



## Satellite-Based Solar Resource Data Sets for India 2002–2012

M. Sengupta,<sup>1</sup> R. Perez,<sup>2</sup> C. Gueymard,<sup>3</sup>  
M. Anderberg,<sup>1</sup> and P. Gotseff<sup>1</sup>

<sup>1</sup> *National Renewable Energy Laboratory*

<sup>2</sup> *State University of New York at Albany*

<sup>3</sup> *Solar Consulting Services*

**NREL is a national laboratory of the U.S. Department of Energy  
Office of Energy Efficiency & Renewable Energy  
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy  
Laboratory (NREL) at [www.nrel.gov/publications](http://www.nrel.gov/publications).

**Technical Report**

NREL/TP-5D00-61121

February 2014

Contract No. DE-AC36-08GO28308

# Satellite-Based Solar Resource Data Sets for India 2002–2012

M. Sengupta,<sup>1</sup> R. Perez,<sup>2</sup> C. Gueymard,<sup>3</sup>  
M. Anderberg,<sup>1</sup> and P. Gotseff<sup>1</sup>

<sup>1</sup> *National Renewable Energy Laboratory*

<sup>2</sup> *State University of New York at Albany*

<sup>3</sup> *Solar Consulting Services*

Prepared under Task No. WFK6.1001

**NREL is a national laboratory of the U.S. Department of Energy  
Office of Energy Efficiency & Renewable Energy  
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy  
Laboratory (NREL) at [www.nrel.gov/publications](http://www.nrel.gov/publications).

## NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at [www.nrel.gov/publications](http://www.nrel.gov/publications).

Available electronically at <http://www.osti.gov/scitech>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
phone: 865.576.8401  
fax: 865.576.5728  
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
phone: 800.553.6847  
fax: 703.605.6900  
email: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
online ordering: <http://www.ntis.gov/help/ordermethods.aspx>

*Cover Photos: (left to right) photo by Pat Corkery, NREL 16416, photo from SunEdison, NREL 17423, photo by Pat Corkery, NREL 16560, photo by Dennis Schroeder, NREL 17613, photo by Dean Armstrong, NREL 17436, photo by Pat Corkery, NREL 17721.*



Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

## Acknowledgements

This work was funded by the U.S. Department of Energy (DOE) and the U.S. Department of State under the U.S.–India Energy Dialogue’s New Technology and Renewable Energy Working Group. The authors would like to acknowledge Michael Mills and Elena Berger of DOE for supporting this research. The authors would also like to thank Dr. Bibek Bandyopadhyay and Dr. P. Saxena of India’s National Institute of Solar Energy for collaboration and providing ground-measured data. Additionally, we express appreciation to Aron Habte and Nate Blair of the National Renewable Energy Laboratory and Stephen Wilcox of Solar Resource Solutions, LLC, for their review of this report.

## Abstract

A new 10-km hourly solar resource product was created for India. This product was created using satellite radiances from the Meteosat series of satellites. The product contains global horizontal irradiances (GHI) and direct normal irradiances (DNI) for the period from 2002 to 2011. An additional solar resource data set covering the period from January 2012 to June 2012 was created solely for validation because this period overlaps ground measurements that were made available from the Indian Ministry of New and Renewable Energy's (MNRE's) National Institute for Solar Energy for five stations that are part of MNRE's solar resource network. These measurements were quality checked using the SERI QC software and used to validate the satellite product. A comparison of the satellite product to the ground measurements for the five stations shows good agreement. This report also presents a comparison of the new version of solar resource data to the previous version, which covered the period from 2002 to 2008. The comparison of the new product to the previous version shows that annual average DNI modeled values are lower by 10% to 15% and the annual average GHI values are lower by 2% to 3%. These changes are highest in low-irradiance regions and lowest in high-irradiance areas.

## List of Acronyms

AOD	aerosol optical depth
DNI	direct normal irradiance
GHI	global horizontal irradiance
MBE	mean bias error
MNRE	Ministry of New and Renewable Energy
RMSE	root mean square error
SERI	Solar Energy Research Institute
QC	quality check

# Table of Contents

<b>List of Figures</b> .....	<b>vii</b>
<b>List of Tables</b> .....	<b>vii</b>
<b>1 Objective</b> .....	<b>1</b>
<b>2 Methodology</b> .....	<b>1</b>
2.1 Aerosol Data Sets .....	1
<b>3 Satellite Product</b> .....	<b>2</b>
3.1 Comparison of Products .....	2
<b>4 Validation of Satellite Product</b> .....	<b>2</b>
<b>5 Recommendations for Further Work</b> .....	<b>3</b>
<b>6 References</b> .....	<b>4</b>
<b>7 Appendix</b> .....	<b>5</b>

## List of Figures

Figure 1. The 700-nm AOD for January 2011 and July 2011. Note the huge variation among geographical regions as well as the temporal variation. ....	5
Figure 2. Annual average DNI and GHI from 2002 to 2011 .....	6
Figure 3. Comparison of the new data sets to the previous data sets for the GHI and DNI annual averages. The solar resource estimates in the new data sets are lower than they were in the old data sets for both GHI and DNI. ....	7
Figure 4. Comparisons of ground measurements (Jan. 2012 to June 2012) and satellite hourly data for (blue) GHI and (red) DNI for the (clockwise from bottom) Bijapur, Bhogat, Amarsagar, Chennai (CWET), and Kadiri stations. The GHI from the satellite product is generally in good agreement with the ground data. The DNI data also shows good agreement but has more scatter than the GHI. ....	8

## List of Tables

Table 1. Stations Where Ground-Based Measurements Are Available for Validation .....	9
Table 2. Difference in DNI Between New and Old Data Sets .....	9
Table 3. Difference in GHI Between New and Old Data Sets .....	9
Table 4. RMSE, MBE, and Correlations (R) Between Satellite-Predicted and Measured DNI .....	9
Table 5. RMSE, MBE, and Correlations (R) Between Satellite-Predicted and Measured GHI.....	10

# 1 Objective

The objective of this project was to create a new satellite-derived hourly solar data set for India covering the period of time from January 2002 to June 2012 to supplement and enhance an earlier data production effort. The goal was also to reduce the uncertainty of the data sets through the use of a newer version of a model that has been developed since the previous data sets were created. In particular, this would be accomplished by using a new set of monthly resolved aerosol optical depth (AOD) data. To determine the quality of the product, it was essential to compare the results to high-quality ground measurement data. Thus, the final objective was to procure ground-based measurements, assess the quality of the measurements, and validate the satellite-based product with the quality-checked ground measurement data. Because accurate solar resource data is critical to assessing project viability and securing project financing, an improved data set is expected to reduce barriers to the deployment of solar technologies throughout India.

## 2 Methodology

The semi-empirical satellite model developed by Perez et al. (2002, 2004) was used to develop the solar resource data set. This type of semi-empirical model is fully described in Perez, Cebecauer, and Suri (2013).

For the present application, the inputs to the model consisted of:

- Hourly visible channel frames from the geostationary satellite covering the Indian subcontinent. For the period from 2002 to 2007, the satellite was Meteosat 5. For the period from 2007 to 2012, the satellite was Meteosat 7. The satellite data have a ground resolution of 0.1 by 0.1 degrees, which is approximately 10 km by 10 km for the considered region.
- Ground elevation
- Climatological precipitable water and ozone (Saha et al. 2010)
- Monthly AOD. Climatological AOD was used in the earlier product. The present product was created using month-specific AOD derived from an ensemble of sources, including satellites remote sensing, transport models, and ground measurements (Gueymard and Sengupta 2013).

### 2.1 Aerosol Data Sets

An improved gridded database of monthly AOD at 550 nm (AOD550) and Ångström exponents over India was produced using point data from ground sites in and around India equipped with multi-wavelength sunphotometers as well as gridded data from space measurements or from existing aerosol climatologies (Gueymard and Sengupta 2013). Data from 83 sunphotometer sites were used here as ground truth to calibrate, optimally combine, and validate monthly gridded data from 2000 to 2012.

To compare the satellite and climatology data (at original resolutions of 1 x 1 degree or 0.5 x 0.5 degree) to the point-like ground-truth data, scale height corrections were applied to the AOD550 data to compensate for the effect of local elevation.

Different optimal combinations of the satellite data were obtained for the three main seasons on the Indian subcontinent. Most generally, the MODIS (Moderate Resolution Imaging Spectroradiometer) data was found to be closest to ground truth, albeit with some bias, which was globally corrected for the whole subcontinent, separately for each season. One main difficulty was the numerous data breaks that were found in the satellite-based databases, particularly over Rajasthan and during the monsoon season. An optimal combination of alternate satellite data and climatologies was applied in such cases.

Additionally, a statistical analysis was undertaken to evaluate the best method of optimally correcting the monthly-mean AOD550 so that more-accurate direct normal irradiance results could be obtained on a mean monthly basis. This analysis showed that the “most-likely” or mode AOD550 might be useful in atmospheres with light aerosol loading. On the other hand, in regions with higher aerosol loads, such as India, the use of seasonally corrected monthly mean AOD550 using available ground measurements provides the best results.

The resulting AOD550 and Ångström exponent databases were used to derive the necessary input to the satellite model, namely a data set of AOD at 700 nm with a spatial resolution of 0.1 x 0.1 degree. Figure 1 shows how the AOD700 could vary between winter (represented by January 2011) and summer (represented by July 2011). Given the wide range of variation between the seasons and the high aerosol loading overall, a monthly average may not be fully capable of representing the overall variability in solar radiation that actually occurs.

### **3 Satellite Product**

The satellite-based solar radiation product covers the period from 2002 to 2011. The product is an hourly time series at a resolution of approximately 10 km by 10 km. The initial product had gaps in which satellite data was not available, thus these missing data points were filled. Missing values including the beginning and end of the day were filled using zenith angle-corrected interpolation. Missing days were filled using data from the previous day. Longer time periods were filled using climatological mean values for years when data corresponding to the missing periods were available, though this option was very rarely exercised. The annual average daily totals for DNI and GHI were also calculated and are shown in Figure 2. The hourly data sets are available from [http://rredc.nrel.gov/solar/new\\_data/India/](http://rredc.nrel.gov/solar/new_data/India/). The maps are available from [http://www.nrel.gov/international/ra\\_india.html](http://www.nrel.gov/international/ra_india.html).

#### **3.1 Comparison of Products**

The satellite data from the previous production were compared to the newly created data sets. It was found that the new DNI and GHI estimates are lower than they were in the previous product. The differences are shown in Figure 3. Table 2 shows that the DNI resource was mostly reduced by 10% to 15%; Table 3 shows that the GHI resource was mostly reduced by 2% to 3%. The differences between the two products can be mostly attributed to differences in the AOD used in the two products.

### **4 Validation of Satellite Product**

Surface-based measurements from pyranometers and pyrheliometers were received from the Ministry of New and Renewable Energy’s (MNRE’s) National Institute for Solar Energy for the

five stations shown in Table 1. The overlap between the satellite and ground measurements covers the period from January 2012 to June 2012. The ground data were initially available at 10-minute averages but were converted to hourly averages corresponding to the resolution of the satellite data sets. These data sets were then quality checked using the SERI QC software (Maxwell, Wilcox, and Rymes 1993). Only data that passed the quality check were used in the comparison.

Validation of the model was undertaken using model validation metrics recommended by the International Energy Agency Solar Heating and Cooling Programme Task 36. The metrics include root mean square error (RMSE) and mean bias error (MBE).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (I_{pred,i} - I_{meas,i})^2} \quad (1)$$

Here,  $N$  is the number of evaluated data pairs, and  $I_{pred,i}$  and  $I_{meas,i}$  represent the modeled and measured irradiances, respectively.

$$MBE = \frac{1}{N} \sum_{i=1}^N (I_{pred,i} - I_{meas,i}) \quad (2)$$

Both the GHI and DNI were compared, and the scatter plots for the five stations are shown in Figure 4. Summaries of the model performance results for the five sites are presented in Table 4 and Table 5. The MBE of the DNI predicted by the satellite was found to be approximately 60 W/m<sup>2</sup> for three stations but more than 110 W/m<sup>2</sup> for the other two stations. Similarly, the MBE for the GHI was found to range from 16 W/m<sup>2</sup> to 62 W/m<sup>2</sup> for the stations that were compared. Note that the MNRE has been collecting solar resource data for 51 ground stations ([http://www.cwet.tn.nic.in/html/srra\\_stations.html](http://www.cwet.tn.nic.in/html/srra_stations.html)), of which 5 have been used for this study. Additional validation for the other stations needs to be conducted to provide a statistically accurate estimate of biases.

## 5 Recommendations for Further Work

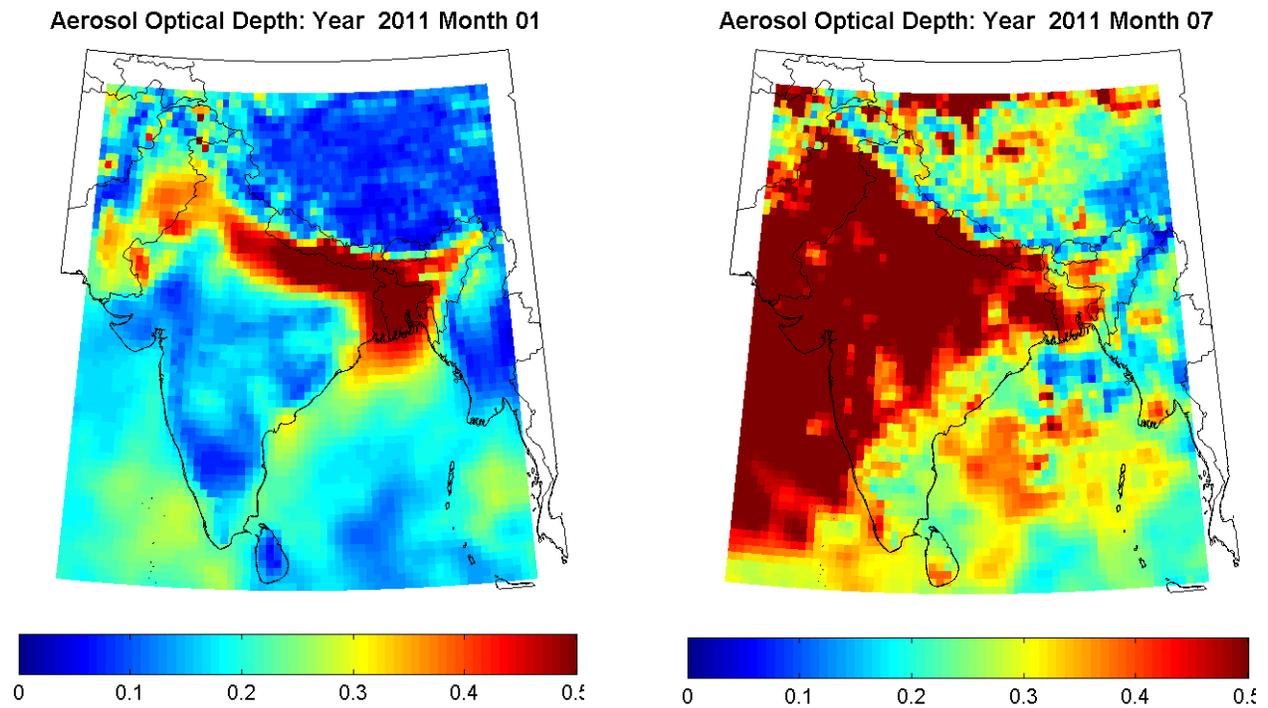
As apparent in Figure 4, issues still remain in modeling DNI, with the overall average bias below 100 W/m<sup>2</sup>. On the other hand, the GHI bias is below 50 W/m<sup>2</sup>, which points to a 5% to 10% error when using the surface measurements as ground truth. This indicates that the quality of the newly created solar resource data sets can be considered acceptable given the uncertainties in the satellite product, the ground data, and the comparison methodology by which a point measurement is compared to an areal average. The signature of the plots suggests that monthly AODs might not be of sufficient resolution to fully capture DNI in the considered climate. Figure 1 shows how variable the 700-nm AOD is both between geographical regions and between seasons. Generally, the variability of AOD in a high-AOD environment is high. Therefore, we can reasonably conclude that a higher frequency of AOD data (daily AOD) could potentially reduce the uncertainty in this climatic environment. Creation of high-resolution AOD data sets using chemical transport models is an active area of research.

In addition, it is important to increase the number of sites for which the comparisons are conducted. The current comparison includes five sites; whereas MNRE currently operates and collects data from 51 sites, and there are plans to expand this monitoring to more than 100 sites. When longer, overlapping time periods of ground and satellite data become available, a longer-term comparison would add value to the satellite product.

## 6 References

- Gueymard, C.; Sengupta, M. (2013). *Improved Gridded Aerosol Data for India*. NREL/SR-5600-58762. Golden, CO: National Renewable Energy Laboratory.
- Maxwell, E.; Wilcox, S.; Rymes, M. (1993). *Users Manual for SERI QC Software: Assessing the Quality of Solar Radiation Data*. NREL/TP-463-5608. Golden, CO: National Renewable Energy Laboratory.
- Perez, R.; Cebecauer, T.; Suri, M. (2013). “Semi-Empirical Satellite Models,” Chapter 2. Kleissl, J., ed. *Solar Resource Assessment and Forecasting*. Waltham, MA: Elsevier.
- Perez, R.; Ineichen, P.; Kmiecik, M.; Moore, K.; George, R.; Renné, D. (2004). “Producing Satellite-Derived Irradiances in Complex Arid Terrain.” *Solar Energy* (77:4); pp. 363–370.
- Perez, R.; Ineichen, P.; Moore, K.; Kmiecik, M.; Chain, C.; George, R.; Vignola, F. (2002). “A New Operational Satellite-to-Irradiance Model.” *Solar Energy* (73:5); pp. 307–317.
- Saha, S., et al. (2010). “The NCEP Climate Forecast System Reanalysis.” *Bulletin of the American Meteorological Society* (91); pp. 1,015–1,057. doi: 10.1175/2010BAMS3001.1.

## 7 Appendix



**Figure 1. The 700-nm AOD for January 2011 and July 2011. Note the huge variation among geographical regions as well as the temporal variation.**

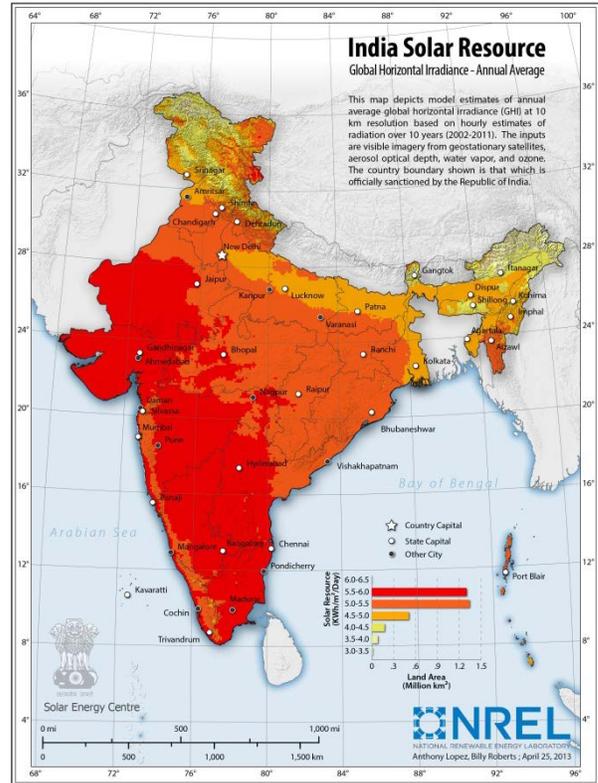
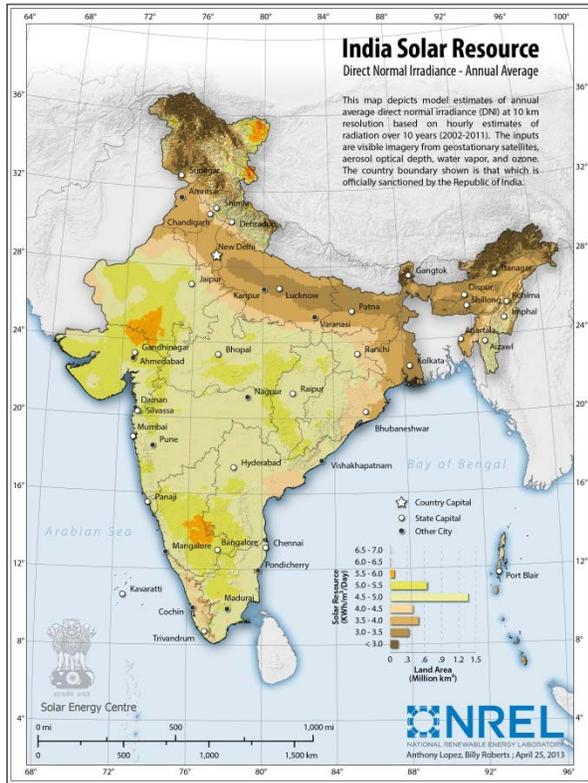
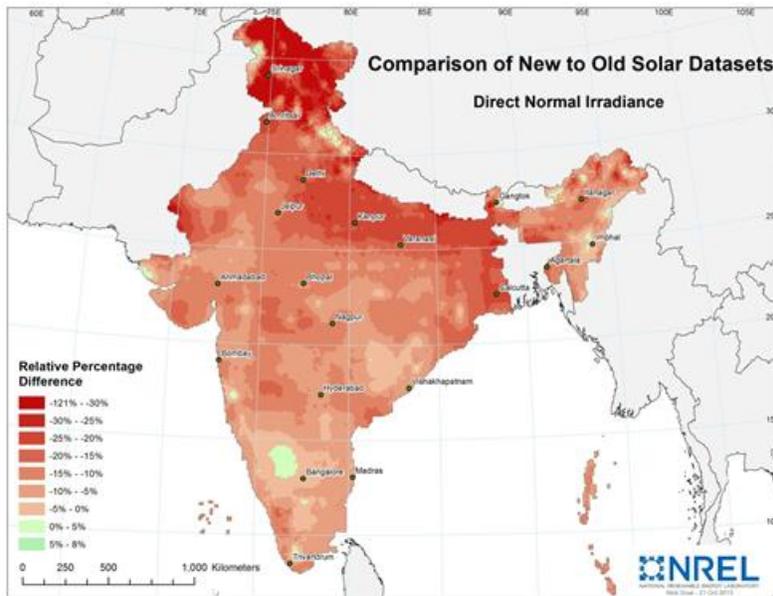
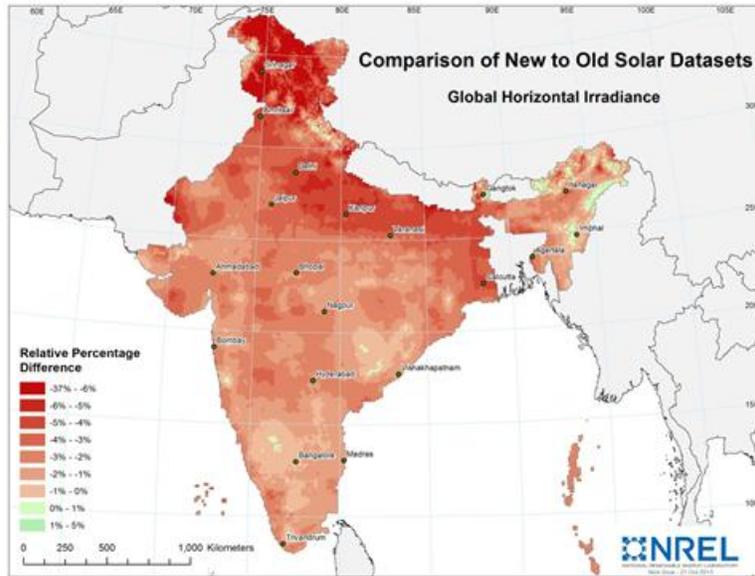
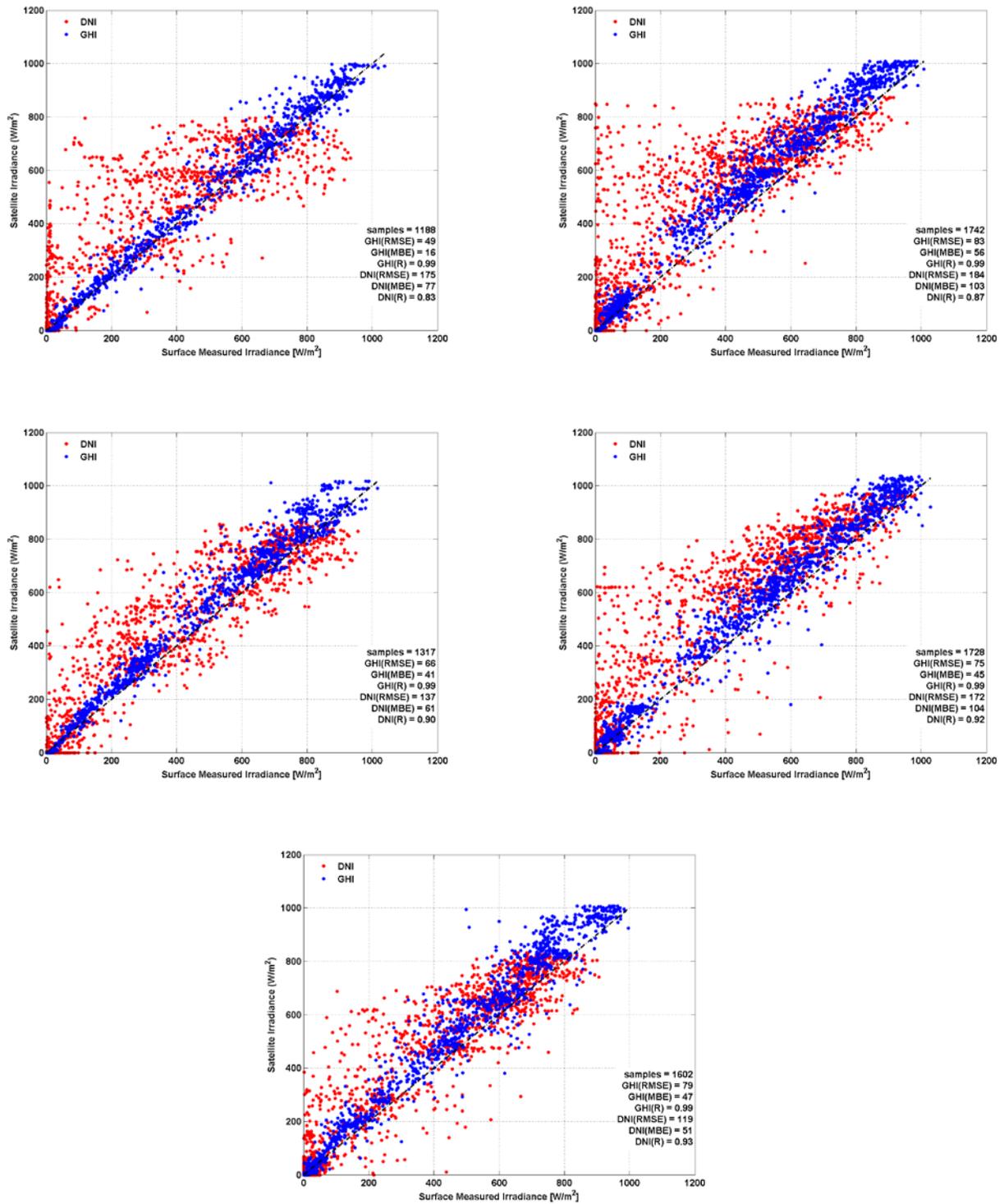


Figure 2. Annual average DNI and GHI from 2002 to 2011



**Figure 3. Comparison of the new data sets to the previous data sets for the GHI and DNI annual averages. The solar resource estimates in the new data sets are lower than they were in the old data sets for both GHI and DNI.**



**Figure 4. Comparisons of ground measurements (Jan. 2012 to June 2012) and satellite hourly data for (blue) GHI and (red) DNI for the (clockwise from bottom) Bijapur, Bhogat, Amarsagar, Chennai (CWET), and Kadiri stations. The GHI from the satellite product is generally in good agreement with the ground data. The DNI data also shows good agreement but has more scatter than the GHI.**

**Table 1. Stations Where Ground-Based Measurements Are Available for Validation**

Station	Coordinates (Latitude, Longitude)	Elevation (m)
Amarsagar	26° 56' 30.89" 70° 52' 27.28"	288
Bhogat	22° 1' 43.2" 69° 15' 40.0"	14
Bijapur	16° 50' 48.5" 75° 45' 5.7"	567
Chennai (CWET)	12° 57' 21.79" 80° 12' 59.75"	1
Kadiri	14° 6' 34.5" 78° 8' 50.1"	531

**Table 2. Difference in DNI Between New and Old Data Sets**

Relative Percentage Difference	Area (km <sup>2</sup> )
-121% to -30%	137,899.36
-30% to -25%	62,979.22
-25% to -20%	387,762.97
-20% to -15%	514,087.84
-15% to -10%	1,082,664.91
-10% to -5%	917,289.11
-5% to 0%	287,862.67
0% to 5%	43,789.64
5% to 8%	1,489.88

**Table 3. Difference in GHI Between New and Old Data Sets**

Relative Percentage Difference	Area (km <sup>2</sup> )
-37% to -6%	117,232.60
-6% to -5%	85,103.88
-5% to -4%	376,601.75
-4% to -3%	489,462.07
-3% to -2%	1,074,811.66
-2% to -1%	934,314.46
-1% to 0%	309,140.77
0% to 1%	44,192.95
1% to 5%	4,965.45

**Table 4. RMSE, MBE, and Correlations (R) Between Satellite-Predicted and Measured DNI**

Station	Hours	DNI (RMSE) W/m <sup>2</sup>	DNI (MBE) W/m <sup>2</sup>	DNI (R)
Amarsagar	2,076	170	60	0.82
Bhogat	1,866	134	60	0.91
Bijapur	2,194	117	52	0.93
CWET	2,377	191	115	0.85
Kadiri	2,337	174	114	0.91

**Table 5. RMSE, MBE, and Correlations (R) Between Satellite-Predicted and Measured GHI**

<b>Station</b>	<b>Hours</b>	<b>GHI (RMSE) W/m<sup>2</sup></b>	<b>GHI (MBE) W/m<sup>2</sup></b>	<b>GHI (R)</b>
Amarsagar	2,076	47	16	0.99
Bhogat	1,866	67	42	0.99
Bijapur	2,194	81	52	0.98
CWET	2,377	89	63	0.98
Kadiri	2,337	79	51	0.99