-VE MBE). The results clearly demonstrate that estimates of model M-3 are better than those of models M-1 and M-2. Among these models, M-3 for Islamabad gave the best fit. Figures 6–10 show the performance of these models through a comparison between the estimated values of K_T and measured data at each station. In Karachi, higher values of K_T are observed in winter months (Jan–Mar and Oct–Dec) and the lowest in July and August, as can be observed from Figure 6. An evident seasonal trend is noticed in the values of K_T throughout the year in Karachi. A similar trend, but of different magnitude, is seen at Multan (Figure 7) with higher values in winter and lower in summer. However, at Lahore, Islamabad, and Quetta the monthly trends show relatively higher values of K_T during summer and lower in winter (Figures 8–10).

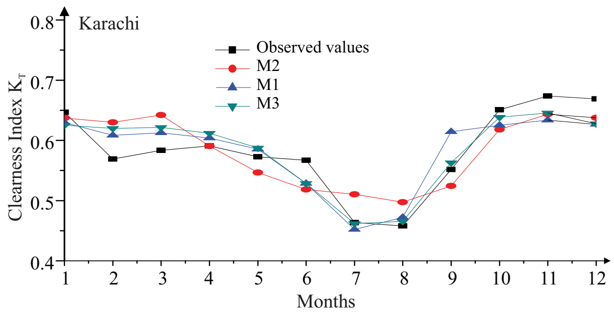

Figure 6. Comparison between observed and estimated monthly average daily values of K_T.

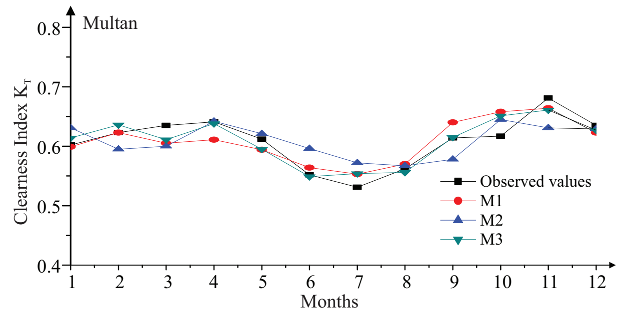

Figure 7. Comparison between observed and estimated monthly average daily values of K_T.

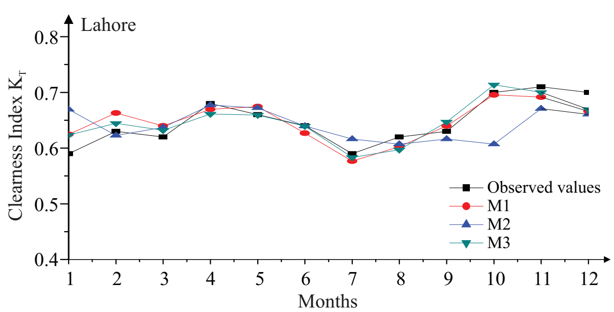

Figure 8. Comparison between observed and estimated monthly average daily values of K_T.

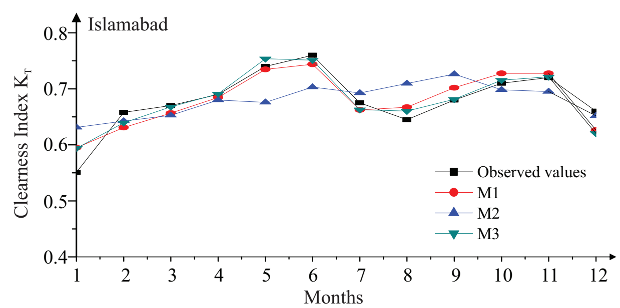

Figure 9. Comparison between observed and estimated monthly average daily values of K_T.

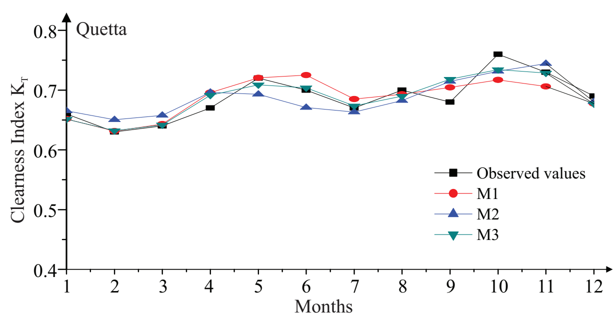

Figure 10. Comparison between observed and estimated monthly average daily values of K_T.

It is evident from Table 4 that the deviation between the measured and calculated value is very small for model M-3. The estimated values of the clearness index are in good agreement with the observed values. In general, temperature-based models are less accurate compared to the two other models with higher RMSE values between 0.022 and 0.039. Model M-2 performed poorly compared to other models with smaller values of R^2 (0.42 to 0.68) and higher values of MPE (10% to 48%). However, this model will be useful when only one meteorological parameter, such as fraction of sunshine hours, is available. Applying the sky conditions classification proposed in [53], which states values for cloudy sky ($0.12 \leq K_T \leq 0.35$), partly cloudy sky ($0.35 \leq K_T \leq 0.65$), and clear sky ($K_T > 0.65$), it is evident that considering clear sky conditions, the annual mean value of K_T of more than 0.65 is reasonable.

5. Conclusions

In this study, the measured clearness index and other meteorological data were obtained for five stations (Karachi, Quetta, Multan, Lahore, and Islamabad) from the PMD. The average monthly clearness index, sunshine duration, cloudiness, temperature, and clearness index data covered a 20-year period between 1991 and 2010. Using relative sunshine hours, cloudiness, and temperature difference as independent parameters, three models were developed for the estimation of clearness index. The performance of the models was evaluated in terms of statistical tests (R^2, MPE, MBE, RMSE, and MARE). The results showed that the multivariate model (M-3) gave the best fit for the estimation of K_T at all stations. This is verified by error analysis with higher values of R^2 (0.75–0.86) and smaller values of RMSE (0.016–0.028), MARE (0.017–0.040), and MPE (0.051–0.213). Furthermore, the comparison of estimated and measured values shows that the two are in good agreement and followed the trends at all stations. The performance of M-3 was found good at the Islamabad station while M-1 ranked second for all stations. The advantage of M-1 over multivariate model M-3 is that it requires only one independent parameter and gave satisfactory values of K_T as reflected by error analysis ($0.688 \leq R^2 \leq 0.850$, $0.017 \leq$ RMSE ≤ 0.033, $0.05 \leq$ MARE ≤ 0.022, and $0.076 \leq$ MPE ≤ 0.298). However, M-2 performed worst compared to the two other models. The results of clearness index showed that the sky is clear all year round over all sites, except for Karachi during the months of July and August, where K_T was less than 0.5.

In the case of models M-1 and M-2, only single parameters of sunshine hours and temperature difference, respectively, are used to reproduce the effect. Such parameterization lacks dependencies on other equally important climate parameters and will therefore be unable to reduce uncertainties in the predicted model. The novelty of our research is based on using all three parameters as in model M-3. This gives a better approximation of the climate system and consequently reduces the uncertainties in the developed model. Based on the overall results, it is concluded that the accuracy of estimation via multiple meteorological data in model M-3 is more reliable than single-parameter estimation.

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