SURFACE RADIATION FROM GOES SATELLITES: IMPROVING RADIATIVE TRANSFER IN A PHYSICAL MODEL

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ABSTRACT

Models to compute global horizontal irradiance (GHI) and direct normal irradiance (DNI) have been in development over the last three decades. These models can be classified as empirical or physical based on the approach. Empirical models relate ground-based observations with satellite measurements and use these relations to compute surface radiation. Physical models consider the physics behind the radiation received at the satellite and create retrievals to estimate surface radiation. While empirical methods have been traditionally used for computing surface radiation for the solar energy industry, the advent of faster computing has made operational physical models viable. The Global Solar Insolation Project (GSIP) uses a physical model that computes DNI and GHI using the visible and infrared channel measurements from a weather satellite. GSIP uses a two-stage scheme that first retrieves cloud properties and uses those properties in a radiative transfer model to calculate GHI and DNI. Developed for polar orbiting satellites, GSIP has been adapted to NOAA's Geostationary Operation Environmental Satellite series and can run operationally at high spatial resolutions. This method holds the possibility of creating high quality datasets of GHI and DNI for use by the solar energy industry. Various radiative transfer models are being considered for improving the GSIP datasets. We will present results of this research and a comparison of improvement from using various radiative transfer models.

1. INTRODUCTION

Achieving higher penetrations of concentrated solar power (CSP) and photovoltaic (PV) power on the grid and reducing integration costs requires accurate knowledge of the available solar resource. Critical to this knowledge is an understanding of the characteristics of the incoming direct normal irradiance (DNI) and global horizontal irradiance (GHI). Knowledge of the impacts of clouds, angle of incidence, spectral distribution, and intra-hour and seasonal variability is essential to accurately design utility-scale CSP and PV projects. This study analyzes the performance and accuracy of the output from the physics-based Global Solar Insolation Project (GSIP) that has been used to characterize the solar radiation resource across the United States. GSIP data sets for the United States were created using measurements from Geostationary Operational Environmental Satellites (GOES). The temporal and spatial evaluation was performed by comparing the GSIP modeled data to concurrent ground measurements. The GSIP model data computes solar irradiance at a resolution of 4 x 4 km using the visible and infrared channels of GOES [1]. High-quality ground-based solar data sets were used to verify the temporal and spatial accuracy of GSIP data. Surface measurements were obtained from the National Oceanic and Atmospheric Administration's (NOAA's) Surface Radiation (SURFRAD) (www.srrb.noaa.gov/surfrad/sitepage.html) and Integrated Surface Insolation Study (ISIS) (www.srrb.noaa.gov/isis/isissites.html), the Solar Radiation Research Laboratory (www.nrel.gov/midc/srrl_bms/) at the National Renewable Energy Laboratory (NREL), and Sun Spot One (SS1) (www.nrel.gov/midc/ss1/). We considered only high-quality ground-based solar data because the quality of data is important in evaluating solar models [2]. The term *high-quality* is used to indicate that station radiometers undergo periodic quality routine maintenance and calibrations traceable to the world radiometeric reference (with typical unceratinity 2% to 5% for such radiometers). The GSIP model uses geostationary satellite measurements in the visible and infrared parts of the spectrum in conjunction with atmospheric profiles from the Global Forecast System weather prediction model to retrieve cloud optical characteristics. This information is then input to a fast radiative transfer model to calculate radiative fluxes [2]. Unlike empirical models based on correlations between surface radiation and satellite measurements, the GSIP model is physics-based and explicitly accounts for nonlinear interactions between clouds and solar radiation. The scarcity of ground-measurement stations and reported inaccuracies in empirical model results makes the GSIP model a possible alternative to provide accurate spatial and temporal irradiance information on a larger scale. The model was run for multiple years for

2 METHOD AND RESULT

Ground-measured and GSIP-estimated GHI data were compared from four locations. A broad filtering was

surface radiation; this study is a preliminary validation of GHI retrieved using the GSIP model.

because the instruments are well calibrated and maintained. The surface data was averaged from 5 min to 120 min at 5-min intervals to represent the spatial extent of the satellite pixel. The 4x4-km GSIP data is available every 30 min. The previous GSIP model

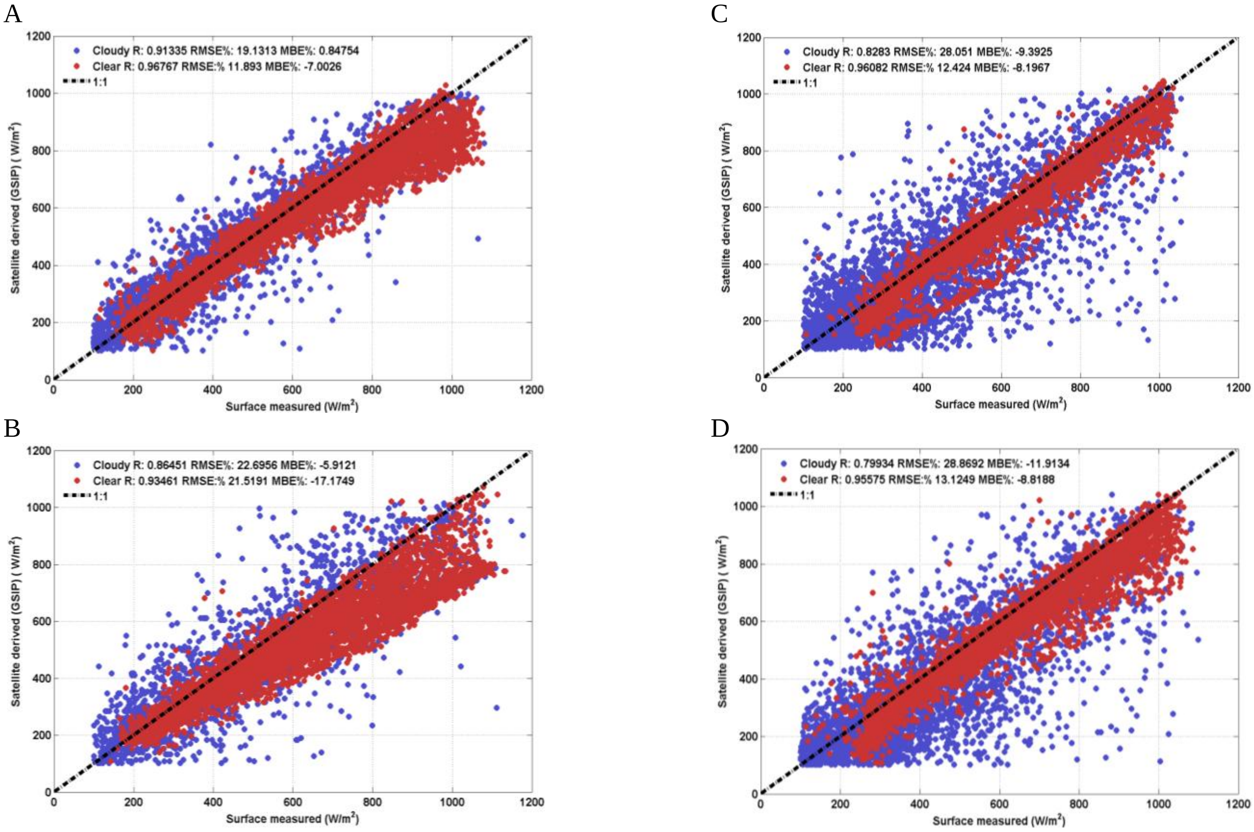

Figure 1. Scatter plots for cloudy and clear sky conditions for (A) Hanford, California; (B) Desert Rock, Nevada; (C) NREL; and (D) SS1.

carried out before the comparison analysis to remove outliers and a high zenith angle data set. Results of differences were calclated as modeled minus ground measured (negative values indicated the model was low). The four locations were NOAA's SURFRAD network's Desert Rock, Nevada, site; NOAA's ISIS Hanford, California, site; NREL; and SS1. These sites were chosen because the ground data is of high quality

version had a 10x10-km grid. From the perspective of the down-looking satellite, ground-based measurements represent a relatively small area above the measurement station. The ground measurements are commonly available at a time resolution of 1 min, which is significantly faster than

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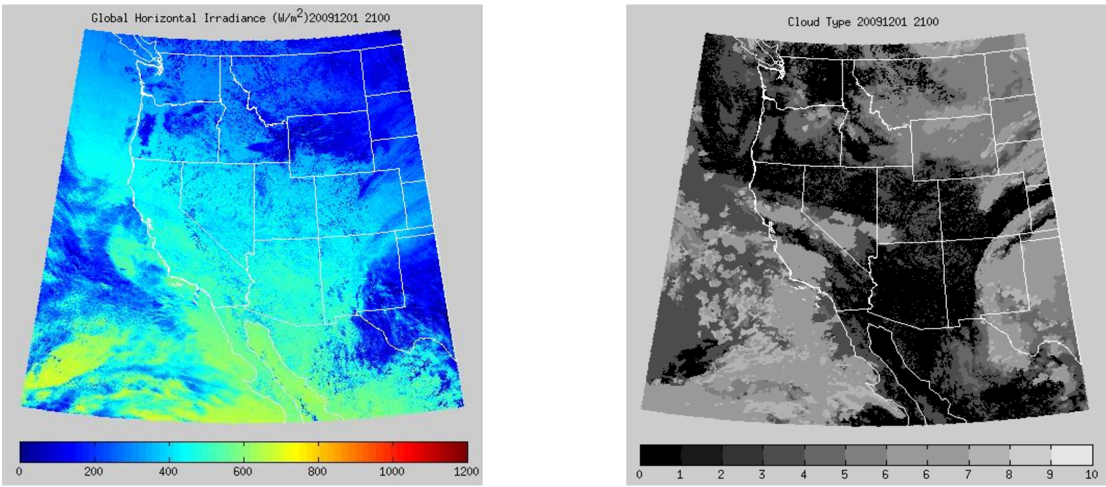

Figure 2. GSIP model outputs for (A) GHI and (B) cloud type for the Western United States for December 1, 2009, at 2100 UTC. Cloud type specification – 0: Clear; 1: Prob_clear; 2: Fog; 3: Water; 4: Supercooled; 5: Mixed; 6: Opaque_ice; 6: Thin_ice; 7: Cirrus; 8: Overlap; 9: Overshooting; 10: Unknown

Table 1. Annual statistics (2009) of correlation (R), mean bias error (MBE%), and root mean square error (RMSE%) for the comparison between the ground measurement averaged to 30 min, 60 min, and 120 min and satellite (30 min) GHI data.

Cloud Type	Annual Statistics	Hanford, CA			Desert Rock, NV			NREL, CO			SS1, CO		
		30-Min Average	60-Min Average	120-Min Average	30-Min Average	60-Min Average	120-Min Average	30-Min Average	60-Min Average	120-Min Average	30-Min Average	60-Min Average	120-Min Average
All	R	0.89	0.9	0.9	0.84	0.84	0.86	0.86	0.87	0.86	0.83	0.84	0.85
	MBE%	-7.48	-7.64	-9.51	-17.66	-17.74	-18.85	-11	-12.2	-16.16	-13.07	-14.43	-18.18
	RMSE %	20.39	20.22	21.67	27.02	26.39	26.96	28.04	28.07	31.05	28.16	28.39	31.31
Cloudy	R	0.9	0.91	0.92	0.84	0.86	0.88	0.82	0.83	0.82	0.78	0.8	0.79
	MBE%	0.85	0.85	0.59	-6.35	-5.91	-5.71	-9.53	-9.39	-9.4	-11.87	-11.91	-12.33
	RMSE %	20.23	19.13	19.07	24.64	22.7	22.13	29.26	28.05	27.95	29.87	28.87	29.33
Clear	R	0.97	0.97	0.96	0.93	0.93	0.94	0.96	0.96	0.96	0.95	0.96	0.95
	MBE%	-7.01	-7	-7.41	-17.53	-17.17	-16.87	-8.11	-8.2	-8.52	-8.67	-8.82	-8.99
	RMSE %	11.89	11.89	12.58	21.8	21.52	21.14	12.51	12.42	13.18	13.37	13.12	13.29

that available from satellite models. The high-frequency ground measurements are very useful for numerous solar resource applications [3], such as irradiance variability over short time intervals. The GSIP data has about 60 output parameters; however, for this study, only the GHI and cloud type were used in the evaluation (Figure 2). For the analysis, the cloud type data from the satellite was used for the clear and cloudy sky classification. Figures 1–4 and Table 1 demonstrate the differences between the

GSIP and ground-measured data. Clear and cloudy conditions were compared separately, with ground-measured data averaged from 5 min to 2 hours at 5-min intervals centered on the satellite measurement time (30 min). The satellite spatial resolution is 4x4 km; therefore, it should be noted that sub-pixel variability in clouds and surface radiation cannot be captured using the satellite data sets (e.g., the varying effects from passing popcorn cumulus clouds).

The frequency distribution of the differences between the ground measurement and the GSIP GHI data appeared to fall between ±100 W/m^2 for the Hanford location and -150 to 50 W/m^2 for the Desert Rock, NREL, and SS1 stations (Figure 3).

For cloudy conditions, as might be expected, the differences showed a higher scatter and a lower correlation coefficient between measured and satellite estimated irradiance data (Figure 1). The correlation was 0.91, 0.86, 0.83, and 0.80 for Hanford, Desert Rock, NREL, and SS1, repsectively, under cloudy conditions, versus 0.97, 0.93, 0.96 and 0.96, respectively, under clear sky conditions. The Desert Rock station (a clearer site) appeared to have lower correlation than the Hanford station. The GSIP model reported lower GHI for clear sky events, especially around solar noon, when the irradiance values were the highest. The four locations had a lower RMSE%, and Desert Rock and Hanford had higher MBE% for the clear sky conditions than the cloudy periods. The higher bias during clear sky events could be related to model misspecification or miscalculation of aerosol optical depth and ground albedo.

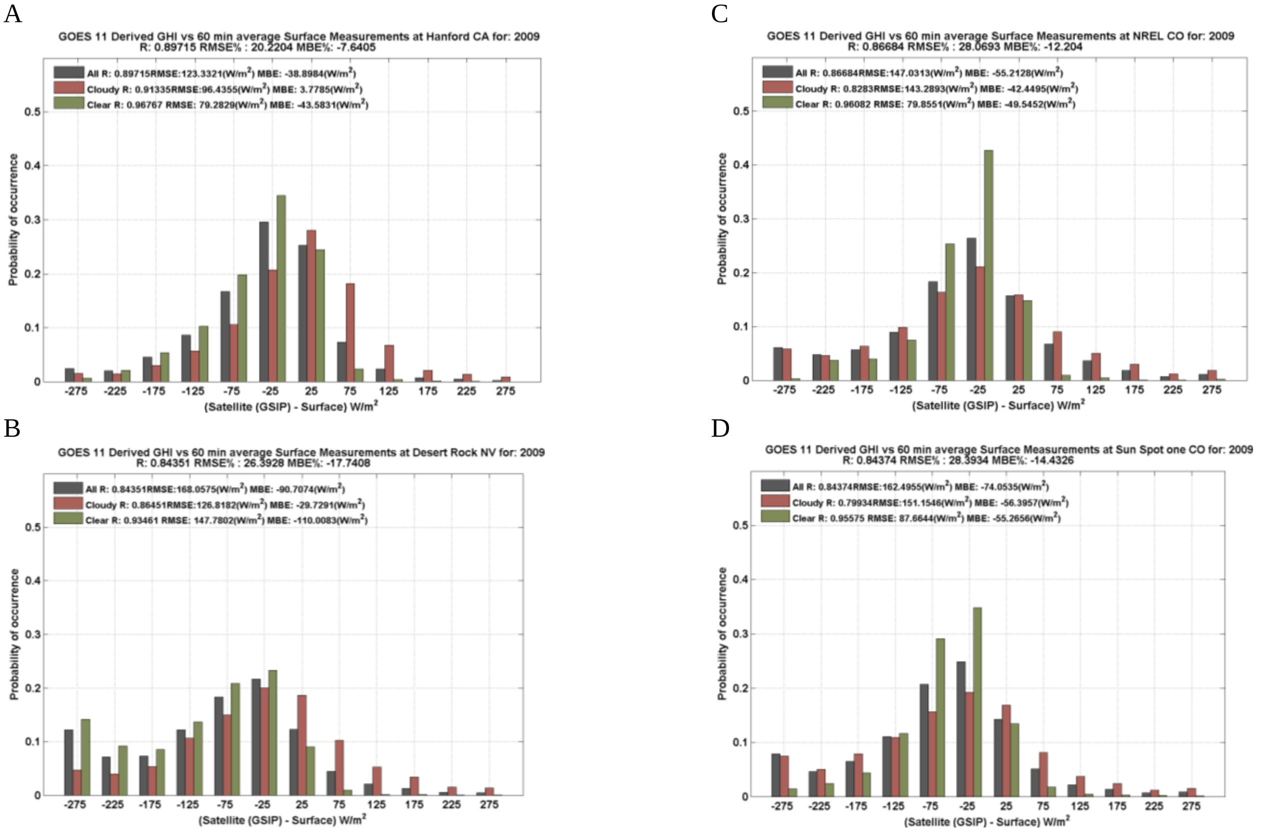

Figure 3. Satellite minus surface measurement for (A) Hanford, California; (B) Desert Rock, Nevada; (C) NREL; and (D) SS1. Negative difference means the satellite GHI data was lower than the surface measurement.

Overall, the results of the bias from this study were similar to the study done by [4], which compared empirical models to ground measurement. As shown in Figure 1, the GSIP model data appeared to lie below the 1:1 line, particularly under clear sky conditions, which indicates ground measurement is often higher than the GSIP model. To understand this situation, the GSIP model was also compared to the Bird clear sky model [5] under clear sky conditions. The results showed that the GSIP model underperforms under clear sky conditions for GHI (figure 5). Therefore, the model requires refinement in addressing these situations, and areas for further

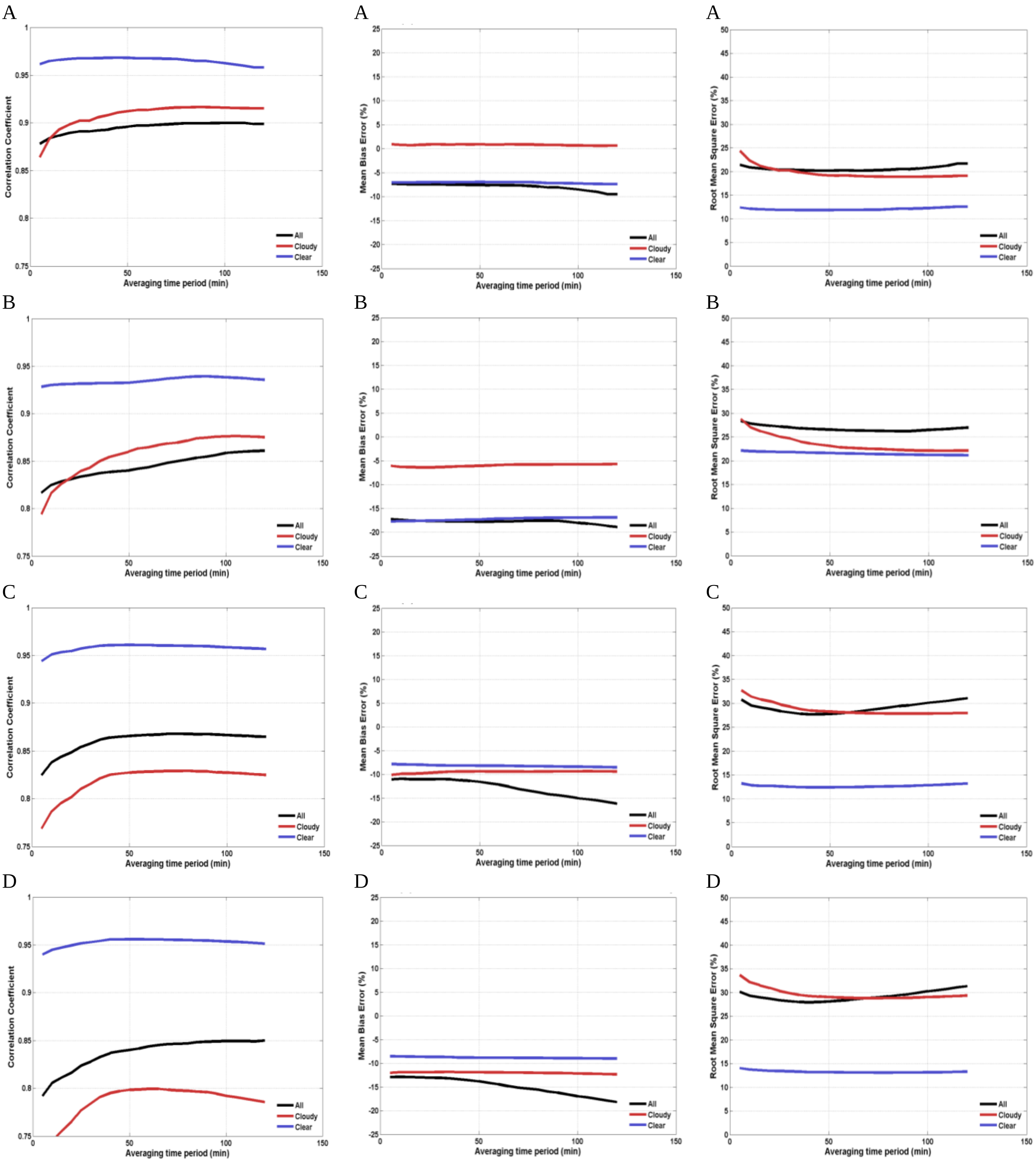

Figure 4. Correlation, MBE%, and RMSE% values under cloudy, clear sky, and all conditions for (A) Hanford, California; (B) Desert Rock, Nevada; (C), NREL; and (D) SS1.

investigation could include greater accuracy in clear sky ground albedo, aerosol estimates, water vapor estimates, and clear sky optical properties.

A satellite pixel represents a nominal 4-km square area; whereas a ground measurement is only a point on the ground. Therefore, we took various time averages of the ground measurement (abscissa of Figure 4) to investigate which time average periods best matched the time interval centered on the GSIP measurement time.

Figure 4 (middle plots) shows that the systematic (bias) differences were relatively constant for all averaging periods. In most cases, the random or root mean square differences decreased as the averaging period increased, probably because of the cancellation of some of the random differences over longer periods of time. The 60-min time average appeared to be a reasonable averaging period for comparing the ground GHI measurement data to the GSIP GHI data; however, it should be noted that for Desert Rock cloudy conditions, the correlation between ground and satellite improved beyond the 60-min averaging time period.

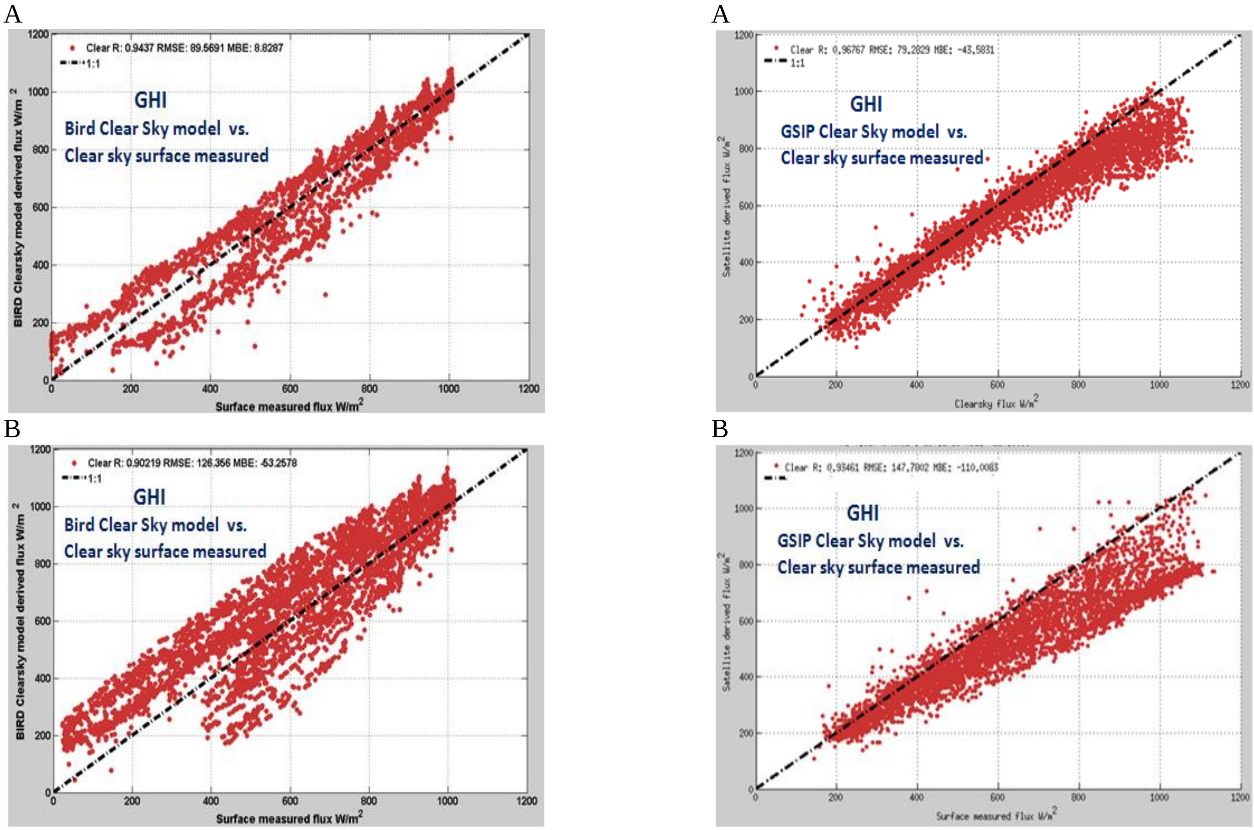

Figure 5. Scatter plot showing the difference between the Bird model and GSIP model under clear sky conditions for (A) Hanford, California, and (B)Desert Rock, Nevada. The units of RMSE and MBE described on the legend are in W/m^2.

The differences (MBE%, RMSE%, and R) on a monthly average basis were also analyzed (Figure 6), and the results were consistent, as mentioned above. In most cases, the percent MBE was lower during summer months than during the rest of the year. Zenith angle effects in both modeled and measured data in the winter months may have contributed to higher MBE in those months. RMSE was lower in almost all months under clear sky conditions than cloudy conditions. Further, the magnitude of RMSE difference between clear sky and cloudy conditions for each month was smaller for the desert environment, such as the Desert Rock station,

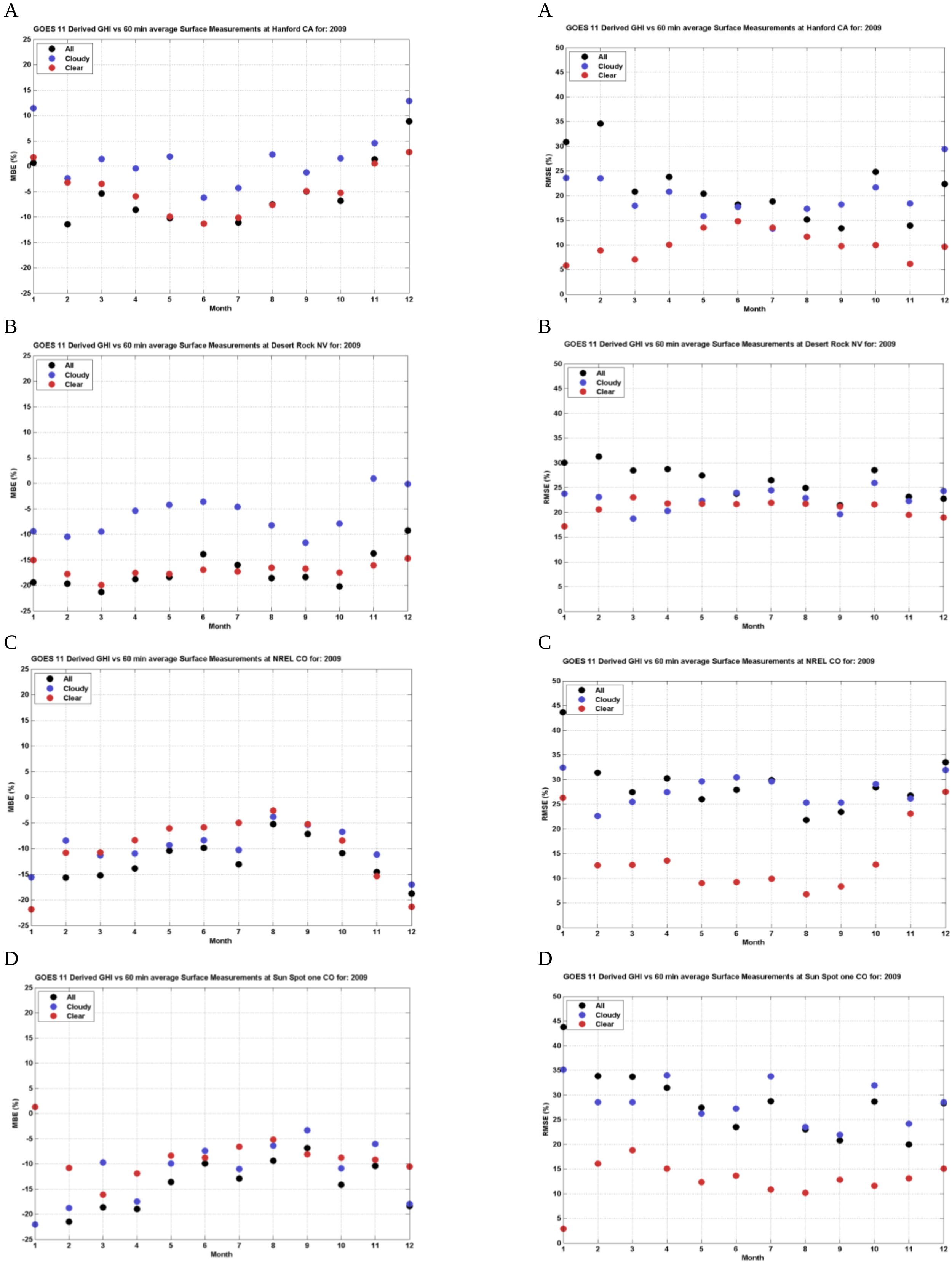

Figure 6. Monthly MBE% and RMSE% for (A) Hanford, California; (B) Desert Rock, Nevada; (C) NREL; and (D) SS1.

than the relatively cloudier stations, such as NREL and SS1; however, MBE difference had the opposite effect.

3. SUMMARY

The GSIP physical model has a higher spatial (4 km) and temporal (30 min) resolution than some other empirical-based models, such as the hourly and 10-km resolution State University of New York Perez model [6] and the European METEOSAT-based Heliostat model [7]. Greater spatial resolution will be beneficial to more accurate solar resource data for CSP and PV projects in areas of high spatial variability [2], [8]. The GSIP averages of clear GHI data demonstrated better correlation to ground-measured clear sky data than averages from the cloudy periods, but clear sky averages had a higher bias, generally negative. Moreover, the ground-measurement data performed better than the GSIP model in capturing the short-term variability of irradiance for a narrow integrated time interval for a specific point on the Earth's surface. However, satellite-based surface radiation data sets are primarily useful for long-term solar resource assessment applications, and in that area the model should be competent once bias issues are addressed. The model requires refinement in addressing clear sky ground albedo, aerosol estimates, water vapor estimates, and clear sky optical properties. Aerosols are external data sets that can be provided to the model. The surface albedo becomes an issue in the current GSIP radiative transfer model [9]. This surface albedo is calculated from the visible satellite channel when a clear sky point is detected. Elevated albedo's show up under certain sun satellite geometries, and those situations result in lower GHI than actual in the current radiative transfer scheme.

Future investigation of the GSIP model will be performed by comparing the model to other empirical models and more extensive comparison with high-quality ground-based measurements. Further, incorporating a larger number of parameters from the GSIP model output in such evaluations could help identify sources of discrepancies between the model's performance and ground-based measurements. The work continues on producing estimated DNI and diffuse from the model, and a future report will evaluate performance for those parameters. Further, future work will also include addressing the use of better aersol data and albedo estimates and applying them to a better clear sky radiative transfer model that properly accounts for the parameters.

4 ACKNOWLEDGEMENTS AND DISCLAIMER

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