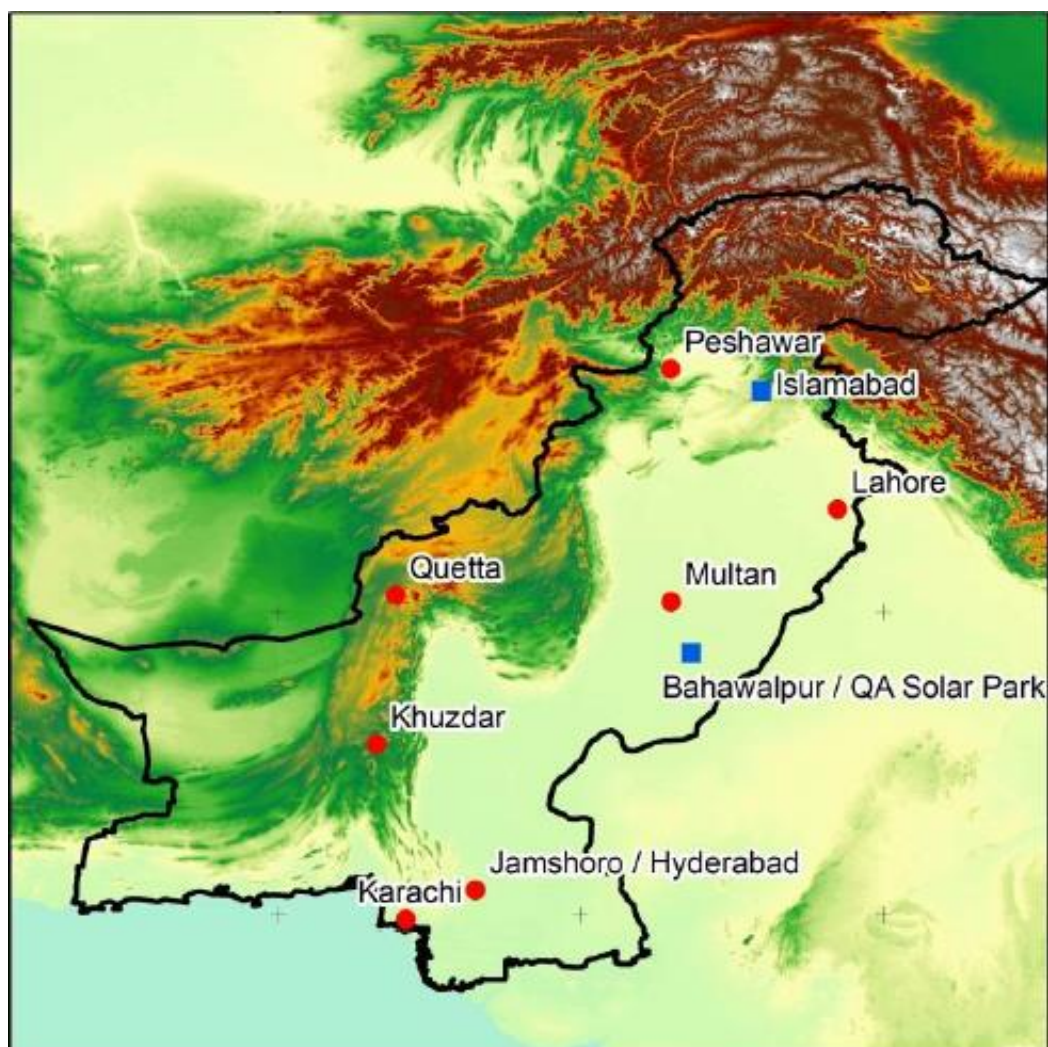


Solar Resource Mapping in Pakistan

FINAL MODEL VALIDATION REPORT

JANUARY 2017



This report was prepared by [DLR](#), under contract to [The World Bank](#). It is one of several outputs from the solar resource mapping component of the activity **“Renewable Energy Resource Mapping and Geospatial Planning – Pakistan”** [Project ID: P146140]. This activity is funded and supported by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank, under a global initiative on Renewable Energy Resource Mapping. Further details on the initiative can be obtained from the [ESMAP website](#).

As a result of the Master Agreement awarded to [Solargis](#) for global solar resource assessment and mapping services and the resulting restructuring of this project component, this report is the final DLR output from the above-mentioned project. Users are strongly advised to exercise caution when utilizing the information and data contained, as the results are preliminary and have not been peer reviewed. The final output from this project will be a validated Pakistan Solar Atlas prepared by Solargis, which will be published once the project is completed.

To obtain maps and information on solar resources globally, please visit:

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ESMAP - Renewable Energy Resource Mapping Initiative

- Solar Resource Mapping for Pakistan -

WB Selection #11260861

Final Model Validation Report

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1 Introduction

This model validation report gives an overview on the results achieved by comparing the solar radiation values based on satellite data developed in phase 1 with ground measurement data achieved up to the present time during the measurement campaign in phase 2 of the Solar Resource Mapping Project for Pakistan (WB Selection #11260861). This work described here is part of phase 3 of the project. After a short introduction of applied comparison method, the comparison between satellite-modelled solar data and ground solar measurements is described for every site.

For each site, the final chapter shortly describes the results of the comparison and validation between ground data and satellite-based data. As phase 3 will not be completed as planned, an adaption of the model will not be conducted.

2 Comparison methodology

The methodology for satellite data comparison within this validation task is to compare both quality checked time series directly, after the datasets are converted to the same temporal resolution. Only days with full data availability have been considered due to algorithm specifications. Beyond this, the full time series has found consideration which includes the daylight hours as well as the night hours to guarantee the homogeneity of datasets on the one hand and serves as a simple quality check on the other hand (alignment of sunrise and sunset hours).

Once the validation for a site is conducted, the typical output of results will be a scatterplot which shows the degree of correlation for every available time step of the satellite estimate and surface measurement. Furthermore, the mean bias (MB) and the root mean square error (RMSE) are processed per site. The MB depicts the average deviation between the satellite estimation and measured data, while the RMSE is a measure for the amount of variation between values. This means, if there are some strong outliers in data, the RMSE will increase significantly.

$$MB = \frac{\sum_{i=1}^n (y_i - x_i)}{n}$$

$$RMSE = \left\{ \frac{\sum_{i=1}^n (y_i - x_i)^2}{n} \right\}^{1/2}$$

The equations above depict the calculation of the MB and RMSE used for the validation. Here y_i is the satellite estimate, x_i is the measured value and n is the sample (both taken from Iqbal, 1983).

3 Validation of measured against satellite data

Before the validation results are screened thoroughly, the reader should be aware that estimates of modelled satellite data by geostationary satellites will not correlate to the measured data to one hundred percent. This is, for instance, caused by differences in temporal and spatial scale in data

acquisition. Ground measurements are typically pin point measurements which are temporally integrated while satellite measurements are instantaneous spatial averages.

4 Site specifics Hyderabad/Jamshoro

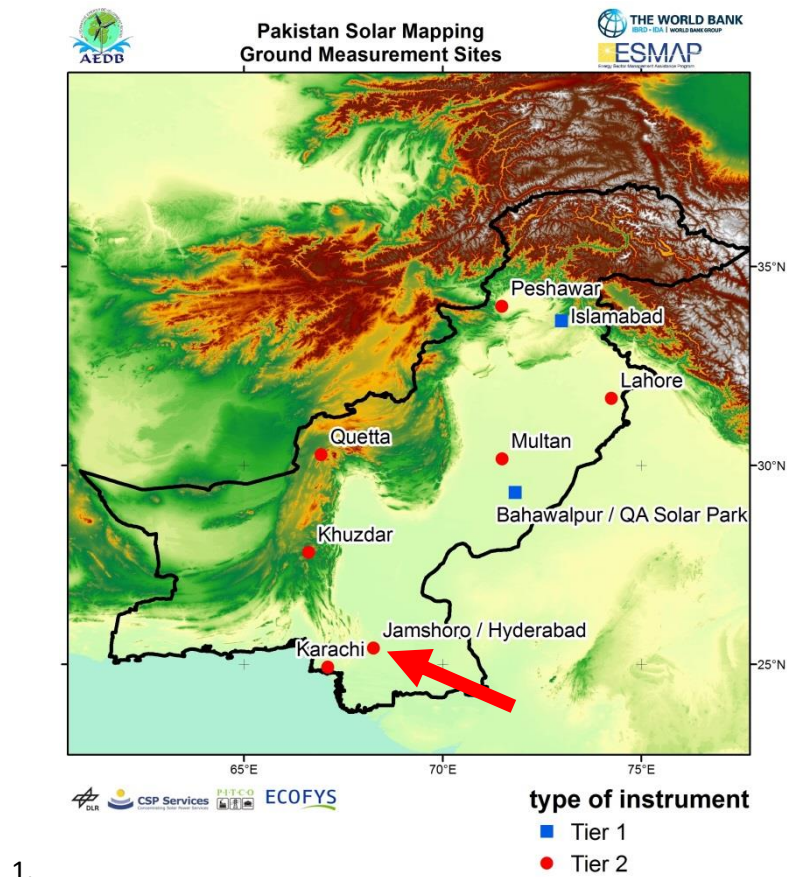


Figure 1: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
Mehran University of Engineering and Technology (M-UET), Jamshoro	Pk-Hyd	25.413°N, 68.260°E	Tier 2	2015-04-21

4.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Hyderabad. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

4.1.1 Validation results of Global Horizontal Irradiance

Table 1: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7087
Stations NAs: 499
Satellite NAs: 4584
Station mean (plus noct.): 249.6
Station mean (no noct.): 459.9
Station max (plus noct.): 1026 on 2015-06-04 19:00:00
Satellite mean (plus noct.): 283.3
Satellite mean (no noct.): 521.9
Satellite max (plus noct.): 1120.7 on 2015-06-08 17:00:00
GHI mean bias (no NA/No noct.): 62.0
GHI RMSE (no NA/No noct.): 100.5

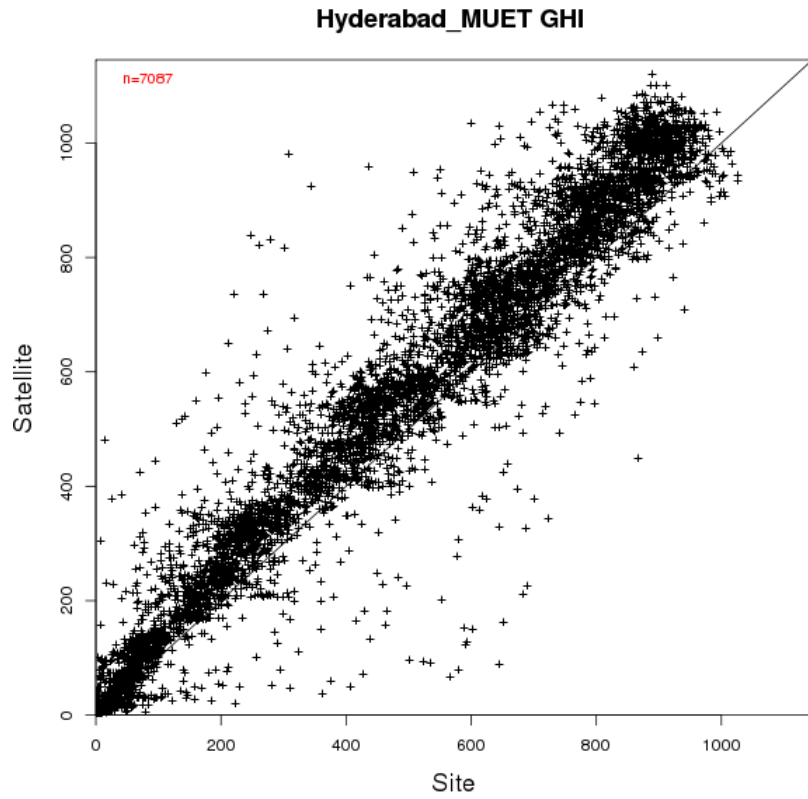


Figure 2: Scatterplot of validation results for GHI at the location of Hyderabad (in W/m^2)

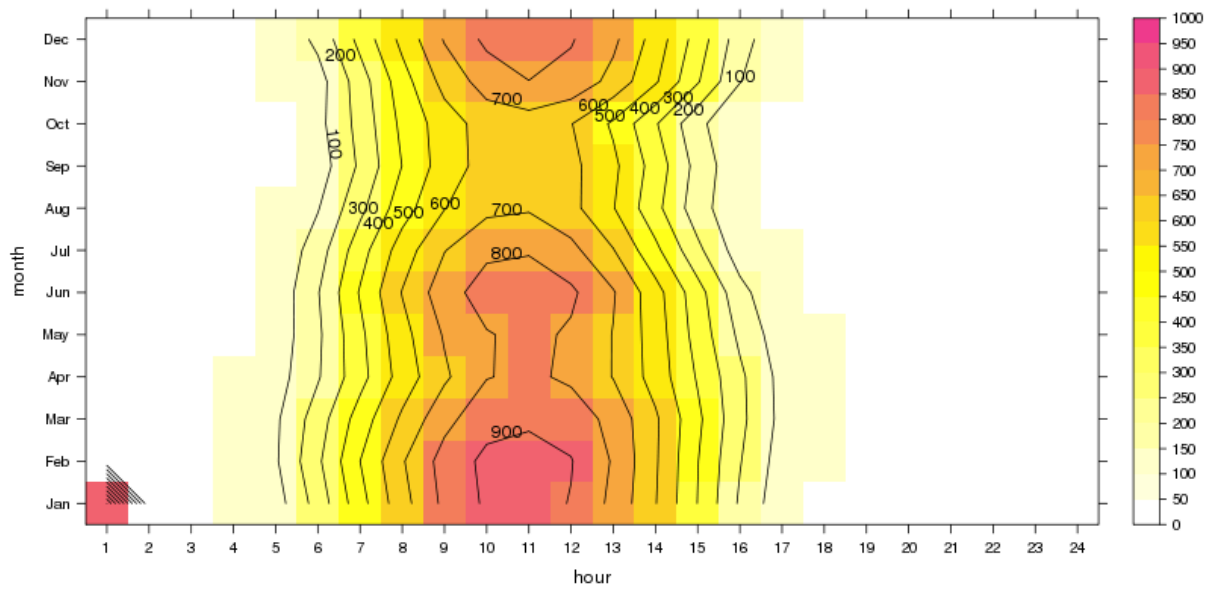


Figure 3: Isopleth graph of ground measurement of GHI at Hyderabad in W/m^2 (UTC)

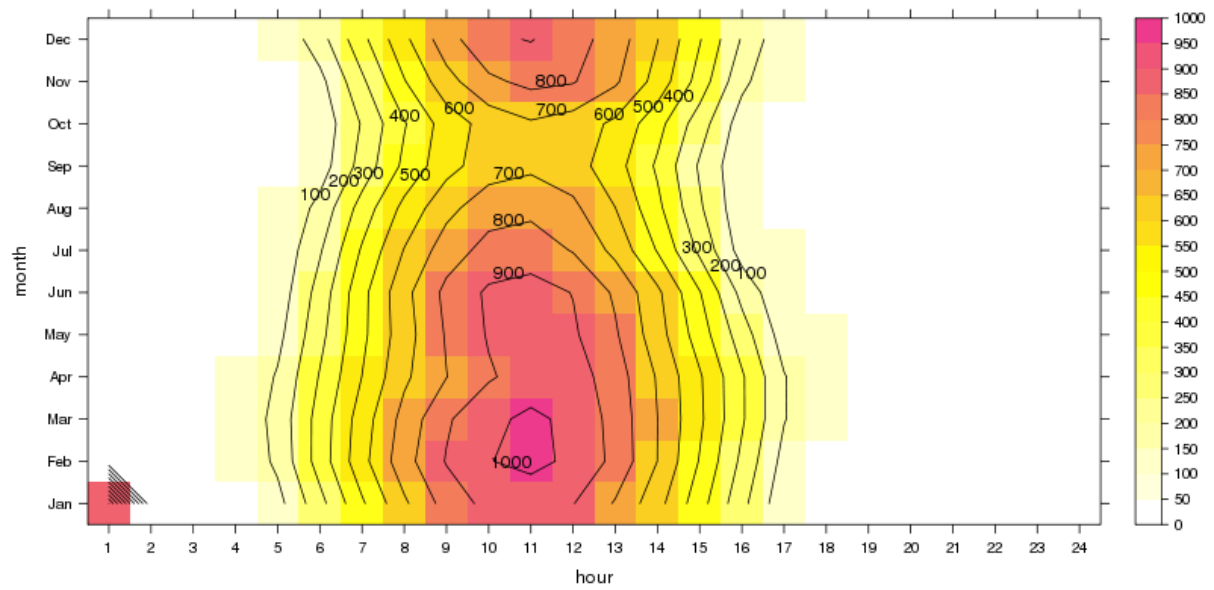


Figure 4: Isoleth graph of satellite estimation of GHI at Hyderabad in W/m² (UTC)

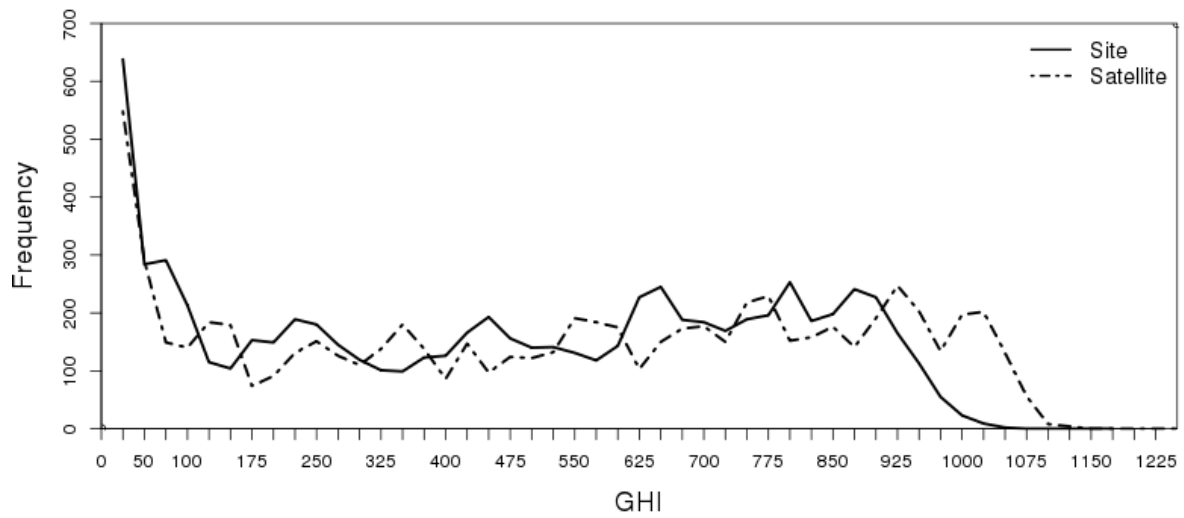


Figure 5: Frequency distribution of hourly GHI at the location of Hyderabad in W/m²

4.1.2 Validation results of Direct Normal Irradiance

Table 2: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 6387
Stations NAs: 499
Satellite NAs: 4584
Station mean (plus noct.): 198.1
Station mean (no noct.): 404.2
Station max (plus noct.): 985 on 2015-06-03 02:00:00
Satellite mean (plus noct.): 315.2
Satellite mean (no noct.): 634.9
Satellite max (plus noct.): 1009.4 on 2015-06-04 02:00:00
DNI mean bias (no NA/No noct.): 230.7
DNI RMSE (no NA/No noct.): 312.1

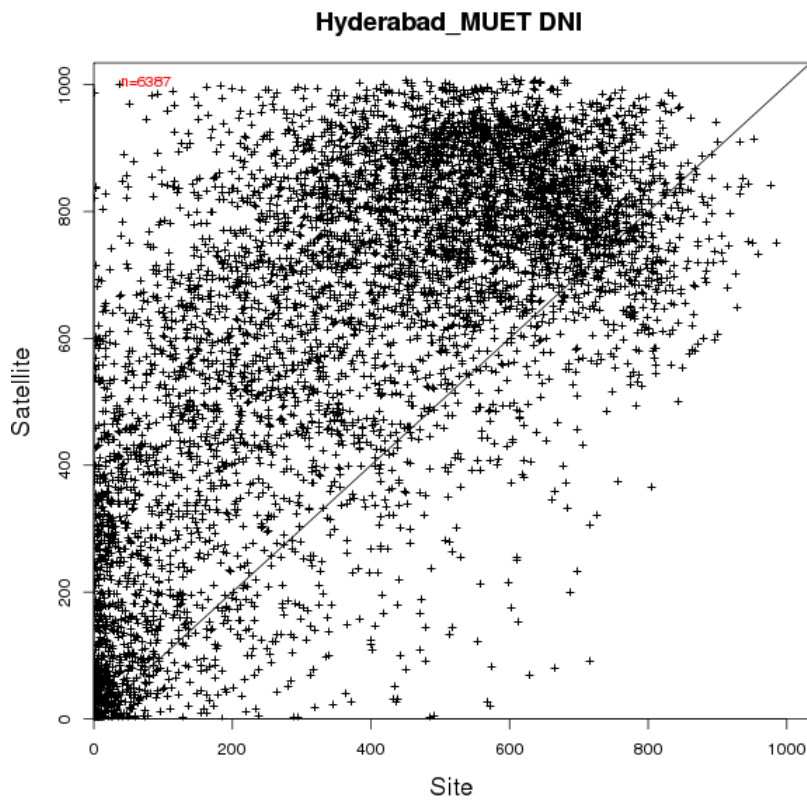


Figure 6: Scatterplot of validation results for DNI at the location of Hyderabad (in W/m^2)

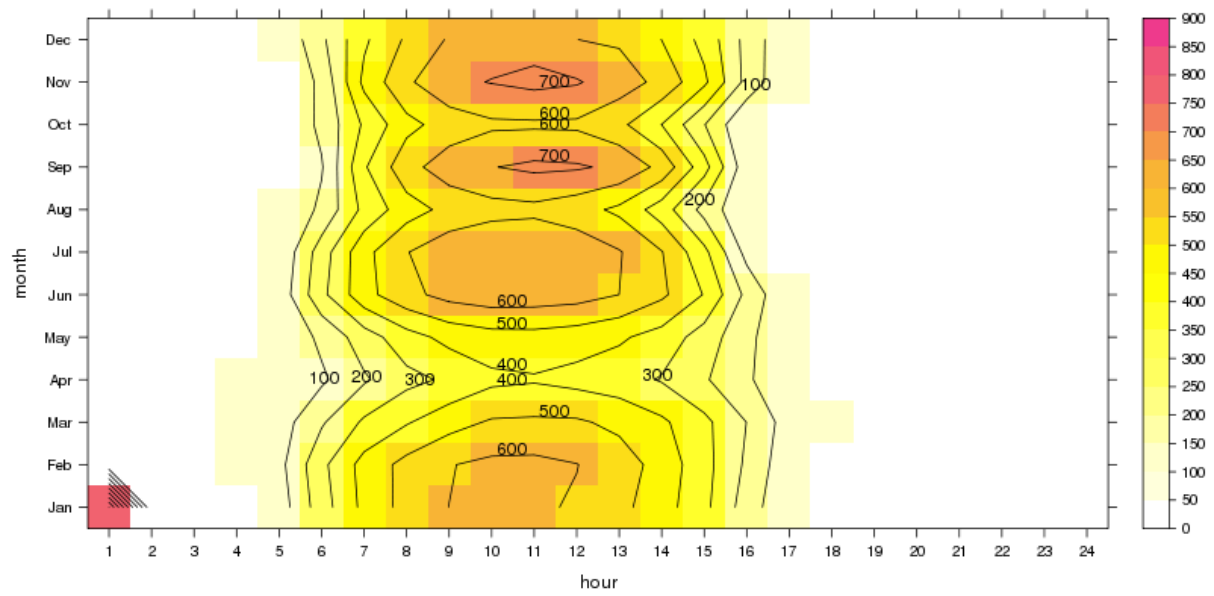


Figure 7: Isopleth graph of ground measurement of DNI at Hyderabad in W/m^2 (UTC)

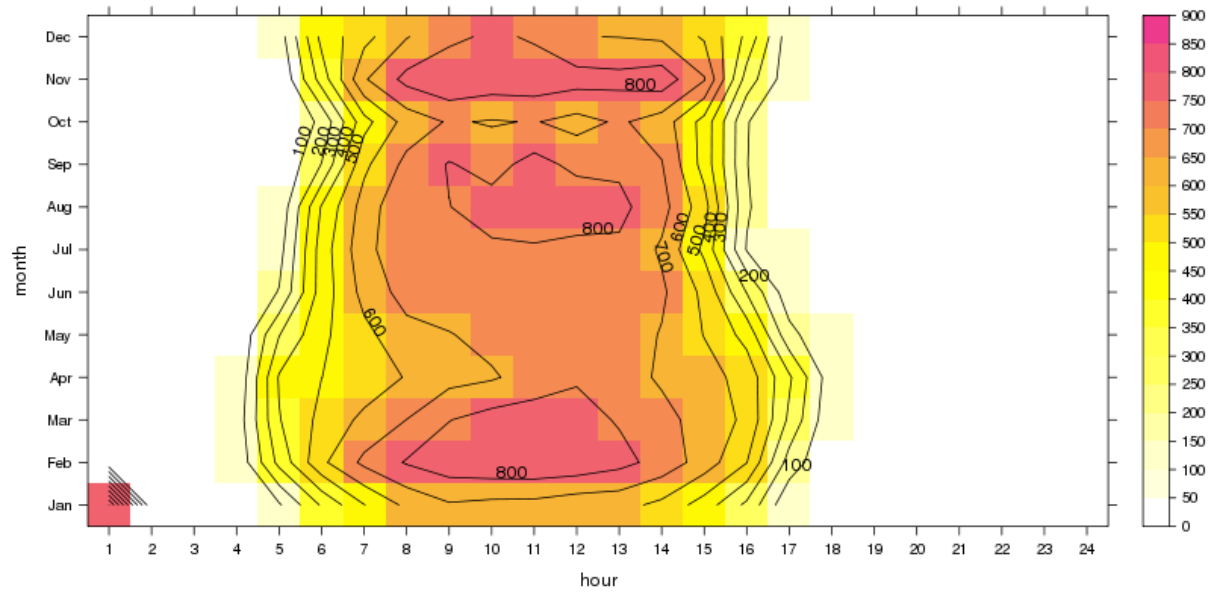


Figure 8: Isopleth graph of satellite estimation of DNI at Hyderabad in W/m^2 (UTC)

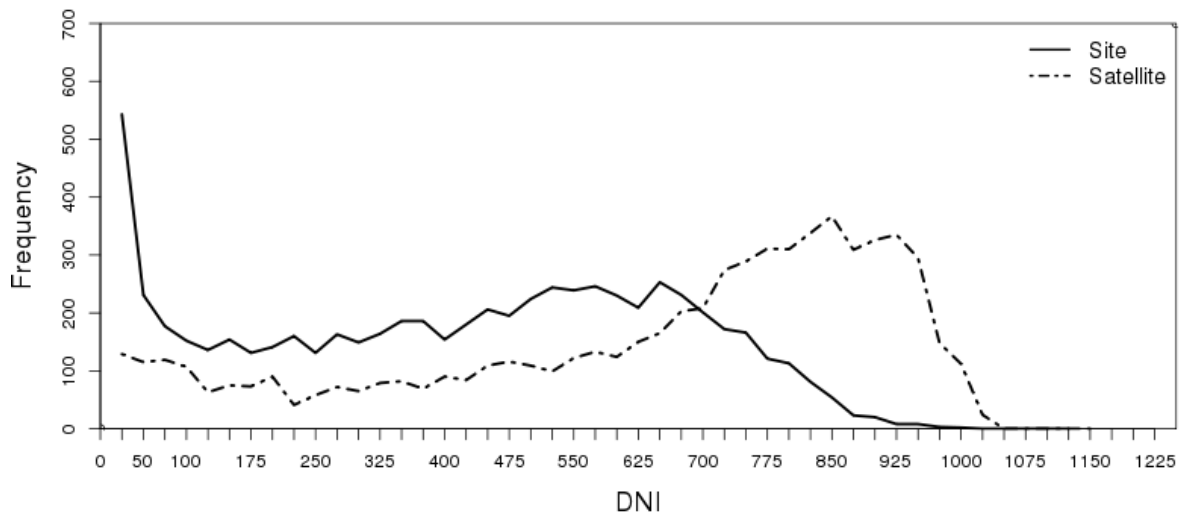


Figure 9: Frequency distribution of hourly DNI at the location of Hyderabad in W/m^2

4.1.3 Validation results of Diffuse Horizontal Irradiance

Table 3: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7087
Stations NAs: 499
Satellite NAs: 4584
Station mean (plus noct.): 108.4
Station mean (no noct.): 199.6
Station max (plus noct.): 646 on 2015-05-19 23:00:00
Satellite mean (plus noct.): 73.8
Satellite mean (no noct.): 136.0
Satellite max (plus noct.): 696.8 on 2015-05-22 01:00:00
DHI mean bias (no NA/No noct.): -63.6
DHI RMSE (no NA/No noct.): 123.3

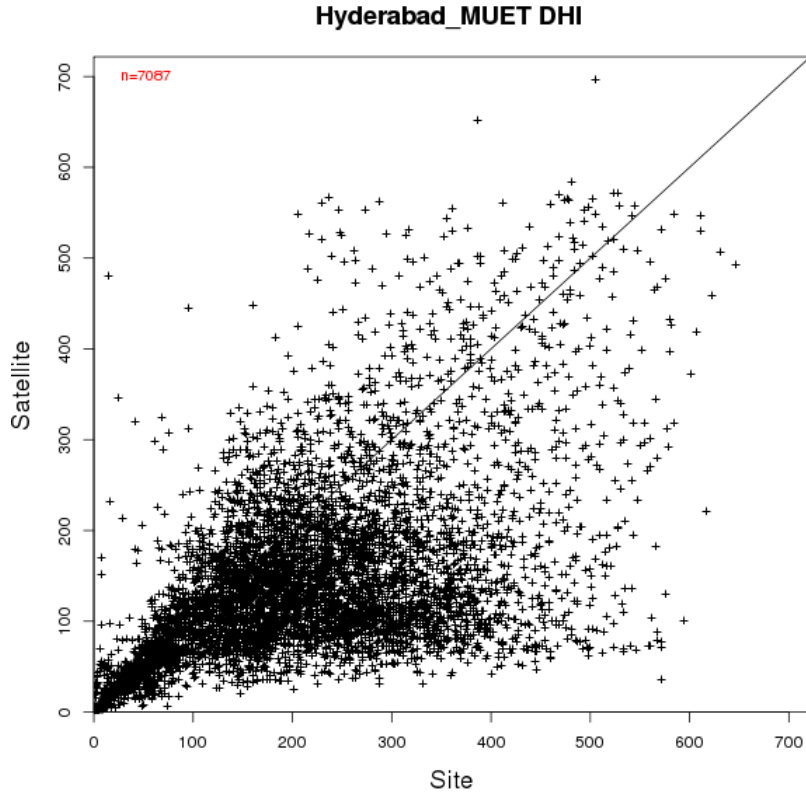


Figure 10: Scatterplot of validation results for DHI at the location of Hyderabad (in W/m^2)

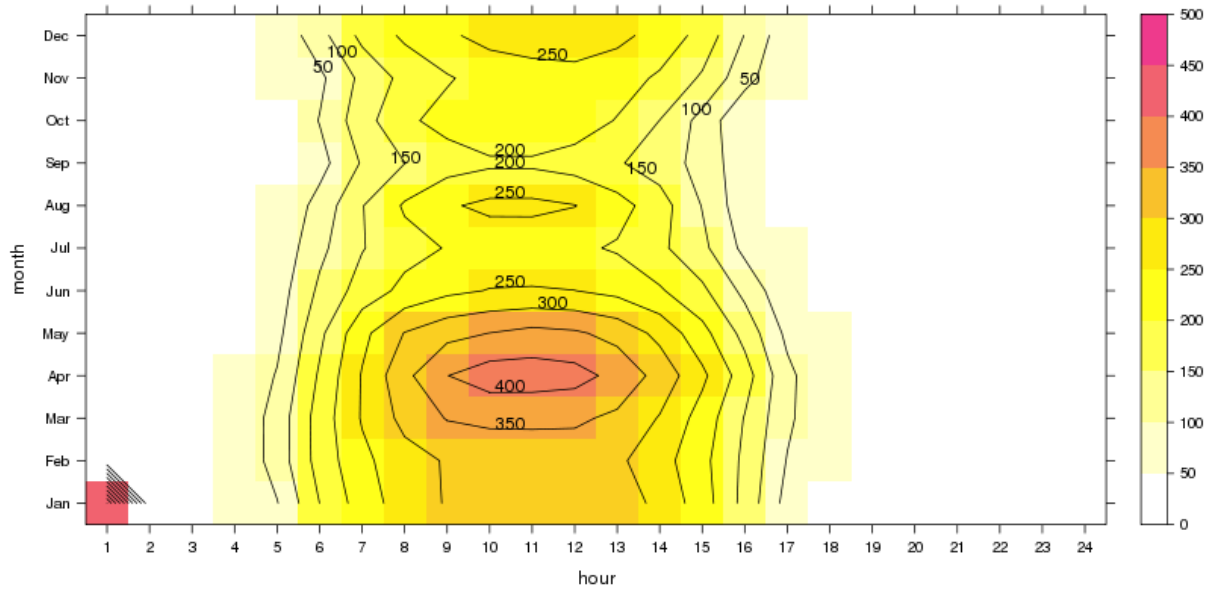


Figure 11: Isopleth graph of ground measurement of DHI at Hyderabad in W/m^2 (UTC)

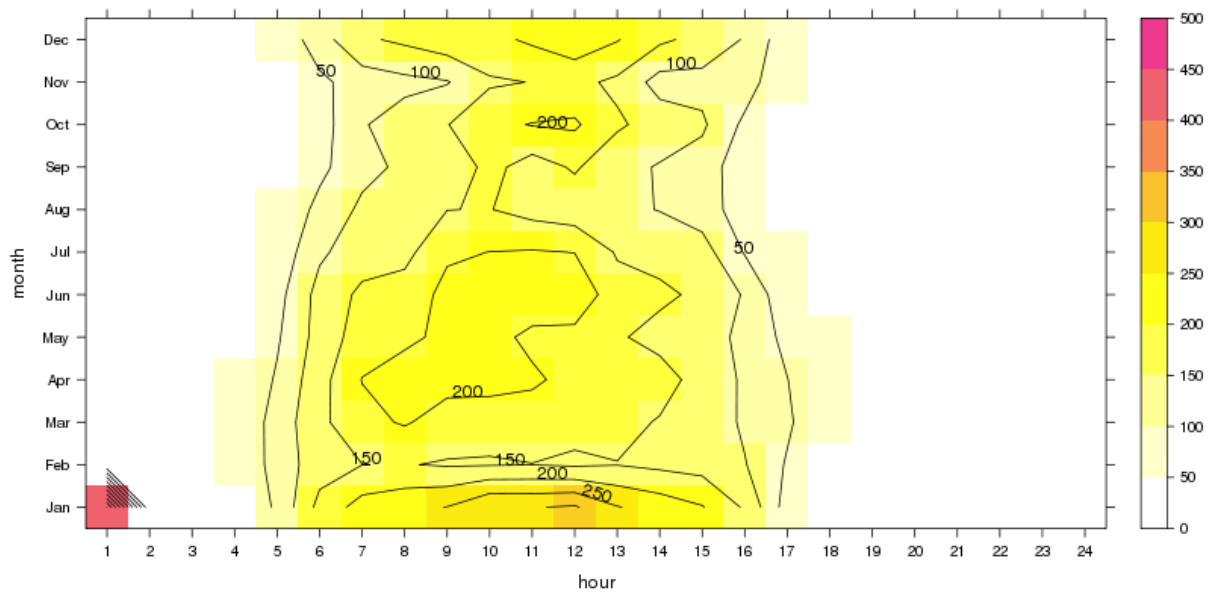


Figure 12: Isopleth graph of satellite estimation of DHI at Hyderabad in W/m^2 (UTC)

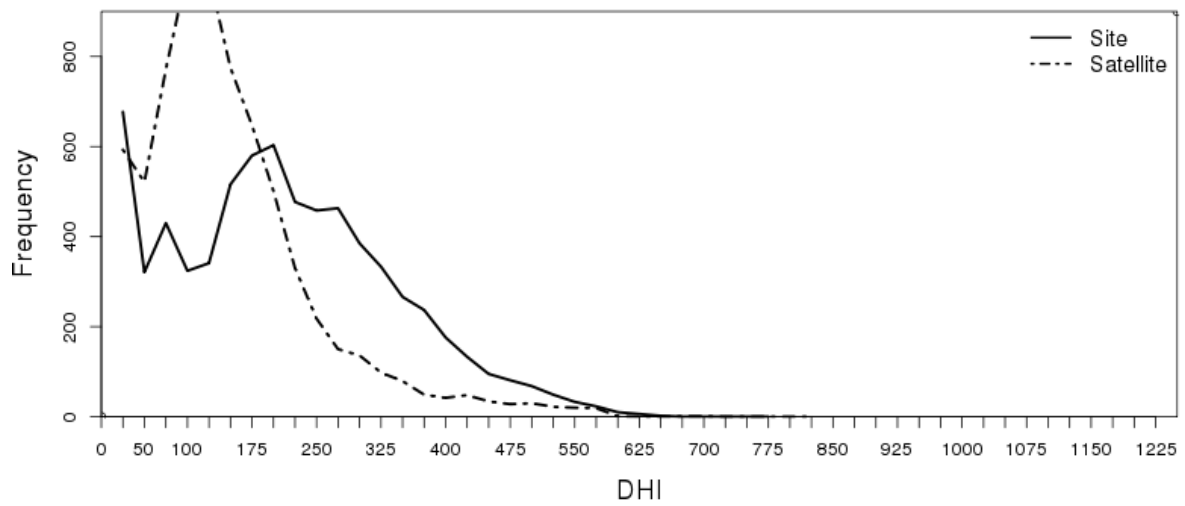


Figure 13: Frequency distribution of hourly DHI at the location of Hyderabad in W/m^2

4.2 Discussion and conclusion

The TIER2 measurement site at Jamshoro/Hyderabad is located only a few kilometers away from the banks of the Indus River and about 120 km inland from the measurement site in Karachi. Though not very far away from the site in Karachi, the irradiance sums in Jamshoro are higher and the fit between modelled estimates and measurement data is slightly better. This can be referred to a higher continentally, which in turn leads to a higher risk of fog, and to the fact that the influence of anthropogenic caused aerosol in the Hyderabad/Jamshoro region should be much smaller. The absolute mean bias for hourly sums of GHI with 60 W/m^2 is among the smallest for the measurement site in low altitudes. Nevertheless, DNI shows a high bias and the same pattern of frequency distribution for hourly sums all other sites in the stronger polluted areas along the Indus river valley and eastern Pakistan. Here, DNI is overestimated significantly by the satellite for clearsky days.

The measurement is conducted in a very populated region and, thus, represents an area with an above-average energy demand. This fact does partly explain the performance of the satellite model and the results presented in this report. The underlying aerosol model has been developed for climatological purposes and is available in relatively big spatial resolution. Reanalysis data with a spatial resolution of about 1° by 1° have difficulties in covering local sources of aerosol as it is the case in Islamabad and in most of the other locations used within this campaign. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents. Within DLR, a solution for this problem is under development and will be presented in a future publication.

5 Site specifics Islamabad

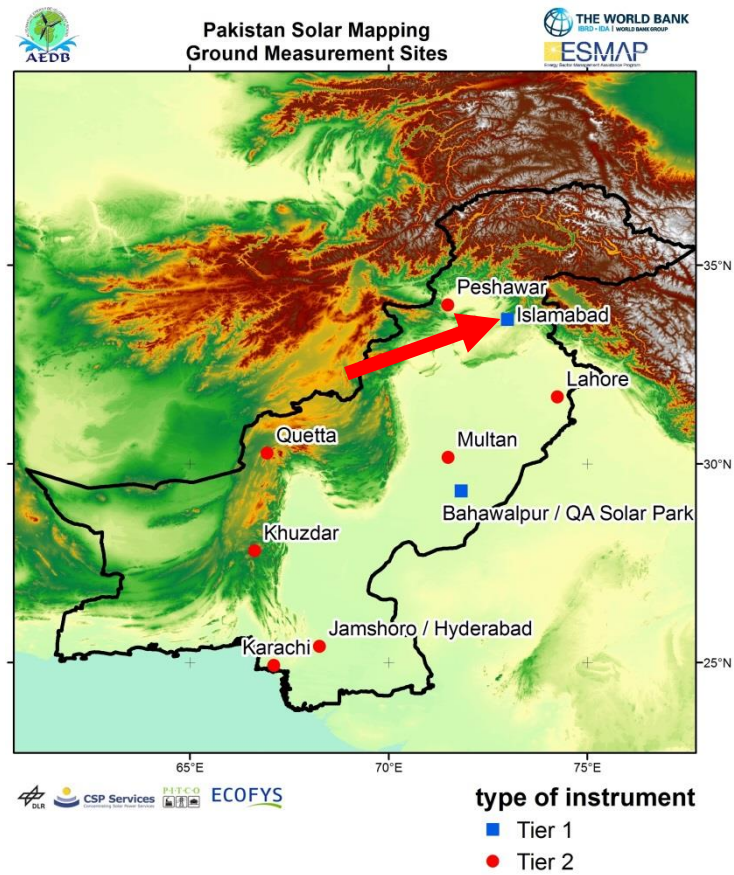


Figure 14: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
National University of Science and Technology (NUST), Islamabad	Pk-Isb	33.642°N, 72.984°E	Tier 1	2014-10-25

5.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Islamabad. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

5.1.1 Validation results of Global Horizontal Irradiance

Table 4: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 9041
Stations NAs: 678
Satellite NAs: 895
Station mean (plus noct.): 194.9
Station mean (no noct.): 372.9
Station max (plus noct.): 1040 on 2014-12-07 18:00:00
Satellite mean (plus noct.): 226.8
Satellite mean (no noct.): 434.1
Satellite max (plus noct.): 1108.9 on 2014-12-10 14:00:00
GHI Mean Bias (no NA/No noct.): 61.1
GHI RMSE (no NA/No noct.): 116.4

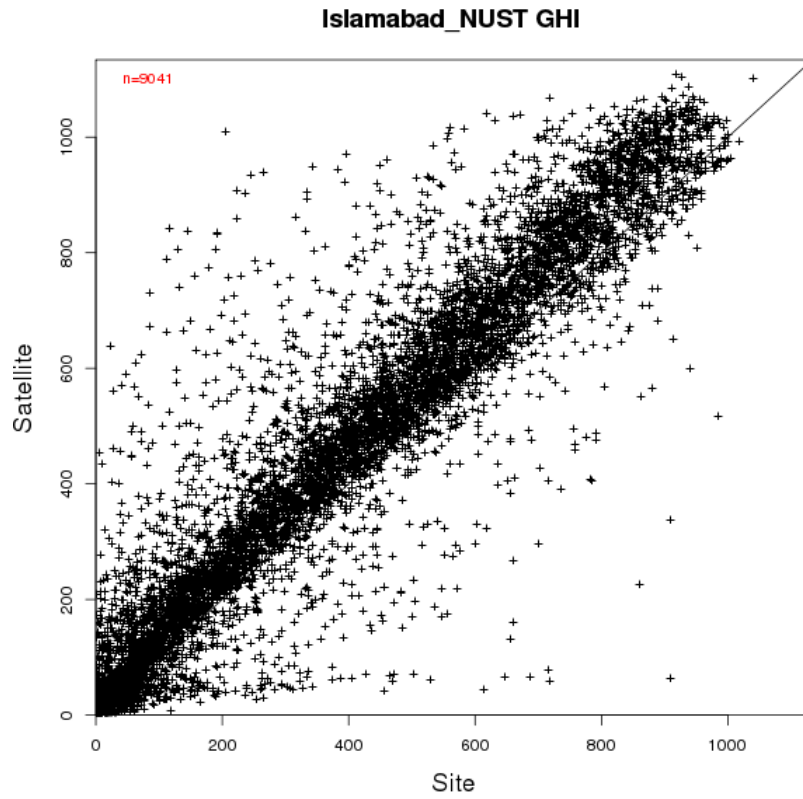


Figure 15: Scatterplot of validation results for GHI at the location of Islamabad (in W/m^2)

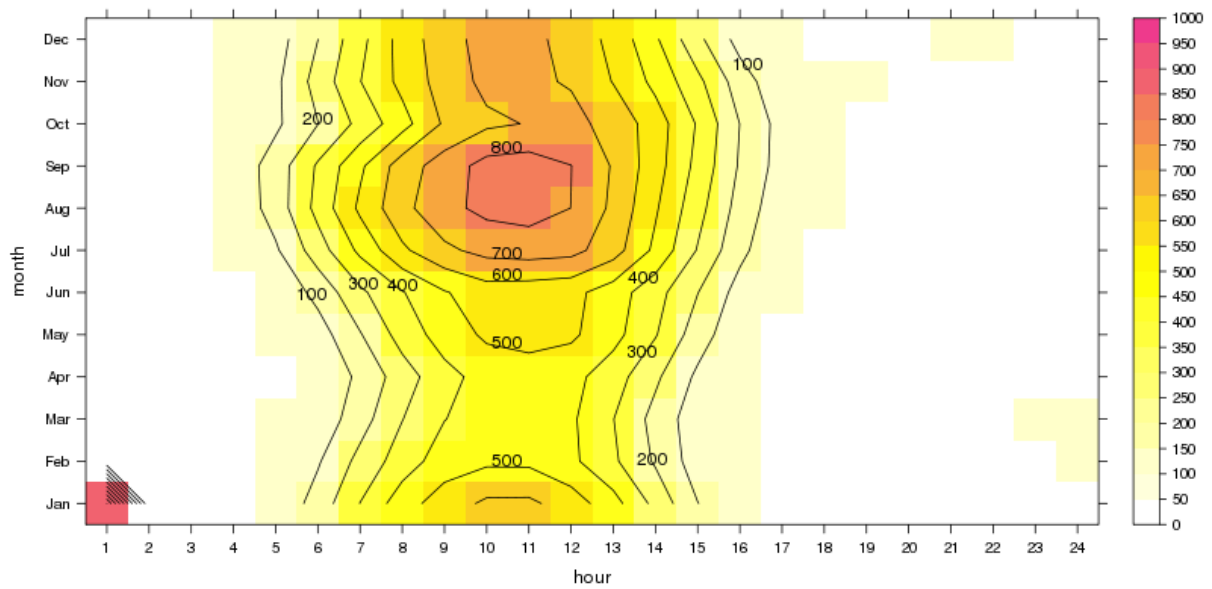


Figure 16: Isopleth graph of ground measurement of GHI at Islamabad in W/m^2 (UTC)

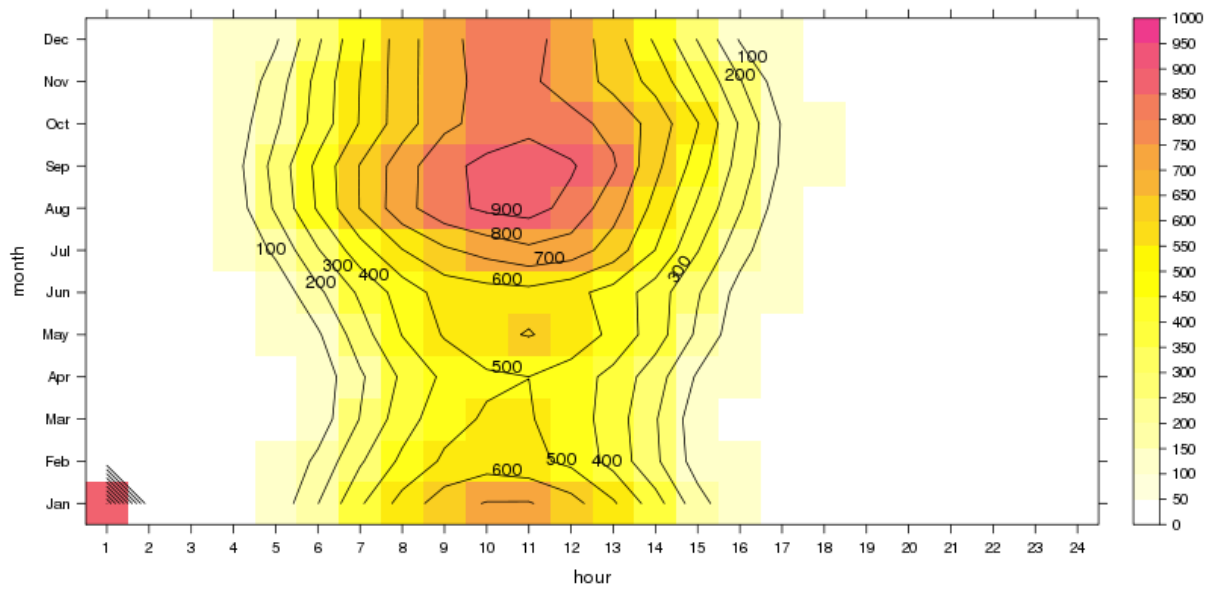


Figure 17: Isopleth graph of satellite estimation of GHI at Islamabad in W/m^2 (UTC)

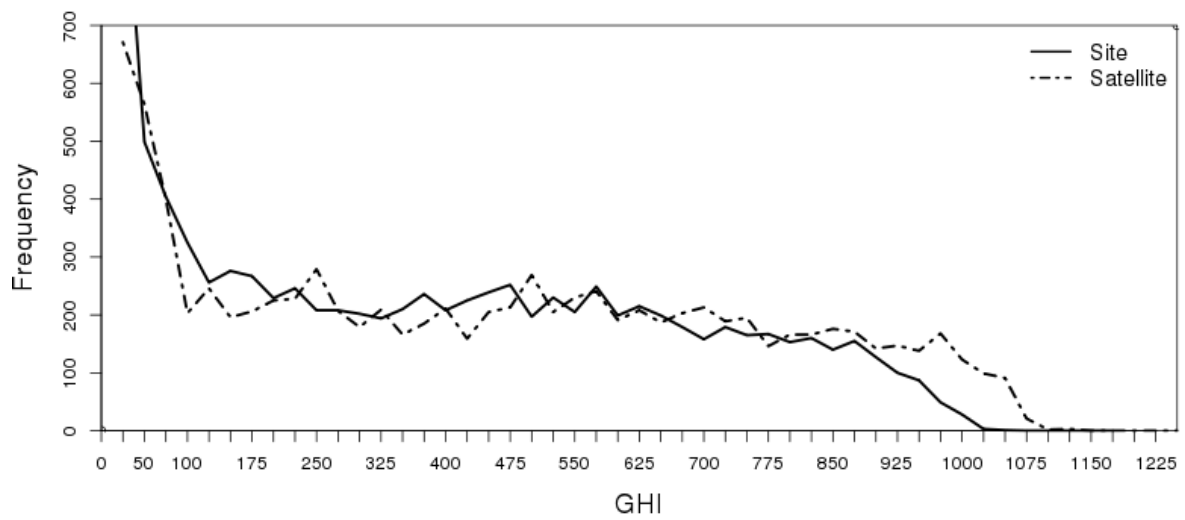


Figure 18: Frequency distribution of hourly GHI at the location of Islamabad in W/m^2

5.1.2 Validation results of Direct Normal Irradiance

Table 5: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 6377
Stations NAs: 3000
Satellite NAs: 895
Station mean (plus noct.): 167.3
Station mean (no noct.): 390.2
Station max (plus noct.): 1026 on 2014-12-07 04:00:00
Satellite mean (plus noct.): 251.8
Satellite mean (no noct.): 579.4
Satellite max (plus noct.): 1024.9 on 2014-12-07 02:00:00
DNI Mean Bias (no NA/No noct.): 189.1
DNI RMSE (no NA/No noct.): 281.8
Valid observations (no NA/No noct.): 6377

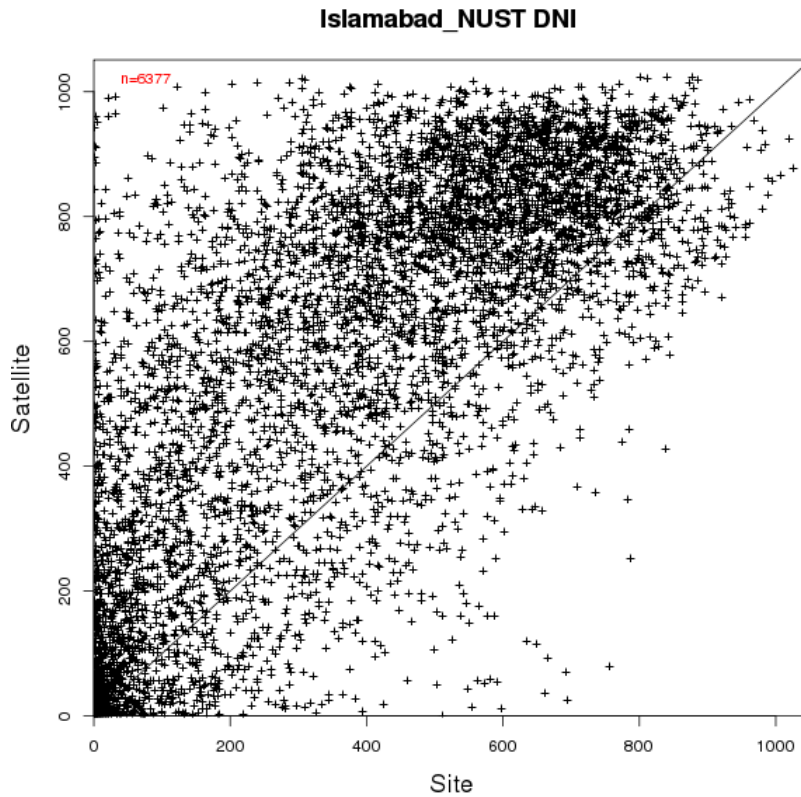


Figure 19: Scatterplot of validation results for DNI at the location of Islamabad (in W/m^2)

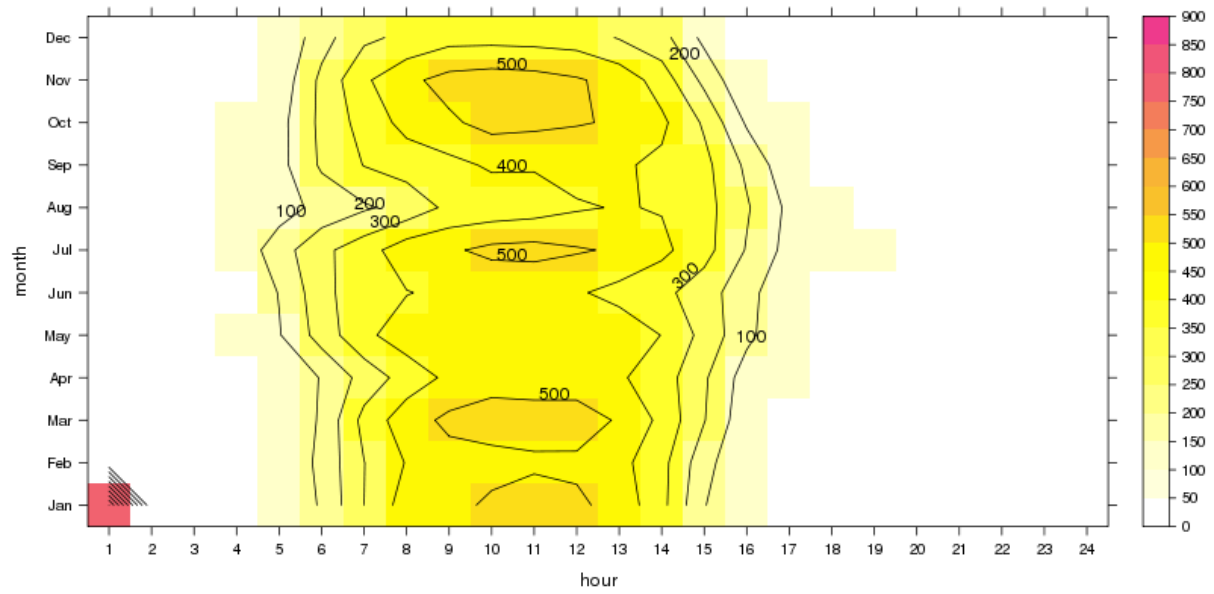


Figure 20: Isopleth graph of ground measurement of DNI at Islamabad in W/m^2 (UTC)

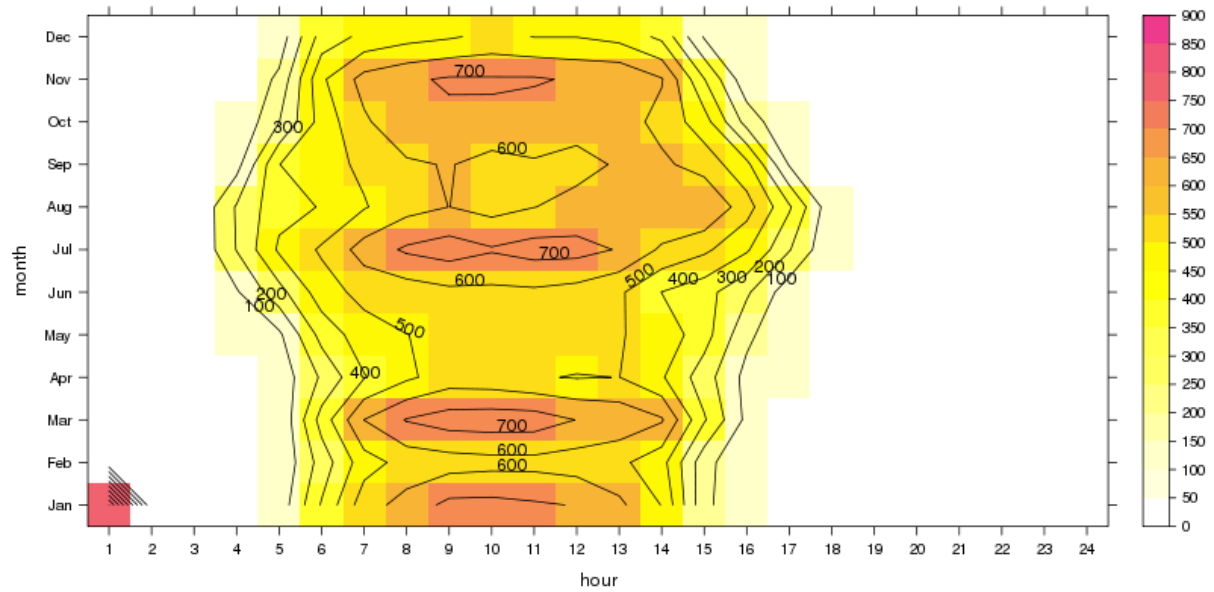


Figure 21: Isopleth graph of satellite estimation of DNI at Islamabad in W/m^2 (UTC)

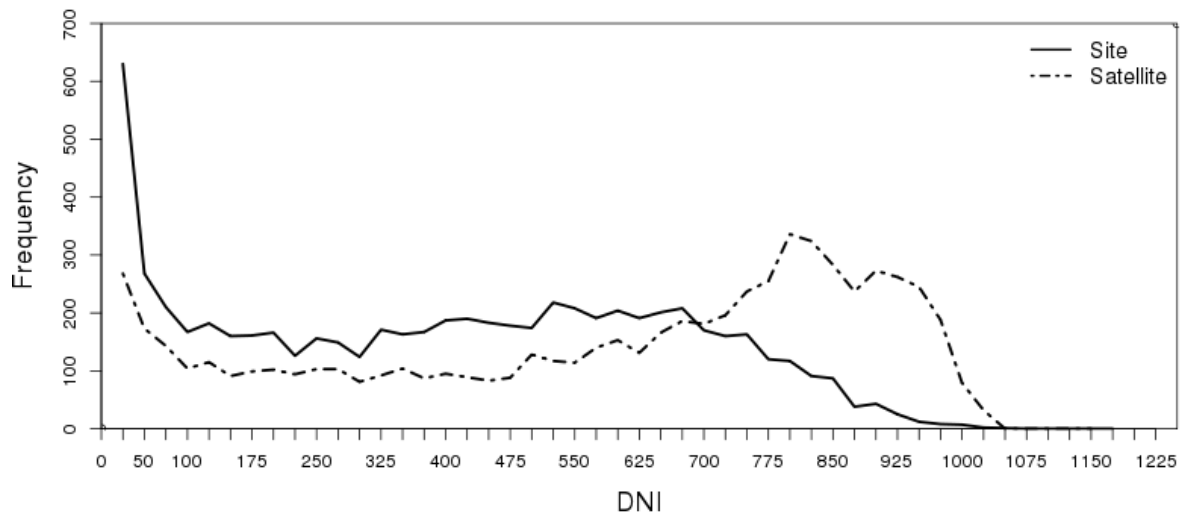


Figure 22: Frequency distribution of hourly DNI at the location of Islamabad in W/m^2

5.1.3 Validation results of Diffuse Horizontal Irradiance

Table 6: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7711
Stations NAs: 3000
Satellite NAs: 895
Station mean (plus noct.): 80.6
Station mean (no noct.): 156.6
Station max (plus noct.): 609 on 2014-11-19 19:00:00
Satellite mean (plus noct.): 71.5
Satellite mean (no noct.): 138.8
Satellite max (plus noct.): 741.7 on 2014-11-25 07:00:00
DHI Mean Bias (No NAs/No noct.): -17.7
DHI RMSE (No NAs/No noct.): 92.2

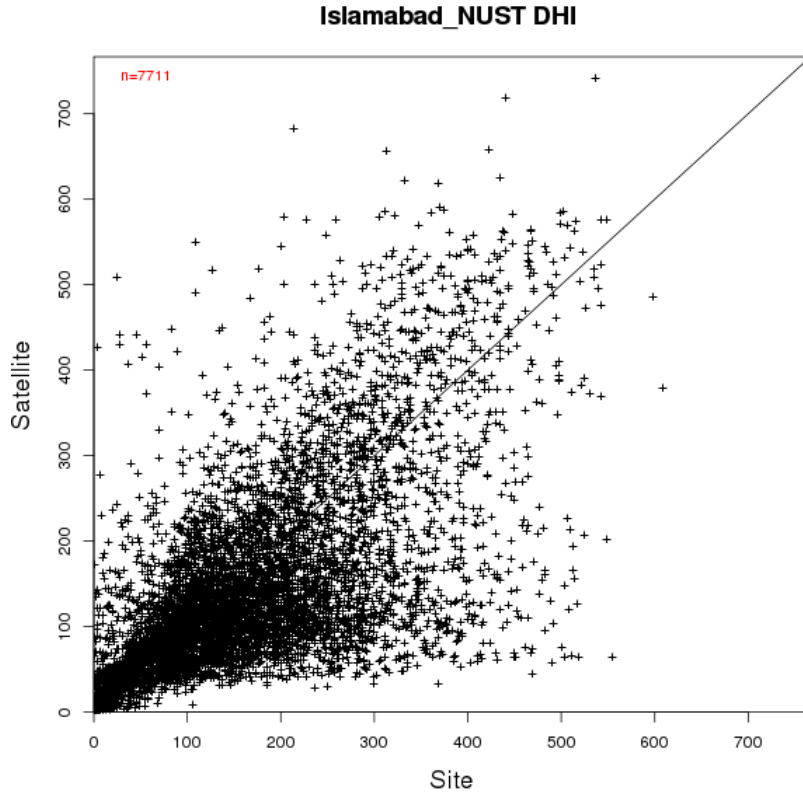


Figure 23: Scatterplot of validation results for DHI at the location of Islamabad (in W/m^2)

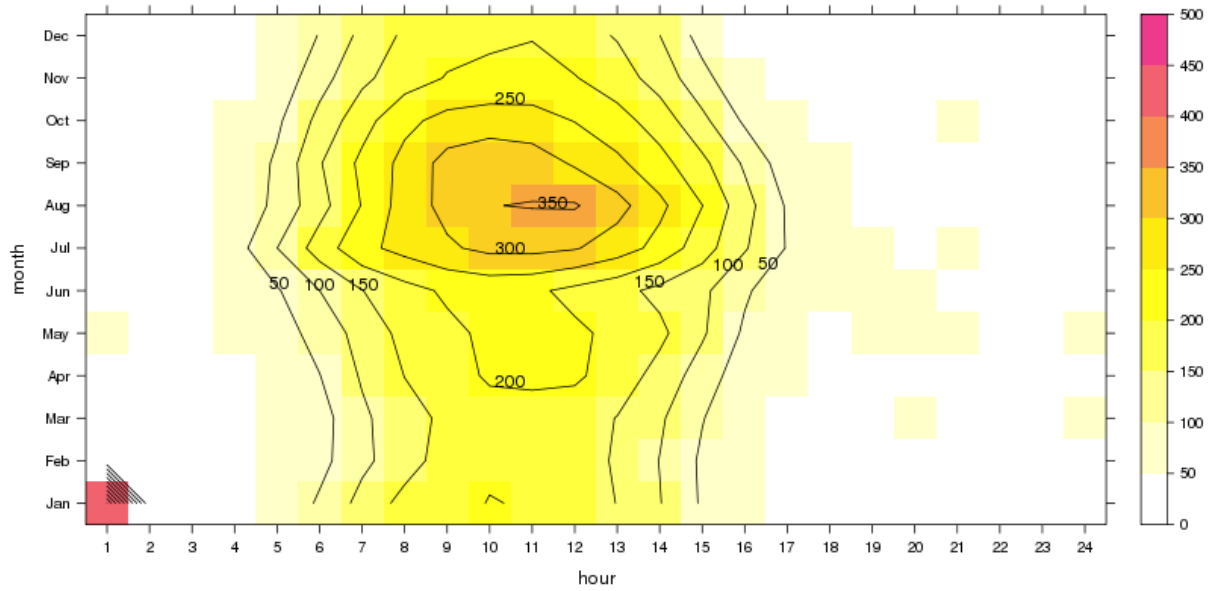


Figure 24: Isopleth graph of ground measurement of DHI at Islamabad in W/m^2 (UTC)

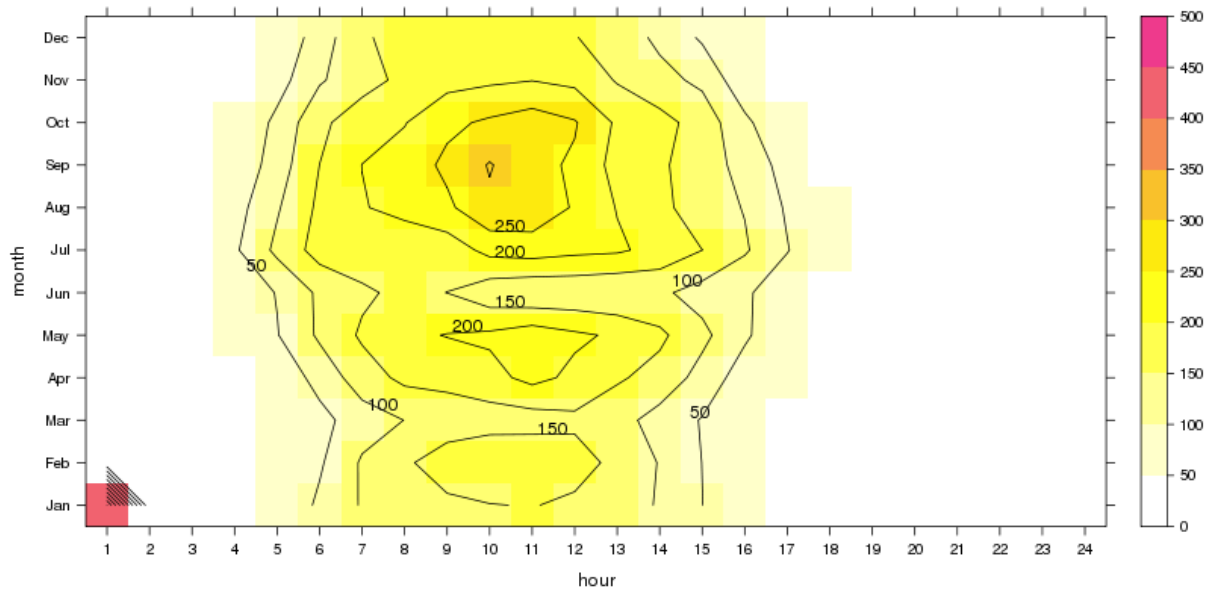


Figure 25: Isoleth graph of satellite estimation of DHI at Islamabad in W/m² (UTC)

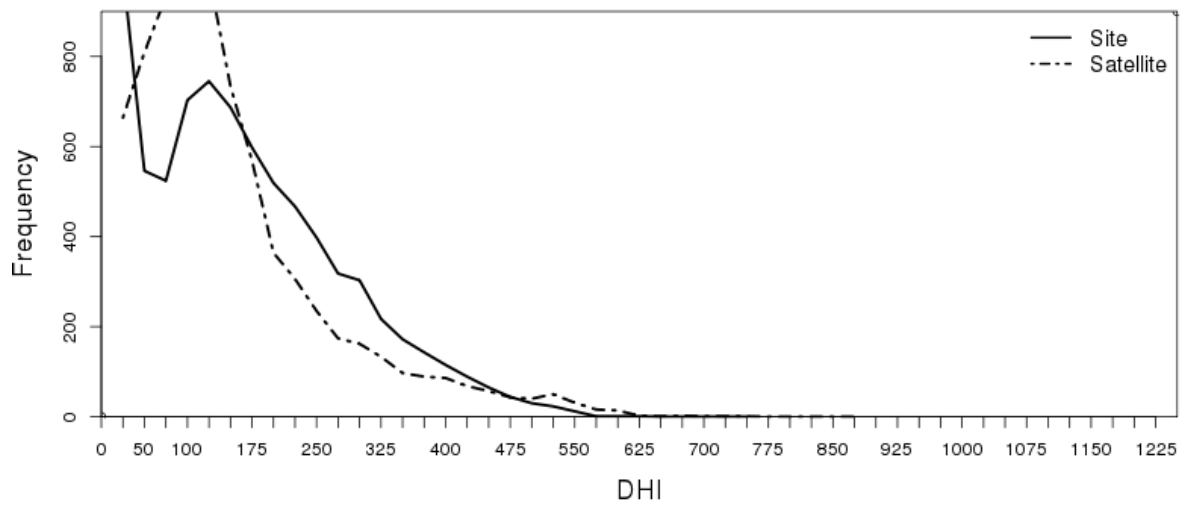


Figure 26: Frequency distribution of hourly DHI at the location of Islamabad in W/m²

5.2 Discussion and conclusion

The TIER1 site at National University of Science and Technology (NUST) in the western region of Islamabad provides one of the longest time-series from within the measurement campaign. The installation date of the station is October 25th, 2014 but there is a significant data gap at the beginning of the year 2015, where the station has been out of order for organizational reasons. Nevertheless, this dataset is very important as the measurement takes place in a heavily populated area and, thus, represents an area with an above-average energy demand. This fact does partly explain the performance of the satellite model and the results presented in this report. The underlying aerosol model has been developed for climatological purposes and is available in relatively big spatial resolution. Reanalysis data with a spatial resolution of about 1° by 1° have difficulties in covering local sources of aerosol as it is the case in Islamabad and in most of the other locations used within this campaign. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents. Within DLR, a solution for this problem is under development and will be presented in a future publication.

The results of the validation campaign illustrates that the satellite model overestimates the irradiance (GHI and DNI) and shows a higher amount of diffuse irradiance compared to the results of the measurement sites at NUST. The seasonal pattern for all three parameters correlates well between model and measurement but the absolute values, especially peaks in irradiance, are overestimated by the modelled data. This is highlighted by the frequency distribution of DNI (Figure 22) that shows a significantly higher amount of hourly sums above 700 W/m^2 than measured data. This can be referred to alleged clearsky-days where the satellite-model relies on the input of the aerosol data. Many of these cases appear to happen on days with a nocturnal inversion layer and fog that lasts until noon and when there is only little advection of fresh air. The same is the case for GHI (Figure 109), but for a lesser extent.

6 Site specifics Karachi

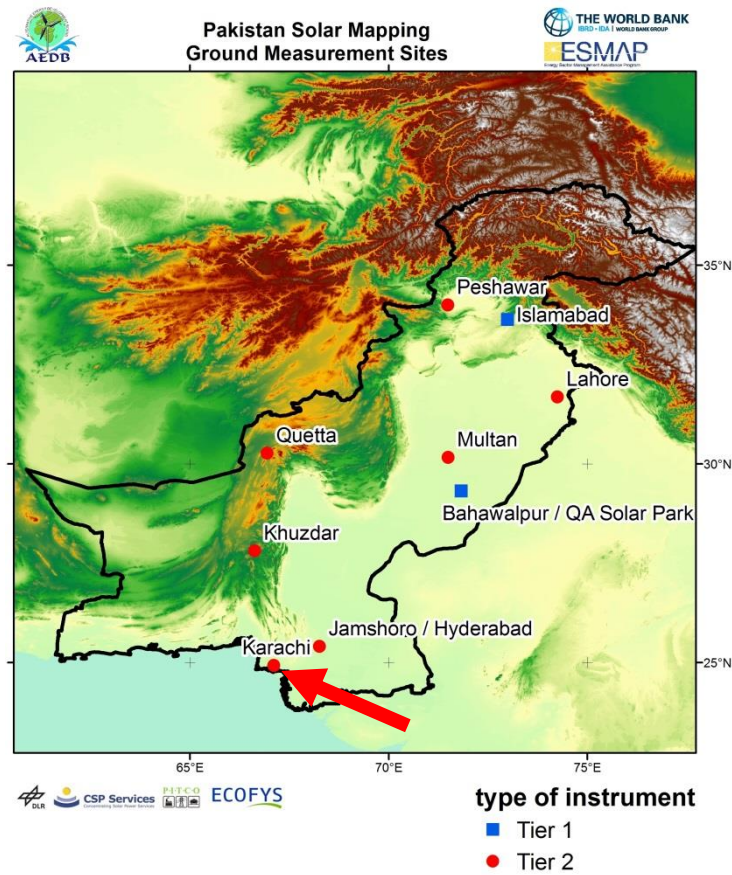


Figure 27: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
NED University of Engineering and Technology (NED-UET), Karachi	Pk-Kar	24.933°N, 67.112°E	Tier 2	2015-04-22

6.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Karachi. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

6.1.1 Validation results of Global Horizontal Irradiance

Table 7: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7081
Stations NAs: 519
Satellite NAs: 864
Station mean (plus noct.): 221.9
Station mean (no noct.): 409.2
Station max (plus noct.): 1001 on 2015-06-03 18:00:00
Satellite mean (plus noct.): 272.9
Satellite mean (no noct.): 503.2
Satellite max (plus noct.): 1132.9 on 2015-06-09 05:00:00
GHI mean bias (no NA/No noct.): 94.0
GHI RMSE (no NA/No noct.): 147.7

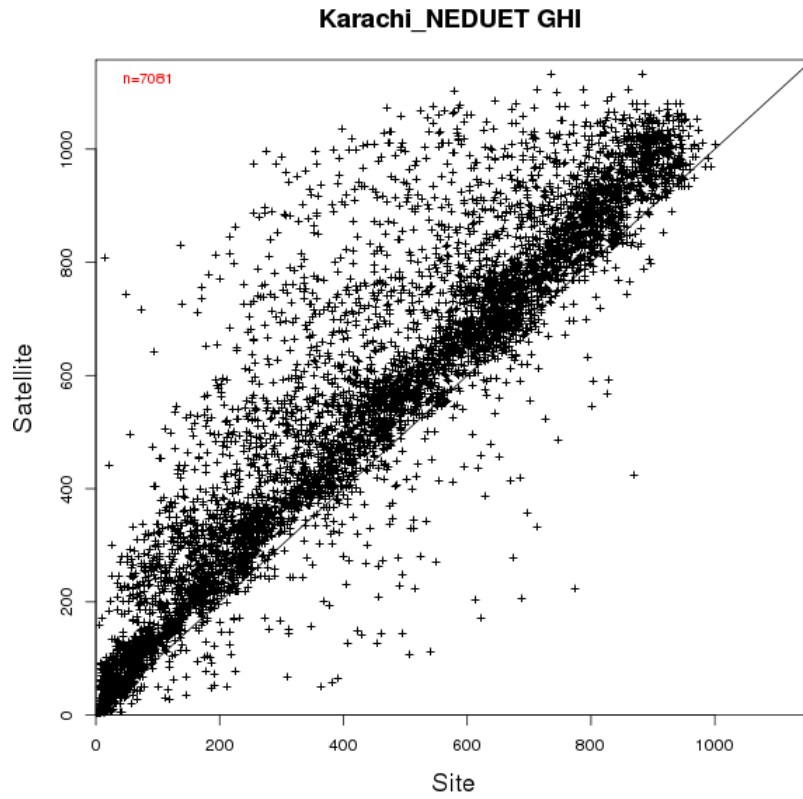


Figure 28: Scatterplot of validation results for GHI at the location of Karachi (in W/m^2)

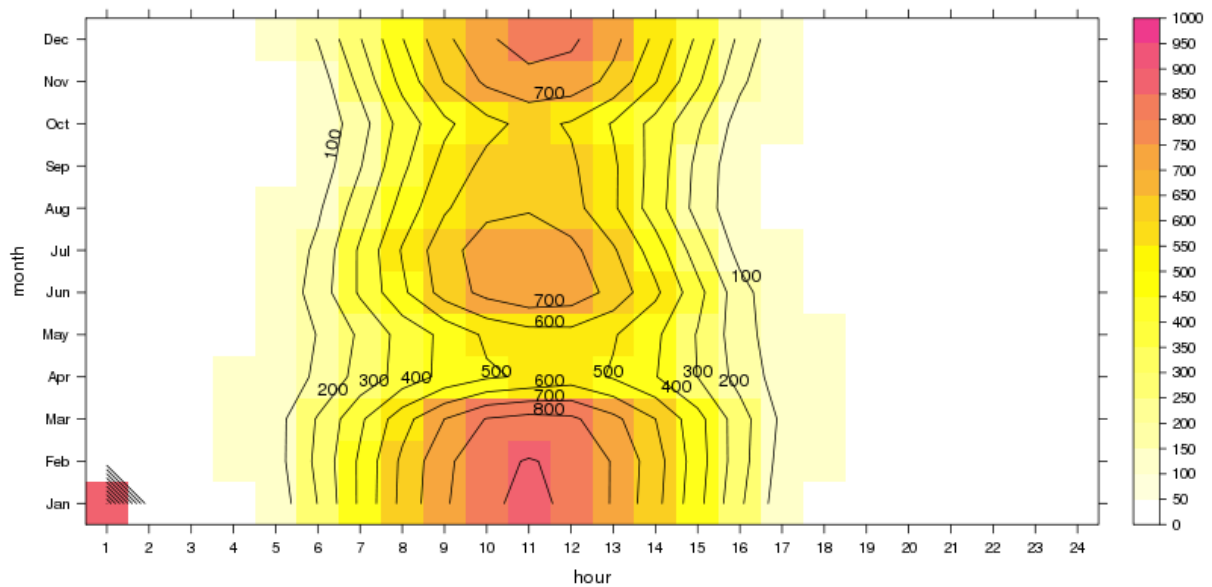


Figure 29: Isopleth graph of ground measurement of GHI at Karachi in W/m^2 (UTC)

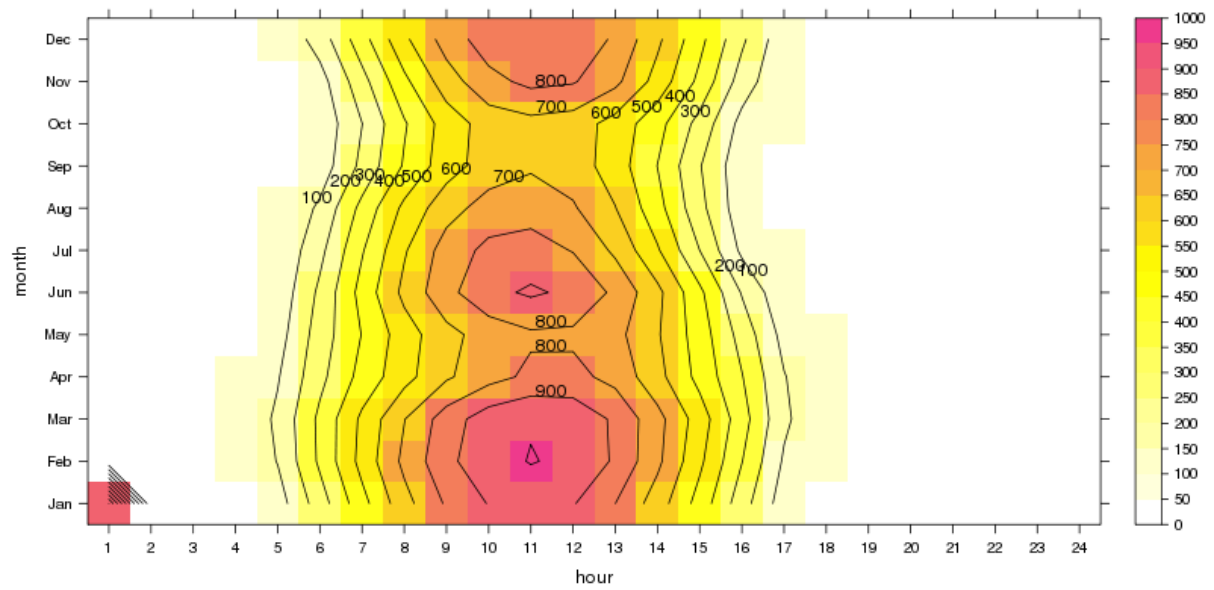


Figure 30: Isopleth graph of satellite estimation of GHI at Karachi in W/m^2 (UTC)

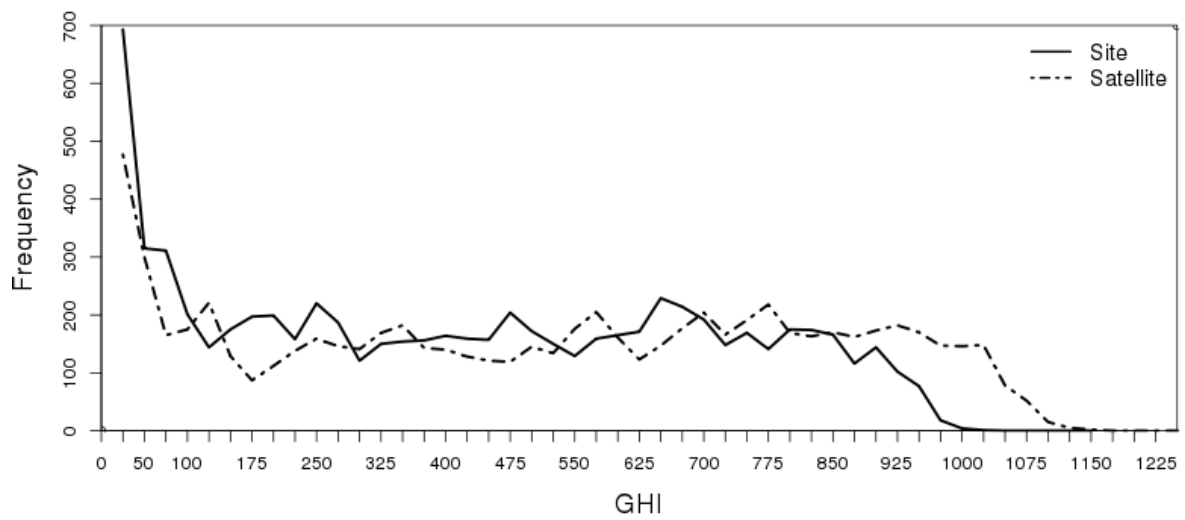


Figure 31: Frequency distribution of hourly GHI at the location of Karachi in W/m^2

6.1.2 Validation results of Direct Normal Irradiance

Table 8: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

valid observations (no NA/No noct.): 5987
Stations NAs: 519
Satellite NAs: 864
Station mean (plus noct.): 158.7
Station mean (no noct.): 345.6
Station max (plus noct.): 932 on 2015-05-31 21:00:00
Satellite mean (plus noct.): 286.9
Satellite mean (no noct.): 601.31
Satellite max (plus noct.): 1008.7 on 2015-06-04 01:00:00
DNI mean bias (no NA/No noct.): 255.6
DNI RMSE (no NA/No noct.): 335.5

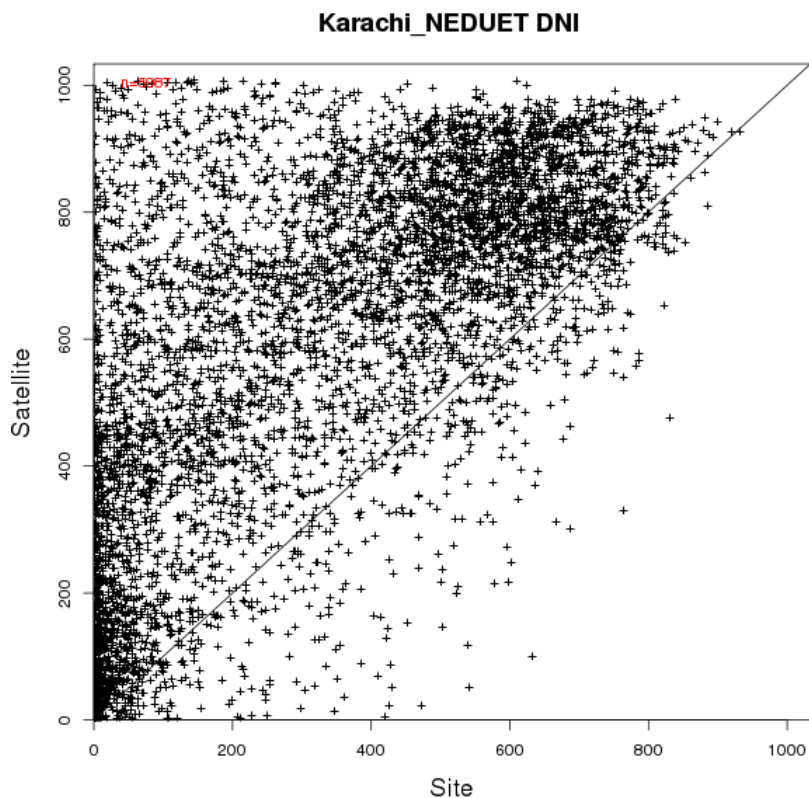


Figure 32: Scatterplot of validation results for DNI at the location of Karachi (in W/m^2)

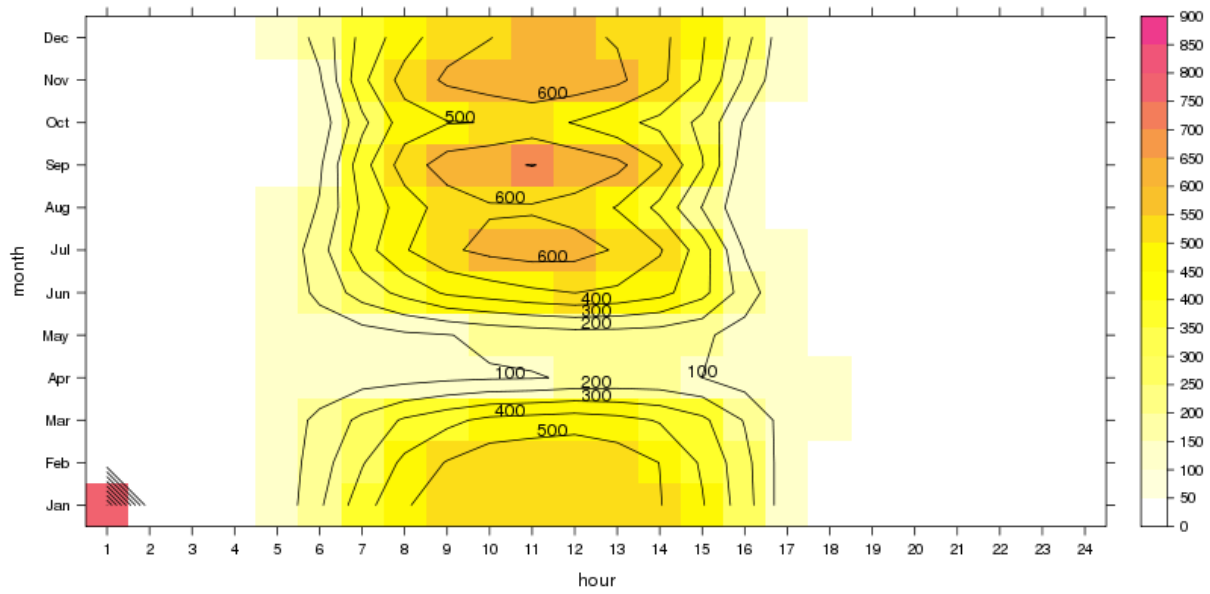


Figure 33: Isopleth graph of ground measurement of DNI at Karachi in W/m² (UTC)

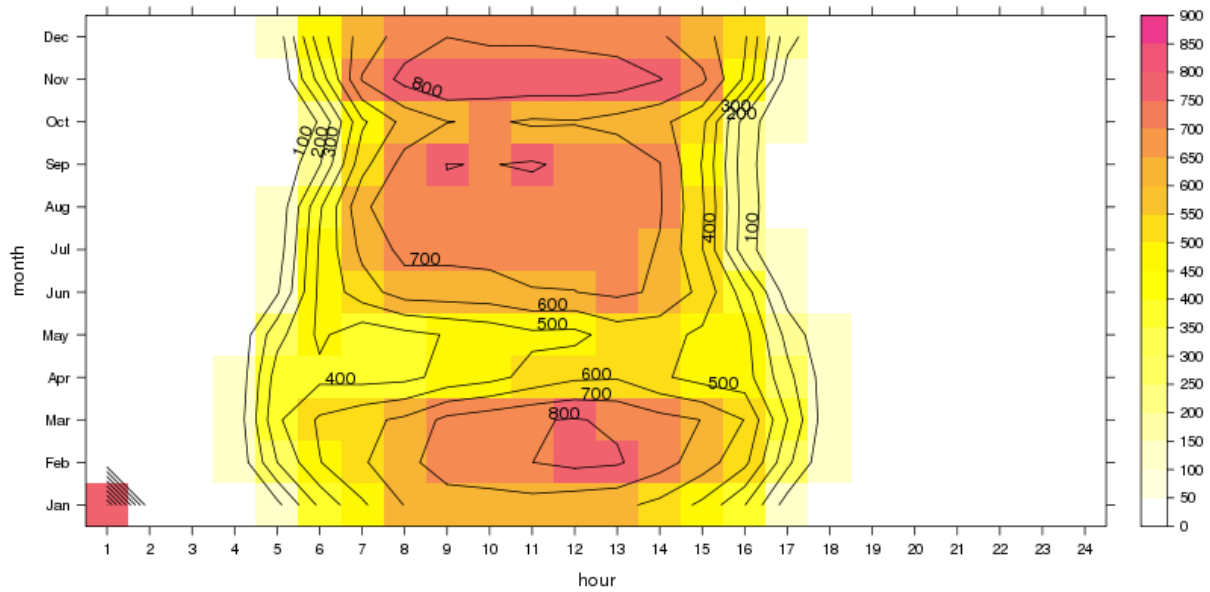


Figure 34: Isopleth graph of satellite estimation of DNI at Karachi in W/m² (UTC)

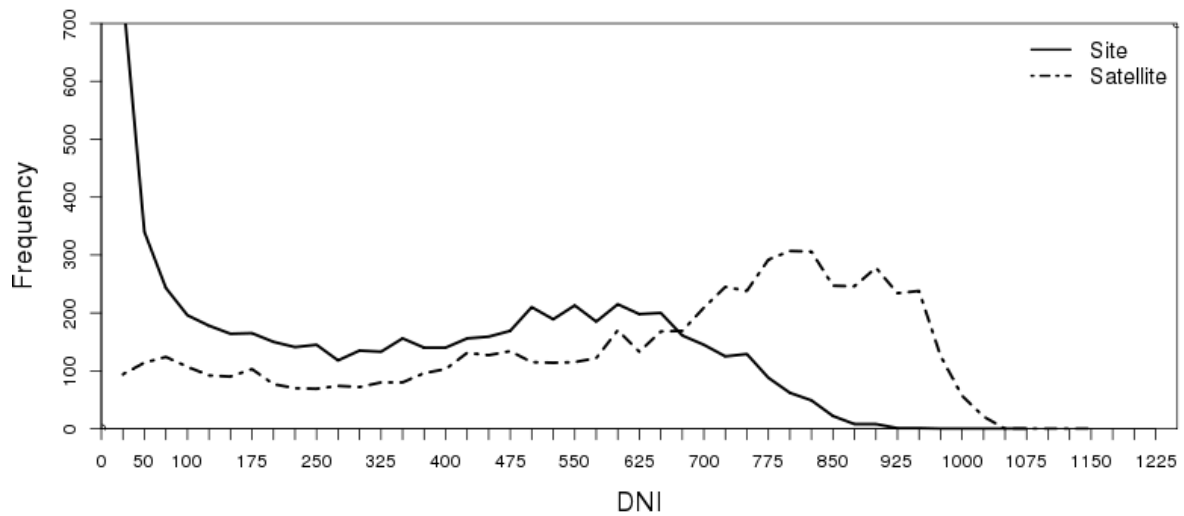


Figure 35: Frequency distribution of hourly DNI at the location of Karachi in W/m^2

6.1.3 Validation results of Diffuse Horizontal Irradiance

Table 9: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7081
Stations NAs: 519
Satellite NAs: 864
Station mean (plus noct.): 110.3
Station mean (no noct.): 203.4
Station max (plus noct.): 653 on 2015-05-20 06:00:00
Satellite mean (plus noct.): 86.1
Satellite mean (no noct.): 158.8
Satellite max (plus noct.): 765.8 on 2015-05-24 22:00:00
DHI mean bias (no NA/No noct.): -44.6
DHI RMSE (no NA/No noct.): 117.7

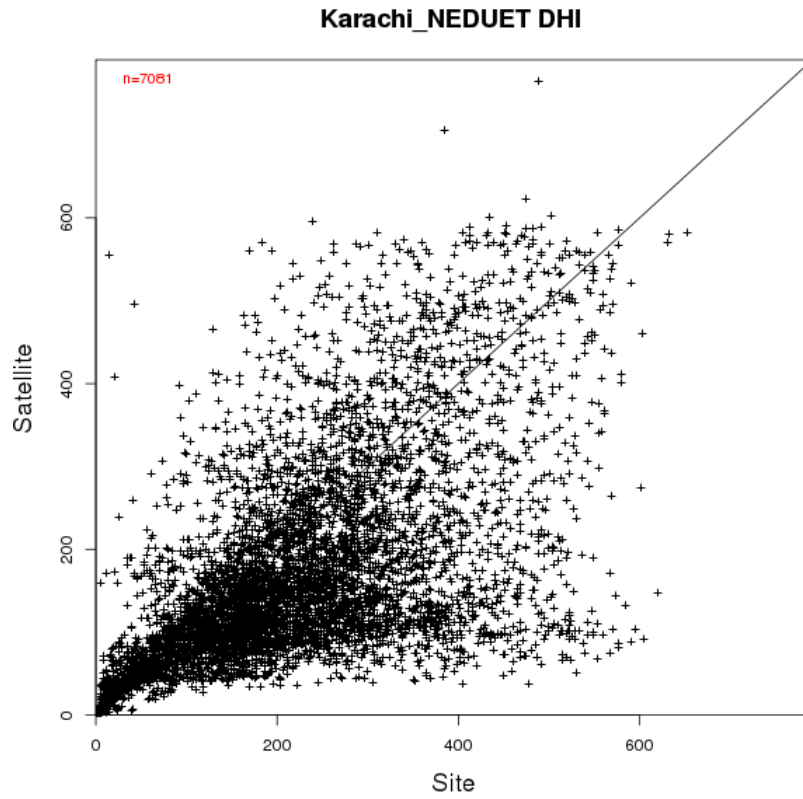


Figure 36: Scatterplot of validation results for DHI at the location of Karachi (in W/m^2)

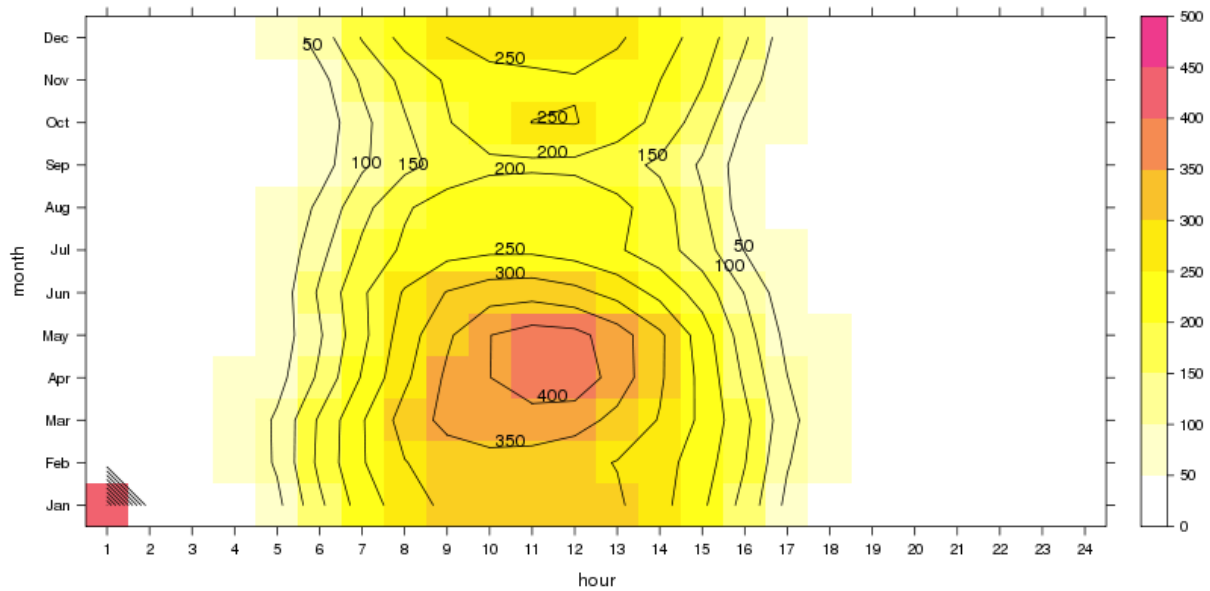


Figure 37: Isopleth graph of ground measurement of DHI at Karachi in W/m^2 (UTC)

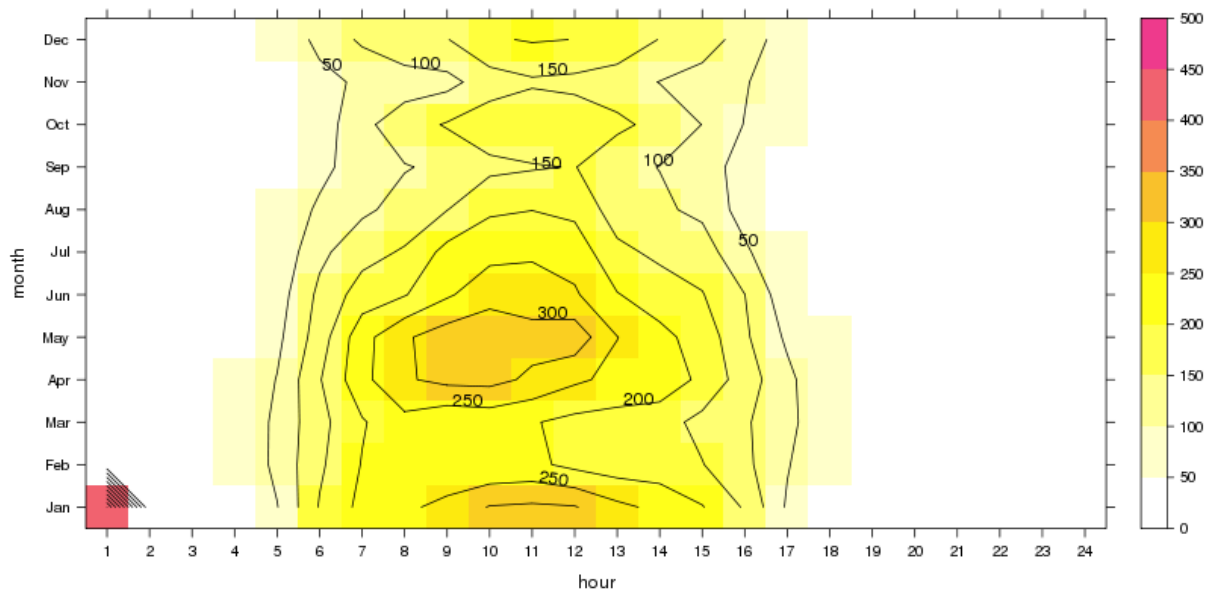


Figure 38: Isoleth graph of satellite estimation of DHI at Karachi in W/m^2 (UTC)

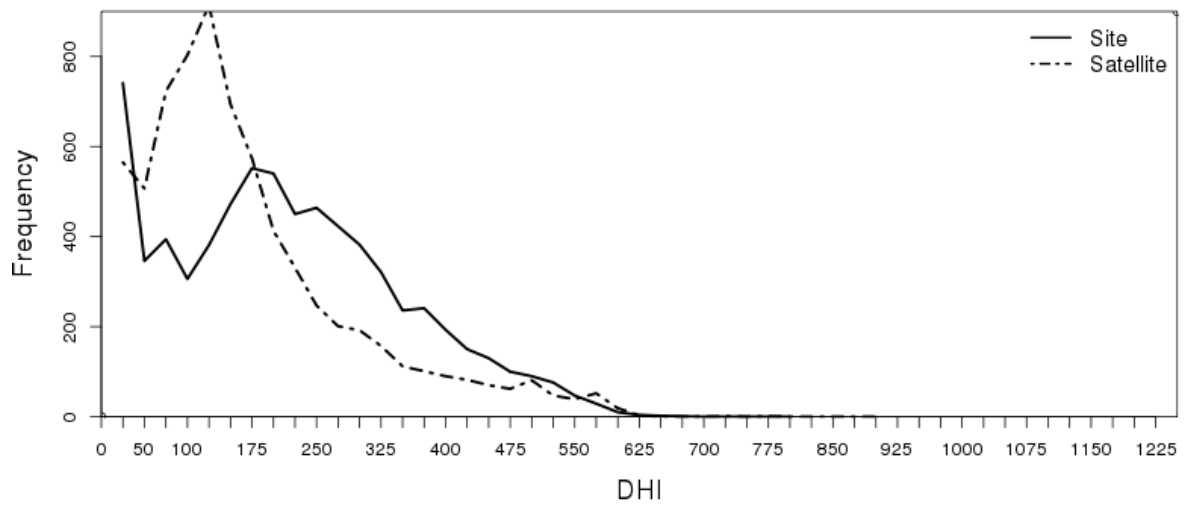


Figure 39: Frequency distribution of hourly DHI at the location of Karachi in W/m^2

6.2 Discussion and conclusion

The TIER2 measurement station at NEDUET Karachi is the only site within the project located in the vicinity of the coastline (distance approx. 20 km) and, thus, is exposed to special meteorological circumstances in Pakistan. Moreover it is the southernmost site in the project and holds the highest theoretical potential in terms of sunlight hours a year. Practically, the irradiance at this site is moderate compared to most other sites and shows a high seasonality, probably caused by maritime influence. For DNI and GHI, an absolute minimum can be found in April and May, with a high share of diffuse irradiance, reaching 400 W/m² during these months. The impact of the diffuse irradiance is underestimated by the model data and which leads to an overestimation of DNI and GHI in general. The site is also located only about 5 km from the center of Karachi, an industrial agglomeration of more than 13 million people. Here the local production of aerosol is very high and might not be covered well by aerosol models that are available for satellite estimation.

7 Site specifics Khuzdar

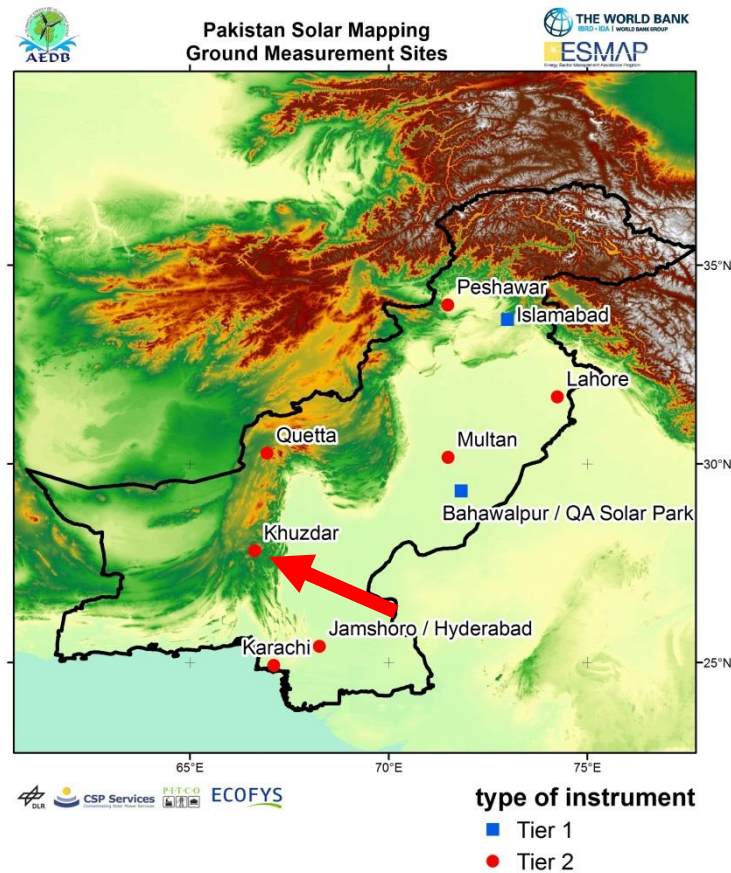


Figure 40: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
Baluchistan University of Engineering and Technology, Khuzdar	Pk-Khu	27.818°N, 66.629°E	Tier 2	2015-09-22

7.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Khuzdar. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

7.1.1 Validation results of Global Horizontal Irradiance

Table 10: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 4997
Stations NAs: 521 Satellite NAs: 840
Station mean (plus noct.): 250.5
Station mean (no noct.): 471.1
Station max (plus noct.): 1100 on 2015-11-07 09:00:00
Satellite mean (plus noct.): 264.3
Satellite mean (no noct.): 497.0
Satellite max (plus noct.): 1079.1 on 2015-11-06 12:00:00
GHI mean bias (no NA/No noct.): 25.9
GHI RMSE (no NA/No noct.): 92.1
valid observations (no NA/No noct.): 4997

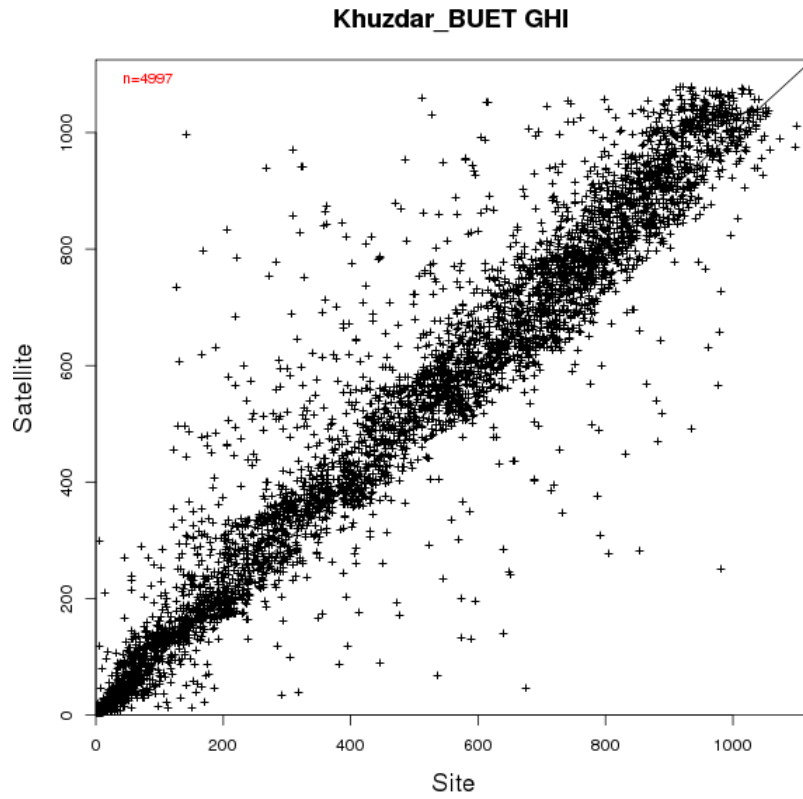


Figure 41: Scatterplot of validation results for GHI at the location of Khuzdar (in W/m^2)

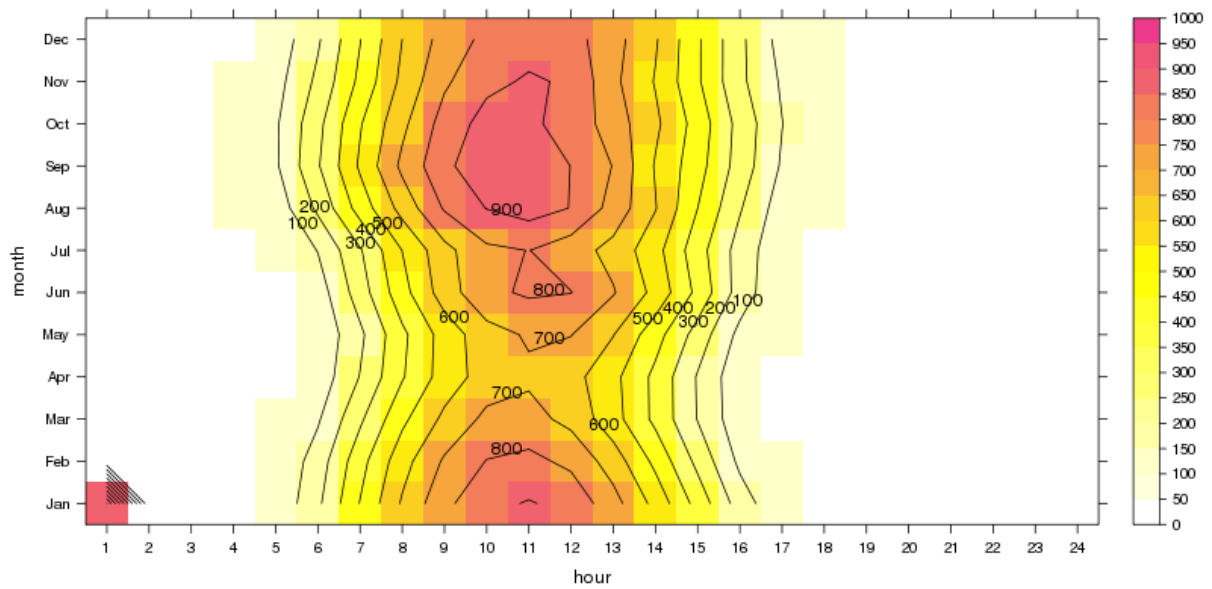


Figure 42: Isopleth graph of ground measurement of GHI at Khuzdar in W/m^2 (UTC)

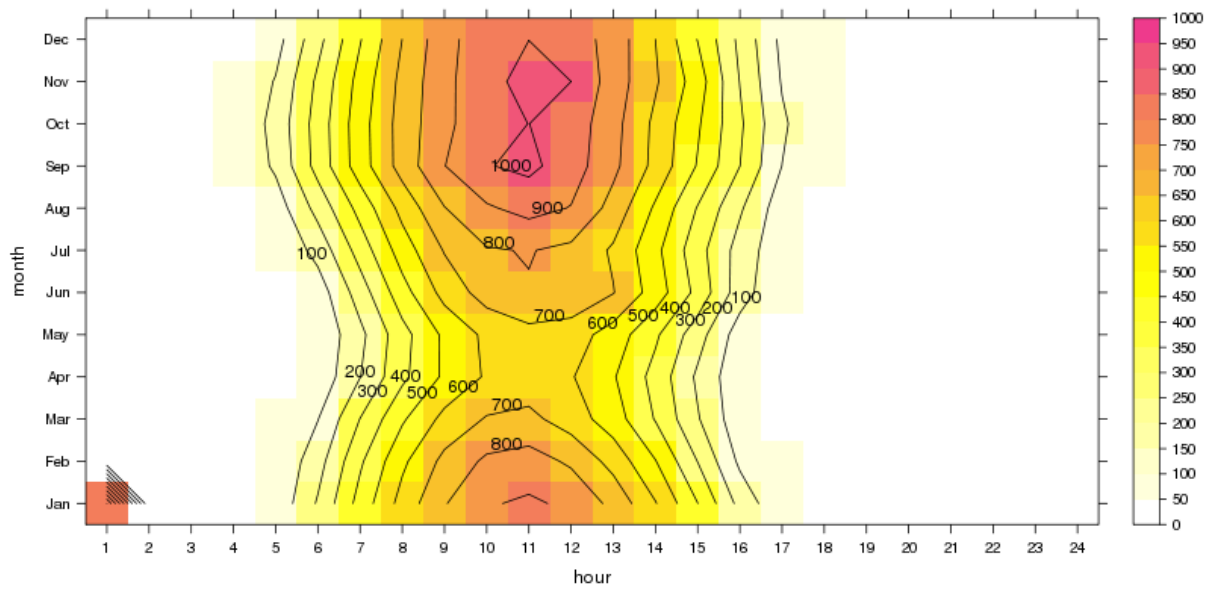


Figure 43: Isopleth graph of satellite estimation of GHI at Khuzdar in W/m^2 (UTC)

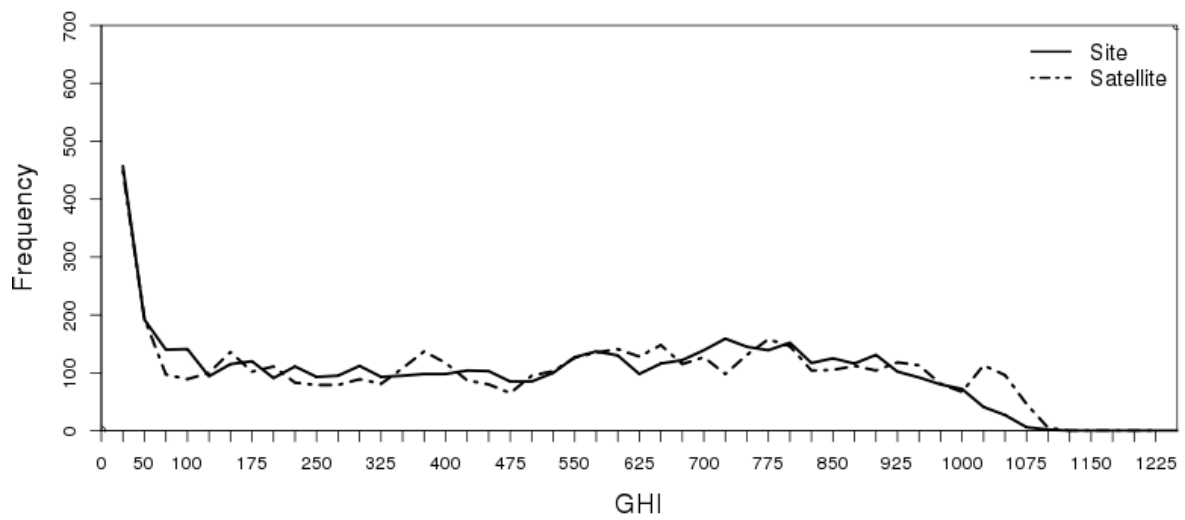


Figure 44: Frequency distribution of hourly GHI at the location of Khuzdar in W/m^2

7.1.2 Validation results of Direct Normal Irradiance

Table 11: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 4538
Stations NAs: 521
Satellite NAs: 840
Station mean (plus noct.): 261.8
Station mean (no noct.): 540.1
Station max (plus noct.): 1085 on 2015-11-06 18:00:00
Satellite mean (plus noct.): 308.9
Satellite mean (no noct.): 633.4
Satellite max (plus noct.): 1024.9 on 2015-11-04 05:00:00
DNI mean bias (no NA/No noct.): 93.2
DNI RMSE (no NA/No noct.): 240.5

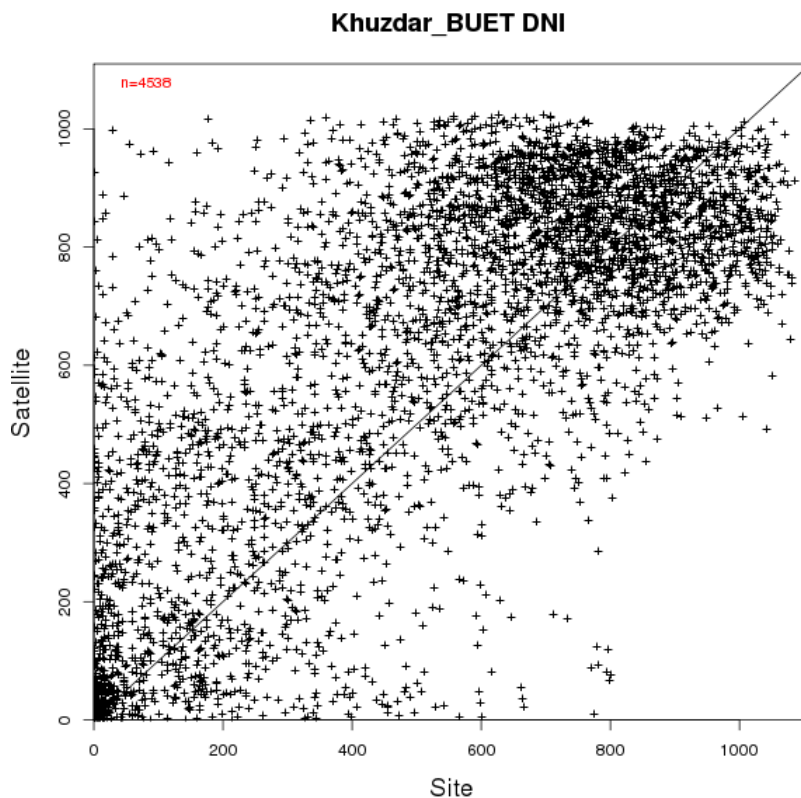


Figure 45: Scatterplot of validation results for DNI at the location of Khuzdar (in W/m^2)

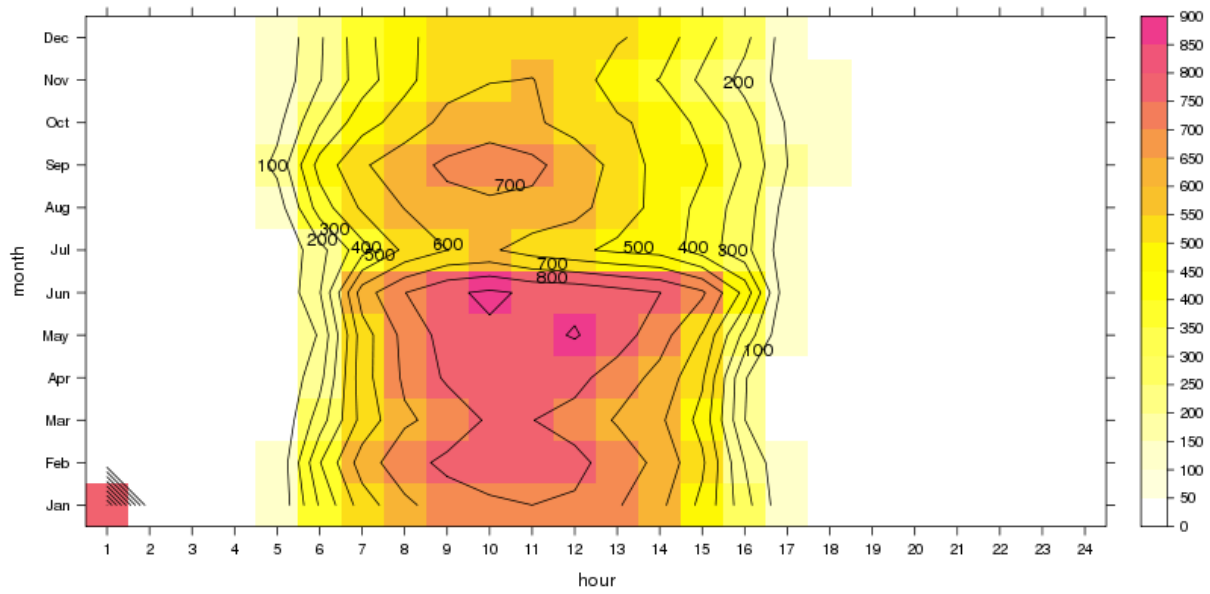


Figure 46: Isopleth graph of ground measurement of DNI at Khuzdar in W/m^2 (UTC)

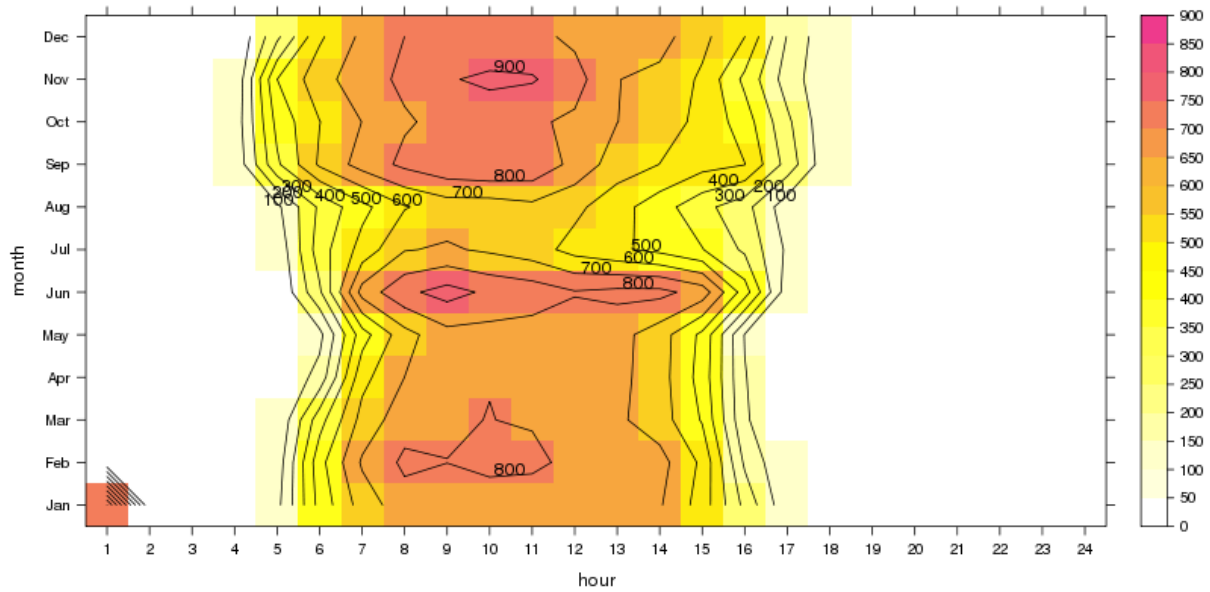


Figure 47: Isopleth graph of satellite estimation of DNI at Khuzdar in W/m^2 (UTC)

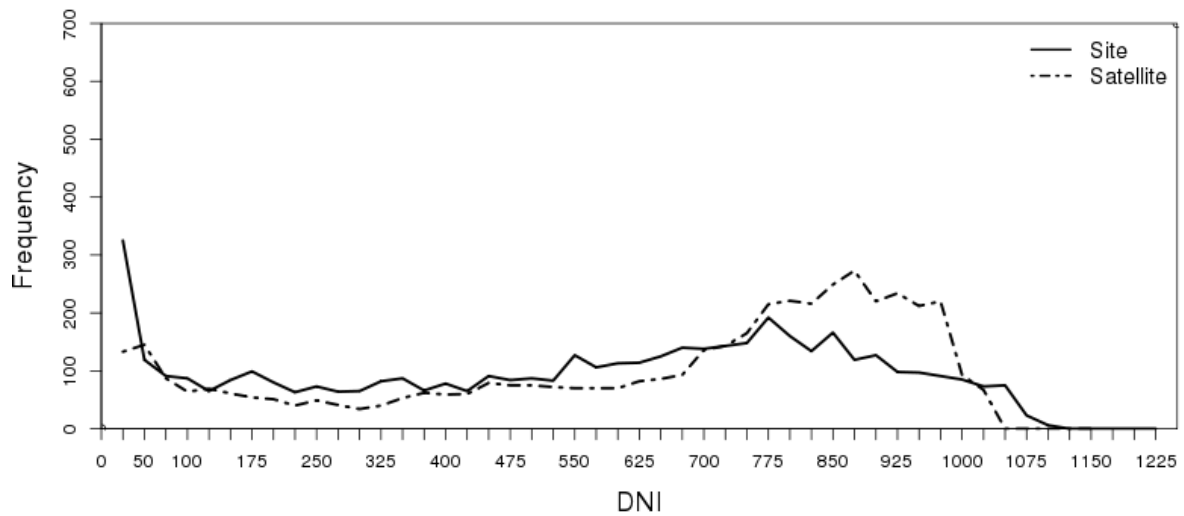


Figure 48: Frequency distribution of hourly DNI at the location of Khuzdar in W/m²

7.1.3 Validation results of Diffuse Horizontal Irradiance

Table 12: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 4997
Stations NAs: 521
Satellite NAs: 840
Station mean (plus noct.): 83.0
Station mean (no noct.): 156.1
Station max (plus noct.): 639 on 2015-10-19 04:00:00
Satellite mean (plus noct.): 69.9
Satellite mean (no noct.): 131.5
Satellite max (plus noct.): 783.6 on 2015-10-25 04:00:00
DHI mean bias (no NA/No noct.): -24.5
DHI RMSE (no NA/No noct.): 93.2

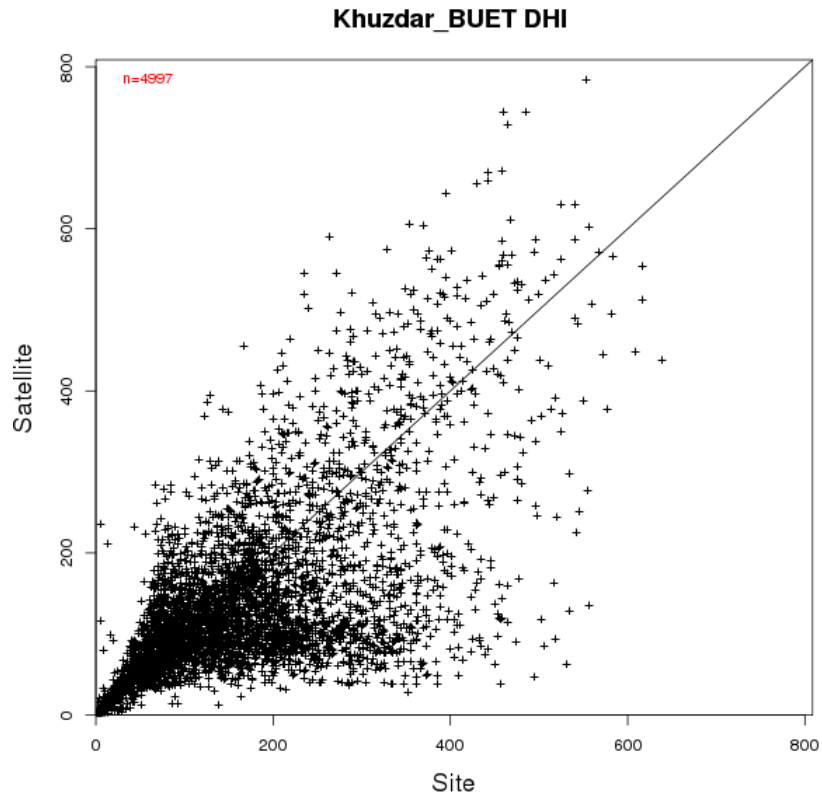


Figure 49: Scatterplot of validation results for DHI at the location of Khuzdar (in W/m^2)

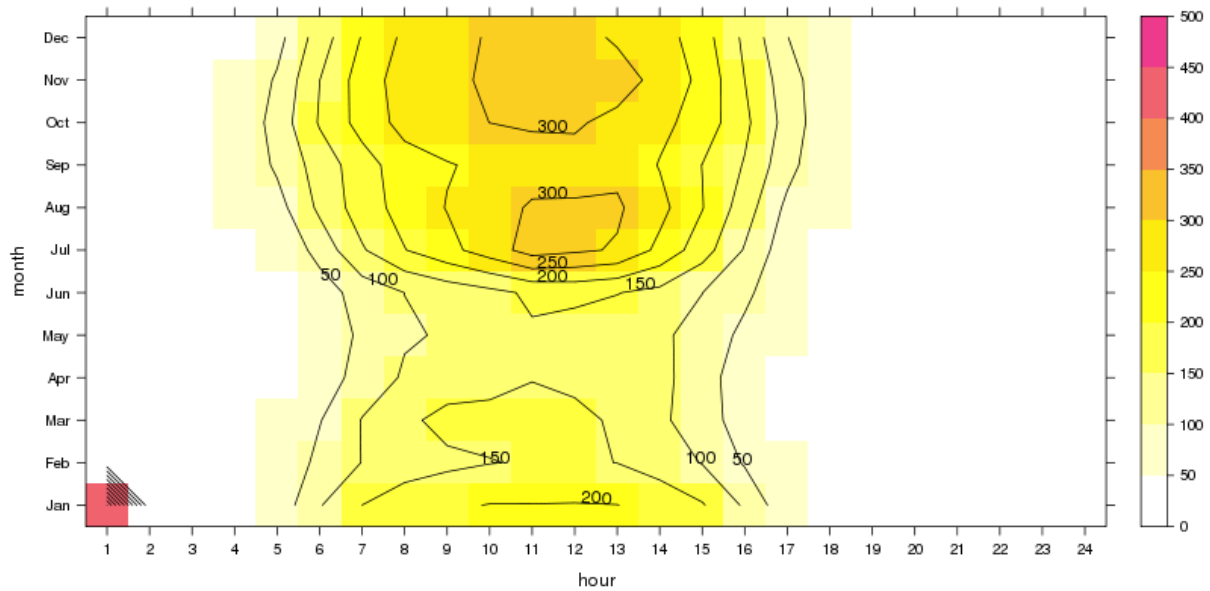


Figure 50: Isopleth graph of ground measurement of DHI at Khuzdar in W/m^2 (UTC)

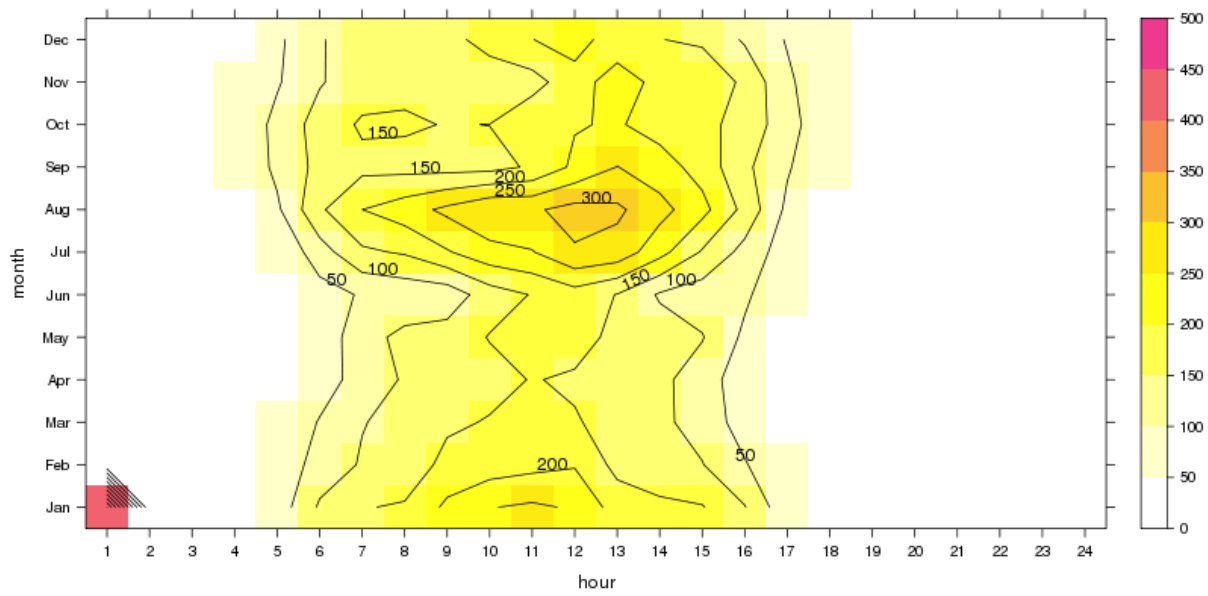


Figure 51: Isopleth graph of satellite estimation of DHI at Khuzdar in W/m^2 (UTC)

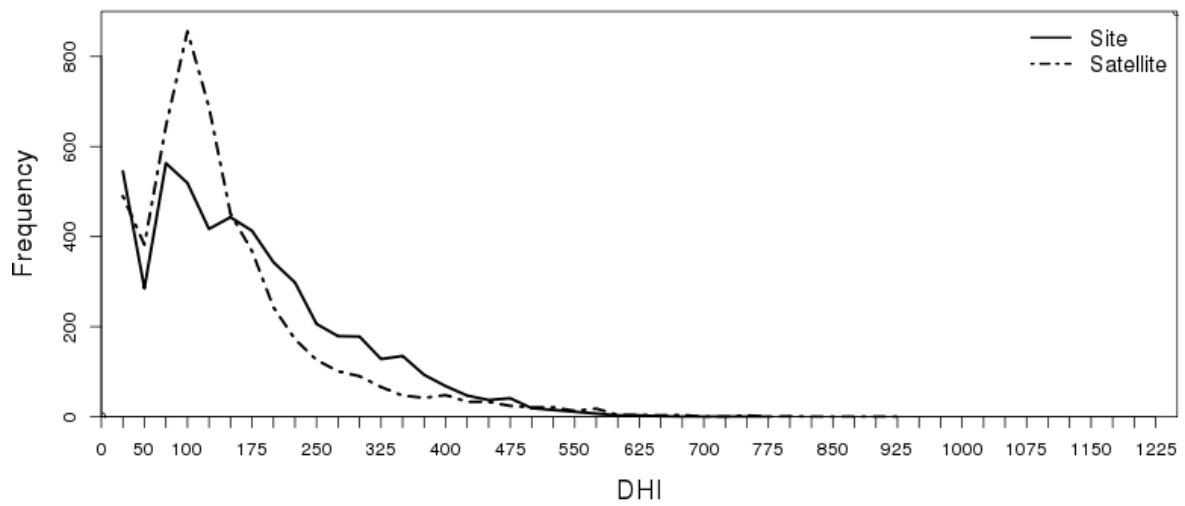


Figure 52: Frequency distribution of hourly DHI at the location of Khuzdar in W/m^2

7.2 Discussion and conclusion

Khuzdar is located at 1200-1300 m in the apex of a narrow valley and has a very arid climate. The preconditions for the validation campaign are similar to those of the measurement site in Quetta. The site is located well outside the inversion layer and in relatively high altitude. The influence of anthropogenic aerosol should be at a normal to low level in the region and so the satellite overestimates the irradiance only in certain cases. As in Quetta, the more intense dust outbreaks (“Habooobs”) in the area are detected by the cloud index algorithm and the atmosphere is treated as completely opaque in these cases.

This leads to only a slight overestimation of the parameters DNI, GHI and DHI by the satellite model but still leads to good results in terms of absolute values. There is a notable overestimation of values between 800 and 1000 W/m² for DNI in terms of frequency. This leads to the assumption that the irradiance at clear sky days still is overestimated to some extent by the modelled data at Khuzdar. Nevertheless, the results are much more satisfying than those achieved in most of the other sites and are within the expected performance of the satellite model. Finally, it has been reported that the maintenance and cleaning of the site has been neglected from August to October 2016. Nevertheless, this data has also been included into the validation for homogeneity of the validation campaign. For the performance of the satellite model this means that the ongoing decrease of the sensor signal of the site during this period, the bias and the overestimation may have been even smaller under well maintained circumstances.

8 Site specifics Lahore

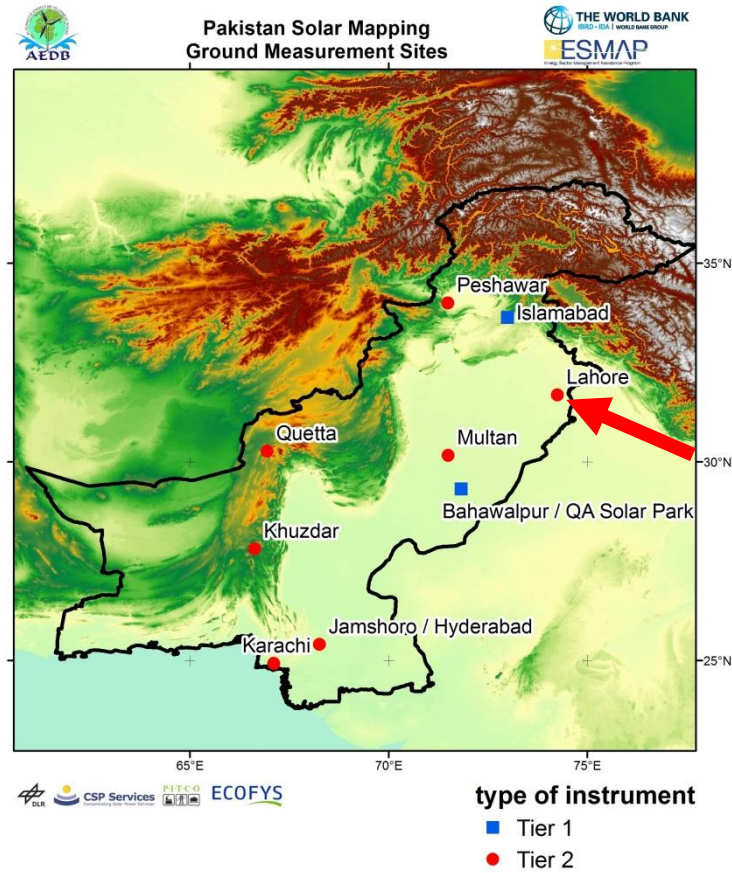


Figure 53: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
University of Engineering and Technology (UET), Lahore	Pk-Lah	31.694°N, 74.244°E	Tier 2	2014-10-22

8.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Lahore. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

8.1.1 Validation results of Global Horizontal Irradiance

Table 13: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 9112
Stations NAs: 519
Satellite NAs: 841
Station mean (plus noct.): 183.2
Station mean (no noct.): 350.5
Station max (plus noct.): 953 on 2014-12-01 02:00:00
Satellite mean (plus noct.): 234.6
Satellite mean (no noct.): 448.9
Satellite max (plus noct.): 1129.5 on 2014-12-08 10:00:00
GHI mean bias (no NA/No noct.): 98.3
GHI RMSE (no NA/No noct.): 150.3

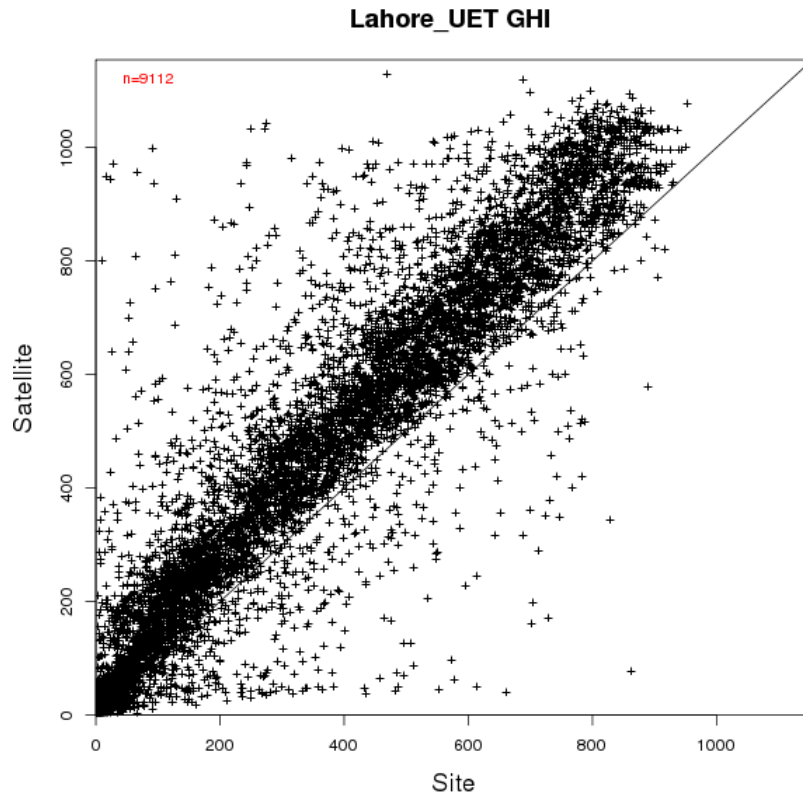


Figure 54: Scatterplot of validation results for GHI at the location of Lahore (in W/m^2)

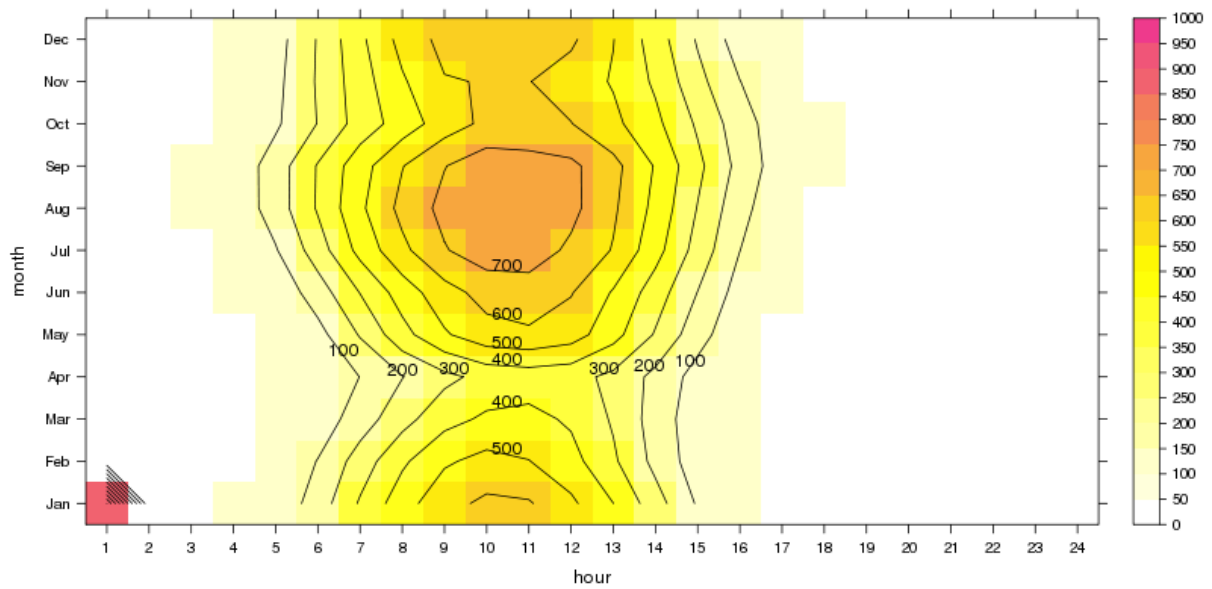


Figure 55: Isopleth graph of ground measurement of GHI at Lahore in W/m^2 (UTC)

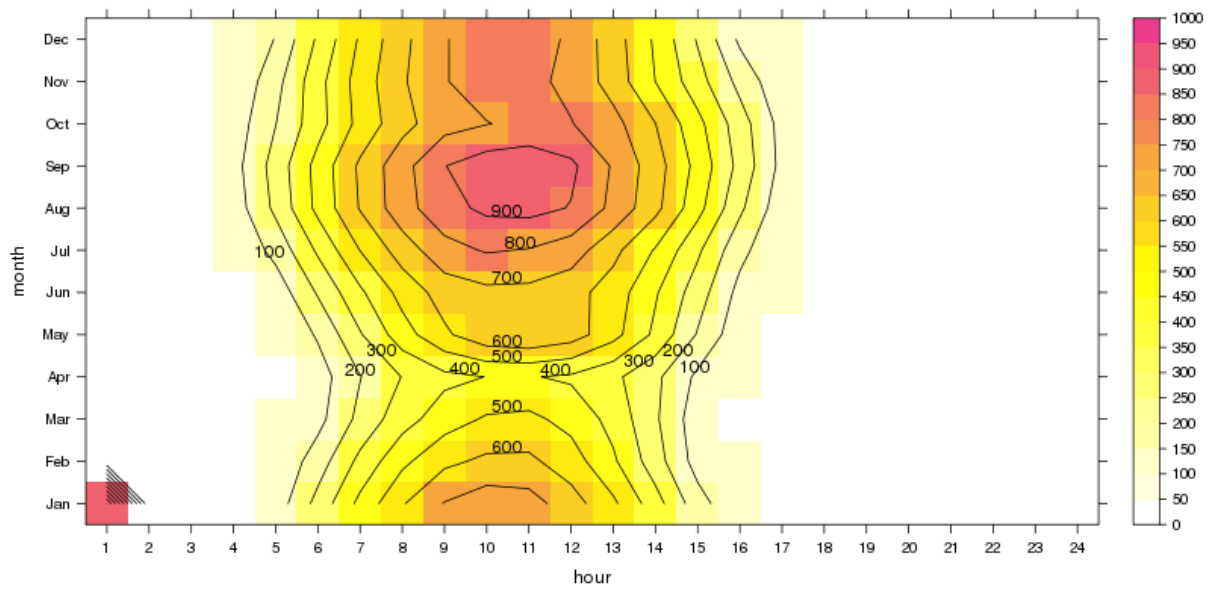


Figure 56: Isopleth graph of satellite estimation of GHI at Lahore in W/m^2 (UTC)

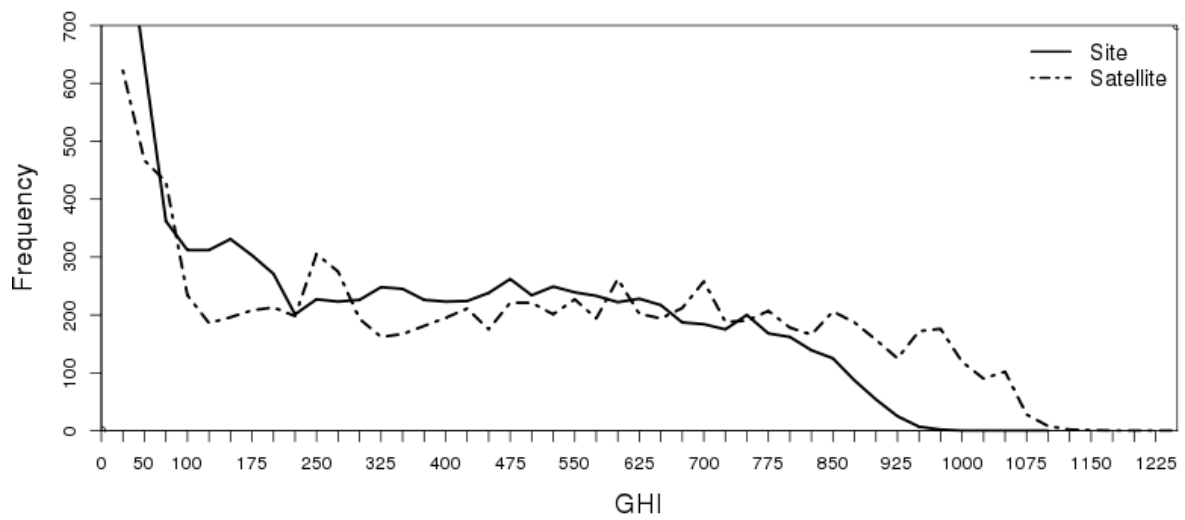


Figure 57: Frequency distribution of hourly GHI at the location of Lahore in W/m^2

8.1.2 Validation results of Direct Normal Irradiance

Table 14: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7339
Stations NAs: 519
Satellite NAs: 841
Station mean (plus noct.): 134.3
Station mean (no noct.): 316.8
Station max (plus noct.): 935 on 2014-11-30 08:00:00
Satellite mean (plus noct.): 256.4
Satellite mean (no noct.): 588.8
Satellite max (plus noct.): 1017.9 on 2014-12-03 18:00:00
DNI mean bias (no NA/No noct.): 271.9
DNI RMSE (no NA/No noct.): 349.4

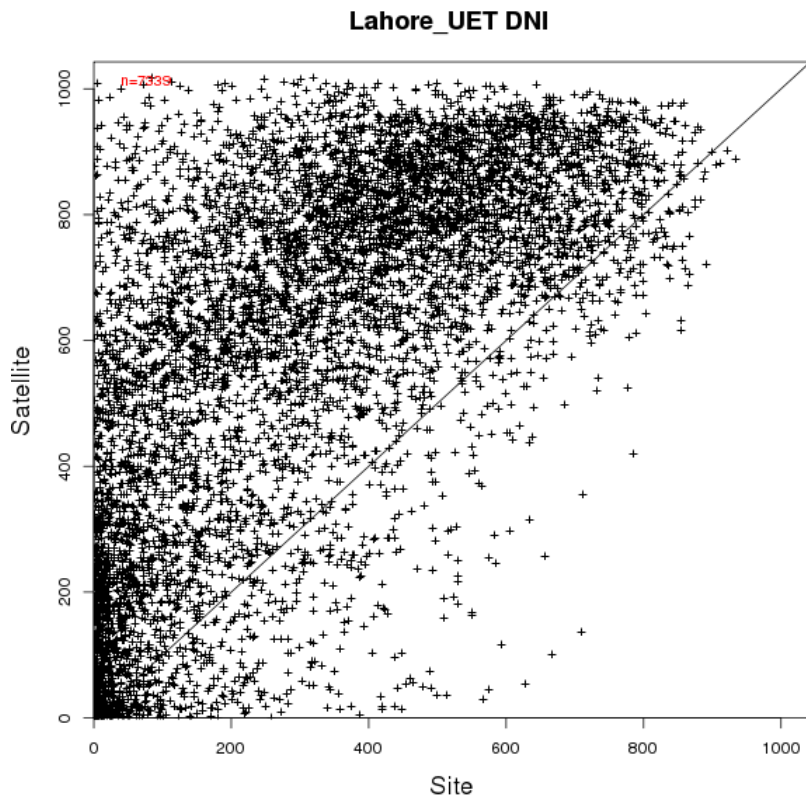


Figure 58: Scatterplot of validation results for DNI at the location of Lahore (in W/m^2)

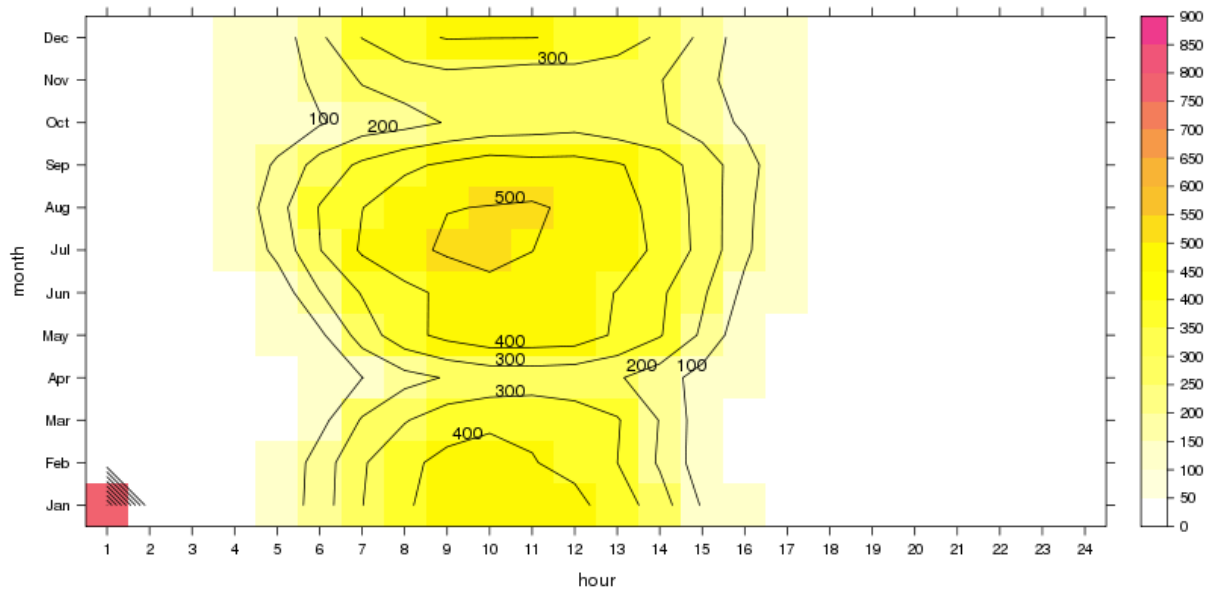


Figure 59: Isopleth graph of ground measurement of DNI at Lahore in W/m² (UTC)

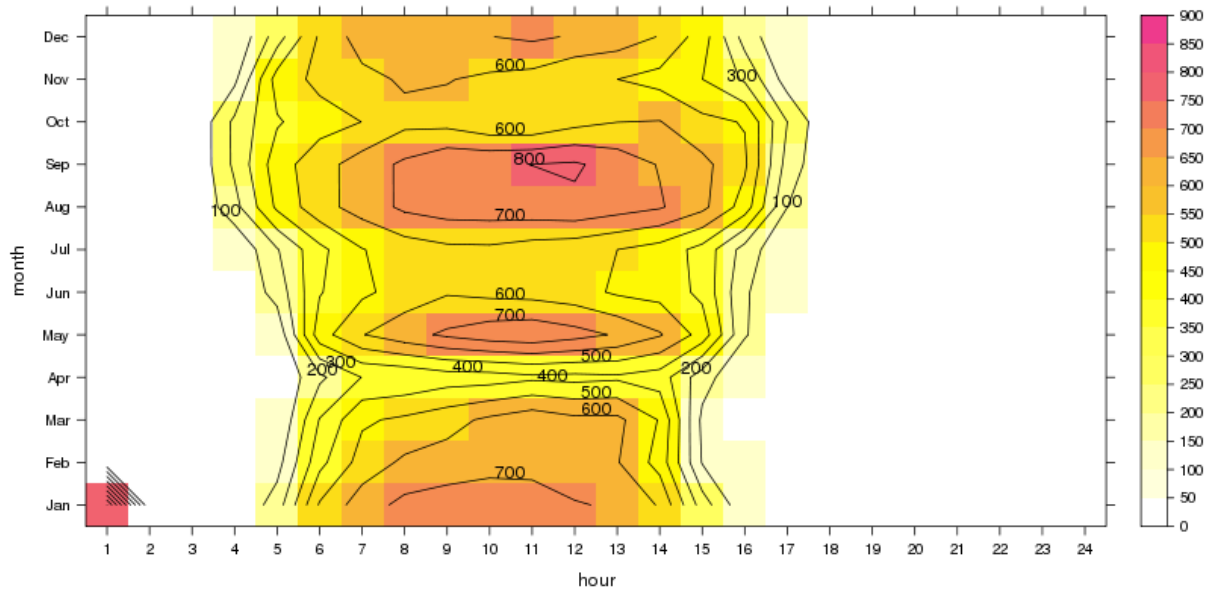


Figure 60: Isopleth graph of satellite estimation of DNI at Lahore in W/m² (UTC)

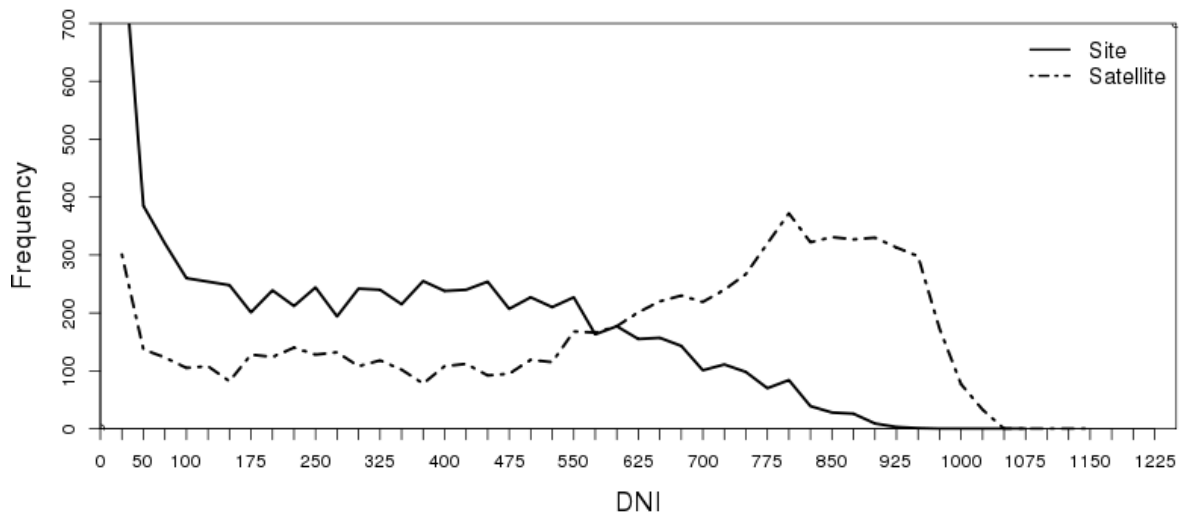


Figure 61: Frequency distribution of hourly DNI at the location of Lahore in W/m^2

8.1.3 Validation results of Diffuse Horizontal Irradiance

Table 15: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 9112
Stations NAs: 519
Satellite NAs: 841
Station mean (plus noct.): 92.9
Station mean (no noct.): 177.8
Station max (plus noct.): 563 on 2014-11-14 20:00:00
Satellite mean (plus noct.): 77.2
Satellite mean (no noct.): 147.8
Satellite max (plus noct.): 820.8 on 2014-11-25 13:00:00
DHI mean bias (no NA/No noct.): -29.9
DHI RMSE (no NA/No noct.): 102.3

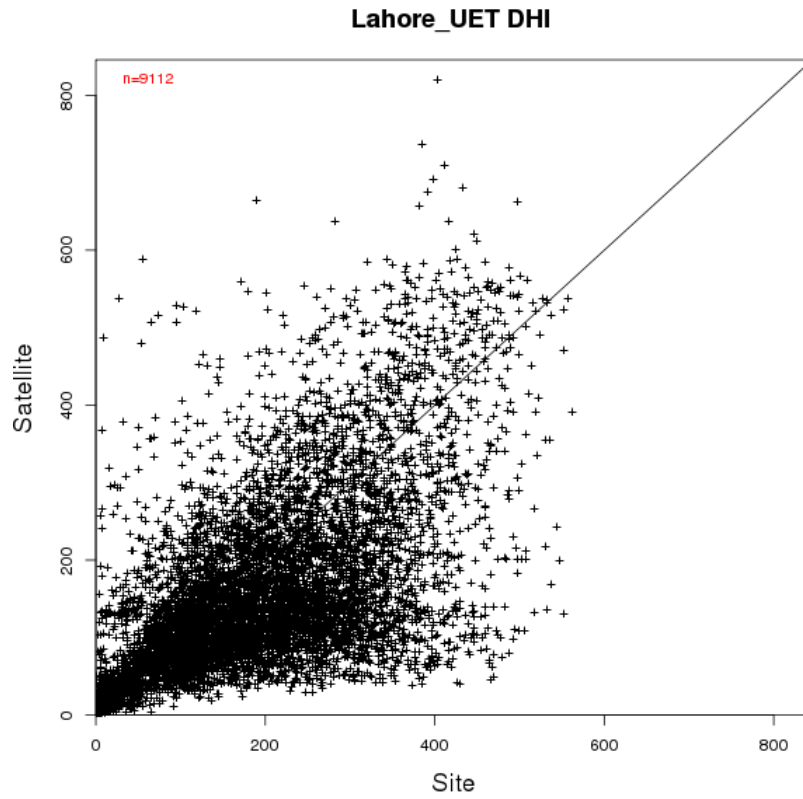


Figure 62: Scatterplot of validation results for DHI at the location of Lahore (in W/m^2)

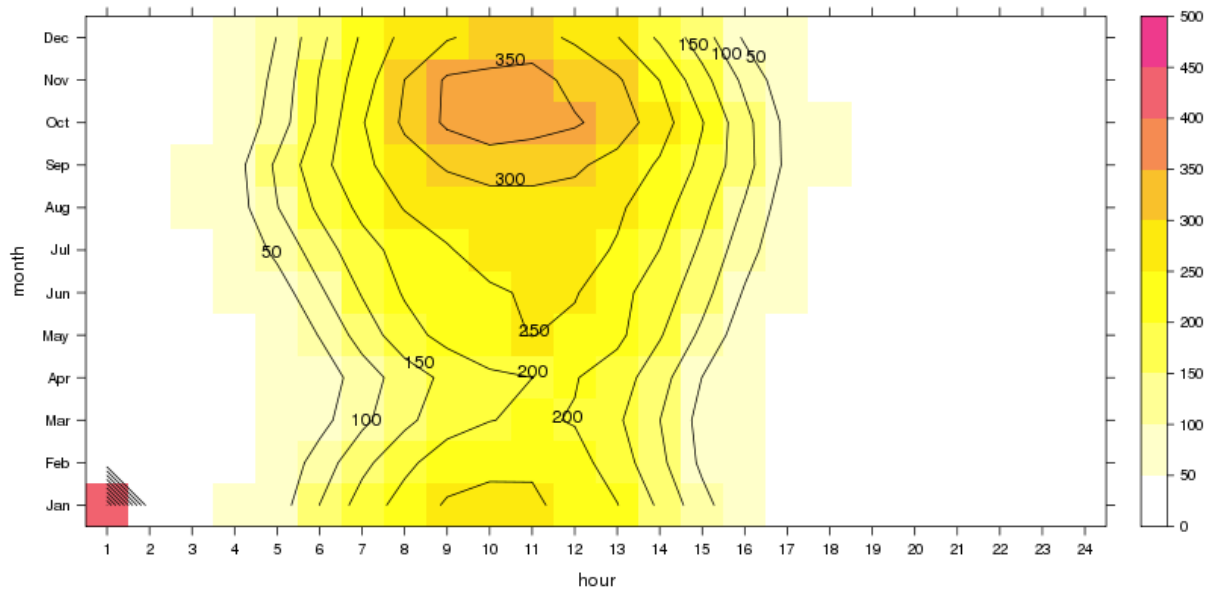


Figure 63: Isopleth graph of ground measurement of DHI at Lahore in W/m^2 (UTC)

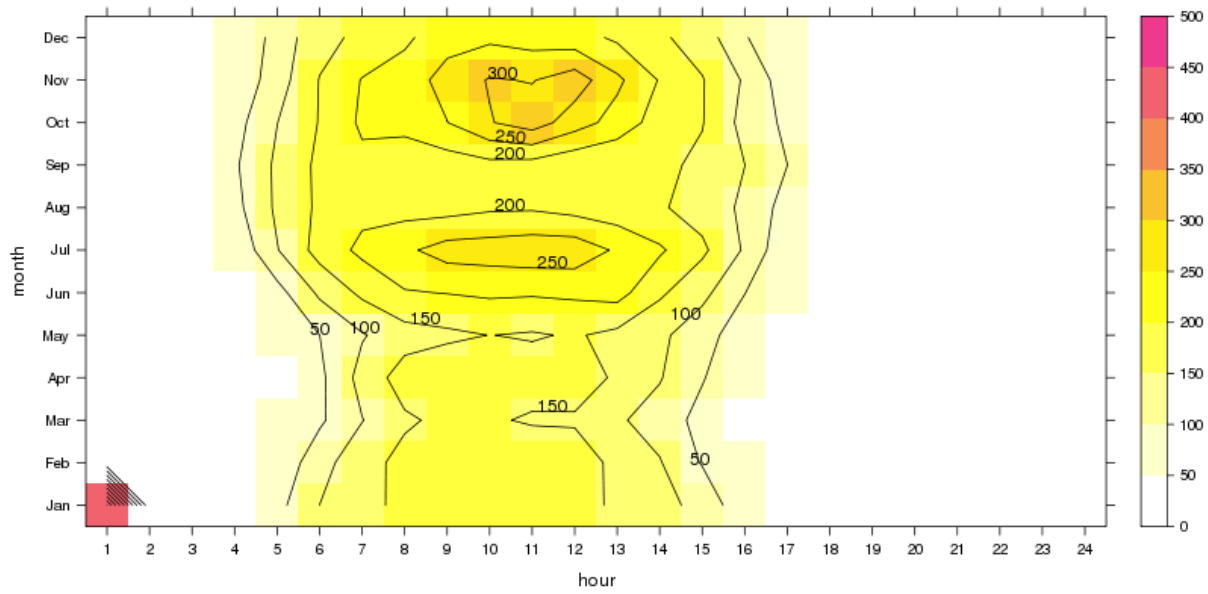


Figure 64: Isopleth graph of satellite estimation of DHI at Lahore in W/m^2 (UTC)

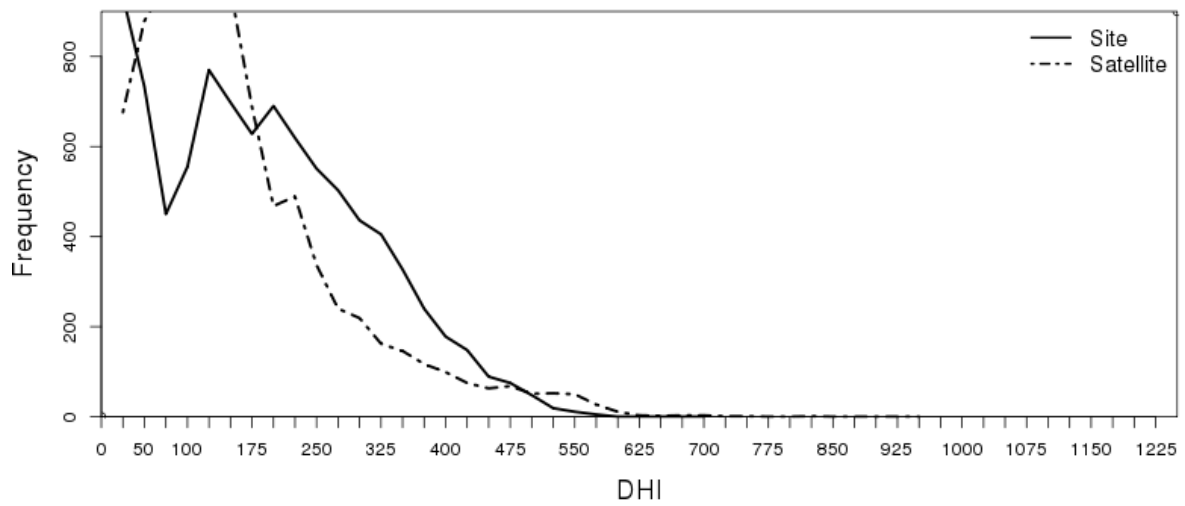


Figure 65: Frequency distribution of hourly DHI at the location of Lahore in W/m^2

8.2 Discussion and conclusion

The TIER2 site in the University City of Lahore is the easternmost measurement site used for validation purposes in the project. Only 10 km west of the river Ravi and not far from the city center of Lahore, there often is a high chance for the formation of fog and a high aerosol load in the region during certain meteorological situations. This is also highlighted by the publicly available aerosol data of the AERONET site 17 south of Lahore UET. This leads to the rather large offset between the datasets, especially for DNI. For the satellite data, the average hourly sum of DNI in October is about 200 W/m² in the afternoon compared to more than 500 W/m² for the measured data at the same time.

The measurement is conducted in a very populated region and, thus, represents an area with an above-average energy demand. This fact does partly explain the performance of the satellite model and the results presented in this report. The underlying aerosol model has been developed for climatological purposes and is available in relatively big spatial resolution. Reanalysis data with a spatial resolution of about 1° by 1° have difficulties in covering local sources of aerosol as it is the case in Islamabad and in most of the other locations used within this campaign. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents. Within DLR, a solution for this problem is under development and will be presented in a future publication.

9 Site specifics Multan

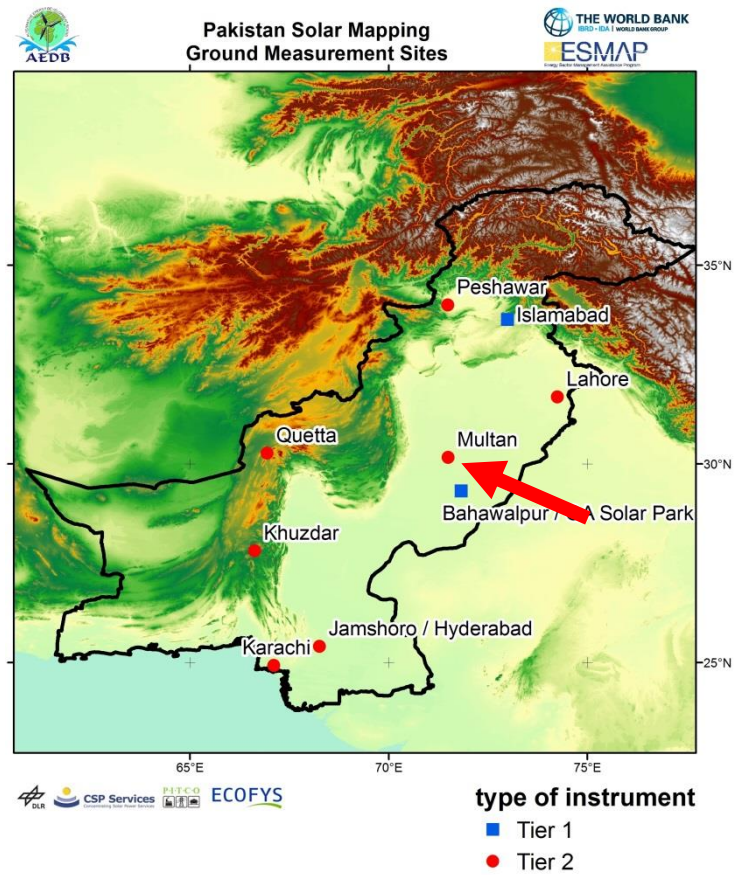


Figure 66: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
M. Nawaz Sharif University of Engineering and Technology (MNS UET), Multan	Pk-Mul	30.165°N, 71.498°E	Tier 2	2014-10-21

9.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Multan. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

9.1.1 Validation results of Global Horizontal Irradiance

Table 16: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid counts (no NA/No noct.): 9279
Stations NAs: 470
Satellite NAs: 721
Station mean (plus noct.): 201.719963401384
Station mean (no noct.): 380.1
Station max (plus noct.): 1005 on 2014-12-01 05:00:00
Satellite mean (plus noct.): 249.0
Satellite mean (no noct.): 469.4
Satellite max (plus noct.): 1118.5 on 2014-12-05 22:00:00
GHI mean bias (no NA/No noct.): 89.2
GHI RMSE (no NA/No noct.): 127.9

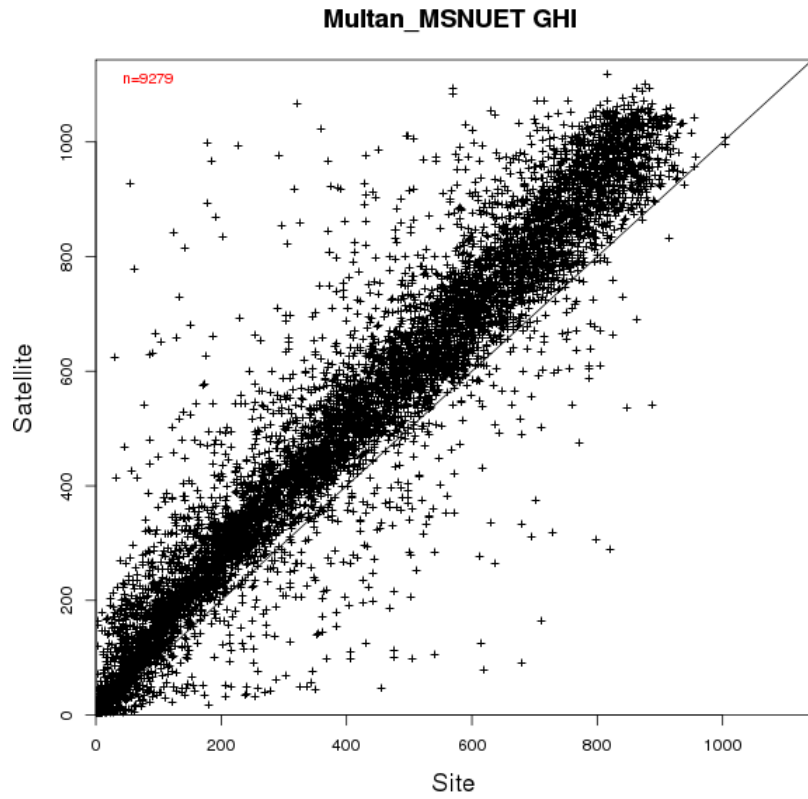


Figure 67: Scatterplot of validation results for GHI at the location of Multan (in W/m^2)

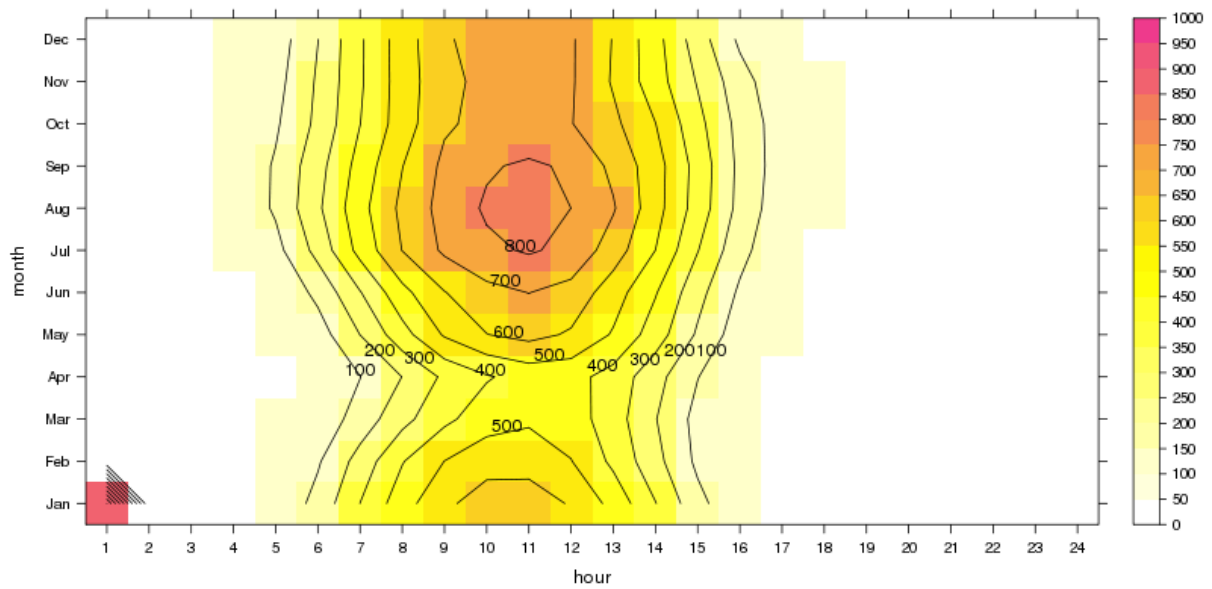


Figure 68: Isopleth graph of ground measurement of GHI at Multan in W/m^2 (UTC)

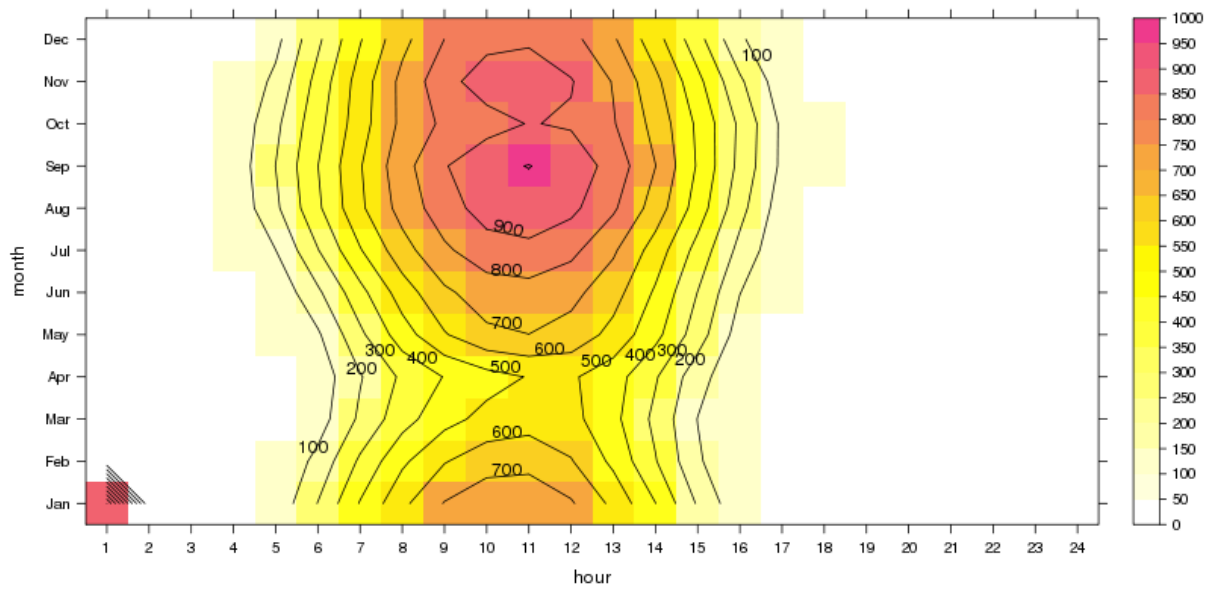


Figure 69: Isopleth graph of satellite estimation of GHI at Multan in W/m^2 (UTC)

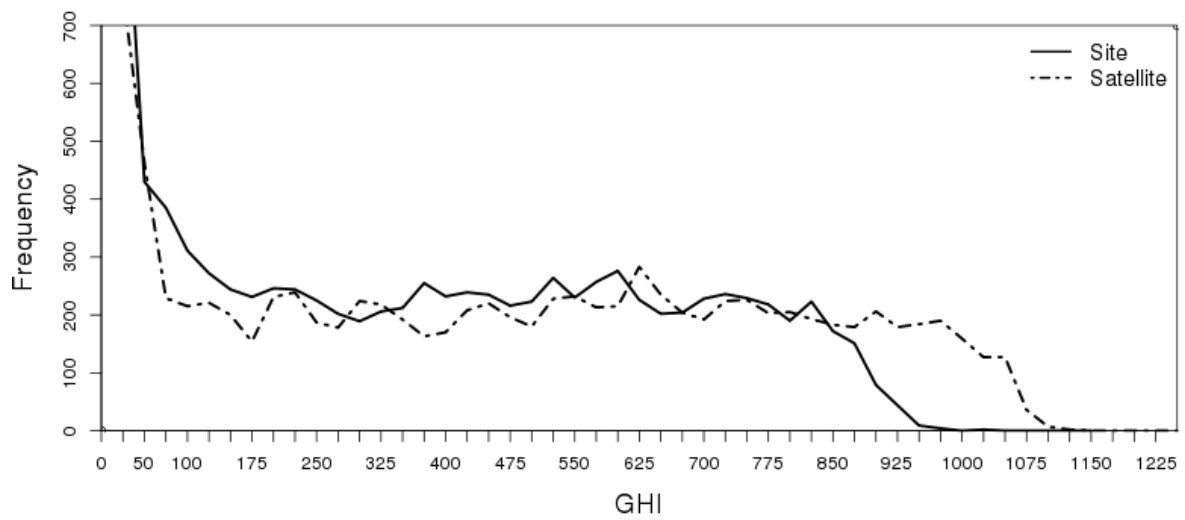


Figure 70: Frequency distribution of hourly GHI at the location of Multan in W/m^2

9.1.2 Validation results of Direct Normal Irradiance

Table 17: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid counts (no NA/No noct.): 7853
Stations NAs: 470
Satellite NAs: 721
Station mean (plus noct.): 151.2
Station mean (no noct.): 335.4
Station max (plus noct.): 899 on 2014-11-26 19:00:00
Satellite mean (plus noct.): 280.9
Satellite mean (no noct.): 611.9
Satellite max (plus noct.): 1013.2 on 2014-12-01 13:00:00
DNI mean bias (no NA/No noct.): 276.5
DNI RMSE (no NA/No noct.): 342.2

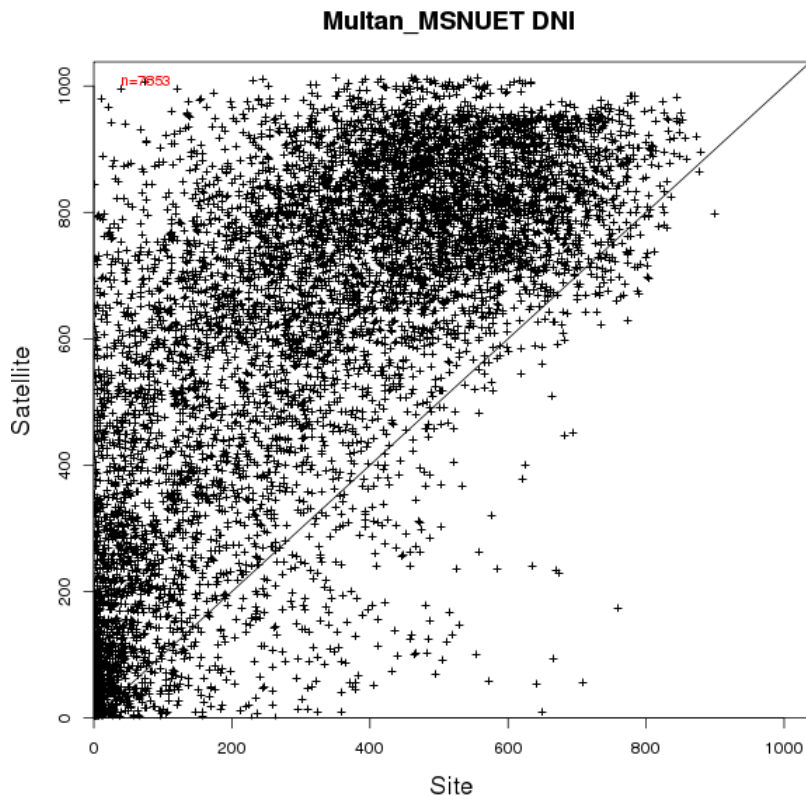


Figure 71: Scatterplot of validation results for DNI at the location of Multan (in W/m^2)

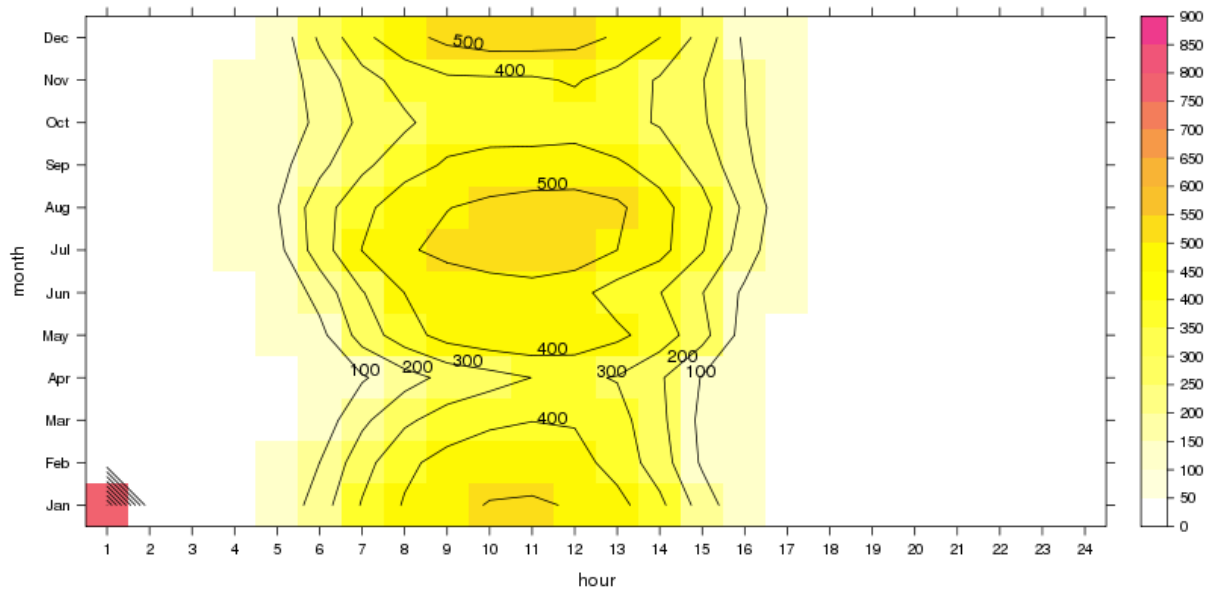


Figure 72: Isopleth graph of ground measurement of DNI at Multan in W/m^2 (UTC)

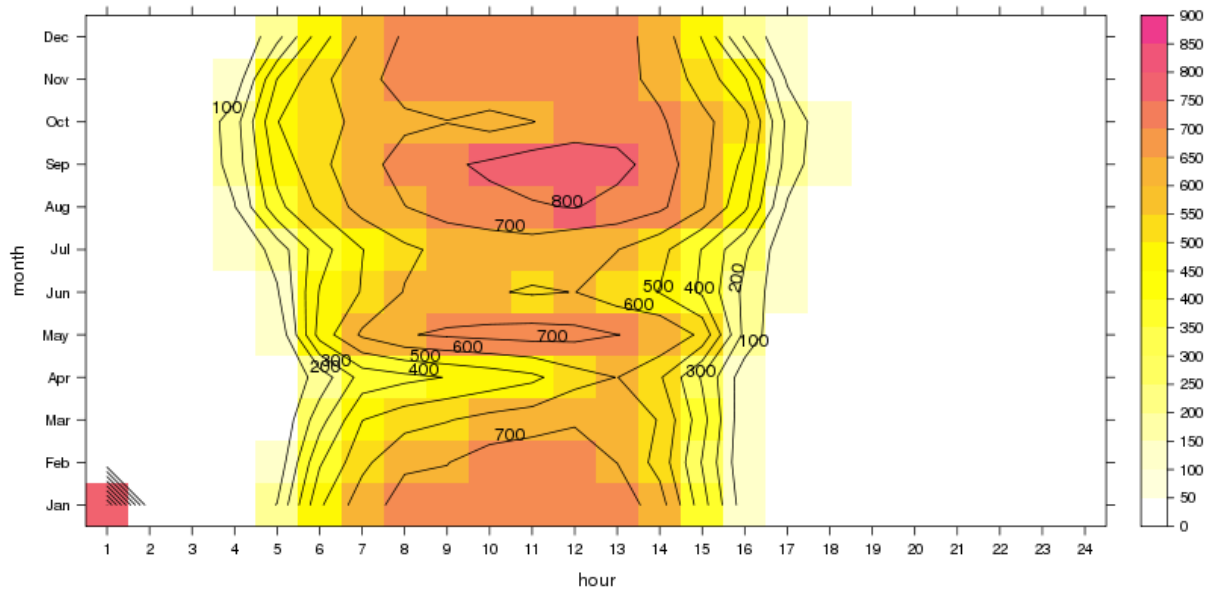


Figure 73: Isopleth graph of satellite estimation of DNI at Multan in W/m^2 (UTC)

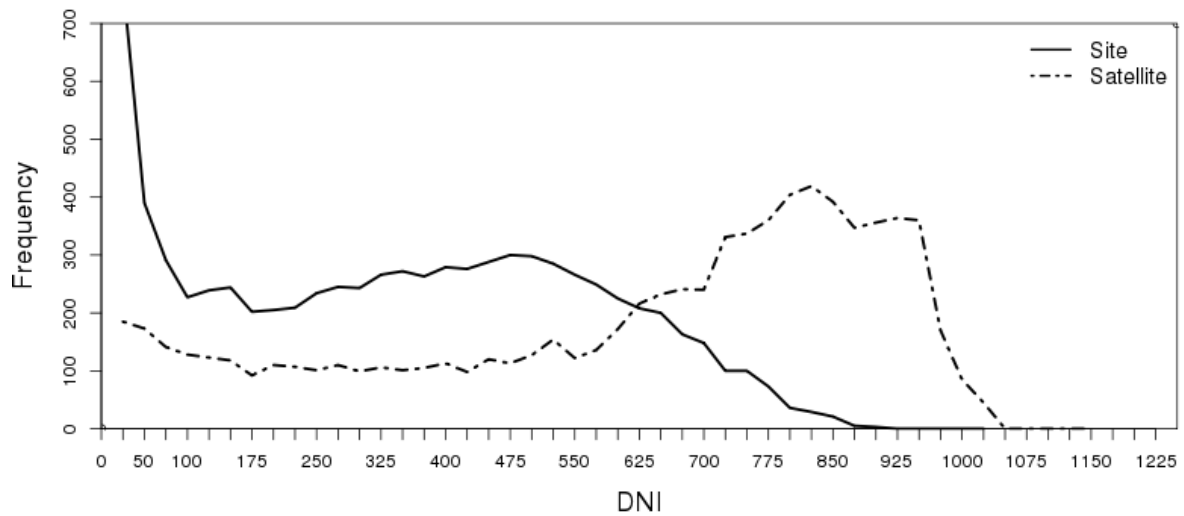


Figure 74: Frequency distribution of hourly DNI at the location of Multan in W/m^2

9.1.3 Validation results of Diffuse Horizontal Irradiance

Table 18: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid counts (no NA/No noct.): 9279
Stations NAs: 470
Satellite NAs: 721
Station mean (plus noct.): 97.6
Station mean (no noct.): 184.0
Station max (plus noct.): 579 on 2014-11-13 11:00:00
Satellite mean (plus noct.): 73.5
Satellite mean (no noct.): 138.5
Satellite max (plus noct.): 725.3 on 2014-11-19 13:00:00
DHI mean bias (no NA/No noct.): -45.5
DHI RMSE (no NA/No noct.): 103.9

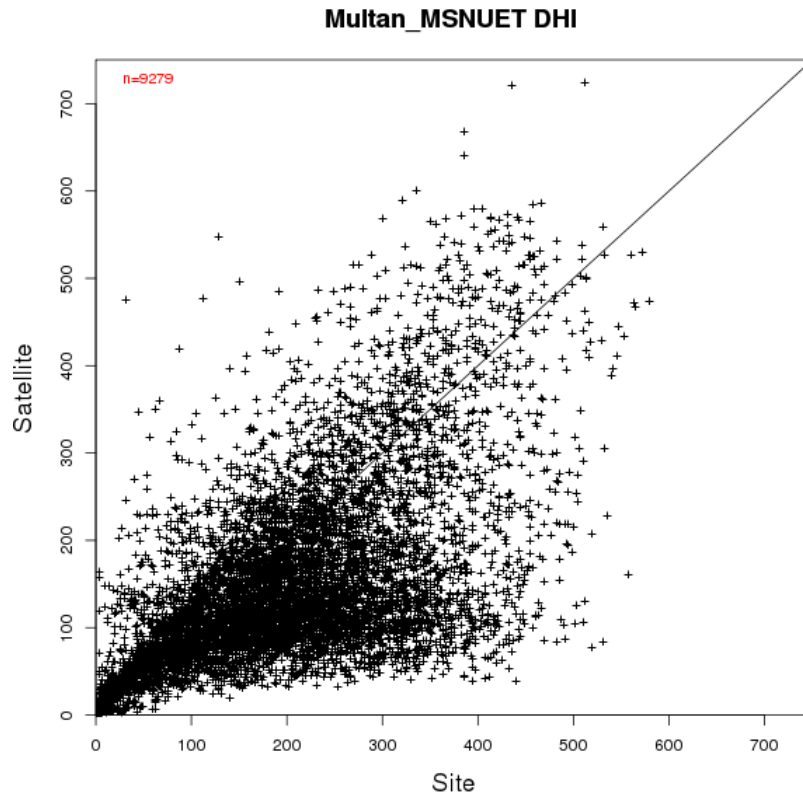


Figure 75: Scatterplot of validation results for DHI at the location of Multan (in W/m^2)

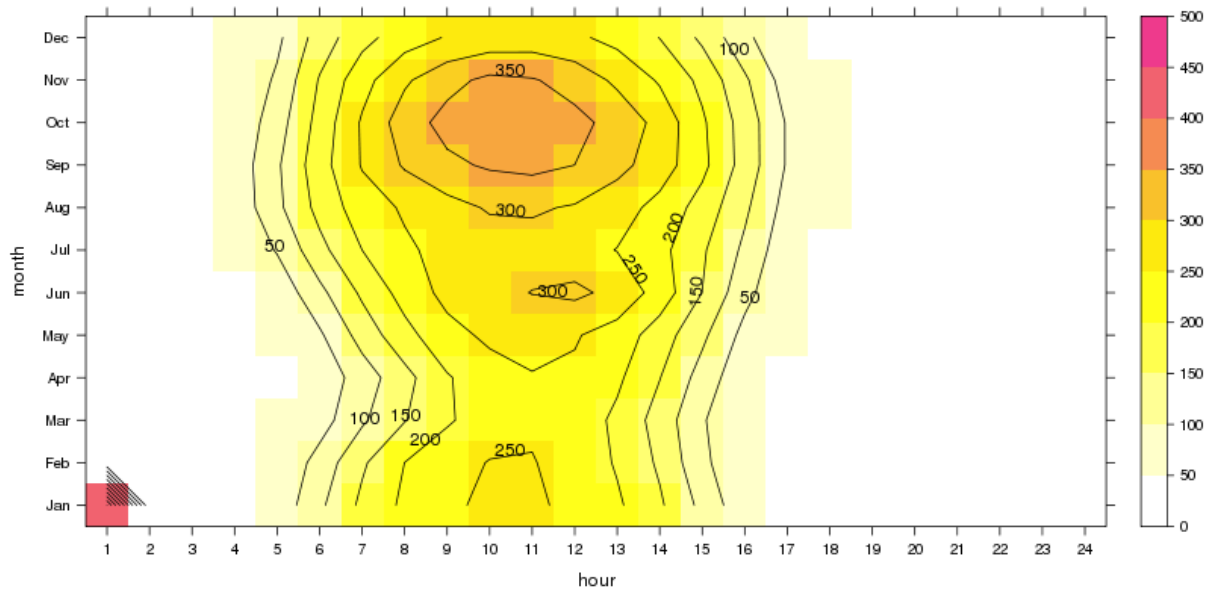


Figure 76: Isopleth graph of ground measurement of DHI at Multan in W/m^2 (UTC)

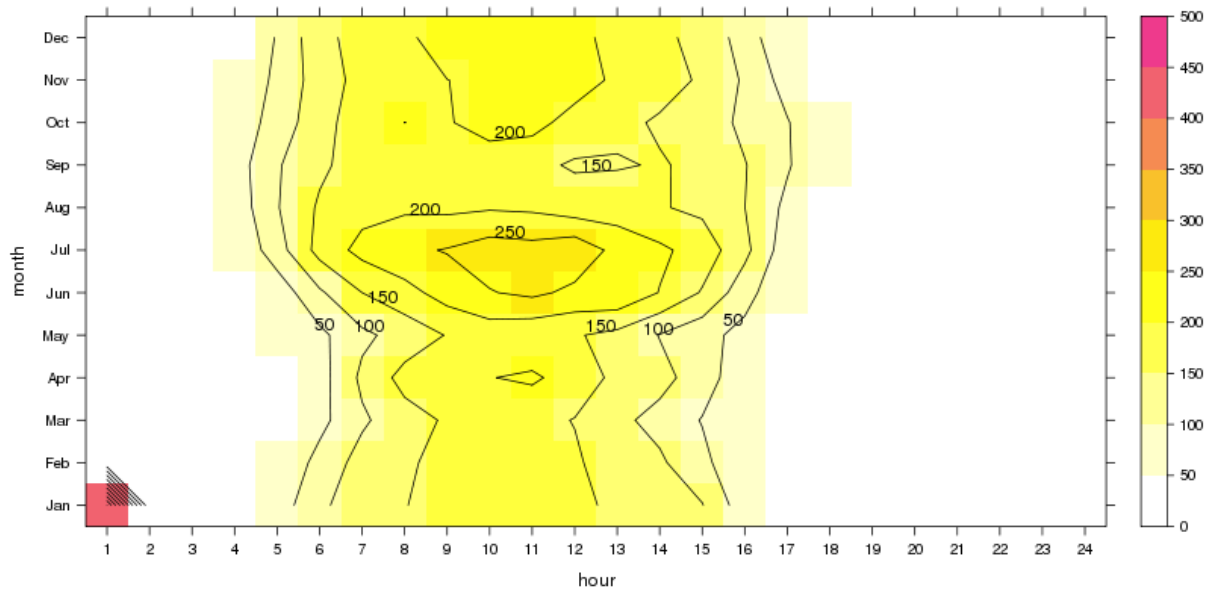


Figure 77: Isoleth graph of satellite estimation of DHI at Multan in W/m^2 (UTC)

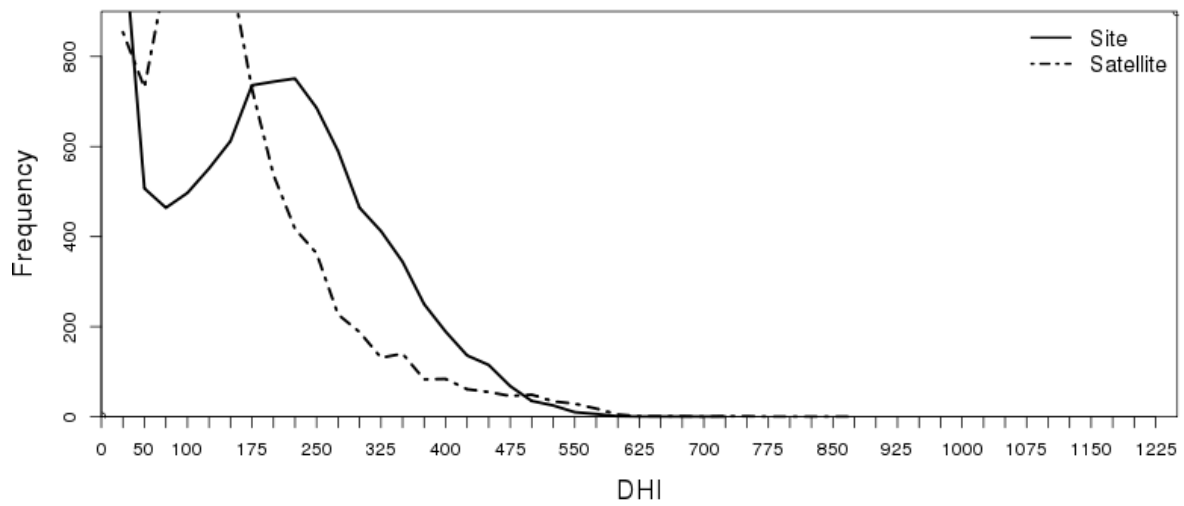


Figure 78: Frequency distribution of hourly DHI at the location of Multan in W/m^2

9.2 Discussion and conclusion

The TIER2 site at UET Multan is located close to the city center and in the valley of the Chenab and Indus River. This leads to a high risk of fog and smog at certain weather conditions (capping due to inversion). The location of the measurement site in an urban surrounding makes it difficult to detect local sources of anthropogenic aerosol by satellite models. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents.

The results of the measurement campaign for the measurement site at MNS-UET Multan are not satisfying and show a big bias for all three observed irradiance parameters. In general it can be noted that DNI and GHI is overestimated by the satellite data, which is partly a result of the underestimation of DHI.

10 Site specifics Peshawar

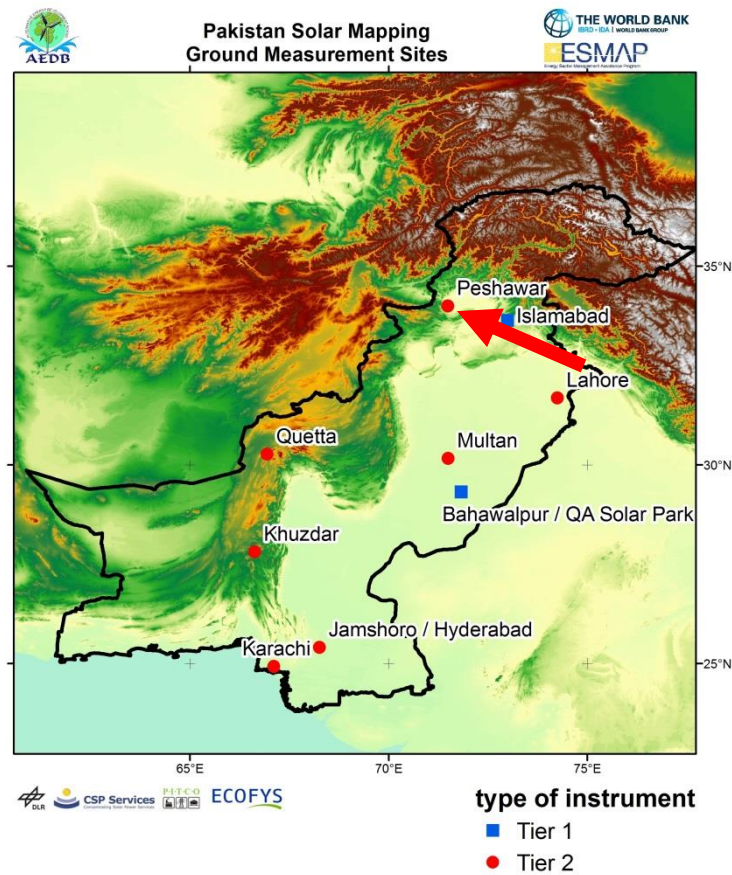


Figure 79: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
University of Engineering and Technology (UET), Peshawar	Pk-Pesh	34.002°N, 71.485°E	Tier 2	2015-04-10

10.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Peshawar. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

10.1.1 Validation results of Global Horizontal Irradiance

Table 19: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7289
Stations NAs: 233
Satellite NAs: 528
Station mean (plus noct.): 199.2
Station mean (no noct.): 365.0
Station max (plus noct.): 1016 on 2015-05-22 20:00:00
Satellite mean (plus noct.): 230.1
Satellite mean (no noct.): 421.7
Satellite max (plus noct.): 1094.9 on 2015-05-26 02:00:00
GHI mean bias (no NA/No noct.): 56.6
GHI RMSE (no NA/No noct.): 133.3

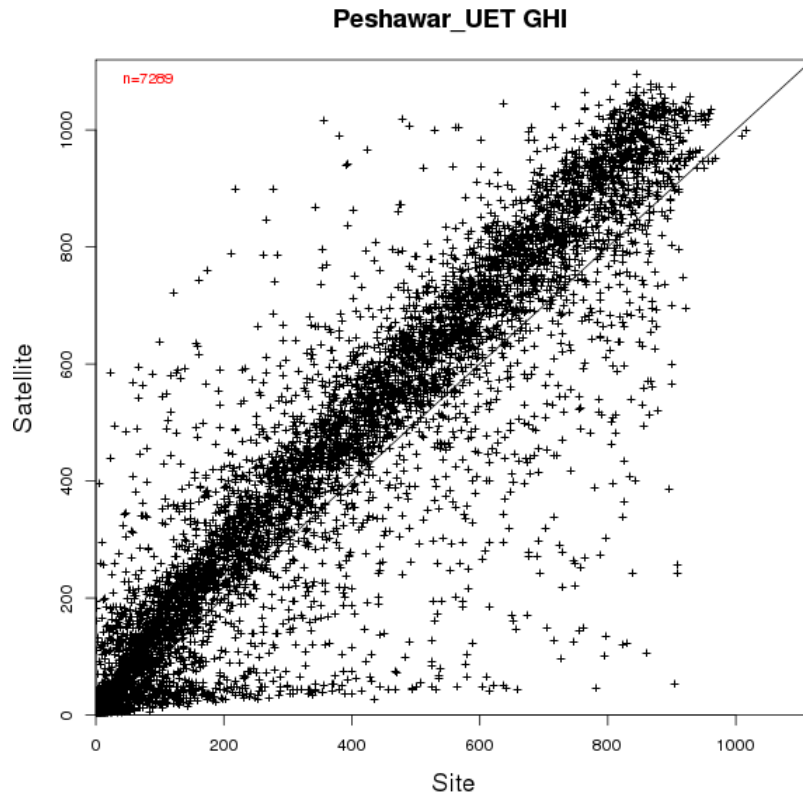


Figure 80: Scatterplot of validation results for GHI at the location of Peshawar (in W/m^2)

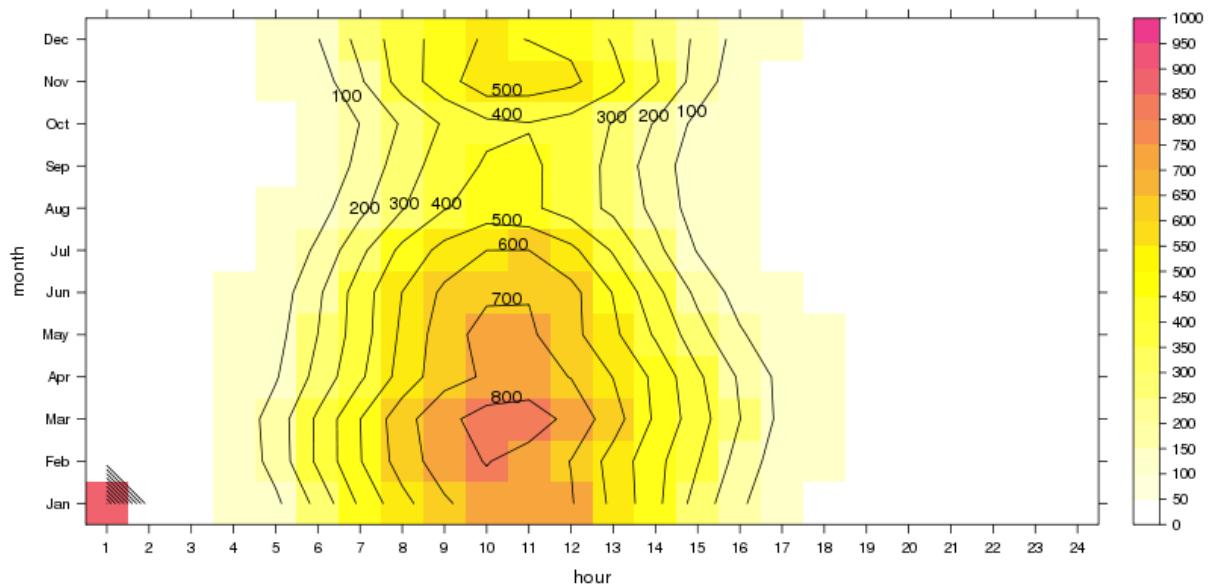


Figure 81: Isopleth graph of ground measurement of GHI at Peshawar in W/m^2 (UTC)

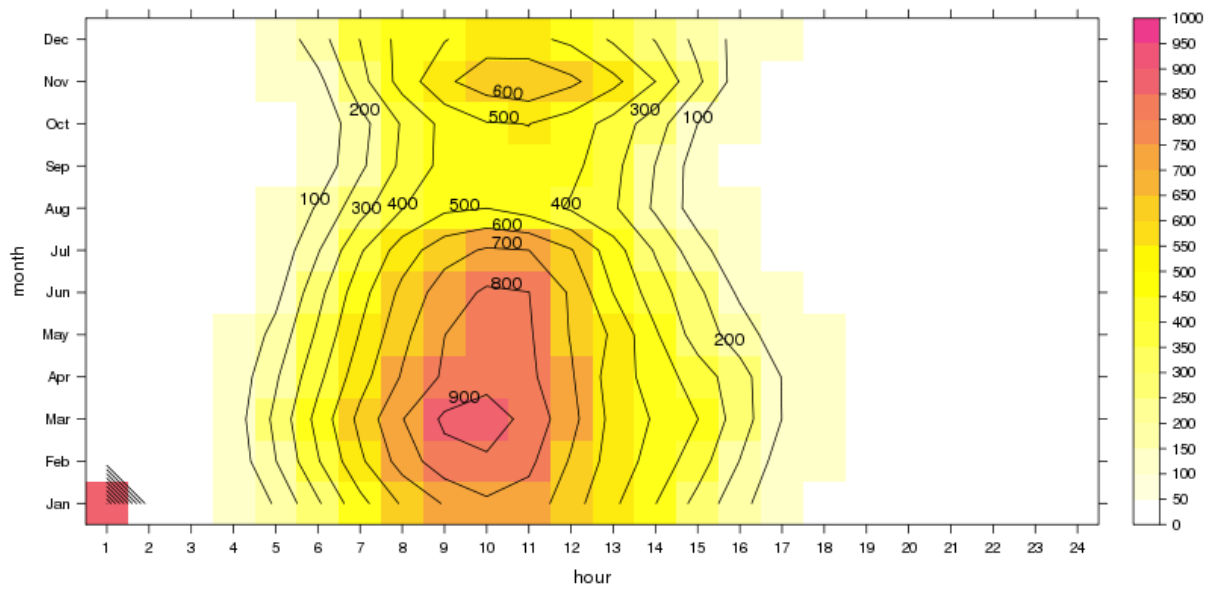


Figure 82: Isopleth graph of satellite estimation of GHI at Peshawar in W/m^2 (UTC)

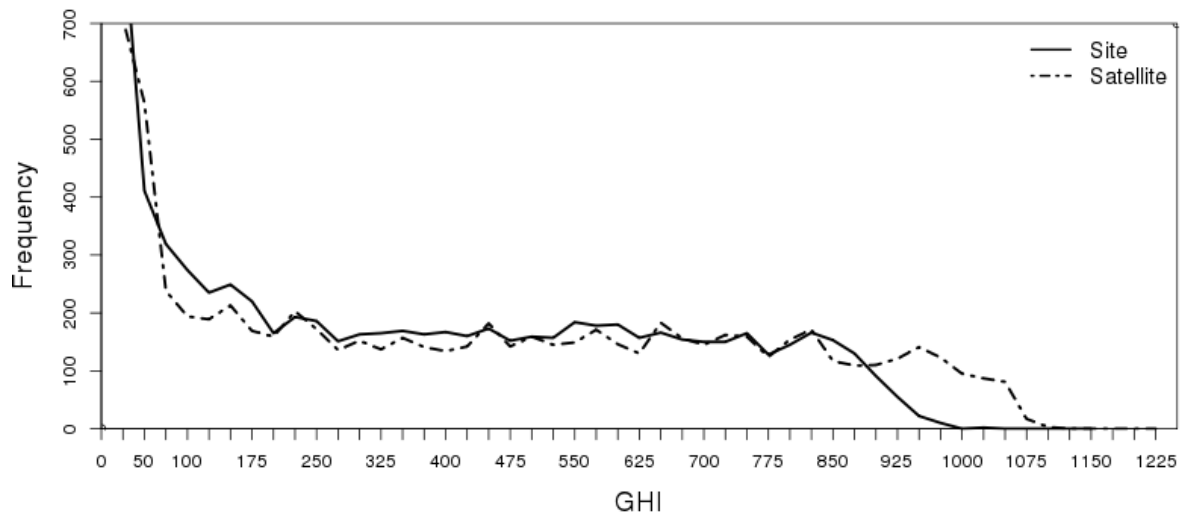


Figure 83: Frequency distribution of hourly GHI at the location of Peshawar in W/m^2

10.1.2 Validation results of Direct Normal Irradiance

Table 20: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 5789
Stations NAs: 233
Satellite NAs: 528
Station mean (plus noct.): 167.1
Station mean (no noct.): 379.5
Station max (plus noct.): 973 on 2015-05-21 01:00:00
Satellite mean (plus noct.): 237.1
Satellite mean (no noct.): 532.7
Satellite max (plus noct.): 1022.6 on 2015-05-23 02:00:00
DNI mean bias (no NA/No noct.): 153.2
DNI RMSE (no NA/No noct.): 286.8

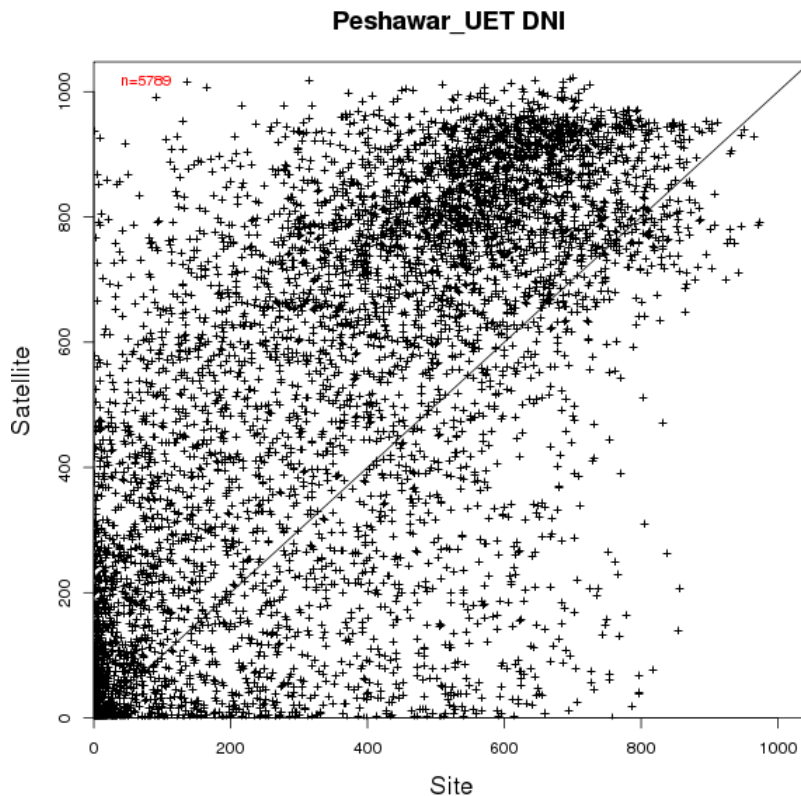


Figure 84: Scatterplot of validation results for DNI at the location of Peshawar (in W/m^2)

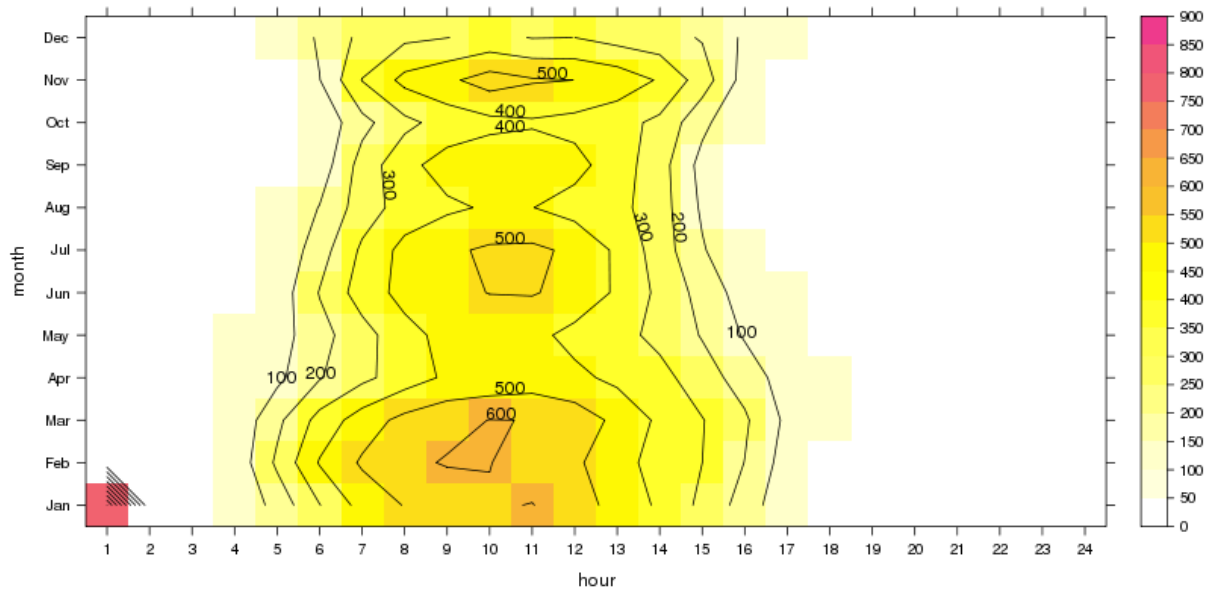


Figure 85: Isopleth graph of ground measurement of DNI at Peshawar in W/m^2 (UTC)

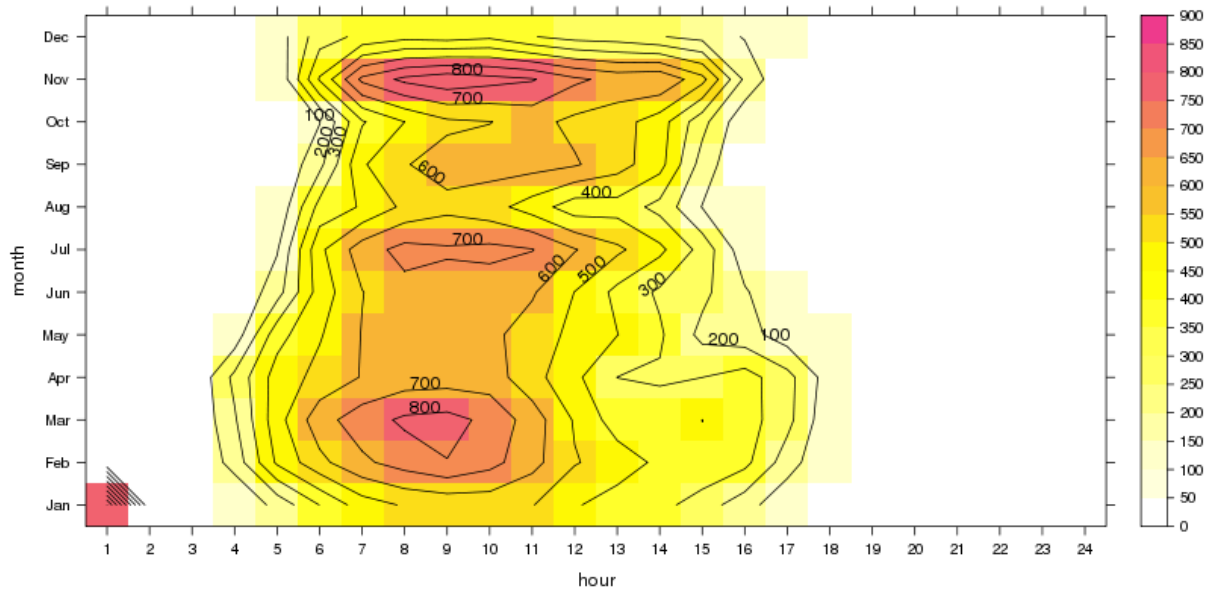


Figure 86: Isopleth graph of satellite estimation of DNI at Peshawar in W/m^2 (UTC)

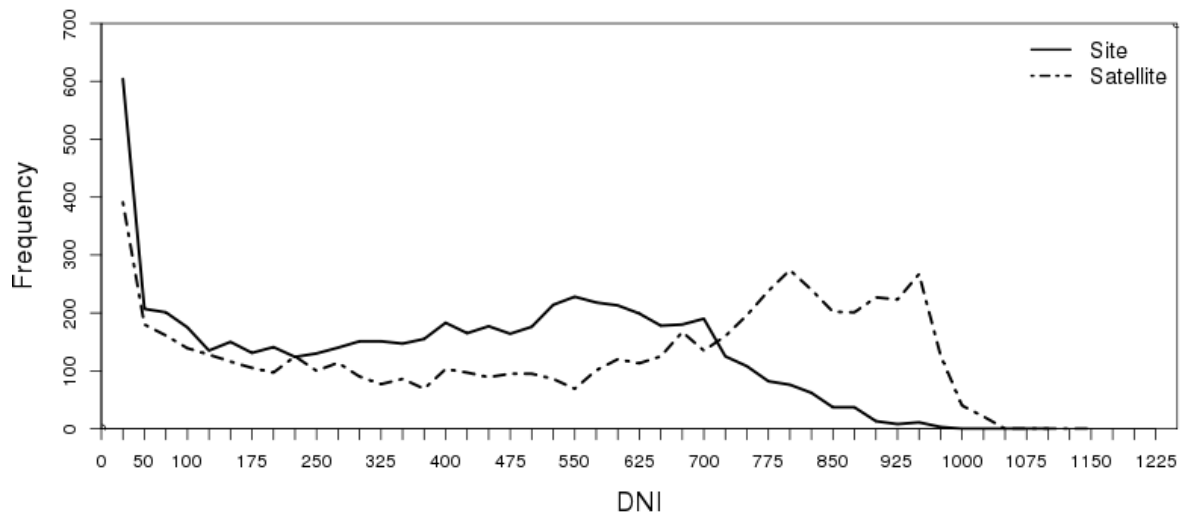


Figure 87: Frequency distribution of hourly DNI at the location of Peshawar in W/m^2

10.1.3 Validation results of Diffuse Horizontal Irradiance

Table 21: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 7289
Stations NAs: 233
Satellite NAs: 528
Station mean (plus noct.): 84.0
Station mean (no noct.): 154.0
Station max (plus noct.): 564 on 2015-05-04
Satellite mean (plus noct.): 82.7
Satellite mean (no noct.): 151.6
Satellite max (plus noct.): 853 on 2015-05-16 01:00:00
DHI mean bias (no NA/No noct.): -2.3
DHI RMSE (no NA/No noct.): 95.3

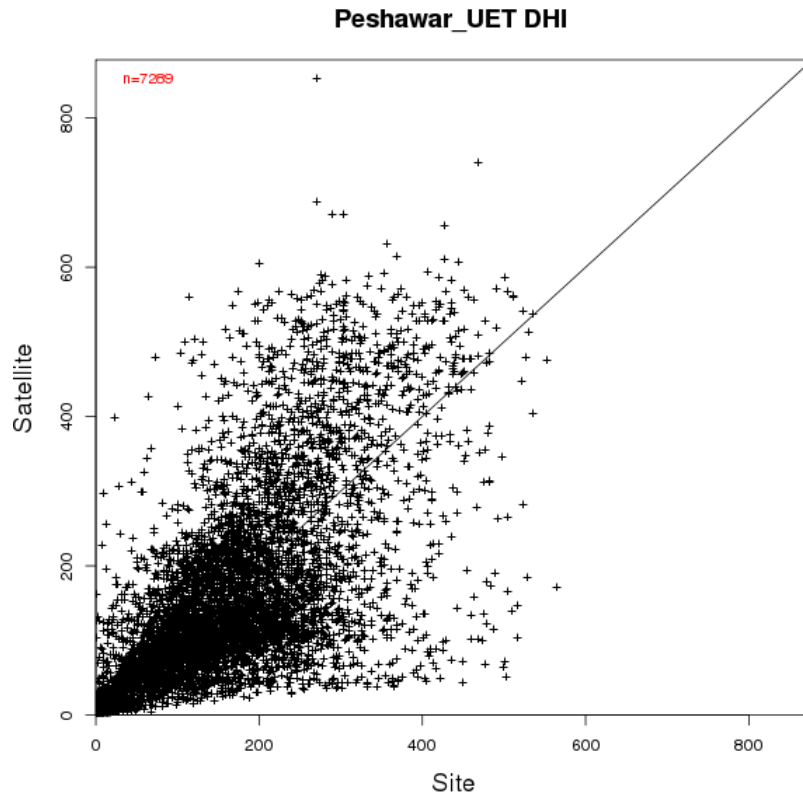


Figure 88: Scatterplot of validation results for DHI at the location of Peshawar (in W/m^2)

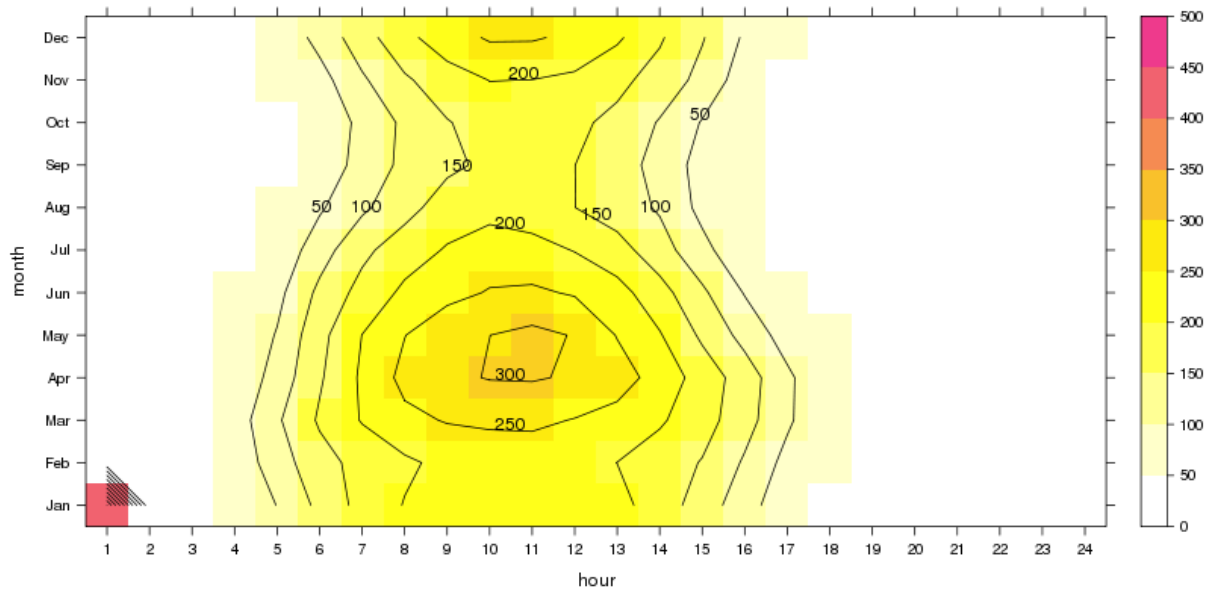


Figure 89: Isopleth graph of ground measurement of DHI at Peshawar in W/m^2 (UTC)

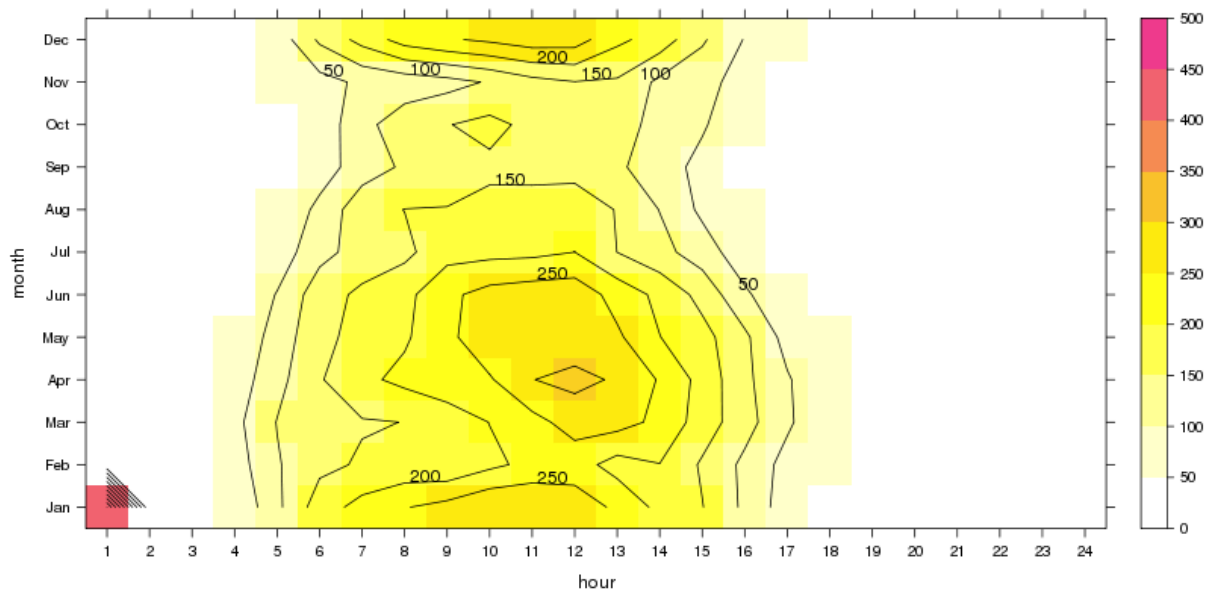


Figure 90: Isoleth graph of satellite estimation of DHI at Peshawar in W/m^2 (UTC)

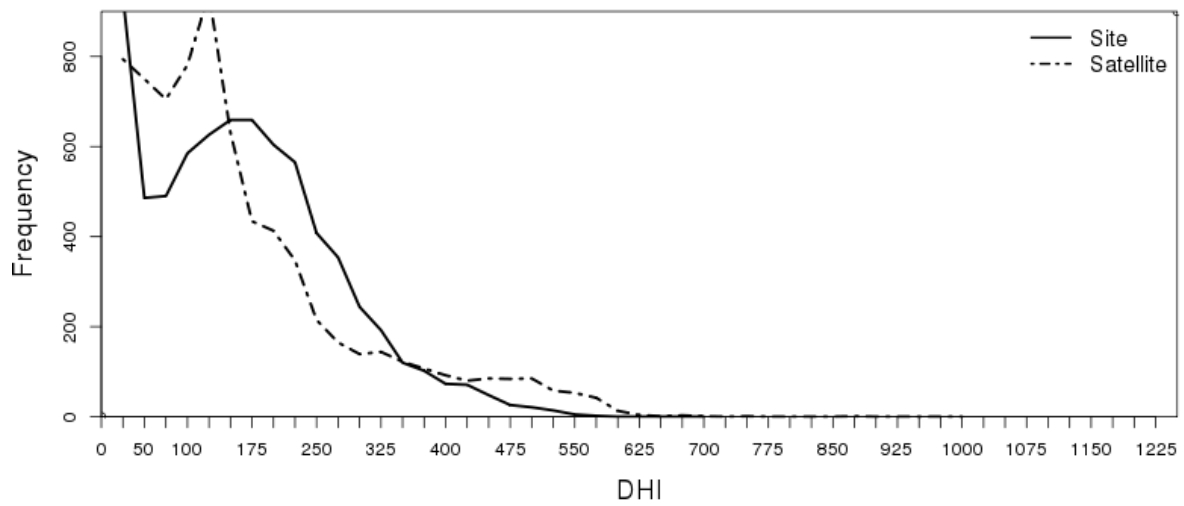


Figure 91: Frequency distribution of hourly DHI at the location of Peshawar in W/m^2

10.2 Discussion and conclusion

The measurement site at UET Peshawar is located in the University Campus. It is the northernmost measurement site of the validation campaign and represents the irradiance regime of a very populated area. It is influenced by the monsoon seasons, but precipitation is possible all year. All these facts are reflected by the results of the measurement campaign. There is a very high bias between the datasets in terms of absolute values and seasonality. This can be referred mainly to aerosol load in the atmosphere as it is the case in many other locations in the measurement campaign.

The measurement is conducted in a very populated region and, thus, represents an area with an above-average energy demand. This fact does partly explain the performance of the satellite model and the results presented in this report. The underlying aerosol model has been developed for climatological purposes and is available in relatively big spatial resolution. Reanalysis data with a spatial resolution of about 1° by 1° have difficulties in covering local sources of aerosol as it is the case in Islamabad and in most of the other locations used within this campaign. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents. Within DLR, a solution for this problem is under development and will be presented in a future publication.

11 Site specifics Quetta

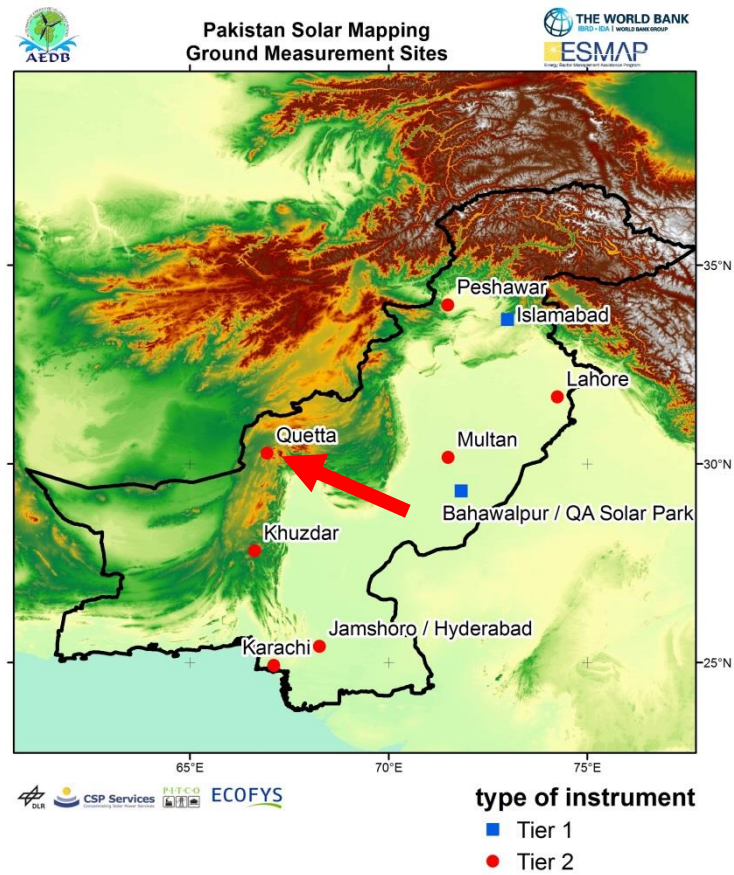


Figure 92: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
Baluchistan University of Information Technology, Engineering and Management Sciences (BUIEMS), Quetta	Pk-Que	30.271°N, 66.940°E	Tier 2	2015-09-17

11.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Quetta. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

11.1.1 Validation results of Global Horizontal Irradiance

Table 22: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 5072
Stations NAs: 401
Satellite NAs: 4320
Station mean (plus noct.): 247.8
Station mean (no noct.): 465.0
Station max (plus noct.): 1139 on 2015-11-04
Satellite mean (plus noct.): 260.3
Satellite mean (no noct.): 488.4
Satellite max (plus noct.): 1085.6 on 2015-11-01 18:00:00
GHI mean bias (no NA/No noct.): 23.4
GHI RMSE (no NA/No noct.): 83.5

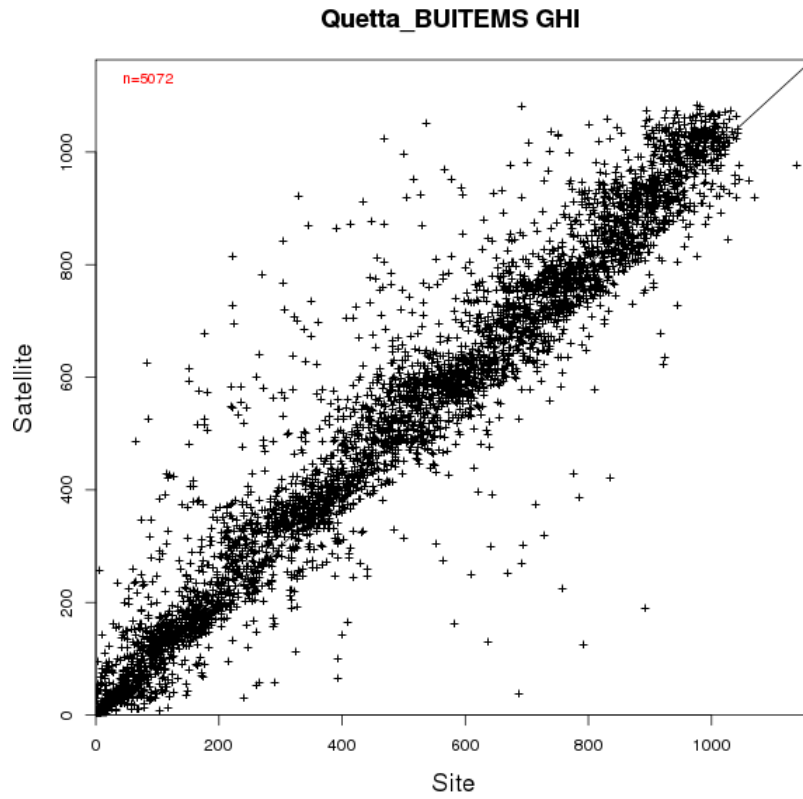


Figure 93: Scatterplot of validation results for GHI at the location of Quetta (in W/m^2)

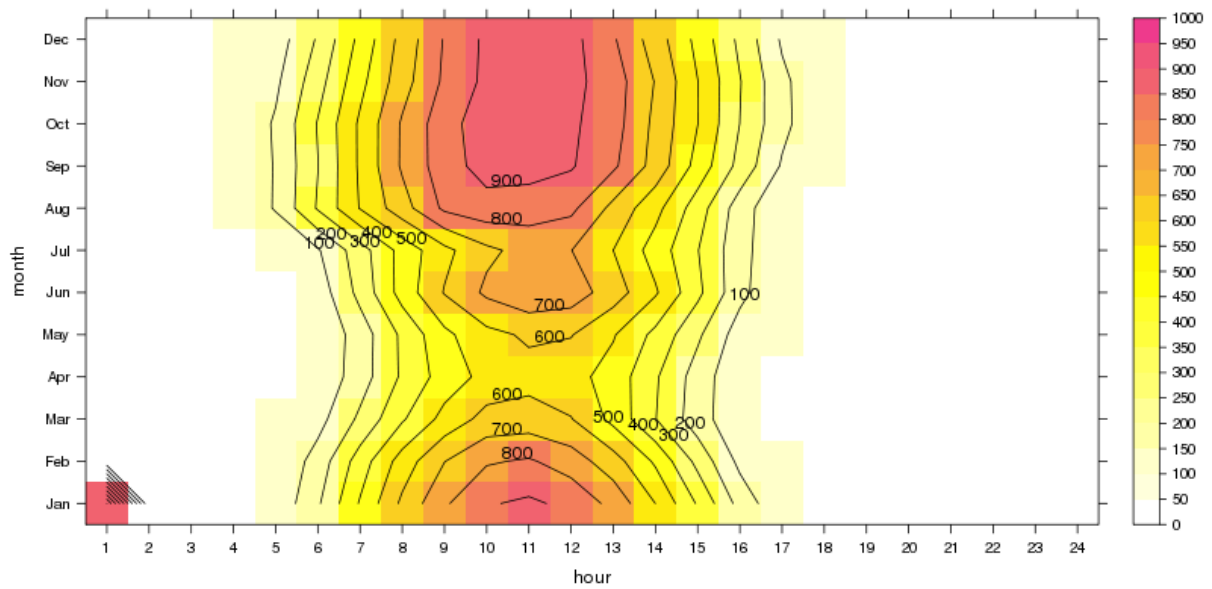


Figure 94: Isopleth graph of ground measurement of GHI at Quetta in W/m^2 (UTC)

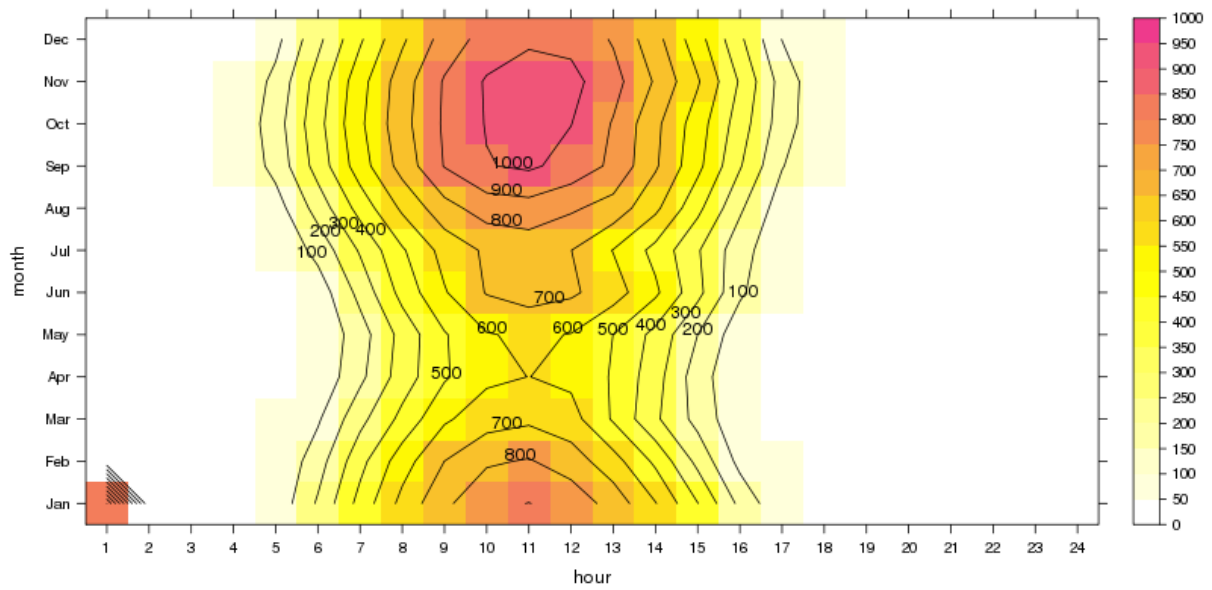


Figure 95: Isopleth graph of satellite estimation of GHI at Quetta in W/m^2 (UTC)

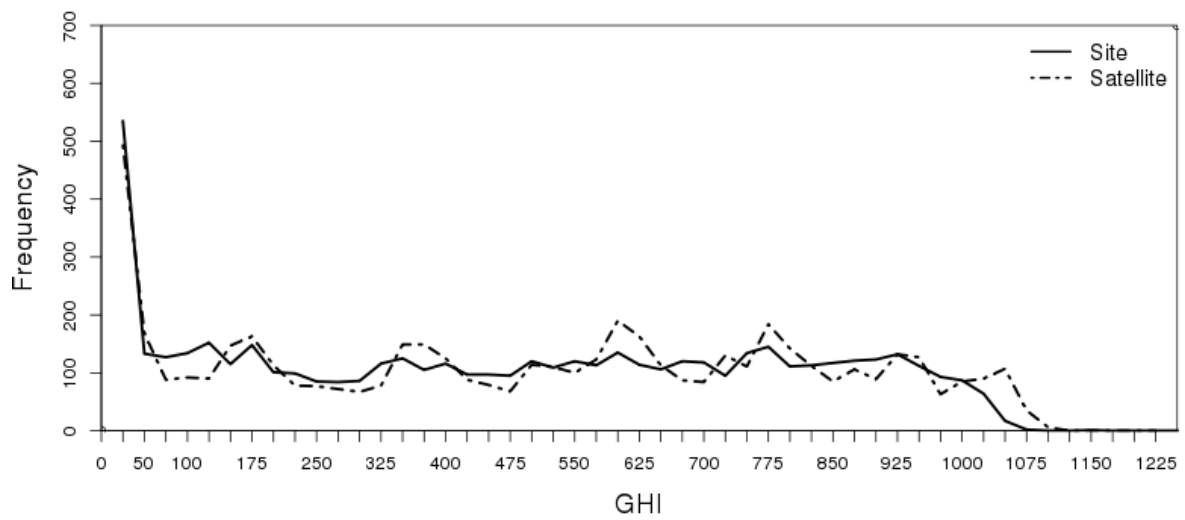


Figure 96: Frequency distribution of hourly GHI at the location of Quetta in W/m^2

11.1.2 Validation results of Direct Normal Irradiance

Table 23: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 4536
Stations NAs: 401
Satellite NAs: 4320
Station mean (plus noct.): 264.9
Station mean (no noct.): 554.3
Station max (plus noct.): 1072 on 2015-11-01 05:00:00
Satellite mean (plus noct.): 315.7
Satellite mean (no noct.): 654.3
Satellite max (plus noct.): 1034.2 on 2015-10-30 15:00:00
DNI mean bias (no NA/No noct.): 100.0
DNI RMSE (no NA/No noct.): 242.0

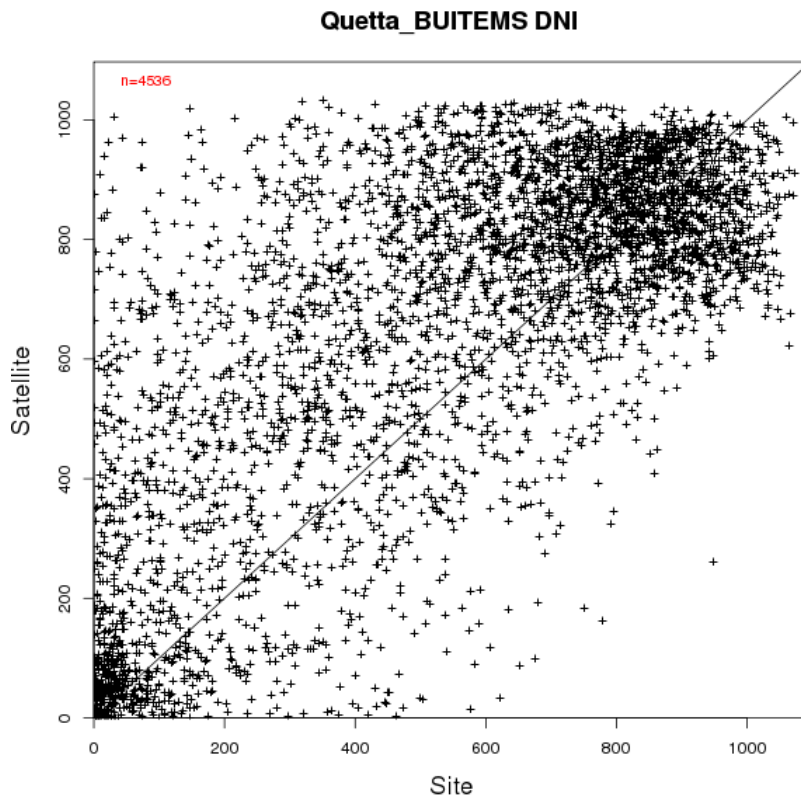


Figure 97: Scatterplot of validation results for DNI at the location of Quetta (in W/m^2)

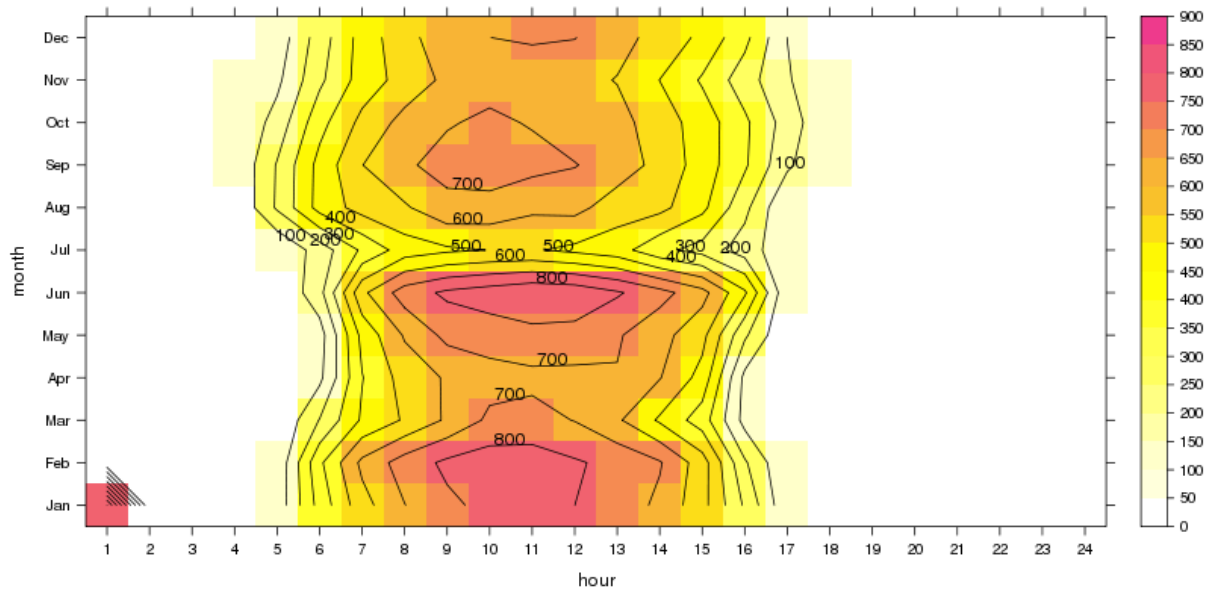


Figure 98: Isopleth graph of ground measurement of DNI at Quetta in W/m^2 (UTC)

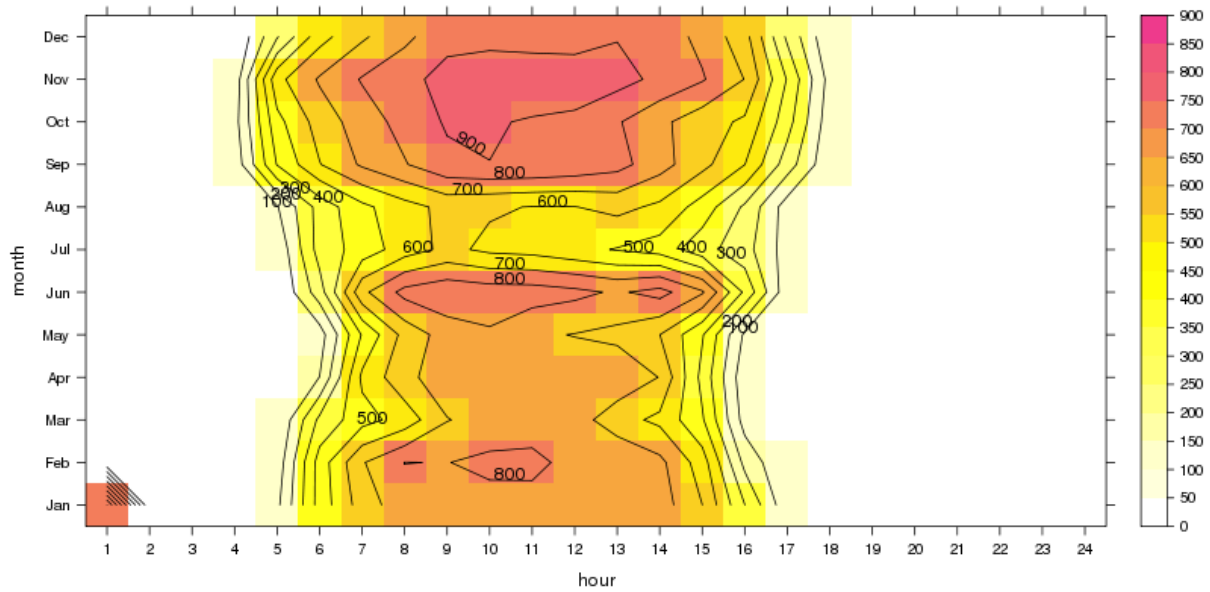


Figure 99: Isopleth graph of satellite estimation of DNI at Quetta in W/m^2 (UTC)

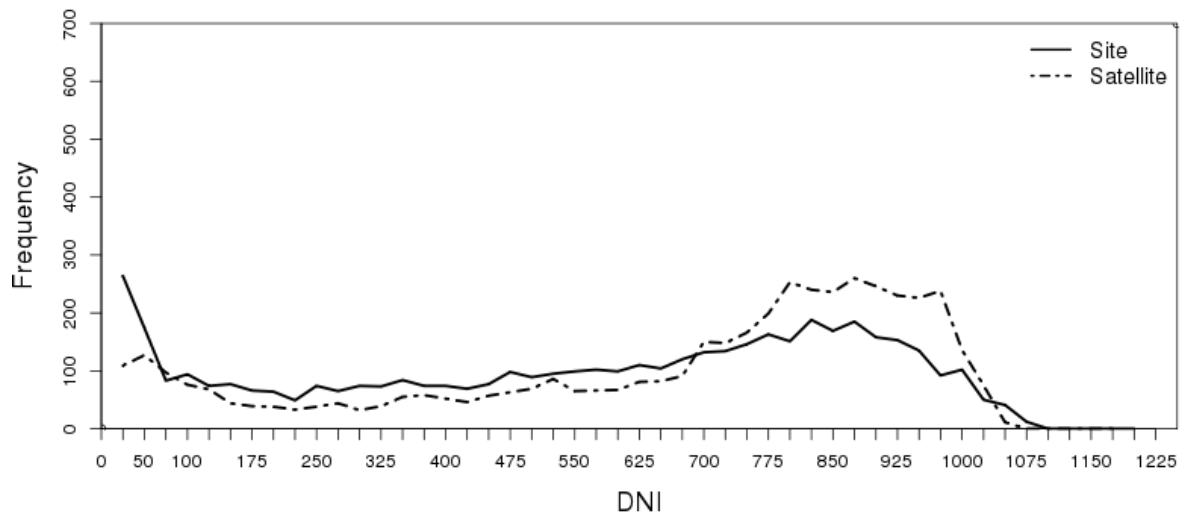


Figure 100: Frequency distribution of hourly DNI at the location of Quetta in W/m^2

11.1.3 Validation results of Diffuse Horizontal Irradiance

Table 24: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 5072
Stations NAs: 401
Satellite NAs: 4320
Station mean (plus noct.): 79.9
Station mean (no noct.): 150.0
Station max (plus noct.): 633 on 2015-10-13 22:00:00
Satellite mean (plus noct.): 64.2
Satellite mean (no noct.): 120.4
Satellite max (plus noct.): 686.5 on 2015-10-16 03:00:00
DHI mean bias (no NA/No noct.): -29.5
DHI RMSE (no NA/No noct.): 96.3

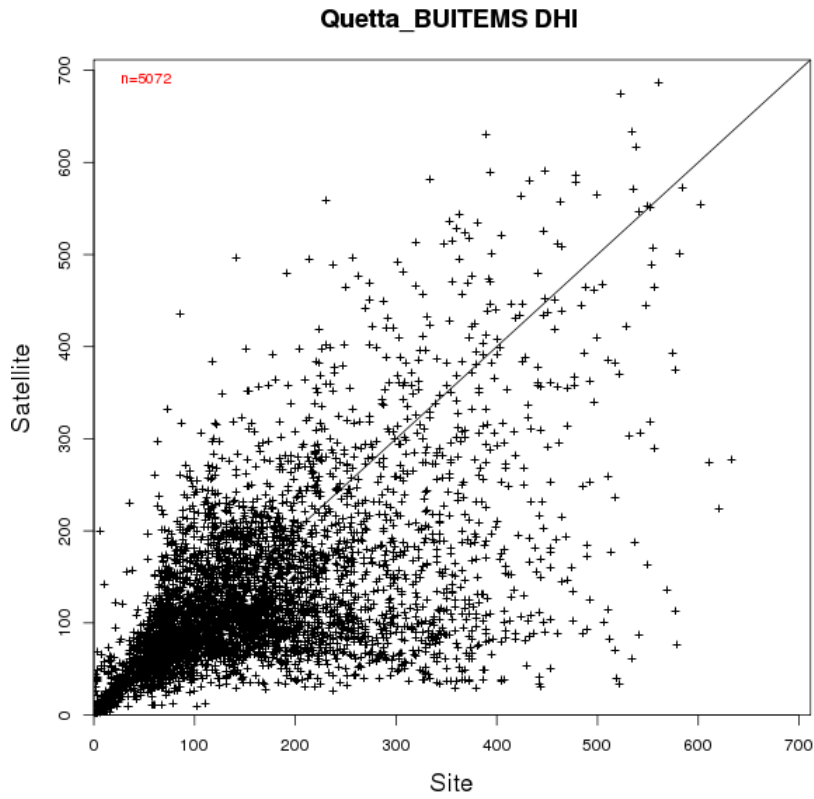


Figure 101: Scatterplot of validation results for DHI at the location of Quetta (in W/m^2)

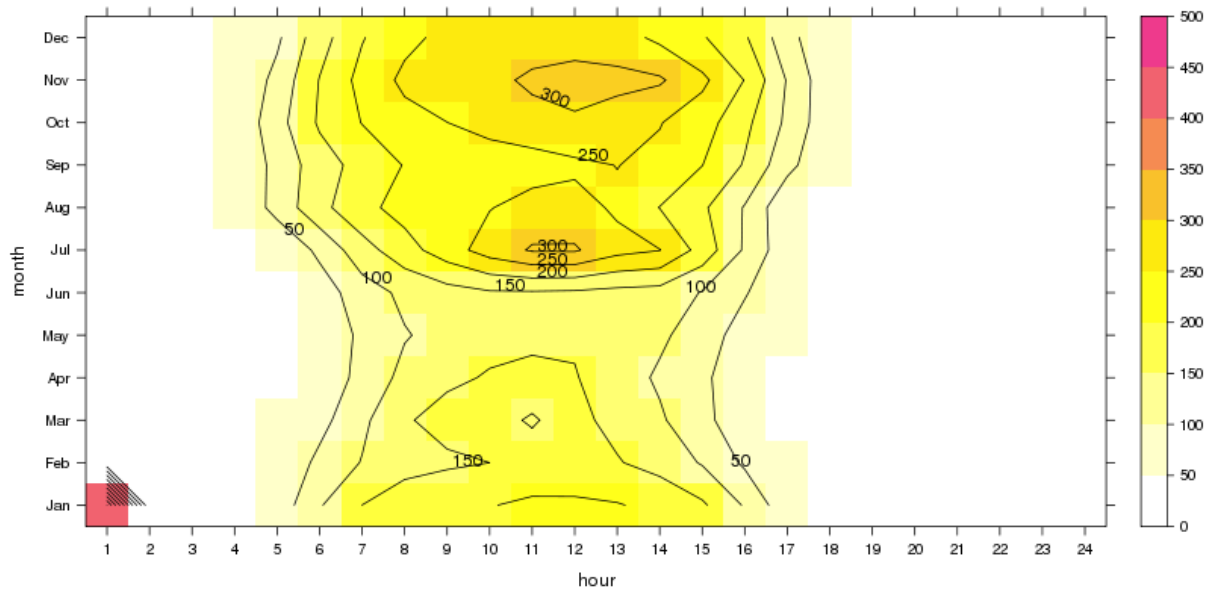


Figure 102: Isopleth graph of ground measurement of DHI at Quetta in W/m^2 (UTC)

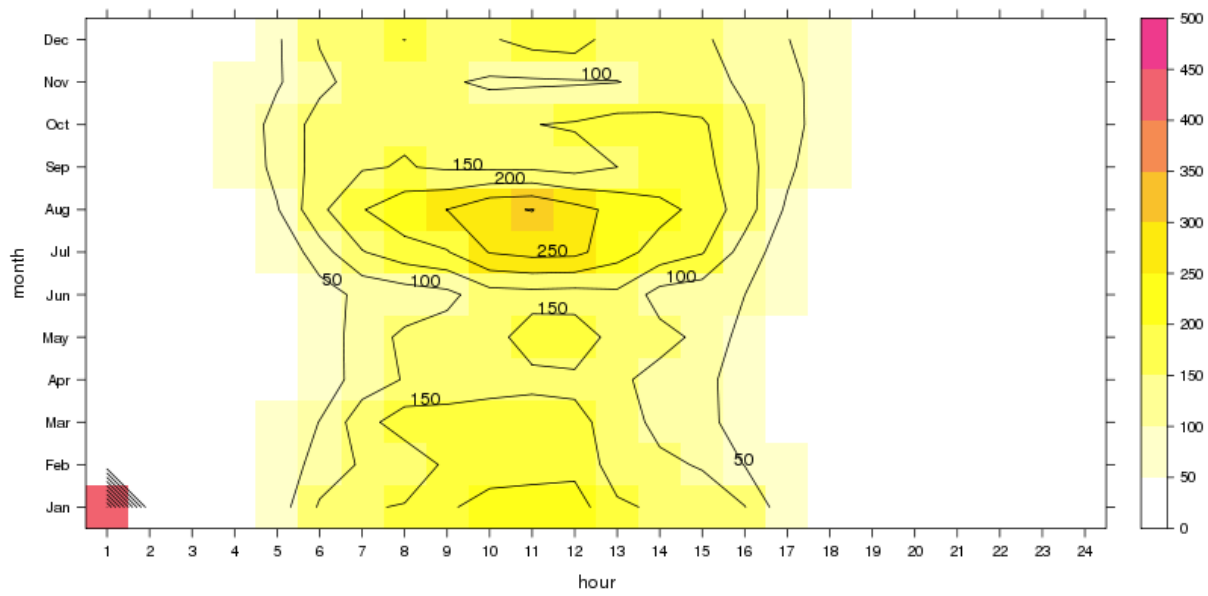


Figure 103: Isopleth graph of satellite estimation of DHI at Quetta in W/m^2 (UTC)

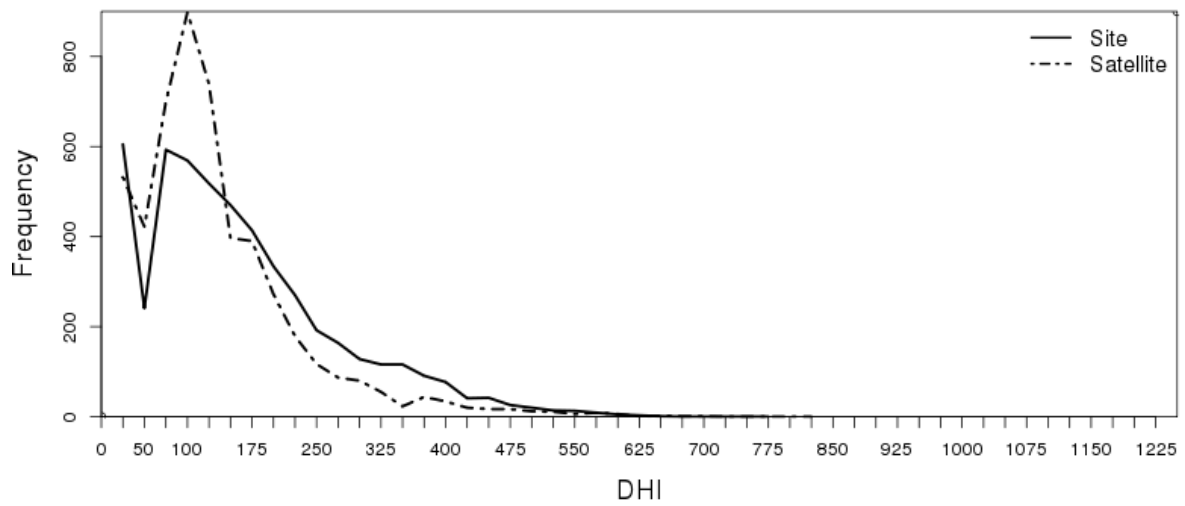


Figure 104: Frequency distribution of hourly DHI at the location of Quetta in W/m^2

11.2 Discussion and conclusion

The measurement site at Quetta is located at the campus of BUIITEMS, about 2 km north of the airport and about 8 km northeast of the city center. Quetta itself is located in 1600 – 1700 m above sea level and is surrounded by mountains that reach to more than 3000 m. Only about 80 km west, just across the border to Afghanistan, the large Kandahar sand/rock dessert represents a huge source of sand for the atmosphere in the region in a prevailing westerly flow. Moreover, Quetta is also influenced by dust outbreaks that have its origin in the Sistan basin even further west.

Nevertheless the results of the validation campaign show a good performance of the satellite model. Not only absolute hourly values show a good accordance between the datasets, also the seasonality is covered well by the satellite estimations. The frequency distribution of hourly values for all three parameters shows a similar pattern and is of no comparison to the results of some other measurement sites further east. There are two approaches to explain these good results achieved in the measurement campaign. The site is located in a relatively high altitude, which reduces the thickness of the atmosphere above the site and, thus, reduces the influence of atmospheric parameters used within the model. The second approach may have much greater influence on the model's performance. Quetta is located outside the inversion layer that affects much of the other measurement stations. The influence of anthropogenic aerosol should be at a normal level in the region and so the satellite does not overestimate irradiance in most cases. The more intense dust outbreaks ("Haboobs") in the area are detected by the cloud index algorithm and the atmosphere is treated as completely opaque in these cases.

The results for the site in Quetta are very satisfying and reflect the originally expected performance of the satellite model in the region. The results are also very important to verify the fact that the smog and fog areas in eastern Pakistan cannot be covered well by chemical transport models at the moment. These facts are also underlined by the results that have been achieved by the measurement site in Khuzdar, which also is located outside the inversion layer that affects the solar irradiance significantly.

12 Site specifics Bahawalpur

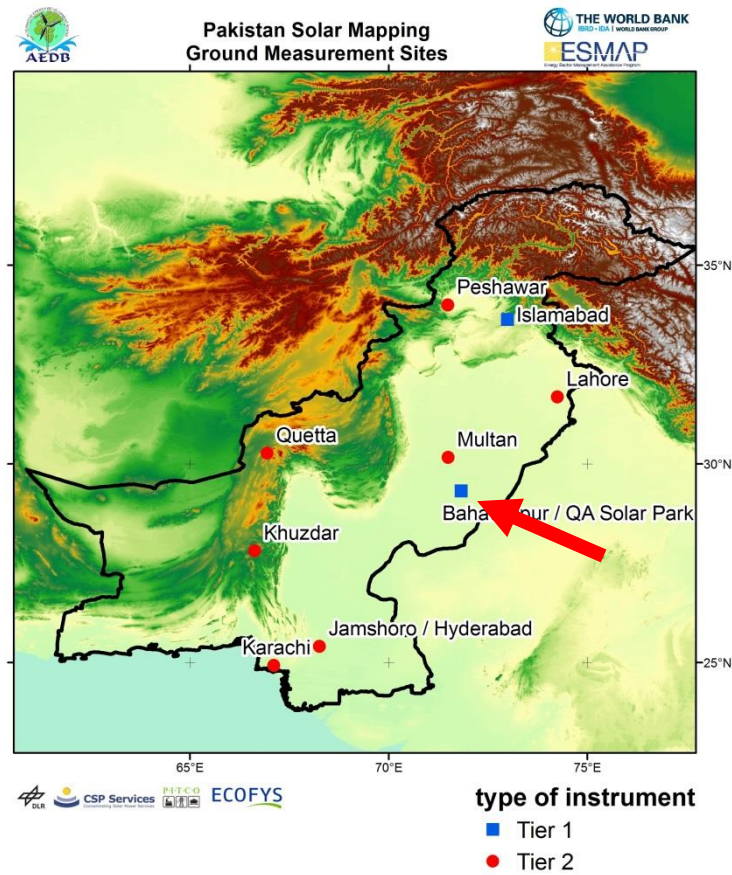


Figure 105: Locations of ground measurement sites and type of instrument

Site	Identifier	Coordinates	Station Type	Installation date
Quaid-e-Azam Solar Park (QASP), Bahawalpur	Pk-QASP	29.325°N, 71.819°E	Tier 1	2014-10-17

12.1 Validation results

Within this section, the results of validation for the parameters GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance) are presented for the location of the measurement site in Bahawalpur. For specifics as well as basic information about these parameters, the measurement equipment and the satellite retrievals, the reader is referred to previous reports published within the ESMAP - Renewable Energy Resource Mapping Initiative in Pakistan.

For satellite data as well as ground data, due to different reasons like maintenance, sensor cleaning etc., there may be data gaps within the time series. These values have been excluded from the analyses. Furthermore, for some statistical parameters or plots, only daytime values have been selected. As for the satellite data, there is a regular gap between November 17th and December 01st 2015. These data could not be delivered by the provider. Ground data also shows gaps within the time series irregularly, which can be referred to the reasons mentioned above.

In section 4 of the report a short conclusion and a discussion is presented for the results.

12.1.1 Validation results of Global Horizontal Irradiance

Table 25: Statistical parameters for GHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

valid observations (no NA/No noct.): 6857
Stations NAs: 1904
Satellite NAs: 3649
Station mean (plus noct.): 212.0
Station mean (no noct.): 405.8
Station max (plus noct.): 1038 on 2014-11-29 14:00:00
Satellite mean (plus noct.): 244.6
Satellite mean (no noct.): 468.1
Satellite max (plus noct.): 1081.1 on 2014-12-01 09:00:00
GHI mean bias (no NA/No noct.): 62.3
GHI RMSE (no NA/No noct.): 103.2

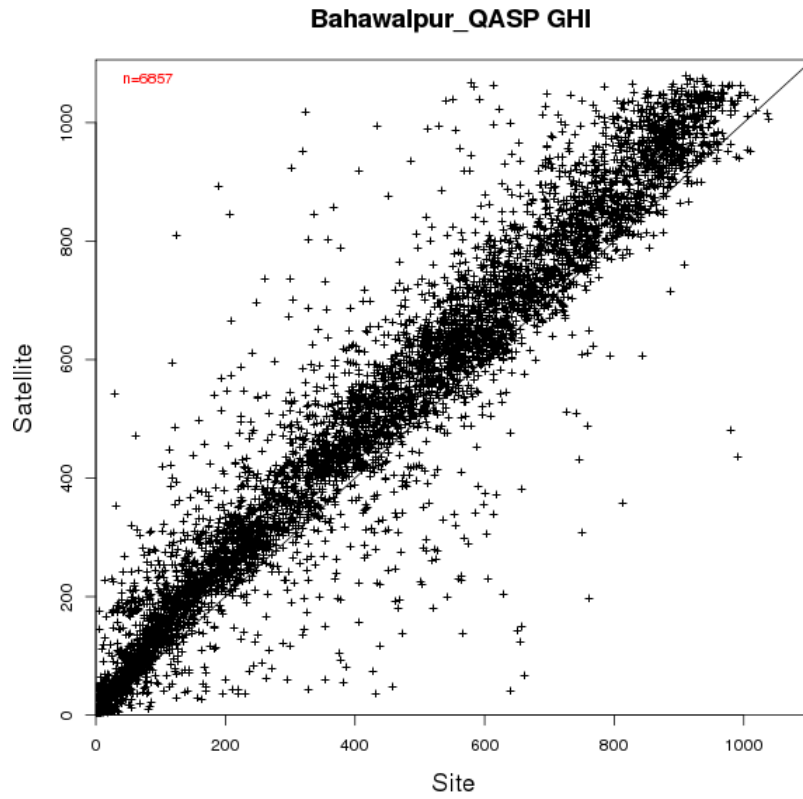


Figure 106: Scatterplot of validation results for GHI at the location of Bahawalpur (in W/m^2)

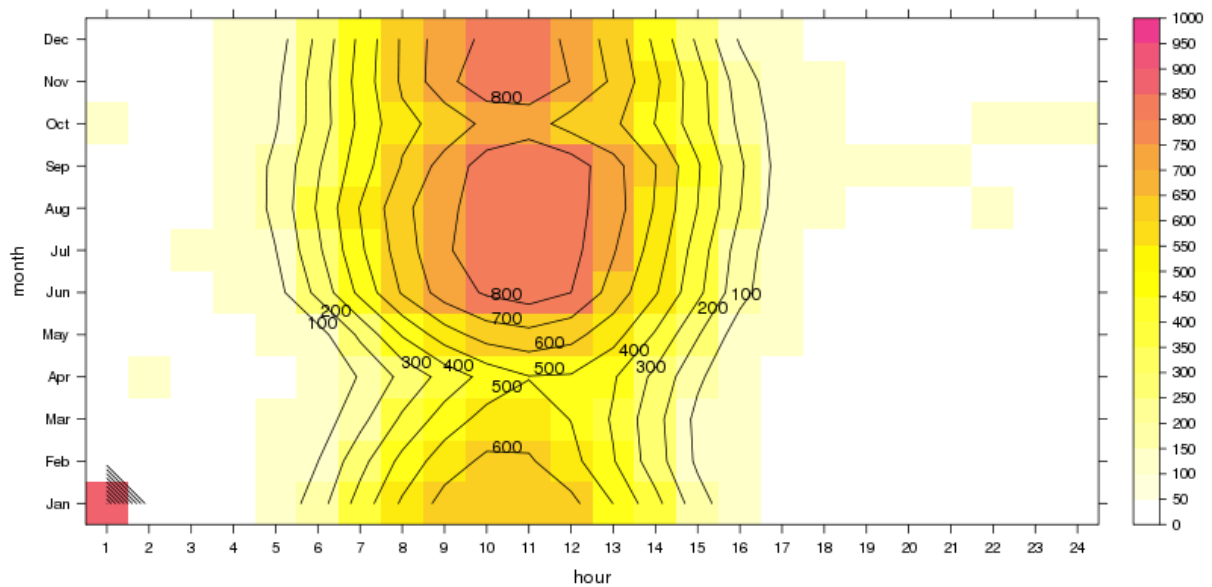


Figure 107: Isopleth graph of ground measurement of GHI at Bahawalpur in W/m^2 (UTC)

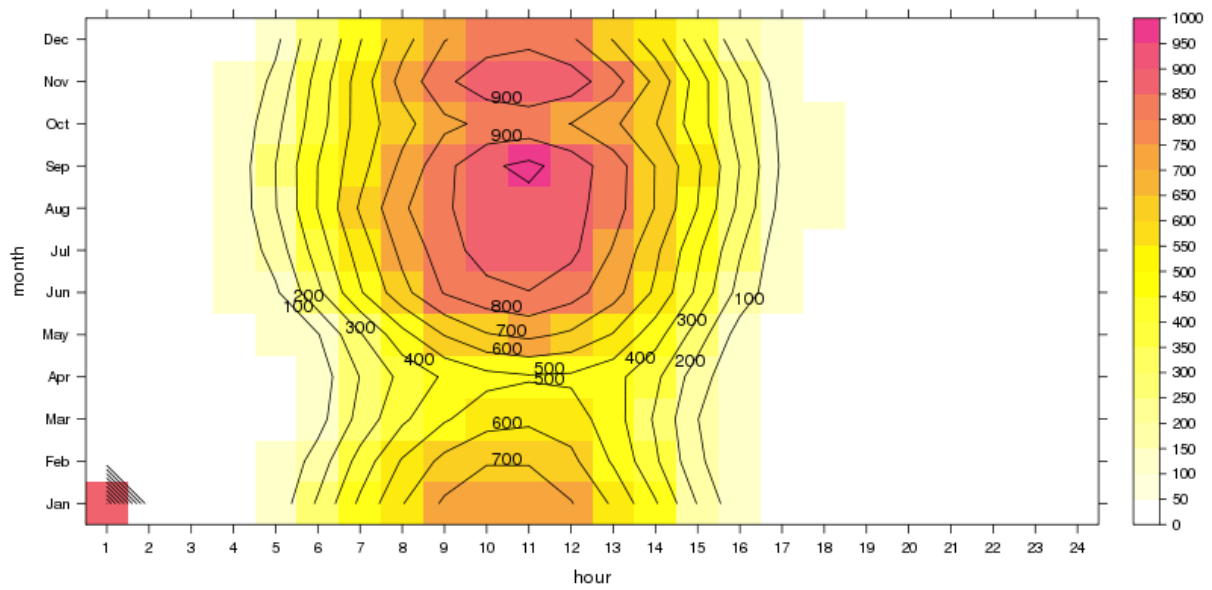


Figure 108: Isopleth graph of satellite estimation of GHI at Bahawalpur in W/m^2 (UTC)

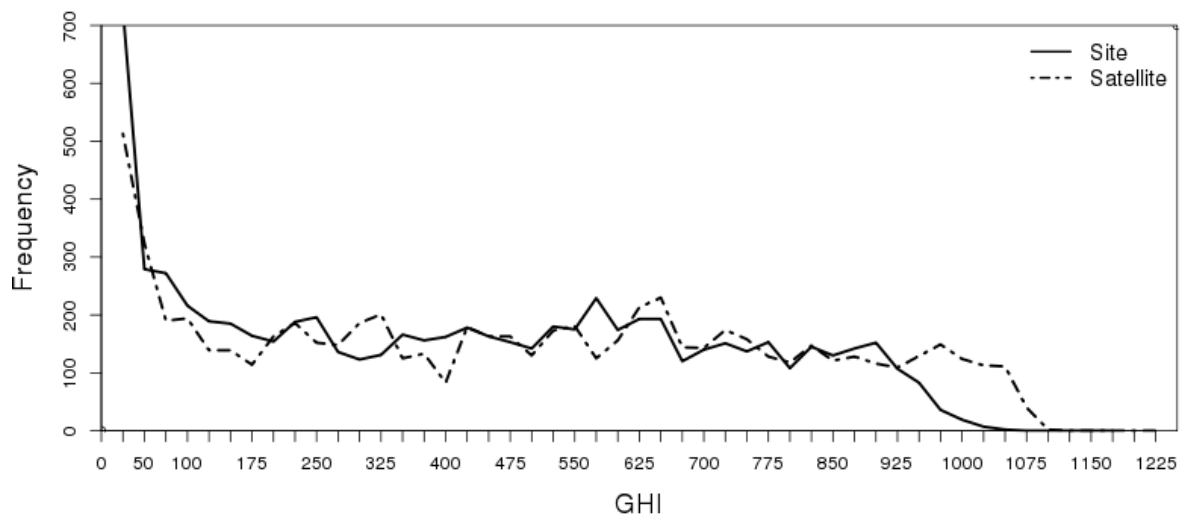


Figure 109: Frequency distribution of hourly GHI at the location of Bahawalpur in W/m^2

12.1.2 Validation results of Direct Normal Irradiance

Table 26: Statistical parameters for DNI of satellite and ground measurement. Radiation values are hourly sums in W/m^2 . No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 5258
Stations NAs: 4274
Satellite NAs: 3649
Station mean (plus noct.): 182.5
Station mean (no noct.): 372.8
Station max (plus noct.): 953 on 2014-11-26 01:00:00
Satellite mean (plus noct.): 304.8
Satellite mean (no noct.): 616.9
Satellite max (plus noct.): 1015.7 on 2014-11-28 15:00:00
DNI mean bias (no NA/No noct.): 244.1
DNI RMSE (no NA/No noct.): 310.0

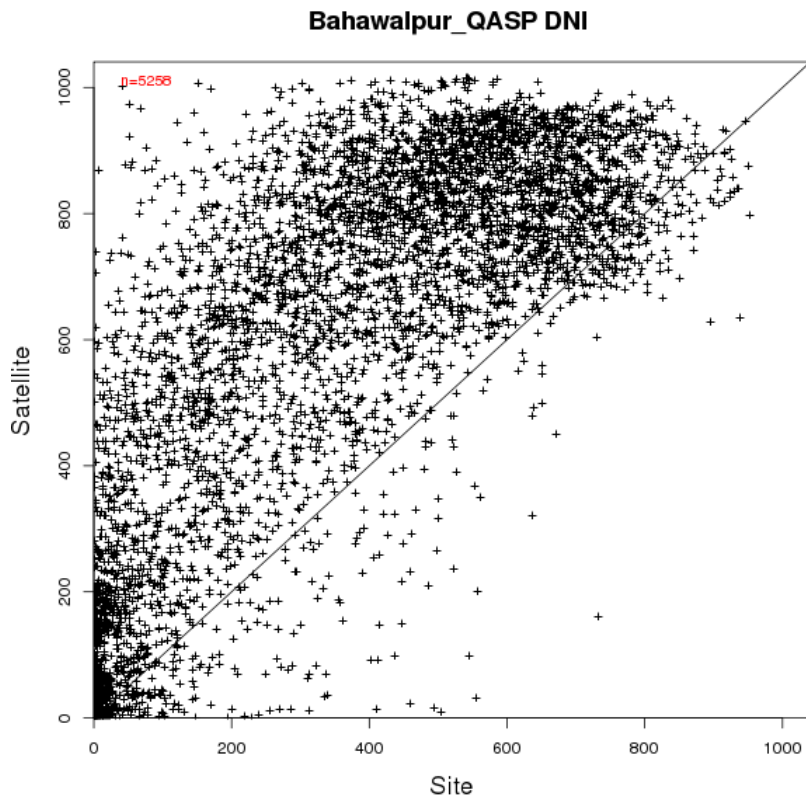


Figure 110: Scatterplot of validation results for DNI at the location of Bahawalpur (in W/m^2)

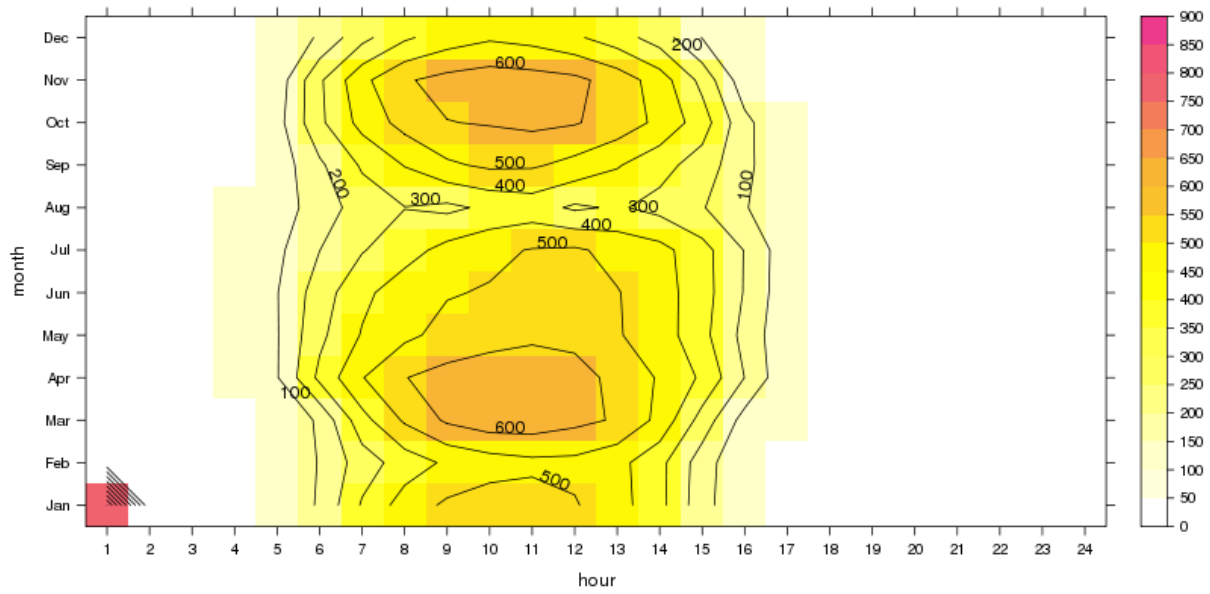


Figure 111: Isopleth graph of ground measurement of DNI at Bahawalpur in W/m^2 (UTC)

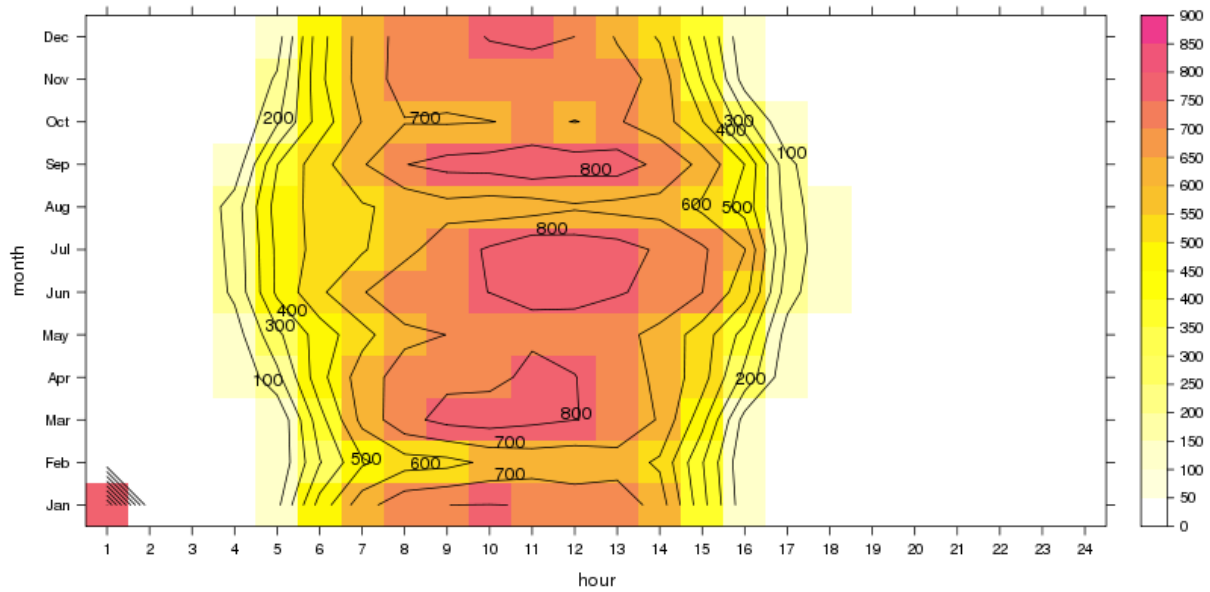


Figure 112: Isopleth graph of satellite estimation of DNI at Bahawalpur in W/m^2 (UTC)

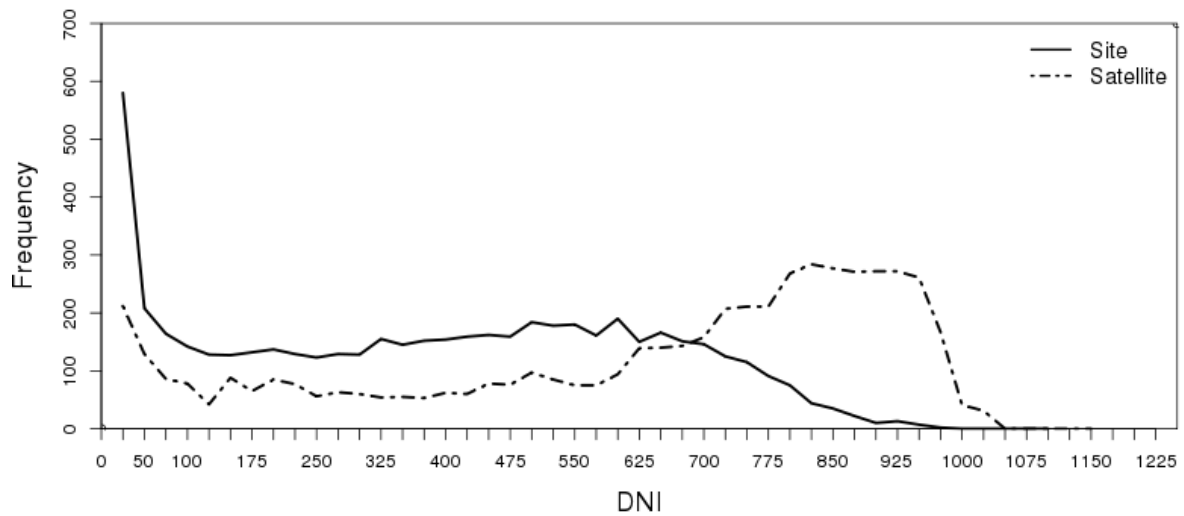


Figure 113: Frequency distribution of hourly DNI at the location of Bahawalpur in W/m²

12.1.3 Validation results of Diffuse Horizontal Irradiance

Table 27: Statistical parameters for DHI of satellite and ground measurement. Radiation values are hourly sums in W/m². No noct. means that values before/after sunset are excluded, NA values are not available.

Valid observations (no NA/No noct.): 5716
Stations NAs: 4274
Satellite NAs: 3649
Station mean (plus noct.): 99.3
Station mean (no noct.): 186.9
Station max (plus noct.): 634 on 2014-11-12 18:00:00
Satellite mean (plus noct.): 68.4
Satellite mean (no noct.): 128.8
Satellite max (plus noct.): 652.7 on 2014-11-13 12:00:00
DHI mean bias (no NA/No noct.): -58.1
DHI RMSE (no NA/No noct.): 113.5

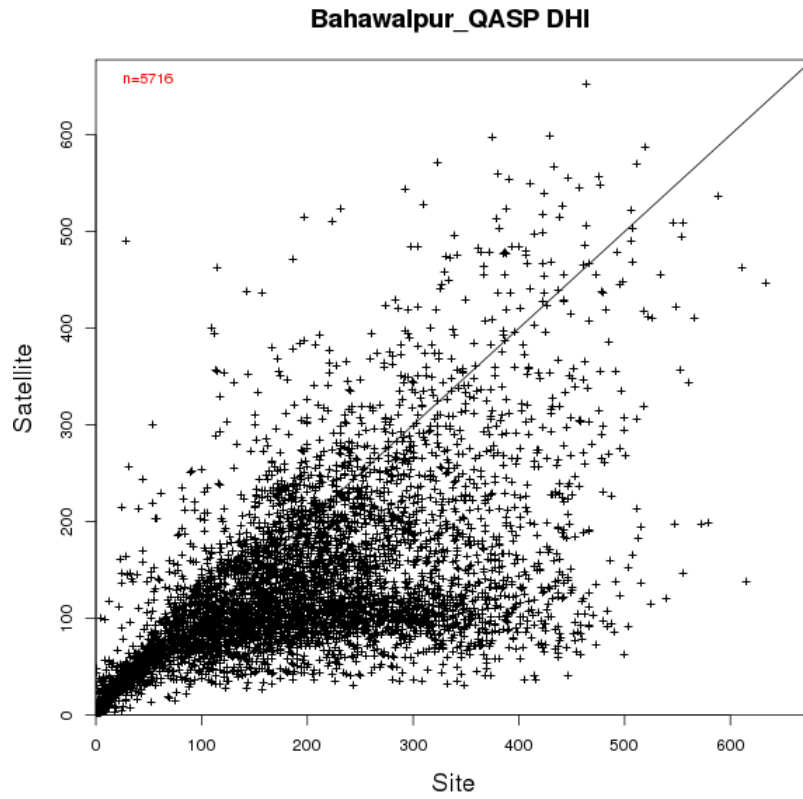


Figure 114: Scatterplot of validation results for DHI at the location of Bahawalpur (in W/m^2)

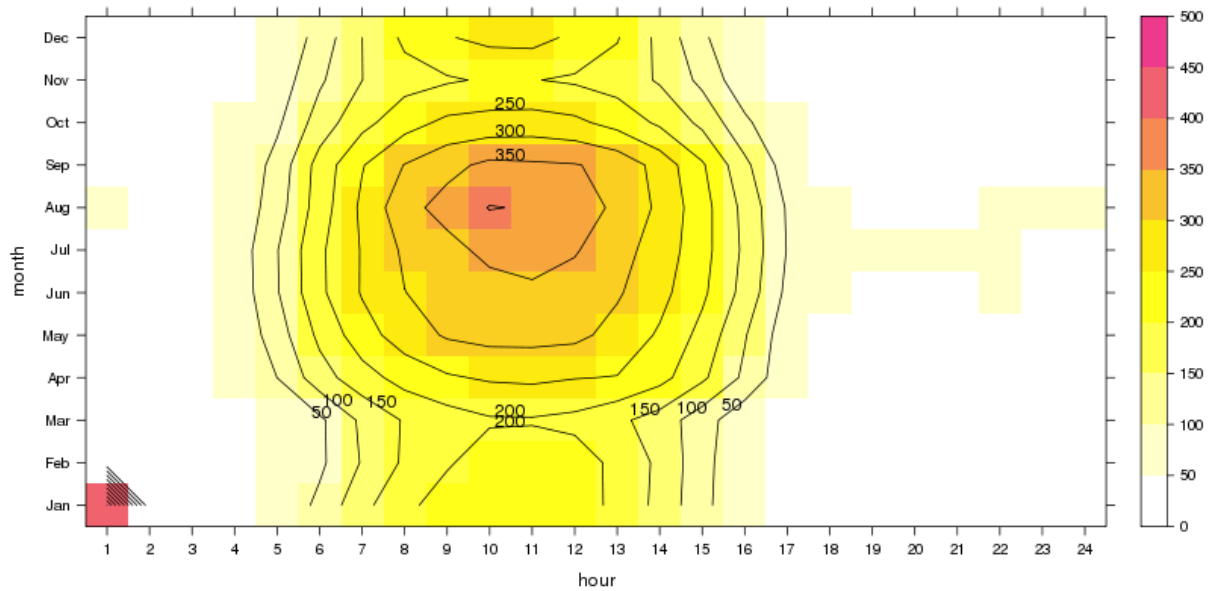


Figure 115: Isopleth graph of ground measurement of DHI at Bahawalpur in W/m^2 (UTC)

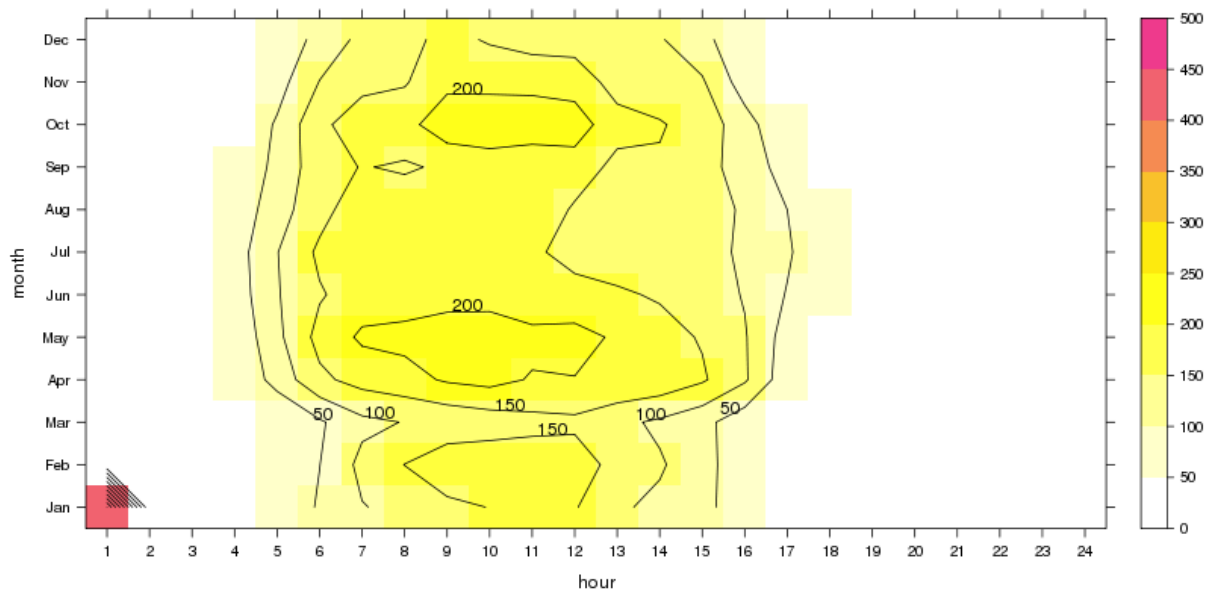


Figure 116: Isopleth graph of satellite estimation of DHI at Bahawalpur in W/m^2 (UTC)

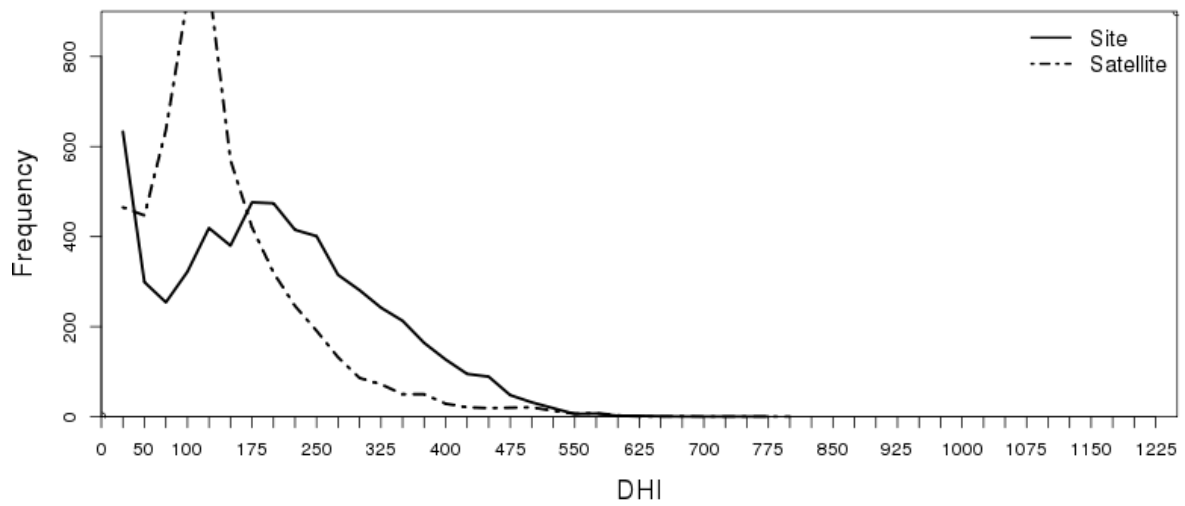


Figure 117: Frequency distribution of hourly DHI at the location of Bahawalpur in W/m^2

12.2 Discussion and conclusion

The TIER1 site at QASP is located about 15 kilometers southeast of the city of Bahawalpur. Even though there are two larger data gaps of the ground measurement sites, the validation campaign at Bahawalpur presents a very important dataset with a sufficient number of measurements. The results of the validation campaign pose a strong overestimation of GHI and a very strong overestimation of DNI at the site for the modelled data.

The region is regularly influenced by fog and a high load of aerosol, which is probably one of the reasons for the strong bias. The results reflect the performance of the satellite estimation in regions of high aerosol load in Pakistan. This fact does partly explain the performance of the satellite model and the results presented in this report. The underlying aerosol model has been developed for climatological purposes and is available in relatively big spatial resolution. Reanalysis data with a spatial resolution of about 1° by 1° have difficulties in covering local sources of aerosol as it is the case in Islamabad and in most of the other locations used within this campaign. These local sources of emission are one of the reasons for the Asian brown cloud, which is present in the area and, due to its complex composition, is hardly to be detected, even by state of the art chemical transport models. All these facts have been presented in previous reports in detail and the reader is referred to these documents. Within DLR, a solution for this problem is under development and will be presented in a future publication.

13 General Conclusion and Outlook

Validation results for seven of nine sites indicate that the satellite model has difficulties with high aerosol loads in the atmosphere. There is a high bias between modelled data and measurements on a regional scale. The measurement sites in the low-lying, eastern regions of Pakistan are affected by this issue in particular. There is a better match between datasets in the western regions (Quetta and Khuzdar), which are less affected by this high aerosol load. This may be referred to the fact that these two measurement sites are located in semi-arid climate in levels above the inversion layer that is abundant further east regularly. These facts, as well as the impact of the aerosol load and seasonality on the results of the statistical analysis, have been discussed in the conclusion chapter of every site validation and in previous reports in detail. Nevertheless, DLR has detected the regions with high atmospheric aerosol load in Pakistan and will develop a method to optimize model data based on local aerosol measurements. These results will be implemented to the Heliosat-Method in the near future and published thereafter.