Evaluation of NCEP Products (NCEP-NCAR, NCEP-DOE, NCEP-FNL, NCEP-GFS) of Solar Radiation for Karachi, Pakistan

Zia ul Rehman Tahir, Muhammad Azhar, Muhammad Asim, Nasir Hayat, Hamza Shahid, and Hasnain Ali

Mechanical Engineering Department, University of Engineering and Technology Lahore, Pakistan

Abstract

The solar radiation data measured by ESMAP for Karachi, Pakistan is compared with four NCEP products (NCEP-NCAR, NCEP-DOE, NCEP FNL, NCEP-GFS). The evaluation of satellite estimates of solar radiation against surface measured data is performed on the basis of statistical analysis and daily mean time series. The statistical analysis shows that the mean bias error (MBE), root mean square error (RMSE) and correlation coefficient (R) for four datasets range from -4.48 to 63.24 W/m^2, 55.70 to 108.77 W/m^2 and 0.966 to 0.976 respectively. The monthly analysis of solar radiation is performed on the basis of daily mean time series to assess the impact of season on their accuracy. Cloud fraction is the main reason for less accuracy of solar radiation products for July and August because of Monsoon in Pakistan. Three-months evaluation of NCEP-FNL is also performed on the basis of monthly mean time series and scatter plots to assess the model performance of dataset in different seasons. The estimates from NCEP-NCAR are least accurate among all datasets whereas the performance of NCEP-FNL is most accurate for initial assessment of solar for Karachi. The results of NCEP-GFS are closer to NCEP-FNL, hence NCEP-GFS can be used to forecast solar energy for Karachi.

Keywords: Solar Radiation, NCEP-NCAR, NCEP-DOE, NCEP FNL, NCEP-GFS

1. Introduction

Energy sector is considered as the backbone for the economic development of a country. Pakistan spent more than 10 Billion USD on imports of fossil fuel in the year 2017 (Wasti, 2018). The solution to avoid or decrease the impact on the country's economy is to use local energy resources. Oil, gas and coal reserves of Pakistan are limited that may last in a few years if we completely utilize these with current reserve to production ratio. The other natural resources are hydroelectric, wind and solar energy. The hydroelectric resources are suitable for the large-scale projects; Indus water treaty, earthquake danger areas and the internal political rift are the key barriers to utilize these resources. Wind is located in the coastal areas and the capacity factor is also low (0.2-0.25).

Pakistan's geographic location and climate offer a very high potential for solar energy applications. Accurate and precise solar resource assessment of the potential site is a prerequisite for the successful deployment of any solar energy system. The high-quality surface measured data for solar radiations is not usually available on the potential site, to ensure proper solar assessment and thus to secure the final acceptance of the project. The long-term time series of solar radiation data are required for the success of the solar projects which might not available for the potential project site. The long-term time series estimates are available in the form of satellite reanalysis and analysis datasets.

The organizations all over the world provide long-term solar radiation datasets: The United States National Centers for Environmental Prediction (NCEP), The European Centre for Medium-Range Weather Forecasts (ECMWF) and The Japan Meteorological Agency (JMA). The National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) collaborated to produce a record of global reanalysis of atmospheric fields and named this project as NCEP-NCAR. The NCEP worked with Department of Energy USA on a project named as NCEP-DOE. The NCEP-FNL was recently launched as the final product of the Global Data Assimilation System (GDAS) used by NCEP Global Forecast Systems (GFS) model, it includes observations in its model.

The evaluation of these datasets is performed to study the model performance of these datasets, the evaluation is carried out on the basis of statistical analysis which includes the parameters: Mean Bias Error (MBE), Root Mean Square Error (RMSE), Relative Errors (rMBE, rMAE, rRMSE) and Correlation Coefficient (R). The statistical analysis of these datasets indicates the errors in the estimation of solar radiation by these datasets. Da Silva et al. (Da Silva et al., 2010) in their study for North Eastern Brazil pointed out errors in the estimation of solar radiation by NCEP-NCAR. Zhang et al. (Zhang et al., 2016) in their study for six products (ERA-Interim, MERRA, NCEP-NCAR, NCEP-DOE, CFSR, and JRA-55) indicated bias in estimation of solar radiation ranging between -2.98 to

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49.80 W/m^2. A study of surface solar radiation for different regions of China by Xia et al. (Xia et al., 2006) revealed that the NCEP-DOE overestimated solar radiations ranging from 55.01 to 80.86 W/m^2.

The datasets like NCEP-NCAR and NCEP-DOE have been widely studied by researchers, the datasets like NCEP-FNL and NCEP-GFS have not been reported much in literature being the recent products of NCEP. This study is first of its own type for Pakistan, the evaluation of these datasets has not been performed for the South Asia region. The aim of this study is to compare surface measured data with four NCEP solar radiation data sets. The surface measured data from Karachi was used for evaluation of NCEP data. The current study will help researchers and project planners to evaluate the initial assessment of a potential site in Pakistan.

2. Datasets

The surface measured data (GHI) for Karachi for the year 2016 was used. The solar surface radiation measurement system for Karachi is installed at NED University of Engineering and Technology (UET) and coordinates of stations are 24.933°N, 67.112°E. The surface data was measured by The Energy Sector Management Assistance Program (ESMAP) of the World Bank. Four globally available NCEP products for solar fluxes were used for the study; NCEP-NCAR, NCEP-DOE, NCEP-FNL, GFS. These datasets have different spatial resolution and radiative transfer model. NCEP-NCAR provides global data of solar radiations from 1948 with spatial resolution is 1.905°×1.875° (Kalnay et al., 1996). NCEP-NCAR uses Lacis and Hansen (Lacis and Hansen, 1974) parameterization method and does not consider aerosol in its model. NCEP in collaboration with the Department of Energy, USA (DOE) gave a new reanalysis dataset known as NCEP-DOE which has a spatial resolution of 1.905°×1.875° (Kanamitsu et al., 2002). The parameterization method of Lacis and Hansen (Lacis and Hansen, 1974) was replaced by Chou (Chou, 1992) and Chou and Li (Chou and Lee, 1996) model in NCEP-DOE. NCEP-FNL commonly known as NCEP final is the product of the Global Data Assimilation System (GDAS), the spatial resolution used for this study is 0.117° × 0.117°. The NCEP operational Global Forecast System (NCEP-GFS) analysis and forecast grids are on a spatial resolution of 0.25º × 0.25º. NCEP-FNL and NCEP-GFS use the same model while NCEP-GFS model runs earlier, also NCEP-FNL has an aerosol component called as NOAA Environment Modeling System GFS Aerosol component (NGAC), that makes it better to predict surface solar radiations. All above four reanalysis or model forecast datasets have a temporal resolution of six hours and runs occur at 00, 06, 12, and 18 UTC daily.

3. Methodology

The evaluation of solar radiation datasets has been performed on the basis of statistical analysis and daily mean time series. To quantify the performance of solar radiation from various NCEP datasets in comparison with surface measured data, mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), relative mean bias error (rMBE), relative mean absolute error (rMAE), relative root mean square error (rRMSE), and correlation coefficient (R) have been calculated. These parameters were used in other similar studies (Espinar et al., 2009). MBE is the average difference between estimated solar radiations from NCEP products and surface measured solar radiations, the values of MBE closer to zero are desirable. RMSE is calculated by squaring the difference estimated and measured solar radiations, the smaller values of RMSE are acceptable. Correlation coefficient explains the linear relationship between estimated and measured solar radiations, the value closer to 1 indicates the 1:1 relation between estimated and measured solar radiations. The NCEP products provide different variables of solar fluxes but the downward shortwave radiations generally represent global horizontal irradiance (GHI). The surface measured data has a temporal resolution of ten minutes, which was converted to the temporal resolution of 6 hours at UTC for comparison with NCEP datasets, the NCEP products used in the study have a temporal resolution of 6 hours. The satellite datasets were downloaded in netCDF format and MATLAB program was used to get time series for a specific location. The satellite data for the specific location was calculated from four nearby grid points using bilinear interpolation.

4. Results and Discussion

To quantify the relationship between solar radiation datasets and surface solar measurements, the statistical parameters: MBE, MAE, RMSE, rMAE, rMBE, rRMSE and R were calculated, the statistical analysis is presented in Table 1. The MBE values can be positive and negative representing overestimation and underestimation of solar radiations on the surface respectively. The RMSE values are always positive and values closer to zero indicate lesser errors. NCEP-NCAR data overestimates solar radiation, the MBE and RMSE values for Karachi are 63.24 W/m^2 and 108.77 W/m^2 respectively, which are close to the results derived in a study by Zhang et al. (Zhang et al., 2016). This overestimation has also been reported by multiple studies (Hicke, 2005). The relative errors: rMBE, rMAE, rRMSE are 29.13 %, 30.12 % and 50.11 % respectively for NCEP-NCAR. The smaller values of relative errors are acceptable, the rRMSE is largest of all the relative errors for NCEP-NCAR which indicates the inefficiency of the solar model to incorporate the larger errors. The slope for NCEP-NCAR is 1.15 which represents the overestimation of large values. The intercept for NCEP-NCAR is 29.83 which represents the relation between solar radiations estimated by NCEP-NCAR and measured solar radiations. The aerosols were not considered in the NCEP-NCAR model which is the potential reason of larger errors and inaccurate estimation of solar radiation to the Earth's surface. The fit for NCEP-NCAR came out to be 0.966, the value is close to 1 hence the points are more scattered along 1:1 Line.

The NCEP-DOE also overestimates the solar radiations on the surface. The MBE and RMSE values are 39.28 W/m^2 and 92.27 W/m^2, the results are in accordance with the study of Jia et al. (Jia et al., 2013) where the reanalysis overestimated the solar radiations. Zhang et al. (Zhang et al., 2016) in their study also indicated similar overestimation of surface solar radiation by NCEP-DOE, the MBE and RMSE values were reported as 30.83 W/m^2 and 46.82 W/m^2 respectively The radiative transfer model of Lacis and Hansen (Lacis and Hansen, 1974) in NCEP-NCAR was replaced by Chou (Chou, 1992) and Chou and Lee (Chou and Lee, 1996) in NCEP-DOE which resulted in better estimation of solar radiations compared to NCEP-NCAR. The NCEP-DOE considers aerosol in its radiative transfer model, also the cloud fraction for NCEP-DOE was improved hence the results are better than NCEP-NCAR. The relative errors rMBE, rMAE, rRMSE are 18.10 %, 22.75 % and 42.51 % respectively for NCEP-DOE. The relative errors are less than NCEP-NCAR, the rRMSE value is 7.6 % lesser which indicates the better model performance of NCEP-DOE to incorporate larger errors compared to NCEP-NCAR. The slope for NCEP-DOE is 1.09 which represents the overestimation of larger values, the slope of NCEP-DOE is comparatively less than NCEP-NCAR. The intercept for NCEP-DOE is 19.70, the smaller values of intercept are acceptable and intercept for NCEP-DOE is smaller than NCEP-NCAR. The fit for NCEP-DOE is 0.961, the points are less scattered along 1:1 Line compared to NCEP-NCAR.

The results for NCEP-FNL are far better than the previous two datasets because its model includes the latest aerosol component known as NGAC, it overestimates solar radiations by 3.13 W/m^2. The RMSE value is 56.57 W/m^2 which is again less than NCEP-NCAR and NCEP-DOE. The relative errors rMBE, rMAE, rRMSE are 1.44 %, 11.98 % and 26.06 % respectively for NCEP-FNL, the relative errors of NCEP-FNL are less than both NCEP-NCAR and NCEP-DOE. The slope for NCEP-FNL is 0.98 which represents the underestimation of larger values. The intercept for NCEP-FNL is 8.06, for NCEP-FNL is smaller than both NCEP-NCAR and NCEP-DOE. The fit for NCEP-FNL is 0.976 which indicates that most of the points are scattered along 1:1 Line, the correlation of NCEP-FNL is better than both NCEP-NCAR and NCEP-DOE. The aerosol component incorporated in NCEP-FNL resulted in a better estimation of solar radiation for the Industrial city of Karachi, the surface solar radiations are reduced because of the air pollution.

The NCEP-GFS has the same trend as NCEP-FNL, there is an overall underestimation of solar radiations by NCEP-GFS and MBE value is -4.48 W/m^2. The MAE value for NCEP-FNL and NCEP-GFS are quite close which indicates that the overall error for both the datasets is same. The RMSE value for NCEP-GFS is 55.70 W/m^2 that is better than NCEP-FNL, the NCEP-GFS has incorporated larger errors and outliers slightly better than NCEP-FNL. The relative errors for NCEP-FNL are less than that of NCEP-GFS. The relative errors rMBE, rMAE, rRMSE are -2.06 %, 12.81 % and 25.66 % respectively for NCEP-GFS, the relative errors of NCEP-GFS are close to NCEP-FNL, the possible reason is similar data assimilation technique. The slope for NCEP-GFS is 0.94 which represents the underestimation of larger values. The intercept for NCEP-DOE is 8.26, the intercept for NCEP-GFS is close to the intercept for NCEP-FNL. The fit for NCEP-GFS is 0.976 which indicates that most of the points are scattered along 1:1 Line, the correlation of NCEP-GFS is same as that of NCEP-FNL. The overall results indicate that the NCEP-FNL has predicted surface solar radiations better for Karachi. The forecast results of NCEP-GFS are also close to NCEP-FNL, the reason being the same solar model except for the new aerosol component.

The daily mean time series of solar radiations for all the four datasets for the year 2016 indicates the variation of solar radiation throughout the year. The time series of solar radiation form NCEP products tended to follow the surface measurements. The NCEP datasets could not predict the exact trends but they followed the solar energy variations in different months. The results for the datasets vary from January to December depending upon the season and seasonal anomalies. The Karachi like rest of Pakistan has four seasons winter, spring, summer and autumn. The spring and autumn are indistinguishable because of no drastic changes of temperature, the summer and winter are the prevalent seasons of the city.

Tab. 1: Comparison between surface measured data and satellite data

Dataset	MBE	MAE	RMSE	rMBE	rMAE	rRMSE	*m*	*c*	R
NCEP-NCAR	63.24	65.39	108.77	29.13	30.12	50.11	1.15	29.83	0.966
NCEP-DOE	39.28	49.39	92.27	18.10	22.75	42.51	1.09	19.70	0.961
NCEP-FNL	**3.13**	**26.01**	56.57	**1.44**	**11.98**	26.06	0.98	8.06	**0.976**
NCEP-GFS	-4.48	27.81	**55.70**	-2.06	12.81	**25.66**	0.94	8.26	**0.976**

The January is the coolest month of the city with mostly clear skies and dry Siberian winds called Quetta waves hit the city, the western disturbances coming from the Persian Gulf bring light rain with them. The measured solar radiations in January range from 89.12 to193.06 W/m^2. The MBE values in January for NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 39.32 W/m^2, 29.19 W/m^2, -1.59 W/m^2 and 4.30 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month. The maximum and minimum values of solar radiation for NCEP-NCAR in January are 240.65 W/m^2 and 147.95 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for January are 216.74 W/m^2 and 148.95 W/m^2 respectively. The NCEP-FNL slightly overestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for January are 185.75 W/m^2 and 91.76 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for January are 178.04 W/m^2 and 105.47 W/m^2 respectively.

From February the warming trend begins in the city, the skies are overcast because of the western disturbances, the intensity of rain is more compared to the preceding month. The measured solar radiations in February range from 174.94 to 238.70 W/m^2. The MBE values in February for NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 55.62 W/m^2, 32.05 W/m^2, -11.25 W/m^2 and -2.13 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month. The maximum and minimum values of solar radiation for NCEP-NCAR in January are 290.85 W/m^2 and 235.25 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for February are 269.88 W/m^2 and 202.16 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for February are 232.96 W/m^2 and 190.59 W/m^2 respectively. The NCEP-GFS also underestimates the solar radiations for the month of February. The maximum and minimum values of solar radiations by NCEP-GFS for February are 223.41 W/m^2 and 181.34 W/m^2 respectively.

The March is springtime in the city with clear blue skies, the western depressions can bring moderate rainfall in this month. The measured solar radiation in March ranges from 155.25 to 288.33 W/m^2. The MBE values for March by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 37.22 W/m^2, 2.44 W/m^2, -18.27 W/m^2 and -8.05 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in March are 339.63 W/m^2 and 118.50 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for March are 314.65 W/m^2 and 99.64 W/m^2 respectively. The estimations of NCEP-DOE for March are better than the preceding month. The NCEP-FNL underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for March are 272.20 W/m^2 and 142.84 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are somehow closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for March are 261.46 W/m^2 and 139.37 W/m^2 respectively.

The April is a relatively hot month of the city with humidity increasing, the western depressions from the Persian Gulf may bring heavy rain with them. The measured solar radiation in April ranges from 190.36 to 315.89 W/m^2. The MBE values for March by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 54.24 W/m^2, 35.26 W/m^2, -20.95 W/m^2 and -9.51 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in April are 374.3 W/m^2 and 212.73 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for April are 345.68 W/m^2 and 237.99 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for April are 295.52 W/m^2 and 174.36 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations, the maximum and minimum values of solar radiations by NCEP-GFS for January are 283.78 W/m^2 and 165.38 W/m^2 respectively.

The May is the hottest month of the city with rare rainfall, the cyclones can hit the city causing overcast. The measured solar radiation in May ranges from 139.16 to 310.75 W/m^2. The MBE values for May by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 64.40 W/m^2, 43.10 W/m^2, -9.36 W/m^2 and 2.74 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in May are 375.59 W/m^2 and 293.31 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for May are 349.67 W/m^2 and 251.83 W/m^2 respectively. The NCEP-FNL slightly overestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for May are 298.60 W/m^2 and 273.07 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and overall estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for May are 285.10 W/m^2 and 262.31 W/m^2 respectively.

The climatic conditions of June are similar to precedent month, the effect of cyclones as tropical depressions along the coast of Karachi can cause rainfalls and overcast. The measured solar radiation in June ranges from 175.18 to 328.27 W/m^2. The MBE values for June by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 71.05 W/m^2, 37.70 W/m^2, -12.76 W/m^2 and -1.87 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in June are 379.24 W/m^2 and 283.74 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for June are 351.03 W/m^2 and 247.59 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for June are 302.23 W/m^2 and 93.58 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for June are 288.71 W/m^2 and 115.26 W/m^2 respectively.

The July is the month when monsoon starts in the city, the low-level layers cover the sky for the most part of the day. The measured solar radiation in July ranges from 43.43 to 287.50 W/m^2. The MBE values for July by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 121.91 W/m^2, 105.67 W/m^2, 20.15 W/m^2 and 19.45 W/m^2 respectively. The time series for NCEP-NCAR highly overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in July are 341.71 W/m^2 and 248.51 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for July are 328.49 W/m^2 and 136.13 W/m^2 respectively. The NCEP-FNL slightly overestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for July are 279.59 W/m^2 and 62.99 W/m^2 respectively. The NCEP-GFS overestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for July are 266.44 W/m^2 and 83.17 W/m^2 respectively.

The climatic conditions of August are similar to precedent month, the monsoon weakens in last week of August. The measured solar radiation in August ranges from 89.12 to 280.52 W/m^2. The MBE values for August by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 116.14 W/m^2, 73.98 W/m^2, 31 W/m^2 and 34.02 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in August are 350.04 W/m^2 and 235.41 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for August are 324.16 W/m^2 and 147.32 W/m^2 respectively. The NCEP-FNL slightly overestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for August are 274.85 W/m^2 and 25.86 W/m^2 respectively. The NCEP-GFS overestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for August are 262.07 W/m^2 and 31.41 W/m^2 respectively.

The September has light rainfall for the first two weeks, the monsoon completely withdraws from the city. The measured solar radiation in September ranges from 75.13 to 276.03W/m^2. The MBE values for September by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 50.13 W/m^2, 31.31 W/m^2, -8.00 W/m^2 and -1.43 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in September are 318 W/m^2 and 217.81 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for September are 294.49 W/m^2 and 172.61 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for September are 267.43 W/m^2 and 48.42 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for September are 255.70 W/m^2 and 72.23 W/m^2 respectively.

The October is the driest month of the city with clear skies, October is the second hottest month of the city after May due to Post-Monsoon summer. The measured solar radiation in October ranges from 196.01 to 246.91 W/m^2. The MBE values for October by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 55.31 W/m^2, 25.64 W/m^2, -11.16 W/m^2 and -2.88 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations in this month, the maximum and minimum values of solar radiation for NCEP-NCAR in October are 304.53 W/m^2 and 245.72 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for October are 282.07 W/m^2 and 128.42 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for October are 239.78 W/m^2 and 179.56 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for October are 229.42 W/m^2 and 177.90 W/m^2 respectively.

The November has warm days and conditions are similar to October. The measured solar radiation in November ranges from 165.47 to 207.55 W/m^2. The time series for NCEP-NCAR overestimates the solar radiations in this month but the estimations are comparatively close to the measured solar radiations. The MBE values for September by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 45.28 W/m^2, 27.23 W/m^2, -9.21 W/m^2 and -1.25 W/m^2 respectively. The maximum and minimum values of solar radiation for NCEP-NCAR in November are 254.18 W/m^2 and 201.90 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for November are 233.49 W/m^2 and 194.35 W/m^2 respectively. The NCEP-FNL slightly underestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for November are 202.322 W/m^2 and 164.97 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for November are 194.01 W/m^2 and 157.82 W/m^2 respectively.

The December is the start of winter in the city, the sky remains overcast for part of the month. The measured solar radiation in December ranges from 137.39 to 179.45 W/m^2. The MBE values for December by NCEP-NCAR, NCEP-DOE, NCEP-GFS and NCEP-FNL are 46.70 W/m^2, 26.48 W/m^2, -3.75 W/m^2 and 2.98 W/m^2 respectively. The time series for NCEP-NCAR overestimates the solar radiations, the maximum and minimum values of solar radiation for NCEP-NCAR in December are 221.15 W/m^2 and 175.581 W/m^2 respectively. The NCEP-DOE also overestimates the solar radiations and estimations are better than NCEP-NCAR. The maximum and minimum values of solar radiations by NCEP-DOE for December are 197.102 W/m^2 and 168.67 W/m^2 respectively. The NCEP-FNL slightly overestimates the solar radiations and estimations are better than both NCEP-NCAR and NCEP-DOE. The maximum and minimum values of solar radiations by NCEP-FNL for December are 173.78 W/m^2 and 158.47 W/m^2 respectively. The NCEP-GFS underestimates the solar radiations and estimations are closer to the results of NCEP-FNL. The maximum and minimum values of solar radiations by NCEP-GFS for December are 167.16 W/m^2 and 149.80 W/m^2 respectively.

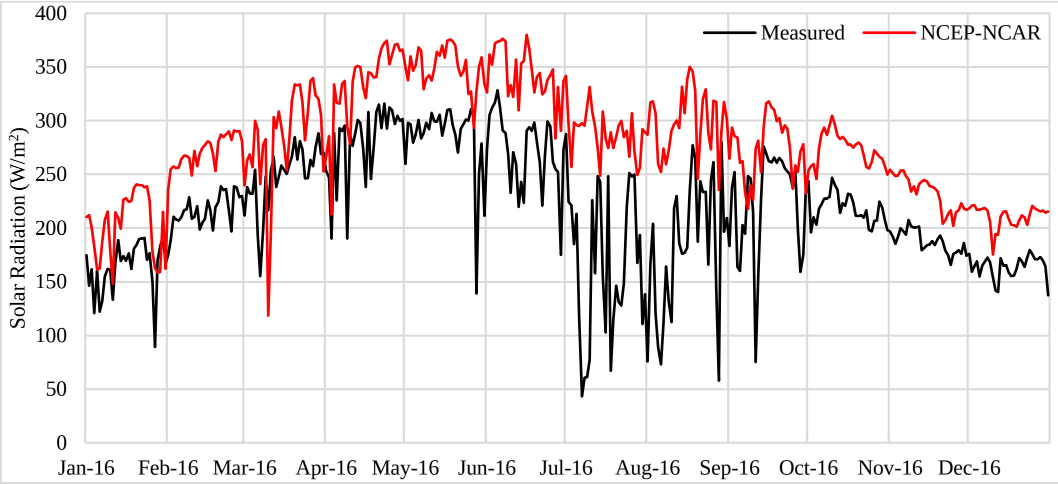


Fig. 1: Comparison of daily mean time series of solar radiation from NCEP-NCAR and measurements

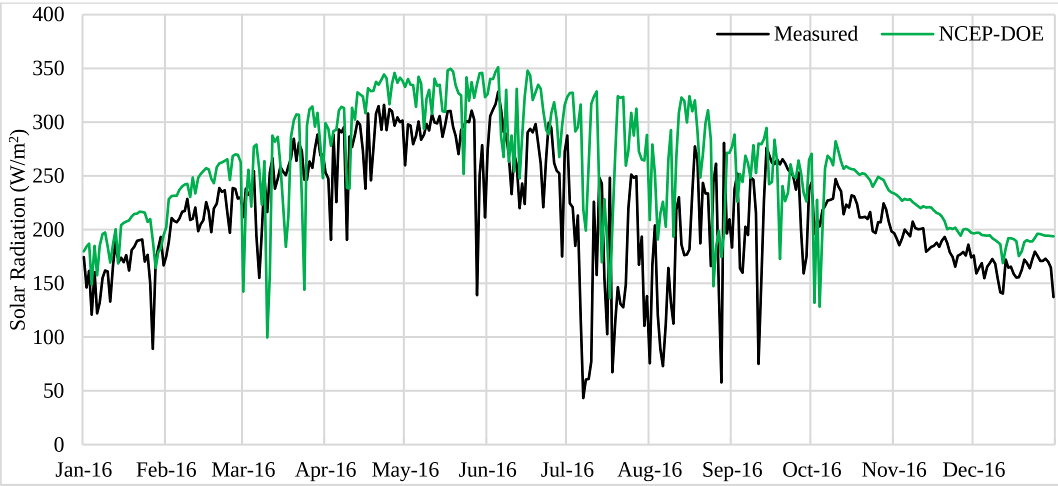


Fig. 2: Comparison of daily mean time series of solar radiation from NCEP-DOE and measurements

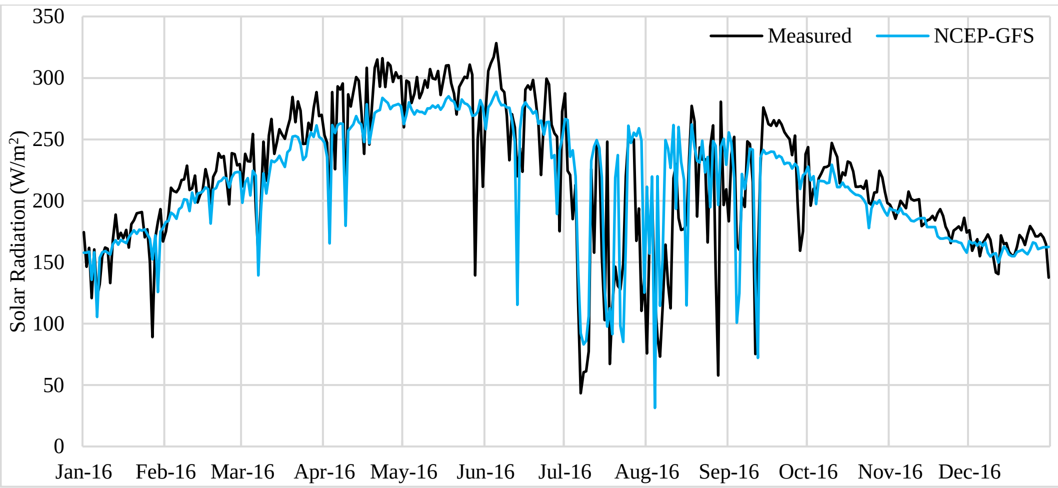


Fig. 3: Comparison of daily mean time series of solar radiation from NCEP-GFS and measurements

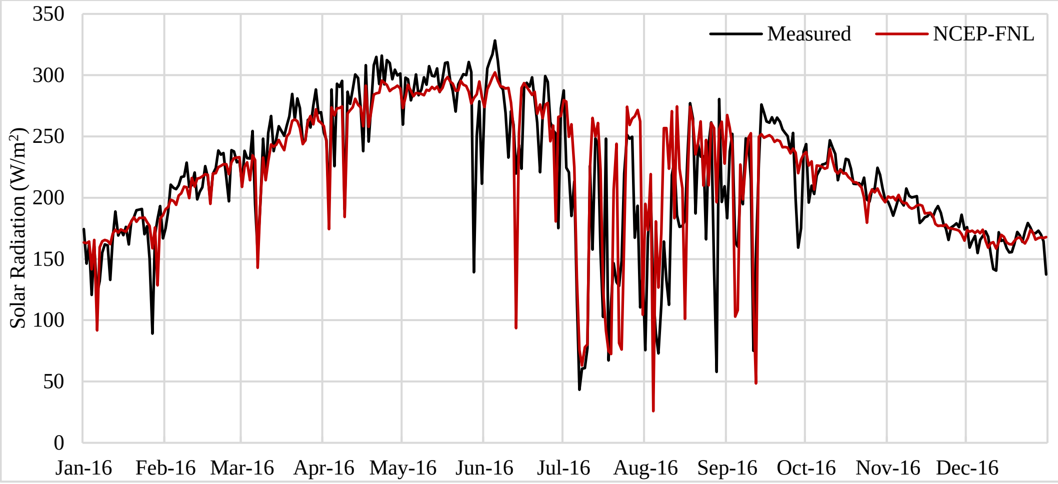
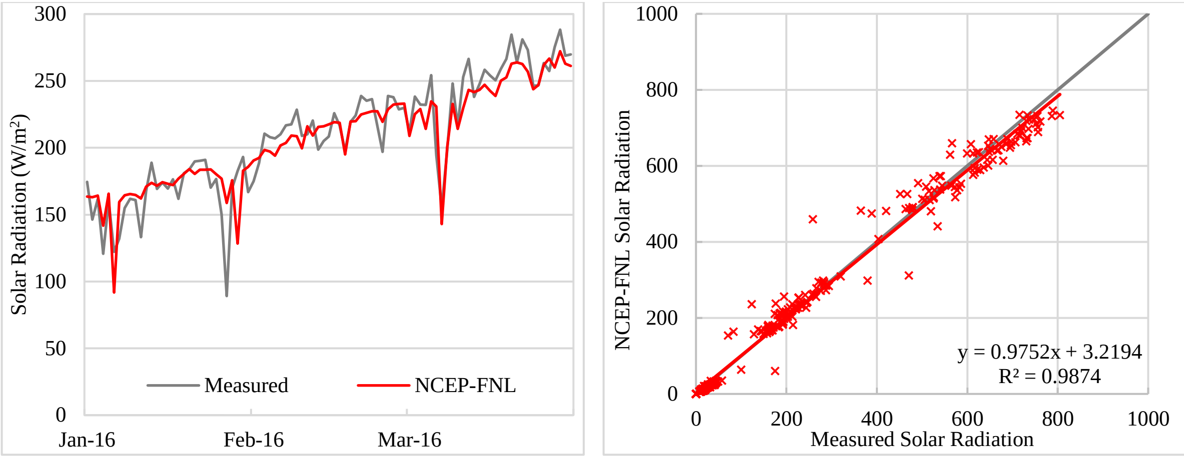


Fig. 4: Comparison of daily mean time series of solar radiation from NCEP-FNL and measurements

The NCEP-NCAR and NCEP-DOE mostly overestimated the solar radiations on the surface except for some days in March and October. The difference between NCEP-NCAR and surface measurements is more compared to the difference between NCEP-DOE and surface measurement. The NCEP-DOE detected the trend of surface solar radiations relatively better compared to NCEP-NCAR, the reason is updated radiative transfer model of NCEP-DOE. The Karachi has more aerosol factor being the industrial city, the pollution causes errors in the estimation of solar radiations. The similar reason has also been reported in a study by Xia et al. (Xia et al., 2006)for China. The optical thickness of aerosol may exceed 2.0 because of heavy pollution (Xiang-Ao et al., 2005), hence the heavy aerosol under cloud layer can cause up to 20-30 W/m^2 overestimation if not properly treated in the solar model (T. Hayasaka et al., 2004). The monthly analysis from daily time series indicates that results are most distorted for the months of June, July and August. This is the time of Monsoon in the city and cloudiness increases which suggests that the errors in the estimation of solar radiation increase with an increase in cloudiness. The cloud cover amount varies from one season to another, the winter season is mostly clear and in summers the sky remains overcast. El-Metwally (El-Metwally, 2005) after analyzing the solar radiation estimation in Egypt pointed out that the cloudiness is the reason for the increase in errors. He explained that the cloudiness increases because of the winter extra-tropical systems crossing over the Mediterranean due to which errors also increase in solar estimation. The daily time series analysis indicates that the predictions of solar radiation datasets are better for less cloudy months. Yang et al. (Yang et al., 2001) in their study have also indicated that the cloudy sky conditions are the potential reason for larger errors.

The NCEP-FNL is most updated dataset of NCEP, the results of NCEP-FNL are better than NCEP-NCAR and NCEP-DOE. The MBE and RMSE values for NCEP-FNL are 3.13 W/m^2 and 26.01 W/m^2 respectively, which indicates a better estimation of solar radiation by NCEP-FNL radiative transfer model. The NCEP-FNL includes oxides of carbon, Sulphur and quick-fire emissions in its model that play an important role in the better prediction of solar radiations for an Industrial city like Karachi. The pollution of Karachi is the potential reason for poor predictions, the atmospheric aerosol component used in NCEP-FNL incorporated most of air pollution components hence the overall results of NCEP-FNL are better. For understanding the seasonal dependency of radiative transfer model of NCEP-FNL three-month variation of estimation has been studied on the basis of daily mean time series and scatter plots.

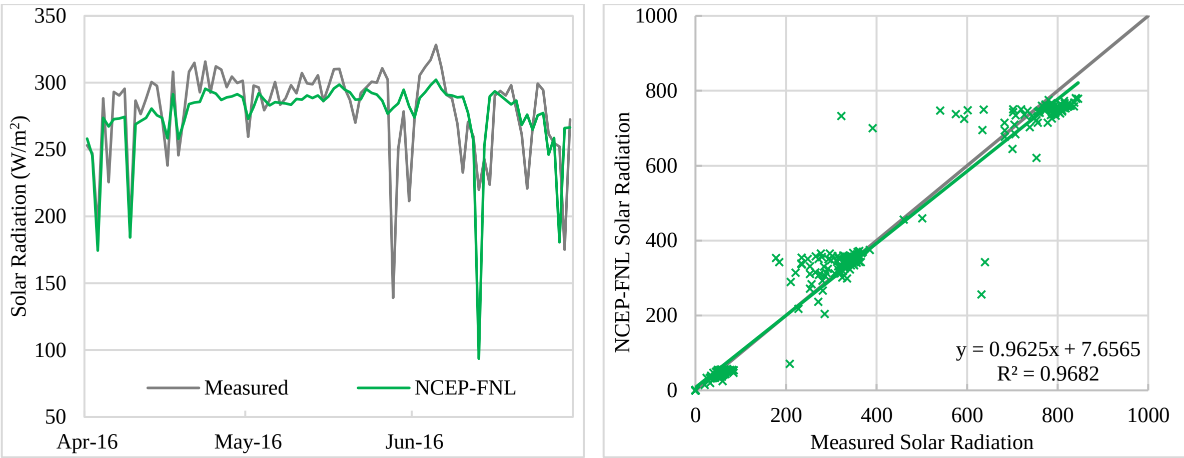
January and March are relatively clear months and there is no issue of cloud fractions, the sky remains overcast for some days of February. The estimated solar radiation by NCEP-FNL follows the trend of measured solar radiation, the bias for these months is comparatively lower. The solar radiations have an overall increasing trend from January to March, the average bias for these months is -1.96 W/m^2. The regression analysis of measured and NCEP-FNL solar radiation for January, February and March is presented in Fig. 5. The R^2 value for these three months is 0.987 which indicates that the scatter of points is close to 1:1 Line, the higher values of solar radiation are underestimated. The slope is 0.97 which indicates that the trend of best-fit is close to 1:1 Line.



(a) **(b)**

Fig. 5: NCEP-FNL versus measured solar radiation for January to March 2016 (a) Daily mean time series (b) Scatter plot

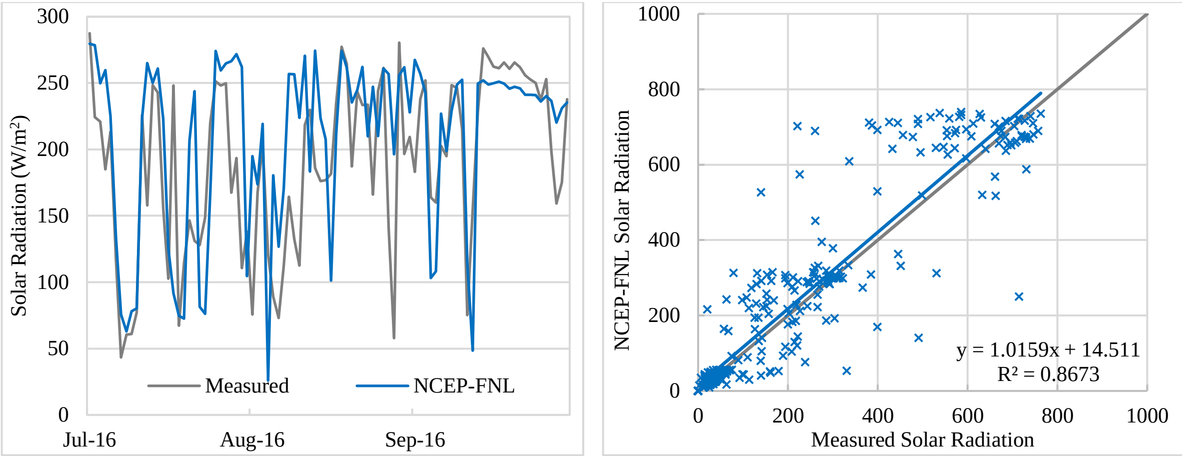
April has the effect of western depressions which causes unclear sky conditions; May and June have similar climatic conditions the effect of cyclones can cause sky overcast in these months. The estimated solar radiation by NCEP-FNL follows the trend of measured solar radiation except for some days of these three months, the bias for these months is higher compared to precedent three months. The average bias for April, May and June is -2.82 W/m^2. The regression analysis of measured and NCEP-FNL solar radiation for April, May and June is presented in Fig. 6. The R^2 value for these three months is 0.968 which indicates that scatter of points is close to 1:1 Line, the higher values of solar radiation are underestimated. The scatter for April, May and June is more compared to January, February and March. The slope is 0.96 which indicates that the trend of best-fit is close to 1:1 Line.



(a) **(b)**

Fig. 6: NCEP-FNL versus measured solar radiation for April to June 2016 (a) Daily mean time series (b) Scatter plot

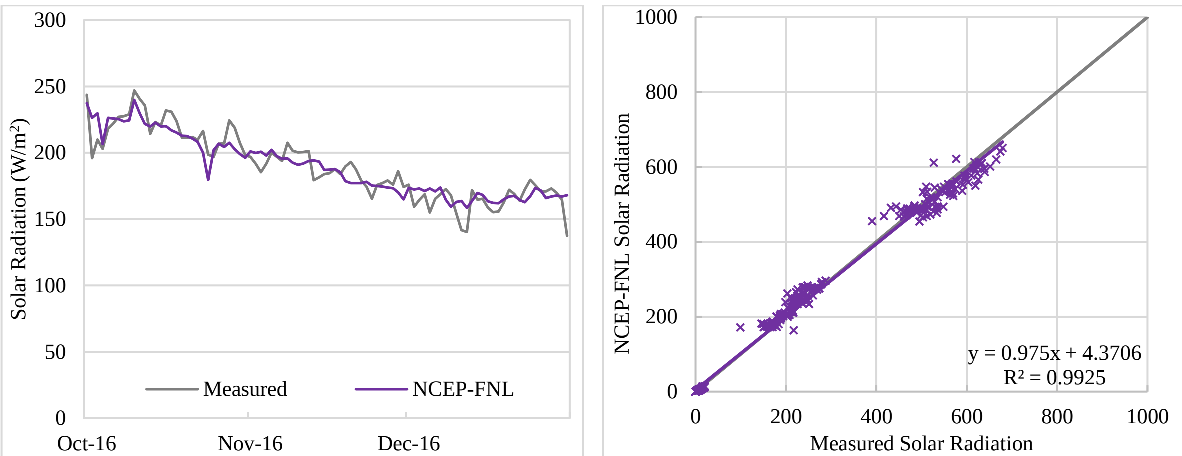
July, August and September are months of Monsoon in the city; the sky remains cloudy during Monsoon. The estimated solar radiation by NCEP-FNL tended to follow the trend of measured solar radiation whereas the predictions are poor due to the unpredictability of Monsoon, the bias for these months is highest for these three months compared to the rest of year. The solar radiations continuously variate from July to September, the average bias for these months is -2.82 W/m^2. The regression analysis of measured and NCEP-FNL solar radiation for July, August and September is presented in Fig. 7. The R^2 value for these three months is 0.867 which indicates more scatter for these months, the values of solar radiation are overestimated. The scatter for July, August and September is more due to Monsoon and cloud fraction considered in the solar model. The slope is 1.01 which indicates that the trend of best-fit is close to 1:1 Line although overestimating.



(a) **(b)**

Fig. 7: NCEP-FNL versus measured solar radiation for July to September 2016 (a) Daily mean time series (b) Scatter plot

October and November are dry months of the city due to post-Monsoon Summer, December is winter month and the sky remains overcast for part of the month. The estimated solar radiation by NCEP-FNL follows the trend of measured solar radiation except for some days of these three months. The solar radiations have an overall increasing trend from October December, the average bias for these months is -0.37 W/m^2. The regression analysis of measured and NCEP-FNL solar radiation for July, August and September is presented in Fig. 8. The R^2 value for these three months is 0.992 which indicates that the scatter is around 1:1 Line, the values of solar radiation are underestimated. The scatter for October, November and December is less due to clear sky conditions. The slope is 0.97 which indicates that the trend of best-fit is close to 1:1 Line.



(a) **(b)**

Fig. 8: NCEP-FNL versus measured solar radiation for October to December 2016 (a) Daily mean time series (b) Scatter plot

The overall results show that the NCEP-NCAR and NCEP-DOE both overestimate solar radiations, the reduction in solar radiation is due to the burning of fossil fuel in power stations and transport, and other atmospheric pollutants. These pollutants reflect solar energy back out to space. The NCEP-NCAR does not consider aerosol in its model hence the reduction in solar radiation was not predicted by NCEP-NCAR. The NCEP-DOE considers aerosol in its model, the results are better than NCEP-NCAR but still, there is an overestimation. The NCEP-FNL has the latest aerosol component in its model that helps it to better predict the solar radiations according to the atmospheric conditions of Karachi. The reason for higher errors in the summer season is because of inaccurate consideration of cloud fraction in solar models.

The NCEP-GFS underestimates the solar radiation throughout the year, except for some months of summer season. The differences between NCEP-GFS and measured values are comparatively less. The overall trend of solar radiations of NCEP-GFS for Karachi is similar to that of NCEP-FNL, the results of NCEP-FNL are better. The NCEP-GFS model runs earlier and provides the forecast of solar radiations for coming 16 days. The relative errors of NCEP-GFS are round about 10 %, the NCEP-GFS can prove to be a useful tool for solar radiation forecast of Karachi.

5. Conclusion

The RMSE and MBE values for Karachi range from 55.70 to 108.77 W/m^2 depending upon the radiative transfer model of NCEP datasets. The results of NCEP-NCAR are least accurate among all datasets because the aerosol component was not considered in its model, the MBE and RMSE values are 63.24 W/m^2 and 108.77 W/m^2 respectively. The results of NCEP-FNL are most accurate among all datasets accurate due to the improved model and better incorporation of aerosol components, the MBE and RMSE values are 3.13 W/m^2 and 56.57 W/m^2 respectively.

These NCEP datasets both overestimate and underestimate solar radiation for Karachi due to seasonal variation. The best correction coefficient for Karachi is 0.976 for NCEP-GFS. The best estimation of solar radiations by datasets is in the months with clear sky, the worst predictions are for July and August due to Monsoon in Pakistan as the sky conditions are cloudy for these months. The improvements in the satellite estimates of solar radiation can be done by refining cloud covers and aerosols in the physical models. Based on the statistical analysis and daily time series analysis the NCEP-FNL is the most suitable dataset for Karachi for initial solar assessment. The results of NCEP-GFS are closer to NCEP-FNL hence NCEP-GFS is suitable to forecast solar energy for Karachi.

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