A PHYSICAL METHOD TO COMPUTE SURFACE RADIATION FROM GEOSTATIONARY SATELLITES

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ABSTRACT. *Since the advent of weather satellites there has been a continuous effort to retrieve global horizontal irradiance (GHI) and direct normal irradiance (DNI) using those measurements. The development has followed two paths leading to models that are either empirical or physical based on the approach. Empirical models relate ground-based observations of surface radiation with satellite measurements. These relations are then used to compute GHI and DNI. On the other hand physical models consider the physics behind shortwave and infrared radiation received at the satellite and create retrievals of the properties of atmospheric constituents. These retrieved properties are then used in a radiative transfer model to estimate surface radiation. The empirical models are attractive for their speed and simplicity and have been used widely by the solar energy industry. The advent of faster computing has made physical models operationally viable. The Global Solar Insolation Project (GSIP) is a physical model that computes GHI using the visible and infrared channel measurements from a weather satellite using a two-stage approach. Cloud properties, that have the largest impact on GHI, are first retrieved and subsequently used in a radiative transfer model to calculate surface radiation. Originally developed for measurement for the Advance Very High Resolution instrument on polar orbiting satellites, GSIP has been adapted to the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operation Environmental Satellite (GOES) series and can run operationally at high spatial resolutions. This method holds the possibility of creating high quality datasets of GHI for use by the solar energy industry. This paper outlines the method and presents some validation results using high quality ground-based measurements.*

Keywords*: Global horizontal irradiance, GHI, Empirical models, Physical models, Global Solar Insolation Project, GSIP, GOES data*

1. INTRODUCTION

The cost of developing utility-scale solar thermal power plants runs into the hundreds of millions of dollars. Determination of new power plant sites requires detailed analyses of multiple considerations, including the availability of transmission lines, amenable terrain, and accessibility. Perhaps the most important factor in site selection involves the availability of sufficient solar energy at the surface. This is true for both the concentrated solar power technology that requires DNI and photovoltaic technology that uses both GHI for operating the energy collection devices.

Addressing the challenge of solar energy availability requires a comprehensive long-term analysis of multiyear surface solar radiation estimates at high spatial and temporal resolution. The most straightforward method is to have well-calibrated instruments such as radiometers located at the surface to take multiyear measurements. These instruments, if maintained well, can provide high quality datasets. However, the high cost of running surface networks limits their use to selected locations. The Baseline Solar Radiation Network (Ohmura et al., 1998) under the auspices of the World Meteorological Organization, Surface Radiation (SURFRAD) (Augustine et al., 2000) under the National Oceanic and Atmospheric Administration (NOAA) and United States Department of Energy Atmospheric Radiation Measurement Program (ARM) (Ackerman and Stokes, 2003) operates networks of surface radiometers for various research and operational purposes. As these networks are sparsely distributed, they cannot serve the needs of the solar energy industry. The National Solar Radiation Database provides simulated solar radiation at the surface based on observations from 293 sites (Renne et al., 2008).

An alternative method for obtaining long-term surface solar radiation data involves retrieving surface flux from satellite measurements. The geostationary satellites used for this purpose offer broad spatial coverage and high temporal resolution. The current Geostationary Operational Environmental Satellite (GOES) series of satellites, operated by the National Oceanic and Atmospheric Administration, provides nominal 4-km resolution coverage of the continental United States at every half-hour (Weinreb et al., 1997). Such coverage from the current series of satellites has been available from 1994, thus providing the potential to develop a long-term, high temporal and spatial resolution surface radiation dataset that will be of utmost necessity to the solar energy companies.

2. CURRENT METHODS

Surface radiation can be derived from satellite measurements in two ways. One method is to form empirical relationships between multi-spectral satellite radiances and surface radiation as measured from terrestrial-based instrumentation (hereafter referred to as the empirical method) (Perez et al., 2002). These empirical relationships are used to compute surface flux directly from satellite measurements.

The second method (hereafter referred to as the physical method) uses a two-stage process. The first stage involves creation of a cloudy/clear-sky mask and cloud type (e.g., cirrus, cumulus, stratocumulus) from multi-spectral satellite measurements (Stowe et al., 1999 ; Heidinger, 2003 ; Pavlonis et al., 2005). The second stage involves the use of the cloud information in a fast radiative transfer model to compute the downwelling surface flux properties while physically accounting for cloud transmittance (Pinker et al., 2002; Laszlo et al., 2008).

Whereas the empirical method is attractive because of its speed, there is the potential for large inaccuracies due to the non-linear relationships that exist between the satellite-measured radiance fields, the cloud properties, and the surface radiation. Therefore, the physical method is expected to produce more accurate results as the two-stage process deals explicitly with these non-linear interactions between clouds and radiation.

2.1 Empirical method

The currently available surface solar radiation datasets used by industry involve empirical fits to the satellite data. Computations are done on the central pixel of a 10 km X 10 km grid box, and the result is then taken as being representative of that box. The data are available hourly for an 8-year period (1998–2005) and are provided by the NOAA National Data Centers for use by the community. This data is also part of the National Solar Radiation Database.

2.2 Physical method

The first stage of the physical method includes the physical retrieval of cloud microphysical and optical properties via a complex multi-stage algorithm that is applicable to multiple satellites. The retrieval algorithm first creates a cloud mask and cloud type using ancillary information including surface type, land-sea masking, surface elevation, and monthly climatologies of sea surface temperature and normalized vegetation index over land. The algorithms vary according to satellite, based on channel characteristics and the availability of a given radiometer. These methods have been applied to the Advanced Very High-Resolution Radiometer[7] (AVHRR), the Moderate-Resolution Imaging Spectroradiometer (MODIS) (Ackerman et al., 2006), and most recently to anticipating capabilities of the future GOES-R Advanced Baseline Imager (ABI) (Heidinger and Calvert, 2008). Among these algorithms, the “Clouds from AVHRR” (CLAVR) algorithm for AVHRR (Stowe et al. 1999) is perhaps the most rigorously tested, as it has been used operationally for several years.

Full radiative transfer computations are slow and cannot be adopted for operational purposes. As such, the second stage involves a fast computation of surface radiation using the cloud information obtained from the first stage (Pinker et al., 2002; Laszlo et al., 2008; Pinker and Laszlo, 1992).

An extended version of the CLAVR algorithm, called CLAVR-x (Heidinger, 2003), has been adapted for the Global Solar Insolation Project (GSIP), which was developed at University of Wisconsin-Madison for operational use by NOAA and is currently undergoing operational testing at NOAA-National Environmental Services Data and Information Services. With assistance from NOAA and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison, a version of the GSIP code has been installed at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University-Fort Collins.

3. RESULTS

The physical -based GSIP algorithm has been set up to run in real time for the GOES-11 satellite. Satellite data is collected from the NOAA National Environmental Services Data and Information Services servers, and Global Forecast System data is collected from the National Weather Service servers. These two datasets are combined with ancillary information about surface type, land/sea mask, surface elevation, sea surface temperature, and other climatological data to produce cloud mask, type, and properties. The cloud information serves as input to a fast radiative transfer scheme that produces surface radiation for every satellite pixel in the scene (Li et al., 2007) (e.g., Figure 1). In these runs the cloud properties are retrieved every half-hour at a nominal resolution of 4 km to match the spatial resolution of the infrared channel on the GOES-Imager. The surface radiation, though, is computed at $1/8^{o}$ resolution and includes information from approximately a grid of 3X3 satellite pixels for which the cloud properties have been retrieved.

Data Type		**Desert Rock, NV**		**Hanford, CA**	
		30 min avg	**60 min avg**	**30 min avg**	**60 min avg**
All	**R**	0.95	0.95	0.95	0.95
	RMSE	97.32	94.14	88	86.22
	MBE	19.81	25.01	-16.07	-10.06
Overcast	**R**	0.90	0.92	0.92	0.94
	RMSE	128	112.87	112.47	101.76
	MBE	-5.23	-7.41	-63.80	-62.83
Partly Clear	**R**	0.96	0.96	0.94	0.96
	RMSE	89.9	83.74	97.52	88.57
	MBE	40.26	37.75	-34.01	-37.41
Partly Cloudy	**R**	0.97	0.97	0.97	0.98
	RMSE	77.03	74.55	76.88	67.75
	MBE	41.54	39.95	-12.50	-13.55
Clear	**R**	0.99	0.98	0.99	0.99
	RMSE	50.46	49.37	38.93	38.62
	MBE	16.30	16.09	-11.10	-9.39

Table 1: Correlation (R), root mean square error (RMSE) (W/m^2) and mean bias error (MBE) (W/m^2) for comparisons between satellite-derived surface GHI and measured GHI averaged to 30 minutes and 60 minutes. One year of data (2009) was used for this comparison where clear, partly cloudy, partly clear, and overcast represent the quartiles that progressively represent cloud cover.

Surface-based measurements provide an excellent tool for validation of the satellite-based algorithm. We therefore selected sites located at Desert Rock, Nevada, and Hanford, California, NOAA SURFRAD and Integrated Surface Irradiance Study sites, respectively. These sites have quality-controlled irradiance measurements available every minute. For our comparisons with the satellite retrievals, surface GHI was averaged from 5 minutes to 2 hours centered on the satellite measurement. The satellite retrievals are available every 30 minutes. Monthly (not shown) and annual comparisons were made for different cloud scenes classified as (a) overcast, (b) partly clear, (c) partly cloudy, and (d) clear to represent decreasing cloudiness derived from the cloud fraction value. These cloud fraction values are calculated using GSIP's cloud retrieval scheme. The results of the annual comparisons are shown in Figure 2, Figure 3, and Table 1. The GHI correlations from all the sites show that the satellite-derived values are well correlated with the surface observations with correlations around 0.95. As expected, the clear sky periods have the highest correlation of 0.99. It is observed that the retrievals are slightly better correlated with a lower root mean square error for surface data averaged over larger time intervals (60 minutes or more), as seen in Figure 3. Those cases with high cloud cover have higher root mean square error and lower correlations. Biases in cases of high cloud cover are also higher, as seen in Figure 3.

4. CONCLUSIONS AND FUTURE WORK

A physical-based, two-stage algorithm for retrieving surface irradiance has been created for the GOES series of satellites but is useful for any other geostationary series of satellites. The goal of this research was to investigate the quality of the surface flux derived from GOES data using the physical method for selected locations in the United States. The desert southwest region is of particular interest to solar utility developers because of the low climatological occurrence of clouds in this region. Validation of the quality of the datasets being produced is necessary to build confidence in the user community. The retrievals were verified using surface-based measurements from Desert Rock, Nevada, and Hanford, California, and the results shown in Figure 2 indicate that the retrievals are realistic and useful.

Future plans include (1) gathering sufficient surface radiation datasets for different sites in the United States to validate the GSIP results, and (2) setting the stage for a comparative study of the quality of the data being produced via GSIP and those using various empirical methodologies (Sengupta et al. 2004). Our hope is to build on this analysis and create a 10- to 15-year high-quality surface radiation dataset that can be used by industry for site location purposes. In addition to the retrospective work proposed here, we plan to examine the skill of surface solar radiation forecasts based on realistic regional-scale models (including explicit cloud microphysics) for the purpose of predicting future power availability. The latter is of keen interest to industry and can be validated through the satellite tools being developed for this phase of the work.

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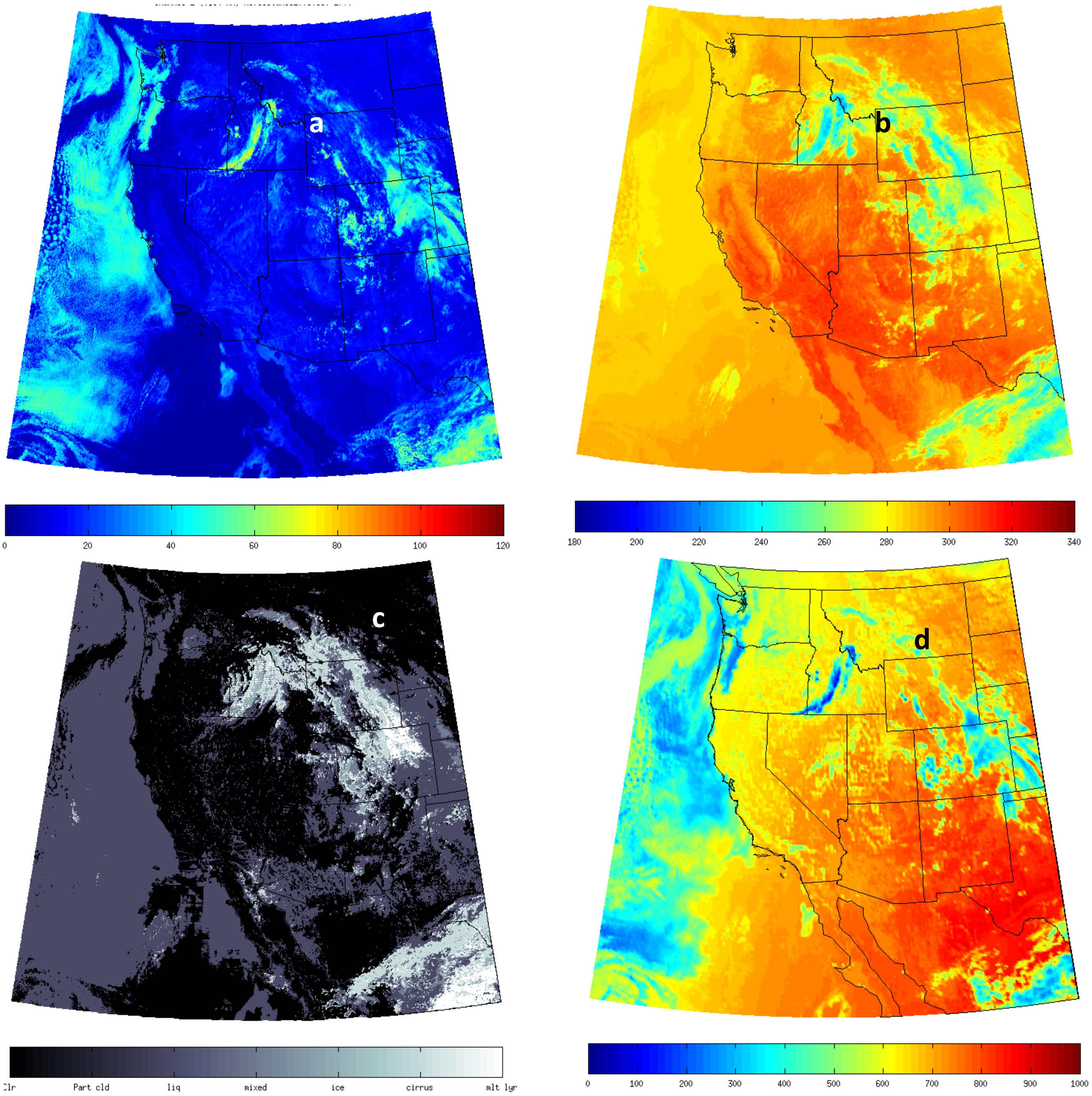

Figure 1. Visible reflectance (1a) and infrared brightness temperature (1b) from GOES 11 and the corresponding cloud (1c) and surface radiation (1d) retrievals for August 30, 2009, at 1700 UTC.

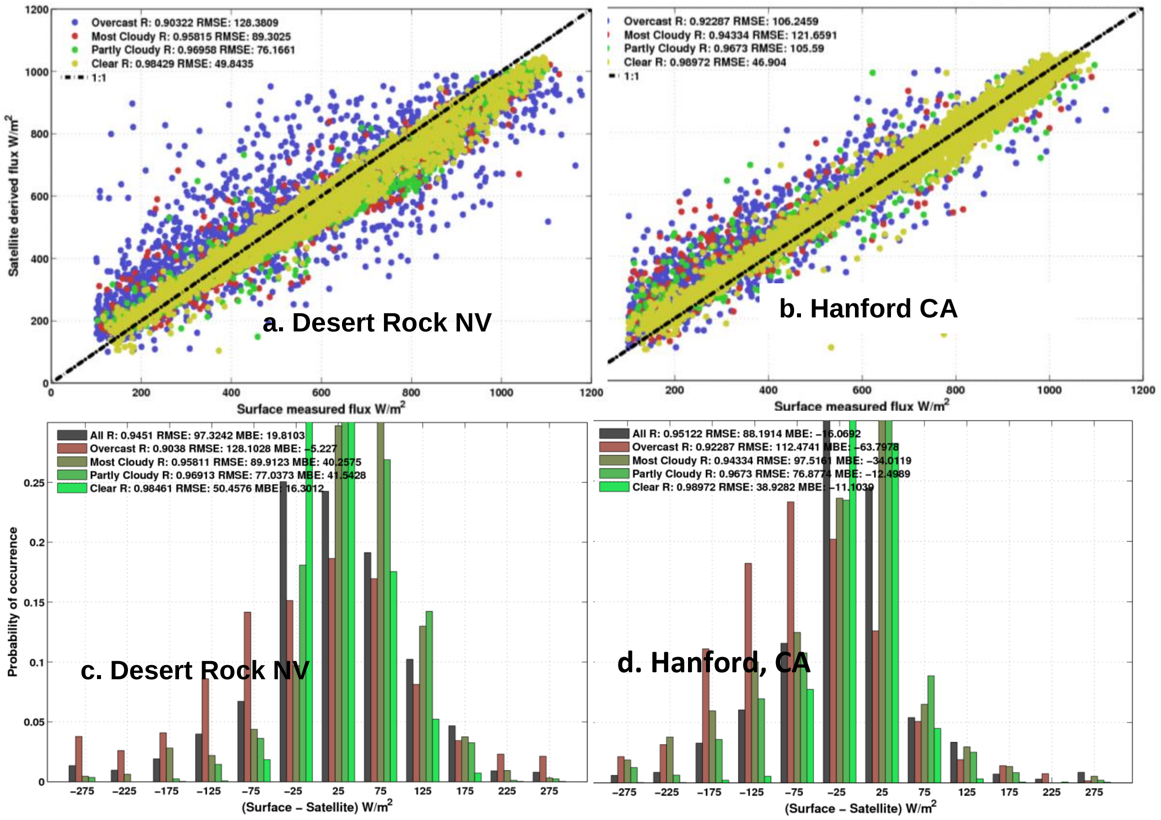

Figure 2. Comparison of GHI measured at Desert Rock, Nevada, (2a and 2c) and Hanford, California, (2b and 2d) with retrievals from the GOES-11 satellite for 2009.

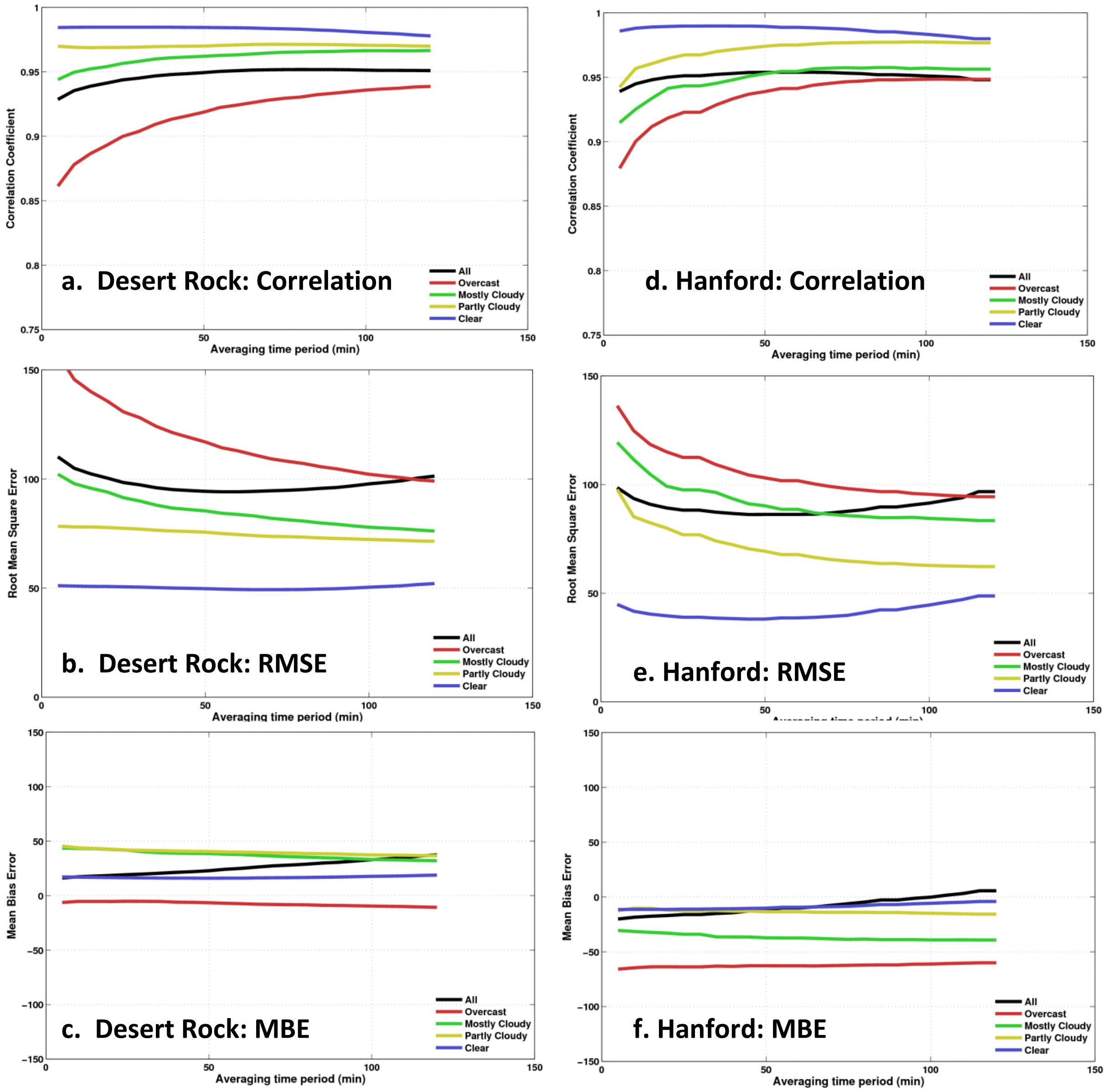

Figure 3. Statistics of the comparison of Global Horizontal Irradiance measured at (a, b &c) Desert Rock, Nevada, and (d, e & f) Hanford, California, with retrievals from the GOES-11 satellite for 2009. The ground measurements are averaged from 5 minutes to 120 minutes centered on the satellite observations.