Solar Resource Assessment Methodology for Northwest India

Introduction

This document describes the development of detailed high-resolution (10-km) solar resource maps for a northwestern portion of India. These maps were created by the United States Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) and the Atmospheric Sciences Research Center (ASRC) at the State University of New York (SUNY)/Albany (USA), in collaboration with the Indian Ministry of New and Renewable Energy (MNRE) in support of the U.S.-India Energy Dialogue.

The solar resource assessment conducted in this study employed a combination of analytical, numerical, and empirical methods. The sections below describe the data sets and analytical methods used to develop the solar data and comparisons of the data products with other solar data sources.

Solar Resource Assessment Methodology

The ASRC has developed a large-area solar resource assessment methodology using the visible image channel from geostationary weather satellites [1]. During the past 10 years, the ASRC has developed and tested their methodology using the Geostationary Operational Environmental Satellites (GOES), which are launched and maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA). Once placed in orbit, these satellites remain at a fixed point above the Earth's surface over the equator. Over the past 25 years, a series of GOES satellites have been launched to cover the entire Western Hemisphere. Among other data sets, these satellites collect high-resolution (~1-km) visible-channel images of the entire hemispheric field of view every 30 minutes.

The ASRC method uses a semiempirical approach to convert visible channel imagery to hourly estimates of solar resources on a 10-km grid. Solar resource estimates include both direct normal insolation (DNI) and global horizontal insolation (GHI). This methodology has been widely used for solar resource assessments in the Western Hemisphere. For example, the model was recently used to produce the 1998-2005 high-resolution data distributed as part of the U.S. National Solar Resource Data Base [2]. Researchers at SUNY and the National Renewable Energy Laboratory (NREL) used the model to develop a solar map of Oaxaca, Mexico, for the U.S. Agency for International Development (USAID) [3], and maps of solar resources in Central America for the United Nations Environment Programme (UNEP) Solar and Wind Energy Resource Assessment (SWERA) project [4]. The model has been extensively validated for these Western Hemisphere applications [e.g., 2].

To estimate solar resources in the Eastern Hemisphere, SUNY adapted the model to use the European Meteosat 5 and 7 geostationary satellites, which are positioned at the longitude of central Asia (57.5^{o} east). This revised model was first used to develop solar resource assessments in Afghanistan and Pakistan [5] and was most recently used to estimate solar resources in northwest India. SUNY and NREL researchers evaluated the model output for India against surface solar measurement data supplied by the Indian Meteorological Department (IMD), National Aeronautics and Space Administration's (NASA's) Surface meteorology and Solar Energy (SSE) data [6], and output from NREL's Climatological Solar Radiation (CSR) model [7].

Comparison of SUNY model output with NASA SSE and NREL CSR output

The NASA SSE data have a resolution of 1° latitude-longitude (~ 100 km at the ground) and are produced by NASA via processing of International Satellite Cloud Climatology Project (ISCCP) data [8]. NREL's CSR data have a resolution of ~ 40 km and are derived from cloud-cover data assembled by the U.S. Air Force. The data covers the entire planet using multiple observational sources, including satellite data, for 1985 through 1991.

The SSE and CSR solar data sets are used as a measure of quality control for the SUNY 10-km resolution data. As shown in Figures 1-4, the SUNY high-resolution data provide somewhat higher values than the CSR and SSE estimates.

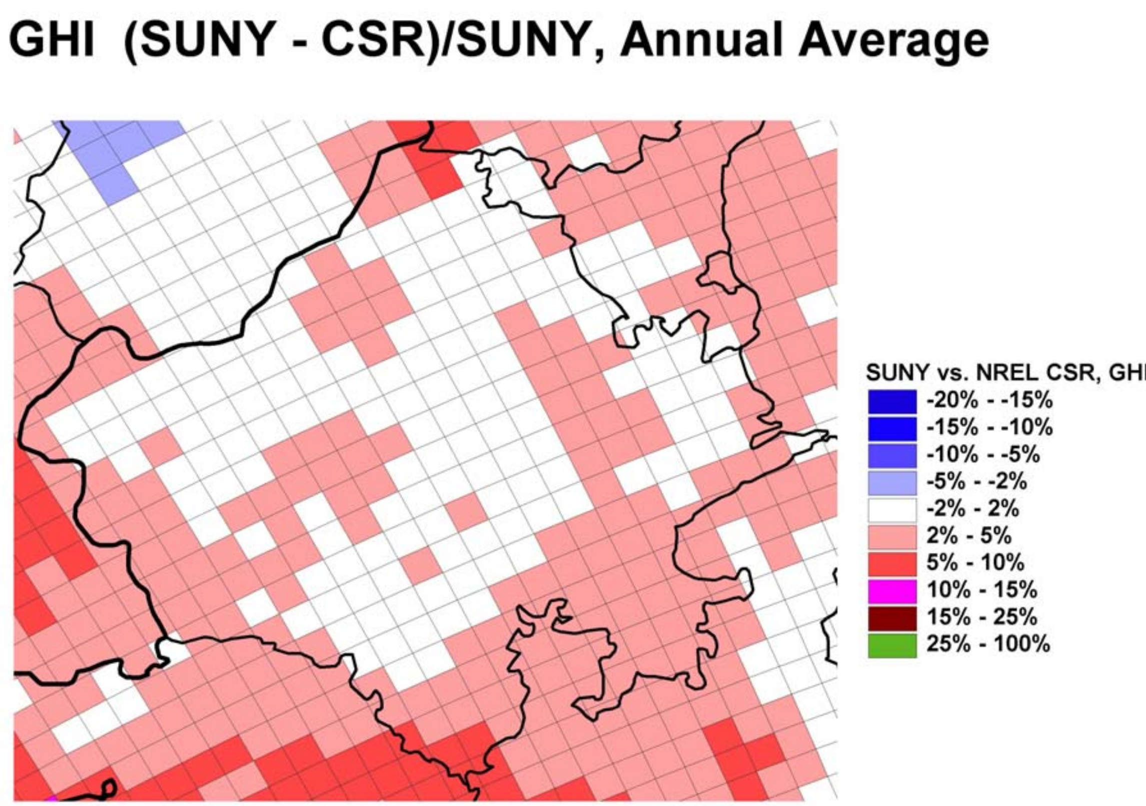

Figure 1. Difference between the SUNY model and the NREL CSR model for global horizontal irradiance. The SUNY model provides slightly higher values than the CSR model.

DNI (SUNY - CSR)/SUNY, Annual Average

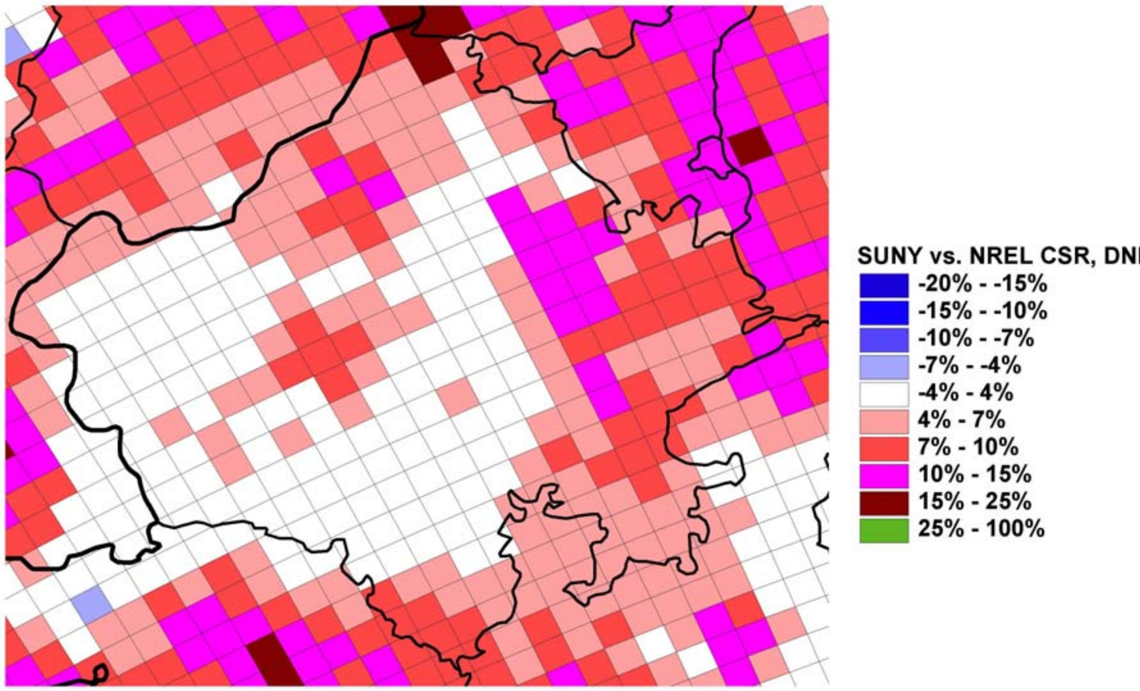

Figure 2. Difference between the SUNY model and the NREL CSR Model for direct normal irradiance.

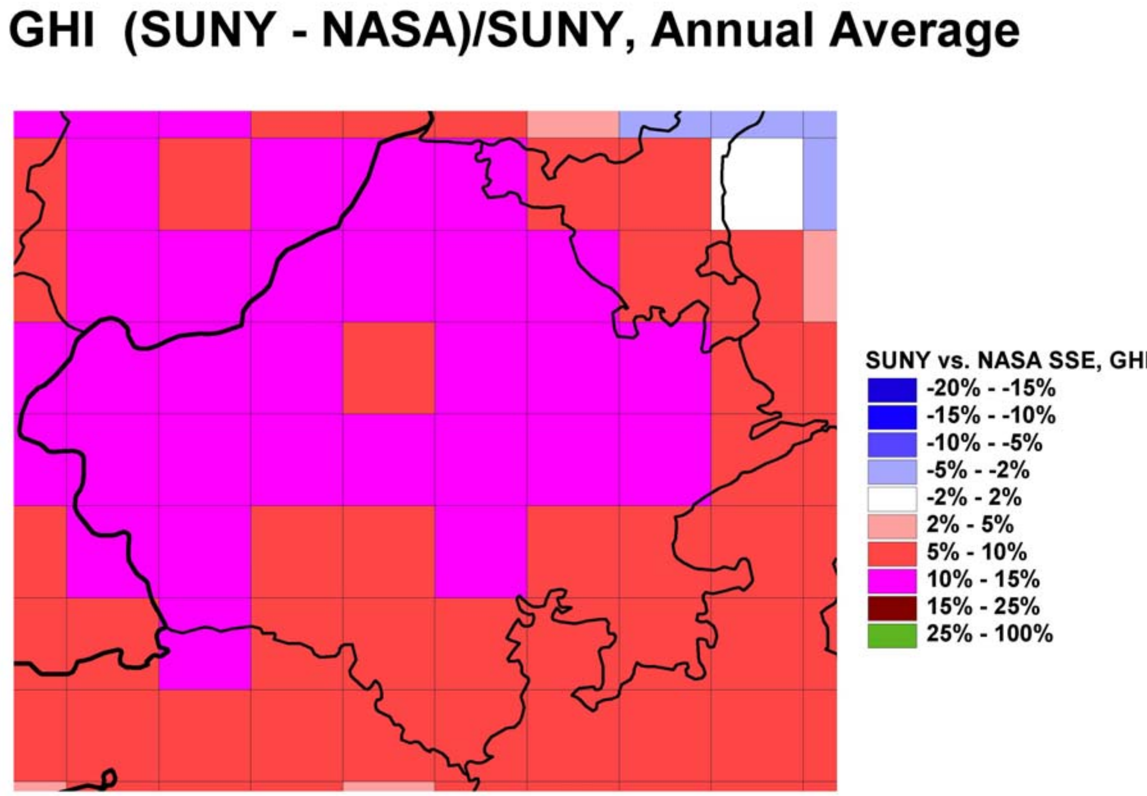

Figure 3. Difference between the NASA-SSE and SUNY-modeled GHI. The SUNY model produces consistently higher values than the NASA model, especially in higher irradiance regions of western Rajasthan. This observation is consistent with recent comparisons between the two methodologies for the arid southwestern United States.

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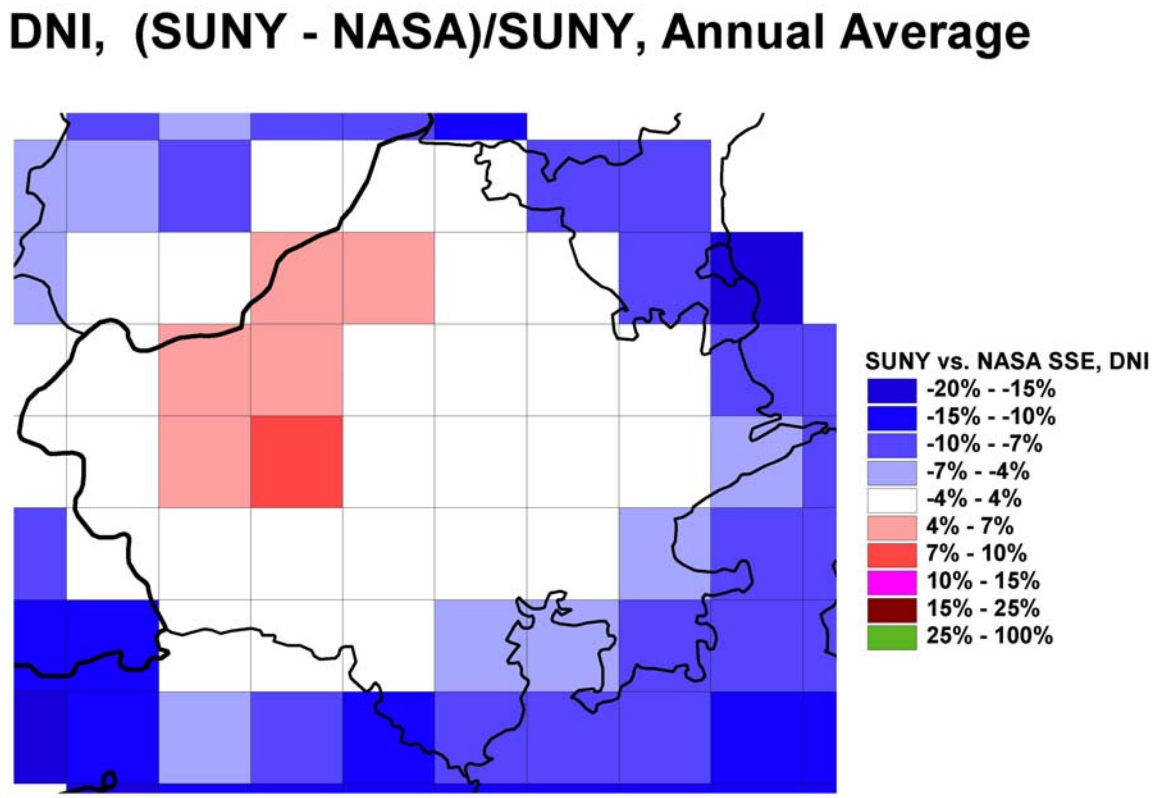

Figure 4. Difference between the NASA-SSE and SUNY-modeled DNI.

Comparison of SUNY model output with ground data from IMD

The results of the ground-truthing evaluation show that in addition to markedly different climatic conditions, there are small but significant differences between the treatment of GOES and Meteosat images, which could affect the accuracy of the SUNY model. These include a different spectral window for the visible channel, and a different processing of the archived images.

In May 2009, analysts will present a paper on the validation of the SUNY algorithm against four ground-truth stations from the IMD solar radiation network located within or near the province of Rajasthan. It will be published in the proceedings of the Annual National Solar Conference 2009, Buffalo, New York, May 13-16, 2009 [9]. The stations include Bhopal, Jaipur, New Delhi, and Jaisalmer. A preview of this validation is discussed here.

An important input data element to the SUNY model is the choice of values for aerosol optical depth (AOD) in the atmosphere. AOD is a unitless parameter that defines the amount of solar attenuation (loss of intensity) attributed to airborne aerosols that can be anticipated between the top of the atmosphere and the Earth’s surface. The SUNY model applied to Afghanistan and Pakistan relied on AOD data from the Moderate Resolution Spectroradiometer (MODIS) flown aboard the U.S. NASA's Terra and Aqua Earth Observing System satellites, combined with the Georgia Tech/NASA Goddard Global Ozone Chemistry Aerosol Radiation Transport (GOCART) model [10]. The satellite data were from only one year (2000). SUNY used this AOD data source for the initial model runs for northwest India. A more recent data set has been derived from a merge of several years of higher-quality MODIS data with information from the Model of Atmospheric Transport and Chemistry (MATCH) developed by the National Center for Atmospheric Research (NCAR) [11]. NREL prepared this newer AOD data set and SUNY applied it to the Jaipur pixel, where ground data are available for both DNI and GHI. This application estimated how AOD would impact the modeling output comparisons with ground data, which is an improvement over the original AOD data applied to the model for this region. The newer data generally show much higher levels of AOD for most of northwest India, resulting in much lower modeled values of DNI, which is very sensitive to AOD. Although the new AOD values improve the comparison with observed DNI at Jaipur, the model still shows an overestimation of 35% with respect to the ground data (Figure 5).

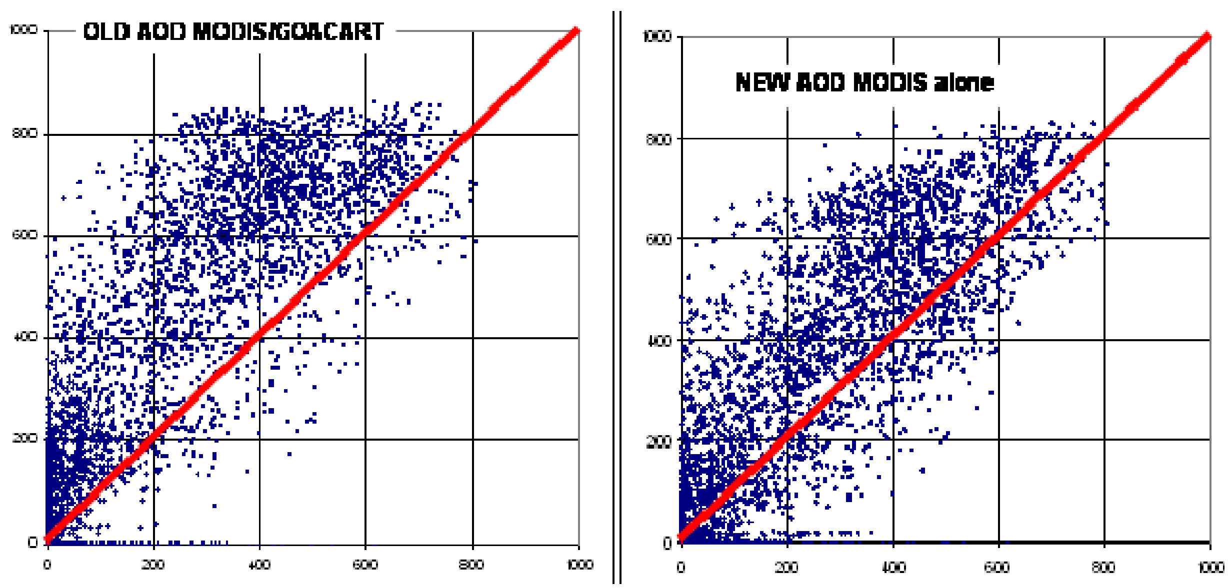

Figure 5. Satellite-derived vs. measured DNI using original and updated AODs

Figure 6 compares the maximum envelope of the original clear sky (Bird) model based on the MODIS/GOCART AOD to that of the updated clear sky model based on MODIS plus MATCH. Although there is a hint of agreement with the DNI profile using the new AOD profile early in the year, both values are well above the ground observations in the latter part of the year. This is an indication that there may have been problems associated with the ground-based DNI measurements, potentially attributed to soiling or tracking issues. This conclusion is further supported in Figures 7 and 8, which compare measured and modeled GHI for both AOD data sets. Figure 7 shows that the new MODIS/MATCH

AOD makes the comparison of modeled GHI with GHI measurements noticeably worse, going from a 2% overestimate to a 7% underestimate. Figure 4 shows that measured GHI agrees quite well with the original AOD. More important, the measured DNI-GHI relationship late in the year does not bear any resemblance to the same early in the year.

The mixed AOD impact on DNI and GHI agreement and the December/January mismatch between measured DNI and GHI suggest that further studies should be done at other ground observational sites. The situation for Jaipur remains unclear, and suggests that IMD and India's Solar Energy Center (SEC) should examine data-quality assessment and calibration procedures at the Jaipur station in greater detail.

Because of these discrepancies, SUNY and NREL researchers decided to continue using the older MODIS/GOCART AOD data sets for the final version of the Rajasthan solar maps.

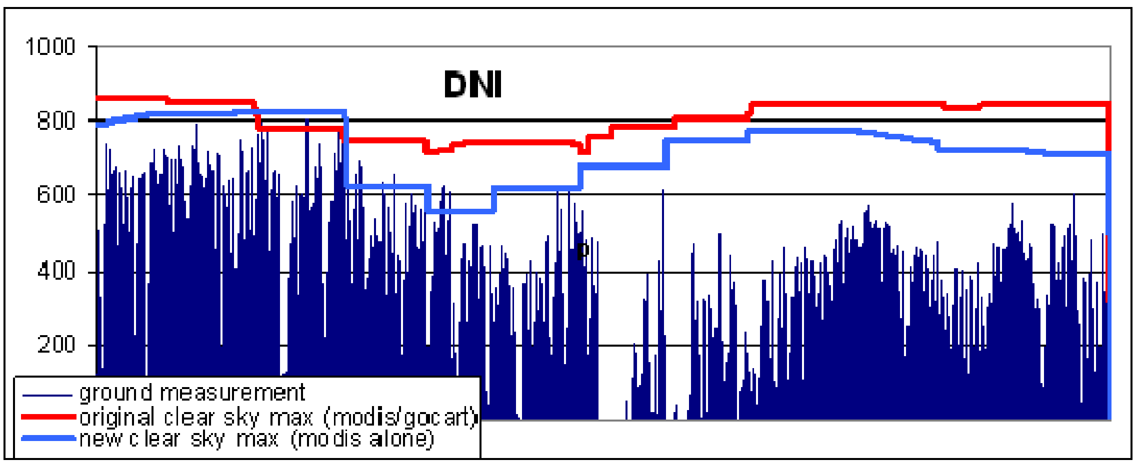

Figure 6. Comparison of measured DNI with original and updated clear sky envelopes.

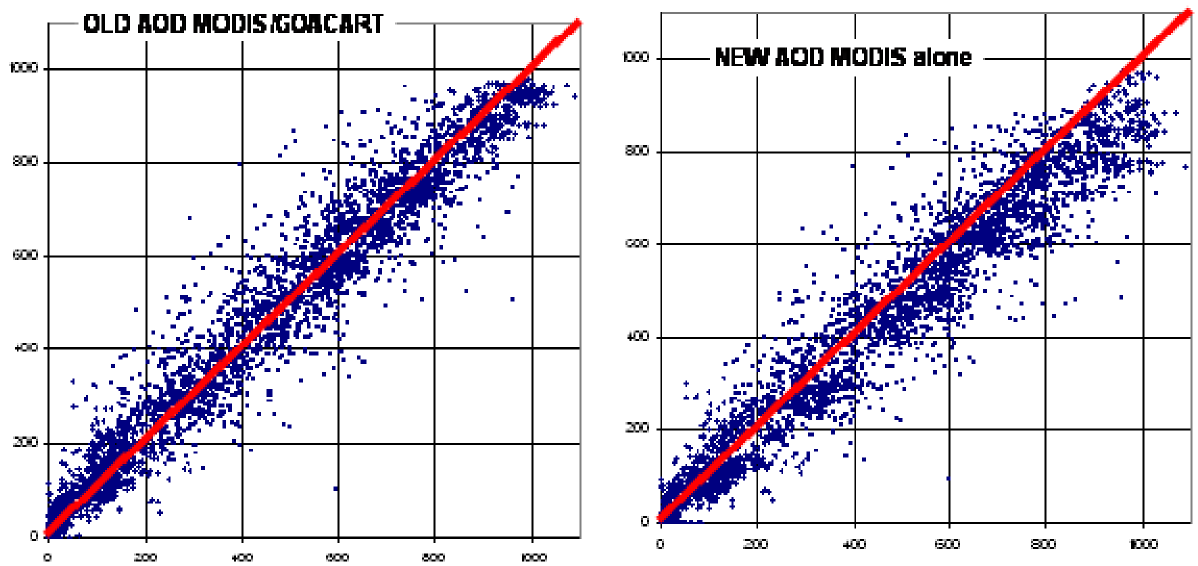

Figure 7. Satellite-derived vs. measured GHI using original and updated AODs.

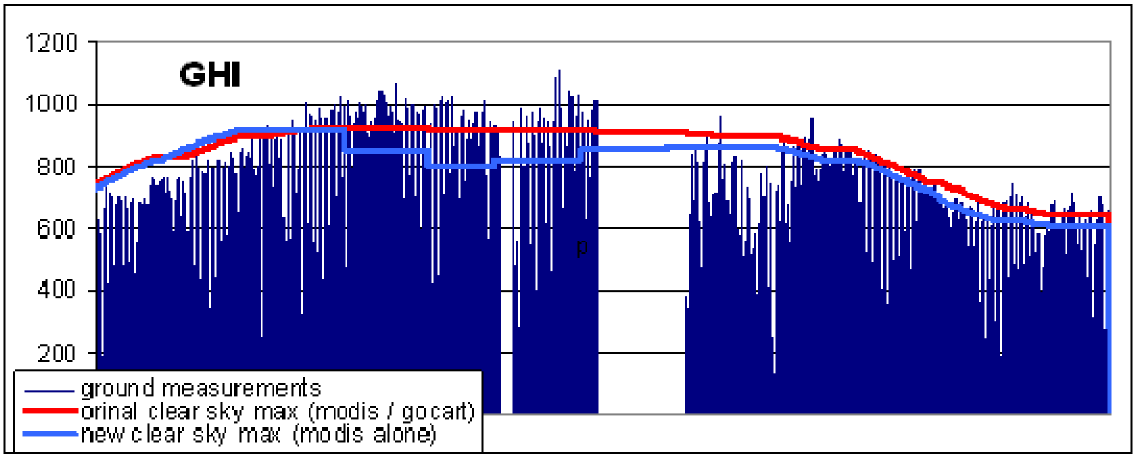

Figure 8. Comparison of measured GHI with original and updated clear sky envelopes.

Conclusions

The solar resource data and maps developed for Northwestern India describe the potential for widespread application of flat-plate and concentrating solar collectors across this region. Comparisons of the SUNY modeling output of GHI with ground data and other available data sets show good agreement, which lends confidence to the satellite-derived data sources. However, the SUNY DNI values show less agreement with the other data sets and particularly with the ground data, indicating that further investigation should be made to identify the source of these discrepancies. These follow-on quality assessment studies are particularly important because this region of India has high potential for concentrating solar power applications, which require high-quality DNI data for proper market assessment and project development.

References

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(3) These maps can be found at http://www.nrel.gov/applying_technologies/maps_atlases_inter_res.html.

(4) These maps can be found at http://unep.swera.net

(5) Maps and documentation for Afghanistan can be found at http://www.nrel.gov/applying_technologies/applying_technologies_afghanistan.html; maps and documentation for Pakistan can be found at http://www.nrel.gov/applying_technologies/applying_technologies_pakistan.html

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(11) Gueymard, C.A. Private communication.