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EFFECT OF SOLAR-TERRESTRIAL PHENOMENA ON SOLAR CELL'S EFFICIENCY

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It is assumed that the solar cell efficiency of PV device is closely related to the solar irradiance, consider the solar parameter Global Solar Irradiance (G) and the meteorological parameters like daily data of Earth Skin Temperature (E), Average Temperature (T), Relative Humidity (H) and Dew Frost Point (D), for the coastal city Karachi and a non-coastal city Jacobabad, K and J is used as a subscripts for parameters of Karachi and Jacobabad respectively. All variables used here are dependent on the location (latitude and longitude) of our stations except G. To employ ARIMA modeling, the first eighteen years data is used for modeling and forecast is done for the last five years data. In most cases results show good correlation among monthly actual and monthly forecasted values of all the predictors. Next, multiple linear regression is employed to the data obtained by ARIMA modeling and models for mean monthly observed G values are constructed. For each station, two equations are constructed, the R^2 values are above 93% for each model, showing adequacy of the fit. Our computations show that solar cell efficiency can be increased if better modeling for meteorological predictors governs the process.

Keywords : Coastal, Non-coastal, Karachi, Jacobabad, ARIMA, Forecast, Correlation, Multiple Linear Regression, Modeling.

Nomenclature: Global solar irradiance (G), Earth Skin Temperature (E), Average Temperature (T), Relative Humidity (H), Dew Frost Point (D), Subscripts of All Parameters taken for Karachi ($_K$), Jacobabad ($_J$), Mean Actual ($_{MA}$), Mean Forecasted ($_{MF}$), Mean Actual Karachi, Jacobabad ($_{MAK,\ MAJ}$) and Mean Forecasted Karachi Jacobabad ($_{MFK,\ MFJ}$), Multiple Linear Regression (MLR).

1. Introduction

The cost of traditional and other non-renewable energy resources are on steady increase, it is essential to test, develop and depend on other alternative, non-traditional and renewable energy sources. The most important alternative source is the solar energy. In this study, an attempt has been made to see the dependence of PV devices, which runs over solar energy, and terrestrial parameters. That is, to analyze, the efficiency of PV devices and equipment in the coastal climates particularly that of Karachi ($_K$). The results are compared with the results for non-coastal city of Sindh like Jacobabad ($_J$) which constitutes the extreme of Sindh.

The efficiency of PVC is based on different parameters which includes various geological, geometrical and electrical factors. This study establishes a statistical relationship between solar cell efficiency and some meteorological predictors having noticeable influence over the process [1]. In next section, clear evidence will be provided for the dependency of solar cell efficiency over solar irradiance. As such, an empirical relation is found between solar irradiance, taking it as response variable and some global as well as local predictors will be sought which are having an impact.

To quantify the solar radiation at any particular part of the earth's surface, position of the point, time of year, atmospheric diffusion and cloud cover, shape of the surface and reflectivity of the surface is taken into account. However, in hilly and mountainous terrains, the distribution of slopes has major effects on surface climate and radiation amounts [9]. Surface radiation may change widely according to the Average Temperature, Relative

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Humidity, Dew Frost Point, Earth Skin Temperature, frequency and optical thickness of clouds, and modeling these factors successfully is important for treatment of the surface energy balance [2]. In our study, a coastal city Karachi of Sindh is taken to model the solar cell efficiency. The effect of location on the efficiency of solar cell is checked by selecting a non-coastal city Jacobabad which lie in the same region. The major difference between two cities is the location of the coast which will be analyzed for its effect of the efficiency of PVC. A comparison of the efficiency of different solar cells which are commonly used is as follows.

Material	Level of efficiency in % Lab	Level of efficiency in % Production
Mono-crystalline Silicon	approx. 24	14 to17
Poly-crystalline Silicon	approx. 18	13 to15
Amorphous Silicon	approx. 13	5 to 7

2. Material and Method

The conversion efficiency of a photovoltaic cell array is defined as the ratio of the electrical energy produced by the array to the solar energy input to the array [7] expressed symbolically,

$$\eta = \frac{E}{A_c H_t \tau} \tag{1}$$

where η = array efficiency

E = electrical energy production of the array

A_c = array area

H_t = solar irradiance per unit area of the tilted array

τ = transmissivity of array cover

By the above formula of conversion efficiency of a photovoltaic cell array, the solar phenomena H_t is inversely proportional to the performance of PV device. Since solar cell efficiency depends upon solar irradiance, it should be influenced by terrestrial parameters. It is assumed that the solar cell efficiency will be better in coastal climate as compared to non-coastal climate. An attempt is to be made in finding a relationship between H_t and different meteorological parameters. Several best suitable models are constructed using Autoregressive Integrated Moving Average (ARIMA) technique [19] to check the adequacy of actual and forecasted data, Pearson correlation as used by [4] is applied. Finally, a multiple linear regression model for Karachi ($_K$) and Jacobabad ($_J$) using all considered solar terrestrial parameters is constructed.

3. Results

ARIMA models depend on different p and q values, as in [5, 11]. Modeling is applied to all the time series and a best fit model based on Minimum AICC criterion is reported. Tables 1−9 show different monthly models for each of the five parameters of Karachi ($_K$) and Jacobabad ($_J$).

For correlation, mean actual values of Global Solar Irradiance (G) is compared with mean forecasts (shown in Table 10). Time series plot is in Fig. 1 whereas the correlation b/w Mean Actual ($_{MA}$) vs. Mean Forecasted ($_{MF}$) Monthly Data of Global Solar Irradiance (G) is in Table 11. Mean Actual ($_{MA}$) and Mean Forecasted ($_{MF}$) Monthly Data for all Parameters of Karachi ($_K$) is presented in Table 12 and Figs. 2–5 represent time series plot of all the parameters for Karachi ($_K$). Table 13 shows strong correlation between Mean Actual ($_{MA}$) vs. Mean Forecasted ($_{MF}$) Monthly Data for all Parameters of Karachi ($_K$) which shows the adequacy of forecast from ARIMA. Mean Actual ($_{MA}$) and Mean Forecasted ($_{MF}$) Monthly Data for all Parameters of Jacobabad ($_J$) is presented in Table 14 and Figs. 6–9 represent time series plot of all the parameters for Jacobabad ($_J$). Table 15 shows strong correlation between Mean Actual ($_{MA}$) vs. Mean Forecasted ($_{MF}$) Monthly Data for all Parameters of Jacobabad ($_J$) which shows the adequacy of forecast from ARIMA, except correlation of H_J which is weak. In Table 16, the correlation between Mean Actual ($_{MA}$) Monthly Data of G vs. all terrestrial parameters of Karachi ($_K$) and Jacobabad ($_J$) shows negative strong correlation which shows the strong inverse proportionality, whereas H_J is weak. In Table 17, the correlation between Mean Forecasted ($_{MF}$) Monthly Data of G vs. all terrestrial parameters of Karachi ($_K$) and Jacobabad ($_J$) strong negative correlation which shows the strong inverse proportionality.

For multiple linear regression model, two different multiple linear regression models are constructed for Karachi ($_K$) viz., (i) modeling mean actual G versus mean of actual parameters, and (ii) modeling mean actual G versus mean of forecasted parameters. Second equation is obtained from forecasted data from ARIMA model (last five years). R^2 values obtained for these models are 93.9 % and 96.4 %, showing good fitting. In the first model D($_K$) and E($_K$) shows an inverse relation whereas H($_K$) and T($_K$) shows direct relation to G. In the second model D($_K$), H($_K$) and T($_K$) shows an inverse relation whereas E($_K$) shows direct relation to G. Our result shows accurate modeling of G using the said predictors.

The MLR Model (1) is:

$$G_{MA} = 1314 - 5.44 D_{MAK} + 1.15 H_{MAK} - 0.60 E_{MAK} + 3.32\, T_{MAK}$$

$$S = 5.68183 \quad R^2 = 93.9\%$$

The MLR Model (2) is

$$G_{MA} = 1400 - 0.74\, D_{MFK} - 0.553\, H_{MFK} + 1.16\, E_{MFK} - 1.17\, T_{MFK}$$

$$S = 4.36493 \quad R^2 = 96.4\%$$

Two different multiple linear regression models are constructed for Jacobabad viz., (i) modeling mean actual G versus mean of actual parameters, and (ii) modeling mean actual G versus mean of forecasted parameters. Second equation is obtained from forecasted data from ARIMA model (last five years). R^2 values obtained for these models are 98.5% and 97.9%, showing good fitting. In the first model H_J and E_J shows an inverse relation whereas D_J and T_J shows direct relation to G. In the second model D_J, H_J and T_J shows an inverse relation whereas E_J shows direct relation to G. Our result shows accurate modeling of G using the said predictors.

The MLR Model (1) is

$$G_{MA} = 1424 + 0.00\, D_{MAJ} - 0.102\, H_{MAJ} - 3.89\, E_{MAJ} + 2.15\, T_{MAJ}$$

$$S = 2.83633 \quad R^2 = 98.5\%$$

The MLR Model (2) is:

$$G_{MA} = 1424 - 0.020\, D_{MFJ} - 0.338\, H_{MFJ} + 0.74\, E_{MFJ} - 2.81\, T_{MFJ}$$

$$S = 3.32845 \quad R^2 = 97.9\%$$

4. Conclusion

This section presents the crux of all the work done in the previous section. This communication deals with a comparatively difficult task of modeling the efficiency with relation to climate. In particular, it deals with the efficiency of PVC devices in coastal as well as non-coastal stations like Karachi ($_K$) and Jacobabad ($_J$). We aim to present the efficiency of PVC in terms of G [13].

ARIMA model for Karachi ($_K$) and Jacobabad ($_J$) are constructed using first order differences to introduce stationarity in the data. For G, different monthly models are constructed and their forecast is obtained. A five year forecast (July 2000 – July 2005) considerably agrees to the data. Same is done for the remaining meteorological predictors and forecast is obtained which quite resembles the data. The correlation of mean actual versus mean forecasted monthly data of GSI is 0.773 with a p–value 0.003 showing sufficient statistical evidence of the ARIMA model. Correlation values among mean of each month for observed and predicted values of RH and AT, at each station shows high values except for H_J whose correlation is 0.405 with p–value 0.191 [13].

As indicated earlier the performance and efficiency of a solar cell may depend considerably on local as well as global meteorological and geographical conditions. Thus setting G, as goal variable is sufficient enough to behave as a major factor for improvement and betterment of the efficiency and performance of PVC. Above results support our basic assumption that solar cell efficiency is directly proportional to all the terrestrial parameters taken into account in this study. On the other hand coastal climate is more suitable for efficient performance of PVC in comparison with the non-coastal climate [13].

5. Tables and Graphs

Table 1. Estimated Model using first difference of Global Solar Irradiance (G).

Month	Estimated Model	AICC
January	ARMA(17,3) Model	-157.107252
February	ARMA(11,5) Model	-120.586942
March	ARMA(7,27) Model	-233.631452
April	ARMA(24,4) Model	-159.763491
May	ARMA(17,5) Model	-429.347631
June	ARMA(9,15) Model	-207.871830
July	ARMA(7,4) Model	-233.982957
August	ARMA(14,20) Model	-406.840317
September	ARMA(15,11) Model	-346.512009
October	ARMA(20,3) Model	-371.932621
November	ARMA(24,20) Model	-361.959595
December	ARMA(16,22) Model	-450.489000

Table 2. Estimated Model using first difference of Karachi Average Temperature (T_K)

Month	Estimated Model	AICC
January	ARMA(20,1) Model	1932.767830
February	ARMA(7,2) Model	1774.604427
March	ARMA(26,17) Model	1920.071916
April	ARMA(7,2) Model	1839.973945
May	ARMA(11,2) Model	1734.271557
June	ARMA(10,21) Model	1540.575483
July	ARMA(5,14) Model	1240.939277
August	ARMA(8,25) Model	1267.072572
September	ARMA(6,20) Model	1393.424217
October	ARMA(4,20) Model	1548.972269
November	ARMA(26,20) Model	1811.469225
December	ARMA(17,20) Model	1921.050659

Table 3. Estimated Model using first difference of Karachi Relative Humidity (H_K)

Month	Estimated Model	AICC
January	ARMA(14,2) Model	4167.754023
February	ARMA(19,2) Model	4025.524090
March	ARMA(16,2) Model	4277.729646
April	ARMA(19,2) Model	4005.434527
May	ARMA(11,3) Model	3960.151299
June	ARMA(11,2) Model	3533.420475
July	ARMA(5,3) Model	3426.556996
August	ARMA(5,15) Model	3311.250407
September	ARMA(10,20) Model	3562.427304
October	ARMA(9,22) Model	4059.758182
November	ARMA(25,20) Model	4017.617572
December	ARMA(18,20) Model	4051.425952

Table 4. Estimated Model using first difference of Karachi Earth Skin Temperature (E_K).

Month	Estimated Model	AICC
January	ARMA(25,2) Model	2021.120232
February	ARMA(15,4) Model	2010.085696
March	ARMA(26,1) Model	2149.125407
April	ARMA(12,2) Model	2116.314800
May	ARMA(11,3) Model	2124.932809
June	ARMA(10,5) Model	2103.872810
July	ARMA(11,4) Model	2211.646762
August	ARMA(10,20) Model	2184.130164
September	ARMA(11,20) Model	1944.307180
October	ARMA(26,23) Model	1889.963026
November	ARMA(26,20) Model	2010.910964
December	ARMA(17,15) Model	2010.710013

Table 5. Estimated Model using first difference of Karachi Dew Frost point (D_K).

Month	Estimated Model	AICC
January	ARMA(11,2) Model	3271.409557
February	ARMA(14,1) Model	3123.278906
March	ARMA(8,2) Model	3216.430011
April	ARMA(24,2) Model	2806.173789
May	ARMA(11,2) Model	2432.332673
June	ARMA(11,2) Model	1634.632513
July	ARMA(12,7) Model	1326.494099
August	ARMA(9,23) Model	1338.639200
September	ARMA(25,20) Model	1857.038296
October	ARMA(9,20) Model	2917.764646
November	ARMA(19,10) Model	3095.942204
December	ARMA(18,20) Model	3186.857201

Table 6. Estimated Model using first difference of Jacobabad Average Temperature (T_J)

Month	Estimated Model	AICC
January	ARMA(24,25) Model	2004.768936
February	ARMA(5,25) Model	2012.367522
March	ARMA(11,26) Model	2325.921771
April	ARMA(26,25) Model	2316.969978
May	ARMA(10,26) Model	2289.673543
June	ARMA(12,25) Model	2261.096701
July	ARMA(15,26) Model	2427.010984
August	ARMA(5,26) Model	2166.059007
September	ARMA(7,20) Model	1952.813770
October	ARMA(26,26) Model	2163.800188
November	ARMA(26,26) Model	2020.386352
December	ARMA(11,26) Model	2079.821741

Table 7. Estimated Model using first difference of Jacobabad Relative Humidity (H_J)

Month	Estimated Model	AICC
January	ARMA(16,25) Model	3923.931385
February	ARMA(15,25) Model	3645.387141
March	ARMA(18,19) Model	3907.447798
April	ARMA(18,3) Model	3858.129116
May	ARMA(10,25) Model	4152.879617
June	ARMA(12,25) Model	4088.057031
July	ARMA(6,26) Model	4407.651120
August	ARMA(3,26) Model	4207.524601
September	ARMA(11,26) Model	4115.625019
October	ARMA(5,26) Model	3790.872821
November	ARMA(8,20) Model	3383.676341
December	ARMA(17,26) Model	3774.797257

Table 8. Estimated model using first difference of Jacobabad earth skin temperature (E_J)

Month	Estimated Model	AICC
January	ARMA(24,15) Model	2007.753766
February	ARMA(7,20) Model	2086.863974
March	ARMA(26,25) Model	2514.856613
April	ARMA(26,26) Model	2495.379784
May	ARMA(10,20) Model	2519.256652
June	ARMA(12,25) Model	2469.849752
July	ARMA(7,26) Model	2805.295567
August	ARMA(5,26) Model	2550.541828
September	ARMA(9,26) Model	2231.568576
October	ARMA(26,26) Model	2335.724593
November	ARMA(26,26) Model	2088.521619
December	ARMA(10,26) Model	2060.863062

Table 9. Estimated model using first difference of Jacobabad dew frost point (D_J)

Month	Estimated Model	AICC
January	ARMA(16,25) Model	2986.311929
February	ARMA(14,25) Model	2979.846713
March	ARMA(18,26) Model	3290.975833
April	ARMA(8,26) Model	3220.248989
May	ARMA(24,13) Model	3319.584407
June	ARMA(10,25) Model	3119.871981
July	ARMA(7,26) Model	2793.885885
August	ARMA(4,26) Model	2541.847181
September	ARMA(11,26) Model	2997.818156
October	ARMA(15,19) Model	3254.531680
November	ARMA(8,20) Model	2852.267952
December	ARMA(17,24) Model	2998.346691

Table 10. Mean Actual and Mean Forecasted Monthly Data of G.

Months	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
G_{MA}	1390.4	1383.9	1372.0	1357.9	1345.7	1338.1	1345.7	1350.6	1358.1	1368	1380.9	1389.5
G_{MF}	1386.9	1367.0	1365.5	1366.3	1366.5	1336.1	1366.4	1366.4	1365.8	1367	1376.5	1386.5

Table 11. Correlation b/w Mean Actual vs. Mean Forecasted Monthly Data of G.

Parameters	Correlation	*p*-values
G	0.773	0.003

Table 12 . Mean Actual and Mean Forecasted Monthly Data for all Parameters of Karachi

Months	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
D_{MAK}	2.745	5.59	10.996	15.173	19.441	22.484	23.315	22.525	20.634	14.949	8.405	2.477
H_{MAK}	36.008	39.262	43.307	47.957	55.838	65.225	72.029	71.741	64.903	46.946	37.376	32.162
E_{MAK}	20.881	23.984	29.039	32.087	33.497	33.67	32.219	31.426	31.558	31.557	27.368	22.22
T_{MAK}	18.916	21.12	25.108	27.89	29.61	29.746	28.85	28.065	27.9	28.071	24.899	20.66
D_{MFK}	-4.947	5.1359	13.179	19.357	24.012	23.121	21.847	21.916	18.883	14.94	2.1909	-0.828
H_{MFK}	23.621	33.633	48.234	64.116	74.621	71.988	68.436	72.826	55.833	47.139	32.604	25.792
E_{MFK}	19.102	29.904	29.017	30.859	31.349	30.363	31.386	30.227	32.467	31.762	23.773	21.311
T_{MFK}	17.916	22.949	25.247	28.44	29.179	28.755	28.161	27.255	28.89	27.711	22.633	20.355

Table 13. Correlation between Mean Actual vs. Mean Forecasted Monthly Data for all Parameters of Karachi

Parameters	Correlation	*p*-values
D_K	0.951	0.000
H_K	0.871	0.000
E_K	0.848	0.000
T_K	0.961	0.000

Table 14. Mean Actual and Mean Forecasted Monthly Data for all Parameters of Jacobabad

Months	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
D_{MAJ}	-2.917	-3.405	-1.508	1.511	4.306	12.532	19.156	19.72	12.885	0.747	-2.647	-3.904
H_{MAJ}	34.015	28.243	22.486	21.754	21.596	32.267	51.496	57.731	39.389	21.806	22.325	28.252
E_{MAJ}	14.999	18.739	25.73	32.313	37.299	38.74	36.872	34.144	33.594	28.556	22.075	16.551
T_{MAJ}	13.582	16.476	22.263	27.796	32.297	33.831	32.099	30.364	29.857	26.019	20.638	15.587
D_{MFJ}	-11.013	-10.779	-6.2875	1.728	10.943	22.519	14.141	15.926	3.435	-7.548	-10.845	-5.8686
H_{MFJ}	19.271	14.791	14.998	29.332	25.929	55.757	28.821	36.655	19.67	6.086	15.253	24.205
E_{MFJ}	14.206	19.834	26.47	34.158	39.331	36.439	41.815	38.228	34.186	27.816	17.442	15.399
T_{MFJ}	12.842	17.888	22.736	29.804	33.968	31.932	35.462	32.886	30.323	26.277	17.217	14.992

Table 15. Correlation between Mean Actual vs. Mean Forecasted Monthly Data for all Parameters of Jacobabad

Parameters	Correlation	*p*-values
D_J	0.861	0.000
H_J	0.405	0.191
E_J	0.971	0.000
T_J	0.975	0.000

Table 16. Correlation between Mean Actual Monthly Data of GSI vs. all terrestrial parameters of Karachi and Jacobabad

Parameters	D_{MAK}	H_{MAK}	E_{MAK}	T_{MAK}	D_{MAJ}	H_{MAJ}	E_{MAJ}	T_{MAJ}
G_{MA}	-0.964	-0.897	-0.925	-0.928	-0.812	-0.365	-0.989	-0.983
p-values	0.000	0.000	0.000	0.000	0.001	0.244	0.000	0.000

Table 17. Correlation between Mean Forecasted Monthly Data of G vs. all terrestrial parameters of Karachi and Jacobabad

Parameters	D_{MFK}	H_{MFK}	E_{MFK}	T_{MFK}	D_{MFJ}	H_{MFJ}	E_{MFJ}	T_{MFJ}
G_{MF}	-0.743	-0.709	-0.699	-0.731	-0.696	-0.634	-0.654	-0.663
p-values	0.006	0.010	0.011	0.007	0.012	0.027	0.021	0.019

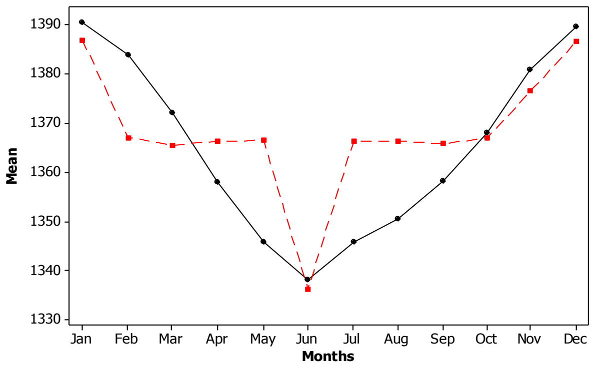

Figure 1. Time Series Plot of G_{MA} vs. G_{MF}

Figs. 2–5. Time Series Plot for Mean Actual vs. Mean Forecasted Monthly Data of Karachi.

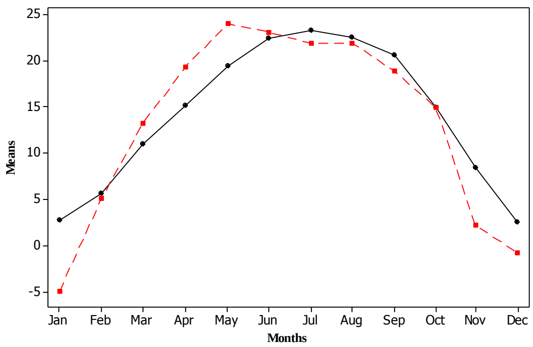

Figure 2. Time Series Plot of Mean $D_{K.}$.

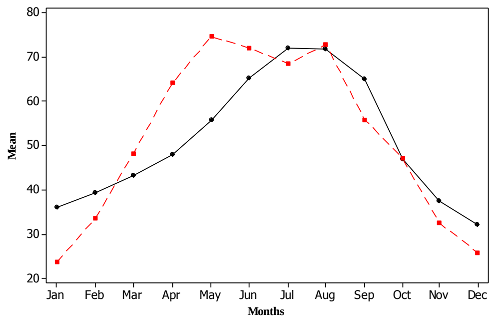

Figure 3. Time Series Plot of Mean $H_{K.}$

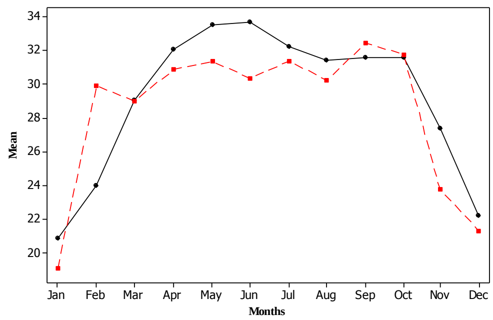

Figure 4. Time Series Plot of Mean E_K .

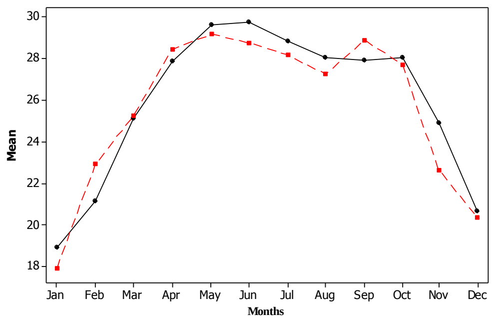

Figure 5. Time Series Plot of Mean $T_{K.}$

Figs. 6–9. Time Series Plot for Mean Actual vs. Mean Forecasted Monthly Data of Jacobabad.

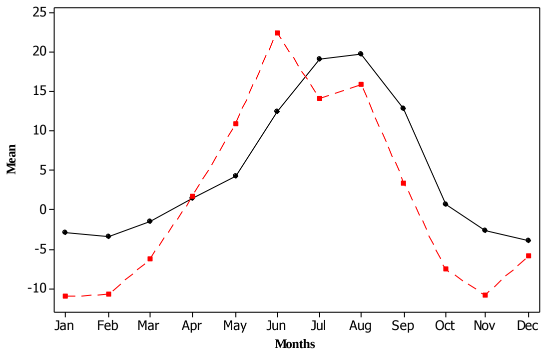

Figure 6. Time Series Plot of Mean D_J.

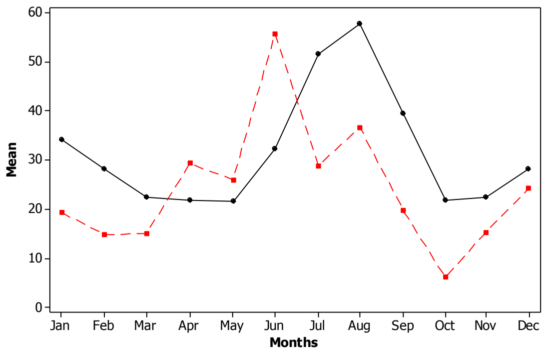

Figure 7. Time Series Plot of Mean H_J.

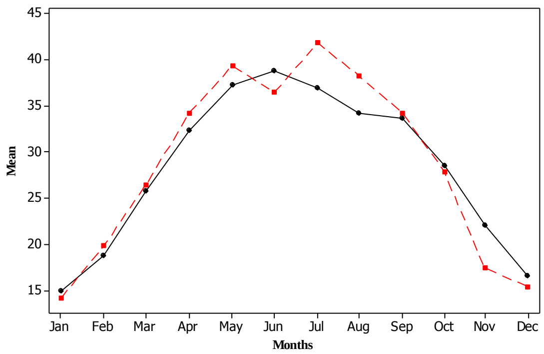

Figure 8. Time Series Plot of Mean E_J.

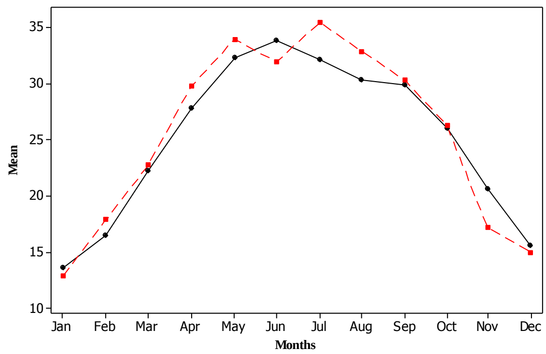

Figure 9. Time Series Plot of Mean T_J.

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