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Alekhya Datta received the B. Tech degree in Electrical Engineering from West Bengal University of Technology, Kolkata, India, in 2008, and the MS degree in *Geo-Informatics* from Symbiosis International University, Pune, India, in 2010. In February 2010, he has joined the Solar Energy Centre, Ministry of New and Renewable Energy (Government of India) as a Project Fellow and was one of the key member for India' Solar Resource Assessment project in collaboration with National Renewable Energy Laboratory, USA under Indo-US Energy Dialogue. In November 2010, he then joined WTI Advanced Technology Limited (A 100% Subsidiary of TATA Consultancy Services Limited) as an Assistant Systems Engineer in GIS domain and has carried out several GIS based projects for Qwest Telecom, USA as well as R-APDRP which is a GIS based

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Validation of Satellite based Solar Radiation Data with Ground Measurements

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Abstract

Solar radiation is very important for the evaluation and wide use of solar renewable energy systems. For modeling solar energy applications global radiation and the amount of radiation on a tilted surface is needed. Satellite-based estimates of radiation, temperature, and wind speed are not expected to be as accurate as ground-based measurements of these parameters for a number of reasons. First, the satellite-based estimates are indirect interpretations of data observed from space (irradiance) and widely-spaced ground stations (temperature and winds speed) and therefore are associated with all the uncertainties inherent in generalized modeling. Second, the spatial and temporal resolution of the satellite imagery is coarse when compared with our ground based measurements. The satellite-based values are calculated from snapshot images (pixel wise) of the earth and do not distinguish differences between locations within a single pixel. These factors can cause significant deviations between satellite and ground measurements.

The study describes a methodology to compare the ground measured data with satellite data of global radiation and tilted radiation for North-West regions of India. Analysis is carried out for the monthly mean daily data of global radiation and tilted global radiation. There are the five stations viz. Ahmedabad, Bhopal, Jodhpur, Jaipur and New Delhi lying in the North-West region of country for which both ground and satellite data are available.

The statistical error tests- Mean Percentage Error (MPE), Mean Bias Error (MBE) and Root Mean Square Error (RMSE) are used to compare the data. The results show that for global radiation, the highest values of MPE, MBE and RMSE are -7.621%, 0.401 kWh/m^2 & 0.421 kWh/m^2 respectively while in the case of tilted global radiation these errors are -10.482%, 0.61 kWh/m^2 & 0.62 kWh/m^2 respectively.

Keywords: Validation, Renewable Energy, Global Radiation, Tilted Global Radiation, Mean Percentage Error (MPE), Mean Bias Error (MBE) and Root Mean Square Error (RMSE)

1. Introduction

The power obtained from solar radiation reaching the Earth is many times greater than the power generated by man by other conventional sources. Solar radiation is a perpetual source of natural energy and has great potential for a wide variety of applications. It is abundant, accessible and pollution free and hence can be used as a supplement to the non-renewable sources of energy which have finite depleting supplies [1-3]. The renewable energy sector depends upon the assessment of resources for planning and marketing their energy production technology. For solar based renewable energy technologies, the basic source is the Sun [3].

India is located between 6^0N to 32^0N latitude and hence most of the locations in India receive abundant supply of solar energy. This energy can be utilized for the development of solar energy systems. For this purpose the solar radiation data are required in various forms depending upon the nature of application. Numerous researchers e.g. Riordan et al. [4], Aladas et al. [5], Hirata and Tani [6] and Antonio et al. [7] have predicted the importance of solar radiation data for design and efficient operation of solar energy systems. Proper design and performance of these solar appliances require accurate information on solar radiation availability [8]. Hence many studies [9-11] have been made on solar climates of specific regions for the development of solar technologies.

The ground measured and satellite derived solar radiation data complement each other and are required to build a comprehensive solar radiation database. It is difficult to have high capability solar radiation monitoring network and also accuracy in the interpolation of data decreases with the increase in distance between sites. However, satellite measurements have lack of accuracy and short time interval data are needed for the engineering and site-specific studies. Hence, combining these two, ground- based and satellite- derived measurements create a comprehensive solar radiation database.

2. Methodology

The analysis is carried out for the North West region (Ahmadabad, Bhopal, Jodhpur, Jaipur and New Delhi) of the country. The ground based data and satellite (Meteosat 5 & 6) data of horizontal and tilted global radiation are used in the study. The ground measured data are taken from Indian Meteorology Department (IMD) while satellite data are derived from the maps developed by National Renewable Energy Laboratory (NREL). Comparative plots of ground-based measurement and satellite derived data are drawn for global horizontal and global tilted radiation.

The three statistical parameters - mean percentage error (MPE), root mean square error (RMSE) and mean bias error (MBE) are used in the validation of data.

The mean percentage error is

$$MPE = \left[\sum\left(\frac{H_{do} - H_{dc}}{H_{do}} \times 100\right)\right] / n \qquad (1)$$

H_{go} is the ground measured and H_{gc} the satellite measured value of solar radiation

The accuracy of these relationships is also tested by calculating RMSE and MBE. These are defined as-

$$RMSE = \left\{\left[\sum\left(H_{i,c} - H_{i,o}\right)^2\right] / n\right\}^{\frac{1}{2}} \qquad (2)$$

$$MBE = \left[\sum\left(H_{i,c} - H_{i,o}\right)\right] / n \qquad (3)$$

where $H_{i,c}$ is the ith satellite derived value, $H_{i,o}$ is the ith ground based measured value and n is the number of observations.

RMSE provides information on the short-term performance of a model. The lower the RMSE, the more accurate is the estimation [12]. MBE provides information on the long-term performance of a model. Positive and negative MBE values show overestimation and underestimation respectively [12]. However, a zero value of RMSE or MBE is ideal.

The ground measurements and satellite derived data are plotted against months to test the systematic difference.

The statistical errors are computed for the each of the five stations viz. Ahmadabad, Bhopal, Jodhpur, Jaipur and New Delhi and then plots showing comparison among the different cities are drawn for each of the statistical parameter.

3. Validation

3.1 Comparative study on global radiation

The ground based and satellite-derived data on monthly mean daily global radiation for all the five station viz. Ahmedabad, Bhopal, Jodhpur, Jaipur and New Delhi are listed in Table 1 and Table 2 respectively. It can be seen that the satellite derived values are higher than the ground measured in all months of the year for Ahmedabad and Jodhpur. In the case of Jaipur and New Delhi, ground based values slightly exceed the satellite data in the months of April and December respectively.

The statistical errors (MPE, MBE and RMSE) for global radiation are given in Tale 3. The extreme values of MPE are for New Delhi (-1.756%) and Ahmadabad (-7.621%). For other cities Bhopal, Jodhpur and Jaipur, mean percentage error is -7.559 %, -6.243 % and -5.742 % respectively.

MBE is lowest for Jaipur (0.278 kWh/m^2) while highest is for Ahmadabad (0.401 kWh/m^2). For Bhopal, Jodhpur and New Delhi, it is 0.385 kWh/m^2, 0.351 kWh/m^2 and 0.105 kWh/m^2 respectively. MBE values show overestimation for all of the locations. RMSE ranges from 0.177 kWh/m^2 to 0.416 kWh/m^2being minimum for New Delhi and maximum for Ahmadabad as illustrated in listed in Table. The other stations Bhopal, Jodhpur and Jaipur have 0.416 kWh/m^2, 0.394 kWh/m^2 and 0.392 kWh/m^2.

3.2 Comparative Study on Tilted Solar Radiation

The ground based and satellite-derived data on monthly mean daily global tilted radiation for all the five stations are tabulated in Table 4 and Table 5 respectively. It is obvious that for all five cities the tilted radiation derived from satellite image exceeds the ground measured values throughout the year.

Table 7 lists the statistical parameters for tilted radiation. MPE has extreme values of -8.097% (Ahmadabad) and -10.482% (Jodhpur). It is -8.397%, -9.7528% and -10.237% for the other stations Bhopal, Jaipur and New Delhi respectively. The MBE being a true measure of difference between the ground based and satellite derived data is lowest for Ahmadabad (0.274 kWh/m^2) and highest for Jodhpur (0.611 kWh/m^2). The remaining locations have 0.44 kWh/m^2 (Bhopal), 0.213 kWh/m^2 (Jaipur) and 0.538 kWh/m^2 (New Delhi) mean bias error.

Again Ahmadabad has the lowest RMSE (0.422 kWh/m^2) for tilted radiation and Jodhpur has the highest one (0.628 kWh/m^2)**.** The other cities have values of 0.526 kWh/m^2 (Bhopal), 0.628 kWh/m^2 (Jaipur) and 0.606 kWh/m^2 (New Delhi). It is obvious that Ahmadabad has smallest while Jodhpur has highest values of all the three statistical indicators. This may be due the different atmospheric conditions of the stations as in the clean atmosphere and clear sky the errors will be less and vice versa.

4. Conclusions

The difference in ground based and satellite derived data should be small on clear sky or totally overcast days. When examining global horizontal radiation, it is found that this dissimilarity is comparatively less mainly in February and March which is obvious from the fact that in these months sky is relatively clear. The variation between the data is high in July for all the stations. New Delhi has the smallest values of mean percentage error and mean bias error while

Ahmadabad has the largest. The root mean square is high between the ground measured and satellite based data which is because of the fact that ground –based sample one small area of the sky while satellite are imaging larger area. It is minimum in New Delhi and maximum in Ahmadabad.
In the case of global tilted radiation, the high difference is observed in the winter (mainly in October). The errors are comparatively high and all the three statistical parameters used in the study have smallest value for Jodhpur and largest for Ahmedabad.

5. Applications

5.1 High Resolution GIS maps

The validated solar radiation data are used in three mapping application examples that exploit the main strengths of the model:

a) A high resolution (**10 km**) geostationary satellite archive for the North – West regions of India which has an ability to account for site-specific average resource is shown in Figure 1.
b) Whole year is divided into four seasons- first (Jan, Feb & Mar), second (Apr, May & Jun), third (July, Aug & Sep) and fourth (Oct, Nov & Dec). The **seasonal** Irradiance maps of **Global & Tilted** Solar Radiation showing the seasonal variation are illustrated in Figures 2 and 3.
c) The **Peak Summer** Irradiance maps of **Global & Tilted** Solar Radiation as shown in Figure 4, are the distribution of solar radiation in peak summer month May.

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Table 1: Ground measured global horizontal radiation (kWh/m^2)

Months	Ahmadabad	Bhopal	Jodhpur	Jaipur	New Delhi
Jan	4.54	4.38	4.24	4.19	3.68
Feb	5.43	5.21	5.03	5	4.53
Mar	6.33	6.26	5.91	6.09	5.73
Apr	6.94	6.97	6.7	7.08	6.72
May	6.98	6.78	6.86	7.23	6.79
Jun	6.02	5.57	6.48	6.64	6.27
Jul	4.34	4.03	5.43	5.15	5.38
Aug	4.29	3.91	5.24	4.81	5.01
Sep	5.19	5.11	5.75	5.42	5.28
Oct	5.26	5.33	5.2	5	4.73
Nov	4.65	4.7	4.43	4.27	3.93
Dec	4.22	4.49	4.09	3.68	3.33

Table 2: Satellite derived global horizontal radiation (kWh/m^2)

Months	Ahmadabad	Bhopal	Jodhpur	Jaipur	New Delhi
Jan	4.81	4.71	4.36	4.18	3.47
Feb	5.75	5.67	5.29	5.21	4.68
Mar	6.65	6.6	6.3	6.24	6.03
Apr	7.29	7.21	6.97	6.99	6.86
May	7.53	7.41	7.45	7.39	6.99
Jun	6.50	6.06	6.93	6.5	6.30
Jul	4.88	4.71	6.08	5.88	5.42
Aug	4.55	4.25	5.72	5.48	5.30
Sep	5.62	5.46	6.08	5.91	5.35
Oct	5.85	5.81	5.64	5.57	4.98
Nov	5.02	4.97	4.67	4.59	3.94
Dec	4.51	4.5	4.09	3.96	3.28

Table 3: MPE, MBE and RMSE for global horizontal radiation

Stations	MPE(%)	MBE (kWh/m^2)	RMSE (kWh/m^2)
Ahmadabad	-7.621	0.401	0.416
Bhopal	-7.559	0.385	0.421
Jodhpur	-6.243	0.351	0.394
Jaipur	-5.742	0.278	0.392
New Delhi	-1.756	0.105	0.177

Table 5: Ground measured data of global tilted radiation (kWh/m^2)

Months	Ahmadabad	Bhopal	Jodhpur	Jaipur	New Delhi
Jan	5.746	5.594	5.696	5.575	4.827
Feb	6.370	6.127	6.102	5.996	5.480
Mar	6.808	6.750	6.473	6.656	6.294
Apr	6.874	6.908	6.688	7.054	6.709
May	6.514	6.349	6.401	6.711	6.320
Jun	5.543	5.129	5.905	6.018	5.692
Jul	4.109	3.784	5.055	4.776	4.964
Aug	4.141	3.771	5.041	4.627	4.794
Sep	5.271	5.183	5.988	5.622	5.476
Oct	5.893	5.977	6.060	5.812	5.481
Nov	5.707	5.759	5.7680	5.422	5.096
Dec	5.424	5.078	5.616	4.898	4.475

Table 6: Satellite derived of global tilted radiation (kWh/m^2)

Months	Ahmadabad	Bhopal	Jodhpur	Jaipur	New Delhi
Jan	6.409	6.161	6.220	5.918	5.164
Feb	6.829	6.765	6.634	6.431	6.030
Mar	6.978	6.811	6.915	6.796	6.668
Apr	7.060	6.890	7.189	7.031	6.956
May	6.890	6.633	7.068	6.848	6.671
Jun	5.636	5.441	6.438	6.218	6.019
Jul	4.537	4.333	5.825	5.491	5.404
Aug	4.316	3.935	5.633	5.293	5.378
Sep	5.787	5.553	6.560	6.331	5.804
Oct	6.830	6.838	7.044	6.897	6.639
Nov	6.337	6.300	6.500	6.374	6.077
Dec	6.211	6.035	6.109	5.800	5.265

Table 7: MPE, MBE and RMSE for global tilted radiation

Months	MPE (%)	MBE (kWh/m^2)	RMSE (kWh/m^2)
Ahmadabad	-4.758	0.274	0.422
Bhopal	-8.397	0.44	0.526
Jodhpur	-10.482	0.611	0.628
Jaipur	-9.752	0.521	0.628
New Delhi	-10.237	0.538	0.606

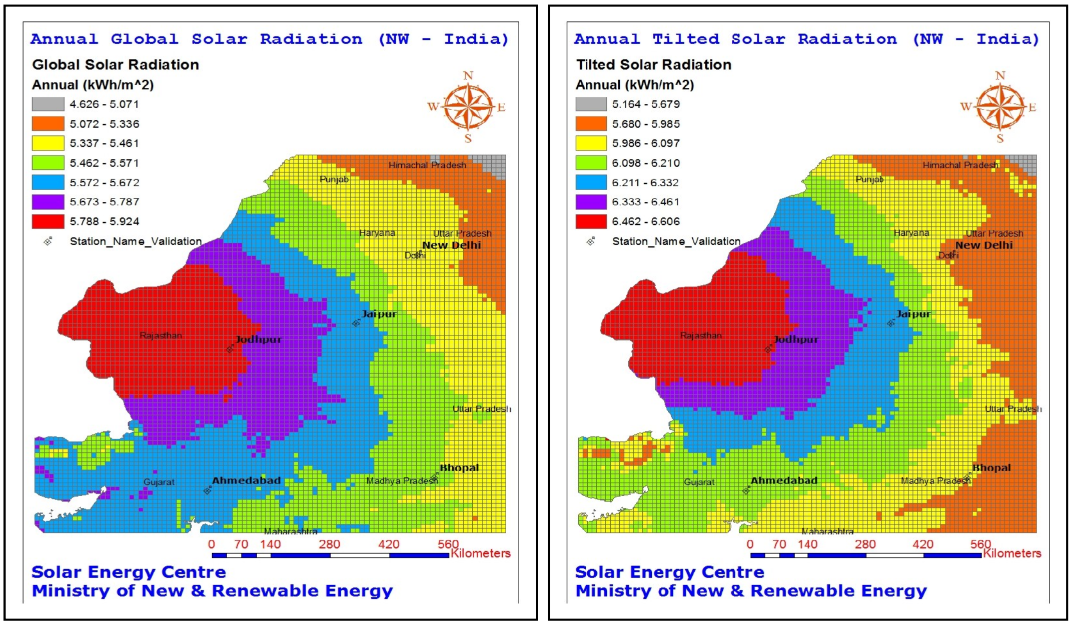

Figure 1: Annual Distribution of global horizontal and tilted radiation

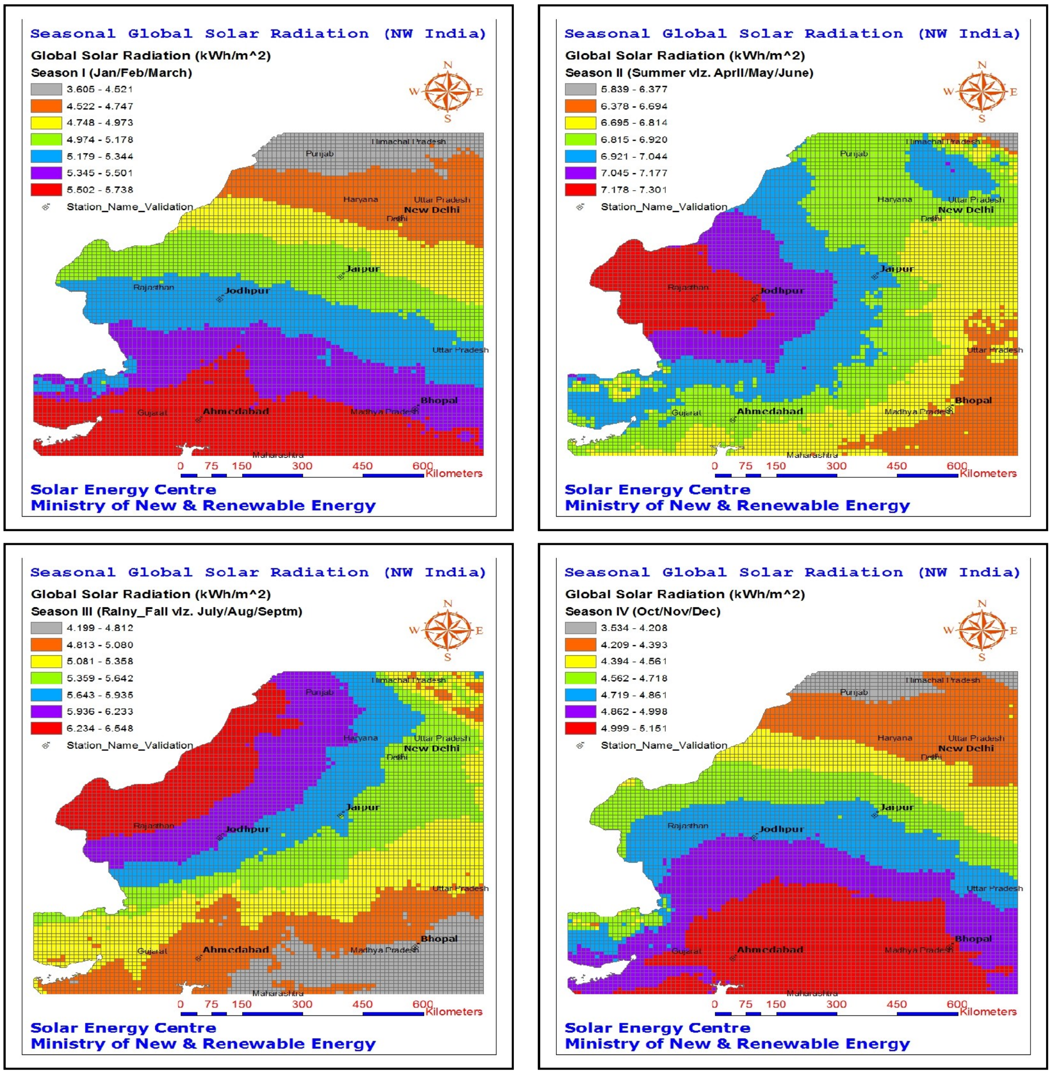

Figure 2: Seasonal variation of global horizontal radiation for four seasons

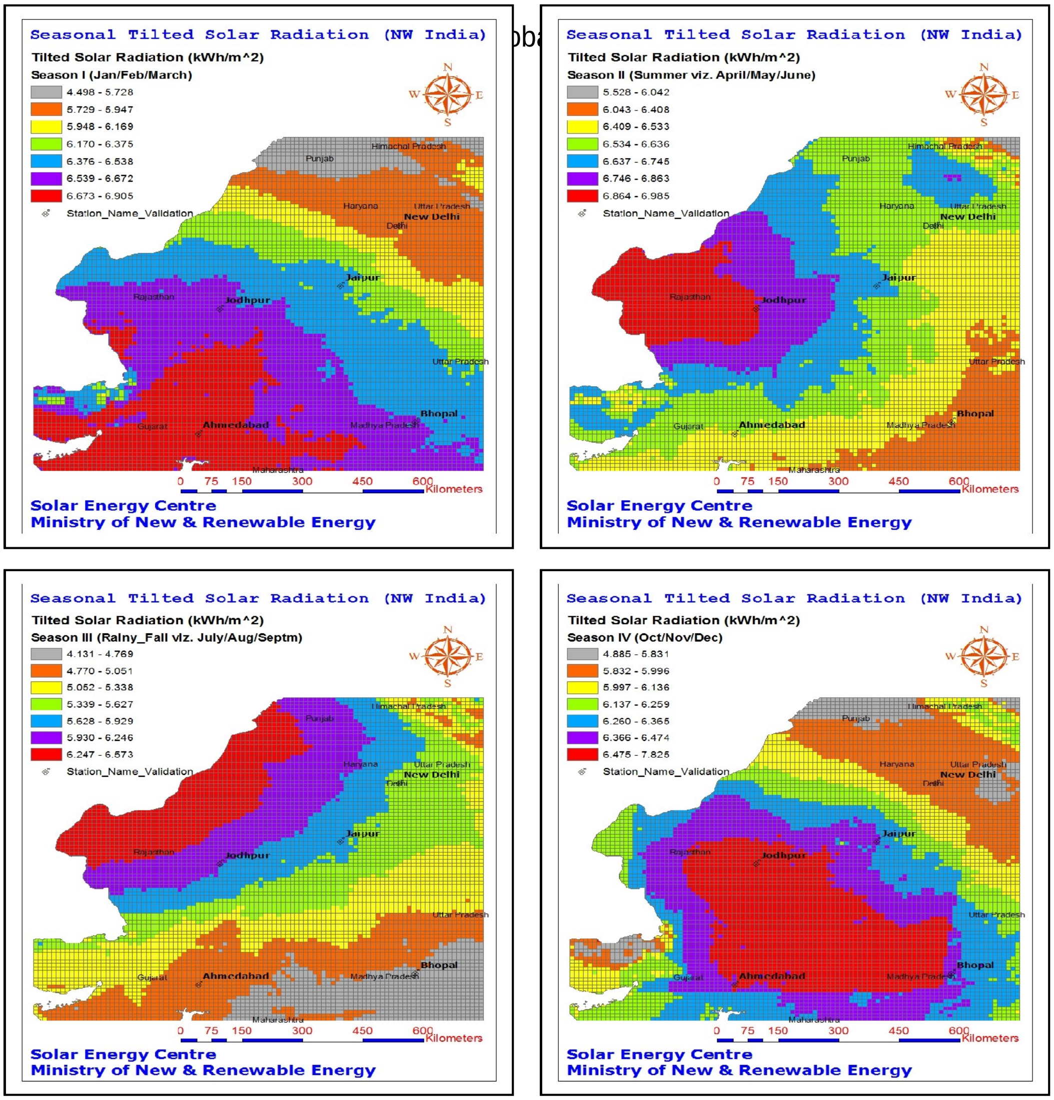

Figure 3: Seasonal variation of global tilted radiation for four seasons

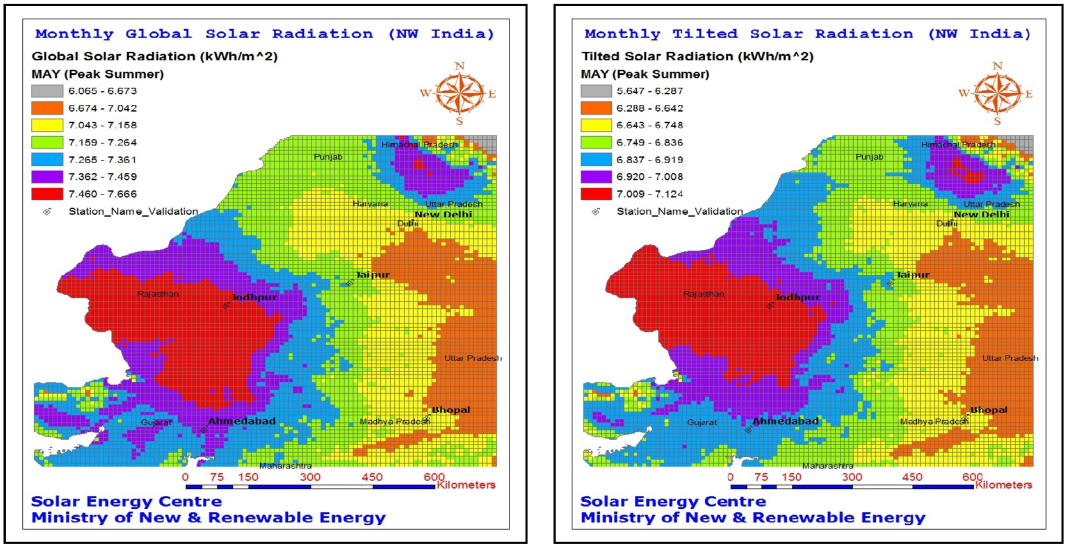

Figure 4: Global horizontal and tilted radiation for the peak summer month (May)